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The Indication of Geomorphic Evidence for Lateral Propagation of Sheikhan Anticline - Zagros Fold and Thrust Belt – Northern Iraq

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ABSTRACT

The Sheikhan anticline is situated north of Mosul City near the Sheikhan town in the southwest boundary of the high folded zone within the part of the Zagros zone in the Iraqi segment. It is an asymmetrical double plunging anticline, and oriented in a NW – SE trend, it is verging to the northeast as the forelimb attitude, and the NW plunging area is wider than the pointed SE plunging area. The oldest exposed outcrops belong to Upper Cretaceous age; it locally forms the backbone of the mountain. Whereas, the thickly bedded hard limestone beds of the Pila Spi Formation, limestone and marls of Fat'ha Formation and, marls, siltstones, sandstones of Injana Formation form the flanks of the anticline. The geomorphological features explained by direct field data, integrated with the analysis of satellite image programs are used to deduce the directional side-propagation of the fold. It was found that the propagation of the anticline was started to form (present situation) northwest toward the southeast. Deep-seated transversal faults were controlled somehow to side-propagation imprinted as dome-like west of Gully Keer valley, and also wind gap and water gap may follow these fault traces. Some structural phenomena that define the progression of folding have been observed and explained.

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الملخص

تقع طية الشيخان المحدبة شمال مدينة الموصل بالقرب من بلدة الشيخان في الجزء الجنوبي الغربي لنطاق الطيات العالية ضمن الجزء العراقي من نطاق زحف وطي زاكروس. طية الشيخان عبارة عن طية محدبة غير متماثلة ذات غاطسين، وباتجاه شمال غرب – جنوب شرق، واتكائها نحو الشمال الشرقي، وتكون منطقة الغطس الشمالية الغربية أوسع من منطقة الغطس الجنوبية الشرقية. تتكشف في الطية التكاوين التي تمتد اعمارها من العصر الطباشيري العلوي الى المايوسين الاعلى؛ ويشكل أقدم التكاوين درع الطية المحدبة. في حين أن طبقات الحجر الجيري الصلبة ذات الطبقات السميكة لتكوين بيلاسبي، والحجر الجيري والمارل لتكوين الفتحة، والمارل، والأحجار الغرينية، والأحجار الرملية لتكوين إنجانة تشكل أطراف الطية المحدبة. تم استخدام الخصائص الجيومورفولوجية المستخلصة من البيانات الحقلية المباشرة والمتكاملة مع تحليل برامج الصور الفضائية لاستنتاج اتجاه الانتشار الجانبي للطية. وقد وجد أن انتشار الطية المحدبة (الوضع الحالي) بدأ يتشكل من الشمال الغربي باتجاه الجنوب الشرقي. تحكمت الصدوع المستعرضة العميقة بطريقة ما من خلال الانتشار الجانبي للطية والتي تمثلت بشكل قبة غرب وادي كلي قير، كما تتبع فجوة الرياح (Wind gap) وفجوة المياه (Water gap) مسارات هذه الصدوع. تمت ملاحظة وتفسير بعض الظواهر التركيبية التي تحدد تطور الطي في تلك المنطقة.

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Introduction

The Arabian and Eurasian Plates collided after their convergence and the closing of Neo-Tethys, which began in the Late Cretaceous, creating the Zagros zone, also known as the Zagros Fold and Thrust Belt, which extends from Turkey to the Hormuz Strait (Berberian and King, 1981; Alavi, 2004). As seen in the study area, geomorphological and geological evidence provides some of the best ways to identify and distinguish active tectonics in regions with low or moderate tectonic deformation rates (Molin *et al*., 2004; Dumont *et al.*, 2005; Necea *et al.*, 2005). Tectonic activity such as lateral growth of anticline could be inferred using indirect data from landscape geomorphology (Burbank *et al.*, 1996; Keller *et al.*, 1999). There are related patterns of lateral growth of anticlines in northern Iraq, as a part of Zagros zone, (Blanc, *et al.*, 2003; Bennett, *et al.*, 2005; Ramsey, *et al.*, 2008). This study investigated the drainage systems i.e., geomorphic aspects associated with the active folds such as the Sheikhan area and suburbs.

To evaluate fold growth, it is possible to apply the geomorphic criteria outlined by researchers, such as Keller, *et al.* (1999), and Keller and Pinter (2002). These criteria involve: (1) younger deposits or landscapes becoming more deformed, (2) the development of recognizable asymmetric drainage patterns, (3) the presence of a set of wind gaps with decreasing elevation in the direction of propagation, (4) the development of water gaps (WG), and (5) the growth of cross-shaped valleys, axial valleys, fork-shaped valleys, and curved valleys. It is worth mentioning that all of these criteria must be integrated to infer the lateral growth of the fold. Also, the distinction between the features is achieved through the integration between interpretations of high-resolution satellite imagery with field investigation.

The current study focuses on create a thorough evolutionary model of side-propagation (lateral propagation) of Sheikhan anticline using geomorphological criteria.

The investigation area includes the Sheikhan anticline, which is located 50 kilometers north of Mosul city near the Sheikhan town and is geographically bounded by Latitude (36° 52' 00" N and 36° 41' 00" N) and Longitude (43° 45' 30" E and 44° 13' 00" E), (Figure 1). This area creates an impressive continuous mountain range along with the Aqra anticline towards the east and Dahqan anticline towards the west.

