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Geometric and kinematic analysis of Dorbadam anticline, North of Quchan, Iran

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Abstract

The geometric and kinematic analyzing of the anticlines and their relation with the large-scale structures are used to determine the structural evolution of the area. The Dorbadam anticline is located in the Kopet-Dagh structural zone, 45 km due north of Quchan and on the Razavi and North Khorasan provinces border. The field study and geometric analysis indicate that the Dorbadam anticline has two culminations with an en-echelon arrangement and different structural evolution. The NW culmination (DA.1) is analyzed as a fault propagation fold geometry, while the SE culmination is known as a simple folding. The axial trend of the Dorbadam anticline has been changed and shows harmonic and Horizontal inclined, 1C subclass of Ramsay's classification, close, asymmetrical over fold in DA.1 part; upright and horizontal, open and symmetrical upright fold in DA.2 part. Aspect ratio on the Dorbadam anticline is 0.64 and has a parabolic appearance. The joint study revealed the existence of five major joints in this area which are bedding and strike joints (tension and compression joints parallel to the axial fold) or dipping joints (tension joints). The systematic joints analyzing of Tirgan Formation with T-Tecto software determined that the trend of maximum stress in the Cretaceous was S07W. The paleo-stress direction determined S25W with axial plane analysis. The Analysis of large-scale faults indicated a change in the stress direction during the time and specified they are post-tectonic and the activity of faults occurred in some various stress systems.
Keywords: *Dorbadam anticline, Kopet-Dag, Tirgan Formation*

1. Introduction

The Kopet-Dagh is a fold-thrust belt with NW-SE trend, which forms the northern border of the Alpine-Himalayan system on the Iranian plateau. The Kopet Dag basin has been formed after the Cimmerian orogeny (Berberian and King 1981; Zanchetta et al. 2013), and post-Miocene pressure deformations have caused the folding and uplift of the basin sediments and forming the structures of the anticline and syncline. (Lyberis et al. 1998; Shabanian et al. 2010; Javidfakhr et al. 2011). Geologically, the Kopet-Dagh Range is made chiefly of Lower Cretaceous sedimentary rocks with a smaller portion of Jurassic rocks in the southeastern parts. The mountains were formed in the Miocene and the Pliocene during the Alpine orogeny (Afshar Harb et al. 1987; Afshar Harb 1994; Navabpour et al. 2003; Sheikholeslami et al. 2013; Afkhami Ardakani et al. 2017). The study area in this research is Dorbadam anticlinal in 45 km due north of Quchan city and is located on the border between two provinces of Khorasan Razavi and Northern Khorasan. This area is in the Kopet-Dagh Structural zone in between 37° 21′ - 37° 32′ North latitude and 58° 10′ - 58° 41′ East longitude. The village of Dorbadam is limited from the north to Bajgiran, from the south to Quchan, from the east to Darehgaz and from west to Shirvan (Fig 1). The deformation of the sedimentary cover in the folded belt of the Kopet-Dagh has been associated with the development of thrust faults and folding in some parts. But thrust faults are less seen on the surface. The Dorbadam anticline with the strike of NW- SE and overturned limb in some parts of the northern limb and due to the general stresses of the area can be folding in connection with fault in depth. On the other hand, the existence of a small anticline with a different axial trace, in the northern limb of the main anticline, can reveal changing the trend of stress in the studied area, which shows the importance of studying this area. With using previous studies in the area, studying maps and aerial photographs and data taken from field surveys, investigating faults and fractures, and using software such as Stereo net and etc. analyze this region geometrically and dynamically.

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2. Kinematics of area

The tectonic shortening applied to the north-east of Iran in the Kopet Dag basin appears in various forms. From this perspective, the basin can be divided into three parts: eastern, middle, and west. In the eastern part, the North-South shortening is conforming with the thrust faulting. In the middle section, it shows North-South shortening and East-West extension. By turning counterclockwise, the blocks are limited to the Quchan fault zone, and we can see escape of the west part of the Kopet-Dagh towards the west near the Caspian Basin (Fig 2a, b) (Hollingsworth et al. 2006, 2008).

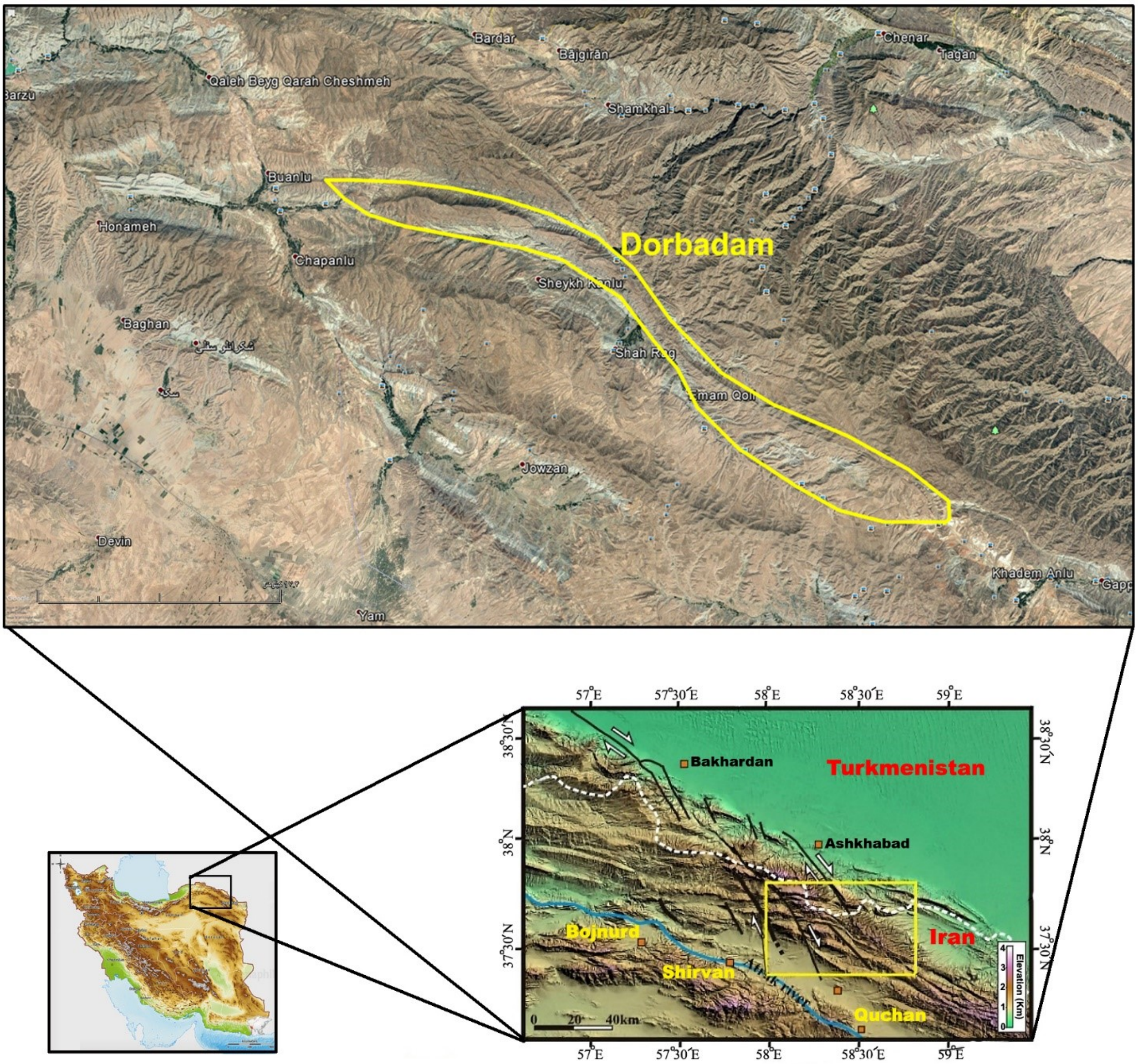

Fig 1. Geographic location of the study area in NE of Iran. Dorbadam anticline is shown with yellow line. Satellite photo from Google Earth.

