

LATERAL GROWTH OF QARA DAGH ANTICLINE, SOUTH OF SULAIMANIYAH CITY, NE IRAQ: A STRUCTURAL – GEOMORPHOLOGICAL STUDY

Varoujan K. Sissakian¹, Rahim M. Amin² and Jamal Gh. Mohammed³

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Key words: Lateral growth, Water gap, Wind gap, Qara Dagh anticline, Iraq

ABSTRACT

The Qara Dagh anticline is located south of Sulaimaniyah city in the High Folded Zone of the Zagros Fold – Thrust Belt, within the Outer Platform of the Arabian Plate. It is about 116 Km long with a NW – SE trend. The oldest exposed rocks in the anticline are of Paleocene age and belong to the Kolosh Formation; whereas, the limestone beds of the Pila Spi Formation form the flanks of the anticline. The Pila Spi Formation locally forms the carapace of the mountain giving whale-back nature to the anticline. We have conducted in this work a structural – geomorphological study of the Qara Dagh anticline using existing features and form of the anticline, observed and checked by field work; different types of satellite images and updated geological maps (scale of 1: 100 000). Structural, geomorphological and stratigraphic data confirm the lateral growth of the anticline in a NW direction, complemented by the presence of: fork-shaped valleys, axial valleys, radiated valleys, abandoned alluvial fans, and the presence of water and wind gaps. The present study indicates that the Qara Dagh anticline was originally comprised of six smaller anticlines that exhibited lateral and vertical growth leading to the development of one major anticline. The NW propagation of the six segments of Qara Dagh anticline is supported by the presence of two en-échelon plunges within the main anticline. The rate of the lateral growth was higher than the rate of the incision of the streams; therefore, the streams were shifted around the tips of the segments; meanwhile abandoning the water gaps to wind gaps and development of new water gaps around the tips.

النمو الجانبي لطية قرّة داغ في جنوب مدينة السليمانية،
شمال شرق العراق: دراسة تركيبية – جيومورفولوجية

فاروجان خاجيك سيساكين، رحيم محمد امين و جمال غانم محمد

المستخلص

تقع طية قرّة داغ في جنوب مدينة السليمانية ضمن نطاق الطيات العالية التابع لحزام زاكروس الطي – الزاحف والواقع في الرصيف الخارجي من الصفحة العربية. يبلغ طول الطية حوالي 116 كلم وتمتد باتجاه شمال غرب-جنوب شرق. تعود اقدم الصخور المتكشفة في الطية لتكوين كولوش من عمر الباليوسين، الا ان الطبقات الجيرية العائدة لتكوين

¹ University of Kurdistan, Hewler, KRG; and Private Consultant Geologist, Erbil, Iraq,

e-mails: f.khajeek@ukh.edu.krd ; varoujan49@yahoo.com

² Retired Senior Chief Geologist, Erbil, Iraq, e-mail: raheemameen@gmail.com

³ Retired Senior Chief Geologist, Mosul, Iraq, e-mail: jamal195483@gmail.com

بيلاسبي تشكل جناحي الطية واحيانا تكون مجمل جبل قره داغ حيث تعطي الطية شكل ظهر الحوت. نفذنا دراسة تركيبية – جيومورفولوجية معتمدين على الظواهر الموجودة في الطية التي تمت ملاحظتها وتدقيقها حقليا فضلا عن استخدام عدة أنواع من المرئيات الفضائية وبمقاييس مختلفة وخرائط جيولوجية محدثة من (مقياس 1: 100 000) لإيجاد معطيات تركيبية وجيومورفولوجية وطباقية استخدمناها في معرفة النمو الجانبي لطية قره داغ. بينت هذه الدراسة وجود ضواهر تشير الى نمو الطية باتجاه الشمال الغربي تتمثل بوجود وديان شوكية وشعاعية الشكل ومراوح نهريّة متروكة فتحات مائية وهوائية. استنتجنا من الدراسة بان طية قره داغ كانت تتكون بالأصل من ستة طيات صغيرة نمت جانبيا وعموديا لتشكل طية قره داغ الحالية ويؤيد ذلك وجود الغواطس المتبادله في جسم الطية الرئيسي. تشير الدلائل الى أن معدل سرعة النمو كانت أعلى من سرعة قطع الجداول للصخور وبالتالي غيرت هذه الجداول مجراها الى نهاية حافات الطيات الصغيرة حيث كونت فتحات مائية جديدة تاركة الفتحات المائية القديمة لتتحول الى فتحات هوائية.

INTRODUCTION

The study area is located south of Sulaimaniyah city, northeast of Iraq (Fig.1), represented by Qara Dagh Mountain, which partly forms the Qara Dag anticline with NW – SE trend. The study area covers about 250 Km². The Qara Dagh Mountain is a NW – SE trending double plunging anticline exhibiting many water and wind gaps, which divided the anticline into six segments (Sissakian and Fouad, 2014). The lowest elevation point is 421 m (a.s.l.) located in the northwestern plunge of the anticline, whereas the southeastern plunge is at elevation of 505 m (a.s.l.) and the highest peak is 1834 m (a.s.l.), in the Sagerma Mountain. The six main segments of Qara Dagh Range are called Hanjira (Qara Darbandi), Ba Sara, Sagerma, Zarda, Spei and Golan; from northwest to southeast, in this study we have identified them as segments of the main Qara Dagh anticline. The aim of this study is to show that the Qara Dagh anticline was originally consisting of six smaller anticlines which were conjugated to each other by lateral and vertical growth to form the nowadays main Qara Dagh anticline.

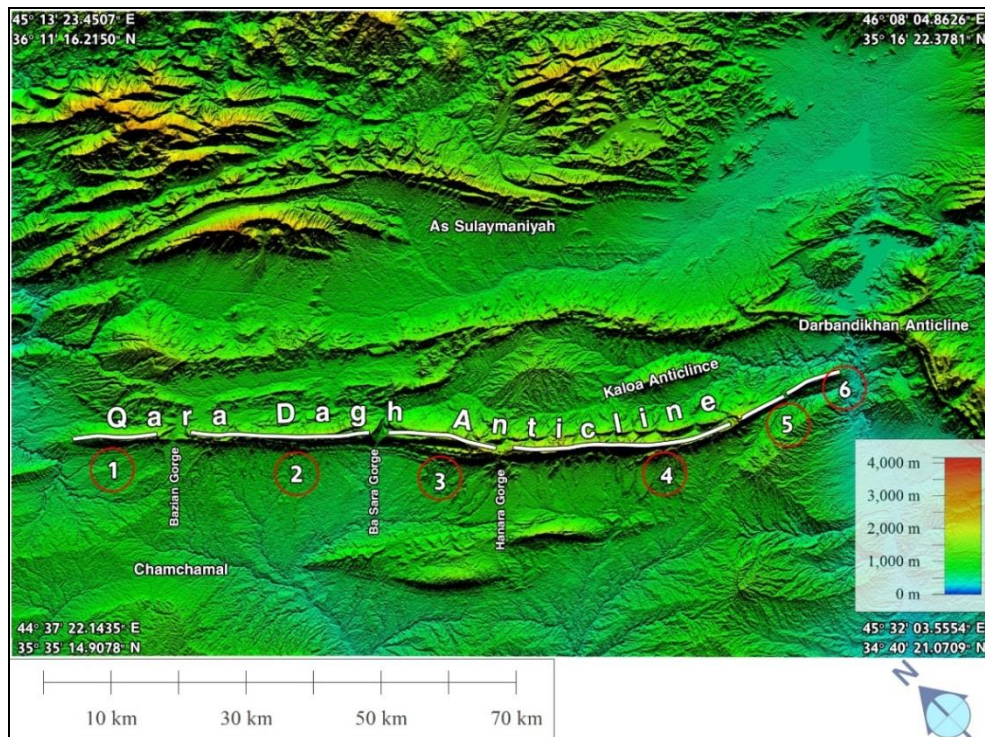


Fig.1: Satellite image showing the study area with the six segments. 1) Hanjira, 2) Ba Sara, 3) Sagerma, 4) Zarda, 5) Spei, and 6) Golan

