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Morphotectonic Features of Some Geological Structures - Northern Iraq

Alaa N. Hamdon[1], Hadeer Gh. M. Adeeb[2*], Rabeea Kh. Znad[3], Mohammad F.O. Khattab[4]

[1] *Remote Sensing Center, University of Mosul, Mosul, Iraq, alaa.hamdon@uomosul.edu.iq*
[2] * *Dams and Water Resources Research Center, University of Mosul, Mosul, Iraq, hadeeradeeb@uomosul.edu.iq*
[3] *Department of Geology and Petroleum, College of Science, University of Mosul, Mosul, Iraq, rabeeazinad@uomosul.edu.iq*
[4] *Remote Sensing Center, University of Mosul, Mosul, Iraq, mohamed76@uomosul.edu.iq*

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Correspondence:
Hadeer Gh. M. Adeeb
hadeeradeeb@uomosul.edu.iq

ABSTRACT

The study sites are located in the governorates of Nineveh and Kirkuk in northern Iraq, which are of great tectonic importance. Geospatial data, which serve as complementary information to illustrate active tectonics and morphotectonic schemes on a thematic map, enhance geological studies, including the current study, as the morphotectonic features of the study area have previously been interpreted using traditional methods. Remote sensing data such as satellite data, digital elevation modeling, and GIS techniques such as ArcMap were used to analyze, identify, and interpret geological and morphotectonic land features to demonstrate the effects of active tectonics on terrain, including identifying strike-slip faults, the effects of thrust faults in moulding fold shape, interpreting the drainage pattern response to new tectonic activity, as well as the tectonic uplift deformation.

The results of the study consisted of the interpretation of three main morphotectonic locations in terms of terrain response to active tectonic deformation: namely, firstly, the Baashiqa anticline, affected by two opposite fault systems; secondly, the Al-Qayyarah area, which represents a tectonic uplift that has laterally grown eastward; and thirdly, the Bai-Hasan anticline, which is affected by a sinistral strike-slip fault. All of these indicate that there is local intense deformation and emerging tectonic activity in the low-folded zone, despite its distance from the collision zone.

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الخصائص المورفوتكتونية لبعض التراكيب الجيولوجية – شمالي العراق

علاء نبيل حمدون[1] هدير غازي محمد أديب[2*] ربيع خلف زناد[3] محمد فوزي عمر خطاب[4]

[1] مركز التحسس النائي، جامعة الموصل، الموصل، العراق alaa.hamdon@uomosul.edu.iq

[2*] مركز بحوث السدود والموارد المائية، جامعة الموصل، الموصل، العراق، hadeeradeeb@uomosul.edu.iq

[3] قسم علوم الأرض والنفط، كلية العلوم، جامعة الموصل، الموصل، العراق، rabeeazinad@uomosul.edu.iq

[4] مركز التحسس النائي، جامعة الموصل، الموصل، العراق، mohamed76@uomosul.edu.iq

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المراسلة:

هدير غازي محمد أديب

hadeeradeeb@uomosul.edu.iq

الملخص

تقع مواقع الدراسة في محافظتي نينوى وكركوك شمالي العراق، واللتان تعدّان ذات أهمية جيولوجية كبيرة من الناحية التكتونية. تعمل البيانات الجغرافية المكانية، وهي معلومات تكميلية لتوضيح التكتونيات النشطة والمخططات المورفوتكتونية على خريطة موضوعية، تعمل على تعزيز الدراسات الجيولوجية ومن ضمنها الدراسة الحالية، اذ تم تفسير المظاهر المورفوتكتونية سابقاً لمواقع منطقة الدراسة بطرق تقليدية. استخدمت بيانات التحسس النائي مثل البيانات الفضائية ونموذج الارتفاع الرقمي وتقنيات نظم المعلومات الجغرافية مثل ArcMap لتحليل وتحديد المعالم الأرضية الجيولوجية والمورفوتكتونية وتفسيرها لإظهار آثار التكتونيات النشطة على التضاريس، بما في ذلك تحديد صدوع الانزلاق المضربي، وتأثيرات الصدوع الزاحفة في قولبة شكل الطية، وتفسير استجابة نمط التصريف المائي للنشاط التكتوني الحديث، وكذلك تشوه النهوض التكتوني.

تمثلت نتائج الدراسة بتفسير ثلاثة مواقع رئيسية مورفوتكتونياً من ناحية استجابة التضاريس للتشوه التكتوني النشط وهي: أولاً، طية بعشيقة المحدبة، المتأثرة بنظامين من الصدوع المتقابلة. ثانياً، منطقة القيارة التي تمثل النهوض التكتوني الذي يمتد جانبياً نحو الشرق. وثالثاً، طية باي–حسن المحدبة المتأثرة بصدع انزلاقي مضربي يساري. وكل هذا يشير الى أن هناك تشوه موقعي وتكتونية ناشئة في نطاق الطيات الواطئة رغم بعده عن نطاق التصادم.

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Introduction

Morphotectonic analyses supported by geospatial techniques, have become a powerful and cost-effective method for investigating active tectonics in these areas. This approach quantitatively links morphology to the underlying tectonic processes. By deriving geomorphic features from Digital Elevation Models (DEMs) and satellite imagery, researchers can evaluate relative tectonic activity, identify active structures, and reconstruct evolutionary histories without depending solely on limited seismic or subsurface data (Abdullah et al., 2023; Othman and Omar, 2023). Morphotectonics is a vital link between internal tectonic processes and surface geomorphological features. Landscapes act as a "natural record" of recent structural movements in the Earth's crust (Keller & Pinter, 2002). These studies are especially significant in tectonically active regions, where landforms rapidly respond to

structural changes. The northern regions of Iraq and the surrounding areas are considered crucial parts of the Arabian Plate due to their unique location at the collisional boundary with the Eurasian Plate and ongoing tectonic activity (Abou Karaki, 1993). Therefore, this study aims to investigate morphotectonic evidence of ongoing tectonic activity in selected areas of northern Iraq. It seeks to evaluate how these tectonic processes shape local landforms, with a particular focus on identifying the geomorphic features that are most affected by active tectonics.

Additionally, many anticlines in the area exhibit low relief (Al-Abaadie, 2012). The uplift extends northwest-southeast, aligning with the regional folding style. Research conducted by Sissakian (2013) and Yousif and Dawood (2016) indicates ongoing tectonic activity near the study area. Additionally, the influence of faults is crucial in shaping geomorphological processes. Faults act as structural weaknesses that influence valley alignment and create various topographic features (Bull, 2007). The processes of faulting and fold growth are closely interconnected; folds often form over blind thrust faults or may be interrupted by transverse faults. This interaction disrupts the fold's symmetrical shape and alters the slope patterns of its forelimbs and backlimbs. Consequently, this change affects the distribution of drainage density and the lengths of valleys along the fold limbs. River systems are vulnerable to alterations in ground tilt and tectonic uplift. Changes in the slope of the landscape can significantly affect a river's flow patterns and direction. Parallel or pinnate drainage patterns often indicate regional tilting or are influenced by longitudinal faults.

