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EFFECT OF LATERAL PROPAGATION OF SELECTED FOLDS ON STREAMS, SULAIMANIAH AREA, NE IRAQ

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ABSTRACT

This study is an attempt to conduct morphotectonic analysis for some selected streams in the folded belt, and to deduce their relationship with the geological structures, which control the drainage system. This work was executed using remote sensing and GIS application. The study area lies within Sulaimaniyah Governorate, NE Iraq. Tectonically, the study area is a part of the High Folded Zone, within the Unstable Shelf of the Arabian Plate.

Geologically, the study area is highly complicated, where wide range of geological formations is exposed.

Hundreds of streams, of different sizes and types, and many rivers dissect the studied area, some of which form gorges along their courses, partly of canyon type. Some of these streams and rivers dissect the anticlines, oriented almost perpendicularly to their trends which oriented NW – SE.

The present folds, and even those surrounding the rivers have played big role on the extension of the basins and the sub-basins of the rivers. Locally, they have formed water and wind gaps.

This study demonstrates that the anticlines have developed from several embryonic folds, which have merged during lateral propagation and form extended fold trains. The merging points of the individual fold segments have major effect on the pattern of the regional drainage system. Along all investigated anticlines, direct evidence for lateral propagation in form of distinctive drainage patterns and wind gaps are found. Furthermore, various geomorphologic parameters, describing tectonic activity and basin maturity, are analyzed. The interpretation of the calculated geomorphologic ratios indicates a high tectonic activity and a low maturity of the drainage basins.

تأثير النمو الجانبي للطيات على الأنـهار، منطقة السليمانية، شمال شرق العراق

منال شاكر الكبيسي و مواهب فاضل عبد الجبار

المستخلص

تمثل هذه الدراسة محاولة لإجراء تحليل مورفوتكتوني لبعض الانهر المختارة في حزام الطي، ولإيجاد علاقاتها مع التراكيب الجيولوجية، التي تسيطر على شبكة التصريف. وقد نفذ هذا العمل بتفسير معطيات التحسس النائي ونظم المعلومات الجغرافية.

تقع منطقة الدراسة ضمن محافظة السليمانية شمال شرق العراق وتقع من الناحية البنيوية، ضمن نطاق الطي العالي في الرصيف غير المستقر من الصفيحة العربية.

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وتتميز من الناحية الجيومورفولوجية، بالتضاريس الجبلية، حيث يبلغ ارتفاع أعلى قمة حوالي 2700 متر (فوق مستوى سطح البحر) وتقع في الزاوية الشمالية الشرقية (جبل بيرة مكرون)، بينما يبلغ أقل ارتفاع حوالي 150 متر وتقع في الزاوية الجنوبية الغربية، وهذا يعني بان منطقة الدراسة تزداد ارتفاعا باتجاه الشمال الشرقي.

وتمتاز المئات من الوديان ذات الأحجام والأنواع المختلفة، إضافة الى العديد من الأنهار، منطقة الدراسة، وبعضها يكون مضايق في مساراتها، وقسما منها يكون خنادق عميقة (Canyons). إن بعض هذه الأنهر والوديان تقطع الطيات المحدبة عموديا وباتجاه الشمال الغربي – الجنوب الشرقي، والشرق – الغرب، مشكلة مضايق باحجام وخصائص مختلفة وذات مناشيء مختلفة.

قد لعبت الطيات المحدبة والمقعرة التي تحيط بالانهار في منطقة الدراسة دورا كبيرا في امتداد أحواض الأنهار وكونت ما يسمى بالفتحات المائية والهوائية.

وأظهرت هذه الدراسة ان هناك بعض التراكيب المحدبة قد تطورت من عدة طيات صغيرة التي اندمجت خلال النمو الجانبي وشكلت سلسلة من الطيات الممتدة، ان نقاط التحام الجزء الواحدة من الطية لها دور كبير على نمط شبكة التصريف العام. وفي كل الطيات المحدبة المدروسة، تم ملاحظة دلائل مباشرة للنمو الجانبي على شكل نمط تصريف خاص إضافة الى الفتحات الهوائية.

لقد تم تحليل العديد من العوامل الجيومورفولوجية ووصف النشاط التكتوني ودرجة بلوغ الأحواض كخطوة إضافية للدراسة. ان تفسير النسب الجيومورفولوجية التي تم احتسابها تدل على نشاط تكتوني عالي في المنطقة ودرجة بلوغ واطئة لأحواض شبكات التصريف والتي أيضا استدل عليها بوجود الفتحات الهوائية المنحنية.

INTRODUCTION

The northeastern parts of Iraq are mountainous region with very rugged topography that attain about 3600 m (a.s.l.). The main lithology, in the area involves very hard carbonate rocks that form the carapace of the mountains (mainly anticlines) with soft clastic rocks, filling the synclines in between; clastic rocks occur as intercalations with the carbonates.

The rivers and streams in Zagros folds, in north Iraq have a long geological history extending back to the Upper Cretaceous (Marouf and Al-Kubaisi, 2002). The courses of the rivers and their later evolution are mainly controlled by the structural and tectonic history of the area; the effect of the lithology is subordinate (Al-Kubaisi, 2000).

It is generally accepted that the present river courses and their associated sediments were formed during the Quaternary (Buday, 1980 and Oberiander, 1985). This idea is mainly based on the assumption that the Zagros is a post-Miocene belt. This does not agree with the long tectonic history, which extends back to the Upper Cretaceous (Marouf and Al-Kubaisi, 2002).

The study area lies within Sulaimaniyah Governorate, bounded by (35° 15' 00") and (35° 50' 35") N and (45° 06' 20") and (46° 10' 00")E. Tectonically, the study area is located as a part of the Unstable Shelf of Arabian Platform including the Imbricate Zone and the High Folded Zone (Fig.1). Geologically, the study area is highly complicated, where wide range of geological formations is exposed. The formations are composed of different rocks type, their age range from Triassic to Quaternary periods. The present study is aimed at carrying out geomorphologic analyses on some selected folds of the region to detect fold geometry as related to drainage pattern.

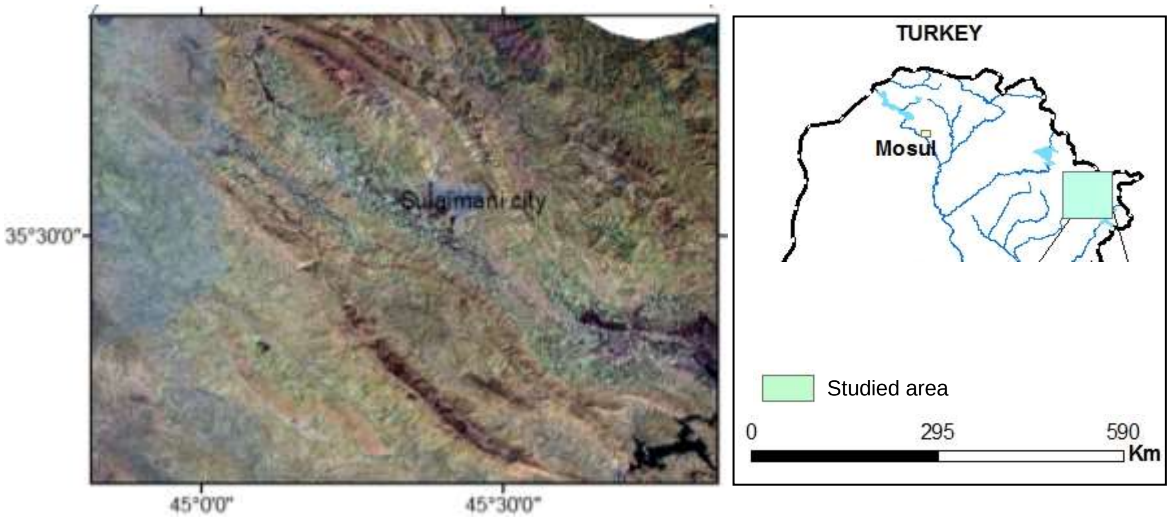


Fig.1: Location map of the study area

METHODOLOGY

The technique used in the present study is as follows:

▪ **The Use of Remote Sensing Data**

Digital satellite images LANDSAT 7 were processed. Image Processing was made using the ERDAS IMAGINE software package. This work can be divided in two steps:
Image Pre-processing (Geometric Correction and Enhancement) Image Interpretation

Additional processing has been applied to the LANDSAT image concerning the combination of spectral zones. Interpretation relating to the tectonic features (mainly faults and other tectonic contacts), geological and geomorphological features, based on the main diagnostic characteristics that are used from geo-scientists (Astaras, 1990 and 1998 and Migiros *et al*., 1995). The direct recognition of the tectonic features on satellite images is based on the concept of morpho-structures and mainly on morpho-tectonics. Faults, joints and lineaments most likely have a rectilinear exposure on images and their determination depends on morphological features or on particular patterns.

Satellite images were used to delimit fold shapes and to mark locations and diversions of the stream network. Colour composites were created by combining Landsat 7 ETM+ bands 5, 3, 1 as red, green and blue, which highlights variation in lithology, and suppresses vegetation (Drury, 2001). Colors were balanced using the balanced contrast enhancement.

Major stream channels have also been identified. In areas of confusion, the concentration of vegetation around streams visible on a 432-RGB image was used to separate stream beds from other features. In order to clarify the relationship between lithology and topography and to identify wind and water gaps in the folds, the enhanced satellite images were draped over a digital elevation model (derived from the Shuttle Radar Topography Mission – SRTM).

▪ **GIS and DEM Applications**

The GIS methodology was chosen, due to the large amount of data available from various sources (Thematic maps, satellite images…etc.) in different forms (raster, vector) and in different map projections. Arc GIS package was used for the data processing, the map composition, the creation of the relational data-base and the data-base management.

Within GIS and Digital Elevation Model (DEM) applications, spatial analysis and hydrological tools of ArcGIS were used to prepare many maps for the study area, such as contour map, drainage system map, and 3D image.

The simplest morphological analysis involves the study of elevation data. In the present approach, DEMs were displayed for visual inspection as contour maps, grey-scale images, 3D surface views, and shaded relief models or as combinations of these. The shaded relief model was a key component throughout this study, because it was the most suitable terrain model for the recognition and interpretation of complex morphological features. Vertical exaggeration of elevations was used to enhance the study of subtle features in flat basin areas, and cross-sections were generated along geological sections to study slope and slope curvature conditions.

In the present study, color-separated geological maps and remotely sensed images were combined with a shaded relief map. These in turn were draped on the three-dimensional perspective view of the study area; to study the relationship between geology and morphology.

- **Field Work**

The geological and tectonic data of the area were collected for the compilation of the Synthetic Geological Map of the studied area. Fieldwork also included checking of the maps of terrain analysis that were automatically produced by the GIS software. Some of the geological morphological and tectonic features were checked in the field too.

PREVIOUS STUDIES IN IRAQ

Not much work was carried out, in Iraq, especially in the study area, related to the objectives of this work. However, the following is the available published literature:

- Al-Daghastani and Al-Daghastani (1994) studied the drainage response of the tectonic activity and geomorphology of Jebel Ishkaft area, northwestern Iraq. They found that the Qabak Stream and its tributaries have evolved in close association with active folds. The clearest evidence of the tectonic effect shows significant changes of the pattern, gradient and valley morphology, indicating antecedent stream origin.
- Al-Kubaisi (2000) studied the courses of the Tigris River and its tributaries, concerning the crossing of the rivers to the anticlines, either from their plunge areas or perpendicularly to both limbs. She concluded that they all are older than Pre-Quaternary and that they all are antecedent type of rivers.
- Marouf and Al-Kubaisi (2002) studied the tectonic history of Zagros rivers and streams in North Iraq and concluded that the courses of the rivers and their later evolution are mainly controlled by the structural and tectonic history of the area and modified during the later progressive deformations.
- Al-Mosawi (2004) studied the Ishkaft and Sasan anticlines, in the northwestern part of Iraq and concluded that one of the main valleys in her studied area that crosses the Ishakaft anticline is of antecedent type.
- Al-Daghastani and Al-Banna (2006) carried out morphotectonic analysis of eight surface drainage basins, in Nainava Governorate, which varies in their basin geometry and concluded that the analysis of longitudinal valley profiles of the studied basins indicated their effects by a group of morphotectonic variables, which characterized each distinct segment differentially.
- Sissakian and Abdul Jabbar (2009) studied the morphometry and genesis of the main transversal gorges in north and northeast Iraq. The study revealed that the origin of the

main gorges is mainly due to structural effect, one is due to karstification and others are due to blockage of streams either by mass movements or by alluvial fans. They are of superimposed – posterior type.

TOPOGRAPHY AND GEOLOGY

The area is characterized by mountainous terrain in which the highest peak reaches 2700 m (a.s.l.) at the northeastern corner (Pira Magroon anticline) and the lowest elevation reaches 250 m (a.s.l.) at the southwestern corner, (Fig.2).

Physiographically, the area can be divided into two main areas (from the southwest to the northeast), the Hilly area and the Mountainous area.

