

Shortening Estimate and Structural Styles Interpretation In the Zagros Belt-Northeast of Iraq

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Abstract: This study emphasizes how crucial it is to combine kinematic modeling, structural restoration, and seismic interpretation in order to comprehend the tectonic evolution of the Zagros FTB. The results shed light on the migration and storage of hydrocarbons, highlighting the impact of different stress regimes and deep-seated underlying structures on the petroleum systems in the area. We present the first regionally balanced reconstructed cross-section of the Zagros fold belt in northeastern Iraq, along with a two-dimensional kinematic model that shows how the belt has changed over time in the study area. Multiple Lower Triassic detachments are identified, detached above the ductile basement level, and intermediate detachments that may have caused internal complexities such as adaptive bending and/or asymmetric folding, and it suggests that the cross-section may have produced low-angle bends at the transition from brittleness to ductility, associated with the two main structural phases of the detachment level in the high and low fold zones. Different stratigraphic units exhibit differing degrees of shortening, according to balanced cross-section analysis; the Oligocene and Eocene units have the greatest shortening (8.14%). Multi-detachment folds, thrust propagation, and a heterogeneous strain distribution are characteristics of the deformation that are associated with uplift and regional compression in the basement. Hydrocarbon entrapment is significantly influenced by key structural features like the Kalar-Kirkuk Thrust (KKT), whereas exploration possibilities are impacted by differential erosion and subsidence.

Keywords: Shortening, Kinematic Model, Zagros Belt, NE Iraq

Introduction

One of the most petroleum-rich areas in Iraq is the Kurdistan Region (KRI), which has the potential to emerge as a major producer soon. While earlier petroleum systems have not yet been thoroughly examined, all major hydrocarbons discovered in the Kurdistan Region of northern Iraq occur in buried pressure structures in the foreland, most likely produced from Cretaceous and Tertiary reservoirs (Jasim & Goff, 2006). The distal portion of the Zagros orogenic belt is part of the Fold-Thrust Belt (FTB), a heavily deformed region made up of several tectonic slices. A fold and thrust system incorporating in the Arabian Margin subducting plate the sedimentary cover is the primary characteristic of the FTB.

Geologists have a great opportunity to learn about the evolution of fold belts and how they relate to the migration, trapping, and generation of hydrocarbons. This is particularly true in the Zagros Mountains, an important study area with excellent outcrop exposure and

significant known hydrocarbon reserves. The most striking and important aspect of the study area is the presence of longitudinal folds of varying geometries and distributions resulting from a variety of orientations.

Fold and thrust belts have been the subject of several investigations in the area under investigation. These studies have examined this area with a focus on (i) the geological stratigraphy and evolution of the Iraqi Zagros (Alavi, 2004) (Aqrawi et al, 2010) (Sissakian, 2013), (ii) the evolution of the High Folded Zone's river drainage and tectonics (Burberry et al, 2010) (Bretis et al, 2011) (Burtscher et al, 2012), and (iii) the belt's structure and deformation style (De Vera et al, 2009) (Chalabi et al, 2010) (Csontos et al, 2012) (de Frehner et al, 2012) (Hinsch & Bretis, 2015), (iv) the geodynamic evolution of the Zagros and the timing of deformation in KRI (Koshnaw et al, 2017), and (v) the fracture patterns and the petrophysical characteristics associated with them (Reif et al, 2012) (Awdal et al, 2016). The top portion of the sedimentary cover is primarily the focus of the numerous Structural cross-sections are available at all locations in KRI (Bretis et al, 2011) (Csontos et al, 2012) (Frehner et al, 2012). To analyze the deep basement structure that regulates the uplift of the high-folding and folding zone, only a few of these cross-sections have been built down to the base (De Vera et al, 2009) (Hayward, 2014).

(Tozer et al, 2019) A study of vertical movements associated with thrust and fold belts using a case study from the Kurdistan region of northern Iraq. The authors demonstrate how the region's subsidence, uplift, and erosion are assessed using a combination of one-dimensional dip analysis of well data, cross-section construction using a common structural source, and vitrinite reflection data. The importance of considering the regional context when studying uplift history is evident; an additional 0.9 km of basement-related uplift is calculated when using the structural reference from the regional cross-section. Importantly, the poor hydrocarbon exploration prospects in some areas of the region may be explained by this additional basement-related uplift.

investigate the potential benefits of using remote sensing techniques in areas like Iran's Zagros Mountains. Geological characteristics revealed at the surface may be thoroughly assessed due to the favorable climate, good exposure, and constantly increasing resolution of satellite photography. It is feasible to map lithologies, perform structural measurements, and forecast the subsurface geology by integrating optical data, digital elevation models, and InSAR data.