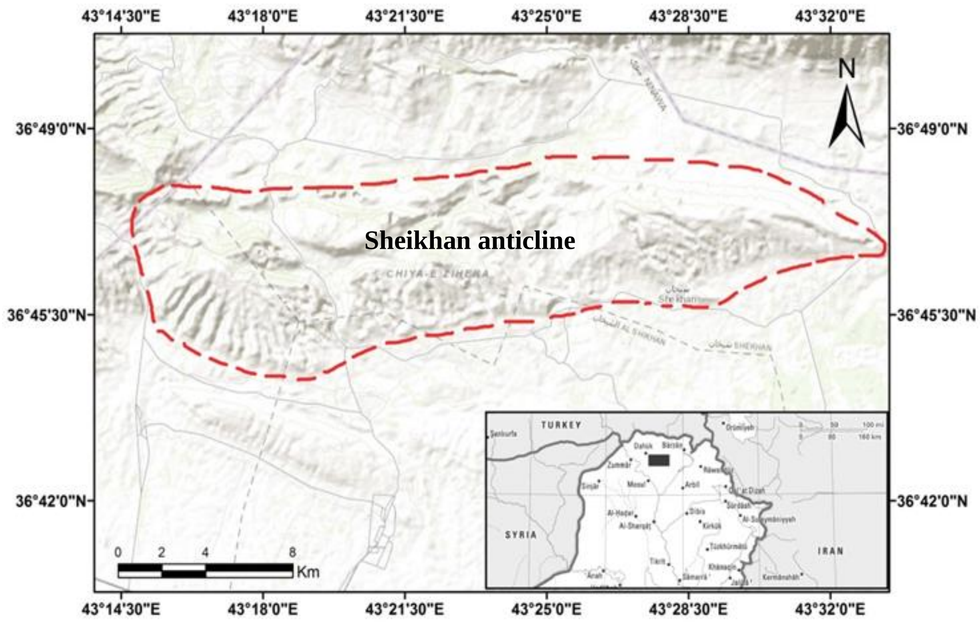

Fig. 1. Geographical location of the study area.

Materials and Methods

The following materials were used to complete the current work and accomplish its goal:

- 1:250,000 scale geological maps.
- 1:100,000 scale topographic maps.
- High-quality satellite imagery for detecting geomorphological features.
- Fieldwork was carried out to verify the identified geomorphological features.

The concept of different studies has been taken into consideration in the present research to designate the side-propagation of the Sheikhan anticline and to verify the attained findings to identify geomorphological features that specify the side-growth of an anticline. Some of these scholars are Keller, et al., 1999; Keller and Pinter, 2002; Ramsey, et al., 2008; and Collignon, et al., 2016. With the use of Google Earth, Global Mapper, and Digital Surface Model (DSM) images, a geospatial interpretation of the data was used in this study using topographical and geological maps of 1: 100000 and 1: 250000 scales. Different geomorphological features have been interpreted to indicate the maneuver between the features of the water gap and wind gap, and then to consider the side-propagation of the Sheikhan anticline and the morphotectonic scene connected to the adjacent geological structures.

Geological Setting

The study area can be summarized as including elements such as geomorphology, tectonics, structural geology and stratigraphy. The study area is highland landscape with steep slopes and extremely rugged cliffs. The following are the primary geomorphological features: anticlinal ridges, dissected slopes, alluvial fans, different drainage patterns, triangular facets, and butterfly features (Al-Azzawi andHamdon, 2008). Also, wind and water gaps are embellishing this anticline. The highest peak on the anticline is about 1120 meters above sea level .

Tectonically, the Sheikhan anticline is situated on the southeastern border of the high folded zone (Jassim and Goff, 2006). The general trend of the Sheikhan anticline is NW-SE swinging to E-W occasionally; it is double plunging asymmetrical with verging to the northeast. The average dip of the northeastern limb is 42 degrees, whereas the average dip of the southwestern limb is 22 degrees. The northwestern plunge has joined with the southeastern plunge of Brifca Anticline near Mamez Dana village, and it extends about (30) km toward southeastern before plunging near Kavrasor village, (Figure 2). Using band ratio technique clearly shows the asymmetrical of anticline toward northeast (Figure 3). The Main suture verging listric fault, which extended under the axis of the anticline, played a significant role in fold style during folding processes (Al-Khatony, 2009).

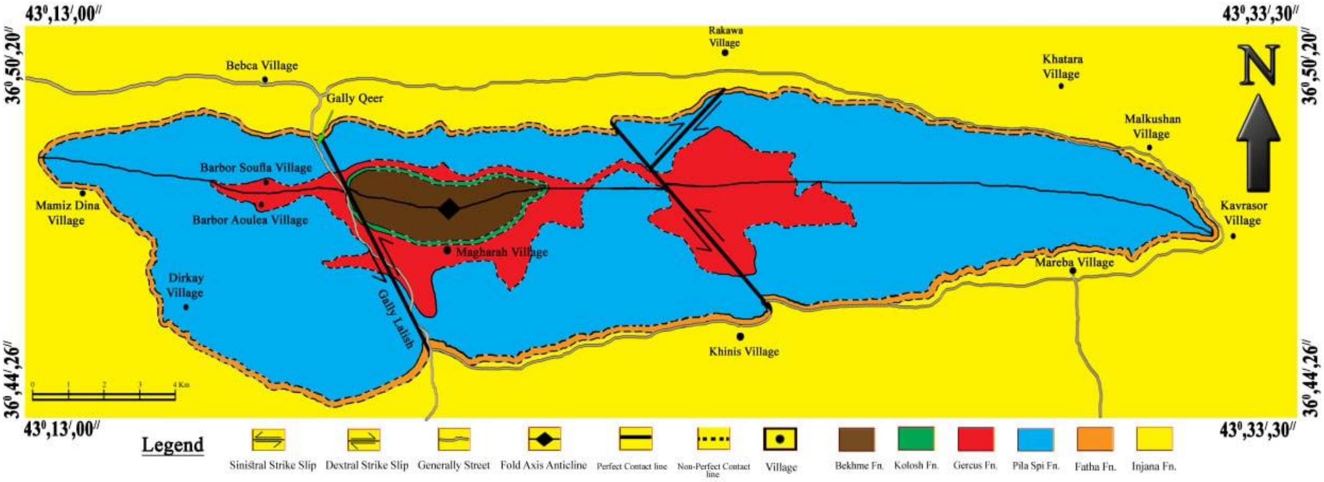

Fig. 2. Geological and structural map of the study area (Al-Khatony, 2009).

The following are short descriptions of the geological formations in the area under study, from oldest to youngest, (Figure 2):

(Upper Cretaceous Unit): It constitutes the carapace of the Sheikhan anticline and is exposed in the core. The exposed unit (225 meters thick) consists of massive dolomitic limestone and dolomite. Tahir (Tahir, 1978 in Ahmed, 1980) referred to this unit as the Qamchuqa Formation, while (Ahmed, 1980) referred to this succession as Upper Cretaceous Dolomite. (Al-Hmeedi, 2007) referred to it as a Bekhme Formation.

