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# Structural Analyses and Oblique Negative Inversion Tectonics of Gara Baran, Part of Baikher Anticline, Kurdistan Region/ Iraq

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## ABSTRACT

The anomalous case of Gara Baran which is a part of a very long Baikher Anticline, is carried out using high-resolution structural analyses such as Fold Geometry, Harmonic (Fourier) analysis, Vertical Investigation of fold style, and Formation Thickness analysis. The Geometrical analysis of three traverses reveals that it is an asymmetrical anticline with average dips of the northeastern and southwestern limb (26°) and (22°) respectively and verging towards the northeast. The Fourier analysis exposes that the shape of the northeastern limb is more developed than the southwestern one. Moreover, the shape of the northeastern limb becomes less developed towards the northwest, whereas the shape of the southwestern limb becomes developed in the same direction. The Vertical Investigations analysis shows that the fold is asymmetrical and verging towards the northeast from Cretaceous to Middle Eocene, except the folding of Pila Spi Fm. which is verging towards the southwest. The fold axis and axial plane are rotated anticlockwise from the Cretaceous to the Paleogene. The dips of bedding planes are reduced towards the younger formation where the interlimb angle increases in the same direction. Formations thickness study shows that Gara Baran is influenced by negative tectonics inversion; which suffered reverse displacement during the Cretaceous to Early Eocene followed by a normal movement during the Middle to the Late Eocene due to the effect of suture listric fault. Fourier and Geometric analyses confirm that the listric fault reduces its effect towards the northwest, so this inversion can be called Oblique Negative Inversion tectonics.

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# التحليلات التركيبية والارتكاس التكتوني السالب المائل في كارا باران، طية بيخير المحدبة، إقليم كردستان، العراق

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**الملخص**

ان الوضع الشاذ لطية كارا باران التي هي جزء من طية بيخير المحدبة قد خضعت لتحليلات تركيبية دقيقة مثل التحليل الهندسي، تحليل فورير ، الاستقصاء العمودي للطية وتحليل سماكات التكوينات الجيولوجية. أظهر التحليل الهندسي ان طية كارا باران طية غير متماثلة وان ميل الجناح الشمالي الشرقي والجنوبي الغربي يساوي 26° و22° بالتوالي وتميل نحو الشمالي الشرقي. أما تحليل فورير فيكشف ان شكل الطية اكثر متطوراً في الجناح الشمالي الشرقي عنه في الجناح الجنوبي الغربي، وان تطور الجناح الشمالي الشرقي يقل باتجاه الشمال الغربي بينما يزداد في الجناح الجنوبي الغربي لنفس الاتجاه. وضح الاستقصاء العمودي ان الطية غير متماثلة مائلة نحو الشمال الشرقي من العصر الطباشيري الى عصر الايوسين الاوسط، عدا الطي في تكوين البلاسبي فظهر انها غير متماثلة مائلة نحو الجنوب الغربي. وظهر ان اتجاهي محور الطية والمستوي المحوري قد انحرفا باتجاه عقرب الساعة من العصر الطباشيري الى عصر الباليوجين. وان ميل اجنحة الطية تقل نحو التكوينات الاحدث وبالتالي تزداد الزاوية الداخلية بنفس الاتجاه. دراسة سماكات التكوينات الجيولوجية أظهر تعرض كارا باران الى ارتكاس تكتوني سالب. حيث انها عانت من حركة معكوس للفالق اللستيري في الفترة من العصر الطباشيري الى عصر الايوسين المبكر، ولحقتها حركة اعتيادية لنفس الفالق في عصر الايوسين الأوسط والمتاخر. كما أكد التحليل الهندسي وتحليل فورير ان الفالق اللستيري قد قل نشاطه باتجاه الشمال الغربي، وهذا يعني ان الارتكاس التكتوني السالب هو من النوع المائل.

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## Introduction.

Gara Baran is a part of the Baikher Anticline in addition to Spi Raiz. The two are considered segments within Baikher Anticline. These segments are separated by a saddle at Germawa village which is covered by Duhok Lake. In this work, Gara Baran is dealt with as an anticline because it looks like an anticline within a major one. Baikher Anticline is one of the major structures in the Foreland Folds Belt within the high folded zone of the Western Zagros Fold/ Thrust Belt (WZFTB). It is located in the northern part of Iraq. The study area is located between longitudes (42° 47' 48.6825") -(42° 59' 44.2503"E) and latitudes (36° 52' 25.2161") - (37° 02' 58.2449"N), (Fig. 1).

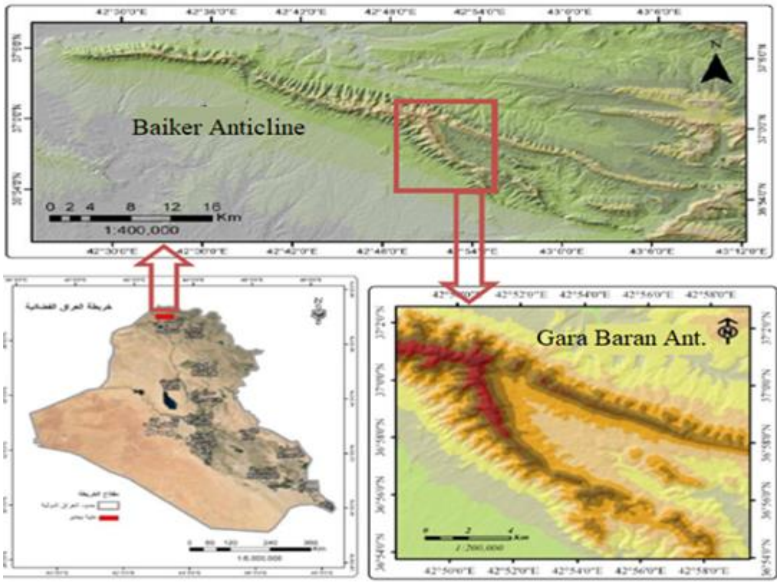


**Fig. 1. Location of Gara Baran Anticline.**

Al-Azzawi and Al Hubiti (2008) have divided the Baikher anticline according to its vergence into four parts. The first (Spi Raiz) and the third parts (between Gara Baran and Zakho Gally) are verging toward the southwest; whereas the second (Gara Baran) and the fourth ones (between Zakho Gally and the northwest plunge) are verging toward the northeast. This Anticline is an asymmetrical plunging in the first and second traverse but it is non-plunging in the third traverse- it is like Baikher is generally extended northwest-southeast (Fig. 1).

