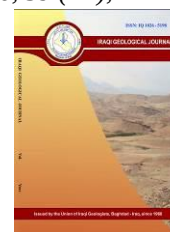




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Geomorphology and Geometry of the Khanuga Anticline, Northern Iraq

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Abstract

The Khanuga anticline is significant for understanding geological processes in northern Iraq's Low Folded Zone, about 90 km east of Salah Al-Din Governorate. The Khanuga anticline is characterized by its double-plunging form, with its axis aligned with the Zagros trend. This study aims to conduct a geomorphological and geometric analysis of the Khanuga anticline using field data and a stereonet diagram for each traverse. In addition to prepare a geological map and stratigraphic section for the study area. Three selected traverses perpendicular to the fold axis and nineteen stations were selected based on the availability of outcrops because most of the rocks are covered by recent deposits. Field and office measurements proved that the southwestern limb dips more than the northeastern limb; this fact may be attributed to the effect of the Khanuga anticline by the foreland listric fault, which plays an active role in the determination of the fold location and its form. The study presented that the Khanuga anticline exhibits a parallel style and is formed by a combined neutral surface and flexural-slip mechanism. The region is categorized by numerous geomorphological features of structural, denudation, and fluvial origin, which have been observed in the field. This study came to conclude that the Khanuga anticline formed as a result of regional horizontal stress in the northeast-southwest direction in the Late Miocene-Pliocene and is related to the second stage of the Alpine Orogeny. The fold geometry was described as asymmetrical, gentle, linear, horizontal, and upright, based on the structure parameters: limbs, fold axis, axial plane, hinge line, and interlimb angle.

Keywords: Khanuga anticline; Listric fault; Flexural slip surface; Neutral slip surface; Fold geometry; Geomorphological features

1. Introduction

The Zagros Fold-Thrust Belt is recognized as one of the most significant continental collision zones, resulting from the convergence of the Arabian and Iranian plates since the Eocene epoch (Jassim and Goff, 2006). In Iraq, this belt is characterized by a series of elongated synclines and anticlines that form the Low Folded Zone. Deformation in this area is primarily controlled by thin-skinned tectonics, with localized influences from the underlying basement (Garzic et al., 2019).

The Zagros Fold-Thrust Belt's Low Folded Zone includes the Khanuga anticline. With softer slopes on one side and steeper limbs on the other, the anticline is asymmetrical (Sissakian et al., 2022).

As is typical in the area, the anticline is also likely a detachment fold. Detachment folds form when a layer of rock separates from the underlying strata, producing folds with a specific shape. Studies of the Korek and Pirat anticlines, which are also part of the Zagros Belt, have demonstrated the presence of detachment folds in the area (Sissakian et al., 2022). GIS has been used as an additional tool in

numerous recent studies of morphotectonic indices and tectonic evaluation in the eastern region of Iraq (Jaddoa et al., 2025).

The current study helps conduct a thorough investigation of the area's geomorphology and structure through repeated field trips. In addition to identifying the geomorphological features and the reasons for their creation, the geomorphological investigation includes producing a stratigraphic column and a geological map. In the structural investigation, folds are geometrically classified using field data and stereonet diagrams. In addition to enhance the understanding of the tectonic forces that formed the Khanuga anticline.

This study aims to conduct a geomorphological and geometric analysis of the Khanuga anticline using field data and a stereonet diagram from repeated field traverses, and to prepare a geological map and stratigraphic section for the study area.

1.1. Location of the Study Area

The study area is located in northern Iraq, specifically north of Salah Al-Din Governorate, within Al Sharqat District, between Latitudes $35^{\circ}15'00''$ and $35^{\circ}26'30''$ N and Longitudes $43^{\circ}20'30''$ and $43^{\circ}14'00''$ E (Fig. 1). The Khanuga anticline extends 26 km in length and 3.5 km in width, with an area of approximately 91 km² based on satellite image and field tours.

The region is bordered by the Tigris River to the east, the Makhoul Mountain Range to the west, the Wadi of Al Sharqat to the north, and Al Zawiya Village to the south. The research area is part of the Makhul Mountain range, which extends to the northwest-southeast (Jassim and Goff, 2006).

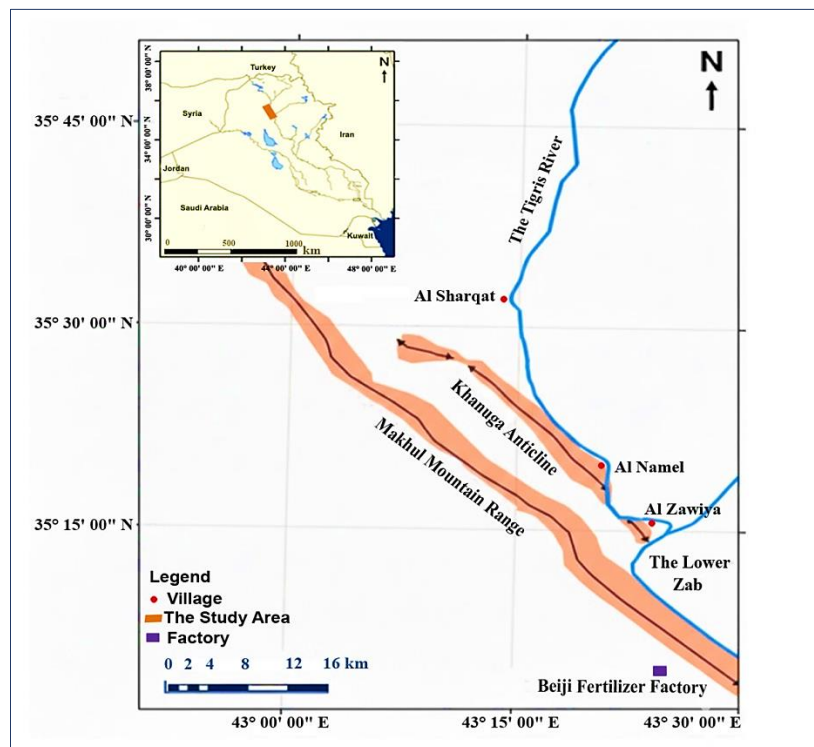


Fig. 1. Location map of the study area

One important geological feature in the Zagros Fold-Thrust is the Khanuga anticline. Because the Arabian and Eurasian plates are colliding, creating many anticlines and synclines, this area is characterized by complex tectonic activity. Although there aren't many studies specifically on the Khanuga anticline, knowledge from nearby formations comparable to it provides a basis for understanding its geomorphology and structure (Al-Ramli and Al-Mamouri, 2024).