Kolosh Formation (Paleocene – Lower Eocene): It is composed of 60 meters of well-bedded cycles of clay, shale, fine sandstone, and fragments of various grains of green-rock, chert, and radiolarite as well as some very thin layers of limestone.

Gercus Formation (Middle Eocene): Its 130 meters are made up of red and purple shales, mudstones, sandy marl, and gritty marl.

Pila Spi Formation (Middle to Upper Eocene): It consists of thickly bedded hard limestone that has been impregnated with hydrocarbon seepage. The thickness of the formation on the NE limb is 304 meters, while the thickness of the SW limb is 604 meters (Al-Azzawi and Al-khatony, 2010). It has been attributed to the role of the foreland-vergent listric fault during the deposition of the formation.

Fat'ha Formation (Middle Miocene): It consists of an alternation of limestone and marls, with thicknesses ranging from 60 to70 meters.

Injana Formation (Upper Miocene): It is made up of purple, red, brown, and grey marls, silts, siltstones, sandstones, and grits that are both sub-continental and continental in origin.

All of the above-mentioned brief lithological descriptions of each formation were obtained from field observation and Bellen van *et al* (1959).

Geomorphic criteria for determining the direction of folding side-propagation

One of the main approaches for increasing the lateral progression of folds is the strong relationship between geomorphological aspects and the growth of the folds. Growth was attributed mainly to the movement slip on a fault plane, (Burbank and Pinter., 1999; Delcaillau, 2001; Champel *et al.*, 2002; Ramsey et al., 2008). Based upon these studies, the history of fold development is strongly related to fault development and fault connectivity. The lateral development of fault-related folds was thoroughly discussed in the Sheikhan anticline.

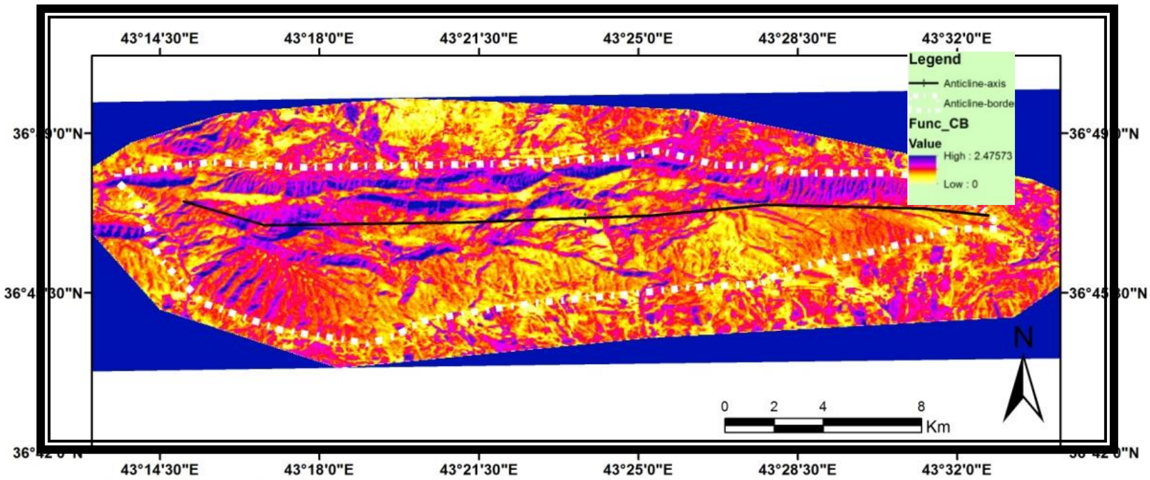

Fig. 3. Band ratio technique showing the steeper morphology in northern limb and at south western part of southern limb.

If drainage patterns are properly evaluated, it may be observed that some folds propagate in two directions and the neighboring folds propagate toward one another or that younger folds in a fold belt propagate parallel to, away from, or toward older folds, (Jackson *et al.*, 1996). The position of an anticline in relation to a nearby syncline might be crucial. A side-propagating of the Sheikhan anticline in which the forelimb is facing northeast upstream and deflected parallel to the fold axis may be more quickly eroded by the deflected drainage than the back limb. This happens because the forelimb is typically much steeper than the back limb in a fault-propagated asymmetric fold. As a result, streams diverted from the mountains may erode severely into the steeper escarpment, potentially leaving a series of meandering scars across the forelimb. Identifying the process of fold side-propagation is extremely useful in understanding the geomorphic problem of identifying processes that result in stream development transverse to structures such as fold belts (Oberlander, 1985). Transverse streams (i.e., cut across), active folds usually believed to have been superposed across structure by erosion of an overlying cover mass, or to have formed antecedent to the uplift (down cutting of the channel with uplift). Furthermore, it has been proposed that transverse drainage might arise as a result of headward extension of drainage as well as stream erosion caused by local stratigraphy and structural control (Oberlander, 1985).

Recognizing side-propagation of folds allows some relatively short courses of streams crossing a fold to be antecedent, while adjacent, comparatively longer reaches are parallel to fold axes.

A water gap forms as the fold grows. The water gap continues as the fold grows laterally by side-propagation and vertically by uplift if there is sufficient stream power (Jackson et al., 1996).

Although it is a complicated process, (Keller *et al.*, 1999) proposed two reasonable hypotheses to describe the transformation of a water gap into a wind gap: (1): The rising of fold may block the water of the channel and force the river to drift towards topographically low-lying areas, which are often towards the side-progression of the fold. (2): A channel intersection near the fold's nose has a stream on the mountain side of the fold that erodes headward parallel to the fold axis toward the water gap. The drainage feeding the water gap is captured by the drainage extension. The combination of both fluvial and tectonic processes can form a wind gap increasing the diversion and lock of drainage. Therefore, Drainage is set up over an evolving fold belt by modeling a number of captures, diversions, and antecedent positioning of the drainage patterns.

Asymmetric forked tributary networks are effective indicators for the side-propagation because their streams across the top of the fold segment do not follow the steepest current topographic gradient and therefore record earlier topographic stages. A water gap in the southeastern part of the fold indicates development in that direction. The northwestern area of the Sheikhan anticline seems to have more dendritic and deeply incised drainage patterns. As a result, it is more developed river networks when compared to the southeastern part of the anticline, which contains drainage patterns that are linear and have less deeply incised, (Figure 4).