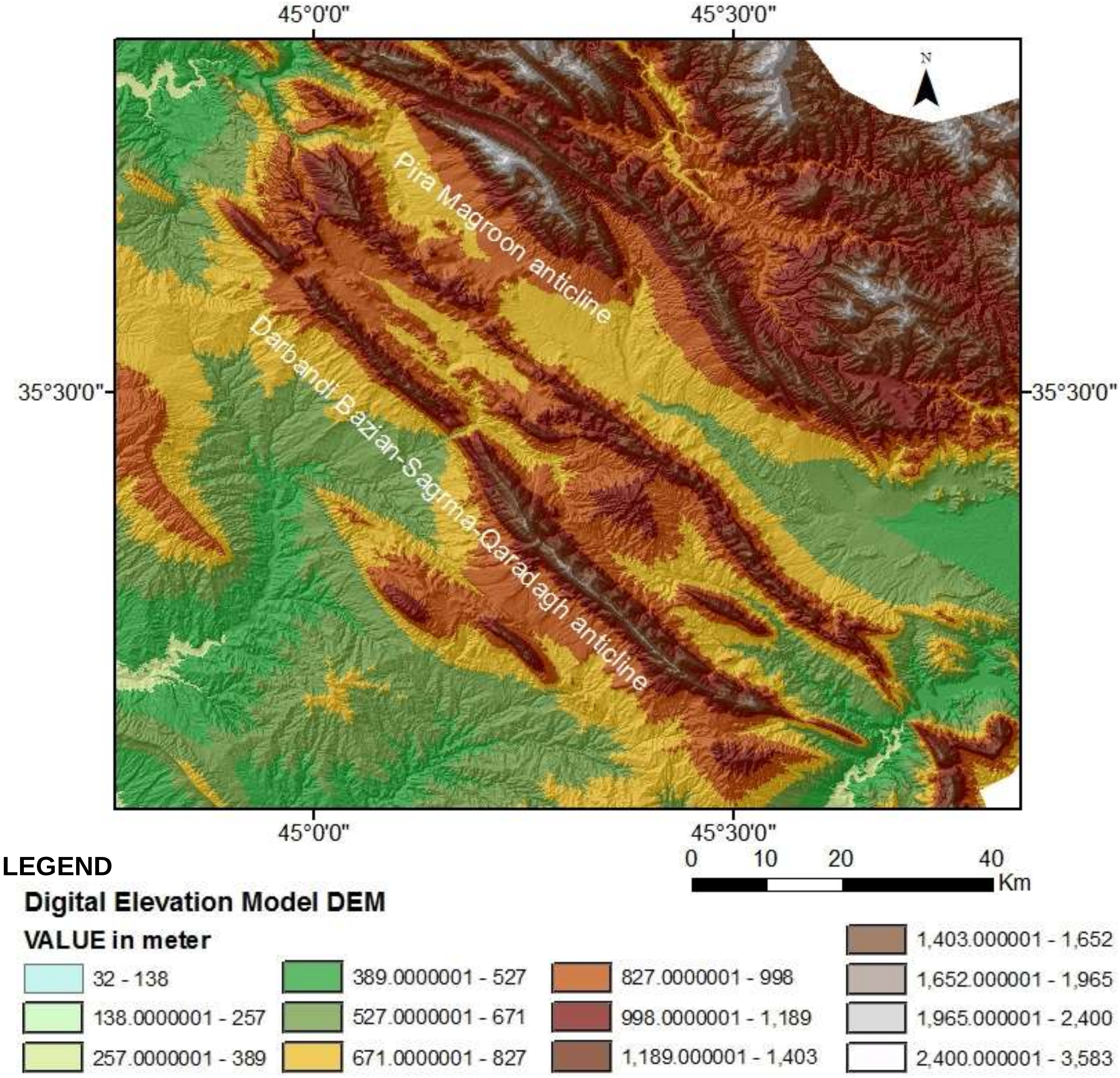


Fig.2: Topographic map of the study area

Stratigraphically, the study area is built up of formations ranging in age from Triassic to Miocene, they are Beduh, Geli Khana, Kurra Chine, Balluti, Sarki Sehkaniyan, Sargelu, Naokelekan, Barsarin, Chia Gara, Balambo, Sarmord, Qamchuqa, Kometan, Shiranish, Tanjero, Kolosh, Khurmala – Sinjar, Gercus, Pila Spi, Khurmala, Fatha, Injana, Mukdadiya and Bai Hassan, beside various types of Quaternary sediments (Fig.3).

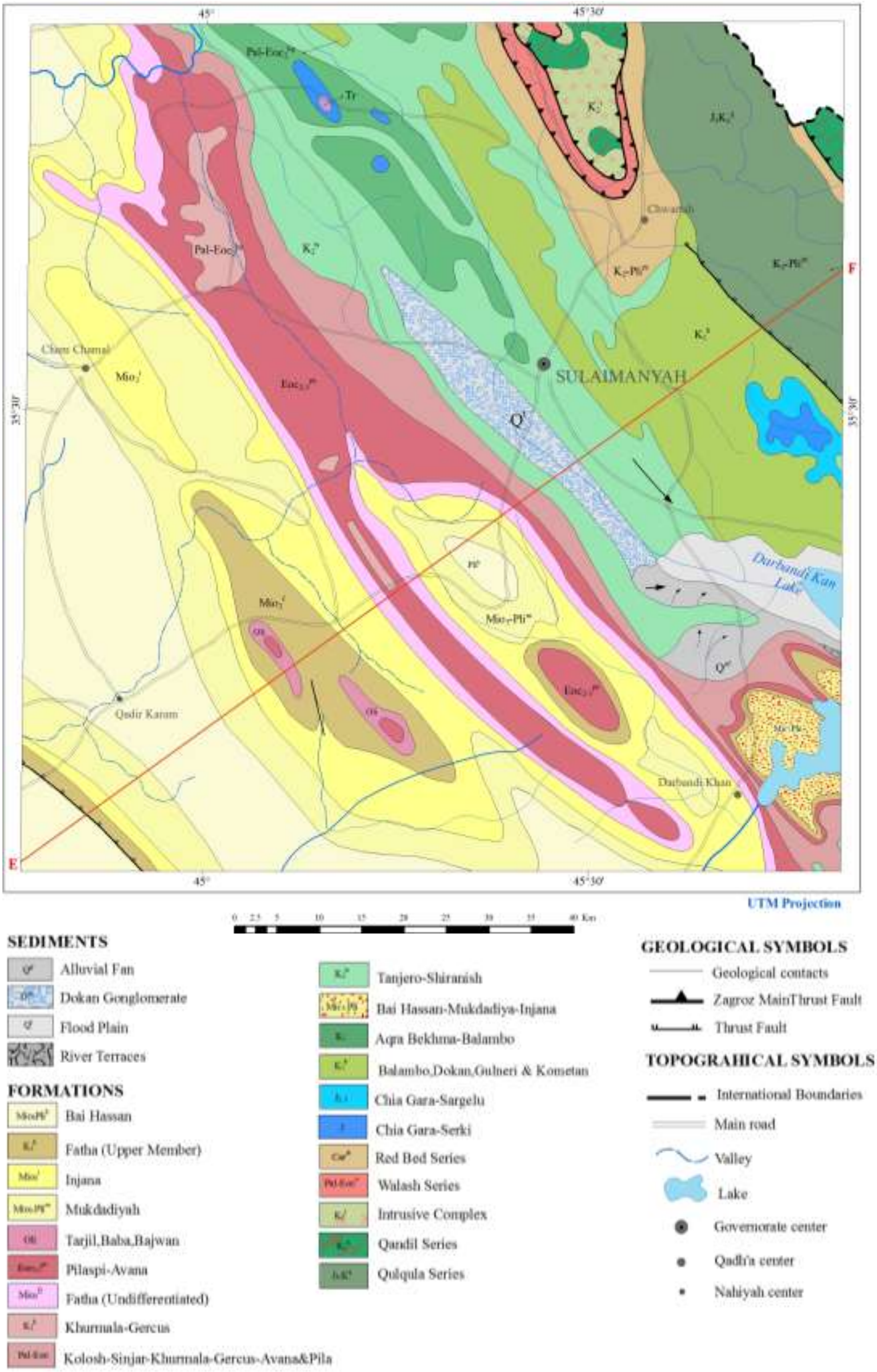


Fig.3: Geological map of the study area, scale 1: 1000 000
(after Sissakian, 2000)

LATERAL PROPAGATION OF FOLDS

Geomorphology is an excellent tool to categorize the direction of lateral fold propagation. If folds are propagating, complex river patterns and topography can most probably reveal the history of lateral propagation and vertical growth (Burbank and Anderson, 2001).

Keller *et al*. (1999) described six main geomorphic criteria to evaluate rates of lateral propagation and vertical growth of folds:

1- Decrease in drainage density and degree of dissection of a folded surface.
2- Decrease in elevation of wind gaps.
3- Decrease in relief of the topographic profile along the crest of the fold.
4- Development of characteristic drainage patterns.
5- Deformation landforms of progressively younger deposits.
6- Decrease in rotation and inclination of fold limbs.

Criteria 4 and 5 are strong evidence of lateral propagation, and if there are at least two wind or water gaps produced by the same stream, then this is very strong evidence of lateral propagation (Keller, 2002).

The first task in evaluating a given fold is to make a detailed drainage map of the fold; this analysis could be conducted by using DEM. Drainage patterns are then analyzed in order to evaluate drainage density, which is a measure of degree of dissection. Construction of topographic profiles along the crest, profiles normal to the fold, and DEM may greatly assist in identifying the geomorphic parameters of folds (Fig.4a). Elevations of wind gaps along the crest of a fold may reveal the direction of the fold plunge and hence the direction of lateral propagation.

Drainage parallel to a fold axis will likely be diverted in the direction of propagation, as diversions develop, tributary streams are captured and the size of the upstream drainage basin increases until there is sufficient stream power to maintain a channel temporarily at the nose of the fold where propagation has not yet occurred (Fig.4b) (Keller, 2002).

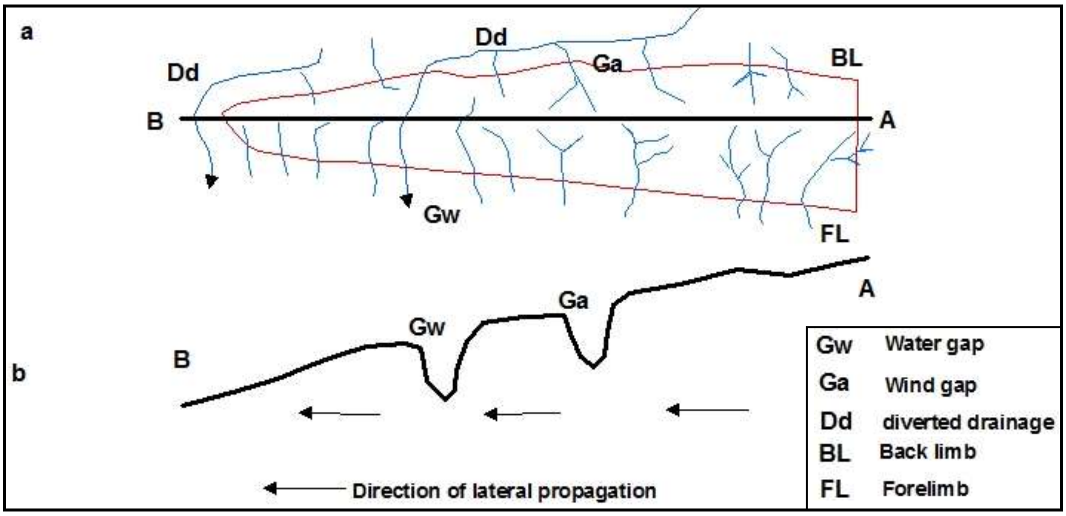


Fig.4: Idealized diagram showing the tectonic geomorphology of a fold that is propagating laterally (Keller, 2002)

This area becomes a water gap and eventually defeated by uplift and/ or stream capture. If defeat occurs, the channel may be diverted again in the direction of the lateral propagation, and in the course of a fold development, the channel may follow several passes around the fold as the drainage develops. For some folds there may be several wind gaps produced in this manner, and the drainage will repeatedly be diverted around the nose of the fold.

Evaluation of drainage patterns for specific folds may suggest that some folds are propagating in two directions where adjacent folds are propagating towards each other; or that younger folds are propagating parallel towards or against older fold in a fold belt.

The processes that transform water gap into a wind gap are generally complex, and at least two hypotheses are possible, these are (Keller, 2002):

- Uplift of the fold may block the channel in the water gap, forcing a diversion in the direction of lower topography, which is likely to be in the direction of the fold propagation.
- A channel crossing the nose of the fold has a tributary on the mountain side of the fold that erodes headward, parallel to the axis of the fold, towards the water gap.

In many cases a wind gap probably is formed by a combination of both tectonic and fluvial processes (uplift diversion and capture of drainage).

Propagation of the fold to the west is also revealed in Fig. (5), that the drainage density is lower in the west, drainage density on the west side decreases systematically, while the drainage density tends to increase with time and relief, so the decrease in drainage density is an additional evidence that the western portion of fold began to fold more recently than the eastern portion (Bull, 2002).

If two emerging folds join together it is possible that a river becomes pinched between the fold noses and forms a gorge in between. Because of the limited discharge through the narrow outlet ponding of sediments behind the anticlines can form characteristic sediment deposition (Ramsey *et al*., 2008, Fig.6).

During the investigation a different form of wind gaps appeared. The curved wind gaps that occur when uplift and lateral propagation rates of the growing fold by far exceed the incision rate of the river. Therefore large part of the river course around the growing anticline become uplifted forming a wind gap. In this study the new model of curved wind gaps is introduced (Fig.7).