▪ Previous Studies

Tectonic – geomorphological studies are relatively scarce in the studied area; however, we have mentioned hereinafter some relevant studies:

Sissakian (2010) conducted tectonic – geomorphological study on Derbendi Bazian gorge and attributed the development of the gorge to neotectonic activity. Sissakian and Abdul Jab'bar (2010) conducted study about the transversal gorges, among them are Ba Sara gorge and concluded that the gorge is developed due to neotectonic activity. Al-Kubaisi and Abdul Jab'bar (2015) conducted morphotectonic study of the Dagh anticline and two other folds in the region and discussed their effect on the Qara drainage systems. They have divided the anticline into five segments and indicated high tectonic activity and low maturity of the drainage basin. Sissakian *et al.* (2014) conducted geomorphological study of the High Folded Zone and attributed the developed gorges in Qara Dagh anticline to lateral propagation. Bretis *et al.* (2011) performed a study about the lateral growth of anticlines in the Zagros Thrust – Fold Belt in the Kurdistan Region. Zebari and Burberry (2015) conducted 4-D evolution of anticlines and implications for hydrocarbon exploration within the Zagros Fold – Thrust Belt, in the Kurdistan Region. Karim and Khanaqa (2017) performed a study related to the growth of synclines as mountain peak building and gave examples from the Iraqi Kurdistan Region. Obaid *et al.* (2017) performed a study about the maturity of landscape and fold growth concerning structural style in the Kirkuk Embayment in northern Iraq. Moreover, Sissakian and Fouad (2013; 2014a and b), updated the geological maps of Sulaimaniyah Quadrangle at scales 1: 100 000 and 1: 250 000 and Erbil Quadrangle at scale of 1: 250 000, respectively. They mapped Qara Dagh anticline with stratigraphic and tectonic details, showing its six segments and marking the water and wind gaps.

MATERIALS AND METHODS

▪ Materials

In order to achieve the main aim of this study the following materials were used:

- Topographic and geological maps of different scales of the studied area.
- Satellite, Google Earth and FLASH Earth images, and DEM of 90 m resolution.

▪ Methods

The work of Keller *et al.* (1999) is considered as the main guide line for our current study and conclusions. Using the available topographical and geological maps of different scales (1: 100 000 and 1: 250 000) with the help of different satellite images, we have studied the tectonic – geomorphological features to indicate the lateral growth of Qara Dagh anticline. The geomorphologic features of Zagros Range have been used here to uncover aspects of the growth, evolution and interaction of anticlinal folds. Geomorphic criteria have been used to evaluate fold growth such as the deformation of progressively younger deposits or landforms; the development of characteristic asymmetric drainage patterns and the occurrence of a series of wind gaps with decreasing elevation in the propagation direction. The DEM of 90 m resolution have been used to draw a cross section of Qara Dagh anticline. We investigated thoroughly the details of drainage behaviour and other geomorphological features, such as alluvial fans, flood plain and valley courses to indicate the lateral growth of Qara Dagh anticline. Furthermore, we have also briefly described the active tectonics, stratigraphy and structural geology of the study area and near surroundings. Field work was conducted to check the acquired data from the satellite imagery.

GEOLOGICAL SETTING

The geological setting of the studied area is briefly described hereinafter based on the most recent available data (Sissakian and Fouad, 2012; Fouad, 2012; and Sissakian *et al.*, 2014).

▪ **Geomorphology**

The studied area is located within the High Mountainous Province (Sissakian and Fouad, 2012). The main geomorphological units and forms in the studied area are:

- **Alluvial Fans:** Tens of alluvial fans are developed along the southwestern limb of Qara Dagh anticline (Fig.2). Locally they form Bajada, usually covered by thin veneer of silty clayey soil.
- **Terraces:** Two levels of terraces occur along the main streams, the pebbles are mainly composed of carbonates with very rare igneous and metamorphic rocks. The average size of the pebbles is (1 – 12) cm, cemented by calcareous and sandy materials.
- **Flood Plain and Valley Fill:** The main streams and valleys have developed their own flood plains and valley fill sediments. The constituents are silt and clay for the former and pebbles and gravels for the latter.
- **Anticlinal Ridges:** These form continuous ridges within the Pila Spi Formation (Fig.2) for few tens of kilometers and are the main outlets of the streams that have developed the alluvial fans and expressing the water and wind gaps. Moreover, the ridges manifest and present the shape of the anticline.
- **Drainage patterns and shapes:** The main drainage pattern is the dendritic, which is developed within the soft rocks. Parallel drainage pattern is developed in the main valleys and/ or streams; following the regional slopes. Fork-shaped valleys and axial valleys are common too.

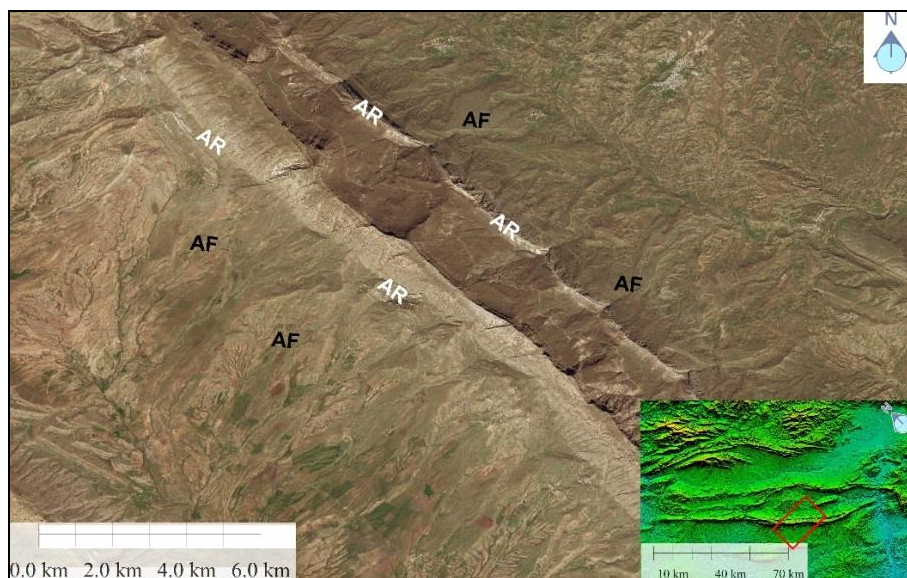


Fig.2: Satellite image showing alluvial fans (AF) and continuous anticlinal ridges (AR) within the Pila Spi Formation surrounding Qara Dagh anticline

▪ Structural Geology and regional tectonics

The studied area is located within the High Folded Zone of the Zagros Fold – Thrust Belt of the Arabian Plate Outer Platform. The zone is characterized by long anticlines and shallow and wide synclines. The Qara Dagh anticline is NW – SE trending double plunging anticline; although many plunges occur within the main anticlinal body (Fouad, 2012). The anticline includes typical anticlinal ridges (Fig.2), which are dissected by streams and valleys and express the segments and shape of the anticline. Generally, the north-eastern limb is gentler than the south-western one, the dip amount ranges from (15 – 55)°. Many small faults of different types exist within the anticline.