The main objective of quantification of geomorphological feature was to identify side-propagation directions and fold segments that may have combined into sub-cylindrical folds during implication. If folds are amplifying and side-propagating, complicated river patterns develop and can occasionally show the history of side-propagation and vertical development (Burbank and Anderson, 2001). In order to evaluate the development of folds, Keller *et al*. (1999) outline six basic geomorphic criteria: (a) the decrease in drainage density and degree of dissection of the landscape on the fold crest in the direction of folds propagation; (b) the decrease in the dip of the forelimb; (c) the decrease in relief of a topographic profile along the fold crest; (d) the deformation of progressively younger deposits or landforms; (e) the development of distinctive asymmetric drainage patterns; and (f) the existence of several wind gaps with decreasing elevation in the propagation direction. The last three criteria mentioned above are taken into consideration when studying the side-propagation of folds, as they are regarded strong indicators in this field. (Keller *et al.*, 1999; Ramsey *et al.*, 2008).

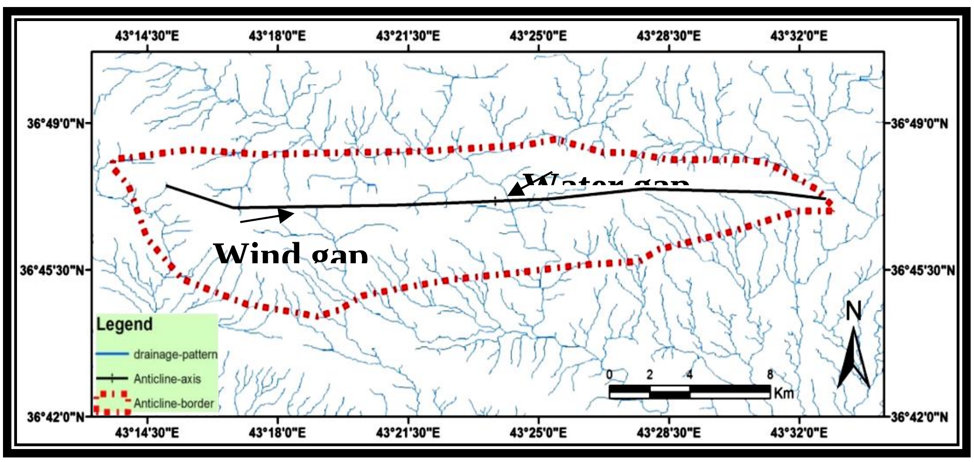

Fig. 4. The relation of water gap/wind gap evolution with topography and drainage pattern.

The decreasing in relief of the long topographic profile will occur along the crest of the fold toward the direction of propagation (Jackson *et al.,* 1996; Keller *et al.,* 1999). When it concerns to the exposed stratigraphy, the younger uplifted parts of the fold typically have less relief than the older uplifted parts. According to Jackson et al. (1996), the elevations of wind gaps, along an anticline, decrease in the direction of propagation and show the direction of fold plunge. Delcaillau et al. (1998) argued that morphometric criteria such as the relief of the topographic profile, the hypsometric integral, the drainage density, the area of the drainage basins, and the longitudinal profiles of streams, show how folds have grown through time. Some of these criteria provide clear evidence of the growth of the Sheikhan anticline, (Figure 5).

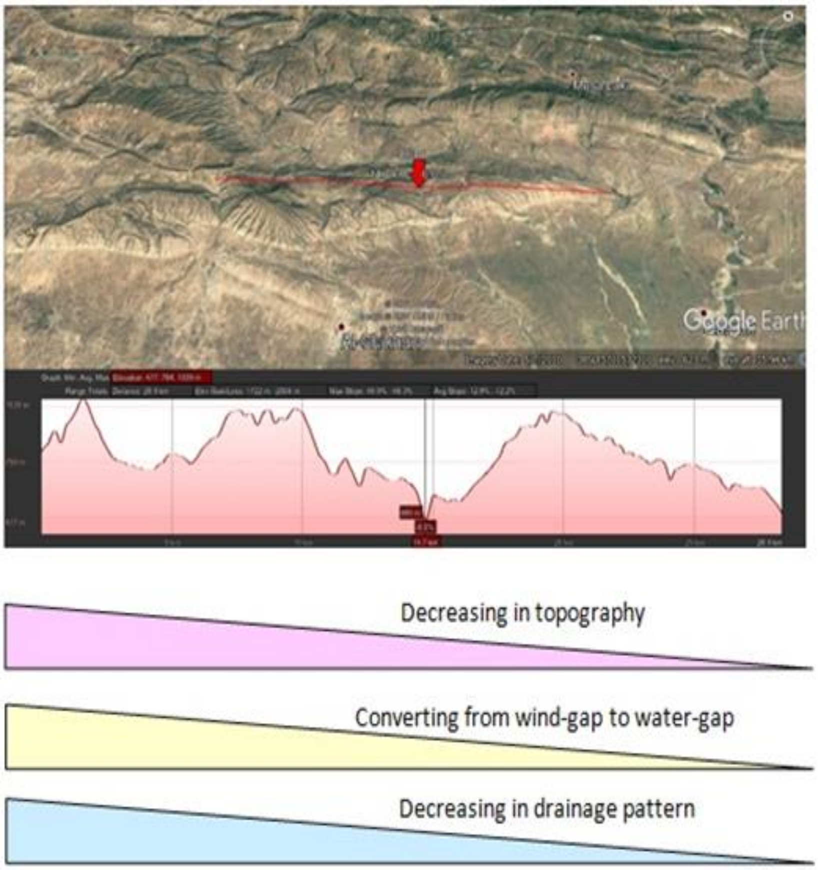

Fig. 5. The relation water gap/wind gap evolution with topography and drainage pattern.

The existence of several wind gaps, in particular, is the greatest indicator for evaluating side-propagation directions. Furthermore, drainage patterns are particularly sensitive to surface slope changes and thus record fold growth and evolution (Jackson et al., 1996). This sensitivity to changes in geomorphology of the fold leads to the development of distinct asymmetric forked tributary patterns that show the direction of fold propagation (Ramsey et al., 2008), (Figure 6).