Stratigraphically, this structure comprises many exposed geological formations extended in the period from the Late Cretaceous to Late Miocene; and they include Bakhme, Shiranish, Kolosh, Gercus, Pila Spi, and Fatha where Injana appeared, mainly, in the northern limb only. The description of these formations, according to Bellen et al. (1959) is shown in Table (1).

**Table 1. The exposed formations in the Gara Baran part of the Baikher anticline and their basic characteristics.**

| Formations | Geological Age | Lithology | Field characteristics |
|---|---|---|---|
| Injana Formation | Late Miocene | It consists of fining upward of sandstone, siltstone, marlstone, and claystone | Coarse and medium-grained carbonate-rich sandstone alternating with brownish-red siltstones. |
| Fatha Formation | Middle Miocene | alternating mud rocks, limestones, gypsum, anhydrite, and halite | These rocks have a color range from grayish-brown to yellowish-white and are thin-bedded, marly, and fractured. |
| Pila Spi Formation | Middle to Late Eocene | well-bedded bituminous chalky and crystalline limestones | It has high barriers and is exposed along the fold, and its outer borders represent lines of tilt interruption |
| Gercus Formation | Middle Eocene | it is exposed as red siliciclastic successions of claystone and sandstone with occasional conglomerate | Red in color because it contains iron oxides and basalt in the northwestern part |
| Kolosh Formation | Paleocene-Early Eocene | Its sequences consist of siltstone, medium to thin beds of calcareous shale marlstone, less common conglomerate, and limestone with calcareous silt shale inter-layers | Its color is green because it contains clay minerals |
| Shiranish Formation | Late Cretaceous | The formation contains thinly-bedded shales, bedded of limestone, white in color, highly jointed, and consists of two strata of conglomerate and argillaceous well-bedded blue marly limestone, highly fractured | Thin layers surround the core of the fold. |
| Bakhme Formation | Late Cretaceous | thick and massive bedded limestone and dolomitic limestone which are highly impregnated with bituminous Materials | represented by the core of the fold |

Previously, few works have studied this area, some of these studies are concentrated on the structure of the area and the others could be marginal. Many regional studies mildly mention the structure of Baikher Anticline such as Doski and McClay, 2022; Al-Duski, 2004 and Al-Shaibani, 1973. However, this anticline's structure is thoroughly detailed in two studies which are Ameen, 1979 and Al-Alawi, 1980, suggesting that Baikher Anticline consists of two parts. The first part is located between Zawita village and Germawa valley and is called Spi Rais Fold, whereas the second one occupies the area between Germawa valley and Sheizi village and is named Gara Baran Fold. Al-Azzawi and Al Hubiti (2008) have also studied Baikher Anticline and divided it into four parts as they are mentioned above.

The motivation of this work is to make high-resolution analyses for the Gara Baran part, that is because the analysis of the individual traverse of Al-Azzawi and Al Hubiti (2008) is not enough to confirm the anomalous case of Gara Baran which is verging towards the northeast. The objective of this work is to prove and confirm this anomalous case. Accordingly, structural analyses of Gara Baran in three traverses to obtain its main geometric properties using the stereographic projection method have been studied, to explore the development of fold shape along the traverses via Fourier analysis (Harmonic analysis), and to investigate the inversion tectonics which is caused by the displacement of listric fault.

## Methodology.

### 1. Geometric analysis of fold using π-diagram:

Analysis of Gara Baran Anticline is carried on using three traverses, which are distributed equitably to demonstrate the geometric differences along the anticline. Data obtained along these traverses are examined using stereographic projection of π-diagrams. The average attitudes of fold parameters are determined by the analysis of the traverses. Collecting the dip and strike from traverse by Compass or Clinometer, analyzing them in the office and laboratory by π-diagram. The stereographic projection will expose most of the geometrical fold parameters using the manual method and by software called (Stereo Net V 10,2008) Accordingly, measurements of the bedding plane produce π- a diagram that exposes all the fold parameters. The geometric analysis of the study of Gara Baran anticline is based on finding the attitudes of the elements of the fold such as the interlimb angel, fold axis, the axial plane axis of the fold, as well as symmetry and asymmetry for each of the three transverses. In addition, classifying the fold according to the aforementioned classifications, then comparing the results and interpreting the changes between the three traverses.

### 2. Fourier Analysis:

Fourier analysis is a solution of a series of trigonometric functions (sines and cosines) to represent the shape of a quarter wavelength from the hinge point to the inflection point of any fold. Mathematics for this method was fully described by (Headings, 1963) and (Kreyszig, 1967), and its procedure and application were explained by (Ramsay and Huber, 1987; Al-Azzawi, 2003; Al-Azzawi and Al-Hubiti, 2008). Fourier coefficients can be determined by drawing the fold profile using the Busk method (Busk, 1929). Each limb is analyzed separately and the shape of the fold is found in it by taking the quarter-wavelength (AQW) of the fold in each traverse. Then, the three vertical axes called Stabler axes, which are (y1, y2, y3), are drawn by measuring them directly from the structural profile that represents the upper surface of the Pila Spi Formation which maintained its thickness during folding (Class 1B, Parallel fold).

### 3. Determination of thicknesses:

It is found that there are several ways to find the true thickness of the layers or geological formations. The method used in this research is taken from (Rowland, 1986) as it is considered one of the best methods used to find the true thickness of the exposed geological formations in the study area. The matching case is where the dip of the bed and the slope of the earth's surface are in the same direction. (Fig. 2), uses this equation $t = h \sin \theta - v \cos \theta$. This case corresponds to the Pila Spi Formation in the northern and southern limb of the fold and all traverses.

