

# The Elements of Fold Style Analysis in the Khaftar Anticline, Zagros, Iran

Zahra Maleki<sup>1\*</sup>, Mehran Arian<sup>1</sup>, Ali Solgi<sup>1</sup>, Mohammad Ali Ganjavian<sup>2</sup>

<sup>1</sup>Department of Geology, College of Basic Sciences, Tehran Science and Research Branch, Islamic Azad University, Tehran, Iran

<sup>2</sup>Department of Geology, Shahrood Branch, Islamic Azad University, Shahrood, Iran

Email: \*[z.maleki@srbiau.ac.ir](mailto:z.maleki@srbiau.ac.ir)

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## Abstract

The Study area is located in the Zagros Simply Folded Belt of Iran and in the interior Fars sub-basin. The Khaftar anticline is located in the West, North-West of Jahrom city in the Fars province (148 km distance from Persian Gulf). The trend of Khaftar anticline has three orientations, consist of North- Northeast, East-West and South- Southwest. This anticline has asymmetric structure and some faults with large strike separation observed in this anticline. In the study area, stratigraphic units are affected by many faults in this area. Also one salt plug cropping out in the middle part of the Khaftar anticline. Maybe this salt plug affected on the stratigraphic units and geometry of structure. Description of fold geometry is important because it allows comparisons within and between folds and allow us to recognize patterns in the occurrence and distribution of fold systems. The main aim of this paper is determination of fold style elements and folding pattern of the Khaftar anticline. This paper presents a part of the results of a regional study of the Fars province in the Zagros Simply folded belt, based on satellite images, geological maps, and well data. Some data, such as geological maps and geological regional data were prepared and provided by the National Iranian Oil Company (NIOC). Because of the Khaftar anticline, has complex structure, the analysis of fold style elements is seems necessary. Therefore, in further studies on this structure the changes of fold style elements will be analyzed and investigated from east to west in the different parts of this anticline. The activity of Nezamabad sinistral strike slip fault in the Khaftar anticline causes changes of axial plane characteristics and fold axis. Some of the results such as folding style analysis, how position of salt plug, changes of fold type and main structural changes (rotation of fold axis and 2.5 km displacement in this anticline) show main changes in the middle parts of the Khaftar anticline. It seems that, these changes have formed by activity of the Nezamabad fault and this fault's activity same as fault zone.

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\*Corresponding author.