The flow direction of the channels will always be down the steepest topographic gradient which is perpendicular to the individual contour lines. There is a variation in the architecture of subsequent generations of tributaries when the topographic gradient, parallel to the fold axis decreases during the side-propagation of the fold. As a result, successively older tributaries gradually become closer to be perpendicular to the fold axis, (Figure 6). As a result of the side-propagation of the fold, the tributaries that were parallel to the former fold axis have shifted to be perpendicular to it, while the new tributaries that form later, due to side-propagation, will be parallel to the subsequent fold axis, i.e., the nose of the fold, (Ramsey et al., 2008), (Figure 6 and 10).

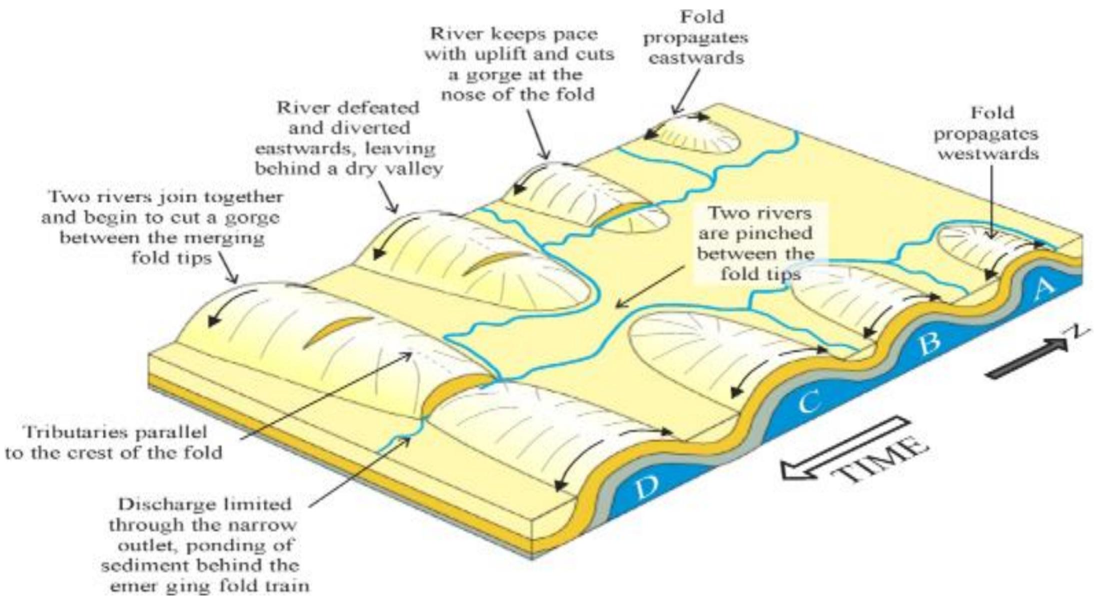

Fig. 6. A cartoon illustration depicts the formation of water and wind gaps by running streams in the side-propagating folds from stages A to D, (Ramsey *et al.,* 2008).

Using only one criterion to detect side-propagation of the fold and progressive fold development is unreliable and can produce inaccurate interpretations. Therefore, it is recommended to use a combination of several geomorphological constraints to distinguish between passive exhumation and active fold development (Burbank and Anderson, 2001).

Response of streams to the growth of the Sheikhan anticline

The existence of the water gap to the east of the wind gap in the Sheikhan anticline, (Figure 7) can be used as indication that the fold has been growing eastward. However, the sharp deviation of the strikes of the layers of the southern limb towards the northwest, which resulted to form a wide plunge area as a result of closing the western fold plunge in the convergence area of three folds (the Dahqan, Prevka, and Sheikhan), allowing the Sheikhan anticline to appear in the form of a triangle tapering to the west.

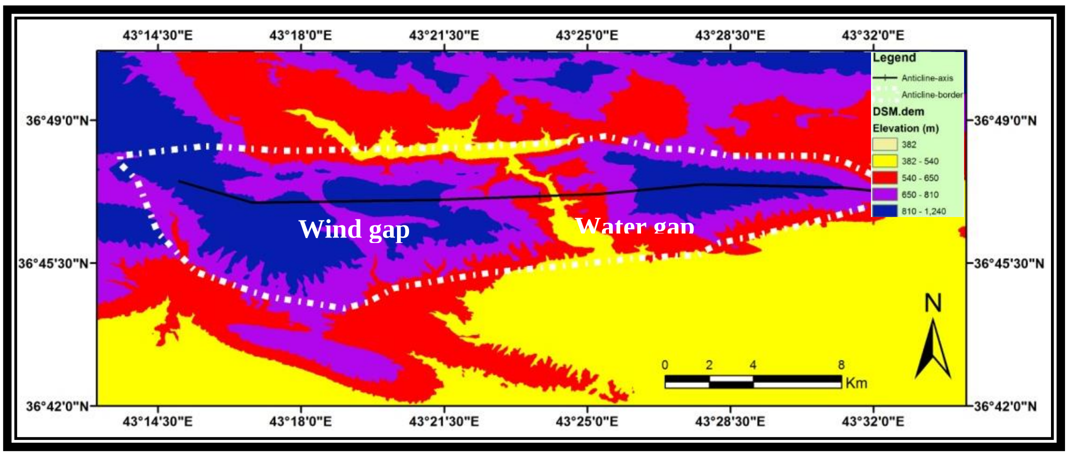

Fig. 7. The topography response to the water gap/wind gap evolution and fold propagation derived from DSM.

The incision activity continuous in the water due to the continuity of Sheikhan anticline folding and increase the possibility of capturing the river. However, the incision has been stopped or decreased on the wind gap, (Figure 8).