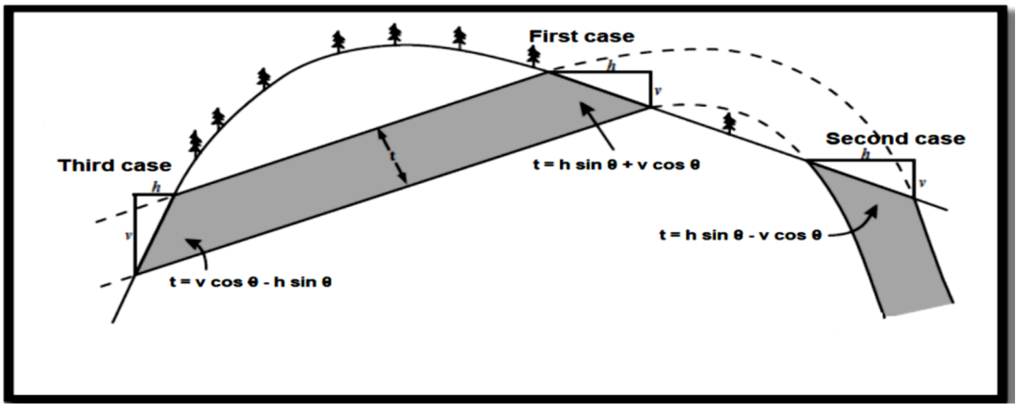


**Fig. 2. Three cases and methods of true thickness measurement of inclined bed (Rowland, et. al, 2007).**

## The Structural analyses

### 1. The geometric analysis;

### 1.1 First Traverse:

Data analysis of this traverse reveals that the dip of the northeastern limb is steeper than that of the southwestern limb, they are 32$^o$ and 28$^o$. Respectively, the interlimb angle is equal to 122$^o$, the plunging and fold axis attitude is 141/04$^{o,}$ and the axial plane attitude is 321/88. This means that the anticline is asymmetrical and verging towards the northeastern. The fold is Gentle according to the classification (Fleuty, 1964). The anticline is considered a sub-horizontal, upright (Fleuty, 1964), horizontal upright fold according to Rickard (l97I), horizontal upright fold (Robert, 1982), (Fig. 3), and cylindrical fold (Ramsay and Huber, 1987).

### 1.2 Second Traverse:

This traverse's data analysis shows that the interlimb angle is equal to 140$^o$, the fold axis is (143/ 02$^o$) and the axial plane attitude is (322/87$^o$). The dip of the northeastern limb is (24$^o$) but the southwestern limb is (21$^o$). This means that the anticline is asymmetrical fold (Hills, 1953 and 1963; Billings, 1972) and verging towards the northeastern. Accordingly, Gara Baran Anticline is considered as a gentle fold and sub-horizontal upright fold (Fleuty, 1964), horizontal upright fold (Rickard, l97l; Roberts, 1982) (Fig. 3), and cylindrical fold (Ramsay and Huber, l987), (Fig. 3).

### 1.3 Third Traverse.

The π-diagram of the fold in this traverse shows that the dips of the northeastern and southwestern limbs are equal to 23$^o$ and 18$^{o.}$ Respectively, it is a non-plunging fold axis (146/00$^o$) and the axial plane is vertical (326/90$^o$). Therefore, the fold in this traverse is considered as an asymmetrical fold according to (Hills, 1953, Hills, 1963 and Billings, 1972). The interlimb angle is 145$^o$. Gara Baran Anticline is considered a gentle fold and sub-horizontal upright fold (fleuty,1964), horizontal upright fold (Rickard, l97l; Roberts, 1982), and cylindrical fold (Ramsay and Huber, l987) (Fig. 3).

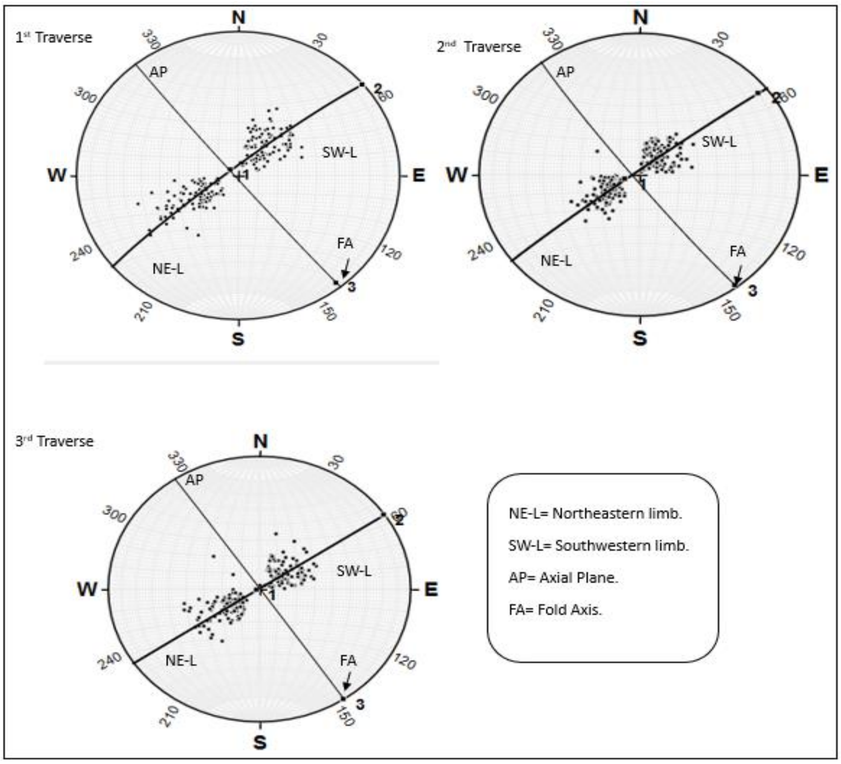


**Fig. 3. Represents the π-diagrams of the three traverses.**

## 2. Fourier Analysis:

### 2.1 First Traverse:

Fourier analysis is used to find the shape of the fold in this traverse. From the analysis of the northeastern limb of the fold in this traverse which extends from the village of Kamaka to the area near Qarqarava village, it is found that the base of quarter wavelength (AQW) is equal to (5 cm) and that the values of the Stabler axes are. (Fig. 4).

y1=1.4cm y2=1.6cm y3=1.8cm

To convert them to standard Yi values, the following equation is used

Y= y * π/ (2*AQW) Y1=0.4396cm Y2=0.5024cm Y3=0.5652cm

And then the three Fourier coefficients can be found using Stabler equations

b1=(Y1+√3Y2+Y3)/3 b3= (2Y1 - Y3)/3 b5=((Y1-√3Y2+Y3)/3

b1=0.6249941086 b3=0.1046666667 b5= 0.04487255809

After finding the three Fourier coefficients, the Fourier ratio is equal to (0.1674682458). From the plotting of the values of Fourier's coefficients onto the Huddleston chart, it appears that the fold (semi ellipses-box fold) (Fig. 5A), and appears on the chart of Singh and Gairola, the fold (Almost Semi-Ellipse Folds), (Fig. 5B).