According to Hasan et al.(2019), shortening deformations in the study area were uneven and non-identical, indicating that they originated at the same age and place. This implies that the defects in this region are not homogenous due to the uneven bottom of the sedimentary basin, fault system, and the shape of the collision zone between the Arabian Plate and the Iranian Plate or the Arabian Plate and the Anatolian Plate. According to these magnitudes, the Arabian Plate's foreland area is influenced by inhomogeneous deformations that are more closely tied to where these structures occurred than when they formed. This study highlights the importance of geologic factors (particularly structure) in the formation and development of structurally derived geomorphological features.

Hasan et al. (2023) used a two-dimensional seismic section and depth contour maps to determine the structural style of three separate reflector formations in the area between the high and low folded zones (Top Kurra Chine, Top Najmah, and Top Shiranish) of the Maqlob anticline. Most of the major and minor faults occurred in both the Mesozoic and Cenozoic periods. This existing structure is an asymmetrical, compressional fold, with its southern end faulted and a small back fault in the northern region. This study aims to provide an interpretation of the thrust geometry of the Zagros fold-thrust belt in northeastern Iraq, and to estimate the shortening and provide a preliminary kinematic interpretation, revealing this geometry, in addition to the genetic relationships between the existing folds and thrusts.

Geologic Setting

This study area is located in the northeast region of Iraq. It is within the High and Low Folded Zones (HLFZ)(Figure 1), a portion of the unstable shelf of the Arabian Plate between the geographical coordinates (35° 30' - 34° 40') N and (45° 51' - 44° 50') E. It covers an area of 13401 square kilometers.

The fold and thrust belt between the Taurus and Zagros Mountains, extending over 2,000 km from Turkey to southeastern Iran, was formed by the closure of the Neotethys Ocean between the Arabian and Eurasian plates (Talbot and Alavi, 1996; Stampfli and Borel, 2002). It consists of two distinct trends: the northwest-southeast Zagros trend and the east-west Taurus trend, which intersect in northern Iraq.

The Zagros orogenic belt features five tectonic domains (from NE to SW) (Blanc et al., 2003):

Urumieh-Dokhtar Magmatic Arc – Formed by NeoTethys subduction.

Sanandaj-Sirjan Zone – A metamorphic-magmatic zone separated from the Thrust Zone by the Main Zagros Fault.

Thrust Zone – Contains highly deformed tectonic slices, including Arabian margin remnants, ophiolites, and island arc materials.

High Folded Zone (HFZ) – A fold-and-thrust system involving Arabian Margin sediments, linked to basal detachment levels.

Low Folded Zone (LFZ) – Transitions to the Mesopotamian foreland basin and Persian Gulf.

The Main Zagros Fault (MZF) marks the NeoTethys suture. The Mountain Front Flexure (MFF) separates HFZ from LFZ, forming a major morphotectonic boundary with significant elevation differences (3–6 km) (Blanc et al, 2003) (McQuarrie, 2004) (Molinario et al, 2004) (Sherkati & Letouzey, 2004) (Alavi, 2007) (Vergés et al, 2011) (Sephehr & Cosgrove, 2004) (Sherkati et al, 2006) (Emami et al, 2010). This MFF defines regional arcs and embayments like the Dezful Embayment, Lurestan Arc and Fars Arc.

Sedimentary strata that were deposited in a range of habitats, from shallow marine to continental environments that date back to Mesozoic and Cenozoic periods, make up the

majority of the geological formations found within the Zagros fold-thrust belt (Peroz et al, 2011) (Mohseni et al, 2011) (Sembroni et al, 2023).

The Bakhtiani, Pabdeh, and Gurpi formations are among the primary stratigraphic units that are crucial to the development of the region's geological structure (Figure 2). Significant differences in lithology and structural geological features, such as failures and fractures products of tectonic compression and subsequent deformation—are present in these units. The ZSFZ's geological complexity paints a complicated picture that is essential for both anticipating subsurface conditions and exploring possible hydrocarbon sources (Alavi, 2004).

In the study area or project, we observe the development of many geomorphological phenomena and units. These units are structural, erosional, and fluvial. The age of these geological formations exposed in the study area or project ranges between the Tertiary and Quaternary periods (Figure 2). They are found on the unstable escarpment, represented by uplift and folding zones (Jassim & Goff, 2006). It is characterized by long anticlines; some of them exhibit different types of faulting (Figure 3).