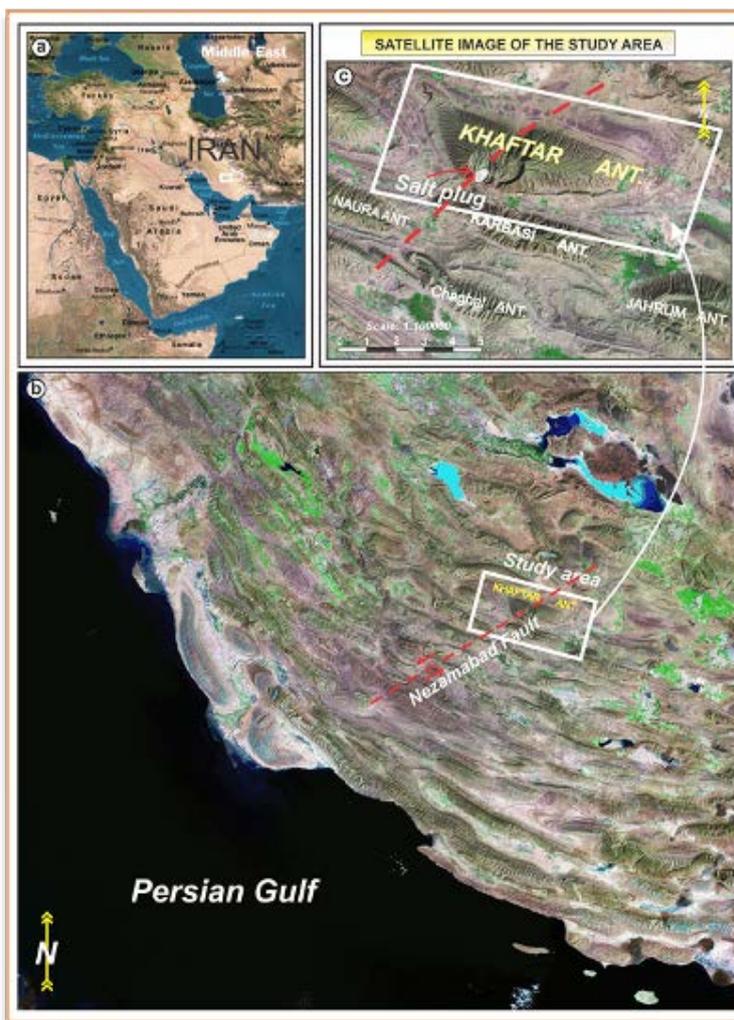
## Keywords

Zagros; Iran; The Khaftar Anticline; Fold Style Elements; Nezamabad Fault

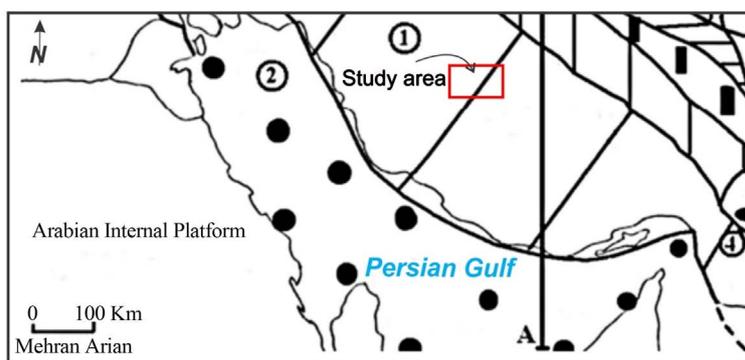
### 1. Introduction

The study area is located in the Zagros Simply Folded Belt of Iran and in the interior Fars sub-basin [1] [2] (Figure 1). The Zagros Fold-thrust belt is home to one of the largest petroleum producing reservoirs in the world [3]. This belt is recognized by the NW-SE trending parallel anticlines that verge to the SW in a 6 - 12 km cover sequence [3] [4]. The Simply Folded Zone (SFZ) is orientation as the southwesterly boundary of the Zagros orogen near the Persian Gulf.

Based on Physiographic-tectonic zoning map of Iran's (sedimentary basins of Iran), the study area is located in the Zagros-East Taurus hinterland [5] (Figure 2). In this region, the folds are capped by the Oligocene Asmari



**Figure 1.** Landsat Satellite image showing the study area and location of the Khaftar anticline in the Zagros fold-thrust belt, southern of Iran. Inset Satellite image (a) shows location of the study area with white framework in the Middle East. Also, in this figure shows location of the Khaftar salt plug in the study area.



**Figure 2.** Physiographic-tectonic zoning map of Iran's sedimentary basins Iran showing the study area in the Zagros-East Taurus hinterland [5]

Limestone [3] [6] [7] and the sedimentary cover sequence is floored by the Hormuz Formation, a dominantly evaporate formation, which acts as a major decollement horizon [8]-[10].

In this area, the Khaftar anticline has asymmetric structure and some faults such as the Nezama bad fault effect on this anticline. This structure is located in the West, North -West Jahrom city in the Fars province (148 km from Persian Gulf). Structures in this area have complications and the study area has complex structure in the Fars region.

The geometry of anticlines in the Zagros fold-thrust belt are affected by type of deformation and mechanical behavior of stratigraphic units specially detachment units [11]. In this belt, detachment units are important for controlled folding pattern [12] [13]. The basal Hormuz and other detachments play important roles for the style of the Zagros Fold-thrust belt structures. One of the main detachment units in the study area is Dashtak formation that belongs to Kazeron group. This formation is composed of evaporate, shale and dolomite units. This formation has important role on folding geometry especially in the Fars region. Also, other detachment formations in this area are Kazdomi and Gachsaran formations that play important roles on the structural style of area.

In the Zagros fold-thrust belt, structural analysis of surface and subsurface data shows that salt layers such as Cambrian Hormuz and the Miocene Gasharan have direct control on the structural style [14]. Until now, In the Zagros fold-thrust belt, many studies have been done on to variation of structural style and effects of detachment folding on folding pattern [12] [13]. Also, many researchers discussed basement involvement and reactivated structures in the Zagros fold-thrust belt and its roll on folding pattern, e.g. [10] [15]-[18]. Several researchers, such as Kashfi (1972), Falkon (1969), Alavi (1994), Letouzey (2005) and Sherhati *et al.*, (2005), emphasized the role of mechanical stratigraphy on the structural style as in above-mentioned.

For the first time, Stearns (1978) introduced concept of mechanical lithology in this area and O'Brien (1950) [19] was the first one to show the effects of detachment layers on folding process and other researchers have discussed about this too, e.g. [20]-[23].

In the Fars region, the Khaftar Anticline possesses Specific structures. This anticline has complex structure and in the middle of anticline, cropping out Salt plug nears the southern limb. This anticline is located in the West, North-West Jahrom city in the Fars province (148 km distance from Persian Gulf) (Figures 1 and 3). Structures in this area have complications and the oldest stratigraphy unit that outcropped in the Khaftar anticline on the surface belongs to Hormuz Series. The age of oldest rock unit is Pre-Cambrian-Cambrian.

The first geological report on the Khaftar anticline dates back to the 1974 by the National Iranian Oil Company (NIOC) and SOFIRAN EGOCO (Exploration Company). Some researchers just briefly study on this region and introduced the Khaftar anticline as a cutted fold by the Nezama bad strike slip fault [25] [26].

Description of fold geometry is important because they allow comparisons within and between folds and pattern-recognition in addition to occurrence and distribution of fold systems. The main aim of this paper is to determine of fold style elements and folding pattern of the Khaftar anticline.