Whereas the southwestern limb which extends from Qarqarava to Shakhke villages, has Stabler axes equal to the following:

y1=1.8cm y2=3.1cm y3=4.1cm

The base of the quarter wavelength which is equal to (4.5cm), the standard axes values, (Fig. 4) are as follows:

Y1=0.628 Y2=1.081555556 Y3=1.430444444 According to,

b1=(Y1+√3Y2+Y3)/3 b3= (2Y1 - Y3)/3 b5=((Y1-√3Y2+Y3)/3 So that,

b1 =1.310584539 b3 =-0.058148148 b5= 0.0617117566

So that the Fourier ratio is equal to (-0.04436810161), by plotting the values of the Fourier coefficients onto the charts, it is found that the shape of the fold in this limb is (Chevronic-Sinusoidal fold), according to the Huddleston classification, (Fig. 5A)., and a (Chevron – Sinusoidal Fold) according to the classification (Singh and Girola, 1992), (Fig. 5B). The average Fourier ratio of northeastern and southwestern limbs is (0.06155007185).

**2.2 Second Traverse:**

This traverse extends from the village of Beshinge to the area near Butiya village, and its base is of quarter wavelength which is equal to (4.9cm), (Fig. 4), after measuring the values of the Stabler axes, the result of Fourier ratios of the northeastern limb is 0.1472559617, it is found that the shape of the fold in this limb is (Almost Semi-Ellipse Folds) according to the Huddleston classification, (Fig. 5A). , and a (Almost Semi-Ellipse Folds) according to the classification (Singh and Girola, 1992), (Fig. 5B).

Whereas the southwestern limb which extends from Butiya to the kevla villages has a base of the quarter wavelength equal to (5.7cm), (Fig. 4), after measuring the values of the Stabler axes, the result of Fourier ratios of the southwestern limb is 0. It is found that the shape of the fold in this limb is (A sine wave fold) according to the Huddleston classification, (Fig. 5A), and a (sinusoidal fold) according to the classification (Singh and Girola, 1992) (Fig. 5B). The average Fourier ratio of northeastern and southwestern limbs is (0.07362798085).

**2.3 Third Traverse:**

It is extended from the village Shawrik to the area of Ghazi Ava village and it is found that the base of the quarter wavelength is equal to (4.5cm). (Fig. 4), after measuring the values of the Stabler axes. the result of Fourier ratios of the northeastern limb is 0.1344572761. It is found that the shape of the fold in this limb is (Parabolic-Semi-Ellipse Folds) according to the Huddleston classification, (Fig. 5A), and (Almost Semi-Ellipse Folds) according to the classification (Singh and Girola, 1992). (Fig. 5B).

Whereas the southwestern limb extends from Ghazi Ava to Seje villages, and it is found that the base of the quarter wavelength is equal to (6.5cm). (Fig. 4), after measuring the values of the Stabler axes. The result of Fourier ratios of the southwestern limb is 0.0189300605 it is found that the shape of the fold in this limb is (Sinusoidal – Parabolic Folds) according to the Huddleston classification, (Fig. 5A), and a (Sinusoidal – Parabolic Folds) according to the classification (Singh and Girola, 1992). (Fig. 5B). The average Fourier ratio of the northeastern and southwestern limbs is (0.0766936683) (Table 2).