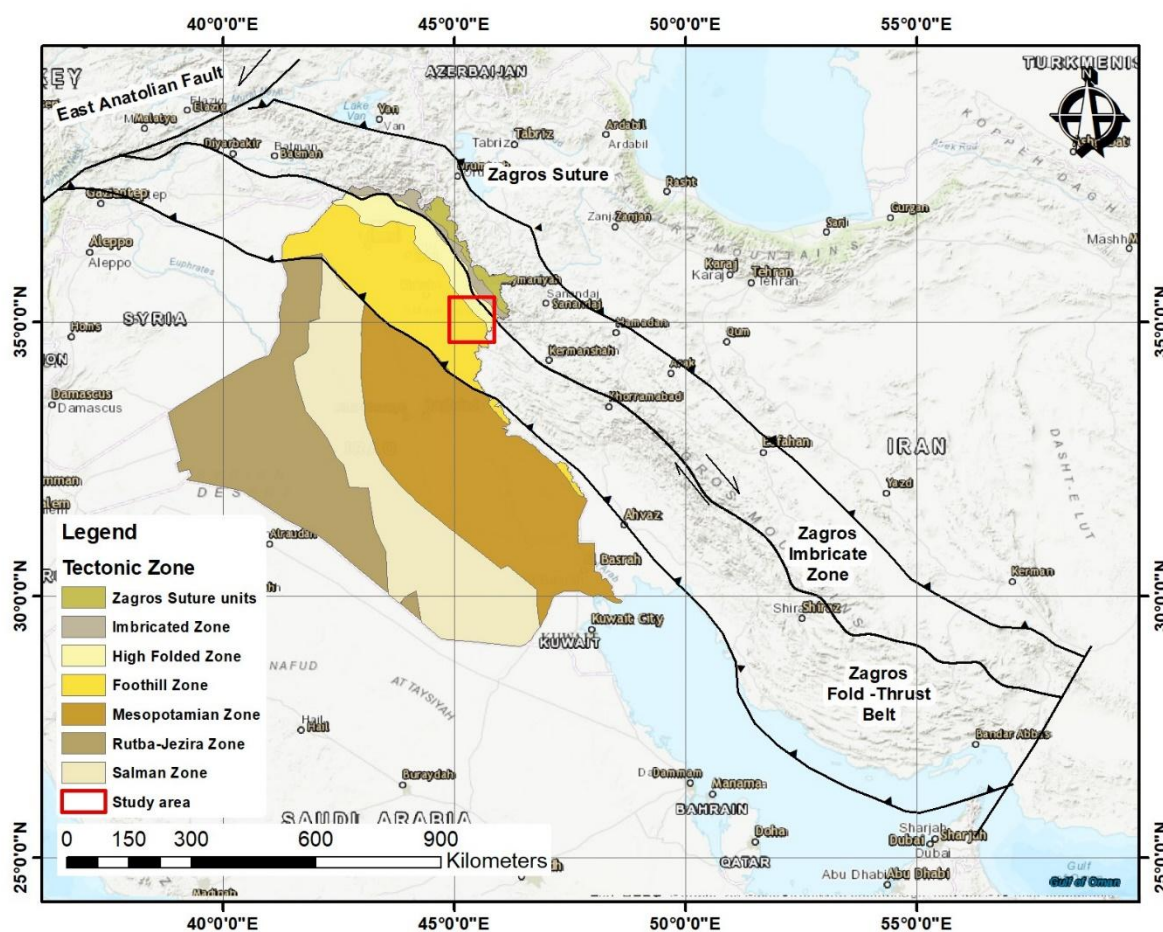
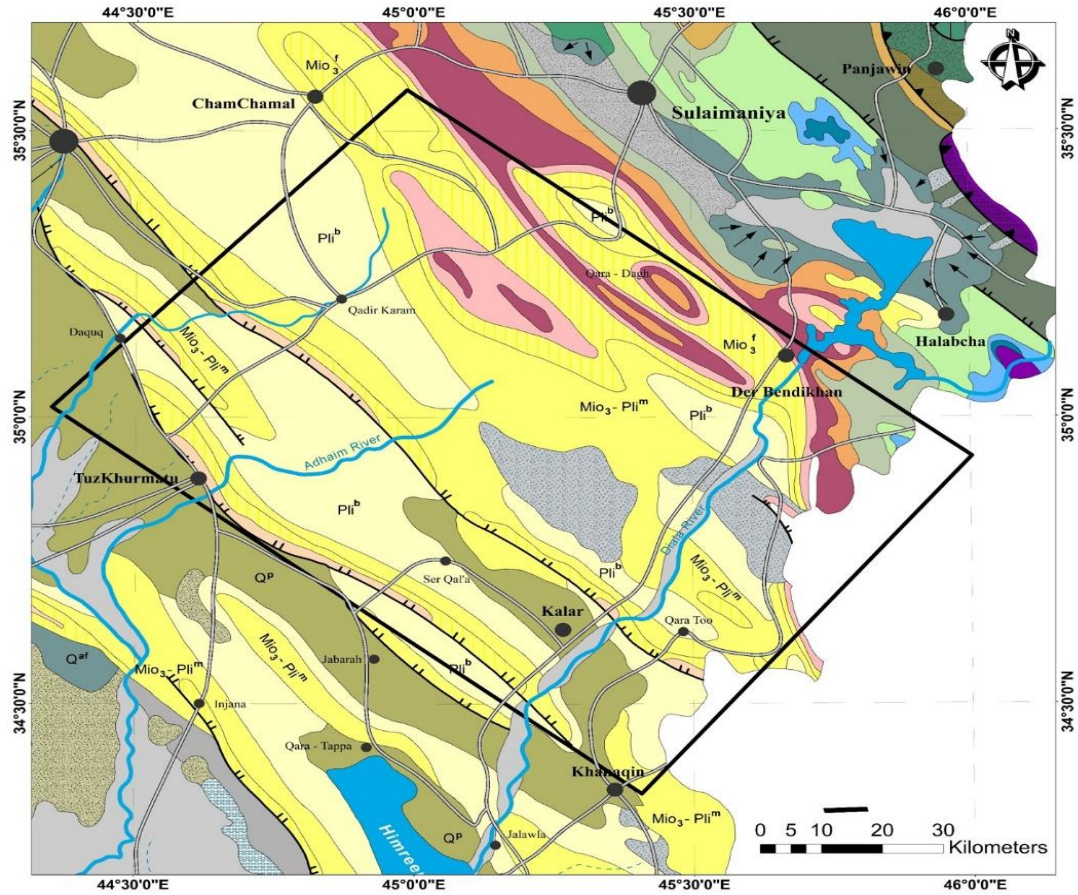