3. Geometric analysis

3.1. Structural geometry of the Dorbadam anticline

The great anticline of Dorbadam with the general trend of NW-SE, is located in the Distance of 45 km from Quchan and north of the anticline of Imam Gholi (Fig 1) This anticline is about 50 km long with doubly hump (DA.1, DA.2) and has a z-shaped axial trace (Fig 3). The axial plane of the segment DA.1 has a curved geometry and is approximately 25 kilometers long and varies from 0.5 to 2 kilometers in width. Field observations indicate that the northern limb of DA.1 has reversal and the Tirgan Formation units are sloping towards the south along this limb (Fig 4).

In the transverse profiles of the Northwest segment (DA.1) of the anticline (A-A ', B-B', C-C ') (Fig 5), the topographic slope, on the northern limb of the anticline relative to the South limb, is a confirmation of the northern limb reversal.

In the northwestern part of the Dorbadam anticlinal (DA-1) and in the geographical position 37° 30´ 35/80 and 58° 23´ 50/1 there is a thrust fault that causes the formation of the S-C structures (Fig 6a). As a result, shear sense of area in which this texture is located is proposed here, which suggests a thrust mechanism for the fault in which the shear zone is located. In this section, the fault mirror with a profile of 125.45 was taken, which confirms the line of scratch on it with a rake angle of about 90 degrees (Fig 6b).

The anticline formation and reversal of the northern limb of anticline in this section are controlled by the growth of a fault in the anticline core and we can see the fault propagation fold in this part of the anticline. Since folding has occurred in the competent layers of limestone of Tirgan formation, with the growth of folding, locking and stress accumulation in the anticline occurred, and due to the greater focus of the fractures in the area of the Hinged plane region, along with the fault occurred. So the movement has occurred on the fault and caused the growth of folding. Thus, the Dorbadam anticline in the DA.1 segment has been an anticlinal breakthrough (Suppe 1983, 1985; Suppe and Medwedeff 1990; McClay 2003) (Fig 7).

3.2. Geometric Parameters of Dorbadam anticline

One of the ways to classify the folds is based on the properties of axial surface and the hinge line. In this method, we first refer to the axial plane slope and then to the Plunge of hinge line of the fold. Since the two sections of the anticline have different structural event, they should be studied separately. In order to calculate the axial plane of fold, field observations were made from the direction and slope of the layering of fold's limbs in both sections DA.1 and DA.2. In the northwestern part (DA.1), the axial plane has 59 degrees' slope and a 28-degree plunge of fold axis (Fig 8a). According to the Fleuty classification, this part of the anticline is Moderately inclined and Gently plunging fold, and is collectively called the Horizontal inclined fold. In the south east of the anticline (DA.2), the axial plane has a slope of 89 degrees and the fold axis has a plunging of about 8 degrees (Fig 8b). According to the Fleuty classification, this section of the anticline is upright and horizontal fold.

Another way of fold classification is based on the appearance of folds in its profile (Ramsay 1967). In a cross section of the Dorbadam anticline in the village of Dorbadam, a geometric drawing was done on two folded layers of Tirgan Formation and Measured the parameters to, tα and Tα (Fig 9) and t'α were calculated (Table 1), which is equal to 0.83 and, due to the slope of the axial plane in this section (59 degrees), Dorbadam anticline in the DA.1 section is in the 1C class of Ramsey classification.

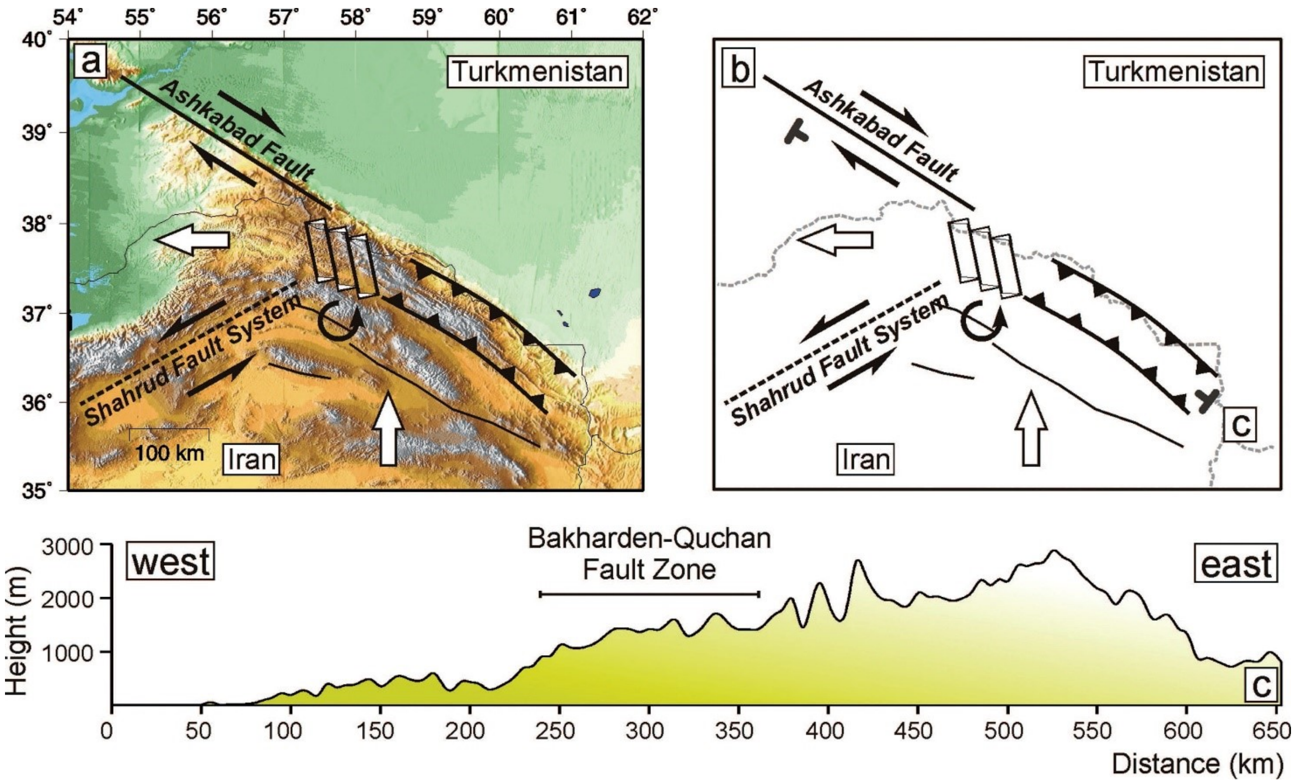

Fig 2. a) Northeast Iran topography map with simplified tectonic model. In the western part of the 59-degree longitude, the north-south convergence of Iran-Eurasia plates is being driven by strike slip movements on the Ashgabat and Shahrood fault systems. The Bakharden-Quchan fault zone accommodates the North-South shortening and East-West traction by counterclockwise rotation of a set of blocks. So the West Cape is driven out to the west. b) A simplified map of the tectonic model of northeastern Iran. c) Topographic profile extracted from SRTM topographic images of the inner Kopet-Dag. The highest elevations in the Bakharden-Quchan fault zone are where the shortening is compensated only by thrust faulting. In the west, the heights are eliminated, and strike slip faults play a more important role in North-South shortening accumulation (Hollingsworth et al. 2006).