In contrast, radial drainage patterns suggest the presence of tectonic domes or developing subsurface folds (Burbank & Anderson, 2011). Lateral fold growth creates dynamic topographic barriers that directly influence river paths. For example, when the Sheikhan anticline in the Zagros fold and thrust belt expands horizontally from northwest to southeast, rivers are compelled to divert around its ends, or noses. This process leads to river diversion and the formation of unique features, such as "curved rivers" and water gaps. Over time, if the rate of tectonic uplift exceeds the river's ability to incise vertically, these water gaps can evolve into wind gaps (Znad et al., 2025).

Location of the Study Area and Geological Setting:

The study area lies within the western Zagros fold and thrust belt, Iraqi segment (Le Garzic et al., 2019), and, according to the tectonic division of Iraq (Jassim& Goff, 2006), is located within the Foot Hill Zone of the unstable shelf. Three areas within the Western Zagros Fold-Thrust Belt were selected to highlight the current landforms shaped by tectonic activity, because the geological landforms in those areas represent significant sites in Low Folded Zone. These locations include: (1) the Al-Fadhliyah anticline north of Mosul, (2) the Al-Qayyarah area south of Mosul, and (3) the Bai Hasan strike-slip fault in the western part of Kirkuk (Figure 1). The various directions or extensions can distinguish the anticlines of this zone according to the parallel of the Taurus and Zagros belts. This region is considered a stress-accumulation area because it lies within the Arabian Plate indenter (Mantovani et al., 2006), which indents the Eurasian Plate. Due to the continuous anticlockwise rotational movement of the Arabian Plate toward the northwest as a result of opening the Red Sea and Gulf of Aden (Sharland et al., 2001), much of the compressional stress has been accumulated. As stress is gradually released, various types of morphological landforms are forming in the region. The presence of faults (normal, reverse, and strike-slip) has played a significant role in releasing accumulated stress by reactivating inherited (ancient) faults (Numan and Al-Azzawi, 1993) or by forming new faults in this zone. Recent studies suggest that the spread of various fault types is primarily confined to this zone. However, the lithology of the selected areas in

the region varies little from one area to another, depending on the exposed formations in each area (Figure 2).

The formations exposed in the study area include the Injana formation (Late Miocene) and Fat'ha formation (Middle Miocene), which are prominently exposed in the Qayyarah area. The Pila Spi Formation (Middle–Upper Eocene) constitutes the main body of the Al-Fadhliyah anticline. In addition, the formations of Bai Hasan, Muqdadiya, Injana, and Fat'ha are exposed in the Bai Hasan anticline.

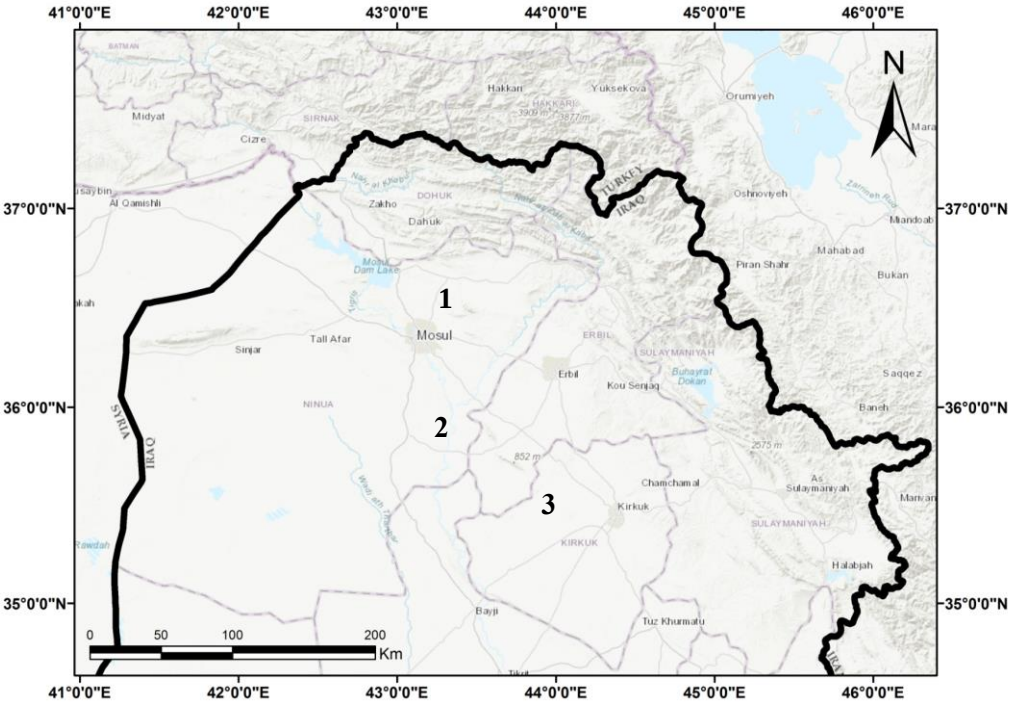


Fig. 1. Location map of the selected areas (1,2,3) for study.