These curved wind gaps are often inherited by the new rising drainage system and therefore strongly influence it. In this case careful study of the asymmetrically forked tributaries has to be made to determine fold propagation directions because these curved wind gaps often change the appearance of the tributary patterns and so possibly lead to wrong results. Because of the appearance of curved wind gaps it is likely that river terraces occur in these dry river gorges. This leads to the assumption of the presence of material suitable for dating methods (Ramsey *et al*., 2008).

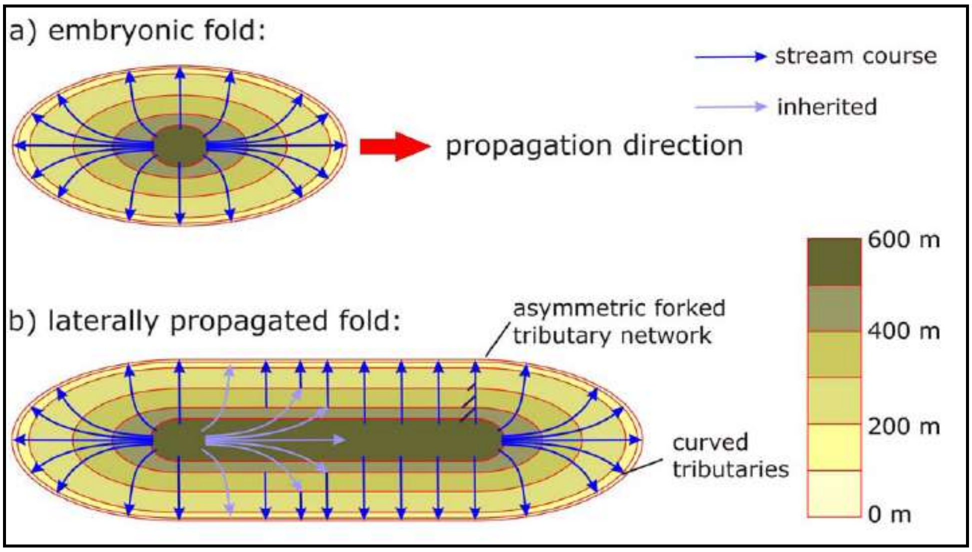


Fig.5: Idealized diagram showing the decrease in drainage density of a fold that is propagating laterally (Bull, 2002)

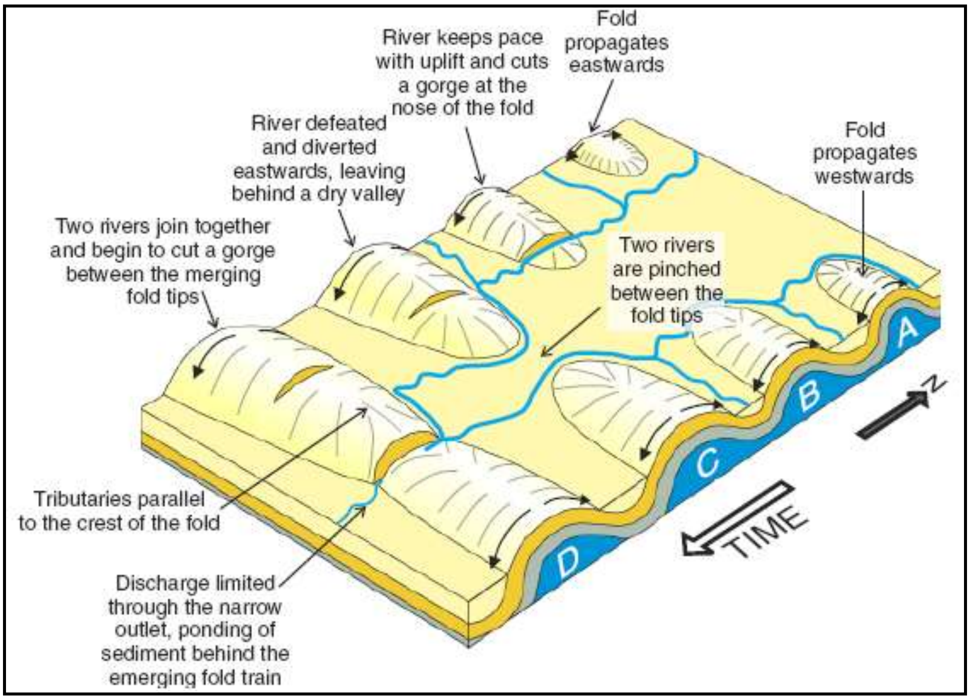


Fig.6: A cartoon showing the formation of a gorge between two propagating anticlines through time.

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 areas of 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 (Ramsey *et al*., 2008)

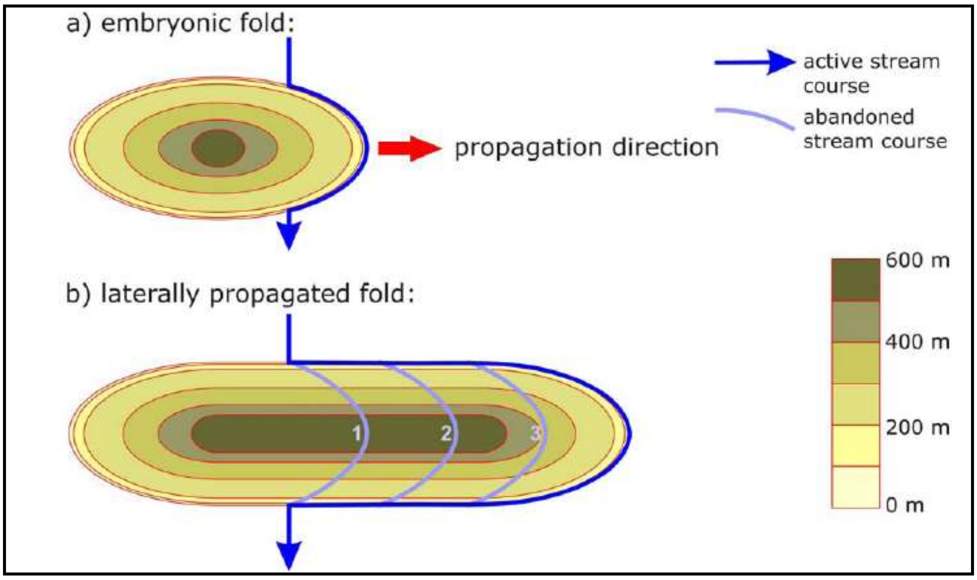


Fig.7: **a)** Map view with contour lines of an idealized embryonic cylindrical fold with elliptical base and convex-up flanks that deflects a river around the fold nose.
b) Series of curved wind gaps due to very fast propagation and high tectonic uplift ratios of a fold growing in length

- **Examples of the Lateral Propogation of Folds**

– **Pira Magroon Anticline:** Pira Magroon anticline is a huge asymmetrical doubly plunging anticline within the High Folded Zone of the Zagros Fold Thrust Belt (Numan, 1997 and Jassim and Goff, 2006). The anticline is located about 10 Km northwest of Sulaimani city, and bounded by 35° 39' 30" and 35° 50' 35" N and 45° 06' 20" and 45° 19' 30" E. The southwestern limb is steeper than northeastern limb, and the southwestern limb in some places, as in Zewe Gorge, shows vertical to overturned strata. The highest peak is about 2710 m, a.s.l.; it is about 30 Km long and ranges in width from 2 – 4 Km. The trend of the anticline is NW – SE in line with the general Zagros fold trend. The strike swings with the vergence to the southwest (Fig.8a).

A river approaches the fold through a narrow outlet to the north and is diverted westwards around the nose of the anticline. Two dry valleys are visible at the western fold tip (Fig.8b). Dry valley No.1 incises about a 2 Km long and 300 m deep valley (Fig.8b) across the fold crest. The valley is deeper on the southwestern limb of the fold than it is on the northeastern limb, suggesting that the river was actively cutting down to maintain a southward gradient in the face of uplift. Dry valley No.2 is considerably shorter (1.5 Km) and more straight and cuts the tip of the fold. The river course occurs 6.5 Km west of the dry valley, forming a water gap.

A distinct asymmetrically forked tributary networks runs obliquely to the slope pattern and is best preserved in the sediments visible (purple) in Fig. (8c). The fan-shaped drainage is overprinted by a second tributary pattern perpendicular to the fold crest and clearest on the southern limb.

Propagation of the fold to the west is also revealed in satellite image, where the drainage density is lower in the west, decreasing systematically westwards, while the drainage density increases with time and relief, so the decrease in drainage density is an additional evidence that the western portion of the fold has began to fold more recently than the eastern portions.

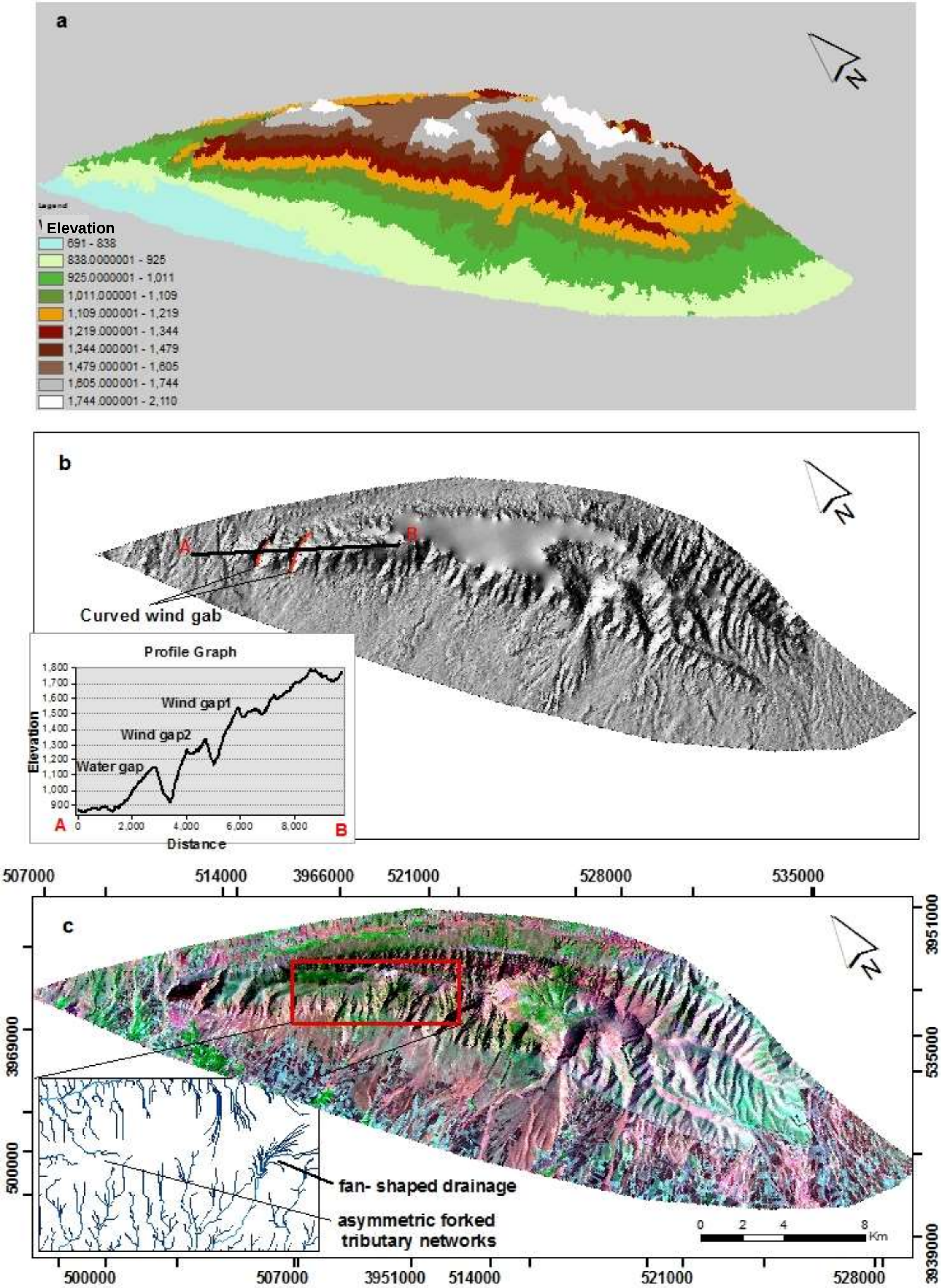


Fig.8: **a)** 3DMap view of Pira Magroon anticline with elevations. **b)** Convex-up flanks that deflect a river around the fold nose with two curved wind gaps due to very fast propagation and high tectonic uplift ratios of a fold growing in length. **c)** A distinct asymmetrically forked tributary networks and the fan- shaped drainage

The present-day river course, has most probably been running more towards the northwest, to cross Pira Magroon anticline from its northwestern plunge is shifted towards the east from water gap to wind gap 2, due to blockage of the stream course by tens of alluvial fan sediments that attain more than 30 m in thickness. The alluvial fans are developed northwestwards, along the southwestern flank of Khalikan Mountain. They blocked the course of the stream as described by Sissakian and Abdul Jabbar (2010), due to their southwestern flow direction, and consequently the stream was shifted to cross the mountain (Fig.9).