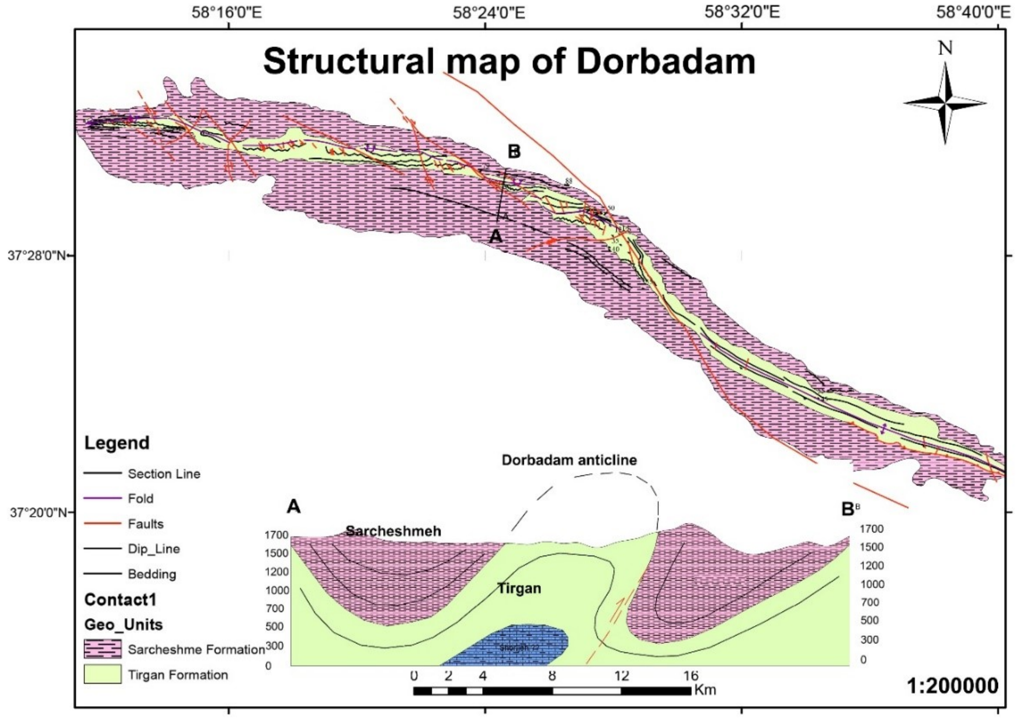

Fig 3. Geological and structural map with cross section of Dorbadam anticline in AB line using field observations including strike and dips of layers and faults, lithology and formations' boundary. The initial map is draws onto Google map and its output in the ArcGIS software was prepared by cartography methods. Geological cross section draws by using field observations, the Global Mapper and ArcGIS software.

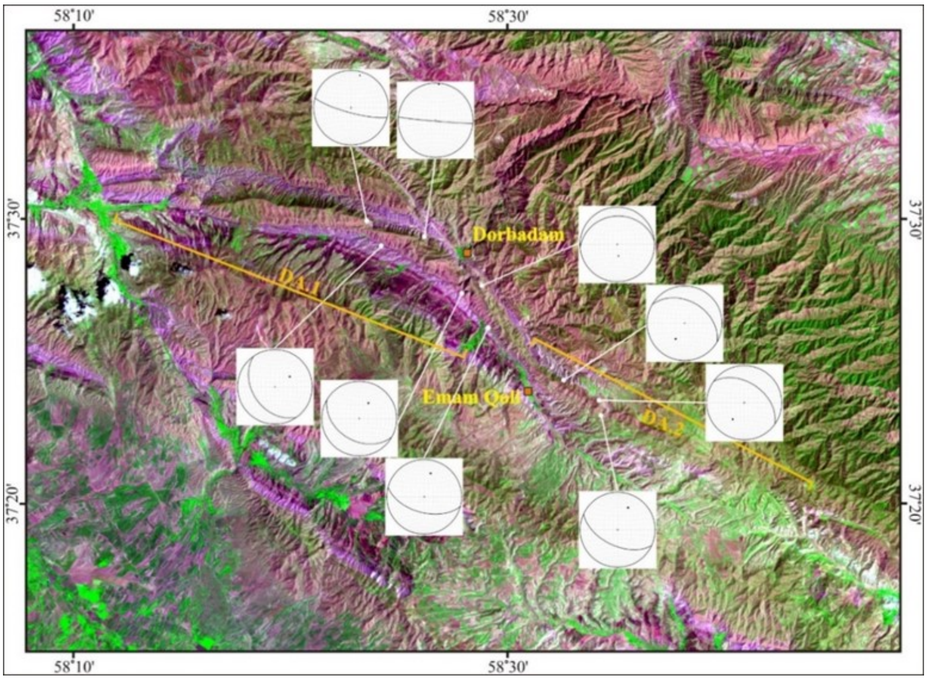

Fig 4. the image shows the characteristics of the layers taken from the Dorbadam anticline on the Landsat 7 satellite image. Notice the reversal of the layers in the northern limb of DA.1. Stereograms represent the slope and dip of the beddings. In the NW of area, the slope of the beds to SW shows the overturning of the beds.