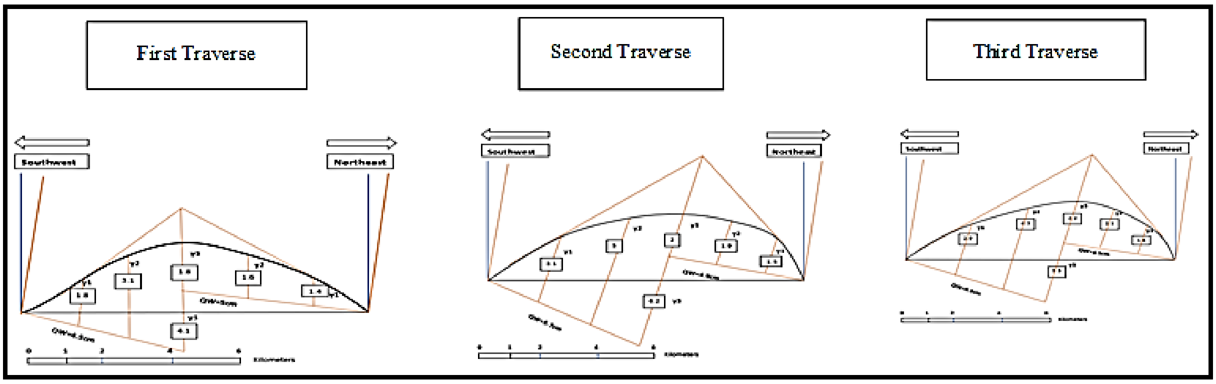


**Fig. 4. The profile of Gara Baran fold in the three traverses.**

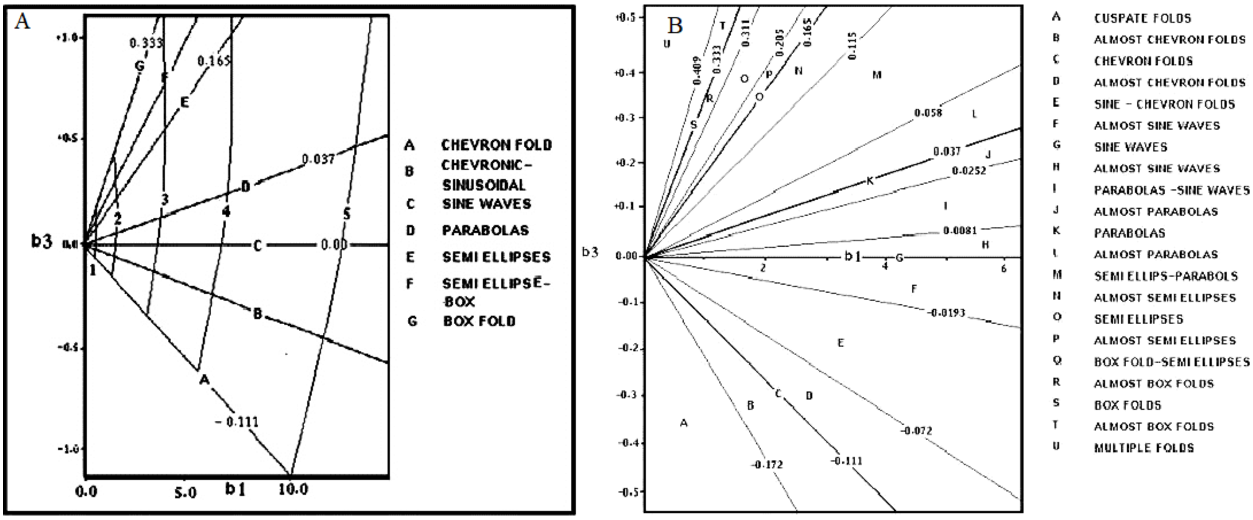


**Fig. 5. (A) a Graphical method for finding the shape of a fold by Fourier coefficients (Hudleston, 1973a) and (B) a graphic representation of fold shape based on Fourier coefficients (Singh and Gairola, 1992).**

**Table 2: Show the (Huddleston, 1972) and (Singh and Girola, 1992) classification of the shape of the Fold for three traverses.**

| Traverses | Fourier analysis of the northeastern limb | Huddleston's classification | Singh and Girola, classification | Fourier analysis of the southwestern limb | Huddleston's classification | Singh and Girola, classification | Average Fourier analysis |
|---|---|---|---|---|---|---|---|
| First, traverse | 0.1674682458 | Semi-Ellipse – Box Folds | Almost Semi-Ellipse Folds | -0.0443681016 | Chevronic – Sinusoidal Folds | Chevronic – Sinusoidal Folds | 0.06155007185 |
| Second traverse | 0.1472559617 | Almost Semi-Ellipse Folds | Almost Semi-Ellipse Folds | 0 | Sine wave Folds | Sinusoidal Folds | 0.07362798085 |
| Third traverse | 0.1344572761 | Parabolic - Semi-Ellipse Folds | Almost Semi-Ellipse Folds | 0.0189300605 | Sinusoidal – Parabolic Folds | Sinusoidal – Parabolic Folds | 0.0766936683 |

## 3. Inversion Tectonics:

Two types of listric faults influence the folds of the WZFTB during their formation and development (Al-Azzawi, 2003). They are foreland listric faults that affect folds making them verging toward the southwest. Whereas the second one called suture listric faults makes the fold verge towards the northeast (Numan and Al-Azzawi, 1993; Sommaruga,1999; Al-Azzawi, 2003). In the study area, the type of the listric fault is suture listric fault according to the geometrical analysis which reveals the anticline is verging towards the northeast. These facts prove the presence of suture listric fault beneath and along the Gara Baran Anticline, (Fig. 6). As mentioned in the previous references, the listric fault movements affect the formation's thicknesses then the thickness variances can be used to determine the inversion tectonics of these faults and also indicate its Reverse or normal sense of movements. Finally, it can conclude whether the type of inversion is either positive or negative.

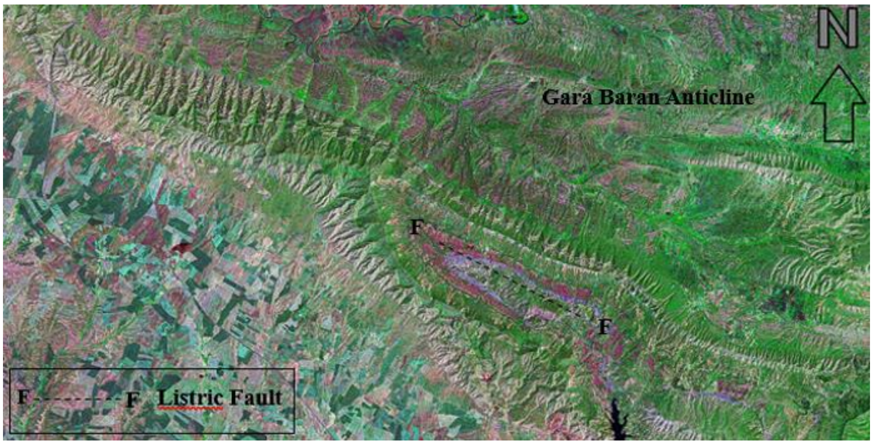


**Fig. 6. Showing the trace of the listric fault on the Gara Baran anticline in the form of a Dash structure (Google, 2008).**

## 3.1 First traverse.

**Table 3: True thickness of the first traverse.**

| Formation | Age | Northeastern limb | Southwestern limb |
|---|---|---|---|
| Pila Spi | Middle to Late Eocene | 14m | 431m |
| Gercus | Middle Eocene | 300m | 309m |
| Kolosh | Paleocene-Early Eeocene | 282m | 145m |
| Shiranish | Cretaceous | 286m | 124m |