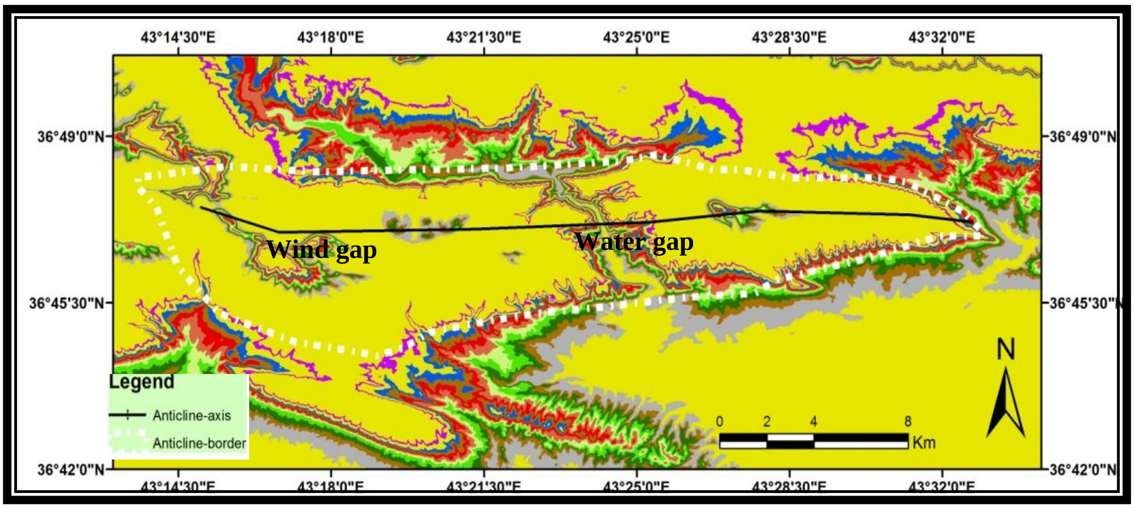

Fig. 8. The morphology detection of active incision in study area derived from DSM.

The eastward growth of the Sheikhan anticline has at least two phases of amplification; as inferred by the evaluation of the drainage pattern and lithology of the stratigraphic sequence. The first stage happened in the western side of the wind gap (Gully Keer) i.e., the growth of the fold is propagating in two directions, but it is blocked from the west due to its restriction in the area where the three folds converge. At the same time, the river to the west was maintaining its course with the uplift i.e., maintaining its course while rising is continues to the nose of the fold, thus digging a valley within the post-Cretaceous Formations such as the friable clastics of Kolosh, Gercus, Pila-Spi, Fat'ha, and Injana Formations. The uplift might not have yet lifted the Cretaceous sequences since the wind-gap course is currently parallel to the exposures of the Bekhma Limestone Formation, (Figure 9). The drainage patterns on the back-limb to the west of the wind gap (Gully Keer) are subparallel to the fold hinge with asymmetric forked tributaries, while the drainage valleys to the west, are perpendicular to the fold hinge, with fewer asymmetric forked tributaries, (Figure 10). According to Jackson et al. (1996), the drainage pattern parallel to an anticline is diverted in the direction of side-propagation. This stage corresponds to stage B in Ramsey *et al.*, 2008, (Figure 5). The second stage is to increasing uplift of the fold leads to exposing the impact rocks of the Bekhme Formation, which is followed by a decrease in the ability of the river to deepen in rocks, and then retreating to the east, leaving dry valley behind it parallel to steeper forelimb to form a new water gap in the low-lying areas around the plunge area. The present shape of this valley (Gully-Keer) was formed as a result of erosion factors and climate.

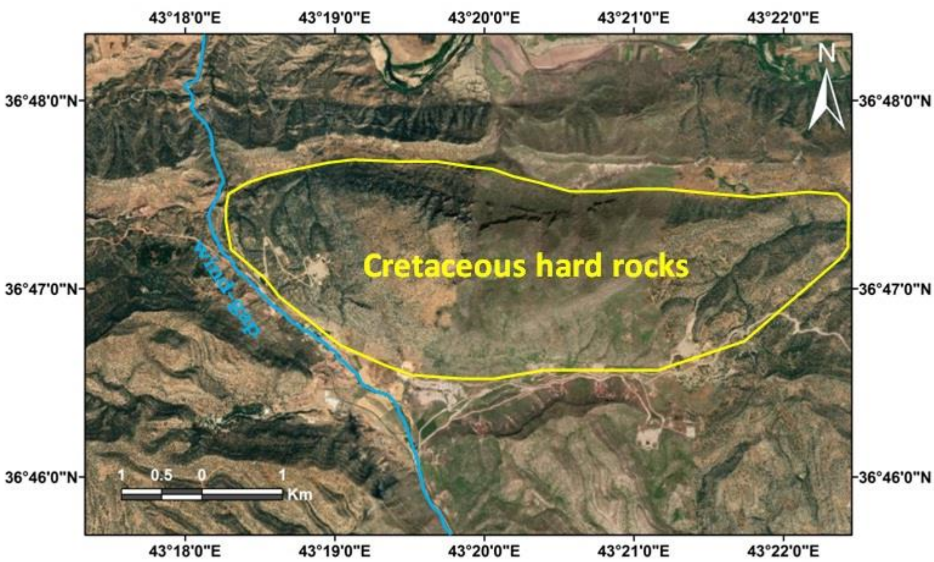

Fig. 9. The wind-gap course is currently parallel to the exposures of the Bekhme Limestone Formation in Gully Keer.