Figure 1: The structural map shows the main tectonic units in Iran, which were formed due to the deformation of the Eurasian and Arabian plates (after Alavi 2004) (Jassim & Goff, 2006) (Doski & Mohammad, 2016).



ORIGINITY	ERA	PERIOD	EPOCH	REGIONAL TECTONIC UNITS						
				ARABIAN PLATE, NORTH ARABIAN PLATFORM		EUFRATES (BALKHAN) PLAIN				
				INNER PLATFORM	Mesopotamian Foredeep and Zagros Fold - Thrust Belt (Low Folded, High Folded and Isoclinal Zones)	Zagros Suture Zone	Shalar Terrace			
LATE ALPINE	CENOZOIC	QUATERNARY	HOLOCENE	[Geological symbols for Quaternary units]						
				[Geological symbols for Quaternary units]						
		NEOGENE	MIOCENE	MIOCENE	[Geological symbols for Miocene units]					
					[Geological symbols for Miocene units]					
					[Geological symbols for Miocene units]					
					[Geological symbols for Miocene units]					
			PALEOGENE	Eocene	Eocene	[Geological symbols for Eocene units]				
						[Geological symbols for Eocene units]				
						[Geological symbols for Eocene units]				
						[Geological symbols for Eocene units]				
EARLY ALPINE	MESOZOIC	CRETACEOUS	Upper	[Geological symbols for Cretaceous units]						
				[Geological symbols for Cretaceous units]						
		TRIASSIC-JURASSIC	Upper	Upper	[Geological symbols for Upper Triassic-Jurassic units]					
					[Geological symbols for Upper Triassic-Jurassic units]					
					Lower	Lower	[Geological symbols for Lower Triassic-Jurassic units]			
							[Geological symbols for Lower Triassic-Jurassic units]			
			[Geological symbols for Lower Triassic-Jurassic units]							
			[Geological symbols for Lower Triassic-Jurassic units]							
			HERCYNIAN	PALEOZOIC	PERMIAN	Lower	[Geological symbols for Permian units]			
							[Geological symbols for Permian units]			
CARBONIFEROUS	Upper	Upper			[Geological symbols for Upper Carboniferous units]					
					[Geological symbols for Upper Carboniferous units]					
					Lower	Lower	[Geological symbols for Lower Carboniferous units]			
							[Geological symbols for Lower Carboniferous units]			
	[Geological symbols for Lower Carboniferous units]									
	[Geological symbols for Lower Carboniferous units]									
	CAMPANIAN	PALAEZOIC			ORDOVICIAN	Upper	[Geological symbols for Ordovician units]			
							[Geological symbols for Ordovician units]			
CAMBRIAN			Middle	Middle	[Geological symbols for Middle Cambrian units]					
					[Geological symbols for Middle Cambrian units]					
					Lower	Lower	[Geological symbols for Lower Cambrian units]			
							[Geological symbols for Lower Cambrian units]			
			[Geological symbols for Lower Cambrian units]							
			[Geological symbols for Lower Cambrian units]							

Figure 2. Geologic map of the studied area (GEOSERV-Iraq).