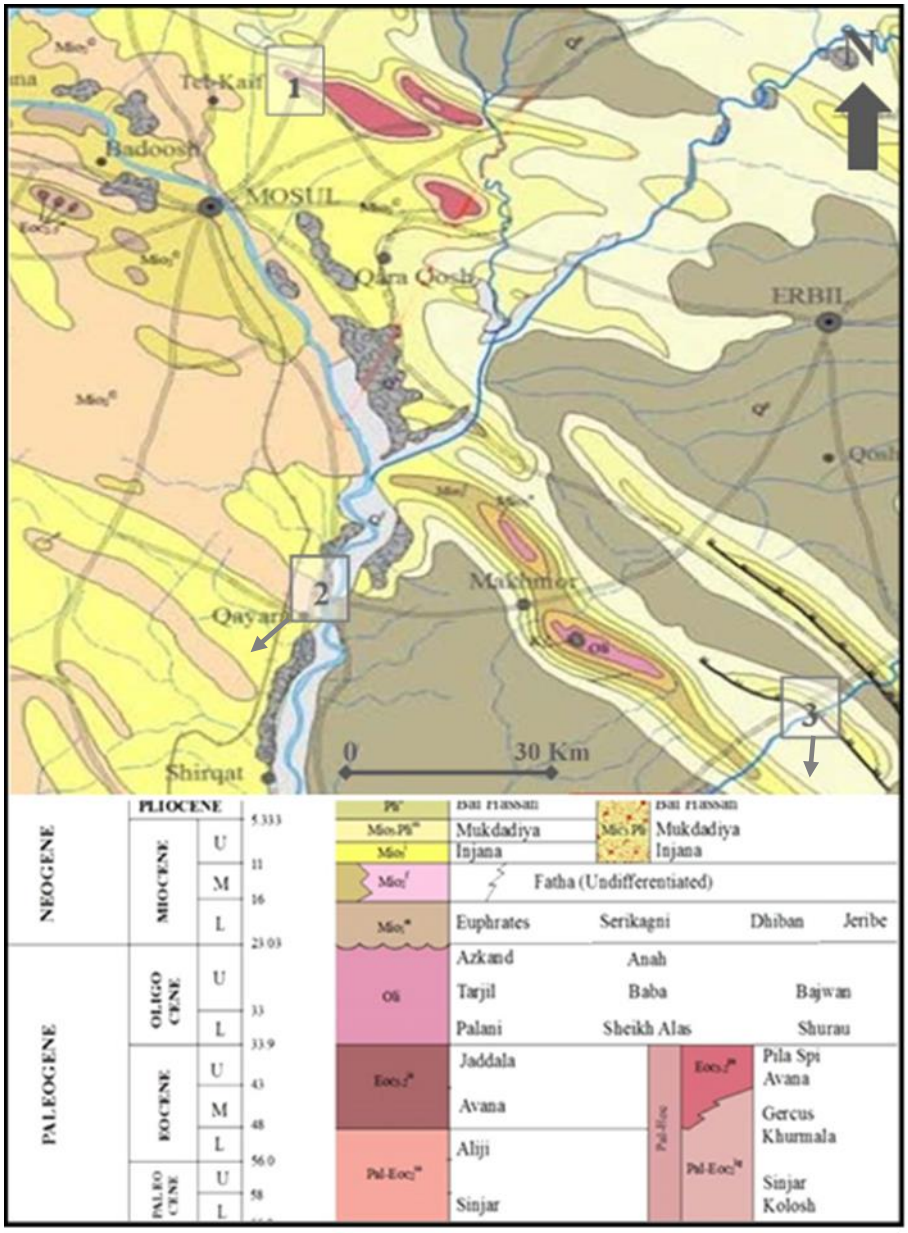


Fig. 2. Geological map of the study area, (After Sissakian et al. 2014). 1= Al-Fadhliyah Anticline, 2= Al-Qayyarah Area. 3= Bai Hasan Anticline.

Materials and Methods

Landforms were analyzed visually and spatially using a range of remote-sensing data to illustrate morphotectonic interpretations. The dataset consisted of:

- Satellite imagery, high-resolution satellite imagery, has been used to recognize the most essential morphotectonic features, such as deformation in anticline ridges, to conclude on the morphotectonic process.
- Digital elevation models (DEMs) with resolution of 12 meters, were utilized as an essential element to the interpretation process, which involves a detailed visual examination of spatial data, and drainage pattern interpretations to assess the effect of tectonic factors on landforms.

- Field-based photographs, with a focus on identifying key geomorphological indicators. These combined lines of evidence formed the basis for deriving reliable morphotectonic interpretations.
- Spatial techniques have been used to draw profile sections using Google Earth Pro and Global Mapper, illustrating the significant shape of the uplifts through the structures.

The methodology of this study is illustrated in the flowchart shown below (Figure 3).

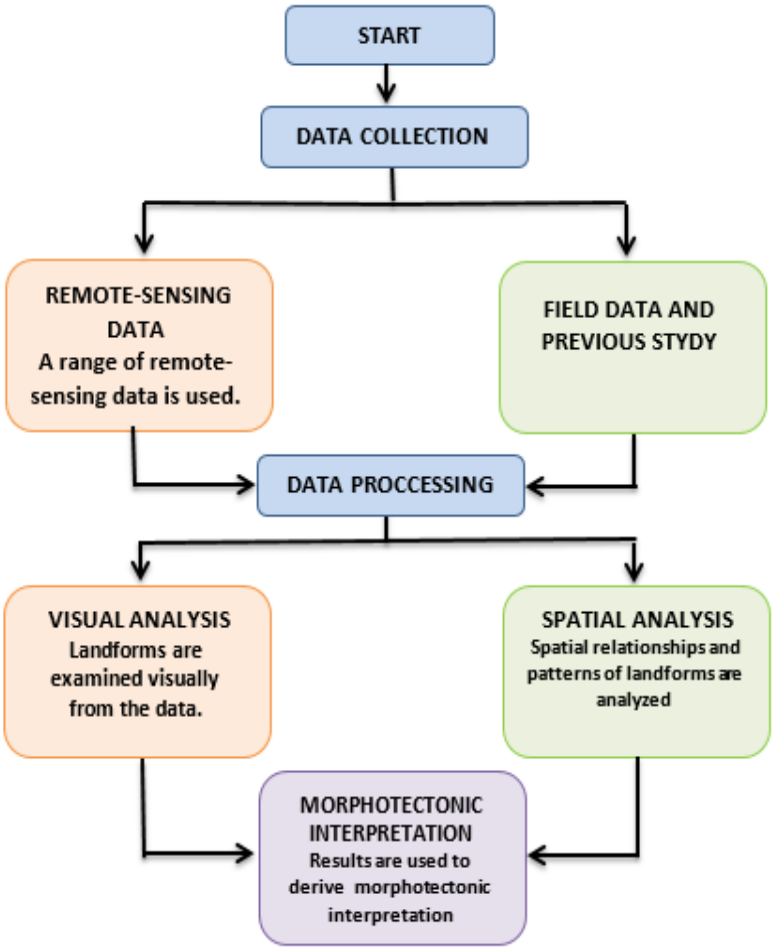


Fig. 3. Flowchart of the methodology.

Results and Discussion

Morphotectonic Features of Study Areas

Al-Fadhliyah Anticline: The anticline extending about 10 km northwest-southeast follows Zagros fold belt trends, with a northwestern plunge at Nawaran spring and a southeastern plunge at Kanona village (Figure 4).