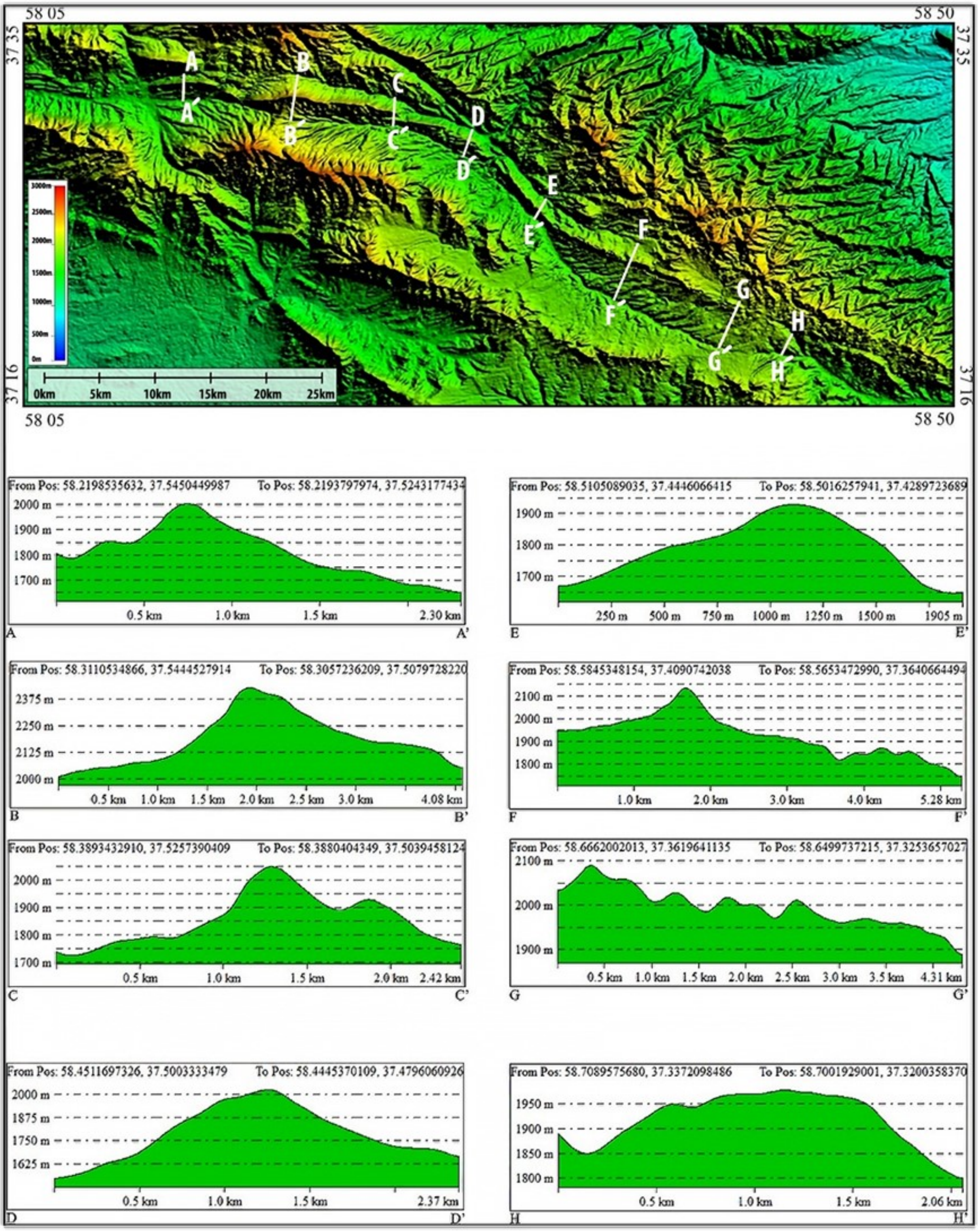

Fig 5. View of the Dorbadam anticline on the SRTM image and the topographic image of the eight profiles drawn on the anticline. A-D profiles are depicted on DA.1 and E-H profiles on DA.2. The more slope of the northern limb in the profiles in section DA.1 shows the reversal of the northern edge. While this phenomenon is not seen in DA.2. The top-level elevation is seen in the B-B′ profile.

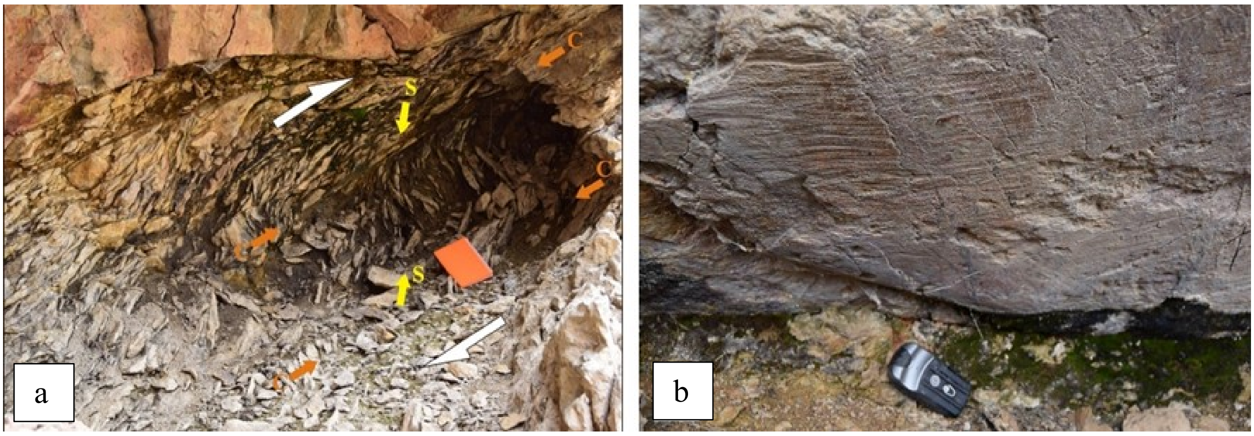

Fig 6. The fault in the northern limb of the DA.1 with a Specification of 125,45 and some slickensides on it, according to rake about 90 degrees shows thrust fault. a) S-C fabric in fault zone. b) slickensides on fault plane.