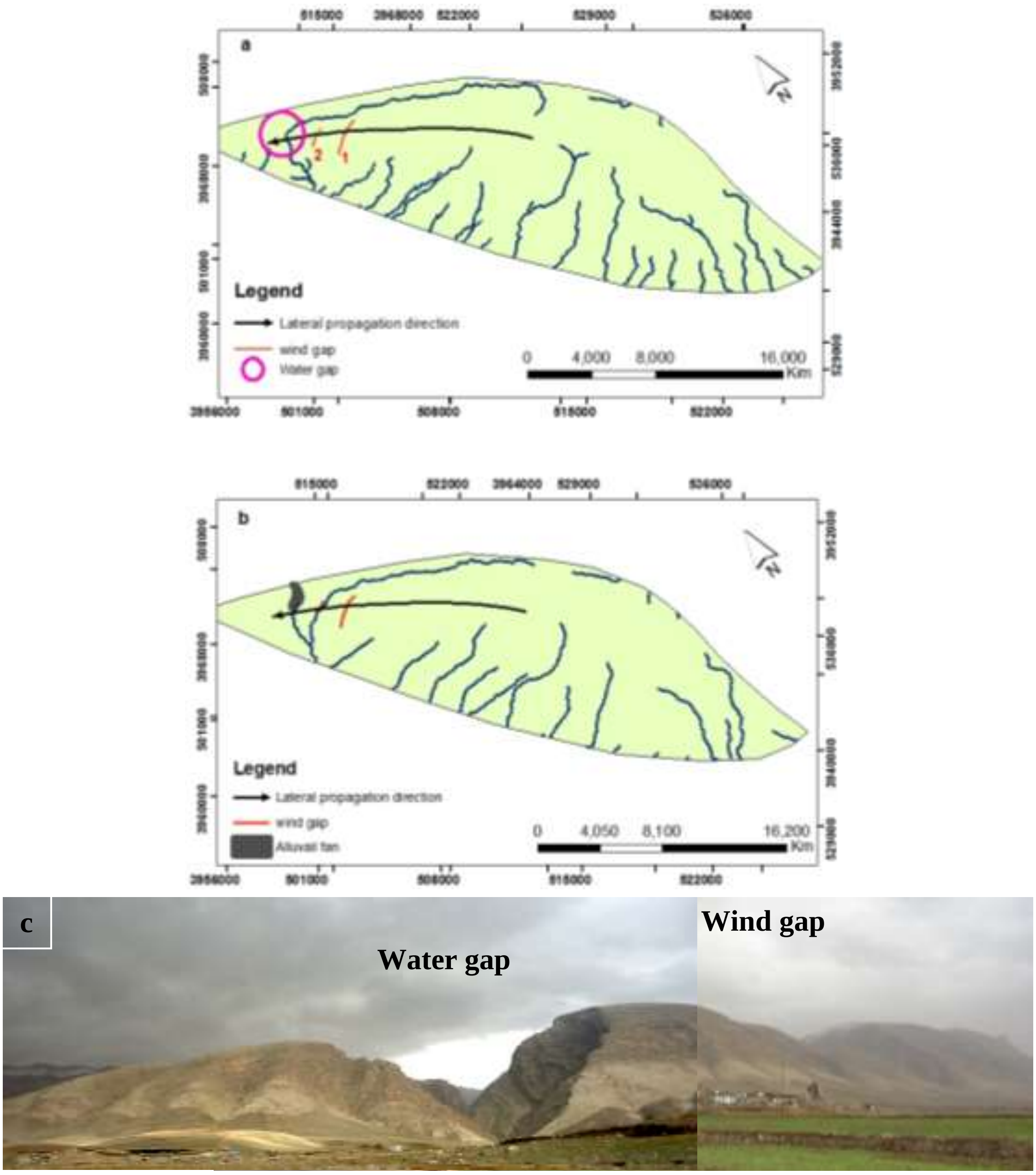


Fig.9: **a)** The main stream that was most probably running more towards northwest, with 2 wind gaps. **b)** The present-day river course, the alluvial fans are developed northwestwards they blocked the course of the stream, the stream is shifted to cross the mountain diagonally. **c)** Photographic image shows the wind and recent water gaps and the plunge of the anticline

▪ **Fold Segmentation and Linkage**

Folds can grow by the lateral propagation of a single segment, the merger of several shorter fold segments into one continuous structure, or by combination of the two (Peacock and Sanderson,1991; Cartwright *et al*., 1995; Dawers and Anders, 1995; Cowie, 1998, and Bennett *et al*., 2005).

There are few studies where lateral propagation of folds has been successfully demonstrated which typically combine geomorphic investigation with quantitative age control to provide constraints on the timing of drainage development and/ or the formation of geomorphic surfaces along the length of the fold (e.g. Bennett *et al*., 2005).

Without age control, interpretations of fold propagation histories from the drainage network alone are often impossible to prove unequivocally (e.g. Keller *et al*., 1999). However, in this study, we do not have any time control on the history of folding within the folded zone, and instead an attempt is made to unravel fold histories purely through the analysis of the geomorphology.

Hereinafter, indications of fold segmentation and lateral growth recorded in the landscape of the folded zone is described. We first assess whether fan shaped tributary patterns observed on the folds might record information about the fold growth. Then one anticline is described that shows different styles of geomorphology and gives different clues to its evolution.

In the absence of independent constraints on the timing of landscape development, the extent to which a study of the geomorphology alone, can be used to isolate lateral growth as a mechanism for producing the observed geomorphology and quantification of various geomorphologic parameters, describing tectonic activity and basin maturity were analyzed as a further step of investigation.

▪ **Example of Fold Segmentation, Growth and Linkage**

– **Darbandi Bazian-Sagrma-Qara Dagh Anticline:** The longest structure in the study area is the Darbandi – Bazian – Sagrma – Qaradagh anticline. Its length approaches 110 Km. It is a double plunging anticline extending NW – SE. The northwestern plunge occurs near Aghjalar town and the southeastern plunge occurs in the Darbandi Khan area; near Bani Khelan village. The anticline is asymmetrical with steep southwestern limb with vergence to the southwest.

Locally, the structure has many names from the northwest to the southeast. Qishlagh extends from the northwestern plunge to the Darbandi Bazian gorge. From Darbandi – Bazian gorge to the southeast is Darbandi Bazian, Hanjera, Bassera, Sagrma Qaradagh and Gulan mountains, respectively (Fig.10). The highest peak is 1850 m in the Sagrma mountain and the width ranges between 2 and 6) Km. In the Bassera mountain near Bassera gorge the width is about 6.5 Km.

Pila Spi Formation forms the core part of the anticline, located in the study area. Towards the southeast in the Bassera gorge, in the core of the Sagrma; Gercus, Sinjar, and Kolosh Formations are exposed, respectively below Pila Spi Formation. In the study area, there is no formation overlying the Pila Spi Formation, in the northeastern limb while in the southwestern limb, it is overlain by Fatha and Injana Formations, respectively. The anticline is separated from Miran west anticline by a broad syncline called the Khaldan syncline. The axis of this syncline is close to the northeastern limb of Qara Dagh anticline (Fig.11A), (Sissakian, 1998 and 1995 and Maala, 2007), in addition to field checks.

The anticline is interpreted as fault propagation fold formed by uplifting of the hanging wall of the large subsurface foreland vergent listric thrust fault. The dip direction of the fault changes to southwest and emerges at the surface to act as back thrust reverse fault (Al-Hakari, 2011).

The anticline varies along its strike. The crest shows variations in height, with individual sections of the fold separated by low saddles. There are significant steps along the fold axis that occur at saddles. The anticline does not show a smooth displacement profile along its axis. Instead, a prominent saddle divides the fold into four convex-up sections (Fig.11B). It is therefore, suspected that the variations in topography along the fold chains that bound the rivers are related to segmentation. Individual segments have now merged to form topographically continuous structures in excess of 110 Km length.

The segments that make up the chain are sketched in Fig. (12a, b, c and d), and the Landsat ETM7 images for four of the clearest segment boundaries. At present, water does not flow through these valleys across the width of the fold, but a through-going paleo- channel is evident in Landsat images (Figs.13 and 14). The channels trace a sinuous path through the youngest deposits.

A possible north-south dry valley running through the saddle suggests that, at some point in the past, the four sections were separated by topographic features that have subsequently merged.

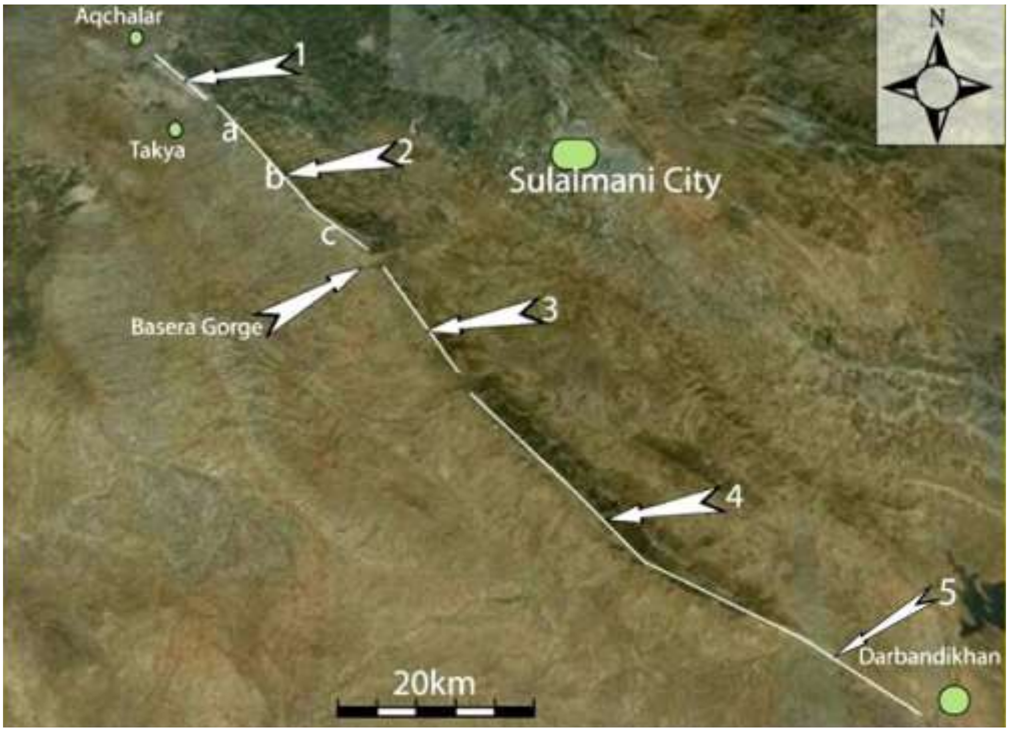


Fig.10: Google Earth image shows Darbandi-Bazian-Sagrma-Qara Dagh Anticline
1) Qishlagh Mountain, **2: a)** Darbandi Bazian, **b)** Hanjera, **c)** Bassera Mountains,
3) Sagrma Mountain, **4)** Qara Dagh Mountain, and **5)** Gulan Mountain

There is a distinct saddle along the fold crest (Fig.12a) from which the tributaries gently radiate away. The tributaries in the west have an asymmetrically forked plan formed on the northeastern limb, and there is a deeply entrenched sinuous channel, slightly oblique to the local slope, on the southwestern limb.

The folds crest and the incised meandering channel is shown in Fig. (12a). The presence of the saddle along the fold axis, which is developed within a single horizon of the hard Pila Spi limestone, shows that it has undergone less uplift than the surrounding parts of the fold. Whether this saddle has resulted from the amalgamation of two laterally propagating fold segments is impossible to test from this one example alone.

As the northeastern limb of the anticline has lost its cover of soft Miocene and Pliocene sediments and is now developed solely in resistant limestone, it is likely that any direct geomorphic evidence of lateral fold growth will have been removed when the soft sediments were stripped away by erosion. It is therefore tempting, according to the evidence from tributary networks, to suggest that saddles such as this were at one point separating fold segments that have grown in length and eventually joined together (Fig.13).

Tributary networks of this anticline are shown in Fig. (12). The fold's western nose has a convex-up profile in cross- section, and the tributaries fan outwards at the fold tip (Fig.13), the forking at the heads of the tributaries would be a first generation of low-order streams responding to local slopes at the fold tip.

The entrenched sinuous channel could be part of a larger through-going drainage system flowing southwards. Furthermore, there is a developed set of channels that flow parallel to the fold crest (Fig.12b) and may have originally flowed along the fold nose. As the two fold tips coalesced, they would begin to form a continuous flank (Fig.15), and the tributaries would straighten their courses accordingly. Figure (15) shows that the two separate ridges have grown together to form one continuous ridge with a saddle through which the active drainage is now trapped and incising a deep gorge. The folds exposed in resistant Pila Spi limestone show fan- shaped tributary networks that follow the steepest topographic gradients down the flanks.

An additional, possible, indication that have been noticed in the lateral propagation and linkage of individual fold segments is that the two convex-up ridges forming the anticline are not perfectly aligned in map view. Instead, there is a left- step in the position of the fold axis as it crosses the saddle (Fig.12c).