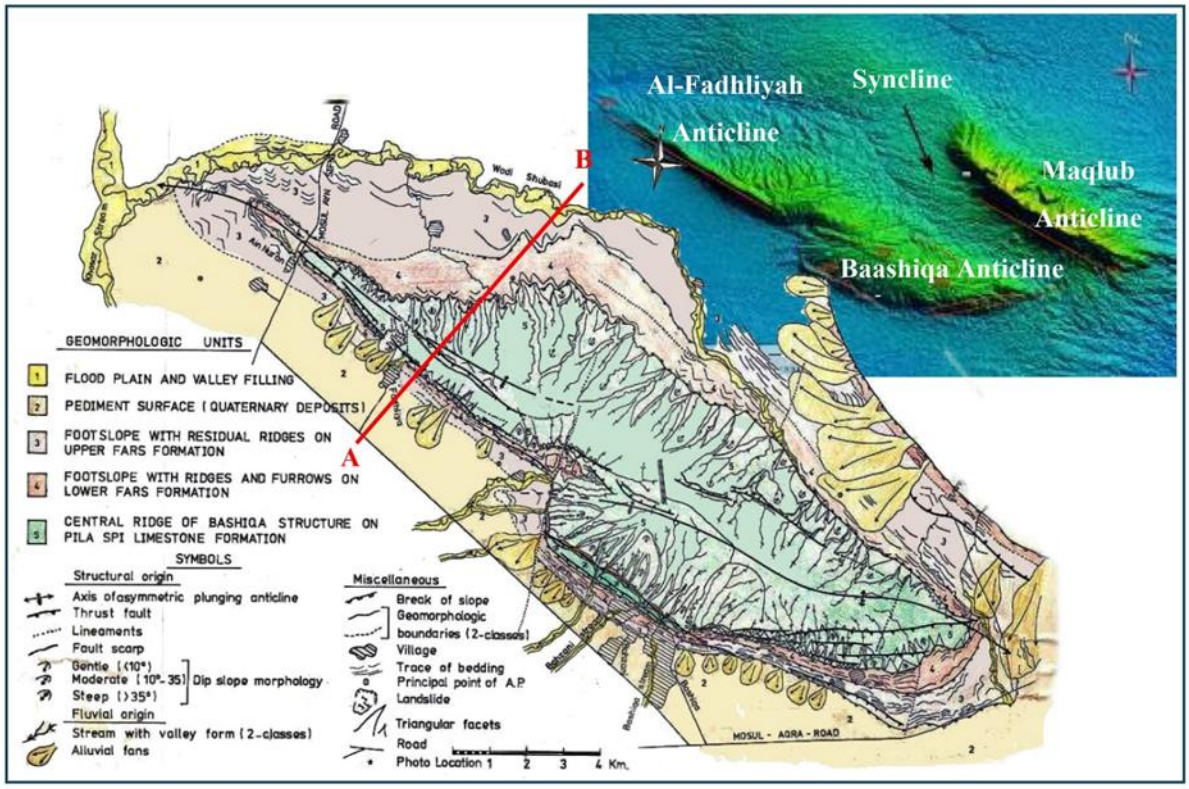


Fig. 4. Tectonic geomorphic map of Baashiqa and Al-Fadhliyah anticlines (modified from Salih & Al-Daghastani, 1993).

The Al-Fadhliyah anticline is broadly asymmetric, with two hinge lines (Al-Jumaily and Al-Azzawi, 2018), giving it a semi-boxy appearance in cross-section (Figure 5). It has steep slope on the southwestern limb and a gentle slope on the northeastern limb, with an almost broad hinge zone (Al-Azzawi, 1982; Hamdon, 2020). Geological formations exposed on the Al-Fadhliyah anticline include the Pila Spi (the core of the anticline), Fat'ha, and Injana formations.

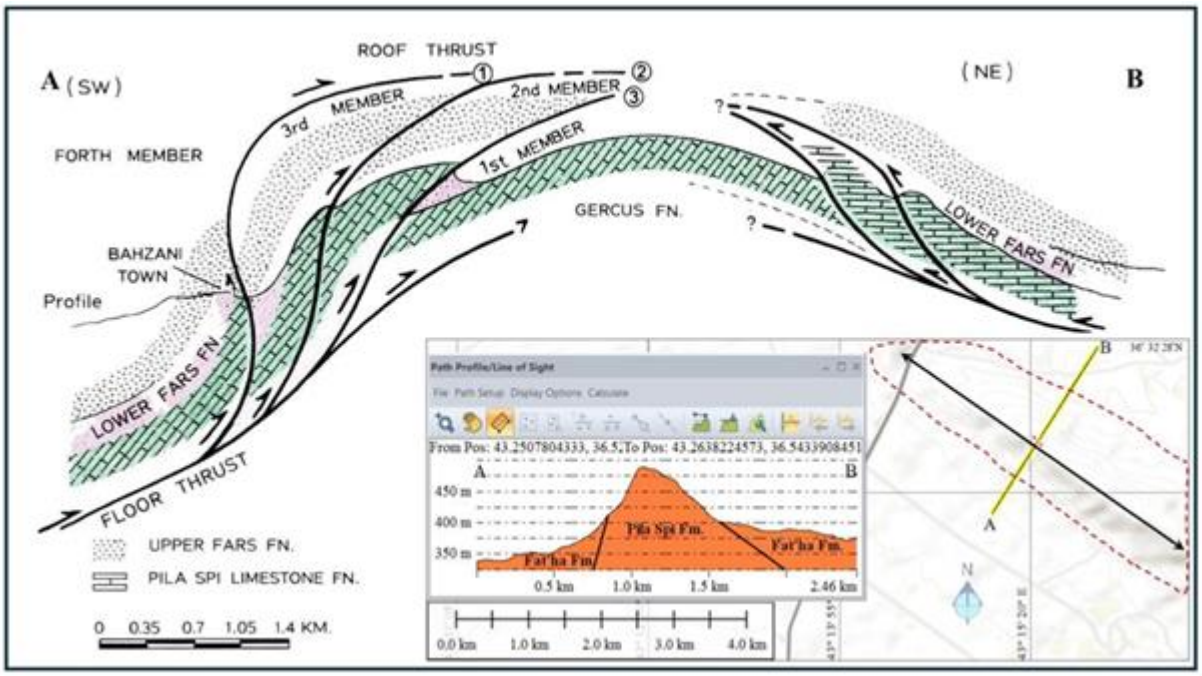


Fig. 5. The generalized cross-section A-B, throughout the Al-Fadhliyah Anticline, illustrates a duplex system with a piggy back sequence and indicates the sense of movement. Thrust No. 1 is the oldest, and Thrust No. 3 is the youngest. (Modified from Salih & Al-Daghastani, 1993).

Two imbricate thrust fault systems have been identified in the Al-Fadhliyah anticline, which help to define the overall shape of the structure. According to Kent (2010), these imbricate thrust faults originate from detachments in the Gercus Formation and can be found in both the southwestern and northeastern limbs of the anticline. The effect of these faults manifests in the following way:

- The southwestern fault (Figure 4) extends along the southwestern limb of the anticline. According to Salih & Al-Daghastani (1993), it is classified as a thrust system exhibiting a duplex structure with a piggyback sequence (Figure 5). Additionally, there is a fault-related fold (Figure 6) located at the northwestern plunge of the fold, which may indicate the extension of these thrust fault systems.
- The northeastern fault (Figure 4) extends along the northeastern limb of the anticline. However, the displacements observed on the surface faults are likely small compared to the deeper displacements required to create the relief of the fold itself.