Methodology

This study relied primarily on the interpretation of a comprehensive geophysical dataset and geological and tectonic maps to study the deformation of the studied area.

In an effort to gain a better understanding of the region's complex geological environment, the geologic sections were constructed. A multifaceted technique was employed to build precise geological sections, emphasizing the integration of data from several sources. This approach improved our understanding of the structural geology of the region by enabling a thorough assessment of the geological data that was already available and guaranteeing the effective inclusion of new findings. Fossen (2016) emphasizes the need of synthesizing many data sets in structure evaluations and states that the integration of various data types, including seismic, geological, and remote sensing data, is essential for creating geological profiles.

Orogenic contraction in the High Folded Zone (study region) probably estimated by comparing concurrently built deformed and put bag the cross-sections; the degree of shortening is indicated by the difference in restored section length (Elliotte & Johnson, 1980) (Salih, 1990). These cross sections are intended for planes parallel to the direction of shortening. Specific locations for the cross section were selected following the determination of the expected Transport Direction. Sections that go from the southwest to the northeast end of the project area and parallel to the thrust transport direction have been selected.

A multi-pronged approach was used to produce accurate geological sections, with a focus on integrating data from several sources. This approach not only made it possible to thoroughly examine the geological data that was already available, but it also made sure that the new discoveries were successfully integrated, enhancing our comprehension of the region's structural geology. As Fossen (2016) points out, integrating diverse data sets—such as seismic, geological, and remote sensing data—is crucial for creating geological profiles, underscoring the need of combining many data sets in structure analysis.

GIS software was used to build the investigated area over northeastern Iraq. The quality of the 2D seismic data, which includes the cross-section's anticlines, varies. In contrast, the Low-Fold Zone (LFZ) and High-Fold Zone (HFZ) have high-quality data.

Result and Discussion

Folding and Faulting

The majority of the Fold-and-Thrust Belt's structural domains are traversed by the examined section (Fig. The cross-section is 71.8 km long and extends from the High part of Zagros Fault to the part of deformation front (Figure 3). Five anticlines in the part of Low folded zone (LFZ), which they divided by wide synclines, and one closely spaced anticline in the part of High folded zone (HFZ) make up the cross-section. Multidetachment folds, that have developed into thrust folds and tight folds with greater shortening in Inner HFZ, are what define the deformation style.

There are several northwest-southeast extending folds in the research region (Figure 3). The Dari anticline is an asymmetrical, linear fold with a double plunging structure and a rounded hinge. Like the Foothill Zone, the Chamchamal anticline lies west of Sinkaw Village. The Fat'ha and Pila Spi formations include the oldest exposed rocks along its northwest-southeast axis. Its structure is described by Sissakian (1993) as brachy, asymmetrical, non-cylindrical, and having a double plunging form. The Qara Wais and Ajdagh domes, two dome formations that are clustered in échelon and divided by a low saddle, make up the heart of the Chamchamal South Anticline. The Qara Dagh Anticline passes through the High-Folded Zone in a northwest-southeast direction. Buday and Jassim (1984), Al-Kadhimi et al. (1996), and Jassim and Goff (2006) have shown that the southwestern flank of this anticline is the southern boundary of the High-Folded Zone. This boundary is associated with a significant fault that results in displacement of more than 3000 meters (Jassim & Goff, 2006). The Tanjero Anticline is situated west of Arbet town in the High-Folded Zone, northwest-southeast. The oldest exposed section, the Shiranish Formation, makes up the majority of the core. The asymmetrical, double plunging, linear construction with a sub-rounded hinge is what distinguishes the anticline, which has a surface length of around 15 km.

The studied area represents a nappe-duplex stack, varied fold-fault frequencies and geometries, less folding, decoupling, and thrusting south of the Kalar-Kirkuk Thrust (KKT) (Figure 4). Variable and disharmonic folding laterally and vertically (Gently dipping towards the foreland and Tectonic thickening in thrust zones), the units progressively steepen and shallow towards NE. A few major reverse faults, associated with large folds and large displacement thrusts (Figure 5).

Figure 5 shows Neogene nappes are broad, gentle synclines and few thrusts. The L. Miocene Thrust Zone: broad, gentle, salt-related folds and thrusts, The Paleogene Duplex: frequent folds and thrusts, The Paleogene strike-slip and inversion structures represent the Mesozoic Duplex. The Mesozoic Duplex has frequent, steep faults and extensional remnants. The Paleozoic binary is characterized by a northeast-oriented wedge of thickening, with few bends. Thus, many of the ground and roof bends are connected by continuous extensions.

The most inactive features in this area are the connected thrust faults, which have a sigma-like shape and are similar to the ceiling and floor faults (Fig. 6). The variations in the dip angles of the thrust fault chain can be explained either by synchronous as well as heterogeneous slip on all faults at approximately the same time, or by the rotation of early faults as a result of the forward propagation of subsequent faults.