A large syncline fold representing the Wadi Al Jaffer Valley, extending northwest-southeast from the southeast contact between the Fatha and Injana formations near Al Zawiya Village, separates the Khanuga Anticline from the Makhul fold. Near the northwest plunge of the Khanuga anticline, the region to the northwest gradually widens to 6.5 km.

Three culminations are composed of the non-cylindrical Khanuga anticline, which is the highest and largest topographically and structurally; the smallest is the Khudhairah anticline; the Ramdhaniyah anticline; and the third is the Khanuga anticline, which is segmented by two low topographic saddles.

1.2. Geological Setting

Tectonically, the study region lies within the foreland quasipatform, which is part of the foreland belt of the Arabian Plate (Ali et al., 2025), and extends into the unstable shelf foothills (Jassim and Goff, 2006). The Zagros Fold-Thrust Belt, which includes the Khanuga anticline, is the result of the collision between the Eurasian and Arabian plates. This collision has created a sequence of NW-SE curving folds, including anticlines and synclines that are characteristic of the region. The anticlines in this belt are often thrust and exhibit lateral growth, as observed in similar structures such as the Qara Chough South Anticline and the Sinjar Anticline (Sissakian et al., 2022 and 2023).

2. Materials and Methods

Three selected traverses perpendicular to the fold axis, and nineteen stations are selected based on the availability of outcrops, because most of the rocks are covered by recent deposits. Field and office measurements proved that the southwestern limb dips more than the northeastern limb; this fact may be attributed to the effect of the Khanuga anticline by the foreland listric fault, which plays an active role in the determination of the fold location and its form.

2.1. Fieldwork

Fieldwork included conducting an exploration tour to identify the geological features of the study area. Three traverses perpendicular to the fold axis are selected to cover all layers, based on available outcrops. Since not all layers are visible at a single location due to erosion, the traverses were selected at varying distances whenever possible. The measurements included the positions of the layers and fractures relative to the strike, as well as the dip and dip direction using a Silva geological compass of Swedish manufacture. The strike values were taken based on the right-hand rule in all measurements.

Additionally, the fieldwork involved determining the locations of nineteen structural stations, constrained by outcrop availability; each was approximately 30 m² in area and located using a GPS device. Boundaries between layers were established to map the geological structure, including stratigraphic sections. The study area was also described stratigraphically and geomorphologically, documenting the main sedimentary structures, rock types, and the formations to which they belong. Photographic documentation was captured of the region's significant structures and geological phenomena.

2.2. Office Work

The field-collected structural geological data were first organized into specialized tables for systematic analysis. Attitudes of bedding planes and fractures were processed using lower-hemisphere equal-area Schmidt net stereographic projections to facilitate geometric classification of the folds. Stereonet software was employed to analyze fold axes, axial planes, and interlimb angles. Geographic coordinates were converted using TatumGIS, and Global Mapper was used to generate cross-sectional geological profiles. Geological maps, stratigraphic sections, and location maps were created in ArcMap. This office work enabled a detailed assessment of fold geometry, including orientation, symmetry, and

kinematic characteristics, providing a foundation for understanding the tectonic forces that formed the Khanuga anticline.

3. Geological Setting

Tectonically, the study region is situated in the foreland quasiplatform, which is part of foreland belt of the Arabian Plate (Ali et al., 2025) and situated in Hemrin-Makhul Subzone and goes to unstable shelf foothills (Jassim and Goff, 2006). Zagros Fold-Thrust Belt, which includes the Khanuga anticline, is an effect of the crash between Eurasian and Arabian plates. This collision has created a sequence of NW-SE curving folds, including anticline and synclines that are characteristic of the region. The anticlines in this belt are often thrust and exhibit lateral growth, as observed in similar structures such as the Qara Chough South Anticline and the Sinjar Anticline (Sissakian et al., 2022 and 2023).

3.1. Topography and Stratigraphy

The highest point in the study area is 381 m, located on the Khanuga anticline. The western bank of the Tigris River running through the area is the lowest point, at 125 m above sea level. Thus, the relief (change between the maximum and minimum elevations) in the region is approximately 256 m. In the study area, sedimentary sequences ranging in age from the Middle Miocene up to the recent are exposed. These sequences include the Fatha Formation, Injana Formation, and Quaternary Deposits. The formations are visible in the study region, arranged from oldest to youngest, and were prepared by the authors based on field observations (Fig. 2).