The age of initial collision between Arabia and Eurasia plates is poorly constrained according to Ramsey *et al.* (2008) and is possibly diachronous from NW to SE (Stoneley, 1981). The minimum age of continental collision was estimated to range from (16 – 23) Ma based on structural and sedimentation records (Robertson, 2000) to no later than ~10 Ma based on the reconstruction of plate motions (McQuarrie *et al.*, 2003). The mechanism by which shortening occurred may have undergone a reorganisation about 5 Ma ago (Axen *et al.*, 2001; Allen *et al.*, 2002 and 2004), which is thought to coincide approximately with the onset of deformation in the so-called “Simple Folded Belt”, which is equivalent to the Low Folded Zone in Iraq, although some shortening within this belt may have started as early as 8 Ma (Homke *et al.*, 2004).

▪ Stratigraphy

The exposed geological formations in the studied area (Fig.3) are described very briefly here depending on Sissakian and Fouad (2012) and Sissakian and Al-Jibouri (2014). Formations younger than the Fatha Formation (Middle Miocene) are not included.

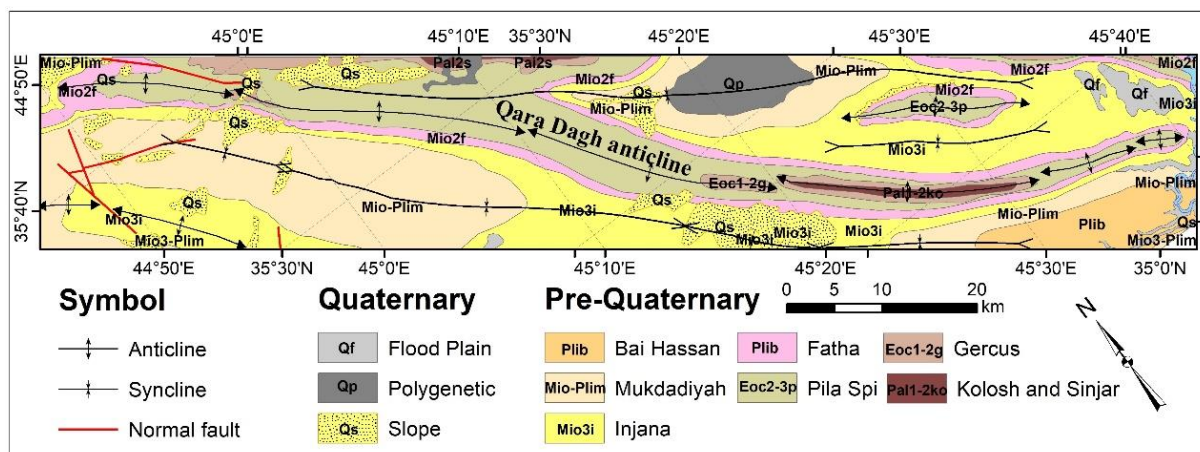


Fig.3: Geological Map of Sulaimaniyah Quadrangle, scale 1: 250 000 showing Qara Dagh anticline (after Sissakian and Fouad, 2014)

- **Kolosh Formation** (Paleocene): It is exposed; locally in the core of Qara Dagh anticline and consists of about 200 m. thick black shale, claystone, sandstone and very rare conglomerate.
- **Sinjar Formation** (Paleocene): It forms continuous ridges inside the core of Qara Dagh anticline. It consists of (40 – 60) m. thick well bedded hard limestone.

- **Gercus Formation** (Eocene): It is exposed along the slopes of Qara Dagh anticline and consists of about 120 m. thick red claystone and sandstone.
- **Pila Spi Formation** (Eocene): It forms continuous ridges surrounding Qara Dagh anticline expressing the six segments of the anticline and manifesting the water and wind gaps, and locally forms the bulk of the anticline. It consists of (80 – 100) m. thick dolomite, dolomitic limestone and limestone.
- **Fatha Formation** (Middle Miocene): It is exposed around Qara Dagh anticline and includes two members, Lower and Upper. Both of which consist of cyclic sediments of green marl, limestone and gypsum. In the Upper Member; however, red claystone occurs in the uppermost cycles above the green marl and reddish brown sandstone.

CHARACTERISTICS OF THE QARA DAGH ANTICLINE

The Qara Dagh anticline is a NW – SE trending structure, about 116.32 Km. long and consists of six segments. The characteristics of the anticline are shown in Table (1). The Qara Dagh anticline exhibits one water gap and two wind gaps, with two main plunges in north western and south eastern sides. Moreover, two en-echelon indications exist in the anticline. The Sagerma segment shows clearly a closed wind gap in its tip, most probably due to tectonic and/ or geomorphic aspects. Moreover, the continuous anticlinal ridge around the Sagerma segment exhibits tens of outlets from the anticline on both sides and may indicate previous water gaps.

The existing water gaps and wind gaps, besides the morphology of the anticline and existing valleys and streams within the main Qara Dagh anticline indicate that originally the anticline was consisting of six anticlines that are grown laterally and vertically, and then merged together forming the present Qara Dagh anticline. This assumption is based on approaches given by Keller and Pinter (2002) and Ramsey *et al.* (2008), as illustrated in Figure (4).

Table 1: Characteristics of the six segments of Qara Dagh anticline

Name	Length (Km)	Width (Km)	Exposed Formations	Shape	Type of tips
Hanjira	16.91	2.6	Gercus, Pila Spi and Fatha	Whale back	Plunges towards NW and water gap in SE
Ba Sara	23.42	2.6 – 3.9	Gercus, Pila Spi and Fatha	Eroded core	Water gaps on both tips
Sagerma	16.50	1.5 – 3.9	Gercus, Pila Spi and Fatha	Anticlinal Ridges with eroded core	Plunges towards SE and water gap in NW
Zarda	43.17	3.9 – 4.28	Kolosh, Sinjar, Gercus, Pila Spi and Fatha	Eroded core with continuous anticlinal ridges	Plunges towards NW and erosional cliff in SE
Spei	6.96	0.81- 4.28	Pila Spi and Fatha	Smoothed carapace	Eroded cliff in NW and dissected by fault in SE
Golan	9.36	0.81 – 2.23	Pila Spi and Fatha	Surrounded by hogbacks and cuestas	Dissected by fault in NW and plunges towards SE

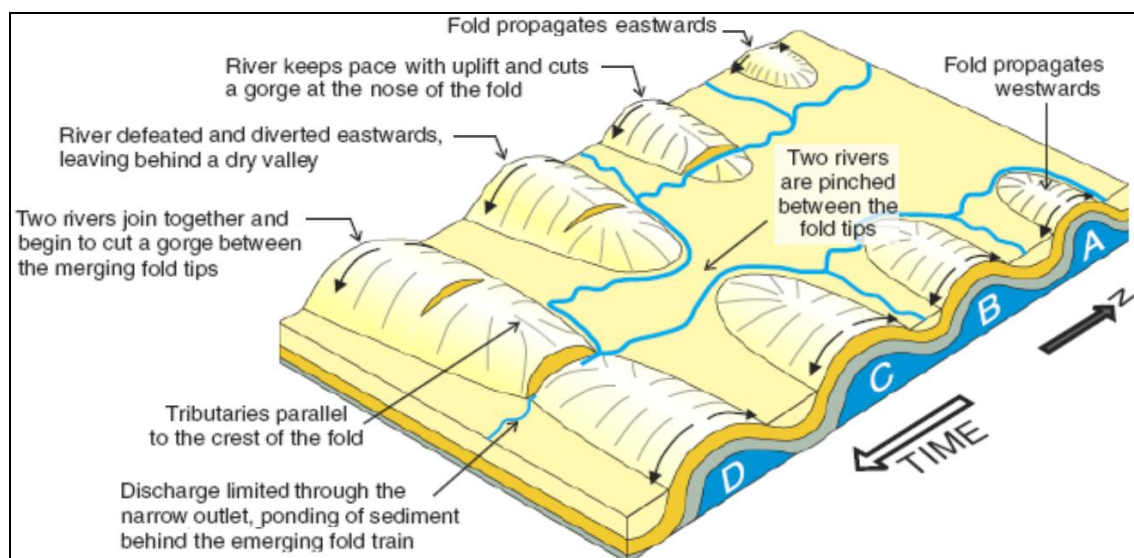


Fig.4: Diagrammatic presentation of the formation of a gorge between two propagating anticlines through time (Ramsey *et al.*, 2008). **A)** Two small folds form in the east and west of the landscape. **B)** The folds propagate towards one another. Growth on aligned fold segments is enhanced by positive feedback in the stress changes around each growing fold. The incision rate of the western river keeps pace with uplift and the river incises a gorge through the nose of the fold. **C)** The western river is unable to keep pace with uplift and the gorge is abandoned and left as a dry valley. The river is diverted to the east and pinched between the tips of the two folds. **D)** The folds continue to propagate towards one another and the tips of the folds begin to form a continuous structure. The rivers have increased their stream power by joining together and incise a gorge through the almost continuous anticline