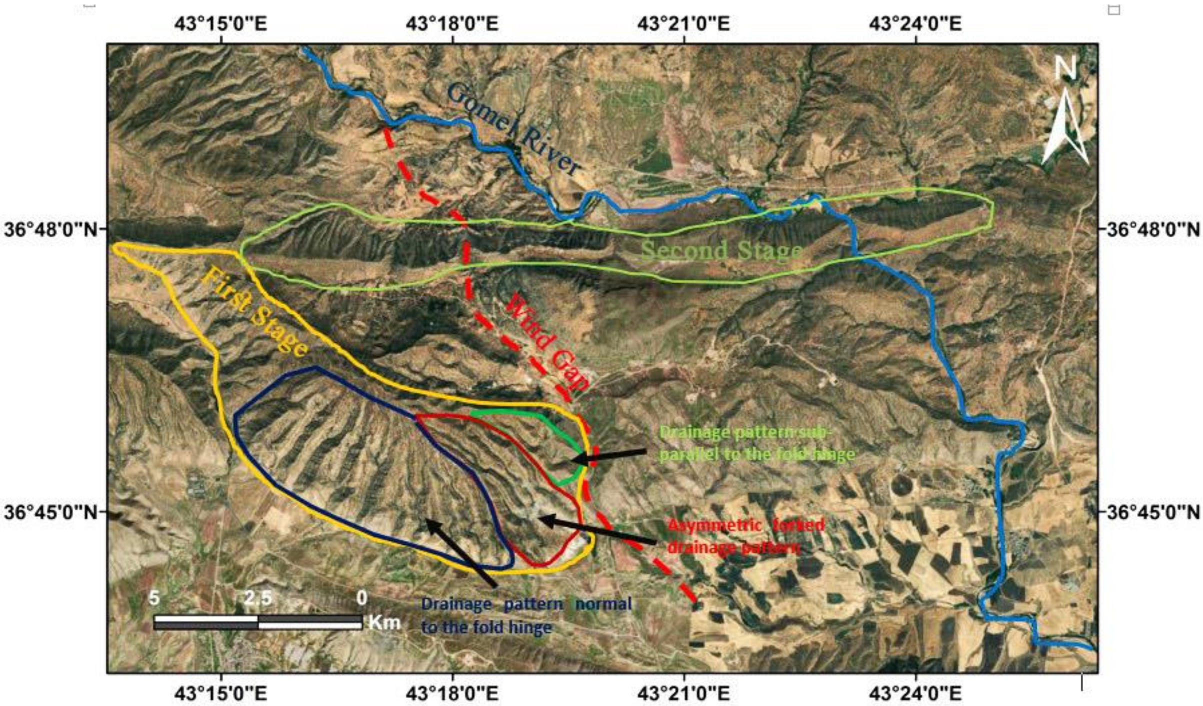

Fig. 10. First and second stage of the Sheikhan anticline

The first water gap was strengthened by a flooded tributary from the east side, (Figure 10), increasing the ability of the Gomel River to incision. The Gomel River is located in the northeast of the Sheikhan district. Its length is about 60 km and flows towards the south until it meets with the Khazer River. As the fold continued to advance towards the east, another water gap emerged around the fold nose. It is important to note that the water gap of the Gomel River won’t develop into a wind gap due to the presence of a high area (pop-up) in the north limb, (Figure 11), (red ellipse) resulting from Firstly, due to the squeezing caused by approaching with Atrosh Anticline. Secondly, the layers will open up in the opposite direction of the plunge of the syncline between the two anticlines. The opposite direction of the drainage pattern is printed across this pop-up.

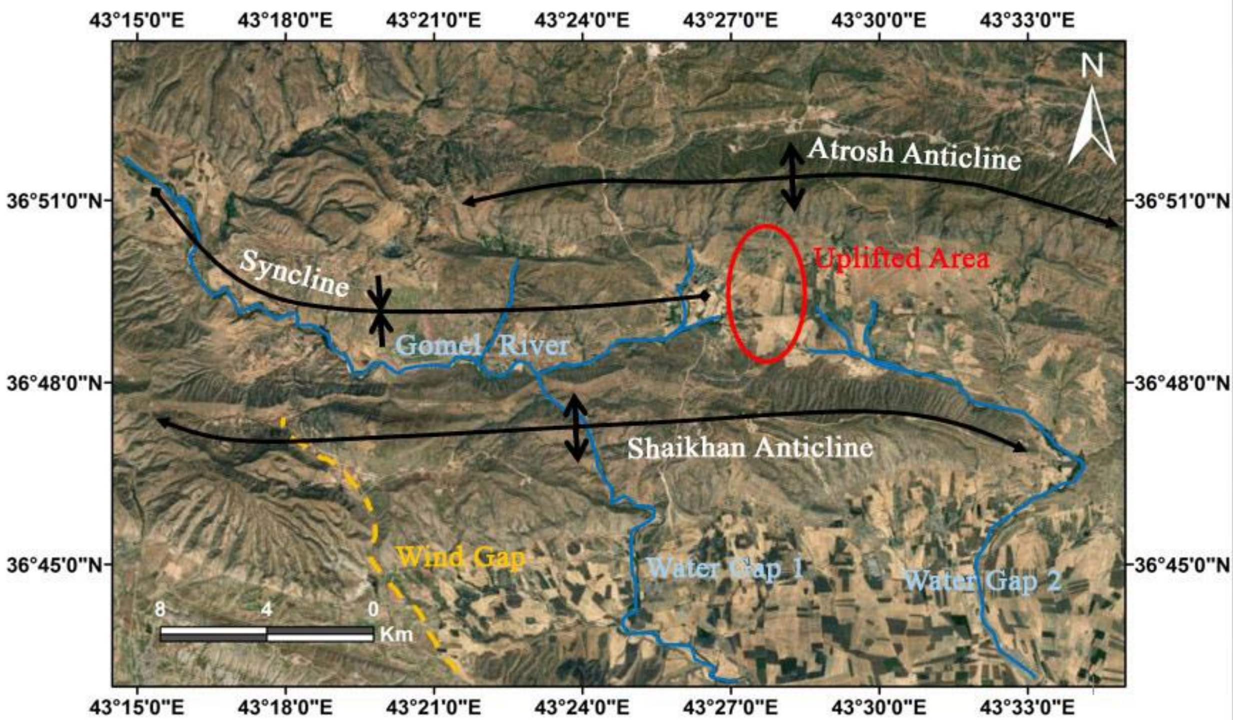

Fig. 11. The first water gap (Komel River) was strengthened by a flooded tributary from the east side, increasing the ability of the incision. The red ellipse refers to the uplifted area.

On the other hand, River terraces are important geomorphic markers that signify how a water gap became a wind gap and the former position of a paleo stream. These were detected in the Gully Keer (wind gap) on the limestone of the Pila Spi Formation, (Figure 12), and a mild tilting was observed on it because it was affected by later stages of fold growth.

Lateral propagation at Skaikhan anticline is accompanied by the evolution of tear faults diagnosed by Awdal *et al.* (2016), (Figure 13), which are steeply dipping faults that strike nearly perpendicular to the buried reverse fault system that formed the fold, creating fault segment boundaries. Subsurface data processing at the Sheikhan anticline, Awdal *et al.* (2016) emphasize that the position of the main wind gap (Gully Keer) and water gap (Gomel River) coincide with a tear fault that formed a scarp facing the direction of side- propagation. This is actively helping in the determination of stream locations at the bases of these scarps where they cross the fold.