## 2. Material and Methods

This paper presents part of the results of a regional study of the Fars province in the Zagros Simply folded belt,



Age	Simplified Formations	Lithology	Thickness
Pliocene	Bakhtiyari	conglomerate	<1 km
Miocene	Lahbari member	red marl, Sandstone sandstone }	1-3 km
	Agha jari		
	Mishan, Gachsaran/Razak	gery marl, limestone, anhydrite, salt/sandstone	1-2 km
	Asmari, Shahbazan/ Jahrum	limestone	<0.5 km
Eocene- Paleocene	Pabadeh-Gurpi, Amiran	calcareous marl, shale, limestone sandstone, conglomerate	1-3 km
Cretaceous	Bangestan Group	limestone, bitumous shale	1-1.5 km
	Khami Group	limestone	1-1.5 km
Jurassic	Neyriz/Dashtak	dolomite, anhydrite, shaly limestone	1-1.5 km
Permo- Triassic	Dalan/Kangan	limestone/ dolomite	1 km
Cambrian- Ordovician		shale, limestone, sandstone	2-3 km
	Hormoz	salt with minor gypsum, shale and carbonate rocks	2-3 km

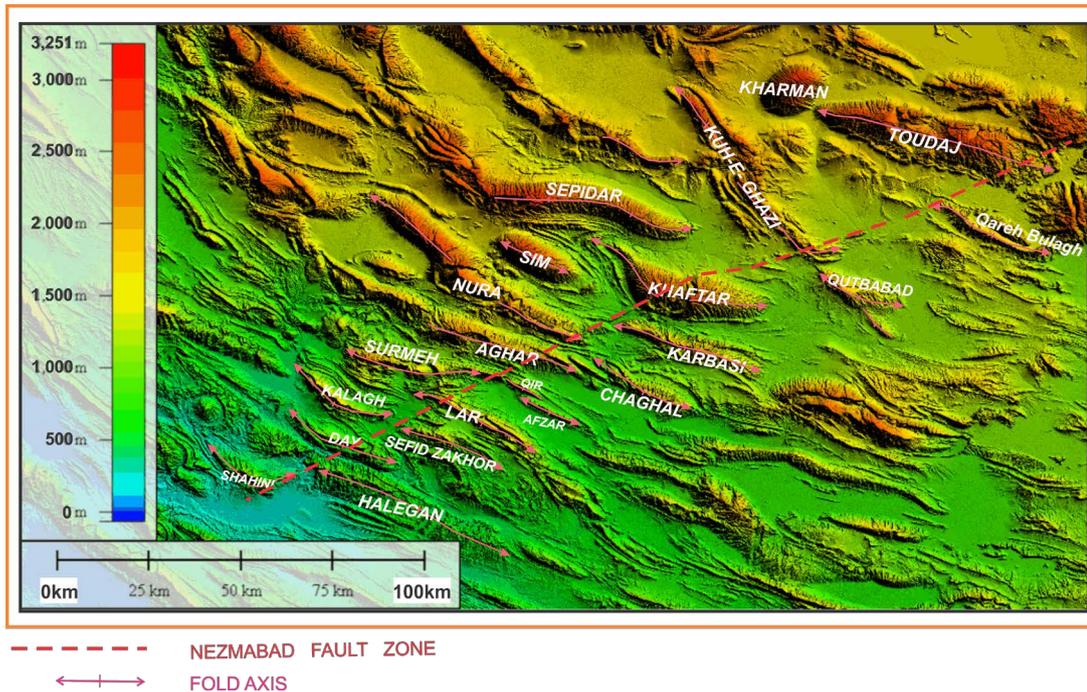
**Figure 4.** Generalised stratigraphic column through the Zagros fold–thrust belt. (Modified after [35]).

The Khaftar anticline is located in the West, North -West of the Jahrom city in the Fars province (148 km to Persian Gulf). This anticline has three orientations that consist of North- Northeast, East-West and South-Southwest. This anticline is bounded from north by the Kuh-e Qazi anticline, from north-northeast by the Qutba bad anticline, from south-southeast by the Karbasi anticline and from southwest by the Sim anticline (**Figure 5**).

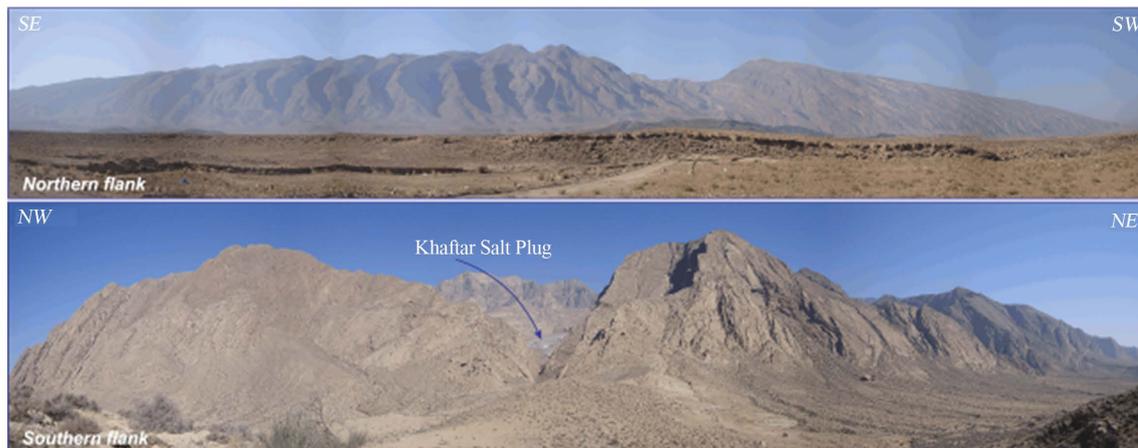
The Khaftar anticline is an asymmetric structure, which has 45 km length and 12.5 km width in the Asmari horizon on the surface (**Figure 3**). The Mund River is flows in northern-southern path in this area and in the north-northwest parts of anticline; this river has flow changes in this of path. By whirling this river in the western part of anticline finally, the Mund River continues its path to south of the study area.