RESULTS

▪ Hanjira

The Hinjira segment forms the extreme NW part of the Qara Dagh anticline (Figs.1 and 5). Apart from the north-western plunge, the segment has whale-back form. It is characterized by a fork-shaped drainage and one water gap (Fig.5), all these features are indications considered for lateral growth of anticlines (Killer and Pinter, 2002 and Ramsey *et al.*, 2008). The north western part forms the north western plunge of Qara Dagh anticline, whereas the south eastern part forms a main wind gap forming Derbendi Bazian Gate, which was formerly a water gap and abandoned due to local neotectonic activity in Derbendi Bazian area (Sissakian, 2010).

▪ Ba Sara Segment

The Ba Sara Segment forms the second segment of Qara Dagh anticline from north western side (Figs.1 and 6). It is limited from NW by a wind gap, which is believed to be originally a water gap and abandoned due to local neotectonic activity in Derbendi Bazian area (Sissakian, 2010). Whereas, the south eastern side is limited by a water gap, called Ba Sara gorge (Fig.6). Other indications supporting lateral growth (Killer and Pinter, 2002 and Ramsey *et al.*, 2008) of this segment include fork-shaped valleys (Fig.6a and b) and axial valleys (Fig.6c).

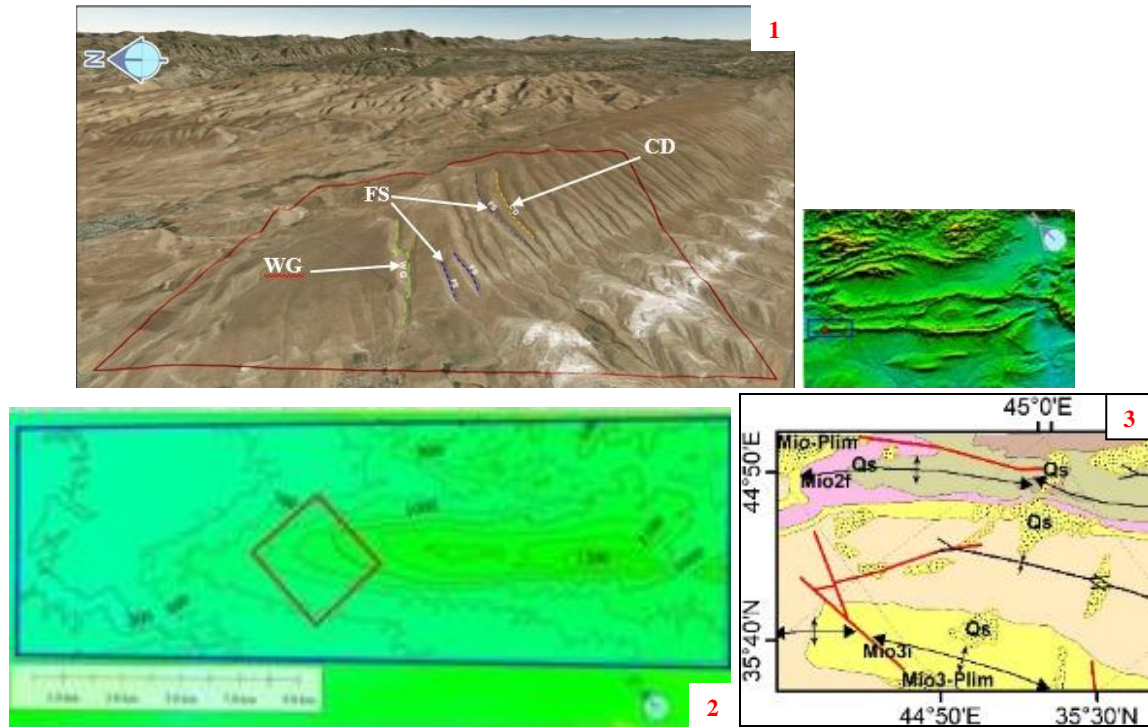


Fig.5: The Hinjira segment of Qara Dagh anticline. **1:** Satellite image; note the whale-back shape of the segment; the water gap (WG); curved drainage (CD); fork-shaped valleys (FS). **2:** Contour map of the segment. **3:** Geological map of Hinjira Segment (for legend, refer to Figure 3)

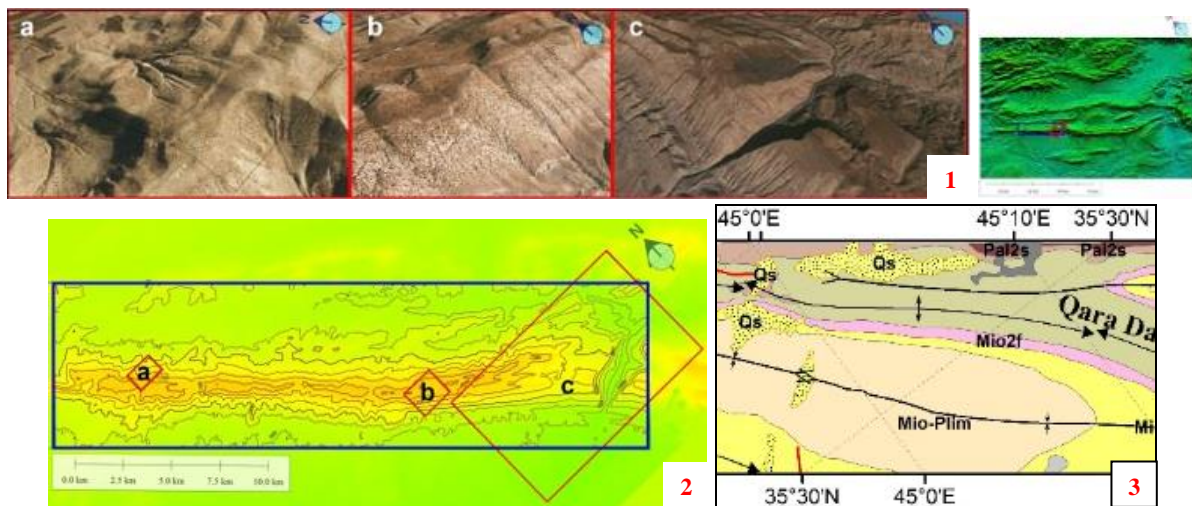


Fig.6: The Ba Sara segment of Qara Dagh anticline. **1:** Satellite images: **a)** and **b)** two fork-shaped valleys, **c)** the water gap (Ba Sara Gorge) and the axial drainage. **2:** Contour map of the segment. **3:** Geological map of the Ba Sara Segment (for the legend refer to Figure 3)

▪ Sagerma Segment

The Sagerma Segment forms the third segment of Qara Dagh anticline from north western side (Figs.1 and 7). It is limited from NW by a water gap, called Ba Sara Gorge; whereas, the SE side is limited by an en-echelon plunge towards SE, which forms a wind gap, called Hanara Gorge, it is clearly expressed by the contour lines. Other indications for lateral growth (Killer and Pinter, 2002, Bull, 2007 and Ramsey *et al.*, 2008) of this segment include tens of fork-shaped valleys located along the southwestern limb (Figs.7a and b) axial valleys (Fig.7c), and a wind gap, called Hanara Gorge (Fig.7b).