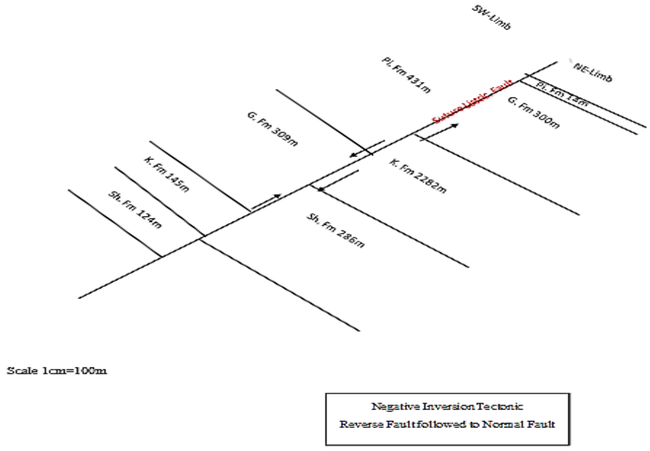


**Fig. 7. Schematic diagram of a negative inversion tectonic** in the first traverse.

## 3.2 Second Traverse.

**Table 4: True thickness of the second traverse.**

| **Formation** | **Age** | **Northeastern limb (NE)** | **Southwestern limb (SW)** |
|---|---|---|---|
| Pila Spi | Middle to Late Eocene | 445m | 745m |
| Gercus | Middle Eocene | 331m | 456m |
| Kolosh | Paleocene-Early Eocene | 374m | 273m |
| Shiranish | Cretaceous | 176m | 154m |

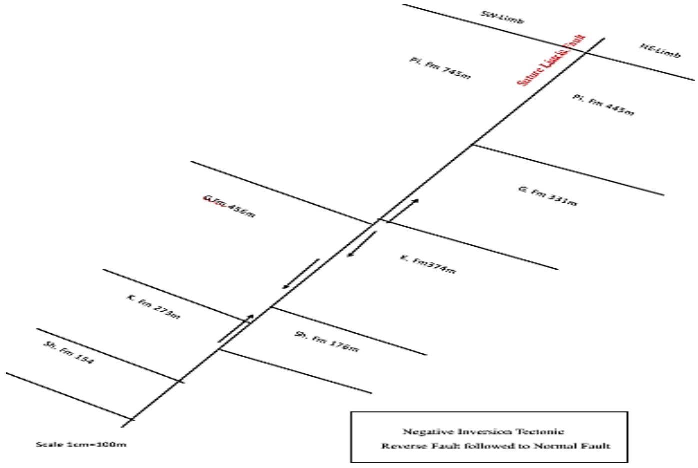


**Fig. 8. Schematic diagram of a negative inversion tectonic in the second traverse.**

## 3.3 Third Traverse.

**Table 5: True thickness of the third traverse.**

| Formation | Age | Northeastern limb (NE) | Southwestern limb (SW) |
|---|---|---|---|
| Pila Spi | Middle to Late Eocene | 377m | 549m |
| Gercus | Middle Eocene | 368m | 372m |
| Kolosh | Paleocene-Early Eocene | 381m | 181m |
| Shiranish | Cretaceous | 152m | 137m |

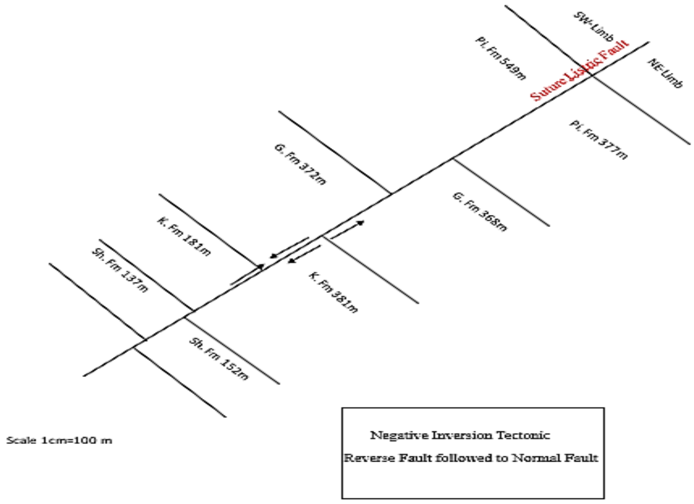


**Fig. 9. Schematic diagram of a negative inversion tectonic in the third traverse.**

Thicknesses of the exposed formations are determined along the three **traverses;** they confirm the dimensions of this suture listric fault and sense of movements in the three traverses. The displacements lead to a subsidence of the sedimentary basin in the area of the northeastern limb of the fold, as evidenced by the increase in the thickness of the geological formations (Kolosh and Shiranish formations, indicating the reverse sense of movement. Whereas subsidence and high thicknesses of (Pila Spi and Gercuse formations) in the southwestern limb in three traverses indicate a normal displacement. It can be concluded that the area is subjected to reverse displacement during the Cretaceous - Eocene and followed by normal one during the Middle and Late Eocene and that is what is called negative inversion.

## 4. The vertical investigations:

The vertical investigation is the study of the fold parameter variations during the period from the older formation to the younger one. This is done by analyzing the folding of individual geological formations in each traverse. Plotting the readings of the bedding planes for each formation individually as poles and determining its π-diagram (Fig. 10). The results of this analysis are shown in (Table 6), in which the dips of the northeastern and southwestern limbs, fold axis, axial plane, inter-limb angle, symmetry, and vergence are listed. The investigation reveals the following variations:

1. Fold axis and Axial plane:

Analysis of the π-diagrams shows that the fold axis changed its direction throughout the geologic time in the three traverses. It reveals that the direction of the fold axis and axial plane of the fold is rotated anticlockwise from Bakhme and Shiranish to Kolosh and Pila Spi formations. It means that this rotation happened from the Cretaceous through the Paleocene to the Eocene (K/Pg unconformity).

2. Dips of bedding planes:

In general, the dips of bedding planes appear to be reduced from the older formation to the younger.

3. Asymmetry and vergence:

The geometric analysis exposes that the fold in the three traverses and all formations are asymmetric and verging towards the northeast, except in the third traverse where the fold appears asymmetrical with southwest vergence in the folding of Pila Spi Fm.

4. The inter-limb angle:

The first and second traverses show that the values of the interlimb angle increase from older to younger formations because the dips of the limbs are reduced from older to younger. While in the third traverse, the values of interlimb angles appear to be opposite to the two. It means it decreases towards the younger formation. This may be due to the disturbance of reversal vergence of the Pila Spi Formation.