Based on Setchell *et al.* (2007), the Khaftar anticline is detachment fold and in the middle part of southern flank of the Khaftar anticline, cropping out salt plug (**Figure 1**). The most surface of anticline is generally covered with Asmari-Jahrom formation. This anticline is an asymmetrical anticline in which the dip of southern flank is greater than the northern flank (**Figures 6 and 7**). On the other hand, plunges dip value in western part of anticline more than eastern part.

The Coordinates of Khaftar salt plug (belongs to the Khaftar anticline) is located between 53°14' to 53°18' longitudes and 28°39' to 28°41' latitudes. Maximum length of the Khaftar salt plug is 3 km and Maximum width is 1.1 km (**Figure 8**). Based on satellite images, total Shape of salt plugs specially the satellite images is rhomboidal (NE-SW trending longer axis). It seems that the shape is influenced by complication of structural zone of the Nezamabad Fault zone with NE-SW direction.



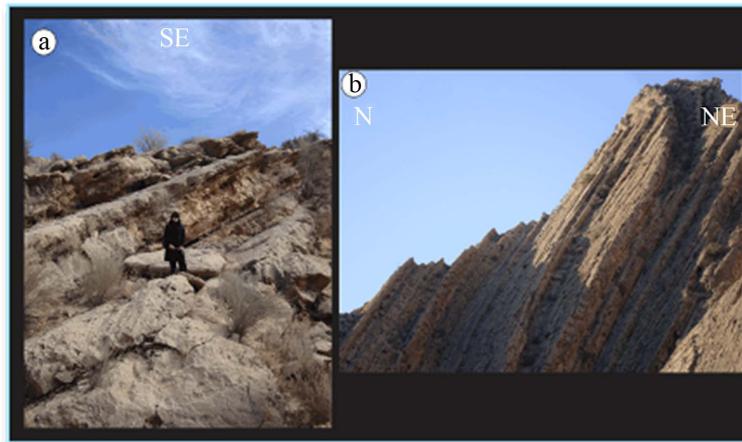
**Figure 5.** SRTM image (base on Digital Elevation Model (DEM)) showing the Khaftar anticline and adjacent anticlines in the Fars region.



**Figure 6.** These photographs showing the panorama of northern and southern flank of the Khaftar anticline.

#### 4. Nezamabad Fault

The Nezamabad fault is one of the strike slip fault with northeast- southwest trend in the Gavbandi High that divided this High from the Central Zagros [37]. The first time Barzegar (1994) introduced the Nezamabad fault based on satellite image. The Nezamabad fault is located between southern flank of the Shahini anticline and southeastern of Neyriz area [16] [25] [38]-[41] (Figure 5). The most displacement of the Nezamabad fault easily observe on the satellite image of the Khaftar anticline about 265 km sinistral displacement (Figures 1 and 5). Also, Based on 3D path profiles of the Khaftar anticline (Figure 9) and gave results; it seems that most of the changes are observed in the D and E 3D path profiles (location of these profiles is located along the cross sections A-A' to G-G' in the Figure 11). These profiles with most of changes are along the Nezamabad fault. It seems that, the activity of this fault in the middle part of the Khaftar anticline causes these changes and rotation of the Khaftar anticline plunge.



**Figure 7.** (a) Photograph and (b) showing the northern (a) and southern flank (b) of the Khaftar anticline. These photographs show the Asmari formation and dip value in the southern flank is greater than the northern flank.