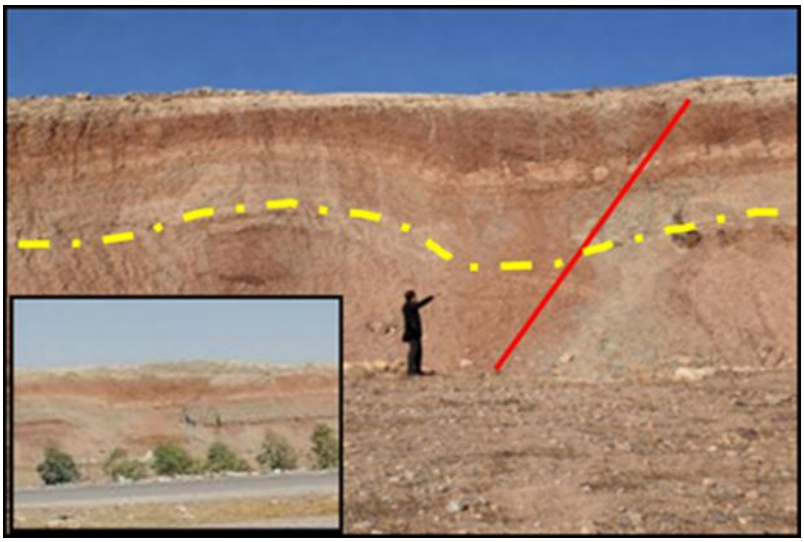


Fig. 6. Fault-related fold at the northwestern plunge of Al-Fadhliyah anticline.

The anticline exhibits a degree of asymmetry, and its drainage patterns reflect this as well (Figure 7). The drainage divide extends near the southwestern limb (steep slope), where a simple system of closely spaced streams flows perpendicular to both the divide and the structural contours. In contrast, longer streams emerge along the northeastern limb (gentle slope) and drain the entire hinge zone eastward toward the drainage divide. Adjacent to the study area, such as the Ain Sifni anticline, exhibits a contrasting drainage geometry. The drainage paterns are completely reversed in configuration at the southwestern and northeastern limbs of this anticline, which are characterized by gentle and steep slopes, respectively (Hamdoon et al., 2021).

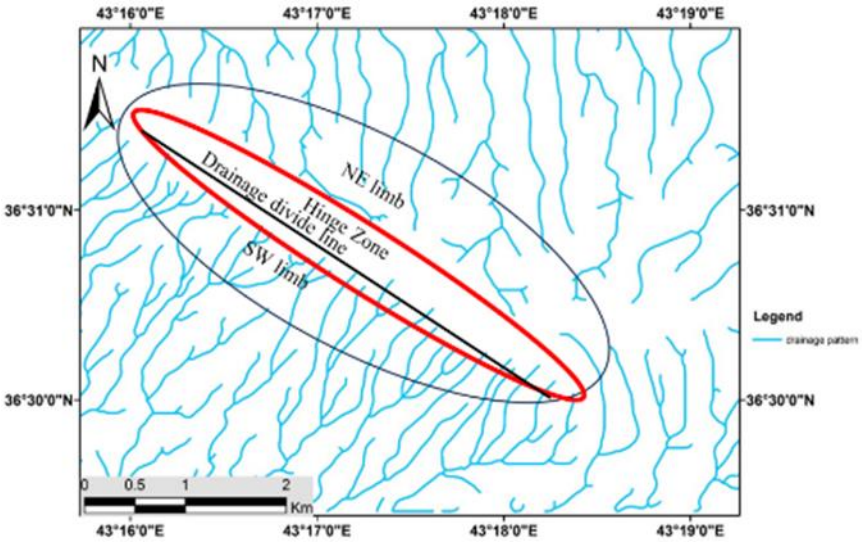


Fig. 7. Drainage pattern map of Al-Fadhliyah Anticline (Note the Pattern difference between the two limbs).

These streams have cut long valleys through the central flat part of the anticline. The drainage systems of the Al-Fadhliyah anticline suggest that the current shape of the anticline evolved from an originally asymmetric fold that established the drainage divide along the southwestern limb. Subsequently, the northeastern limb was elevated and slightly tilted, causing streams draining to the northwest to cut down and form ravines. These longer streams, with larger catchment areas and greater erosive power, have resulted in a more complex pattern of captured streams in the central part of the anticline, northwest of the drainage divide. Additionally, a well-developed radial drainage pattern is evident around the northwestern plunge of the anticline (Figure 8).

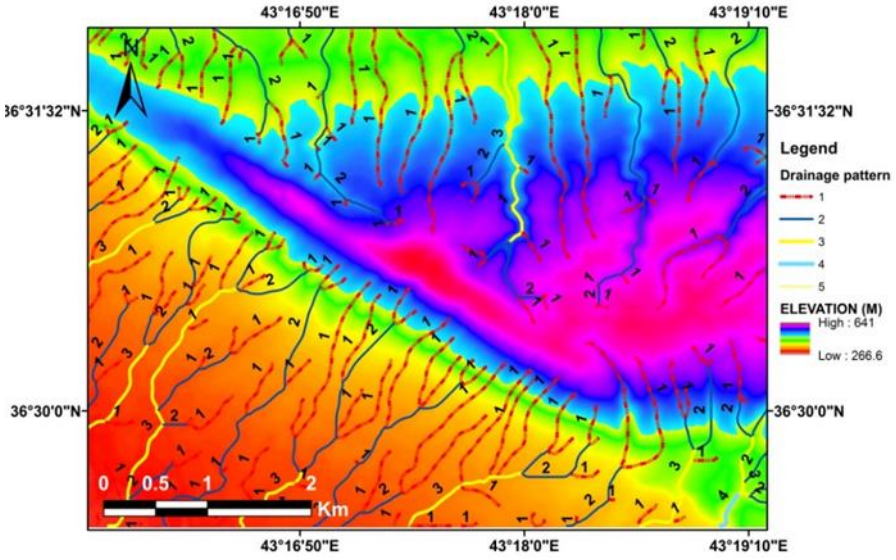


Fig. 8. The orders of drainage systems in the Al-Fadhliyah anticline, where the structure controls the drainage systems

The drainage pattern is influenced by a duplex thrust fault system located along the southwestern limb of the anticline, followed by another duplex thrust fault system along the northeastern limb (Figure 9).