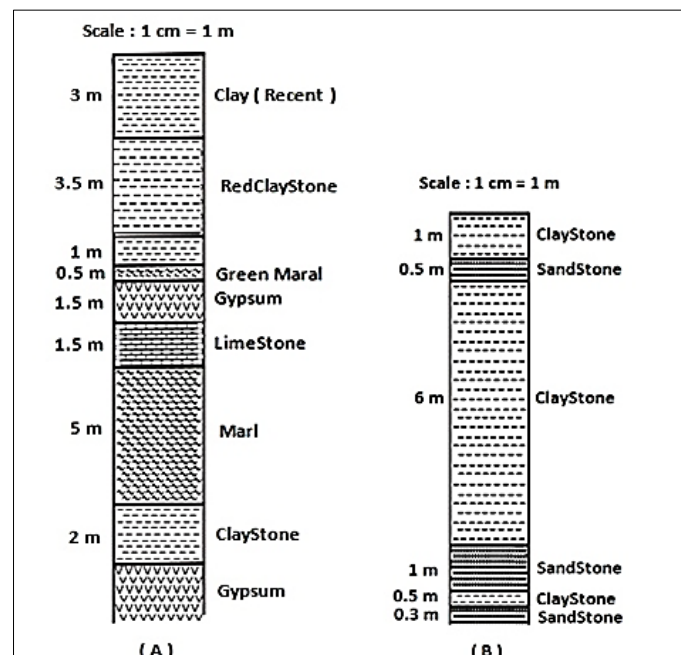


Fig. 2. Stratigraphic succession in the study area. A) Fatha Formation. B) Injana Formation

3.2. Geomorphological Features

Tectonic activity and erosion processes affect the geomorphology of the Khanuga anticline. As is typical of many anticlines in the area, the anticline is probably whaleback-shaped but has been eroded by the river and weathering. Harder and softer rock layers are differentially eroded to form this pattern; the weaker layers form the limbs, while the harder layers form the anticline's crest. The presence of longitudinal valleys, which often run parallel to the layers' strike, characterizes the studied area (Fig. 3A).

The drainage pattern of these valleys is trellis. There are also transverse valleys on both sides of the Khanuga anticline that run parallel to the layers' dip and cross the longitudinal valleys, with a drainage pattern that is parallel to, or sub-parallel to, the layers' dip (Fig. 3A). These valleys keep extending till they come to Wadi Al Jaffer at the southwestern anticline limb and the Tigris River at the northeastern limb of the fold (Fig. 3B). The existence of geomorphological characteristics, including radial and fork-shaped valleys and abandoned alluvial fans, indicates that the anticline is expanding nearby. Streams and rivers were diverted around the expanding fold as the anticline grew laterally, creating these landscapes. Similar characteristics have been noted in the Qara Dagħ Anticline, where fork-shaped valleys and abandoned alluvial fans have been formed because of the anticline's lateral expansion (Sissakian et al., 2018). According to the Dutch Remote Sensing Institute's approach (Wheaton et al., 2015), the geomorphological units were divided into three primary categories: structural, erosional, and fluvial, as follows:

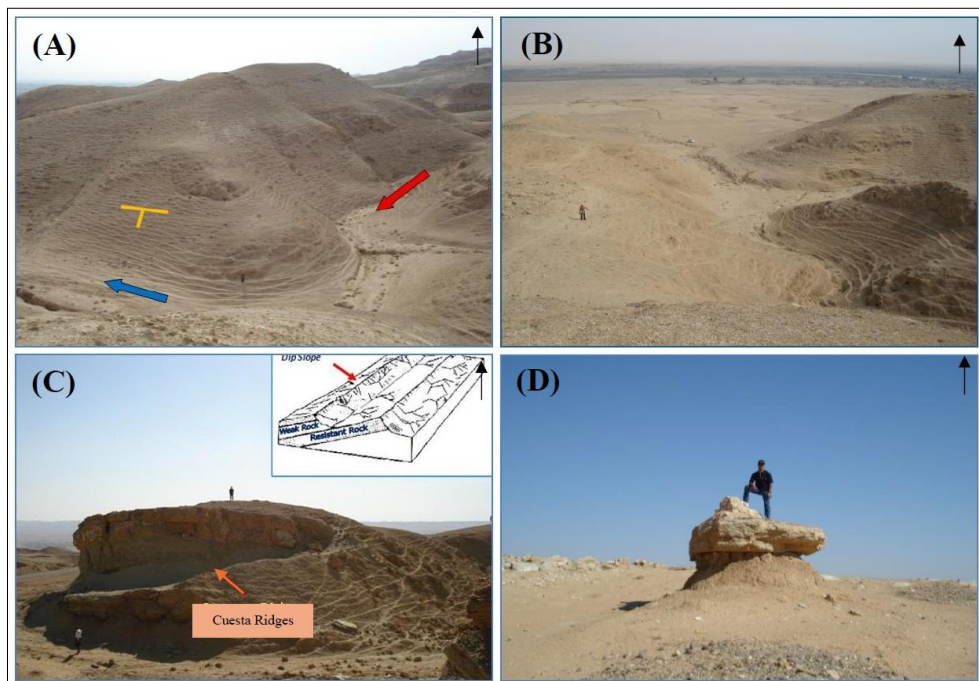


Fig. 3. A) Intersection of the longitudinal or strike valley (the blue arrow) and transverse or dip valley (the red arrow) at the study area during the fieldwork. B) River drainage towards the Tigris River. C) Cuesta Ridges in the study area. D) Butte Ridges at the top of the fold during the fieldwork

3.2.1. Units of structural origin

Structural units result from tectonic deformation, rock type, and resistance to erosion, and include cuesta and butte ridges. The cuesta forms in rock layers with a gentle slope of less than 35 degrees, which has high resistance to erosion (Fig. 3C). However, if the slope exceeds 35 degrees, it is called a hogback. These units are found along the contact between Fatha and Injana, as is the case near the southeastern plunge of the fold. The height and shape of these ridges depend on the thickness and resistance to erosion of the sedimentary rocks, the angle of inclination of the rocks, and the duration of erosion. Butte ridges develop along Wadi Al Jaffer, where there are thick layers of claystone covered by sandstone (Fig. 3D).

3.2.2. Units of denudation origin

They are formed by rock erosion and weathering in the area, such as in badlands. The badlands are well developed in many parts of the region within the Injana formation, especially near the southeastern part of the Khanuga anticline, where claystone alternates with medium-hard sandstone, creating very

rugged terrain. In addition to its presence in the central part of Wadi Al Jaffer, the specifications are also present along the southwestern limbs of the Khanuga anticline (Fig. 4A).