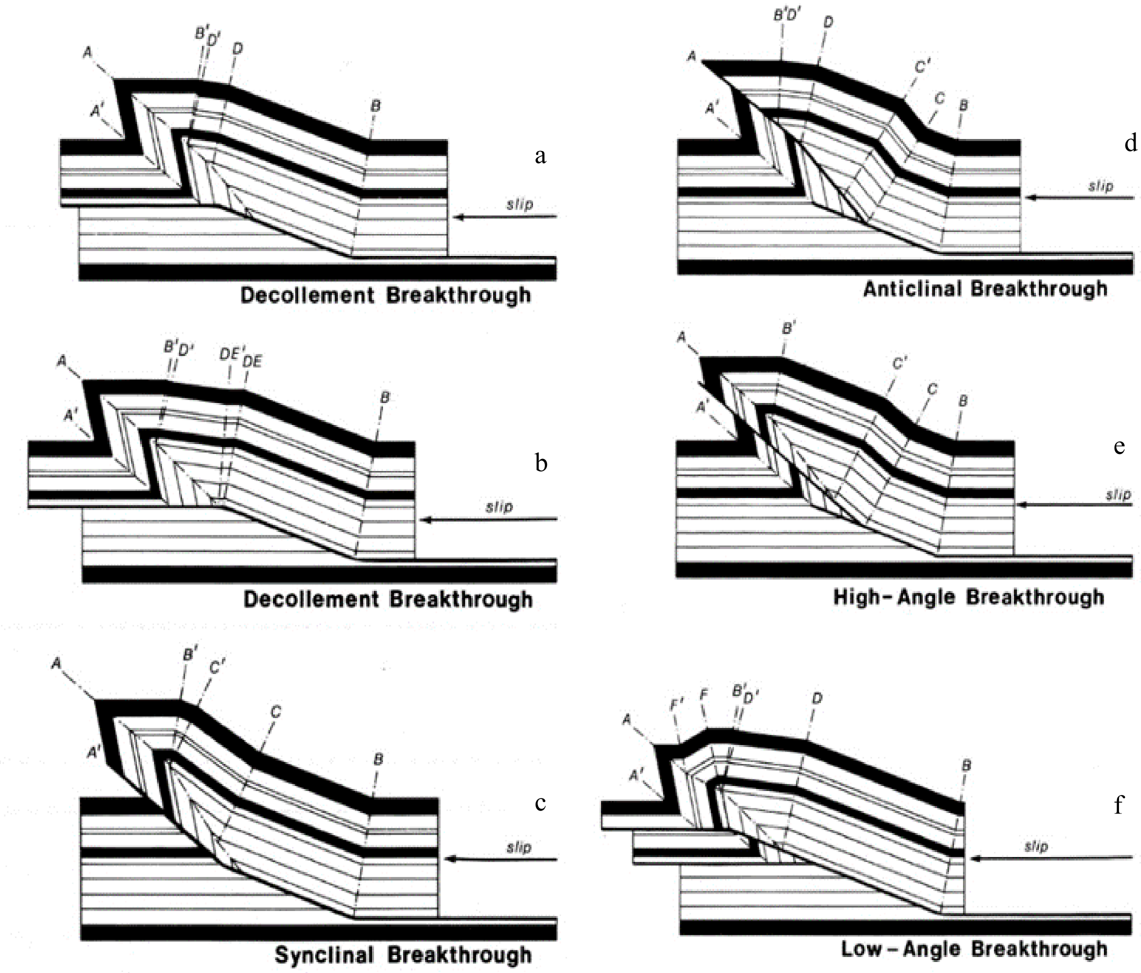

Fig 7. Balanced structural models that represent a number of possible types of penetrating developmental structures. These models are drawn with the assumption of a slip parallel to layers and axial surfaces pre-existing in the material. Retrieved from (Suppe and Medwedeff 1990).

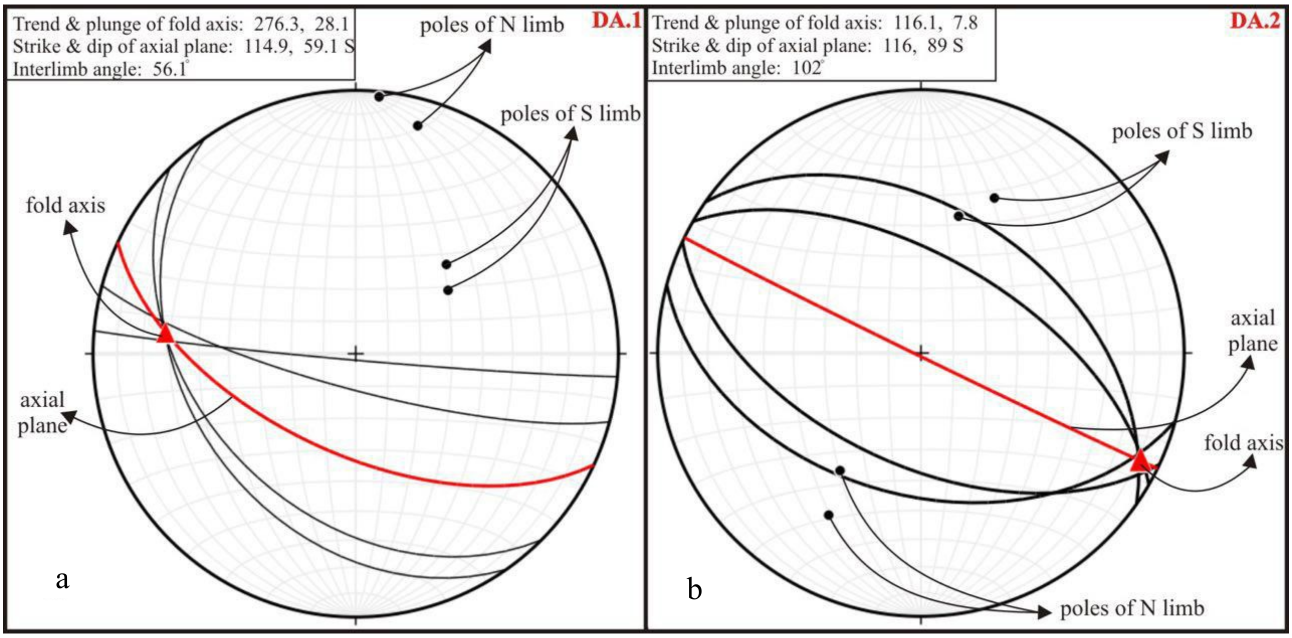

Fig 8. Display the layers' data from the limbs of the two segments of the Dorbadam anticline (DA.1, DA.2). The poles of the plates, the fold axis, the axial plane and the angle between the limbs in the software (sterionet-win-64) are calculated.

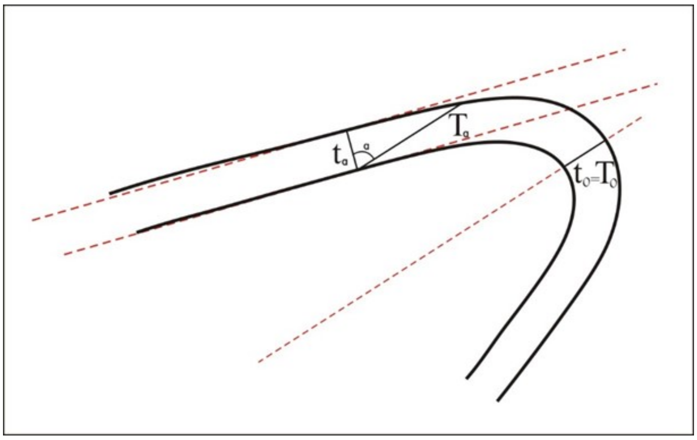

Fig 9. Drawing view on the folded surface of Tirgan Formation to calculate geometric parameters in the cross sectional profile of the Dorbadam anticline.

On the basis of the interlimb angle of folds there is another classification (Fleuty 1964), which is based on drawings done in the village of Dorbadam, placed in the close fold category (Fig 10). Based on the interlimb angle calculated in the stereographic drawings, in the Northwest segment of Dorbadam anticline (DA.1), the interlimb angle is 56 degrees (Fig 8a), and fold is still in the close category. While the southeast (DA.2) with 102 degrees interlimb angle is located in open fold category.

4. Kinematic analysis

The forces caused by movements of lithospheric plates at different times in different parts of the crust caused the stress fields to create deformation in the rocks. Based on the amount and direction of the stress and the geological and structural characteristics of the affected units, various deformations and, consequently, various structures are formed in the rock units. Therefore, the study of the structures of each area, provides comprehensive information of deformation method and the stress field in a wide range of time periods. In structural geology, while studying these deformations, we try to identify how to apply stress at different times. The study of the movements that occurred during the formation and deformation of rocks, such as displacement, volume change, rotation, and dislocation, are called kinematic analysis. In order to achieve the appropriate kinematic pattern in each area, the following items should be studied.

- The geometry and mechanism of the formation of main structures, such as folds and faults.
- Local variations of geometry of structures (displacements).
- Achieving the main axis of stress and strain in the studied area.
- Investigation of the distribution of the main axis of stress.
- Achieving a proper kinematic model based on the results of the studies mentioned.