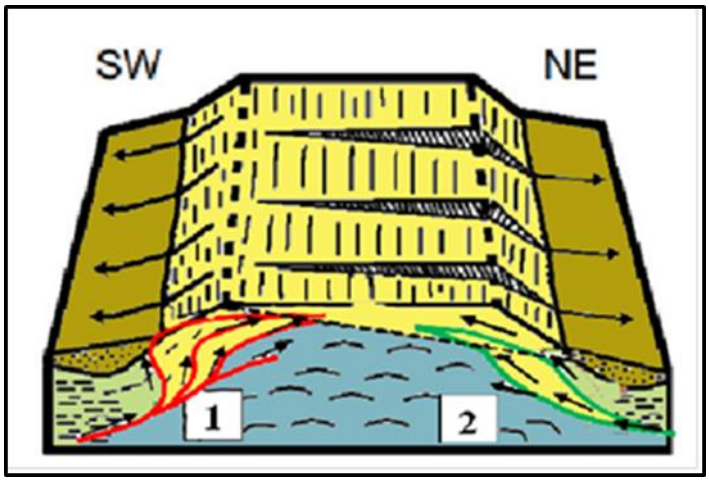


Fig. 9. Sketch diagram showing the relationship of the Al-Fadhliyah anticline to the drainage systems, including early faults (1) (Red color), that produced an asymmetric fold profile (dashed line) which was later steepened by second faults (2) (Green color), (modified from Jackson et al.,1996).

The drainage patterns in Figures (8) and (9) indicate how a simple asymmetric fold can evolve into a larger box fold, similar to the Al-Fadhliyah anticline. It occurs through the development of a later thrust duplex system in the hanging wall of the initial fault. In our case, the uplifted fold comprises a uniform lithology, with the Pila Spi Formation (limestone) occupying the central part. It is difficult to ascertain that this information could be obtained in any way other than from the drainage pattern (Jackson et al.,1996).

Al-Qayyarah Area: The active tectonic uplift in the Al-Qayyarah area has been identified through visual interpretation of satellite imagery. This analysis indicates that the area south of Al-Qayyarah exhibits a topographic elevation that may be the result of tectonic activity, based on the following criteria:

- The topographic elevation in the area is approximately 210 meters above sea level, as shown in the topographical cross-section (Figure 10). Additionally, this elevation is situated within a synclinal fold between two anticlinal folds—one to the north and one to the south. This unique geological structure has raised interest in the potential for tectonic activity in the region.

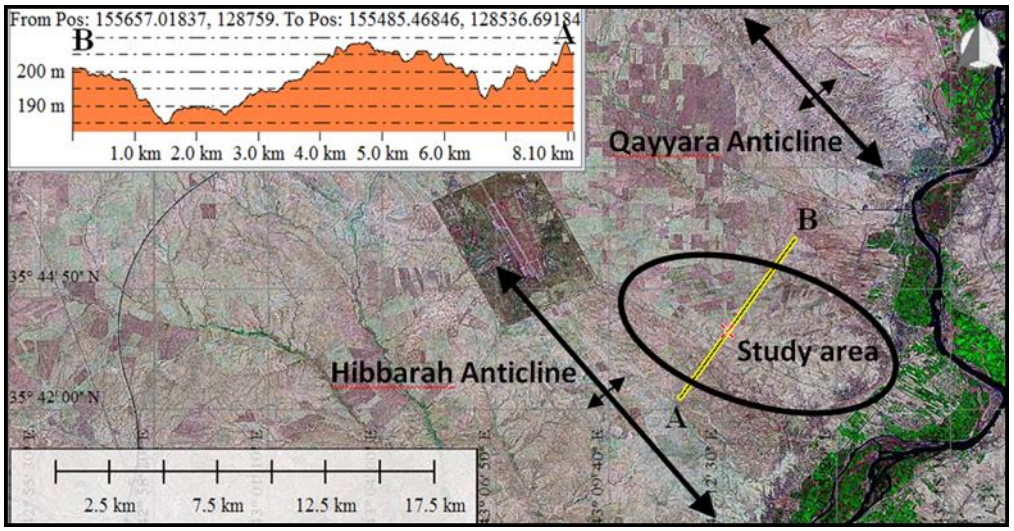


Fig. 10. Topographic section of the elevation located south of Al-Qayyarah anticline.

- Two basins parallel to the drainage pattern of this elevation indicate that an elevation may have formed during or before the development of the drainage pattern, causing the valleys of this pattern to flow in this manner (Keller & Pinter, 2002) (Figure 11).
- Changing the direction of the Tigris River course towards the east may indicate the presence of successive tectonic activity in the form of a tectonic elevation that pushes the direction of the river course towards the east, in addition to that, the observation of the successive development of river beds on the western bank of the river, which supports the hypothesis of migration (propagation) of the river course towards the east (Keller & Pinter, 2002) (Figure 11).

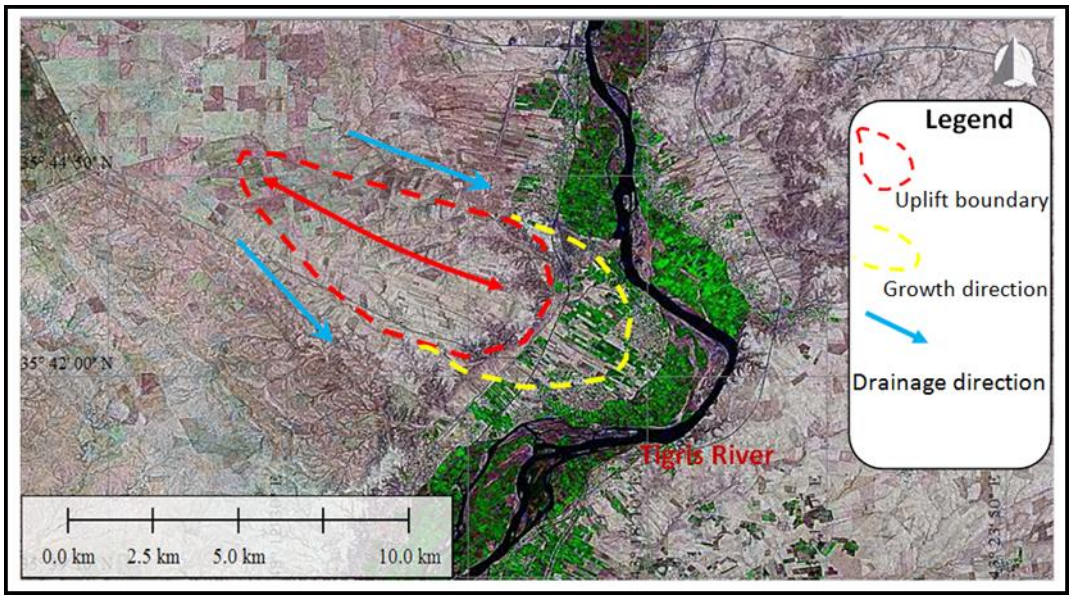


Fig. 11. A Satellite image showing the location of the elevation and its effect on the drainage pattern and course of the Tigris River.

- There is a noticeable decrease in the relief of the topographic profile along the crest, which indicates that the anticline is plunging in the direction of its propagation (Keller et al., 1999). These criteria clearly demonstrate the lateral propagation in the Al-Qayyarah area (Figure 11). This observation is further supported by the drainage pattern, which shows two distinct radial steps (R1 and R2) in the plunge direction (Figures 12 and 13).