▪ Zarda Segment

The Zarda Segment forms the fourth segment of the Qara Dagh anticline from the north western side (Figs.1 and 8). It is limited from NW by an en-echelon plunge, which forms a wind gap, called Hanara Gorge, whereas the SE side is limited by a wind gap; its eastern bank forms a steep cliff (Fig.8a and b). Indications for lateral growth (Bull, 1991 and 2007, Killer and Pinter, 2002 and Ramsey *et al.*, 2008) of this segment include tens of fork-shaped valleys located along the SW limb (Fig.8a and c) and tens of outlets within the anticlinal ridge that surrounds Zarda Segment within the Pila Spi Formation (Fig.8a).

▪ Spei Segment

The Spei Segment is the fifth segment of the Qara Dagh anticline from NW side (Figs.1 and 9a-c). It is limited from NW by a wind gap, which forms a steep cliff in its eastern side (Fig.9a); whereas, the SE side is limited by en-echelon plunge (Fig.9c). The plunge is very clearly represented in the contour map (Fig.9, middle left). Other indications for lateral growth (Bull, 1991 and 2007, Killer and Pinter, 2002 and Ramsey *et al.*, 2008) of this segment include tens of fork-shaped valleys located along the southwestern limb (Fig.9a) and curved valleys (Fig.9b) and inclined valleys along the southwestern limb (Fig.9c).

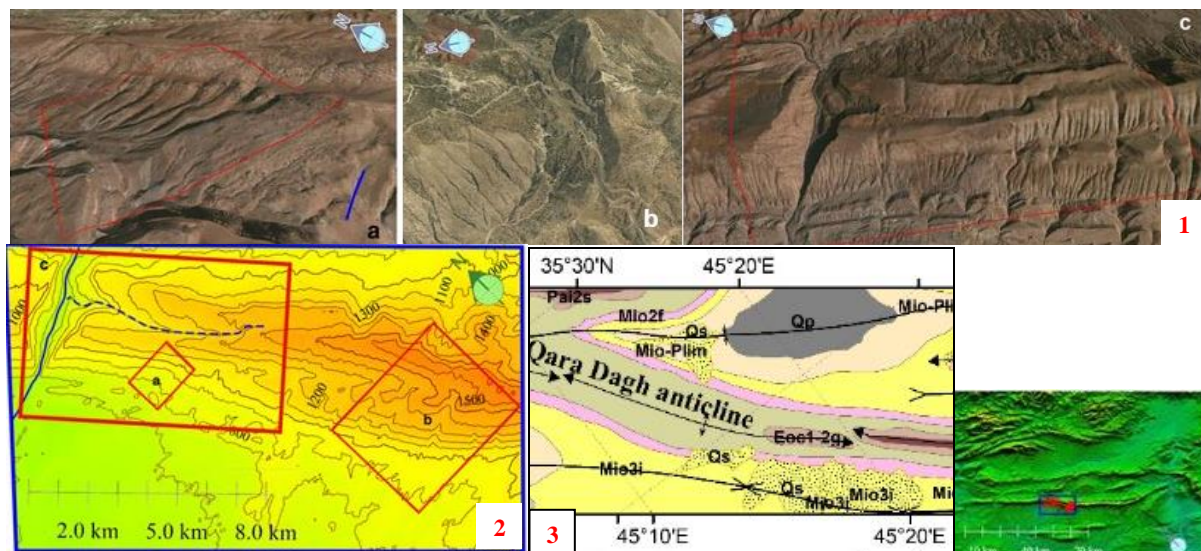


Fig.7: The Sagerma segment of Qara Dagh anticline. **1:** Enlarged satellite images of three parts: **a** and **b**) fork-shaped valleys, **b**) wind gap (Hanara Gorge), **c**) axial drainage and wind gap (Ba Sara Gorge). **2:** Contour map of the segment. **3:** Geological map of the Segment, note the en-echelon folding style on both plunge areas (for the legend refer to Figure 3)

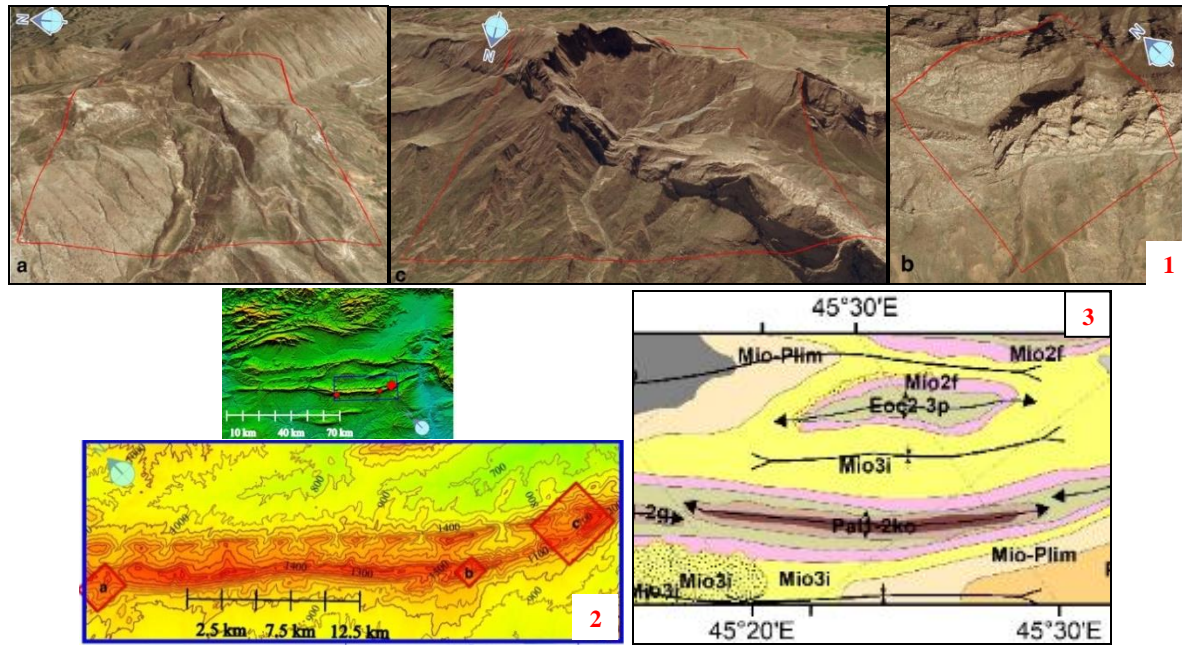


Fig.8: The Zarda Segment of Qara Dagh anticline. **1:** Satellite images: Note the wind gap (Hanara Gorge), **a)** en-echelon plunge with fork-shaped valleys, **b)** tens of fork-shaped valleys and **c)** wind gap forming steep cliff. **2:** Contour map of the segment. **3:** Geological map of Zarda Segment, note the en-echelon folding style on both plunge areas (For the legend refer to Figure 3)