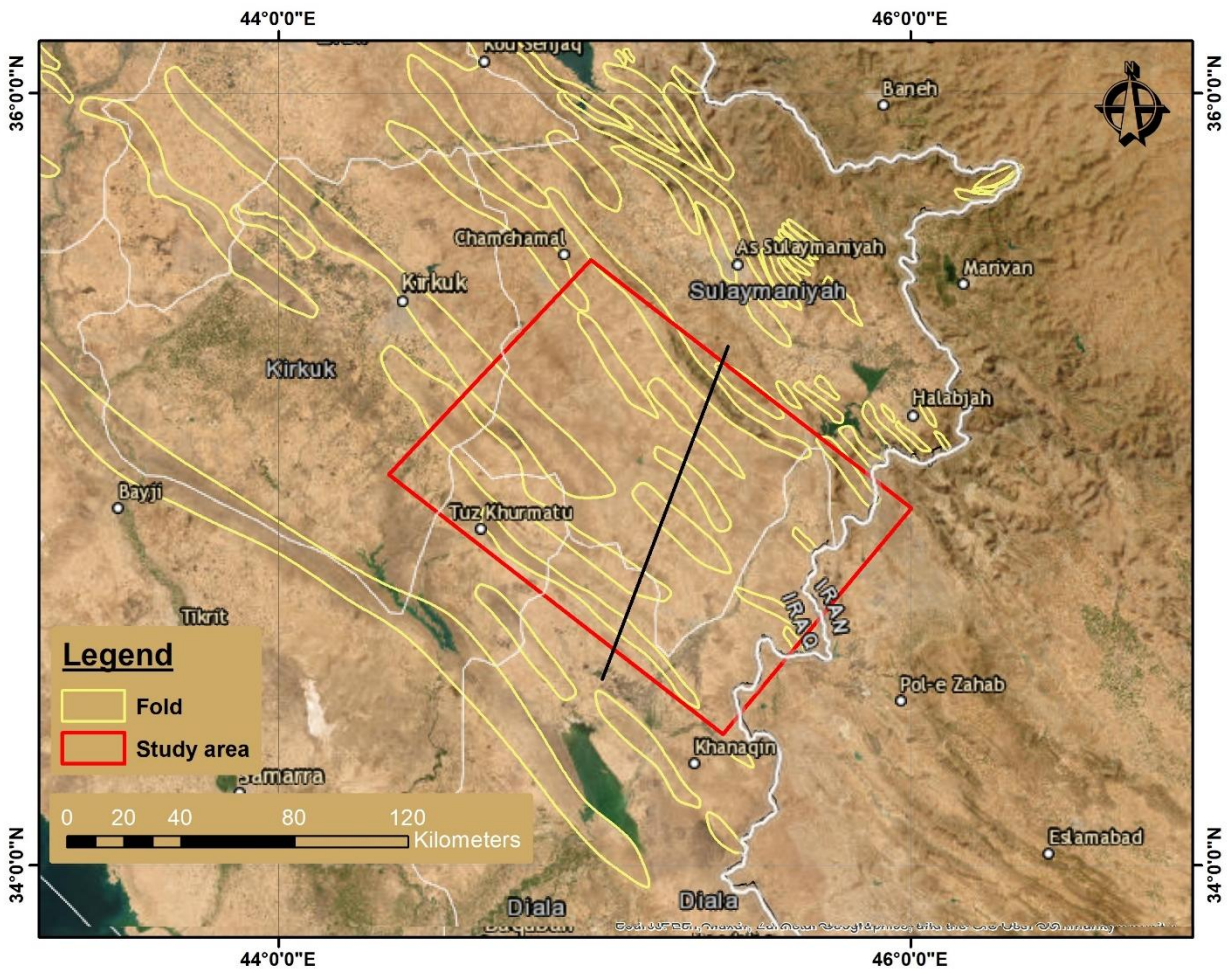


Figure 3. shows anticlines in the research region depicted on the satellite image.