3.2.3. Units of fluvial origin

The rivers play an active role in transporting sediments and depositing them due to the low flow velocity. River terraces are topographic surfaces that indicate former levels of valley bottoms and represent remnants of the river's former floodplains. It is believed to have formed in the study area from the deposits of the old Tigris River, and most of it consists of layers of coarse gravel at the bottom that gradually fine upward (fining upward) (Fig. 4B).

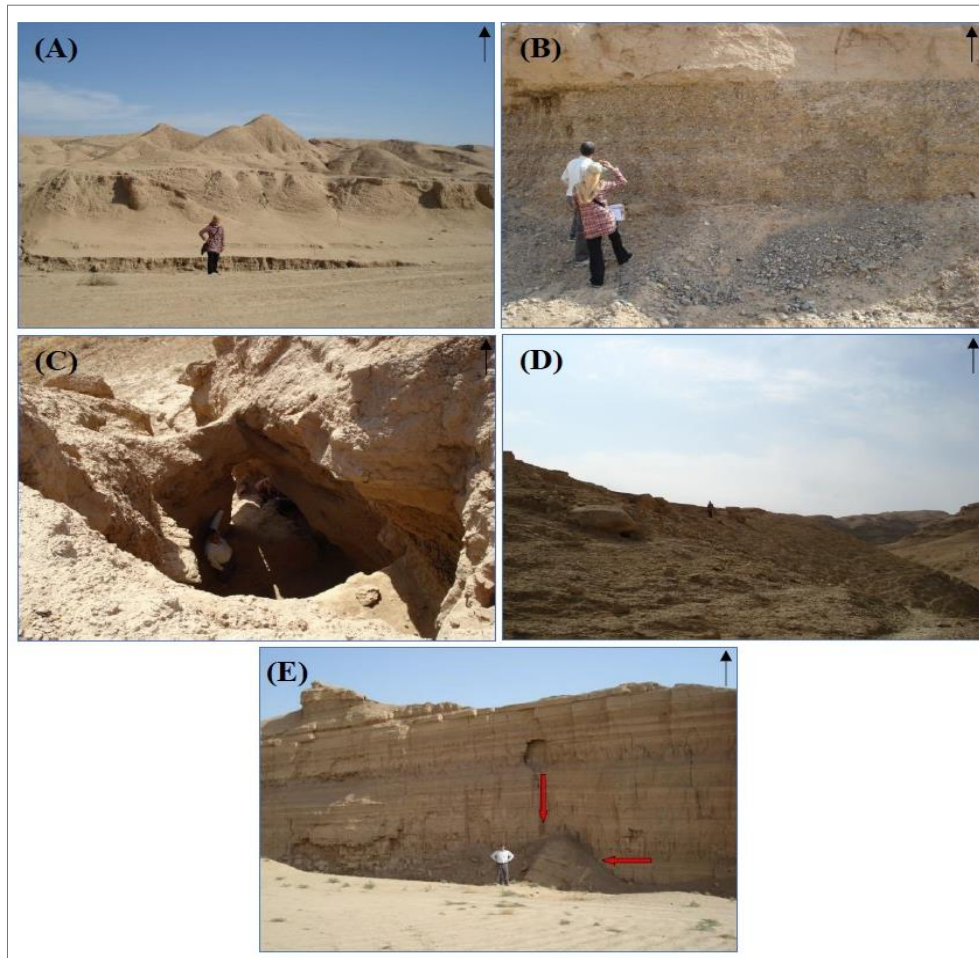


Fig. 4. A) Badlands in the study area, B) River Terraces in the study area, C) Sinkholes in clay due to its high content of gypsum materials, D) Rocks toppling in the study area, E) Rockfall in the study area

Other geomorphological features observed in the study area included dissolution, due to the presence of limestone and gypsum in the region, which are highly soluble and characterized by fractures that increase their permeability and facilitate the movement of groundwater through them (Al-Ramli and Al-Mamouri, 2024). This leads to the expansion of cracks because of dissolution processes, which increase the size of caves and their development due to the inability of the surface of these cavities to bear the weight of the deposits, resulting in the collapse of these cracks and consequently the formation of karst or sinkholes (Fig. 4C).

The rock mass movement in the study area consists of rock toppling and rockfall. Rocks toppling occurs when cohesion is zero across discontinuities, and failure occurs, causing rocks to roll down the valley when the center of gravity of the mass shifts away from the support base due to erosion of the clay

layers beneath the gypsum layers (Fig. 4D). The same applies to the sandstone located above the clay rocks concerning the Injana Formation. Rockfall occurs in the case of a vertical slope and the exposure of weak rocks; the rocks above remain overhanging, and when the cohesion across the discontinuities becomes zero, the rock mass falls (Fig. 4E).

3.3. Structural Features

The fractures represent surfaces where the rock loses its cohesive strength, forming due to brittle deformation under stress. These deformations are typically discontinuous. Many types of fractures exist in the study area: faults, joints, fissures, veins, and listric faults.

The faults are fractures that exhibit noticeable movement along their surfaces (Fig. 5A). They can be identified through slickensides (Fig. 5B), or from fissures located near fault planes known as feather structures, or from the fault breccia concentrated on the fault surface (Fig. 5C), or from the layering discontinuities.