The movements that happens from the stresses in each area, lead to the appearance of structural elements and the creation of displacements on those structures. The study of these structural elements and sense of motion on these elements can contribute to the kinematic analysis of structures. In the meantime, the study of the structural relation between tectonic units is a great way to help in a more accurate analysis. Amongst the compressive structures, it is possible to point out the folds and thrust faults, respectively, whose axis and their extensions are perpendicular to the maximum stress, or the conjugate shear joints that the acute angle between these joints corresponds to the maximum stress. These structures can also be used for kinematic analysis of the region.

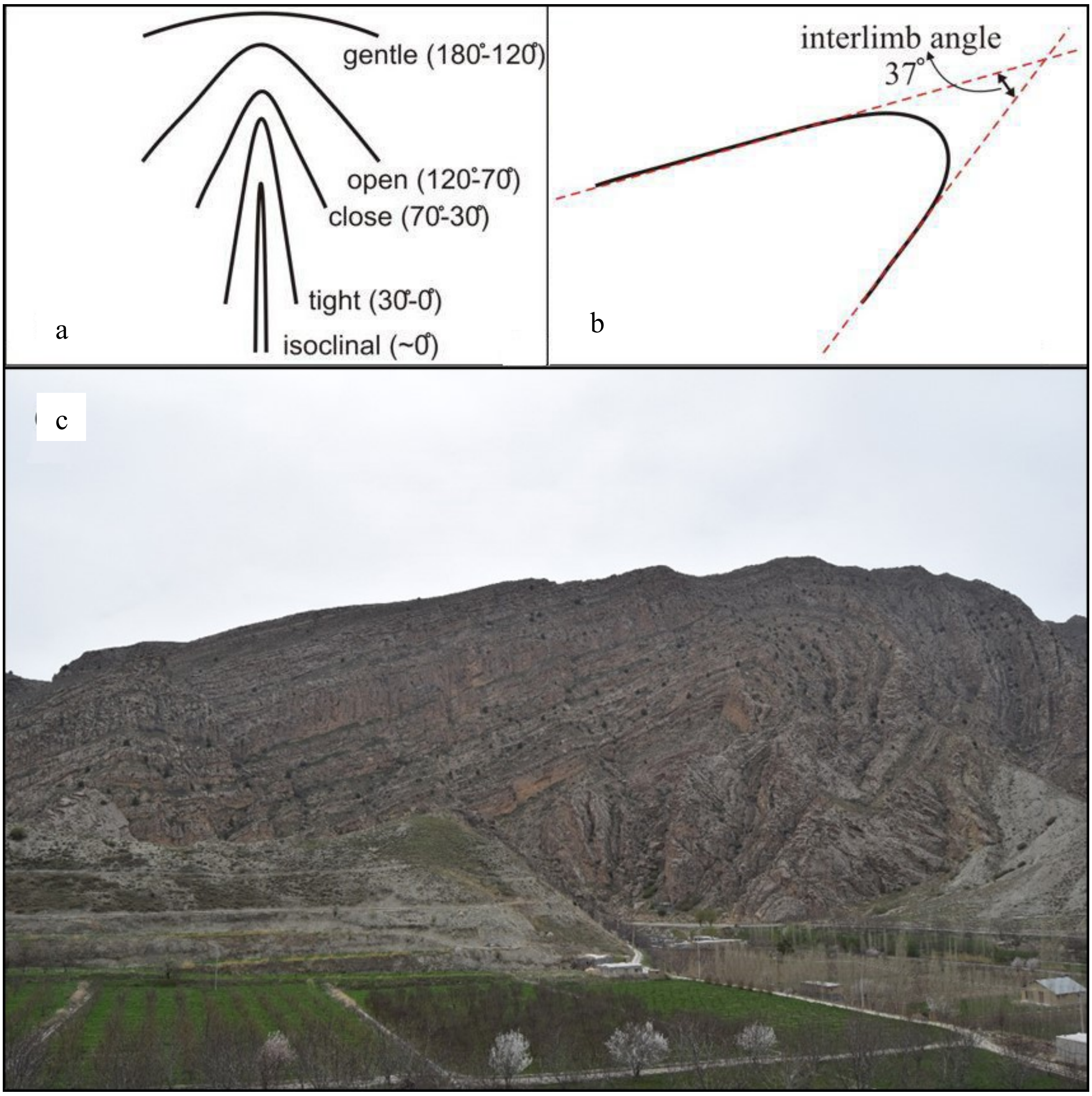

Fig 10. a) Fold classification based on the interlimb angle (Fleuty 1964). b) The interlimb angle calculated for the Dorbadam anticline. c) cross-sectional of the Dorbadam anticline.

4.1. Joint study

The joints and fractures of this region have been picked up stationary, and in those stations, the dominant trend and systematic have been studied. In order to study the pattern of joints in the study area, 9 stations with appropriate dispersion were selected and analyzed. The results are plotted in the form of a stereogram for layers in Fig 11. In order to study the statistics of the joints in these 9 stations, the results were drawn in the form of rose diagrams (Fig 12). The most important matter of the joint study in this area is to determine the stress field and to specify the relation between the joints with other structures in the region, including folds and faults.

An examination of the Rose diagrams of joints in the Dorbadam anticline shows the existence of five main sets and a number of other sub-sets for the region. The main joints are often aligned with layers, which are strike joints or layered joints (which are in the set of tensile joints or compressional joints parallel with the fold axis) or aligned in the direction The slope of the layering is located in the set of dip joints, which also fall into the set of tensile joints. In the 2,3 and 7 stations, the joints with NW-SE azimuth are not dominated. Because there is a shear zone in these regions, and they represent different joints.

Table 1. The results of geometric analysis of the Dorbadam anticline.

Parameteres		Amount
Geometric parameters		AA'
Interlimb angle (degrees)		37°
Folding angle (degrees)		140
Symmetry (degrees)		asymmetrical
Fold Shape		parabolic
Vergence		NE
Tightness		close
Harmony		harmonic
Axial plane Geometry		simple
P=A/M (P= 26.8/41.7)	Aspect	0.64
Log P		- 0.19
r_h (cm)	Bluntness	12.38
r_i (cm)		22
$r_h / r_i = b$		0.56
Descriptive word		subrounded
α (degrees)	(Ramsay and Huber 1987) classification	73°
T_α (cm)		19
$T_{o\ (cm)}$		7.2
$t_{\alpha\ (cm)}$		6
$t_{o\ (cm)}$		7.2
$T'_\alpha = T_\alpha / T_o$		2.6
$t'_\alpha = t_\alpha / t_o$		0.83
t_α , t_o		$t_o > t\alpha$
T'_α , Sec α		T'_α , Sec α
t'_α		١> t'_α
Fold class		1B to 1C
Rear limb slope (degree)		16°
Fault ramp slope (degree)		73°