Fold segments grow in length and divert drainage around their ends. Following the healing-reloading mechanism of 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 (Fig.16). Drainage is thus focused into narrow regions between the tips of folds that grow towards one another. The individual fold segments eventually merge together, forcing the focused drainage to incise through the growing fold, limiting discharge through a narrow outlet, and caused the ponding of sediment upstream of the emerging fold train and forming alluvial fans (Fig.17). Eventually, if river incision cannot keep pace with uplift, the outlet may become abandoned, leading either to a large-scale diversion of drainage around the end of the entire fold-train, or the formation of an internally drained basin. The drainage diversions developed in this model are independent of whether the fold-trains are composed of discrete fold segments that have merged as a result of lateral propagation or of the gradual emergence of a single, long, anticline with significant variations in displacement rate along its axis.

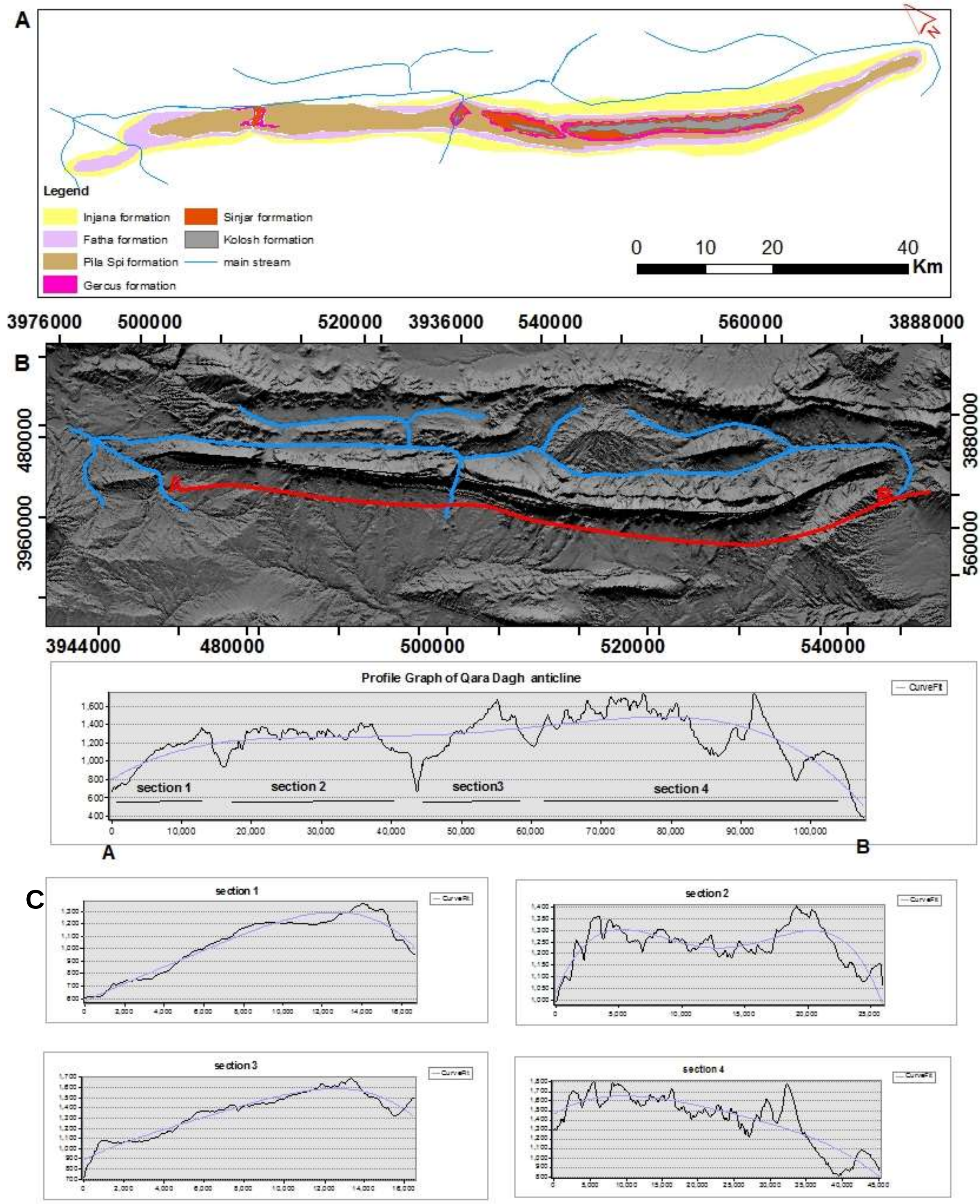


Fig.11: **A)** Geological map of the anticline (based on geological maps of the GEOSURV and field checks), **B)** 3D image with profile, graphs **(C)** do not show a smooth displacement along the axis

Significantly, a series of concave to four wind gaps exist to the NW of the present-day channel, and a further two wind-gaps are visible to the SE (Fig.12d). Each wind-gap cuts across the entire width of the fold over 100 m wide and up to 200 m deep. Furthermore, the base of each individual wind-gap increases in height away from the topographic low and the valley itself becomes shallower and wider (Fig.14). Alternatively, the southeastern wind-gaps might instead mark the progressive deflection of a river channel around the end of a fold segment whose topographic expression is growing to the east (Fig.14). As suggested by Keller *et al*. (2004), the wind-gaps presumably were formed by the deflection of a single river, as the river was repeatedly defeated by the uplifting anticline. If the topography associated with the anticline results from variable displacement rate along a fold of fixed length, the presence of multiple wind-gaps will require multiple, closely spaced, rivers initially drained southwards across the region. After the start of folding, and the uplift of resistant Pila Spi rocks, each river must have cut vertically to form gorges that are now preserved as wind-gaps. Such cases are mentioned by Ramsey *et al*. (2008).

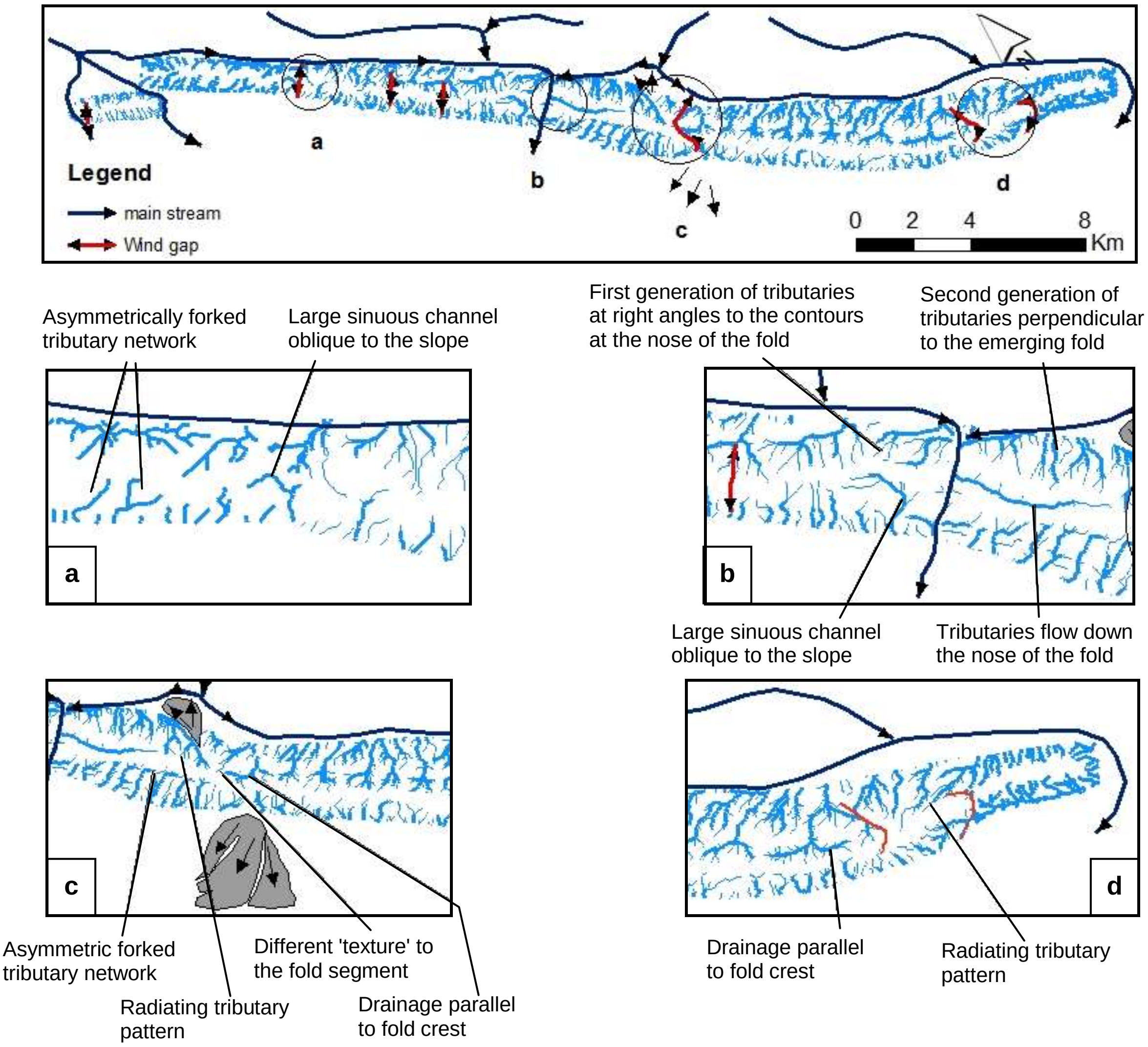


Fig.12: Tributary networks for the Darbandi – Bazian – Sagrma – Qaradagh Anticline segments

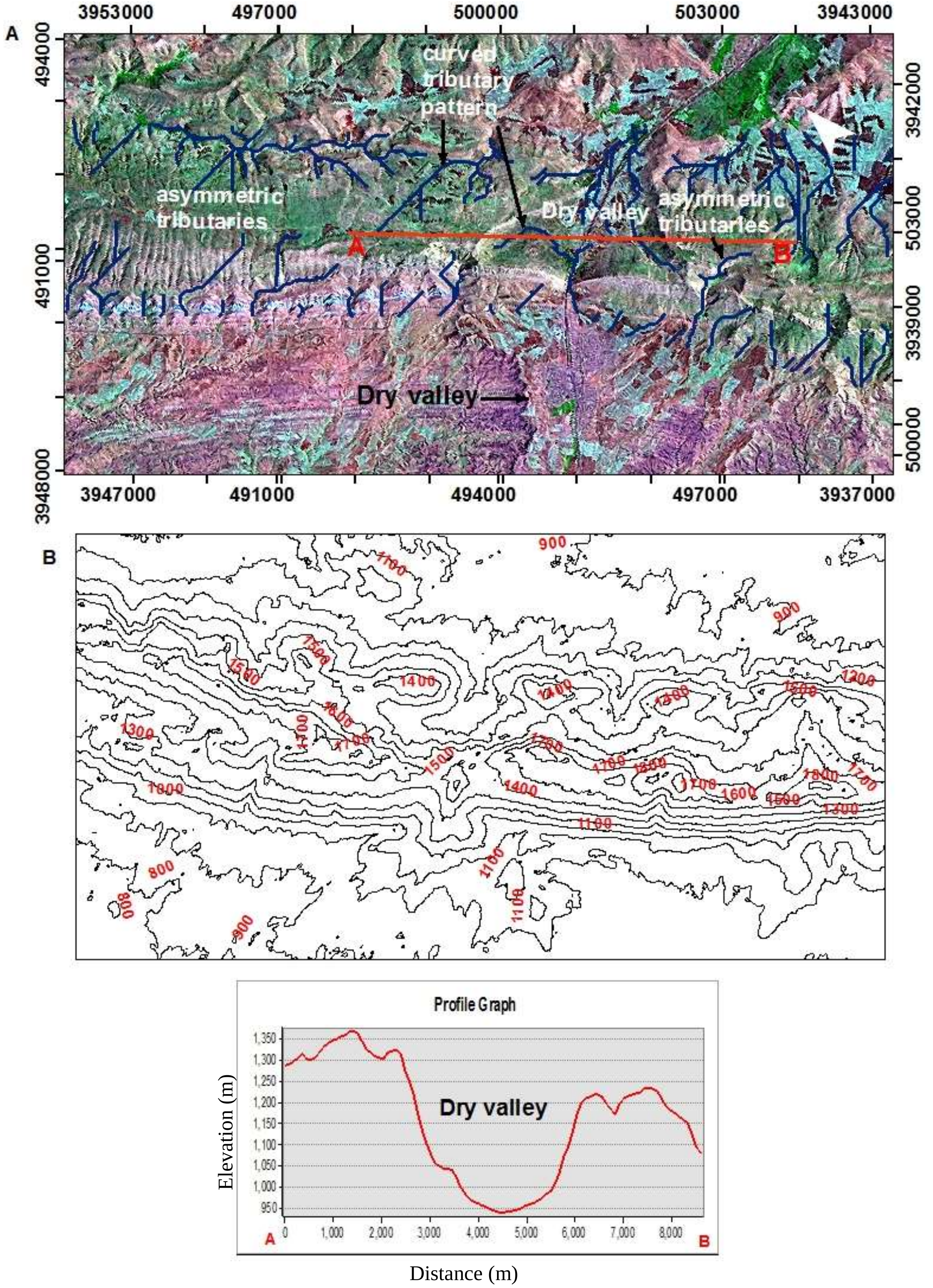


Fig.13: **A)** The two fold segments are separated by an 2 Km wide low relief valley,
B) Contour map with topographic profile across the wind gap.
For location see Fig. (12a)