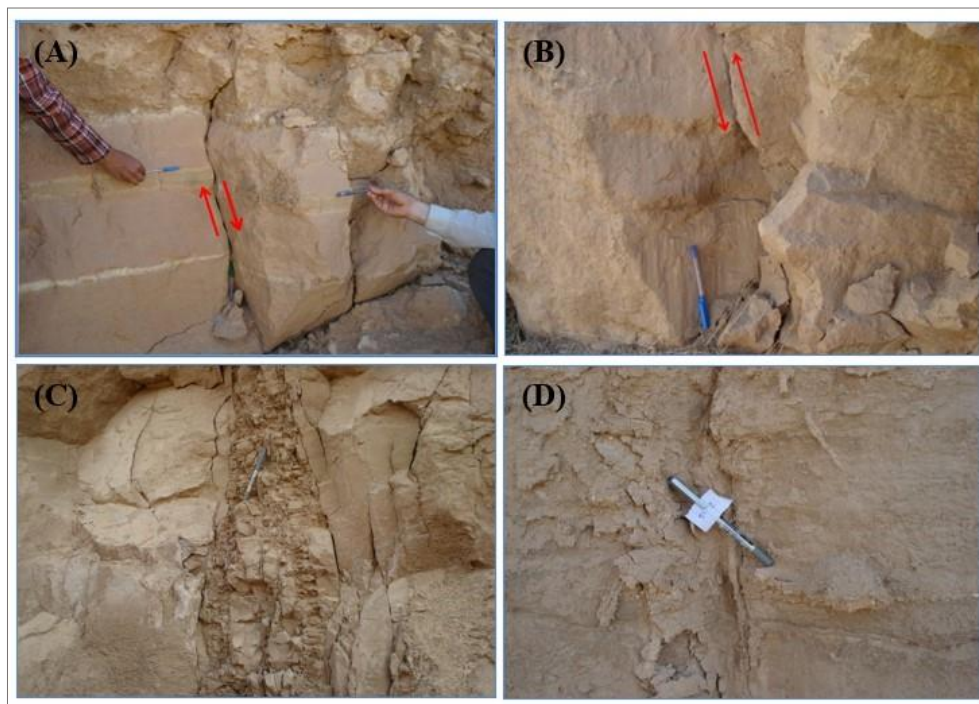


Fig. 5. A) Normal fault affects a layer of limestone in the study area. B) Slickensides on the reverse fault surface. C) Fault breccia in the study area. D) A vein filled with gypsum within claystone rocks in the study area

Joints are present in the study area as fractures in the rock layers, where no significant movement occurs along their surfaces. If movement does occur, it is very minimal and is perpendicular to the fracture surface, without extending along or parallel to it (Eshiet and Sheng, 2017). Joints appear as a set when they are planar and parallel in direction and dip, indicating a stable geometric relationship among themselves and with the containing structures; these are referred to as systematic joints. In contrast, if the fracture surfaces have random orientations and do not geometrically relate to the containing structures, they are called non-systematic joints and have not been considered in this study because their formation is unlikely to be affected by tectonic forces (Eshiet and Sheng, 2017).

Many fissures were observed in the study area, where no significant movement occurs along their surfaces, and no mineral deposition has occurred. These fissures result from the continued action of the forces that cause them to move, or from various erosion processes (Gudmundsson, 2000).

Veins exist in the area as fissures filled with crystalline materials (Bons et al., 2012) (Fig. 5D). There are two types of veins: one that fills the fissures during the widening process and the other that results from the crystallization of materials from solutions in previously open fissures. They also categorized veins into fibrous and non-fibrous (or blocky) veins. Fibrous veins are important geological structures for determining the directions of the forces causing fracturing, as the orientation of the fibrous crystal axes within the vein is equivalent to the path of principal maximum strain responsible for the fracture formation. This stress can either be perpendicular to the fracture surface or inclined to it.

The listric faults present in the study area caused the southwestern limb to be more inclined than the northeastern limb (Al-Azzawi, 2003; Al-Sumaidaie et al., 2020). Generally, faults characterized by a progressive decrease in dip with depth are called listric faults. The surfaces of these faults exhibit a concave or spoon-like shape. Listric faults typically develop during the divergent phase and manifest as listric normal faults within passive plate margins (Ward et al., 2020).

4. Results and Discussion

4.1. The Selected Traverses

Three traverses were selected vertically on the strike (Fig. 6). Topographic sections and stereonet diagrams were drawn for each traverse to describe and classify the fold geometry based on the information obtained from these traverses, which are as follows:

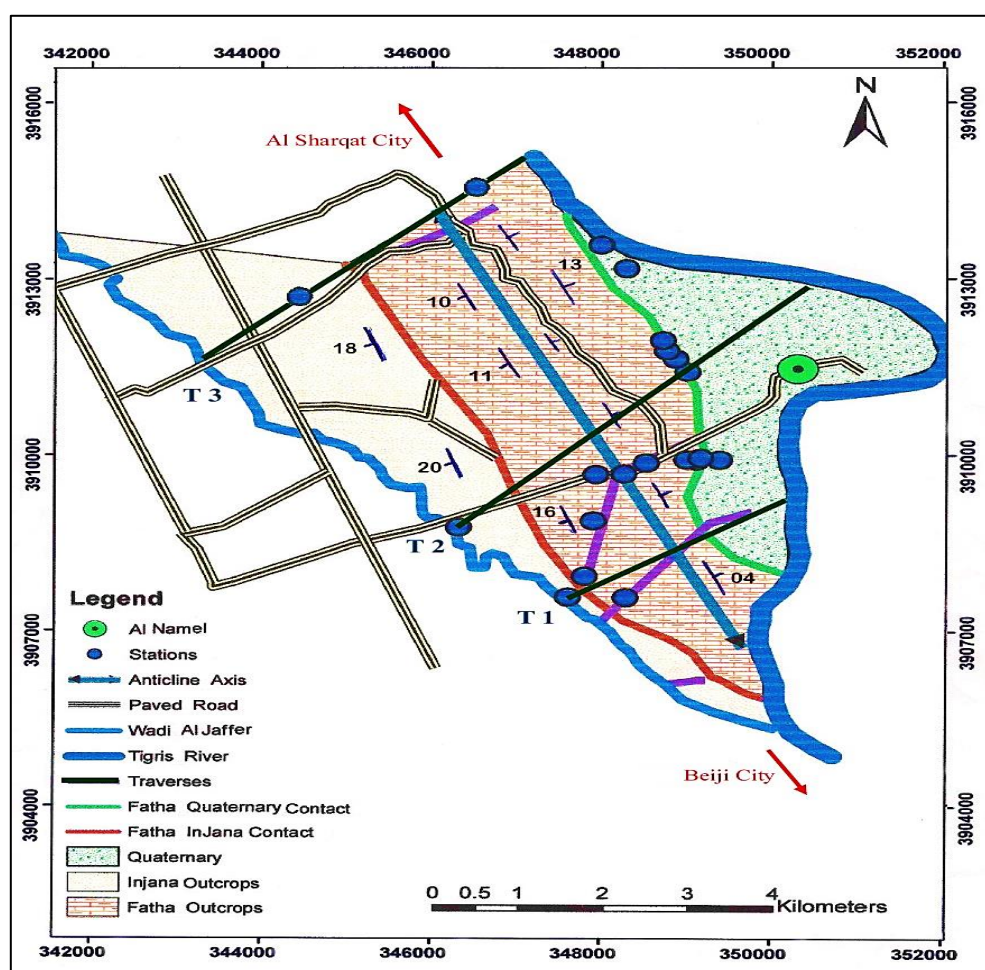


Fig. 6. The geological map with three traverses followed in the study area

4.1.1. The first traverse

This traverse extends from the southwest to the northeast limb near Al Namel Village, because it is a paved road, and it is easy to reach the stations within the two limbs of the fold. As shown in the geological map (Fig. 7), the traverse length is approximately 1800 m. The stereonet diagram and the geometric classification of the anticline (Figs. 7 and 8) are shown in Table 1.

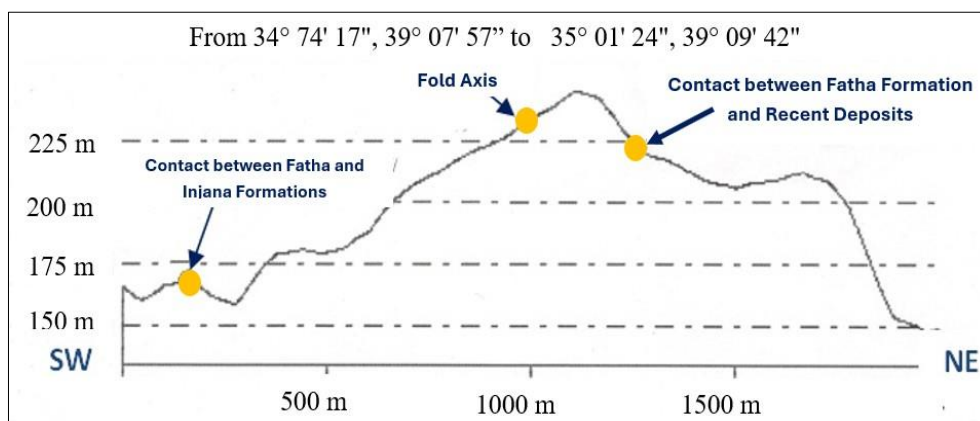


Fig. 7. Topographic section of the first traverse in the study area

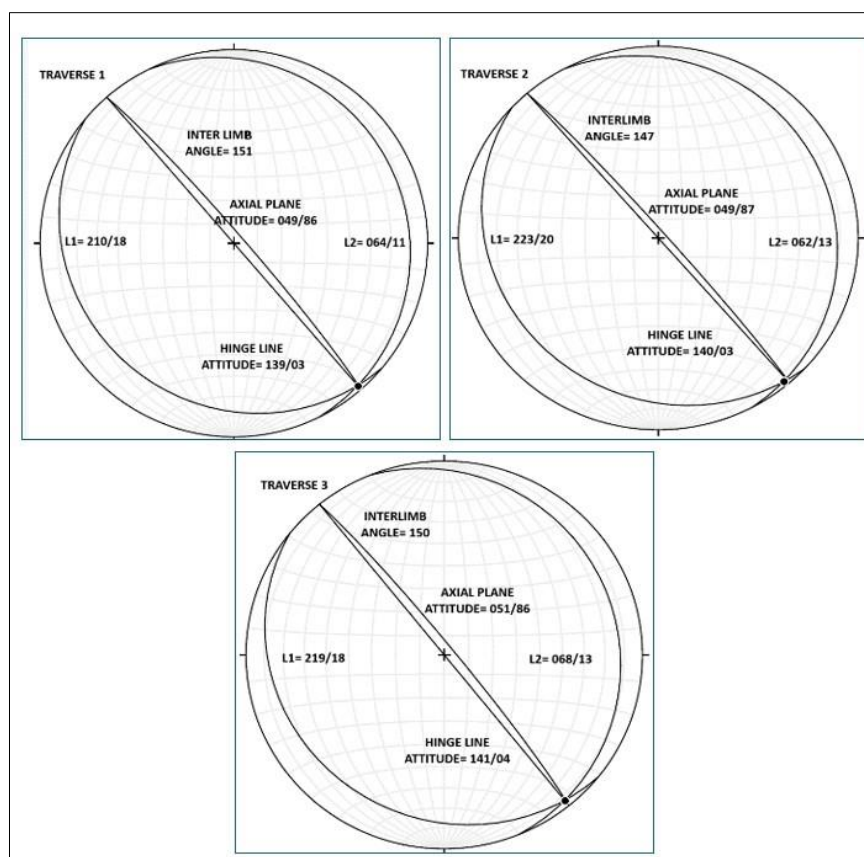


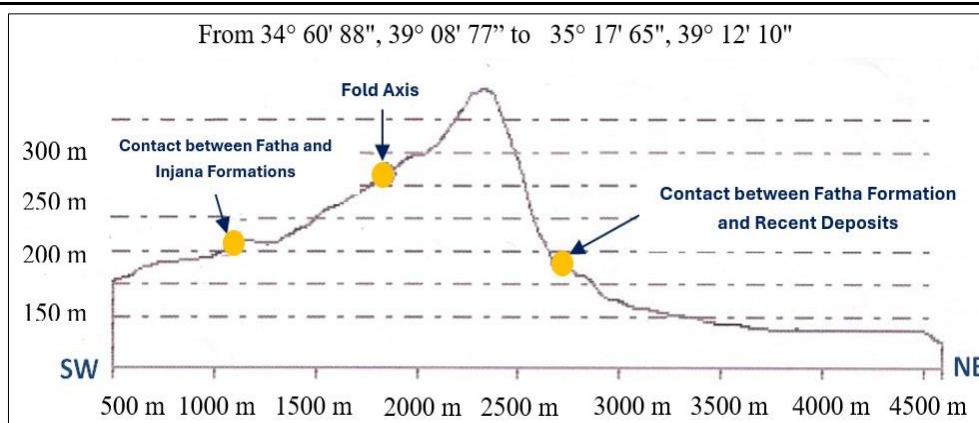
Fig. 8. Stereonet diagram showing the geometry of the Khanuga anticline in three traverses