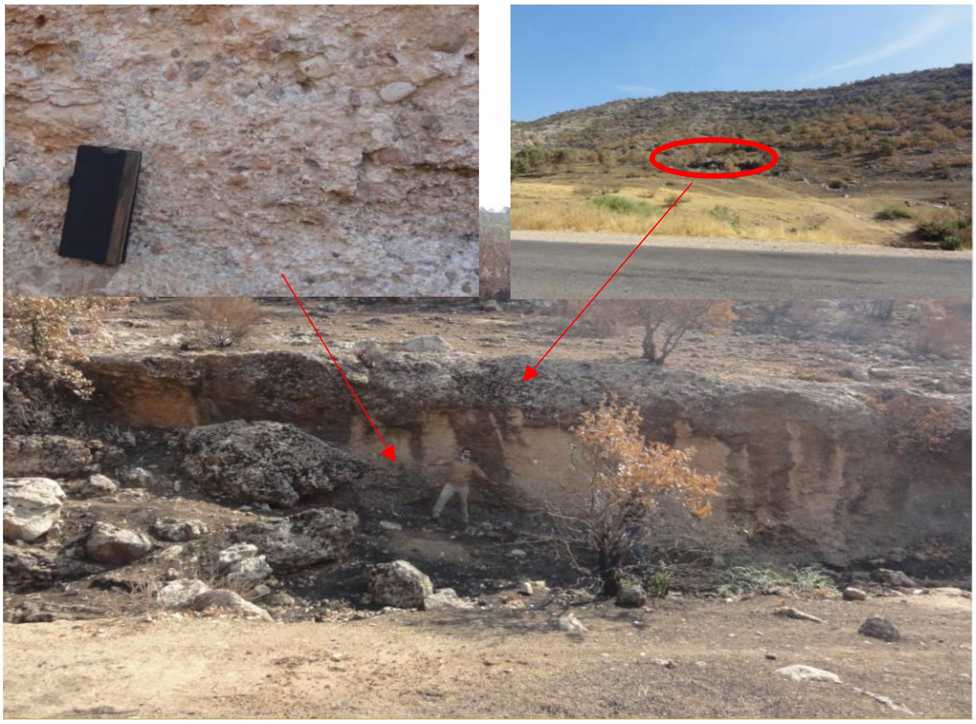

Fig. 12. River terraces with mild tilting in the Gully Keer (wind gap) on the limestone of the Pila Spi Formation.

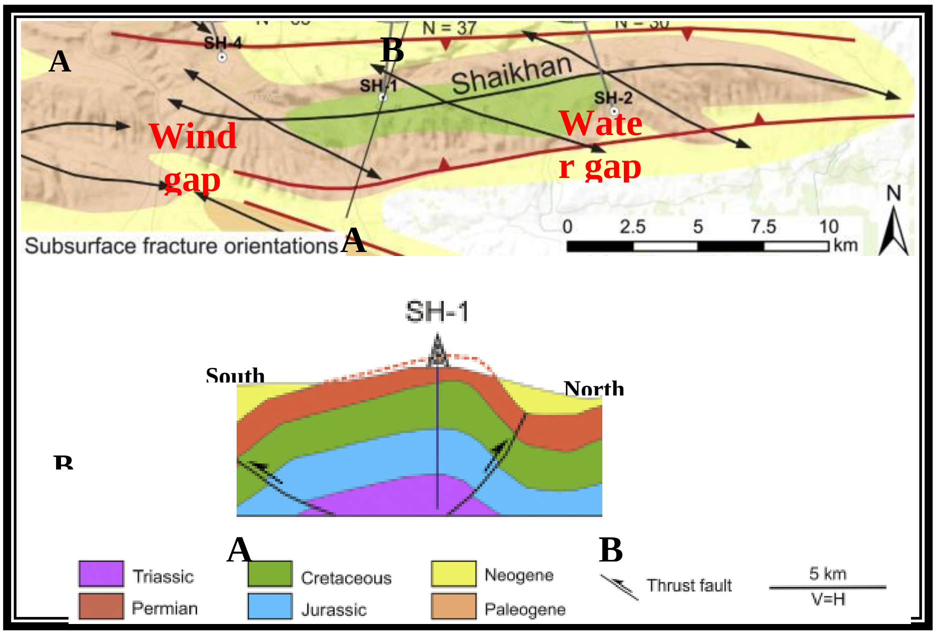

Fig. 13. (A) A simplified geological map; (B) Schematic regional cross-section across the Sheikhan anticline s, Awdal *et al.* (2016).

Conclusion

Many geomorphological features, including the existence of water and wind gaps, abandoned alluvial fans, cross-shaped valleys, radial valleys, axial valleys, and fork-shaped valleys, suggest that the Sheikhan anticline is experiencing side-propagation to the east.

The analysis of the current study reached the following conclusions:

1. The propagation of the fold in the Sheikhan anticline is towards the east, depending on the change in the stage of the wind gap.

2. The Sheikhan anticline is divided into two stages, each marked by the existence of two domes: one to the west of the wind gap (Gully Keer), and the other to the east. This was geomorphologically reflected in the studied area by the occurrence of two stages of the tectonic uplift. The first stage occurred on the southern limb of the anticline in the southwestern part, while the second stage occurred along the northern limb of the anticline.

3. On the fold crest, the drainage density and intensity of landscape dissection decreased towards the side- propagation of the fold.

4. The presence of the topographic uplift (Pop-up), which is located east of the first water gap and north of the Sheikhan anticline, prevents the first water gap from developing to the east. As a result, if the fold growth is faster than the river's incision, a pond will form.

5. The existence of river terraces in the southern part of the wind gap (Gully Keer) indicates that it was previously a water gap, confirming the side eastward propagation of the Sheikhan anticline.

6. Due to the prevalence of the uplifted area east of the river on the northern limb of the Sheikhan anticline the water gap (the Gomel River) will not be turned into a wind gap in the future, whether the river's ability to incision will not be faster than the side-growth of the anticline. Eventually, the river flows into a pond in the area.

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