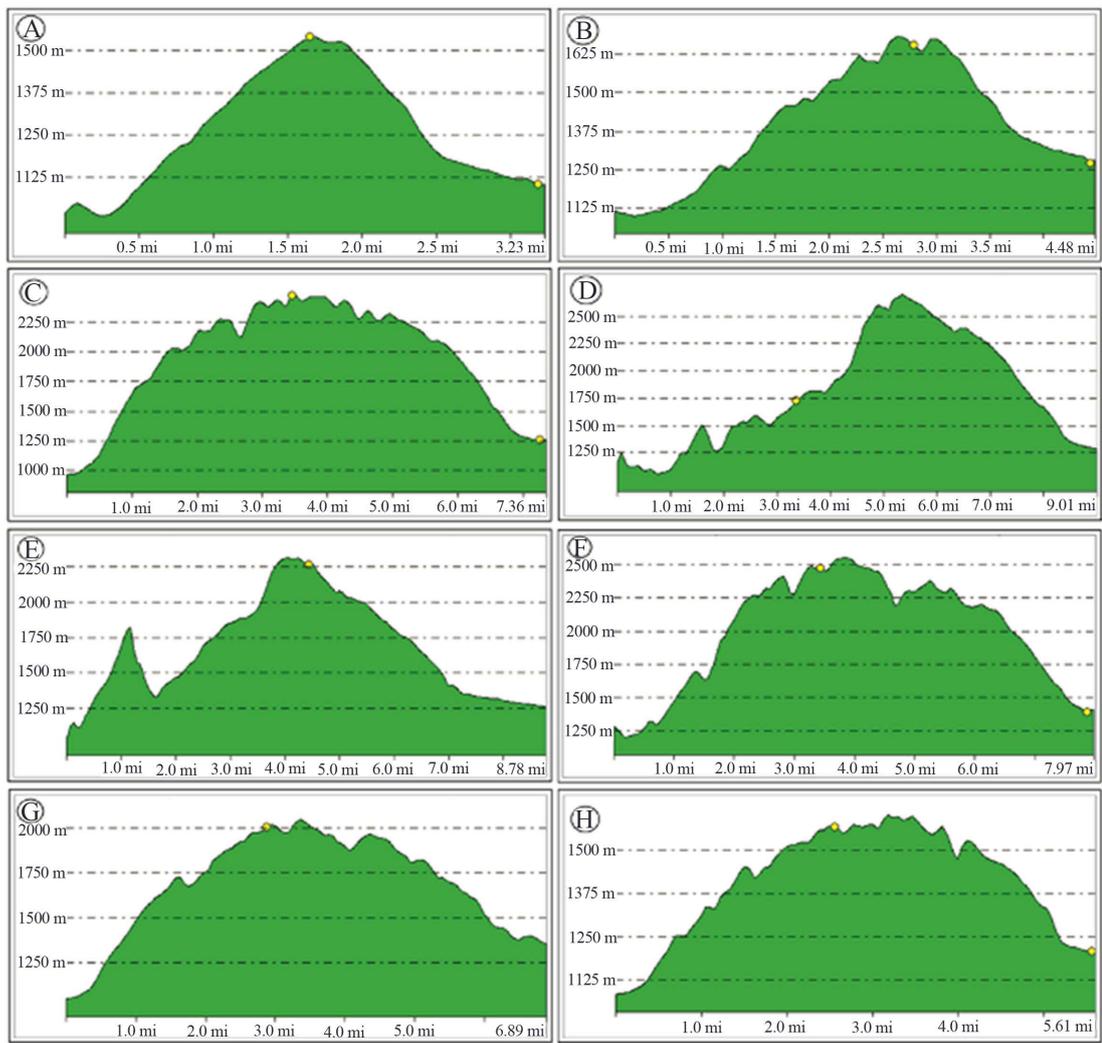


**Figure 8.** Photograph showing the location of salt plug (View to the northeast) in Southern flank of the Khaftar Anticline.

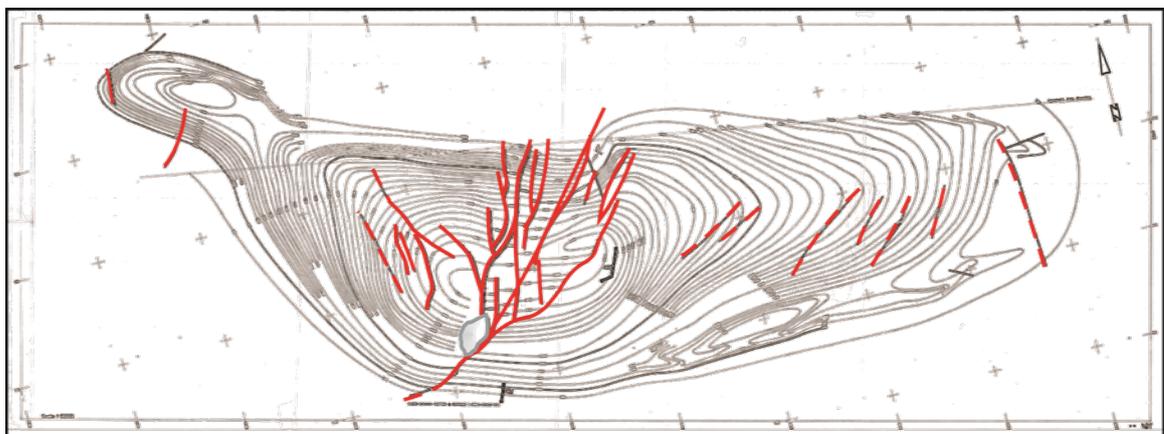
The numerous faults exist in the Khaftar anticline with different lengths and activities (**Figure 10**). Based on structural contour map (**Figure 10**) and our fieldwork, in the study area generally faults can be classified to two orders: major faults and minor faults. The Nezamabad sinistral strike slip fault is a major fault in the study area that specially affects on middle part of the Khaftar anticline. May be, cropping out of salt plug in middle part of the Khaftar anticline formed by the Nezamabad strike slip fault. In this area, the minor faults are located parallel with major fault and some of the minor faults are located parallel with fold axis (**Figure 10**).

## 5. The Description of Folds

Description of fold geometry is important because they allow comparisons within and between folds and allow us to recognize patterns in the occurrence and distribution of fold systems. For example, orogenic belts contain characteristic fold systems: along their flanks are large fold and thrust belts, with little metamorphism, but underlain by décollements; and in core zones where intense folding has accomplished, accompanied by high-grade metamorphism under high temperature and pressure.



**Figure 9.** These diagrams showing 3D path profiles of the Khaftar anticline (location of these profiles is located along the cross sections A-A' to G-G' in the **Figure 11**). The horizontal axis and vertical axis showing distance (mile) and elevation (meter).



**Figure 10.** This map showing the structural contour map and many faults that exist in the Khaftar anticline (NIOC-EGOCO Map, 1:50,000; Distance between contours is 50 meter).

## 6. Elements of Fold Style

The style of a fold is the set of characteristic that describe its form. Over years of working with folds, geologists have identified certain features as particularly useful in describing fold and understanding how they develop [29].

Because the Khaftar anticline, has complex structure; the analysis of fold style elements is seems necessary. Therefore, for more studies on this structure the changes of fold style elements will be analyzed and investigated from east to west in the different parts of this anticline. Because of the Nezamabad fault effect on the middle parts of the Khaftar anticline, we have evaluated and calculated some elements of fold style, that measurable in this structure. In this respect, symmetry, cylindricity, Geometry of axial plane and Folding Mechanism have evaluated.