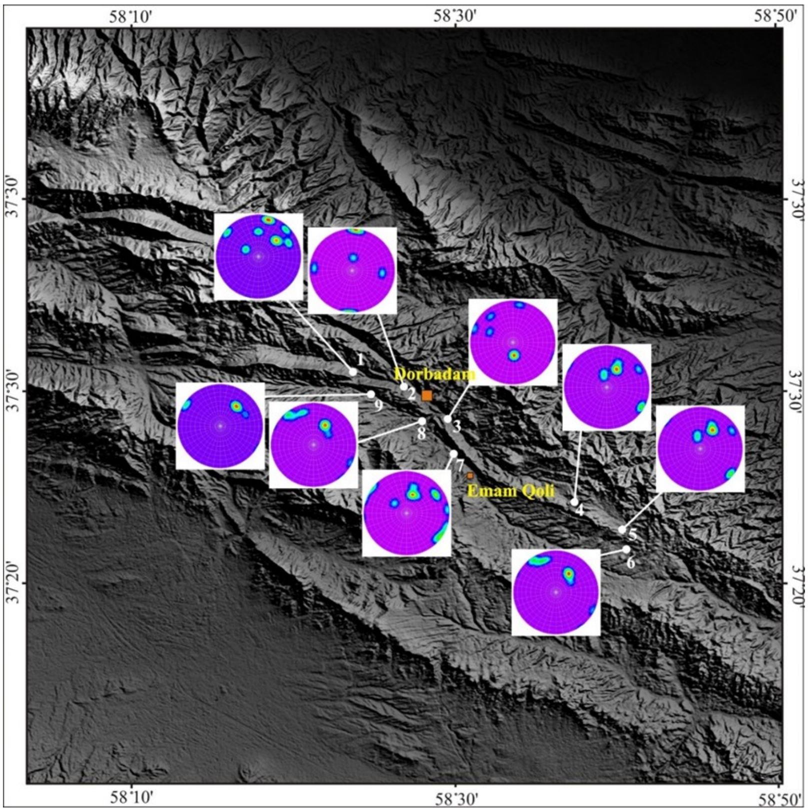

Fig 11. Shows the Stereographic Projection of the poles of the joints on the stereogram. At station number 1, there are 19 joint; at station 2, 22 joint; at station 3; 20 joint; at station 4; 21joint; at station 5; 18 joint; At station number 6, there were 18 joint; at station 7, 22 joint; at station 8; 20 joint; and at station 9, 23 joint were studied.

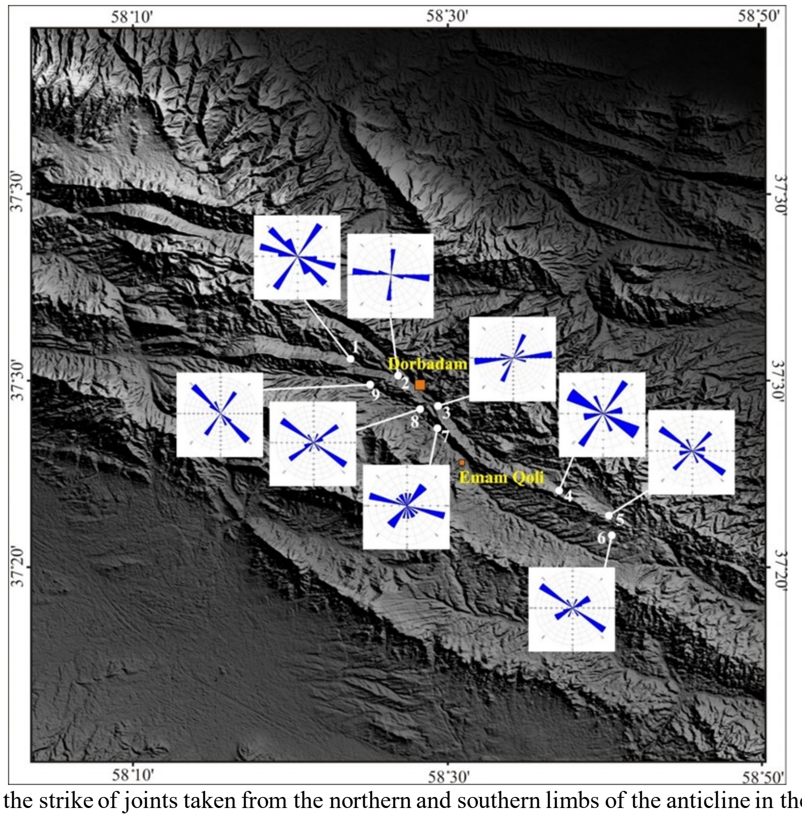

Fig 12. Rose diagrams of the strike of joints taken from the northern and southern limbs of the anticline in the Dorbadam anticline on both humps DA.1 and DA.2.

4.2. Determination of paleo stress based on layering and joints

Since the number and distribution of joints are suitable for the Dorbadam anticline, their analysis can be used to determine the paleo stress in the study area. In order to achieve this purpose, the systematic joints of the Tirgan Formation (Cretaceous) were used and with the help of T-Tecto software, we calculated the maximum stress (minimum strain) and minimum stress (maximum strain) directions. As the result shown in Fig 13, the Azimuth of the maximum stress is 187°, that is, the NE-SW.

4.3. Determination of paleo stress based on faults in the region

In order to analyze the trend of maximum stress in study area based on the existing faults in the region, information was obtained from geological maps for large scale faults. Since the mechanism of these faults is strike slip, their slope is nearly vertical. The secondary faults are also picked up (Fig 6, 14 and 15), and based on their summation, the stress trend was calculated by T-Tecto software. As it is shown in Figure 16, the stress's trend obtained from the study of faults, are different in terms of the calculated stress for the Cretaceous units, and this posits shows the post tectonic activity of the faults and their formation and activity in a more distinct and new stress system.

4.4. Determination of paleo stress by using the axial plane of the folds

The position of the axial plane of the folds in each area can be used to determine the paleo stress. The line perpendicular to the axial plane of the folds is the same as the compression axis (Z) that creates the fold, which is equal to the axis of maximum stress (σ1).

As can be seen from Figure 17, the trend of maximum stress is 205°, and it's somewhat different from the analysis of the joints for the direction of stress, but shows the same direction in the NE-SW.

5.The fold mechanism of the Dorbadam anticline

The folding style is controlled by competent units. Although less competent units can have unpredictable effects on folding and structures of the region. The competent layers tend to have a 1B class of folding, while the weaker layers form the class 3 of Ramsey fold classification (Table 2).

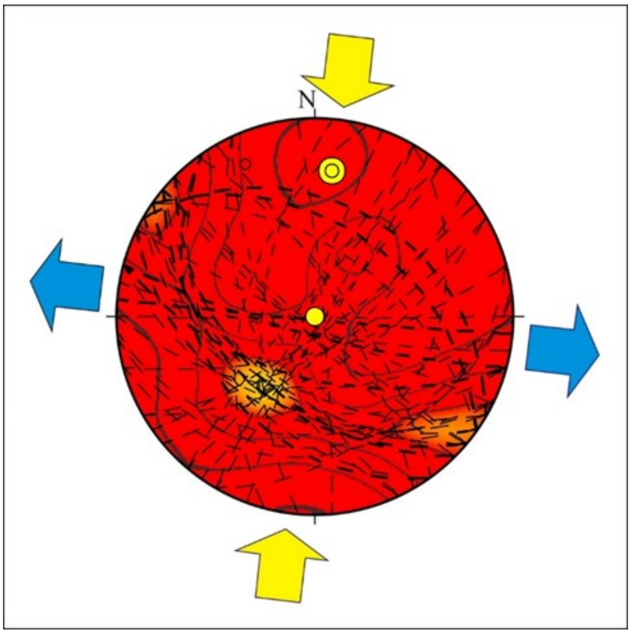

Fig 13. Yellow arrow is the maximum stress axis (187°) (minimum strain axis) and the blue arrow is minimum stress axis (maximum strain axis) during the Cretaceous period in the studied area using the Specification of layers and joints of the fold limbs.