4.1.2. The second traverse

This traverse extends from the southwest limb to the northeast limb near the Tigris River (Fig. 6); its length is approximately 1950 m. The stereonet diagram and Table 1 show the geometric classification of the anticline (Figs. 8 and 9).

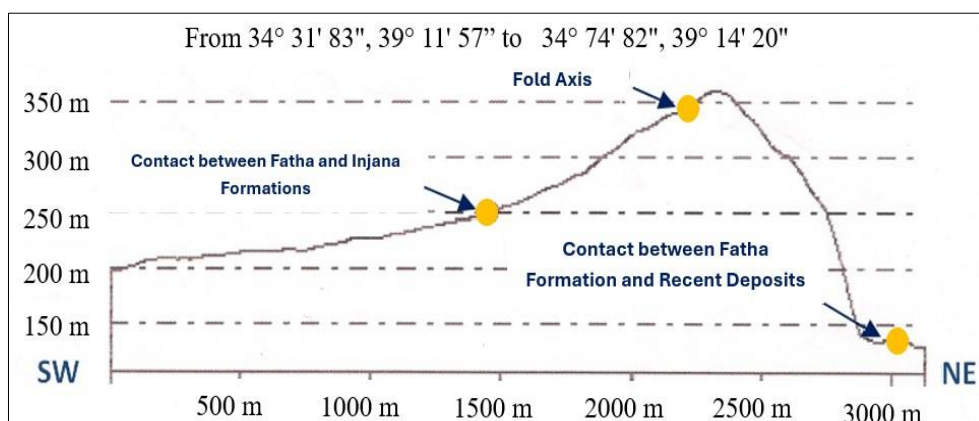
Table 1. Stereonet diagram and the geometry of the Khanuga anticline in three traverses (Fig. 6), where the attitude is the dip direction to dip angle

Information	Traverse No. 1	Traverse No. 2	Traverse No. 3
SW limb attitude	220°/18°	223°/20°	219°/18°
NE limb attitude	64°/11°	62°/13°	68°/13°
Interlimb angle	151°	147°	150°
Axial plane attitude	049°/86°	049°/87°	051°/86°
Hing line attitude	139°/03°	140°/03°	141°/04°
Fold classification (Fleuty, 1964)	Gentle fold	Gentle fold	Gentle fold

**Fig. 9.** Topographic section of the second traverse in the study area

4.1.3. The third traverse

This traverse extends from the southwest to the northeast limb near the Tigris River (Fig. 6); its length is approximately 1450 m. The stereonet diagram and Table 1 showed the geometric classification of the anticline (Figs. 8 and 10).

**Fig. 10.** Topographic section of the third traverse in the study area

4.2. Fold Mechanism and Tectonic Progress of Khanuga Anticline

The progress of the Khanuga anticline involves the interaction of tectonic forces over time. As numerous anticlines in the Zagros Belt, the anticline most likely originated during the Late Miocene to Pliocene. Regional tectonic forces, such as the ongoing collision between the Arabian and Eurasian plates, influence the development of the anticline. En-echelon folds and other structural elements support the anticline's lateral propagation. In streams, the rate of lateral growth is probably higher than the range of incision, leading to wind gaps and the abandonment of water gaps. Other anticlines in the

area have also shown this trend, including the Qara Dagħ Anticline, where lateral expansion has resulted in the abandonment of alluvial fans and the development of en-echelon folds (Sissakian et al., 2018).

The collision of the Arabian and Eurasian plates commenced in the Late Cretaceous and lasted until the Late Tertiary. The collision created the Zagros Folded and Thrust Belt, and today's earthquakes are just an indication of the continuing mountain-building in this belt. This collision caused a regional E-W shortening stress in the eastern part of the plate with an E-W direction, which has been regularly changed in N-S direction in the north of the Arabian plate. This style of deformation, referred to as the structural trend, was imposed over and culminated in folding about axes that trended northwest-southeast in the eastern part of the Arabian plate and curved about to the east-west in the northwest of the Arabian, such as its northwestern subduction zones.

The Khanuga anticline is primarily influenced by the second phase of Alpine tectonic activity. The arrangement of secondary fractures in the area shows a consistent geometric relationship with the axes of the folds and bedding planes. This indicates that these fractures are expected to form under the effect of horizontal regional pressures originating from the northeast and directed toward the southwest. This force contributed to both folding and fracturing, along with the local stresses associated with folding growth.

The presence of secondary reverse faults, confined to the inner arches of the joints of the anticline folds in the area, is evidence of compaction and squeezing of the stratigraphic units in a direction perpendicular to the axes of the folds. Layer stretching and elongation in the outer arches of anticline folds, accompanied by compaction and squeezing in the inner arches, occur during neutral-surface folding (Callot et al., 2010). Based on this, the folding process in the study area was completed with the participation of the sliding flexure and the neutral surface mechanisms.

Most of the folds in this range are asymmetrical due to the difference in the interlimb angles, box folds, and parallel folds that are formed by the mechanism of flexural slip or by neutral surface mechanics, or both. The low fold range is due to Alpine tectonic forces, which are the main factor in the folding process, in conjunction with the movement of basement blocks.