### 6.1. Symmetry

A folded surface forms a symmetric fold if in profile, the shape on one side of the hinge is a mirror image of the shape on the other side, and if adjacent limbs are identifiable in length [27]. The study anticline is an asymmetric fold with changed plunge in the north of the western part of fold. The Khaftar anticline is an asymmetric anticline. In the southern flank dip of layers is greater than the northern flank on the Asmari formation horizon (Figures 6 and 7). The Southern flank, layers have dip changes from about 60° to 88° and dip value in the northern flank ranges about 35° to 50°.

### 6.2. Cylindricity

The Cylindricity is represented qualitatively on a stereonet by how closely the poles to planes around a fold fit a great circle distribution [27]. The studied anticline is a cylindrical to conical fold with changed plunge in the north of the western part of fold. The output of Tectonics FP software for seven parts of the Khaftar anticline is shown in the Figure 11.

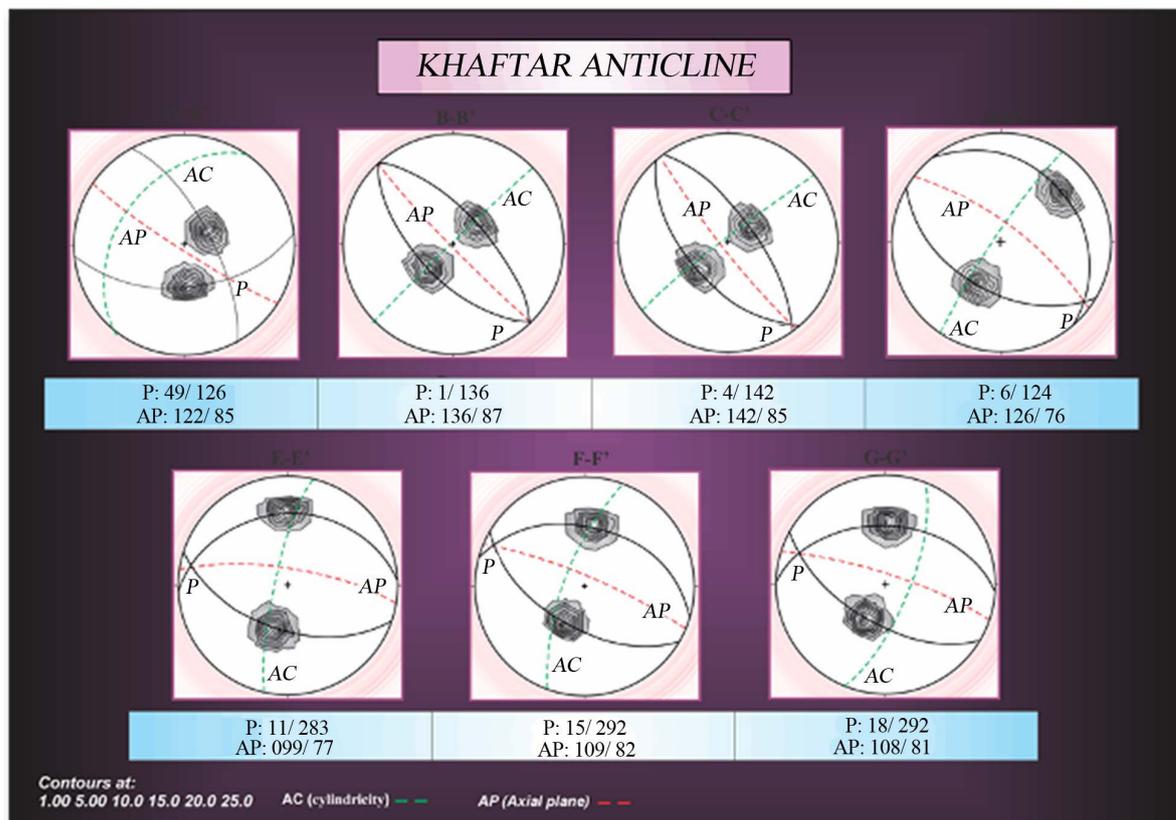


Figure 11. Stereoplots showing axial planes (AP), cylindricity (AC) for seven sections of the Khaftar anticline (based on [27]).

## 7. Classification of the Fold

### 7.1. Based on Geometry of Axial Plane

Based on Twiss and Moors method (1992) for description of fold, seven stereoplots (output of Tectonics FP software) were prepared for seven parts of the Khaftar anticline. According to results, these stereoplots show the location of axial plane (AP) and cylindricity (AC) and Plunge of Fold ( $P$ ) (Figure 12). This part to be done based on seven structural cross sections of the Khaftar anticline. The locations of these structural cross sections (from A-A' to G-G') is shown in the Figure 11.

According to description of fold [27] for seven sections in the Khaftar anticline (from A-A' to G-G'), the geometry of axial plane is planer. Also from A-A' to C-C', axial plane follow from one-pattern orientation of axial plane (dip of axial plane toward SW) and from D-D' to G-G' follows another pattern (dip of axial plane toward NE) (Figure 12). It seems that these changes (changes of orientation of axial plane from East to West in Khaftar anticline) affected by sinistral displacement of Nezamabad fault. For more explanation, based on orientations of axial plane, see Figure 12. Change of dip of axial plane from NE (D-D' to G-G') to SW (A-A' to C-C') confirms sinistral displacement of Nezamabad fault and effect of this fault on the geometry of axial plane.