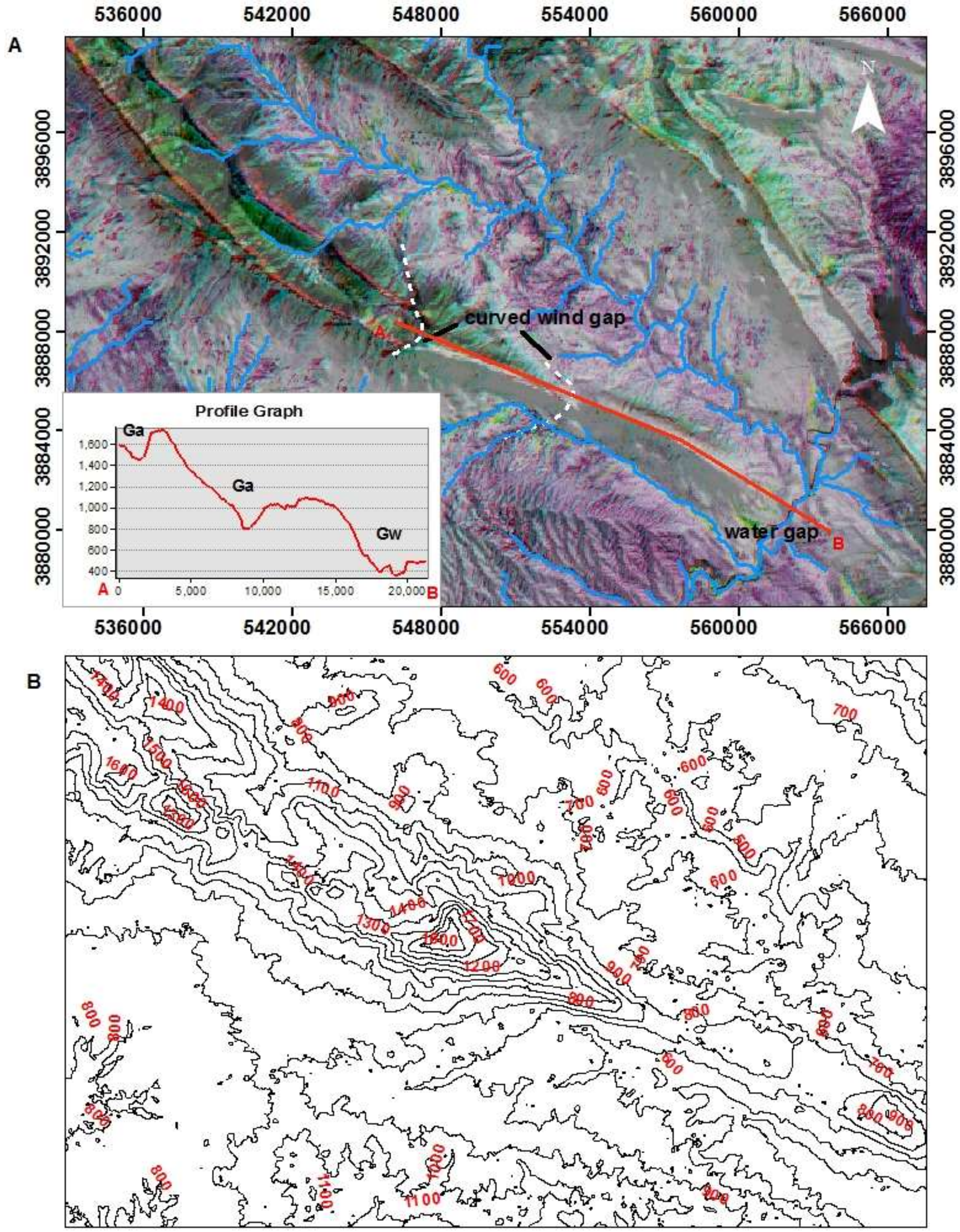


Fig.14: **A)** The southeastern wind-gaps might instead mark the progressive deflection of a river channel around the end of a fold segment whose topographic expression is growing to the east, **B)** Contour map; for location see Fig. (12d)

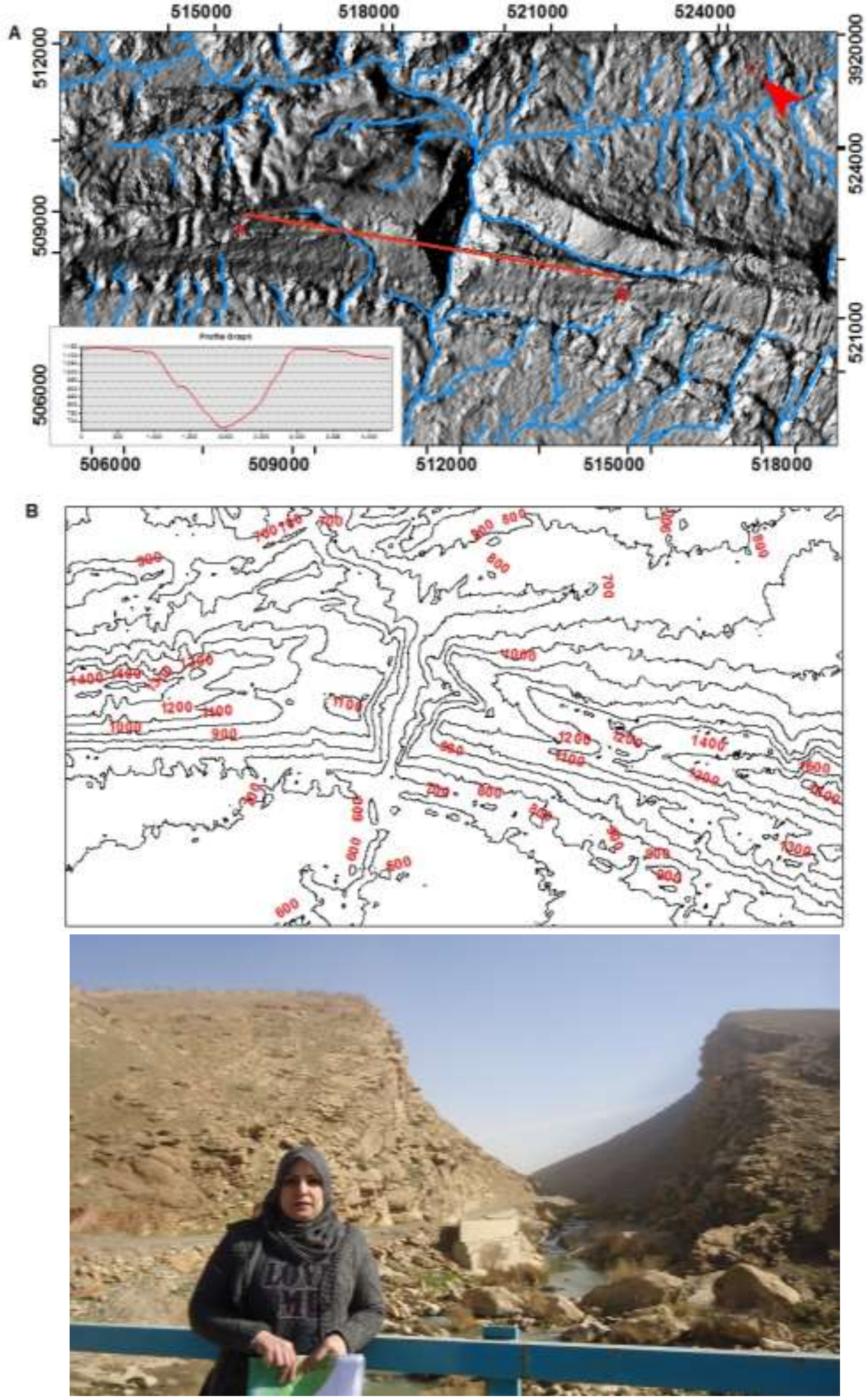


Fig.15: **A)** The folds continue to propagate towards one another and the tips of the folds begin to form a continuous structure, a gorge (Bassera), through the almost continuous anticline. A tributary pattern parallel to the crest of the fold is inherited from an earlier stage of growth, **B)** Contour map shows the gorge, **C)** Plate shows Bassera gorge; for location see Fig. (12b)

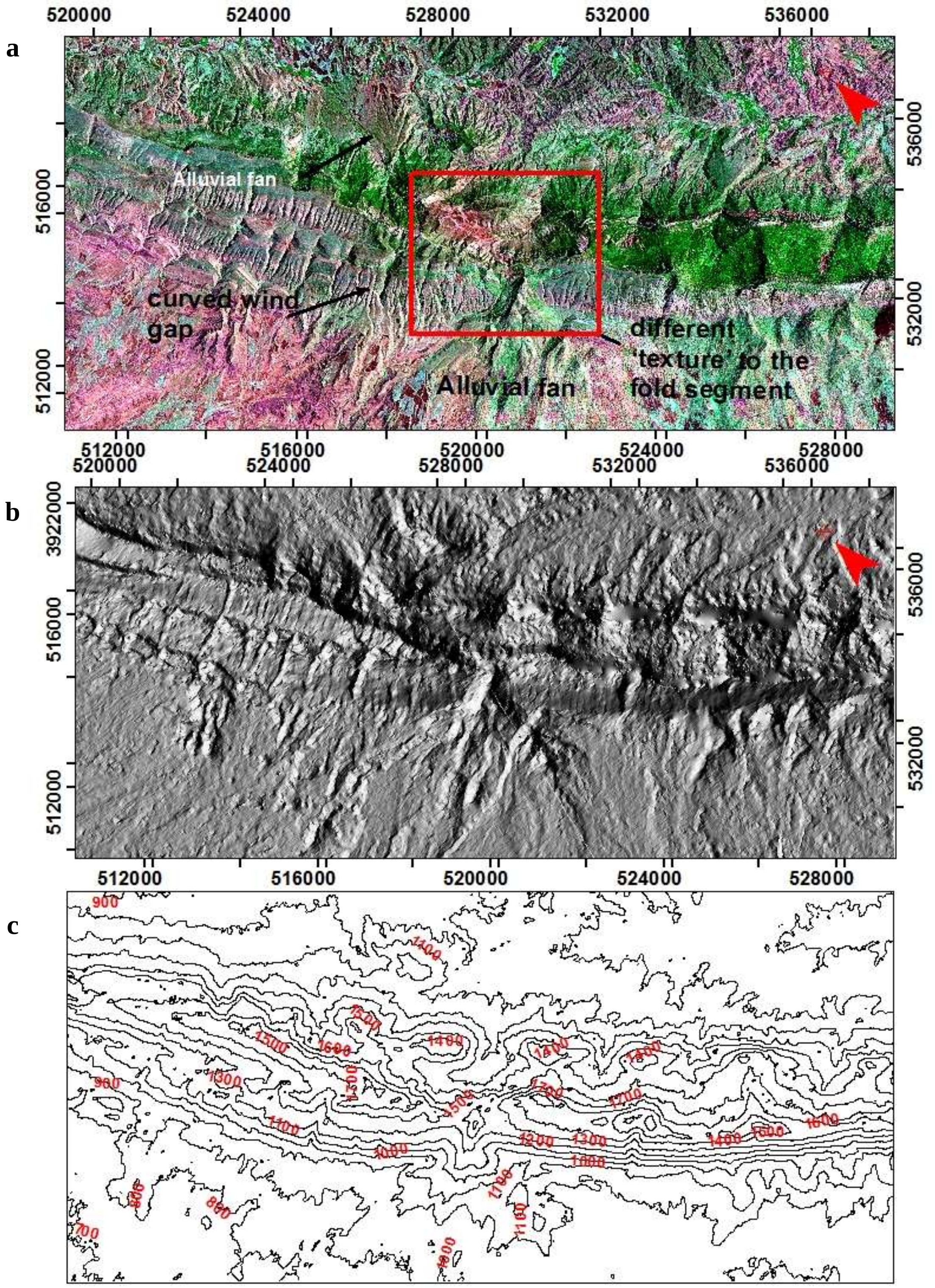


Fig.16: **a)** Satellite image shows different textures of the fold segment. **b)** Non-aligned segments; drainage is focused into narrow regions between the tips of folds, limiting discharge through a narrow outlet, and cause the ponding of sediment upstream of the emerging fold train and forming the alluvial fan. **c)** Contour map; for location see Fig. (12c)

Fig.17: Limiting discharge through a narrow outlet, caused the ponding of sediments upstream forming the alluvial fan; for location see Fig. (12c)

QUANTIFICATION OF GEOMORPHOLOGIC PARAMETERS

Selected geomorphologic parameters, such as the spacing ratio (R) the basin elongation ratio (Bs) the circularity index (C) and the basin shape (Rf) can be used to characterize the tectonic activity and basin maturity of certain regions (Anderson, 2005). Observations of topographic maps indicate that the spacing of drainage basin outlets often shows very constant values along mountain fronts (Mayer, 1986; Talling *et al*., 1993 and 1997).

High spacing ratios indicate high rates of tectonic activity, while lower spacing ratios indicate lower rates of active tectonics (Anderson, 2005). It is expressed as:

$$R = W / S$$

Where W is the half-width, measured from the mouth of the basin to the main drainage divide perpendicular to the mountain front, and S is the spacing between two mouths (Fig.18a).