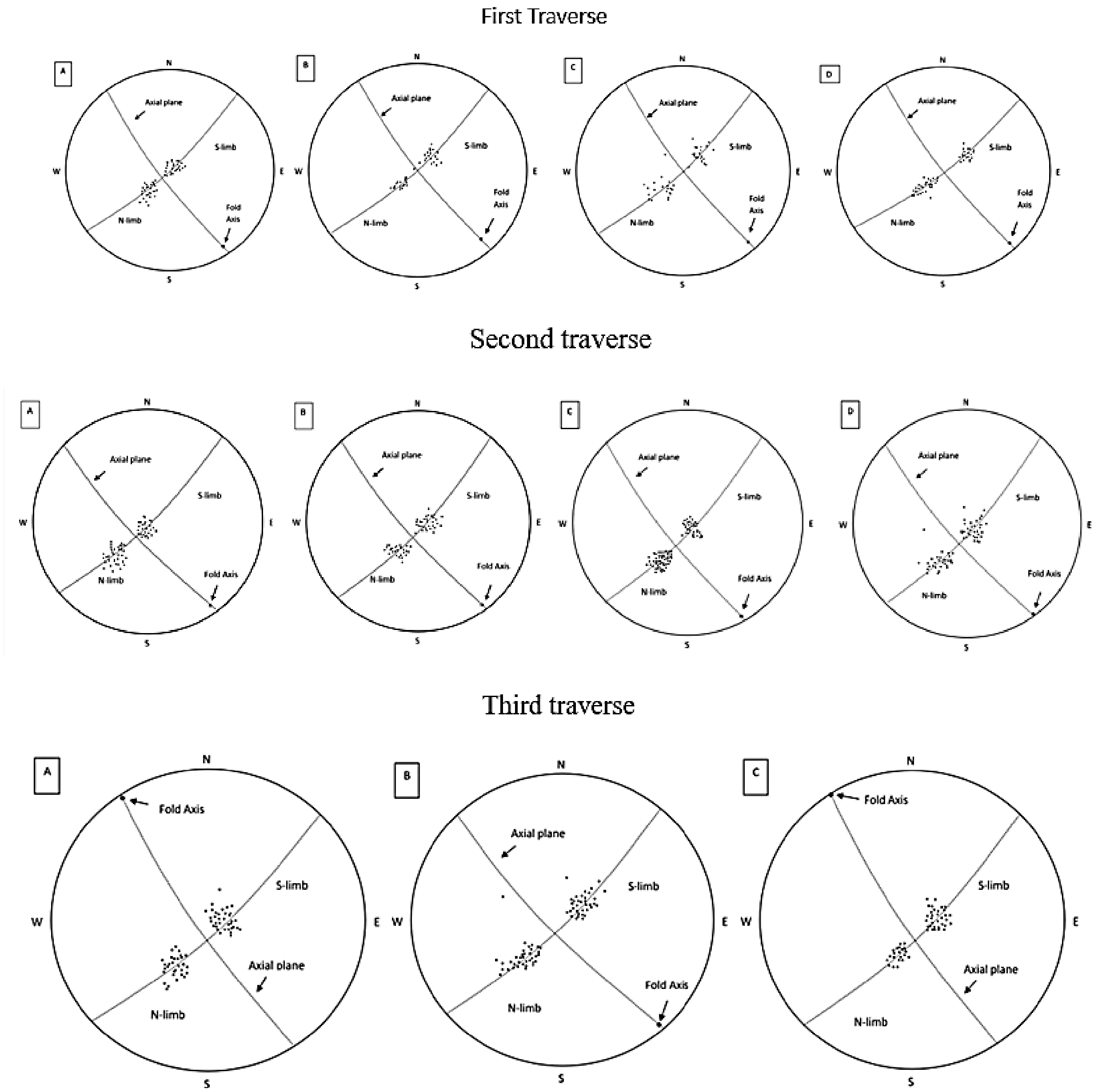


**Fig. 10. Shows the stereographic projection of the formations in three traverses.**

**Table 6: Show the parameter of the π-diagram of three traverses for vertical investigation.**

| Formation | Dip of the northeastern limb | Dip of the southwestern limb | The value of the inter-limb angle | Fold axis attitude | Axial plane attitude | Symmetry | Vergence |
|---|---|---|---|---|---|---|---|
| | | | First Traverse | | | | |
| A. Pila Spi | 12° | 8° | 162 ° | 139/03 ° | 319/88 ° | Asymmetry | northeast |
| B. Kolosh | 20° | 16° | 154 ° | 137/06 ° | 317/72 ° | Asymmetry | northeast |
| C. Shiranish | 40° | 29° | 149 ° | 145/05 ° | 325/84 ° | Asymmetry | northeast |
| D. Bakhme | 35° | 32° | 115° | 142/04 ° | 322/88 ° | Asymmetry | northeast |
| | | | Second Traverse | | | | |
| A.Pila Spi | 12° | 08° | 158° | 139/03° | 319/87° | Asymmetry | northeast |
| B. Kolosh | 27° | 25° | 132° | 139/02° | 320/88 ° | Asymmetry | northeast |
| C.Shiranish | 15° | 15° | 149° | 145/02° | 322/87° | Asymmetry | northeast |
| D.Bakhme | 17° | 15° | 147° | 142/00° | 322/86° | Asymmetry | northeast |
| | | | Third Traverse | | | | |
| A. Pila Spi | 18 ° | 22 ° | 140 ° | 326/02 ° | 326/88 ° | Asymmetry | southwest |
| B.Shiranish | 18° | 15° | 154 ° | 140/01 ° | 320/87 ° | Asymmetry | northeast |
| C. Bakhme | 20 ° | 16 ° | 164 ° | 327/00 ° | 327/82 ° | Asymmetry | northeast |

## Discussion and Conclusion

Gara Baran is an anticlinal part of the Baikher Anticline, which is one of the major structures within the high-folded zone of the Western Zagros Fold/ Thrust Belt (WZFTB). Gara Baran is considered and studied in this work as an anticline due to having different and distinct properties compared with the remaining parts of the Baikher Anticline. Generally, it is asymmetrical and extends northwest-southeast. The study proves and confirms that the anticline is verging towards the northeast which is one of the anomalous cases in the WZFTB. Moreover, the study analyzes the data collected from the field by several techniques to reach the cause of this anomalous vergence. These techniques are Geometrical analysis using π-diagram, and Fourier analysis to find the fold shape, vertical investigations, and formations thickness variance for studying the inversion tectonics. The geometric analysis using π-diagram for all geological formations reveals that the average dip of the northeastern and southwestern limbs is ($26^{o}$) and ($22^{o}$); respectively, this indicates that the fold is generally asymmetrical in the three traverses and verging towards the northeast. Consequently, and according to Al-Azzawi (2003), the northeast verging anticline was subjected to a suture listric fault which affected the northeastern limb and made it steeper.