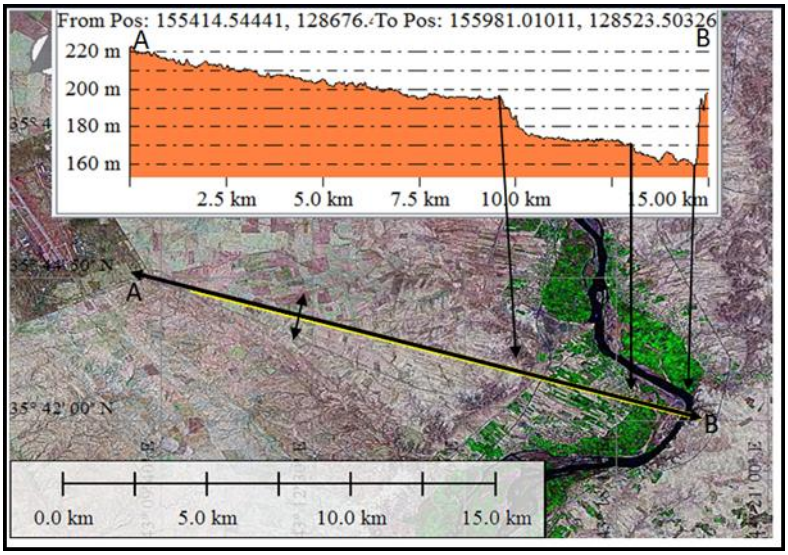


Fig. 12. Decreasing topographic longitudinal profile along the axis toward the propagation of the Al-Qayyarah area.

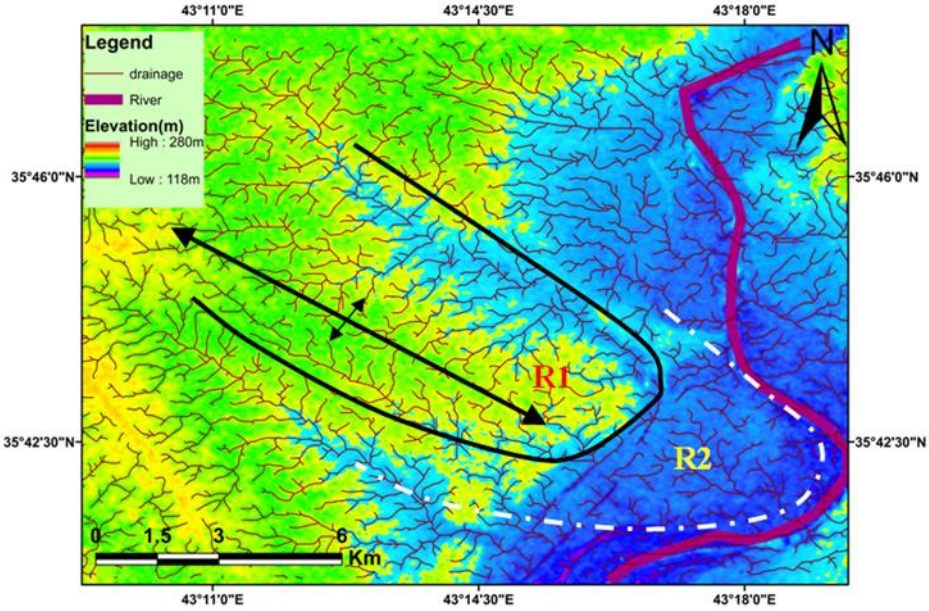


Fig. 13. Drainage patterns of the Al-Qayyarah area. Note radial pattern steps (R1, R2) toward the plunge area.

- Sissakian (2013), examined the geomorphological and morphometric features of the Greater Zab River basin and its four tributaries, as well as the characteristics of its sub-basins. Six morphometric indices were measured for the five sub-basins. The results indicated that these basins exhibited varying levels of relative tectonic activity, categorized as high, medium, very high, and very high, respectively. This area is relatively close to the current study region, where the observed high tectonic activity corresponds with the described geomorphological phenomena.

Bai Hasan Anticline: The Bai Hasan anticline oil field is located parallel to the giant Kirkuk oil field structure, approximately 34 km from Kirkuk city (Dunnington, 2005). It has a long axis measuring 32 km and a width of 4 km. The anticline consists of two domes: the southeastern dome, known as the Kithka dome, and the northwestern dome, referred to as the Dawood dome (Shahab et al., 2022) (Figure 14). These domes are separated by a shallow feature called the Shahl saddle (Al-Shaikh & Ziyaioglu, 1992 in Al-Sheikhly et al., 2015). Numerous surface faults, varying in length, have been identified in this anticline, with a general northwest–southeast trend.

The reservoirs in the Bai Hasan field are classified as Cretaceous-Tertiary, comprising the Garagu, Shuaiba, Mauddud, Shiranish, and Mashura Formations. In contrast, the Tertiary reservoir consists of the Baba, Bagwan, and Jeribi Formations and part of the Fat'ha Formation (transitional layers). The cap rocks in this structure are the Jawan and Aliji Formations for the Cretaceous reservoirs, as well as the salt layers of the Fat'ha Formation for the Tertiary reservoirs. In contrast, the generating rocks are the lower Sarmord Formation (Makhul Formation) and the Batiyah Formation.

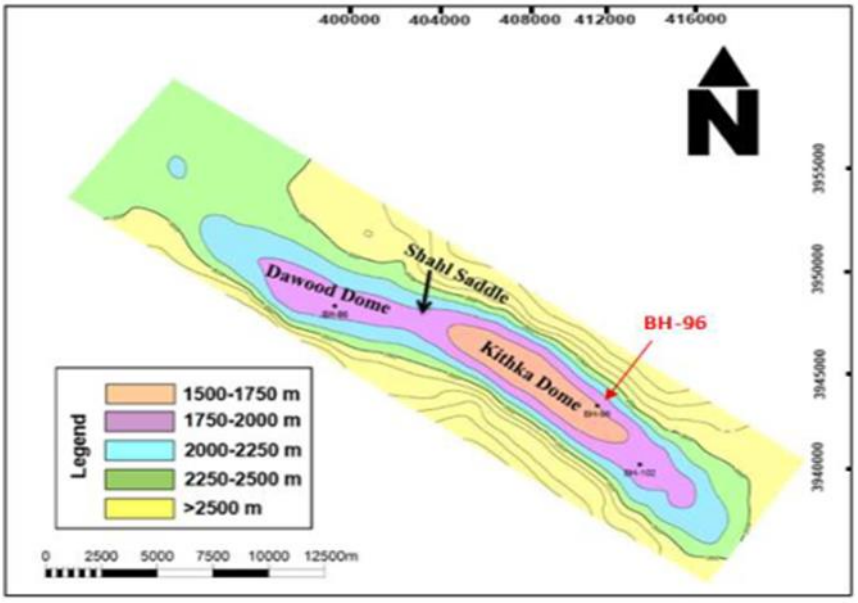


Fig. 14. The structural contour map of Bai Hasan oilfield and location of the well BH-96 (after Shahab et al., 2022).