The elongation ratio of the drainage basins is another useful indicator to characterize the tectonic activity of a mountain range area. Elongated basins occur in active areas, while more circular basins form after cessation of mountain uplift (Bull and McFadden, 1977), and it is expressed as:

$$Bs = Bl / Bw,$$

Where Bl is the length of the basin from its mouth to the most distal point, and Bw is the width of the basin.

Literature, such as Bull and Mc'Fadden (1977); Hovius (1996); Talling *et al*. (1997); Ramirez-Herrera (1998); Burbank and Anderson (2001) and Tsodoulos *et al*. (2008) do not explicitly describe how to measure the required distances for basin analysis. This fact causes problems; mainly at measuring curved basins. Therefore, a specially adapted method is used for this study. Bl is measured from the mouth of the basin to the most distal point in the drainage divide. As long as a straight line between these two points does not cross the drainage divide, the distance is measured as a straight line (Fig.18b). If the straight line between these two points crosses the drainage divide, then the distance will be measured as a curved line, which runs along the centre of the basin to the most distal point of the main drainage divide (Fig.18c). In both cases Bw is measured perpendicular to Bl through its midpoint (Fig.18b and 18c).

An additional index, which correlates with the elongation ratio, is the basin shape. It describes how squarish the shape of a basin is. Hence:

$$Rf = Ab / Bl^2$$

Where Ab is the area of the basin, and Bl is the length of the basin, as mentioned previously.

In this study, the spacing ratio (R), the elongation ratio (Bs), and the basin shape ratio (Rf) were calculated for 89 drainage basins in the investigated anticline (Fig.19), to figure out the differences in the rates of the tectonic activity between the different fold segments (Fig.20). Additionally, differences in the morphology of fore and backlimbs were analyzed. The values of the ratios and parameters discussed can be found in Table (1).

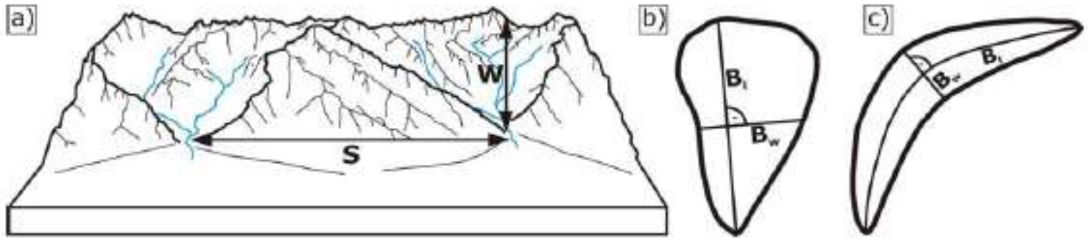


Fig.18: **a)** Two mountainous catchments. **W** is the half width of a drainage basin, and **S** is the distance between the outlets of two catchments (modified after Hovius, 1996). **b)** Drainage basin, where **Bl** is a straight line between the mouth of the basin and **Bw** is a straight line perpendicular through the midpoint of **Bl**. **c)** Curved drainage basin, where **Bl** is a curved line between the mouth of the basin, and **Bw** is a straight line perpendicular through the midpoint of Bl.

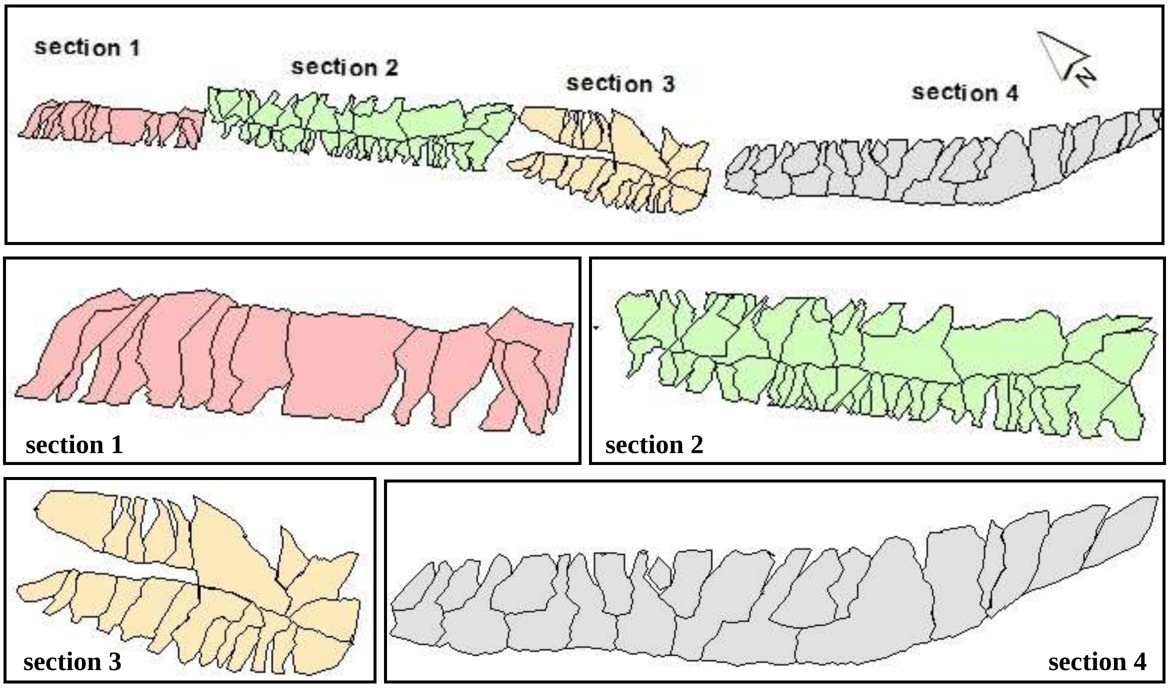
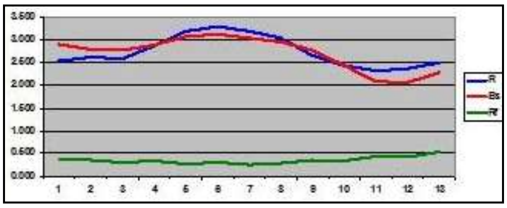


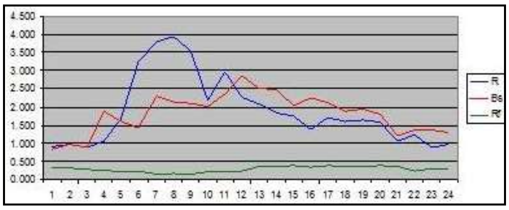
Fig.19: Location of different fold segments used for quantification and their individual basins as well as the courses of the main streams (sections 1 to 4)

In the NW part of the anticline (Fig.20, section 1), convenient values can be extracted from the forelimb only because the appearance of the backlimb is strongly influenced by the neighboring Miran Anticline, whereas in the southeastern part (section 4) the drainage pattern occurs with narrower spacing and consequently more elongated basins. This behavior can be analyzed on the backlimb only, because due to the high order fold on the forelimb the drainage basins are distorted and, moreover, they are too short to extract useful values for quantification.

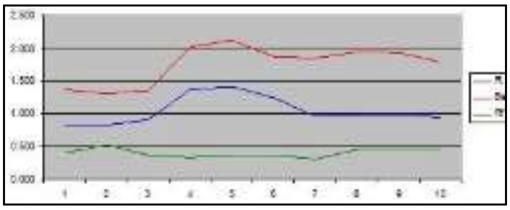
The northwestern part of segment 1, shows a drainage pattern with narrower spacing and consequently more elongated basins, which causes the high values of R and Bs in this area. In the southeastern part of this segment, the values drop significantly. Consequently, the values of Rf show an opposing trend. The forelimb of section 2, shows a narrower spacing and lower sinuosities in contrast to the backlimb. R and Bs are higher on the forelimbs, while consequently Rf values are higher on the backlimbs. Values of R and Bs are higher on the center, while Rf is lower. The high elongation and spacing ratios on this section substantiate the statement of increasing tectonic activity. Section 3 shows differences in the shape of the drainage network occurring with higher sinuosities and wider channel spacing along the backlimb in contrast to the forelimb. Similarly to section2, R and Bs show a decreasing trend towards the SE and NW, whereas the values for Rf increases in these directions R and Bs values show a decreasing trend towards the SE, whereas the values of Rf increases in this direction on section 4. This statement is supported by the appearance of curved wind gaps in the extreme southeastern part of the anticline. There is an abnormal behavior between sections 3 and 4. This is attributed to the fold aligned segments that are likely to grow at the expense of other, non-aligned segments, by a positive feedback in the stress changes around the structure.



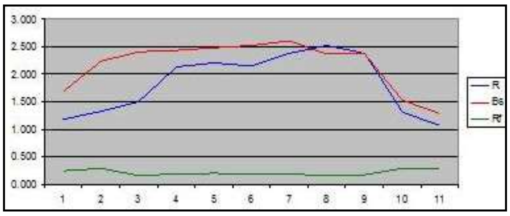
R, Bs and Rf index for section 1, forelimb



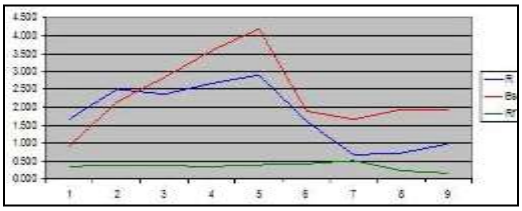
R, Bs and Rf index for section 2, forelimb



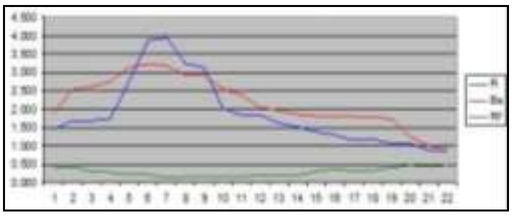
R, Bs and Rf index for section 2, backlimb



R, Bs and Rf index for section 3, forelimb



R, Bs and Rf index for section 3, backlimb



R, Bs and Rf index for section 4, backlimb

Fig.20: The spacing ratio (R), the elongation ratio (Bs), and the basin shape (Rf) are calculated to figure out differences in the rates of the tectonic activity between the different fold segments

Table 1: The values of the ratios and parameters (the numbering is from W to E)

Section1 forelimb

Area	W (Km)	S (Km)	R	Bl (Km)	Bw (Km)	Bs	Ab (Km^2)	Bl*2 (Km)	Rf
1	1.790	0.706	2.535	2.323	0.799	2.907	1.994	5.396	0.370
2	1.736	0.663	2.618	2.298	0.821	2.799	1.906	5.281	0.361
3	1.779	0.685	2.597	2.163	0.778	2.780	1.438	4.679	0.307
4	1.728	0.602	2.870	2.226	0.767	2.902	1.681	4.955	0.339
5	1.892	0.592	3.196	2.103	0.683	3.079	1.176	4.423	0.266
6	1.891	0.572	3.306	1.861	0.595	3.128	1.024	3.463	0.296
7	1.958	0.613	3.194	2.019	0.662	3.050	1.038	4.076	0.255
8	1.615	0.529	3.053	1.889	0.638	2.961	1.025	3.568	0.287
9	1.598	0.602	2.654	2.055	0.741	2.773	1.512	4.223	0.358
10	1.843	0.757	2.435	1.999	0.818	2.444	1.357	3.996	0.340
11	1.247	0.536	2.326	1.498	0.717	2.089	0.974	2.244	0.434
12	1.880	0.795	2.365	1.88	0.908	2.070	1.496	3.534	0.423
13	1.899	0.758	2.505	1.883	0.823	2.288	1.906	3.546	0.538

Section 2 forelimb

Area	W (Km)	S (Km)	R	Bl (Km)	Bw (Km)	Bs	Ab (Km^2)	Bl*2 (Km)	Rf
1	1.077	1.191	0.904	1.088	1.303	0.835	0.393	1.184	0.332
2	1.257	1.296	0.970	1.349	1.386	0.973	0.586	1.820	0.322
3	1.141	1.292	0.883	1.188	1.354	0.877	0.397	1.411	0.281
4	1.594	1.494	1.067	1.934	1.025	1.887	0.991	3.740	0.265
5	1.441	0.849	1.697	1.937	1.217	1.592	0.805	3.752	0.215
6	1.492	0.461	3.236	1.531	1.067	1.435	0.541	2.344	0.231
7	1.345	0.355	3.789	1.877	0.818	2.295	0.514	3.523	0.146
8	1.173	0.298	3.936	1.687	0.785	2.149	0.514	2.846	0.181
9	1.799	0.506	3.555	2.101	1	2.101	0.712	4.414	0.161
10	1.376	0.631	2.181	1.917	0.953	2.012	0.834	3.675	0.227
11	1.26	0.426	2.958	1.982	0.838	2.365	0.849	3.928	0.216
12	1.521	0.67	2.270	1.979	0.691	2.864	0.902	3.916	0.230
13	1.466	0.704	2.082	1.877	0.745	2.519	1.272	3.523	0.361
14	1.475	0.806	1.830	2.001	0.807	2.480	1.461	4.004	0.365
15	1.373	0.788	1.742	1.805	0.889	2.030	1.244	3.258	0.382
16	1.326	0.951	1.394	1.749	0.781	2.239	1.049	3.059	0.343
17	1.288	0.755	1.706	1.799	0.851	2.114	1.238	3.236	0.383
18	1.419	0.885	1.603	1.819	0.969	1.877	1.187	3.309	0.359
19	1.383	0.845	1.637	1.904	0.981	1.941	1.301	3.625	0.359
20	1.281	0.809	1.583	1.631	0.911	1.790	1.022	2.660	0.384
21	1.372	1.298	1.057	2.121	1.759	1.206	1.681	4.499	0.374
22	1.667	1.352	1.233	2.433	1.796	1.355	1.389	5.919	0.235
23	1.211	1.369	0.885	2.318	1.696	1.367	1.671	5.373	0.311
24	1.368	1.419	0.964	2.189	1.676	1.306	1.453	4.792	0.303