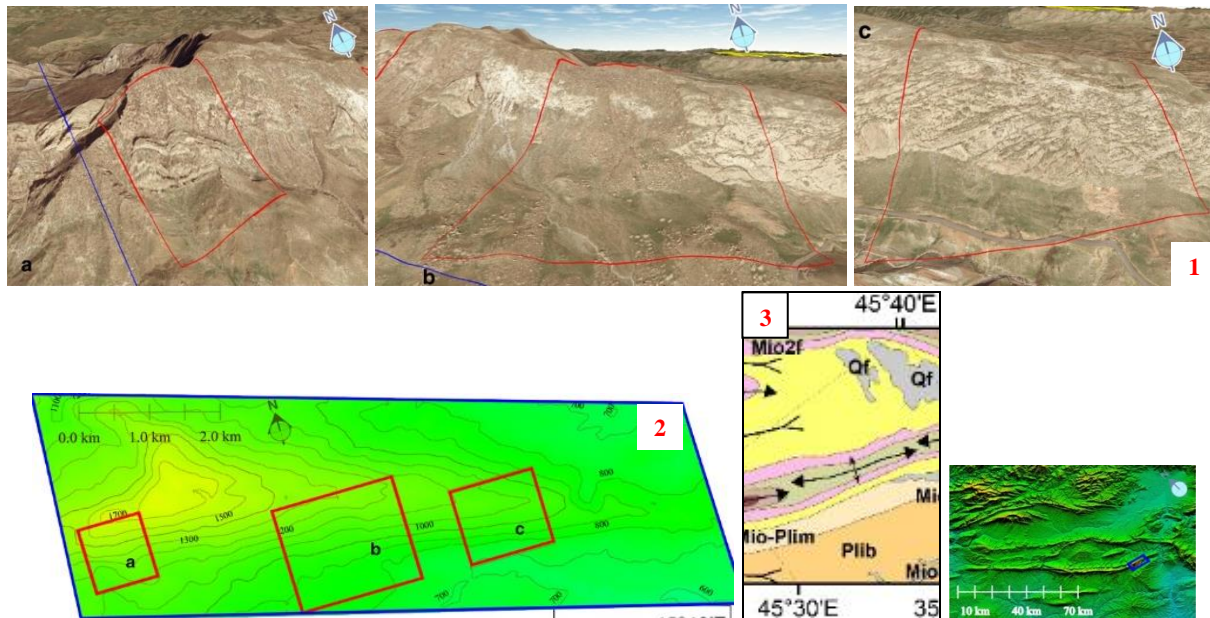


Fig.9: The Spei Segment of Qara Dagh anticline. **1:** Enlarged satellite images: **a)** fork-shaped valleys **b)** curved valleys and **c)** inclined valleys. **2:** Contour map of the segment showing the expression of the plunge by contour lines. **3:** Geological map of the Spei Segment, note the en-echelon folding style on both plunge areas (for the legend refer to Figure 3)

▪ Golan Segment

The Golan Segment forms the sixth (last) segment of Qara Dagh anticline from the north-western part (Figs.1 and 10a-d). It is limited from the north-western side by an en-echelon plunge towards NW; very clearly expressed by the contour lines in the topographic map; whereas, the south-eastern side is limited by a wide and steep plunge forming the south-eastern plunge of the main Qara Dagh anticline (Fig.10d). Other indications for lateral growth (Killer and Pinter, 2002 and Ramsey *et al.*, 2008) of this segment include tens of fork-shaped valleys located along the south-western limb (Fig.10a and b), axial valleys (Fig.10b), abandoned alluvial fan (Fig.10c), and radial valleys (Fig.10d).

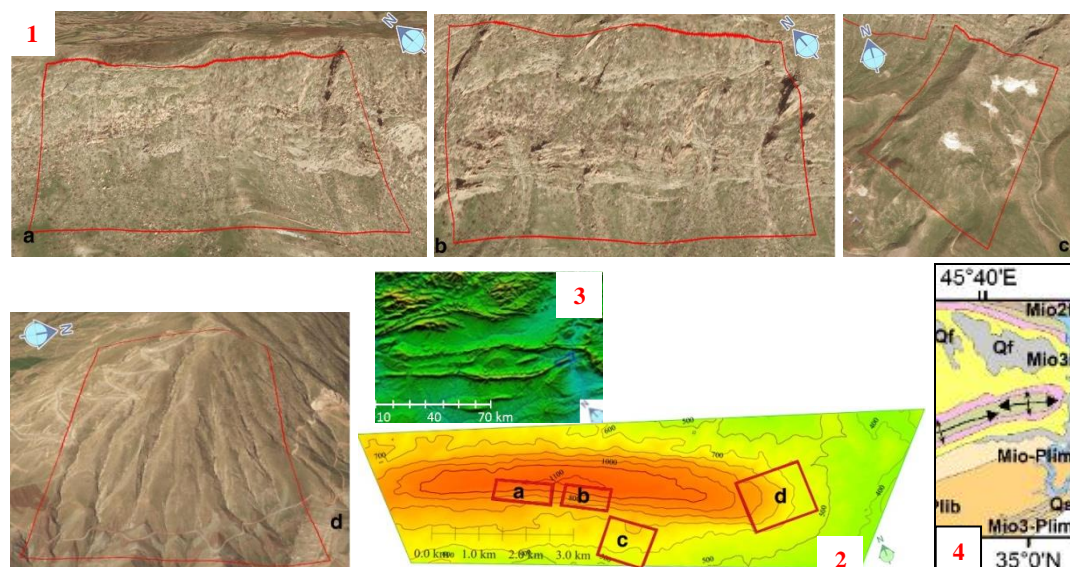


Fig.10: The Golan Segment of Qara Dagh anticline. **1:** Enlarged satellite images: **a** and **b)** fork-shaped valleys, **b)** axial valleys, **c)** abandoned alluvial fan, and **d)** radial valleys. **2:** Contour map of the segment. **3:** DEM image. **4:** Geological map of Golan Segment, note the en-echelon folding style in the northern plunge area (for the legend refer to Figure 3)

DISCUSSION

After thorough interpretation of different satellite images, geological and topographic maps, supported by field check in Qara Dagh anticline and near surroundings, we have found excellent geomorphological and structural indications, suggesting that the Qara Dagh anticline was originally consisting of six segments. Each of these segments was originally an anticline. The lateral growth of anticlines is indicated by many land forms, among them are: **1)** Fork-shaped valleys, **2)** Presence of water gaps and wind gaps, **3)** Decrease in elevation of wind gaps, **4)** Deformation landforms of progressively younger deposits; such as alluvial fans, **5)** Axial valleys, **6)** Abandoned valleys and alluvial fans, **7)** Radial valleys, **8)** En-échelon folds (Killer and Pinter, 2002 and Ramsey *et al.*, 2008). We have used these criteria to study the Qara Dagh anticline and have presented evidence of lateral growth in the six segments of the anticline illustrated in Figures (5, 6, 7, 8, 9 and 10). According to Peacock and Sanderson (1991); Bull (1991 and 2007), Cartwright *et al.* (1995); Dawers and Anders (1995); Cowie (1998), Blanc *et al.* (2003) and Bennett *et al.* (2005), folds can grow by the lateral propagation of a single segment and merging of several fold segments into one continuous fold. This is the case in Qara Dagh anticline, which consists of six segments of different characters (Table 1).

Keller and Pinter (2002) considered the presence of at least two wind or water gaps produced by the same stream as very strong evidence of lateral propagation. In the study area, the Tinal stream exhibits one wind gap represented by Derbendi Bazian gate; the limit between Hinjira and Ba Sara segments (Fig.6). It also exhibits a water gap represented by the Ba Sara Gorge. The Derbendi Bazian wind gaps was formerly a water gap from which the Tinal stream was flowing out of Qara Dagh Mountain and due to local neotectonic activity, the water gap was abandoned and Tinal stream diverted to flow out of Qara Dagh Mountain through Ba Sara Gorge (Sissakian, 2011). The river terraces can be still seen on the western margin of the wind gap, at an elevation of about 7 m from the nowadays base level of the abandoned stream.