In the seven structural cross sections of the Khaftar anticline, dip value of axial plane is changing from  $76^\circ$  to  $87^\circ$ . Based on classification of Ramsay (1967) for fold classification and changes of axial plane in different parts of anticline, the fold type in the D-D' and E-E' are different from other parts (Figure 13). Based on classification of

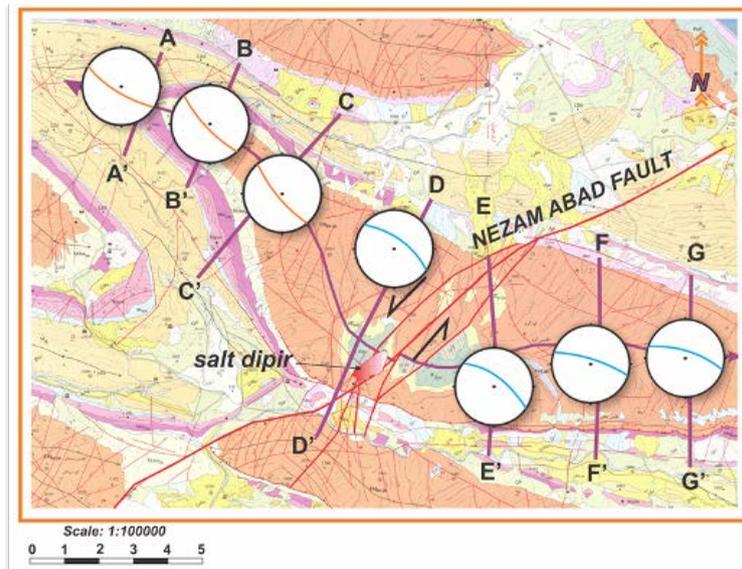


Figure 12. How located axial plane based on gave results in seven sections of Khaftar anticline, map scale 1:100000 [24].

Structural cross sections	A-A'	B-B'	C-C'	D-D'	E-E'	F-F'	G-G'
Dip of axial surface	$85^\circ$	$87^\circ$	$85^\circ$	$76^\circ$	$77^\circ$	$82^\circ$	$81^\circ$
classification of fold	upright	upright	upright	Steeply inclined	Steeply inclined	upright	upright

Figure 13. How located axial plane based on [29] gave results in seven sections of Khaftar anticline (Based on Ramsay, 1967).

Ramsay (1967), in most parts of the Khaftar anticline, axial plane of fold is upright but in D-D' and E-E' sections axial plane is steeply inclined. May be sinistral displacement of the Nezamabad fault and cutted Khaftar anticline by this fault caused this change.

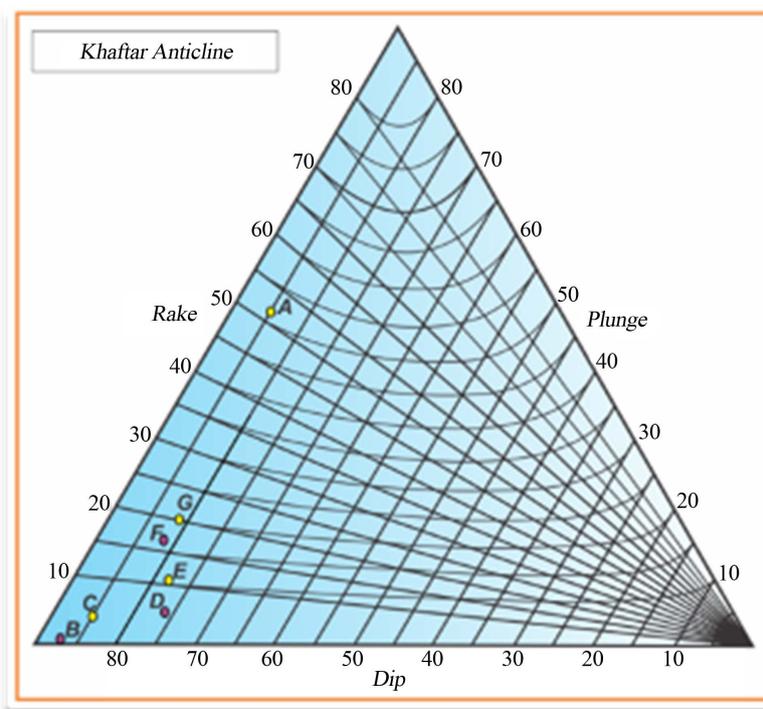
## 7.2. Based on Folding Mechanism

In this part, based on classification of Rickard (1971) and Ragan (1985), in the different parts of the Khaftar anticline, type of fold is variable and four types are recognize (Figures 14 and 15). In some parts of anticline as A-A', F-F' and G-G' sections, type of fold is moderately inclined moderately plunging. In the B-B' and C-C' sections, type of fold is upright horizontal. In the D-D' section type of fold is horizontal plunging and E-E' section type of fold is plunging fold. According to these results, because in some parts of fold dip value is less than other parts (D-D' and C-C') may be the Nezamabad fault affected on this case. Also based on classification of Ramsay (1967), in D-D' and E-E' sections axial plane is steeply inclined. The activity of the Nezama bad sinistral strike slip fault in the Khaftar anticline causes changes of axial plane characteristics and fold axis.