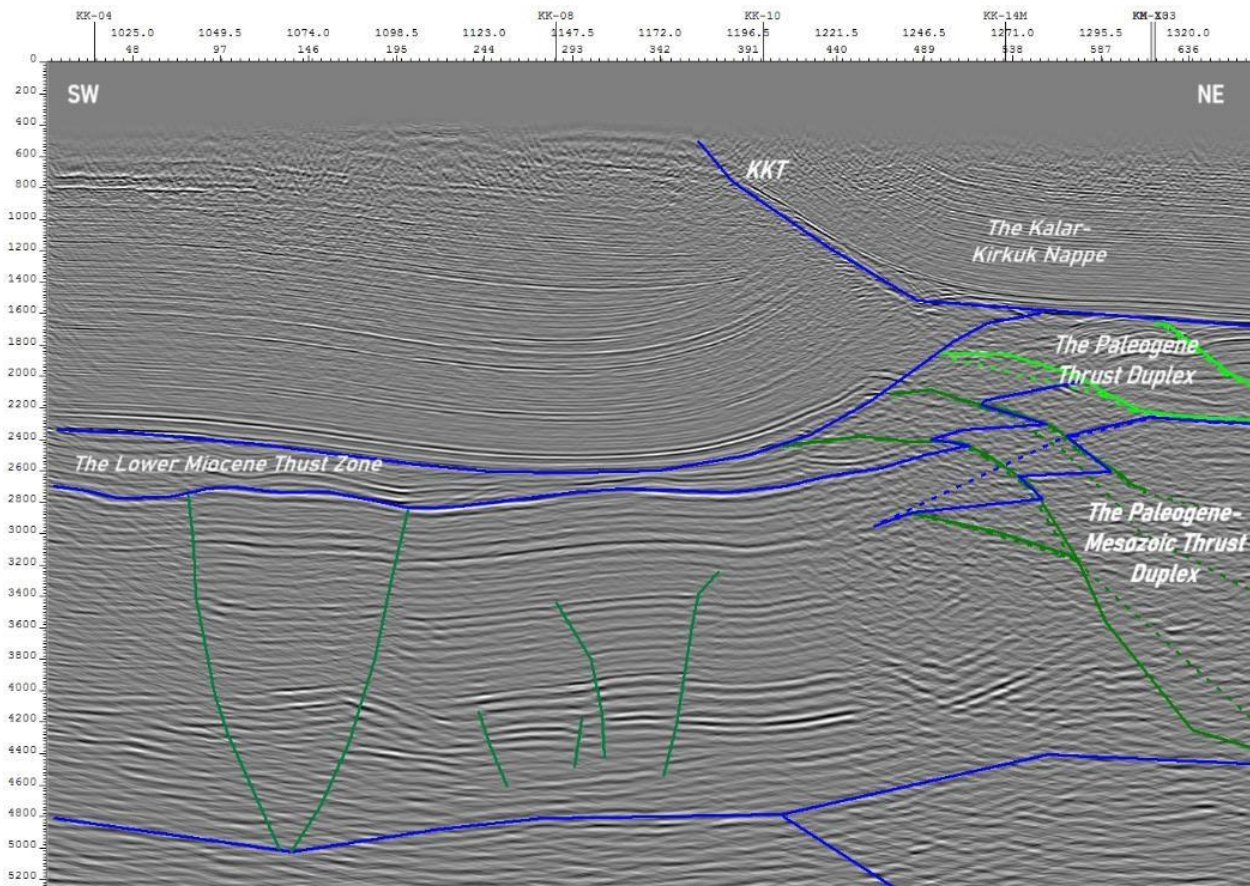


Figure 4. A south-west to north-east dip seismic section of the studied area (Gulf Keystone Petroleum, 2010).

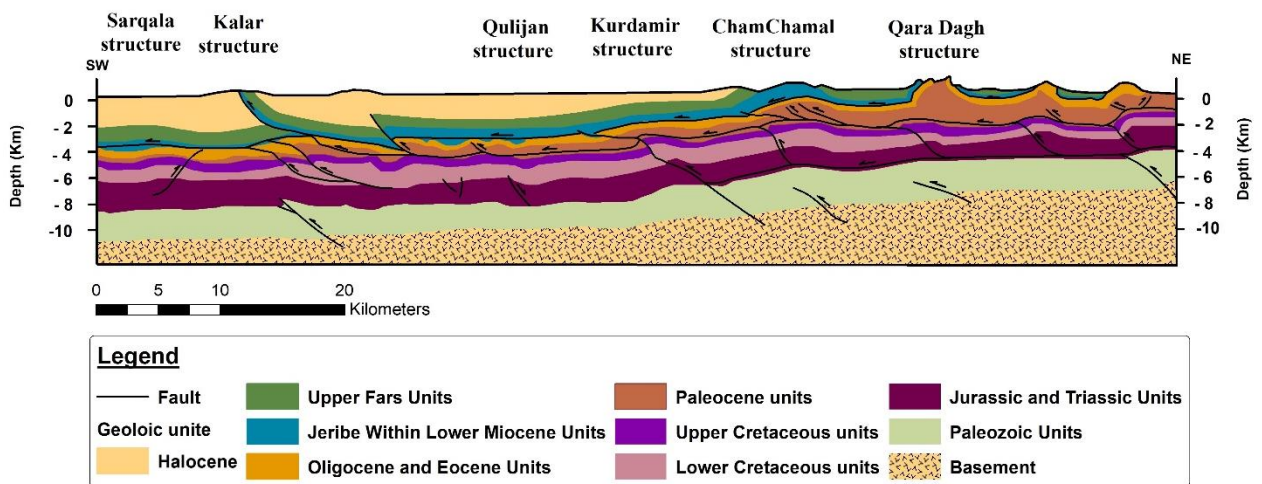


Figure 5. Reinstated cross-sections during the Fold-Thrust Belt in northeast Iraq.