The presence of en-échelon plunges along the Qara Dagh anticline is considered in this study as good evidence for lateral propagation and growth of the six segments towards northwest. Graveleau *et al.* (2012) produced en échelon folds and miniature arcuate mountain systems experimentally in several ways. In their work, differential stress transmission in the horizontal plane through rigid materials bordering incompetent beds gave rise to en-échelon folds and arcuate systems even though non-rotational compression was applied. In the studied area, the stress transmission in a horizontal plane through rigid materials is represented by the hard and thick carbonates of the Pila Spi Formation; while the bordering incompetent beds are represented by the clastics of the Gercus and Kolosh formations. Moreover, the carbonates of the Pila Spi Formation are overlain by the clastics of the Fatha Formation.

The developed en-échelon plunges between Sagerma and Zarda segments, and Spei and Golan segments are good indications that the lateral growth (propagation) was towards northwest; since both en-échelon plunges have moved towards northwest (Fig.11). Moreover, the north-western plunge of the main Qara Dagh anticline forms en-échelon plunge with Agh Jallar anticline (Fig.11). The developed en-échelon plunge between Qara Dagh and Agh Jallar anticlines (Fig.11) exhibits an axial valley that runs in the trough of the syncline between the two anticlines. Moreover, the beds along both plunges are disturbed (Fig.12), which indicates that there is a shear between the two plunges. This is can indicate that the en-echelon plunges were developed due to the growth of Qara Dagh anticline northwest wards.



Fig.11: A) Google Earth image: Note the en-echelon plunge between Sagerma and Zarda segments; moved towards NW. Also note the developed gorge in between them with the developed fork-shaped valleys in Zarda Segment. **B)** Flash Earth image: Note the en-echelon plunge between Spei and Golan segments, moved towards NW. Also note the abandoned alluvial fan (AF). **C)** Google Earth image: Note the en-echelon plunge between Agh Jallar and Qara Dagh anticlines, also moved towards NW. Also note the whale-back shape of Hinjira Segment of Qara Dagh anticline

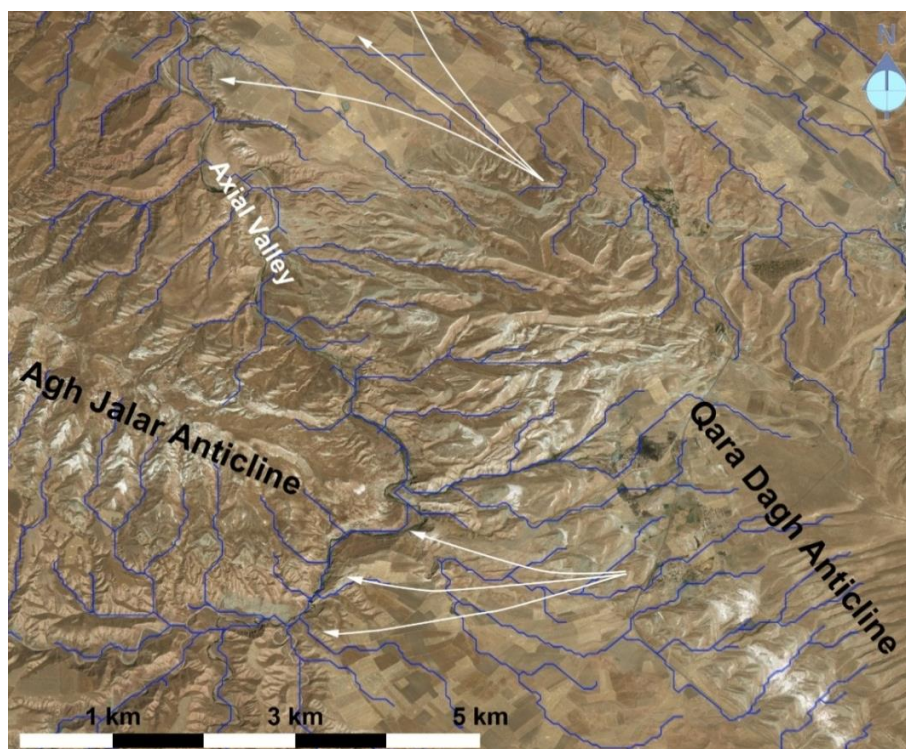


Fig.12: Google Earth image showing the axial valley between the two plunges of Qara Dagh and Agh Jalar anticlines. Note the disturbed beds in both plunges, and the abandoned alluvial fans

Other evidence for the propagation of Qara Dagh anticline to the northwest is shown in the variation in drainage density in the Qara Dagh anticline. The drainage density is lower in the NW direction as compared to SE. The drainage density towards the north-western side decreases gradually, while the drainage density tends to increase with time and relief. Therefore, we have considered the decrease in drainage density as additional evidence that the north-western part of Qara Dagh began to fold more recently than the remaining parts. Such evidence is considered by Bull (1991 and 2009).

According to Cowie (1998), aligned fold segments are likely to grow at the expense of other, non-aligned segments, by a positive feedback in the stress changes around the structure. Therefore, fold segments grow in length and divert drainage around their ends. In the studied area, the formed water gaps and wind gaps, which were originally water gaps, are developed due to incision of the streams, which were running round the tips of the segments through the growing fold segments. When the individual fold segments merge together due to lateral growth, each segment forces the existing stream to incise through the growing fold; consequently, the discharge is limited through a narrow outlet causing the development of alluvial fans. The presence of abandoned alluvial fans in front of wind gaps is a good evidence for such case. A good example is the abandoned alluvial fan (Sissakian, 2011) in front of Derbendi Bazian gorge (Figs.13 and 14) and the alluvial fan on the Golan Segment (Fig.10c).

If the stream incision is lower than the rate of the uplift, then the outlet most probably will be abandoned; consequently, either the stream will be diverted around the end of the fold, or a new water outlet will be formed around the tip of a nearest segment. In the studied area, the same case exists, which is represented by the diversion of Tenal stream from flowing out

of Qara Dagh anticline through Derbendi Bazian gorge (Fig.13, a wind gap; nowadays) to flow out of the anticline through Ba Sara Gorge (Fig. 6).

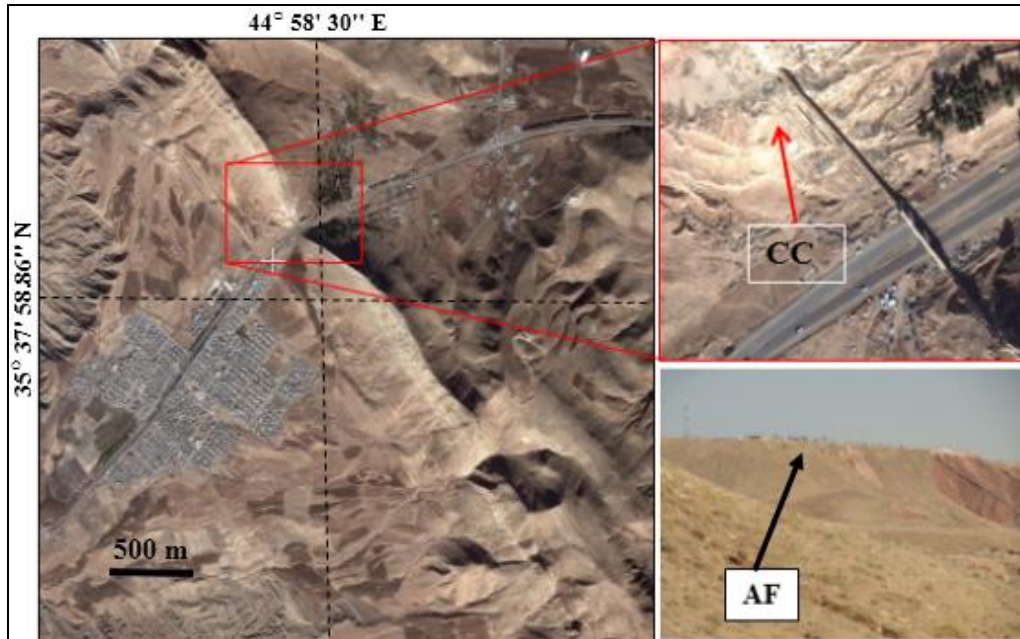


Fig.13: Flash Earth image showing the alluvial fan in Derbendi Bazian gorge, the town of Takia is built above the fan (**AF**), note the bedded rocks of the Injana Formation capped horizontally by the alluvial fan sediments (**bottom right**). Relics of coarse clastics (**CC**) of the fan's sediments can be seen on the slopes, west of the gorge (**top right**)