The Fourier analysis exposes that the northeastern limb is more developed in shape than the southwestern one. This is because the first one suffered more tectonic stresses than the second. Normally, the regional stresses made most of WZFTB folds verging toward the southwest so the anomalous case of Gara Baran makes the author emphasize the presence and the effects of the suture listric fault which is verging towards the northeast and dipping southwestward. For this reason, the Fourier ratios of the northeastern limb appear more than the southwestern one. Moreover, the Fourier ratio of the northeastern limb is decreased from the first traverse to the third one, in other words, toward the northwest direction. Whereas the ratios of the southwestern limb are increasing in the same direction. This means that the effects of the listric fault decreased towards the northwestern plunge and the influence of the regional stresses increased in the same direction and became more dominant, (Table 2). This conclusion agrees with the average Fourier ratios of the entire fold along the three traverses (Table 2), the table shows that the three ratios are mostly similar especially the last two, which are around Semi-Ellipse Folds. Furthermore, the vertical investigations show that the individual analysis of the fold of the Pila Spi Formation in the third traverse reveals that the fold verges towards the southwest, which proves the dominant of the regional stresses after the deposition of Pila Spi Formation during the Middle to Late Eocene (Table 6). The vertical investigations reflect some facts about the geometry of the fold. The analysis is carried out on Bakhme, Shiranish, Kolosh, and Plia Spi formations, while, there are no reliable readings of bedding planes that can be taken from the Gercus and Fatha formations. In three traverses the folded formation appeared asymmetrical with northeast vergence except for the fold in the Pila Spi, which is verging toward southwest in the third traverse. This phenomenon proves the diminishing of the stresses of the suture listric fault and the domination of the regional stresses in the northwestern plunge. The direction of the fold axis and axial plane of the fold is rotated anticlockwise from Cretaceous to Paleogene rocks. The researchers believe that is due to the effect of Mesozoic/ Cenozoic unconformity. Generally, the dips of bedding planes are reduced from the older formations to the younger ones, on the other hand, the interlimb angle values are increased due to the same reason. Formation thickness analysis produces the type of inversion tectonics of the listric fault. The formation thicknesses prove the movements of the suture listric fault, which affect the anticline and make it move towards the northeast. The analysis of the three traverses reveals that the thicknesses of the Shiranish and Kolosh formations during (the Cretaceous to Early Eocene) are higher in the northeastern limb, while the thicknesses of the Pila Spi and Gercus formations during (the Middle to Late Eocene) are higher in the southwestern limb. This proves the influence of the negative inversion tectonics of the suture listric fault (reverse fault followed by normal fault), (Tables 3, 4 and 5). It is worth mentioning that the differences in the thicknesses of the Kolosh Formation are due to the continuous effect of the Cretaceous reverse displacements and they come homogenous along the three traverses. The most important note is shown in the (Table 7) is the decreasing amounts of reverse and normal displacements from the first traverse to the third one. This indicates the diminishing stresses of the suture listric fault towards the northeastward and the domination of the regional stresses. This is proved by the reduced amount of negative inversions towards the northwest, (Table 7), and the southwestward vergence of Pila Spi folding in the third traverse. Accordingly, this inversion may be called oblique negative inversion tectonics compared with (Heja et. al 2022).

**Table 7: Show the all information that affected the northeastern limb in the three traverses.**

| Traverses | Normal displacement | Negative inversion | Dip of the northeastern limb | The Fourier ratio of the northeastern limb | Huddleston's classification |
|---|---|---|---|---|---|
| First | 417m | 225m | 32° | 0.1674682458 | Semi-Ellipse – Box Folds |
| Second | 300m | 183m | 24° | 0.1472559617 | Almost Semi-Ellipse Folds |
| Third | 172m | 85m | 23° | 0.1344572761 | Parabolic -Semi-Ellipse Folds |

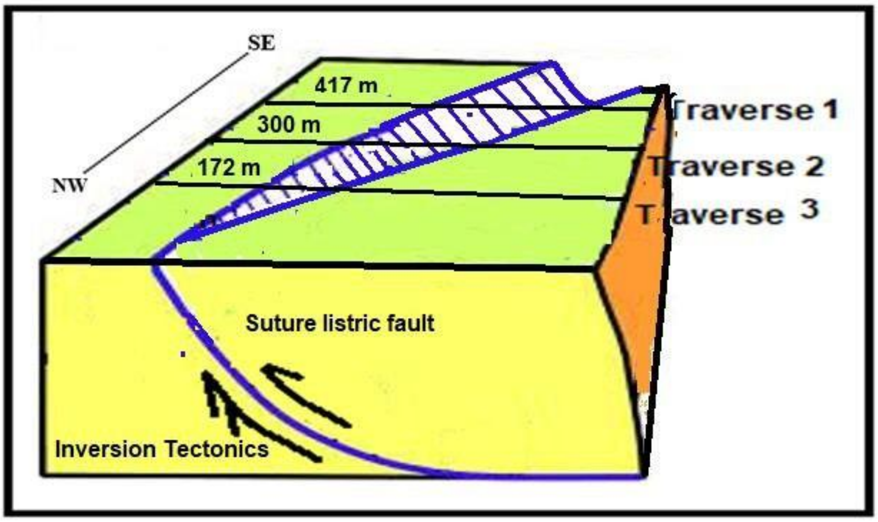


**Fig. 11. Schematic diagram for the proposed model of the oblique negative inversion.**

(Fig. 11) shows the proposed model of the suture listric fault that affected Gara Baran Anticline. The normal displacement of this fault is decreasing from traverse one to the third, this indicates the rotation or oblique type of rotation. The author also believes that the two blocks of the fault are moved upward but the northern one is faster making normal displacement. This conclusion comes due to the study area being subjected to a compression environment as a result of the continental collision of the Arabian and Iranian plates.

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