Based on the classification of Rickard (1971), in different parts of the Khaftar anticline, type of fold is different (Figure 15). In the eastern part of anticline (A-A' section) type of fold moderately inclined moderately plunging, so in the western part of anticline (G-G' section) type of fold is moderately inclined moderately plunging (Figure 15). Based on classification of Ramsay (1967) the orientation of fold in this anticline evaluated, for A-A' to G-G' profiles (Figure 16). Results show the orientation of fold in this anticline especially in the D-D' and E-E' parts are different than other parts. May be the Nezama bad fault has affected on the orientation of fold in these parts.

## 8. Conclusions

In the Khaftar anticline, activity of the Nezamabad sinistral strike slip fault has caused main changes on the fold style characteristics. According to give results of fold style elements analysis of the Khaftar anticline, it becomes clear that middle parts of the Khaftar anticline have affected by more deformation.



**Figure 14.** Triangle form Diagram showed type of fold in seven sections of Khaftar anticline, based on [30]. Type of fold in Part G (G-G' section) is different to other section completely.

	<b>A-A'</b> P:49/ 126 AP:122/ 85	<b>B-B'</b> P:1/ 136 AP:136/ 87	<b>C-C'</b> P:4/ 142 AP:142/ 85
	Fold type: Moderately inclined moderately plunging	Fold type: upright horizontal	Fold type: upright horizontal
<b>D-D'</b> P:6/ 124 AP:126/ 76	<b>E-E'</b> P:11/ 283 AP:099/ 77	<b>F-F'</b> P:15/ 292 AP:109/82	<b>G-G'</b> P:18/ 292 AP:108/ 81
Fold type: Horizontal Plunging fold	Fold type: Plunging fold	Fold type: Moderately inclined moderately plunging	Fold type: Moderately inclined moderately plunging

**P: Plunge AP: Axial Plane**

Figure 15. This table showing type of fold in seven sections of the Khaftar anticline. This classification based on [19] [28]-[30] [42] [43].

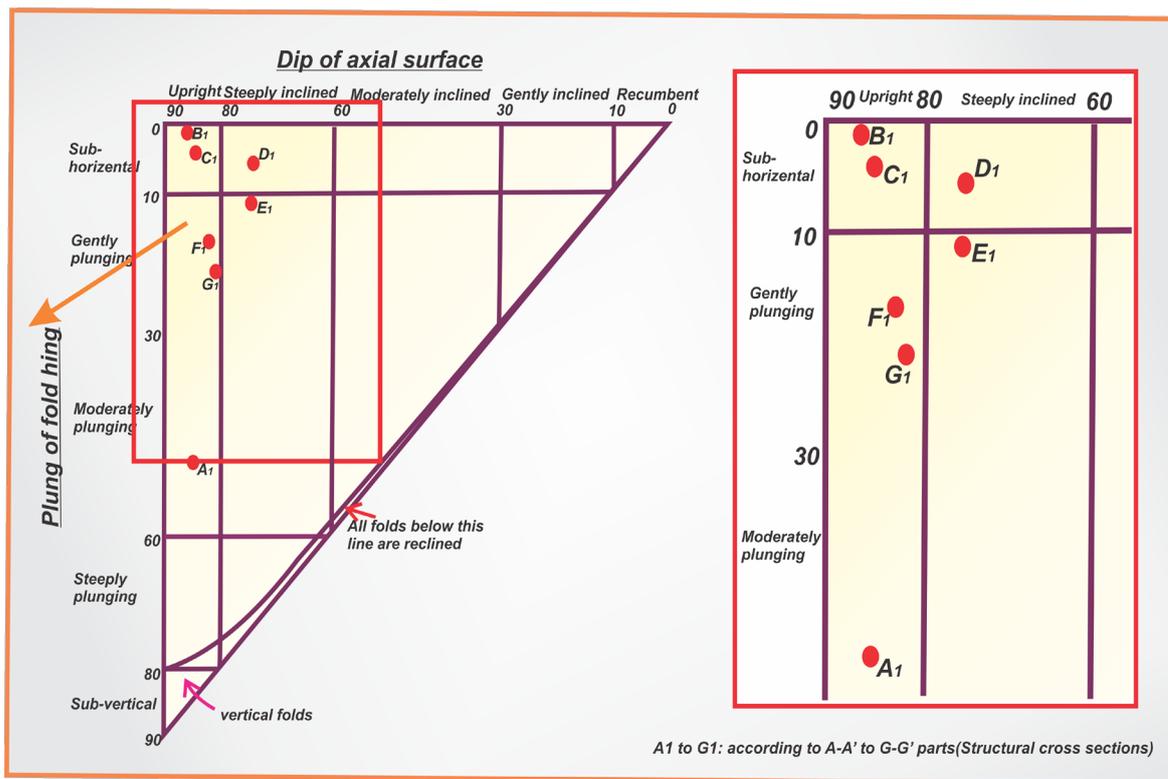


Figure 16. This figure showing the classification for orientation of the Khaftar anticline based on [29].

Some given results such as folding style analysis, how position of salt plug, changes of fold type and main structural changes (rotation of fold axis and 2.5 km displacement in this anticline) show main changes in the middle parts of the Khaftar anticline. It seems that, these changes have formed by activity of the Nezama bad fault and activity this fault, same as fault zone.

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