Section 2 backlimb

Area	W (Km)	S (Km)	R	Bl (Km)	Bw (Km)	Bs	Ab (Km^2)	Bl*2 (Km)	Rf
1	1.152	1.382	0.834	2.673	1.944	1.375	2.908	7.145	0.407
2	1.499	1.798	0.834	2.001	1.527	1.310	2.099	4.004	0.524
3	1.191	1.305	0.913	2.329	1.719	1.355	2.001	5.424	0.369
4	1.403	1.027	1.366	3.222	1.599	2.015	3.555	10.381	0.342
5	2.001	1.409	1.420	2.532	1.193	2.122	2.418	6.411	0.377
6	1.599	1.282	1.247	2.443	1.302	1.876	2.258	5.968	0.378
7	1.884	1.965	0.959	3.157	1.704	1.853	3.111	9.967	0.312
8	2.805	2.871	0.977	5.557	2.851	1.949	14.012	30.880	0.454
9	2.791	2.843	0.982	4.483	2.312	1.939	9.271	20.097	0.461
10	2.774	2.911	0.953	3.964	2.214	1.790	7.106	15.713	0.452

Cont. Table 1:

Section 3 forelimb

Area	W (Km)	S (Km)	R	Bl (Km)	Bw (Km)	Bs	Ab (Km^2)	Bl*2 (Km)	Rf
1	2.301	1.935	1.189	2.286	1.357	1.685	1.317	5.226	0.252
2	1.991	1.499	1.328	2.366	1.061	2.230	1.615	5.598	0.288
3	2.105	1.399	1.505	2.408	1	2.408	0.913	5.798	0.157
4	2.398	1.124	2.133	3.645	1.492	2.443	2.501	13.286	0.188
5	2.747	1.245	2.206	2.999	1.212	2.474	1.774	8.994	0.197
6	2.325	1.081	2.151	3.963	1.569	2.526	2.999	15.705	0.191
7	2.492	1.046	2.382	2.192	0.838	2.616	0.884	4.805	0.184
8	2.111	0.838	2.519	3.304	1.399	2.362	1.747	10.916	0.160
9	2.384	0.999	2.386	3.155	1.333	2.367	1.672	9.954	0.168
10	1.843	1.401	1.315	2.574	1.687	1.526	1.931	6.625	0.291
11	1.386	1.301	1.065	2.174	1.686	1.289	1.355	4.726	0.287

Section 3 backlimb

Area	W (Km)	S (Km)	R	Bl (Km)	Bw (Km)	Bs	Ab (Km^2)	Bl*2 (Km)	Rf
1	1.152	0.682	1.689	2.673	2.844	0.940	2.508	7.145	0.351
2	1.499	0.598	2.507	2.001	0.927	2.159	1.599	4.004	0.399
3	1.191	0.505	2.358	2.329	0.819	2.844	2.001	5.424	0.369
4	1.403	0.527	2.662	3.222	0.899	3.584	3.555	10.381	0.342
5	2.001	0.689	2.904	2.532	0.603	4.199	2.518	6.411	0.393
6	1.599	0.982	1.628	2.443	1.292	1.891	2.558	5.968	0.429
7	1.884	2.765	0.681	3.157	1.904	1.658	5.111	9.967	0.513
8	2.005	2.771	0.724	5.557	2.851	1.949	7.012	30.880	0.227
9	2.791	2.843	0.982	4.483	2.312	1.939	3.271	20.097	0.163

Section 4 backlimb

Area	W (Km)	S (Km)	R	Bl (Km)	Bw (Km)	Bs	Ab (Km^2)	Bl*2 (Km)	Rf
1	1.907	1.307	1.459	2.964	1.565	1.894	3.694	8.785	0.420
2	2.263	1.346	1.681	3.552	1.402	2.534	5.537	12.617	0.439
3	3.012	1.774	1.698	4.891	1.867	2.620	7.418	23.922	0.310
4	2.106	1.217	1.730	3.532	1.289	2.740	3.439	12.475	0.276
5	2.665	0.978	2.725	4.564	1.451	3.145	4.566	20.830	0.219
6	3.328	0.857	3.883	4.66	1.45	3.214	4.779	21.716	0.220
7	3.523	0.891	3.954	4.936	1.557	3.170	3.358	24.364	0.138
8	2.989	0.923	3.238	3.012	1.026	2.936	1.301	9.072	0.143
9	4.793	1.531	3.131	5.415	1.836	2.949	5.321	29.322	0.181
10	3.985	1.955	2.038	5.374	2.105	2.553	4.765	28.880	0.165
11	2.762	1.506	1.834	4.636	1.954	2.373	3.891	21.492	0.181
12	3.589	1.946	1.844	3.69	1.797	2.053	2.714	13.616	0.199
13	3.357	2.068	1.623	3.474	1.767	1.966	2.276	12.069	0.189
14	4.112	2.721	1.511	5.152	2.767	1.862	5.214	26.543	0.196
15	3.348	2.427	1.379	5.019	2.771	1.811	7.715	25.190	0.306
16	2.666	2.052	1.299	4.752	2.623	1.812	8.096	22.582	0.359
17	2.602	2.256	1.153	4.656	2.579	1.805	6.913	21.678	0.319
18	3.226	2.736	1.179	3.537	1.998	1.770	4.036	12.510	0.323
19	2.701	2.552	1.058	3.312	1.881	1.761	4.453	10.969	0.406
20	2.666	2.491	1.070	2.189	1.757	1.246	2.261	4.792	0.472
21	2.112	2.364	0.893	1.761	1.766	0.997	1.399	3.101	0.451
22	1.986	2.336	0.850	1.502	1.625	0.924	1.064	2.256	0.472

DISCUSSION

The present observations have implications for the formation of the deep gorges in the folded region. A river that does not have sufficient stream power to incise a course across a propagating anticline tip is persistently deflected away from its southwestwards path. Eventually, the river is trapped between the original fold tip and a second anticline, which is propagating in the opposite direction.

The river with any transverse drainage or rivers diverted parallel to this second fold, flow through the topographic low between the two fold noses. As uplift continues and the fold segments begin to merge together, the river must incise a transverse gorge at the topographic low or risk being defeated and the channel abandoned. If the transverse gorge is abandoned, the river will flow parallel to the fold axes. However, the drainage area of the river will increase significantly with the amalgamation of several river segments at the gorge, the stream power of the river will increase, and it may be more successful in keeping pace with uplift here than it was initially at the anticline tip.

An alternative explanation for the drainage history of the Zagros was suggested by Oberlander (1968 and 1985), who interpreted the transverse rivers cutting the structural highs NE of Dezful; as a consequence of the regional stratigraphy. His observations focused on the ‘tangs’ of the Dezful Zagros. The tangs are steep, narrow gorges cut by rivers transverse to the fold length, often through the highest structural and topographic part of the anticline crests. Oberlander (1986) suggested that the morphology of the gorges varied from V-shaped valleys in the older northern parts of the mountain belt, to slot-like canyons in the Simple Folded Belt, the present-day focus of deformation. He believed that the pattern was repeated too often to be by chance, and that previous explanations for transverse drainage formation (e.g. that the rivers are antecedent to the structure) did not account for the close proximity of the tangs to the anticline structural highs. Oberlander (1968) suggested that the drainage network in the NW Zagros was instead superimposed from structurally conformable younger horizons.

According to Oberlander's model (1968), breaching of hard Asmari limestone, and exposure of the underlying easily erodible rocks, results in the formation of a low-relief landscape on which new through-going drainage systems can be developed. These new drainage systems are then superposed on the Mesozoic limestone as it is exhumed by continued fold growth. In Oberlander’s hypothesis, it is the Pabdeh and Gurpimarls that facilitate the creation of a low-relief landscape across the anticlinal crests and are, therefore, integral to the story of drainage superposition. Instead, the drainage systems evolve in response to folding in hard and resistant lithologies, resulting in the landscapes described in "Fold segmentation, lateral growth and linkage in the SE Zagros", and "Effects of fold growth on the through-going drainage in the Zagros".

The suggested model by the authors for the evolution of drainage in the folded zone, in which rivers are diverted around the tips of laterally growing anticlines until the merger of individual fold segments becomes important in forcing drainage evolution, may also occur in other areas of active shortening. By a mechanism similar to that proposed here, Champel *et al*. (2002) concluded that the Dundwa anticline formed by the propagation and merging of smaller fold segments (10 to 20 Km in length) that ‘pinched’ rivers between the merging fold tips. The segment boundaries are now marked by abandoned river channels. The Himalayan deformation front has stepped southwards through time and the landscape along the Dundwa anticline provides a modern-day analogue to the early stages of landscape development at the Main Boundary thrust farther north. Gupta (1997) recognized that the rivers to the north of the

Main Boundary thrust form a 'grid-iron' drainage pattern that implies river deflections about multiple fold segments.

The segmentation of the original anticline boundaries has now been obscured by continued long term uplift in the hanging wall of the Main Boundary thrust. The deflection of rivers parallel to anticline axis and the trapping of rivers between fold tips appear, therefore, to be a consequence of the growth of fold-and-thrust belts.

In the folded zone, the drainage is observed at relatively young stages in its evolution. The geomorphology is thus sufficiently well preserved to retain clues on the early development of the fold structures. Continued growth, erosion, and exhumation of the folds are likely to make these geomorphic signals much more difficult to identify.

The geomorphic record suggests that anticlines in the folded zone are likely to have increased in length until neighboring folds merge together to form long fold-trains. The merger of individual fold segments has had a major effect on the patterns of through-going drainage in north Iraq (Fig.21).

Direct evidence for lateral propagation, in the form of anomalous drainage patterns and preservation of wind gaps, is best preserved on the flanks, which has retained a cover of soft sediments. In the majority of the folded zone, which are developed in resistant limestones, the remnants of drainage systems from the early stages of folding, and therefore, direct evidence of lateral growth, will have been removed when the cover of soft sediments was eroded away.

Each fold segment may be underlain by discrete thrust faults that did not form a continuous structure at depth. Although a greater understanding of this zone subsurface structure is needed to be sure. The merger of individual segments forms topographic barriers in excess of 100 Km long that have controlled the distribution of drainage and sedimentation seen at the present day.

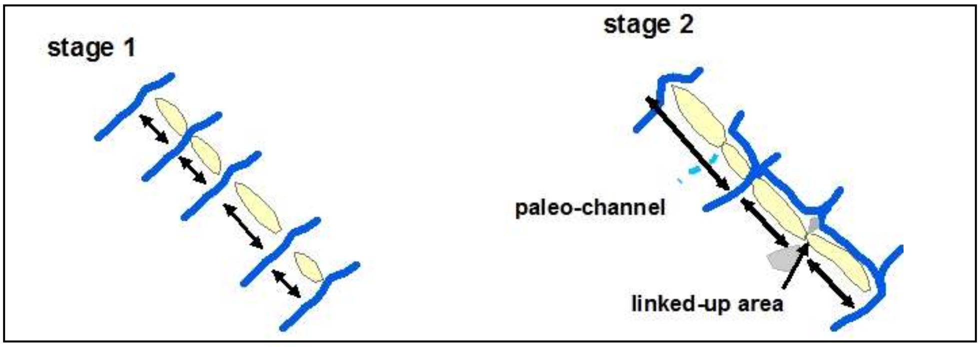


Fig.21: **Stage 1)** fold growth initiated along the smaller segments along NW, Gaps between the growing folds allowed the rivers to flow through. **Stage 2)** The lateral propagation of the growing folds resulted into linkage segments. Uplift of the linked segments caused disruption and deflection of rivers

CONCLUSION

- This study demonstrates that the anticlines in study area have developed from several embryonic folds, which have merged during lateral propagation and form extended fold trains by use of geomorphologic criteria.
- The geomorphic record suggests that anticlines in the folded zone are likely to have increased in length until neighbouring folds merge together to form long fold-trains.

- As a further step of investigation various geomorphologic parameters, describing tectonic activity and basin maturity, are analyzed and the interpretation of these calculated geomorphologic ratios indicates a high tectonic activity of the region and a low maturity of the drainage basins, with a slightly opposing trend, which is also highlighted by the occurrence of curved wind gaps in the south-eastern part of the investigated area.
- The merging points of the individual fold segments have major effects on the pattern of the regional drainage system. All along the investigated anticlines, direct evidence for lateral propagation in form of distinctive drainage patterns and wind gaps can be found.
- As a special form of wind gaps, the new model of "curved wind gaps" was determined. This form of wind gaps develops in areas with high tectonic uplift and propagation rates with simultaneous low incision rates.
- The phenomenon of fault related fold growth, lateral propagation and fault segmentation-linkage in many tectonically active regions have played pivotal role in shaping the landscape and could be considered as a source for future earthquakes.

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