In this study, a strike-slip displacement was distinguished that cuts Bai Hasan anticline in an oblique attitude and transversally to the axis of the anticline and extends from the northern limb to the southern limb of the anticline, near the village of Bai Hasan. To appropriately identify this strike-slip fault, this work aims to describe its morphotectonic indicators. Through visual interpretation of satellite images of the region, it was observed that there is a strike-slip displacement along the extension of this fault, as evidenced by the shifting of rock layers, forming an anticline with sinistral strike-slip movement. This strike-slip fault is significantly distinct in these layers and can be easily distinguished (Figure 15). The strike-slip fault shown in the figure below was arbitrarily identified in a previous study by Thannoun et al. 2021 on the Bai Hassan anticline using visual interpretation of enhanced Landsat images. They reported that the local effect of this fault is the cutting and displacement of surface rocks, with some local breaks also resulting from the displacement.

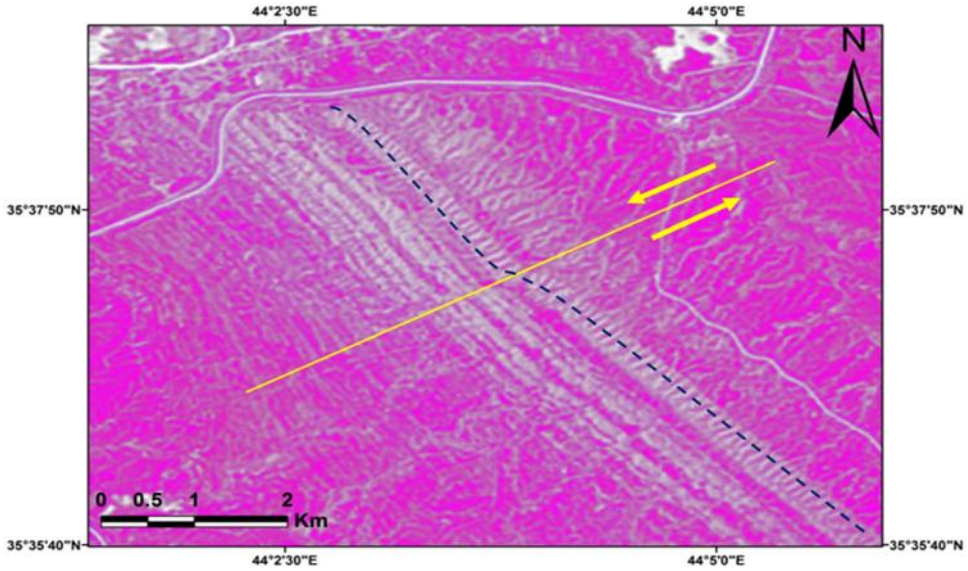


Fig. 15. The Bai Hasan strike-slip fault and its effect on the layers in the Bai Hasan anticline using Landsat 7, band combination 5, 6, 7 for False Color Composite.

It appears this fault is shallow, and its effects do not reach the oil reservoir because there is no hydrocarbon seepage along the fault line. The presence of numerous faults and salt layers may have absorbed and dispersed stress in the area, preventing the fault from extending to greater depths. This conclusion aligns with the findings of Al-Mufti & Qanber (2019), who studied other faults in the Bai Hasan oil field.

However, the structural ridge located southwest of the Bai Hasan anticline, which marks the fault's endpoint, deviates significantly from its initial extension towards the southwest. This indicates that the fault has affected the ridge by continuous displacement and sliding, due to the presence of highly curved layers in the structural ridge (Figure 16).

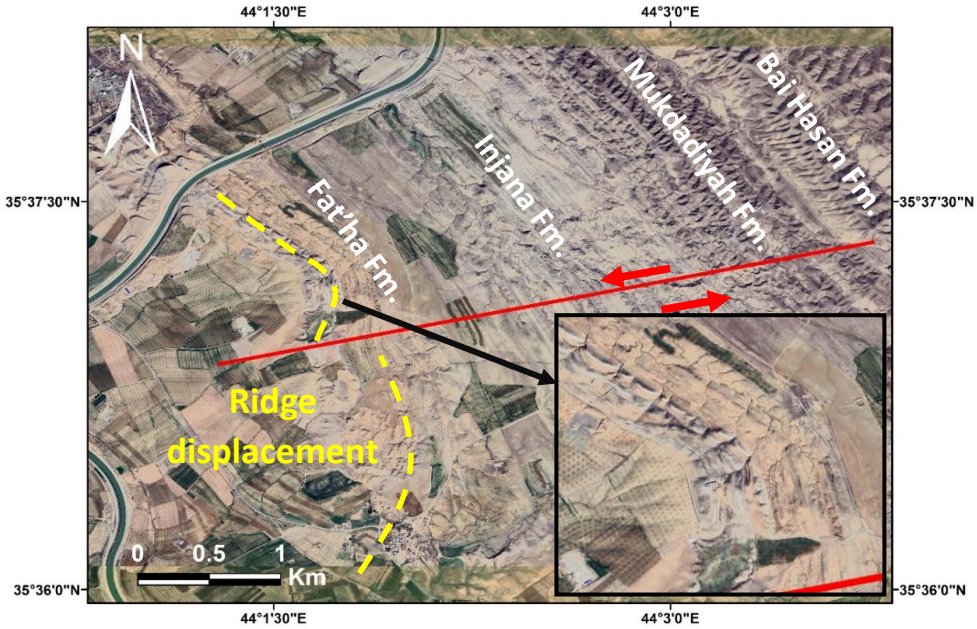


Fig. 16. Hinge deviation of the structural ridge southwest of Bai Hasan anticline (True color image).

Conclusion

Based on the results of this study, three findings were concluded to illustrate how tectonic activity affects the landforms in the selected areas in northern Iraq:

1. Determination of the duplex reverse fault system on both the Al-Fadhliyah anticline and expect the relative age of them. These faults impact the morphology of the anticlines and the continuity of the layers.
2. A tectonic elevation associated with the tectonic activity in the Al-Qayyarah area was tracked by analyzing the response of the drainage system, characterized by parallel and distinct radial patterns. Additionally, the sudden eastward shift of the Tigris River coincided with a decrease in topographic elevation, confirming the lateral propagation of the Al-Qayyarah area towards the east. In addition to a cross-section indicating topographic uplift in the area, there was also evidence of a syncline, suggesting a low-lying area.
3. In the Bai Hasan Anticline, a sinistral strike-slip fault has been recognized oblique to the anticlinal axis, causing apparent displacement. Since there is no hydrocarbon seepage along the fault line, it seems that this fault is shallow and does not affect the oil reservoir.

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