Fig 14. The fault in the northern limb of the DA.1 with a Specification of 115,50 and some slickensides on it. the displacement of the units indicates that the fault mechanism is normal.

Fig 15. The fault in the northern limb of DA.1 with a Specification of 89,59 and some slickensides on it, according to rake about 30 degrees shows oblique slip fault.

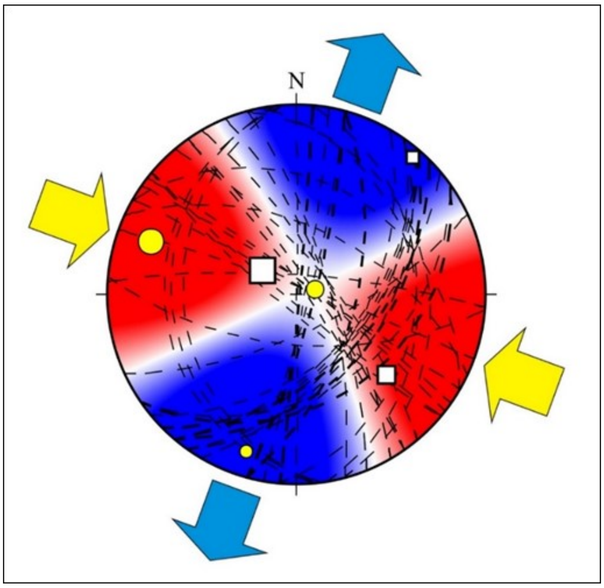

Fig 16. The yellow arrow of the maximum stress axis (the minimum strain axis) and the blue arrow of the minimum stress axis (maximum strain axis), derived from the 20 fault data of the Dorbadam anticline

Less competent units in the form of separation surfaces and lateral changes in facies, can cause changes in wavelength, amplitude, and folding style. In the studied area, we have sequences of Shurijeh and Tirgan layers as competent units (including limestone and sandstone, which according to Table 2 are medium to high competence units) and the Sarcheshmeh and Sanganeh layers as low competent units (including marl and shale, which according to Table 2 are low competence units).

In Dorbadam anticline, based on the Ramsey fold classification, anticlinal core consists of the competent units and the more ductile units formed surface layers. According to the diagram (Donath and Parker 1964), (Fig 17), the relation between the types of mechanism of folding with mean competence and the competence contrast of the units involved in folding, the dominant mechanism of the folding of Dorbadam anticline is the flexural-slip or the flexural-flow type because the average competency of the units is relatively high and the competency difference of the units involved in the folding is low. In this kind of folding, slip occurs at the layering levels and the thickness of the layers remains constant.

Table 2. Showing the classification of common rock units in folding from the highest to the lowest competence at low and very low metamorphic levels (Ramsay 1982). From 1 to 10, the competence value decreases.

Low or very low grade of metamorphism	
1	Dolomite
2	Arkose
3	Quartz sandstone
4	Greywacke
5	Coarse-grained limestone
6	Fine-grained limestone
7	Siltstone
8	Marl
9	Shale
10	Halite, anhydrite

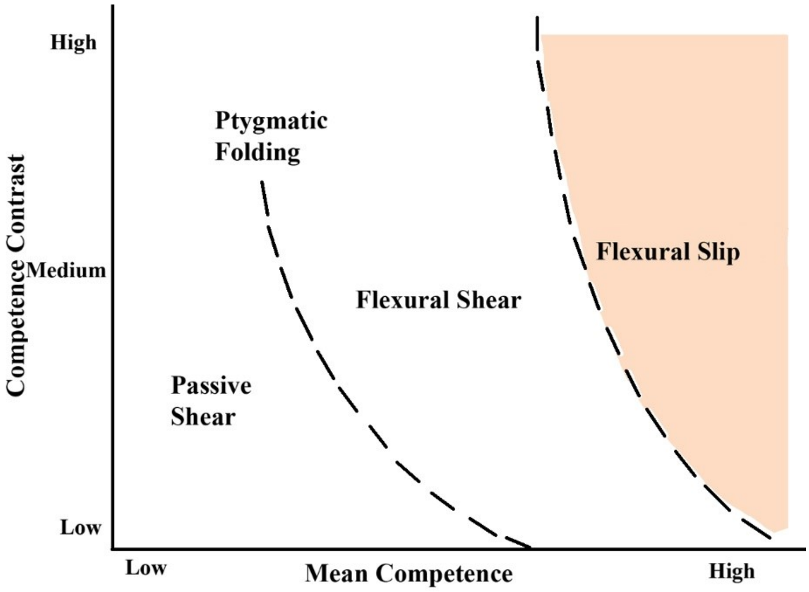

Fig 17. the kinematic model of folding based on the difference in competence and mean competence (Donath and Parker 1964).

6. Conclusion

The Dorbadam anticline is a bi-humps fold divided into two parts of northwest (DA.1) and south east (DA.2) with a different structural shape. The Dorbadam anticline in DA1 segment has a northern reversal limb and based on McClay's (2003) classification is a fault propagation fold, and the growth and formation of the anticline in this section is controlled by the growth of a fault in the anticline core. The southeast part of anticline (DA.2) has different characteristics from the northwest. The anticline limbs in this section are normal and have shaped a simple fold. Based on Fleuty classification, the DA.1 section, is the gently inclined and gently plunging fold and are collectively called the Horizontal inclined fold. In this classification, the southeast part of the anticline (DA.2) is an upright and horizontal fold. The classification based on the appearance of fold in the profile (Ramsay 1967), the fold of the Dorbadam anticline in DA. 1 part is in the 1C class of Ramsey classification and the t'α value is 0.83. And there is no possibility of fold classification based on this in Section DA.2.based of an interlimb angle in the folds, the Dorbadam anticline in the DA.1 section is placed in the closed category. While the southeast segment (DA.2) is located in the open category. Based on the angle between the axial plane and horizon level (Marshak, 1988), northwest part of Dorbadam anticline (DA.1), is positioned in in the asymmetrical over fold, and in the southeast (DA.2), anticline is a symmetrical upright fold.

The analysis of systematic joints that picked up from the Dorbadam anticline with the T-Tecto software, the trend of the maximum stress in the Cretaceous is 187 degrees (NE-SW). Analysis of large scale faults of Dorbadam anticline shows the changing of the trend of the maximum stress associated with this structure and is the post-tectonic nature of these faults. So Faults have acted in a separate stress system that cuts and replaces the anticlines of the range in a newer stress system.

The axial plane analysis of the Dorbadam anticline shows the trend of the maximum stress of 205 degrees, which is similar with little difference compared to the T-Tecto analysis of stress´s trend. The kinematic model of folding based on the difference in competency and mean competence (Parker and Dunnet 1964) shows that the anticline of Dorbadam, produced with flexural-slip or flexural-flow mechanism of folding, so folding occurs with the occurrence of slipping at the layering levels and the thickness of the beds stays constant.

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