Fig.14: Enlarged photo of the Takya alluvial fan (Fig.13, bottom right), which was developed when Teenal stream was flowing out from Darbandi Bazian gorge

The longitudinal topographic cross section through Qara Dagh anticline (Fig.15) shows 1 water gap and 2 wind gaps. The lateral growth of anticlines leads to development of new water gaps and abandonment of older water gaps, which turns to wind gap. The heights of the wind gaps decrease towards the lateral propagation direction. In Qara Dagh anticline, which exhibits lateral growth towards NW, the wind gaps decrease in height in Hanara and Derbendi Bazian gorges (wind gaps No. 3 and 1). However, the present water gap is in Ba Sara gorge (gorge No. 2) which is located between the two mentioned wind gaps and is lower in height.

This is attributed to a local neotectonic activity which caused rising of Derbendi Bazian area (Sissakian, 2011). Consequently, the Tainal stream has changed its direction towards east and started to flow out of Qara Dagh anticline from Ba Sara Gorge (Fig.15).

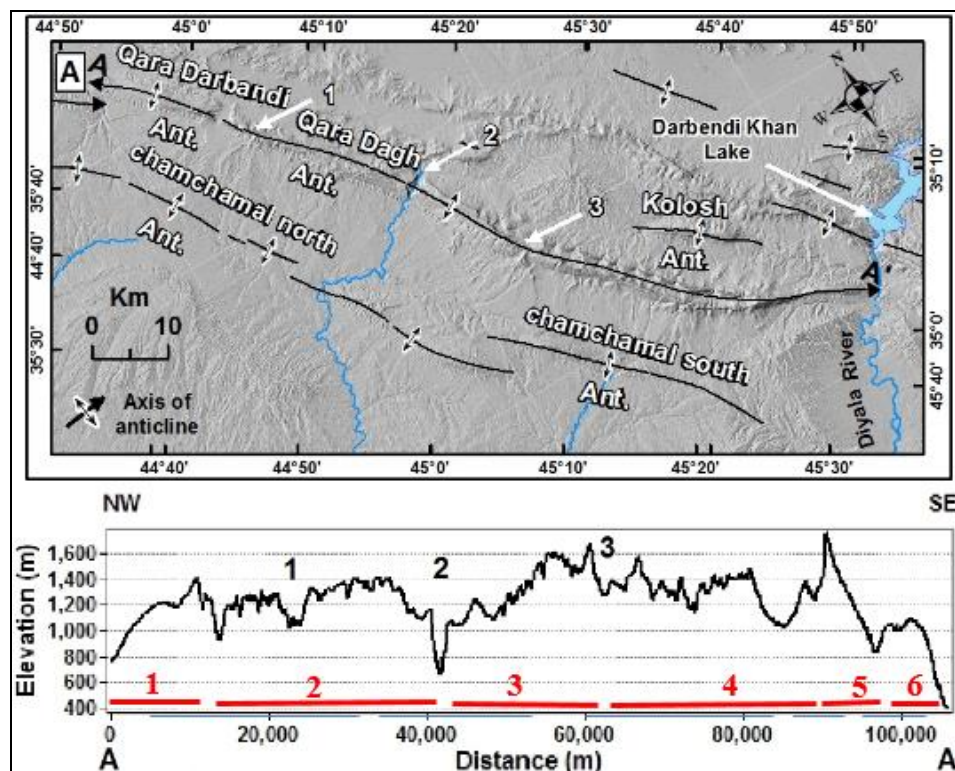


Fig.15: DEM showing the Qara Dagh anticline with its six segments (1 – 6) and a topographic cross section with three gorges (1 = Derbendi Bazian, 2 = Ba Sara, 3 = Hanara)

CONCLUSIONS

The Qara Dagh anticline was originally consisting of six segments, which were merged together by lateral growth in the NW direction. The lateral growth is indicated by the presence of: fork-shaped valleys, axial valleys, radiated valleys, abandoned alluvial fans, and the presence of water and wind gaps. The rate of the lateral growth was higher than the rate of the incision of the streams; therefore, the streams were shifted around the tips of the segments; meanwhile abandoning the water gaps to wind gaps and development of new water gaps around the tips. The NW propagation of the six segments of Qara Dagh anticline is supported by the presence of two en-échelon plunges within the main anticline; between Ba Sara and Sagerma segments and Spei and Golan segments. They were moved northwest wards as indicated by their style of folding, especially the north-western plunge of the main Qara Dagh anticline and Agh Jallar anticline.

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About the author

Mr. Varoujan K. Sissakian graduated from University of Baghdad in 1969 with B.Sc. degree in Geology, and M.Sc. in Engineering Geological Mapping from I.T.C., the Netherlands in 1982. He joined Iraq Geological Survey (GEOSURV) in 1971 and was nominated as Expert in 2005; he was the Director of Geology Department since May 2004 until October 2012. He has 126 documented reports in GEOSURV's library and 131 published articles. He was the Deputy Vice President of the Middle East Subcommission of the Committee of Compilation the Geological Map of the World (CGMW), Paris, from February 2010 until August 2012. Retired on 2012. His major fields of interest are geological mapping, stratigraphy, and geological hazards. He was Visiting Lecturer in University of Kurdistan, Hewler, since October, 2014 and Lecturer since February, 2017.



e-mail: varoujan49@yahoo.com ; f.khajeek@ukh.edu.krd

Mailing address: Iraq, Erbil, Ainkawa, District 108, 245/ 7/ 404

Mr. Rahim M. Amin, Graduated from the Baghdad University on 1973 with B.Sc. degree in Geology. He joined Iraq Geological Survey (GEOSURV) in the same year of graduation and started working in geological mapping projects in different parts of Iraq. He became one of the best geologists in geological mapping, especially in mapping of the Southern and Western Deserts. In 1984, he contributed in Engineering Geological Mapping and continued until 1987. After that, he was involved in mineral exploration at different parts of the northern part of Iraq (Kurdistan Region). He retired on 1998 according to his request, then joined again GEOSURV on 2005 and retired on 2014. He has 12 documented reports in GEOSURV's library. Currently, he is living in Erbil, Ainkawa



e-mail: raheemameen@gmail.com

Mr. Jamal Gh. Mohammed, Graduated from the Mosul University on 1976 with B.Sc. degree in Geology. He joined Iraq Geological Survey (GEOSURV) in 1978 as field geologist in the Geological Survey Department. Then he was assigned to work in the Southern Desert with Hyrdogeological Project, as Site geologist. His last responsibility was the Director of Mosul Regional Office of GEOSURV. His major field of interest is investigation of raw materials for cement industry. He was retired in 2015.



e-mail: jamal195483@gmail.com