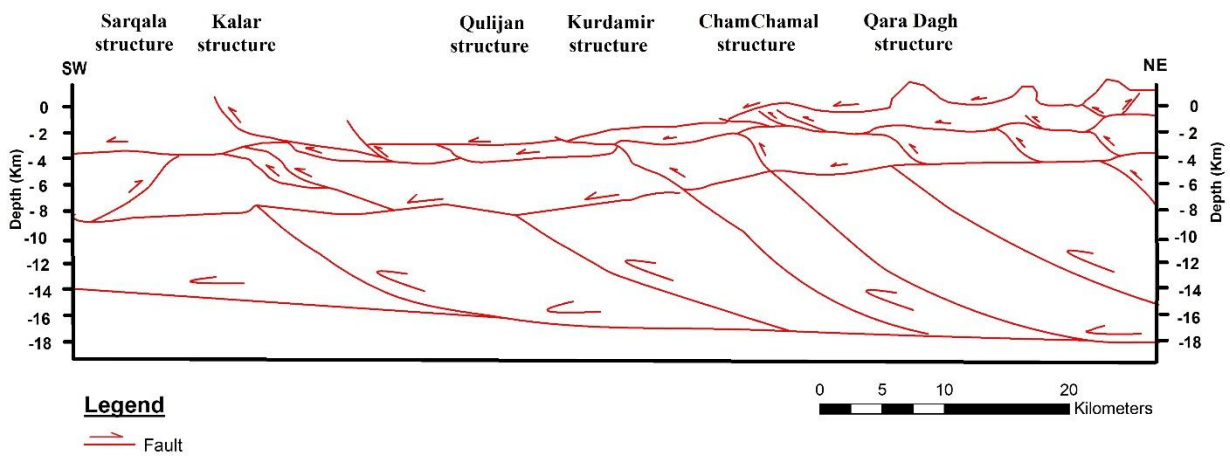


Figure 6. Kinematic model of thrusts in the studied section.

Shortening

In structural geology, mesoscale structures can be utilized to forecast larger ones. The challenges are determining the links between the small-scale structures and the bigger characteristics, and precisely analyzing the primary structure's geometric shape.

The shortening in this stretch was calculated using the line length restoration approach (Table 1). The horizon's original length was preserved when the portion was repaired. The pin line was positioned at the end of southwest of the section because the layers near which somewhat slanted also not significantly different from the regional dip. The following formula was used to determine the percentage shortening of a key bed:

$$\text{Shortening \%} = \frac{L_0 - L}{L_0} * 100 \quad \text{----- Eq.1}$$

Where L° represents the bed's starting length before the deformation, and L represents the bed's ultimate length following the deformation.

Table 1. Shortening estimates by Balanced Cross Section Method along the studied cross section.

Units	Total length in (Km) before deformation	Total length in (Km) after deformation	Shortening (Km)	Shortening %
Paleozoic Units	72.423	71.458	0.965	1.33
Triassic, Jurassic, and Cretaceous Units	74.348	71.458	2.89	3.88
Oligocene and Eocene Units	81.4125	71.458	9.9545	8.14

Conclusion

The east and south-east edges of the foreland basins are deeper and broader than the north and northwest sides, which may be connected to the varying orientations of the disturbance zones in this region. The Middle-late Cretaceous and Late-Tertiary Periods saw two significant orogenies that are responsible for the current tectonic characteristics of the Taurus and Zagros Mountains. Since the Paleozoic, faulting and vertical block movements have been ongoing. Given this tectonic background and the structural discoveries made throughout the investigation, the region's structural architecture was caused by both block faulting and compressional stresses.

The sedimentary sheet that filled and covered several tiny basins with varying sediment thicknesses, physical characteristics, and planes of detachment faults was impacted by the regional compressive stress, which was oriented NE-SW. Horizontal compressive stress was the primary cause of the sediment basin's folding, followed by vertically produced stress. Folds were likely more noticeable in heavier strata above the separation plane and greater in basins. Complex directional resolution of the stress fields in various regions of the region has resulted from the sediments' deformation and lack of stress uniformity. To fully understand the intricate interactions between tectonics, sedimentation, and petroleum systems in this area, future research should concentrate on interdisciplinary techniques.

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