4.3. Geometry of Khanuga Anticline

4.3.1. The geometric classification based on fold symmetry and vergence

Van der Pluijm and Marshak (1997) showed that a symmetrical fold is generated when the limbs of a fold have equal dip angles, and the axial plane is vertical. An asymmetrical fold occurs when the dip angles of the limbs are unequal and the axial plane is inclined.

The southwestern limb of the Khanuga anticline is characterized by being shorter and more steeply inclined than the northeastern limb. The axial plane is inclined at an angle greater than 60° towards the northeast. Based on this classification, the Khanuga anticline is an asymmetrical fold.

4.3.2. The geometric classification based on interlimb angle

The interlimb angle of the Khanuga anticline is about 147° to 151°, so the fold is a gentle fold according to Fleuty (1964) (Table 2).

4.3.3. The geometric classification based on fold dimensions

Folds can be classified according to the relationship between their length and width into three different types (Fleuty, 1964). When the ratio of length to width is less than two, then the anticline is a basin and dome fold; if the ratio is between two and five, the anticline is a brachy fold; and if the ratio exceeds five, then the anticline is called a linear fold. The length and width of the Khanuga anticline are around 26 km and 3.5 km, respectively. Ratio of length to width is 7 [26/3.5 = 7.428], and that means the Khanuga anticline is a linear fold.

Table 2. Fold types based on interlimb angle (Fleuty, 1964)

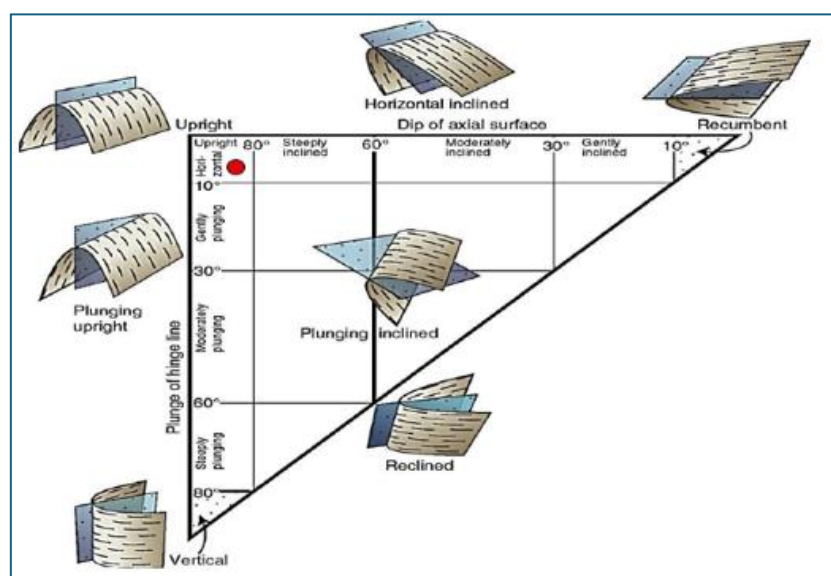
No.	Fold type	Interlimb angle
1	Gentle	180 ⁰ -120 ⁰
2	Open	120 ⁰ -70 ⁰
3	Close	70 ⁰ -30 ⁰
4	Tight	30 ⁰ -0 ⁰
5	Isoclinal	0 ⁰

4.3.4. The geometric classification based on axial surface and the direction of hinge line

Based on this classification of Van der Pluijm and Marshak (1997) (Table 3), since the dip angle of the hinge line ranges between 2⁰ and 4⁰, and the dip of the axial plane ranges between 86⁰ and 87⁰ according to the stereographic projection diagram, the Khanuga anticline is considered a horizontal and upright fold (Fig. 11).

Table 3. Geometrical grouping of fold according to plunge angle of hinge line (Van der Pluijm and Marshak, 1997)

No.	Fold type	Plunge angle of the hinge line
1	Horizontal	0 ⁰ -10 ⁰
2	Shallow	10 ⁰ -30 ⁰
3	Intermediate	30 ⁰ -60 ⁰
4	Steep	60 ⁰ -80 ⁰
5	Vertical	80 ⁰ -90 ⁰

**Fig. 11.** Fold classification according to axial surface and hinge line orientation (Fleuty, 1964). The red circle represents the site of the Khanuga anticline

5. Conclusions

- The tectonic setting of the region involves the collision of the Arabian and Eurasian plates in the creation and evolution of the Khanuga anticline. The Khanuga anticline formed due to a principal compressive stress directed northeast-southwest, as the study area lies within regions affected by horizontal compressive forces resulting from this collision. The anticline is formed by slip folding and a neutral surface.

- The study of the exposed and folded stratigraphic sequence in the Khanuga anticline shows that it formed during the Middle Miocene-present, indicating that the fold formed during the Late Miocene–Pliocene as a result of the second phase of the Alpine Orogeny.
- Khanuga anticline is a significant geological structure within the Zagros Fold-Thrust Belt with a detachment-fold geometry, and it exhibits many significant geomorphological features observed in the field. Khanuga anticline is a non-cylindrical, asymmetrical fold where the southwestern limb dips more than the northeastern limb.
- The fold is an asymmetrical fold, with the southwestern limb dipping more steeply than the northeastern limb. Based on measured parameters, it is classified as a gentle fold (interlimb angle is 1470 to 1510), a linear fold (length/width ratio is 7), and a horizontal, upright fold (dip angle of the hinge line ranges between 2° and 4°, and dip of axial plane ranges between 86° and 87°).

Author contributions

Hanan A. Darweesh: Conceptualization, Methodology, Validation, Investigation, Data curtain, writing – original draft, Visualization, Project administration. Mohammed R. Abood: Methodology, Visualization, Project administration, Writing, Review, and Editing. Suad M. Ali: Conceptualization, Methodology, writing review, and editing. Ayyed H. Ward: Software, writing review, and editing.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Data will be made available on request.

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