Ministry of Higher Education
and Scientific Research
University of Diyala
College of Science
Department of Petroleum Geology and Minerals

Structural Analysis of Bijeel Anticline- Syncline Couple

A Thesis Submitted to the Council of the College of Science, University of Diyala in Partial Fulfillment of the Requirements for the Master Degree in Geology/ Earth Science

By
Haneen Abd-Alradha Mohammed

B.Sc. 2016

Supervised by
Prof. Dr. Asem Ahmed Hassan
Prof. Dr. Manal Shakir Al-Kubaisi

2025 A.D **IRAQ** **1446 A.H**

Abstract

This study aims to analyze the geometry of the Bijeel anticline and syncline, which situated in the Unstable Shelf Zone High Folded Zone, north of Iraq, as well as their relationship with the Aqra anticline as the major structure in the region. It also aims to conduct a structural analysis of joints, faults, veins, and stylolites to find their geometrical and genetic relationships with the principal tectonic axes of the anticline and syncline in the studied area.

To achieve these goals, the structural data (the dip and dip direction of the bedding and fracture planes) was gathered on 24 stations distributed in the study area, and by using the stereographic projection method, the folds were analyzed, and classified based on several geometric classifications, also, the fractures were classified into sets and systems based on their specific types.

The Bijeel anticline was described as an asymmetrical fold with the attitude of the north limb 010˚/82º in terms of dip direction and dip amount, while the south one shows 181/85º. Its hinge line attitude regarding trend and plunge is 094.5˚/34.5°; its axial surface attitude is 005˚-010˚/88º as dip direction, and dip amount. By relying on the attitude of the axial surfaces and the inclinations of the hinge lines, the anticline is moderately plunging-an upright fold. The interlimb angle measures 15.8°, thus categorizing the fold as a tight fold, while the Bijeel syncline has an attitudes of the northern and southern limbs are 002˚/80° and 187˚/79°, respectively. so the Bijeel syncline has a hinge line with a trend and plunge of 274.4˚/13.2°, the axial surface attitude is at 004˚/89.5° for the dip direction, and dip amount in the inner arc, but in the direction of the outer arc, the dip of the axial surface decreases until it becomes almost horizontal. The interlimb angle measures 21.6°, and according to this angle, the syncline is categorized as a tight fold. It is also classified as a gently plunging-upright fold. The hinge lines of both folds are directed east-west, and they are parallel to the hinge line in the eastern section of the Aqra anticline. Thus, they are categorized as congruous minor folds.

The results of fracture analysis showed that the main compression stress is expressed through the shear fracture system hko>a, which is in a direction almost perpendicular to the fold axis (NNE-SSW trending), whereas hko > b is an indication of the presence of secondary horizontal compression stress in parallel to the fold axis. Consequentially, the hko system may be formed by the compressional pulses, while the hko>b may be formed by the relaxation stages followed, in addition to the effect of local stress that might arise from the plunging. This system is attributed to the syn-folding fractures, also, it appears that the proportion of the joints hko>a with ac is higher than the proportion of the joints hko>b with bc, and this indicates to the high compression phase that the fold was exposed.

Most of the thrust faults that were recognized in the study area are hol acute about (c) fracture systems, which are described in comparison with the direction of flexural slip movement as synthetic faults and as antithetic faults, also, most of the veins are non-tectonic veins because the fractures are filled with blocky crystalline materials. The stylolites were running parallel to the bedding surface resulting from the weight of the overlying material.

The direction of the maximum stresses that caused the folds ($\sigma 1$) was NNE-SSW, which appeared to correspond to the direction of the stress that caused shear fractures system hko > a. This reveals that the compressional phase that made the Anticline and Syncline have formed many types of conjugate shear fractures systems, such as hko > a.

Chapter One

Introduction

1.1 Preface

Structural geology involves the study of features at various scales resulting from deformations on the Earth's surface and subsurface. These deformations, such as folds and fractures, are caused by previous alterations in the local and regional stress and strain (Rey, 2005); which can be analyzed and interpreted geometrically during the fieldwork.

Although extensive geological and structural studies have been conducted in the northern and northeastern regions of Iraq, further studies are required to fully comprehend the structural analysis and evolution of specific areas as they relate to the broader patterns of rock deformation caused by plate tectonics. Certain regions in Iraq have extensive anticlines, or anticlinorium, with a northwest-southeast orientation. These structures consist of numerous smaller folds, including anticlines and synclines (Karim, 2011). The geometrical analysis of these structures enables the determination of the local stress regimes and their relation to the major structure. In addition, determining the age relation between different features could produce the sequence of events and consequently the stress history of structural evolution (Peacoock, 2001). Furthermore, studying the surface structural features helps highlight the structural and tectonic history of selected areas and solves issues related to subsurface geological structures.

The Bjeel anticline-syncline couple is one of the geological features that has not received a comprehensive structural study. Therefore, the present study deals with the structural analysis of this couple to enhance our geological scientific knowledge in the northern region of Iraq. Studying these features has also economic importance, as anticlines and domes are potential oil locations and recharge areas for groundwater. They are also important in the industrial field, as exposure to limestone rocks makes them easy to access and exploit as raw materials in the cement industry.

1.2 Geographic Location of the Study Area:

The Bijeel anticline-syncline couple lies in the Zagros / Taurus folded belt north of Iraq and is defined by longitudes of (44° 1' 5" - 44° 1' 25" E) and latitudes of (36°43' 42" - 36°43' 54" N). More precisely, it is located in the southeastern region of the Duhok Province, which lies within the Iraqi Kurdistan Region. The Bijeel anticline-syncline couple is positioned on the south of the eastern plunging of Aqra anticline Figure (1– 1).

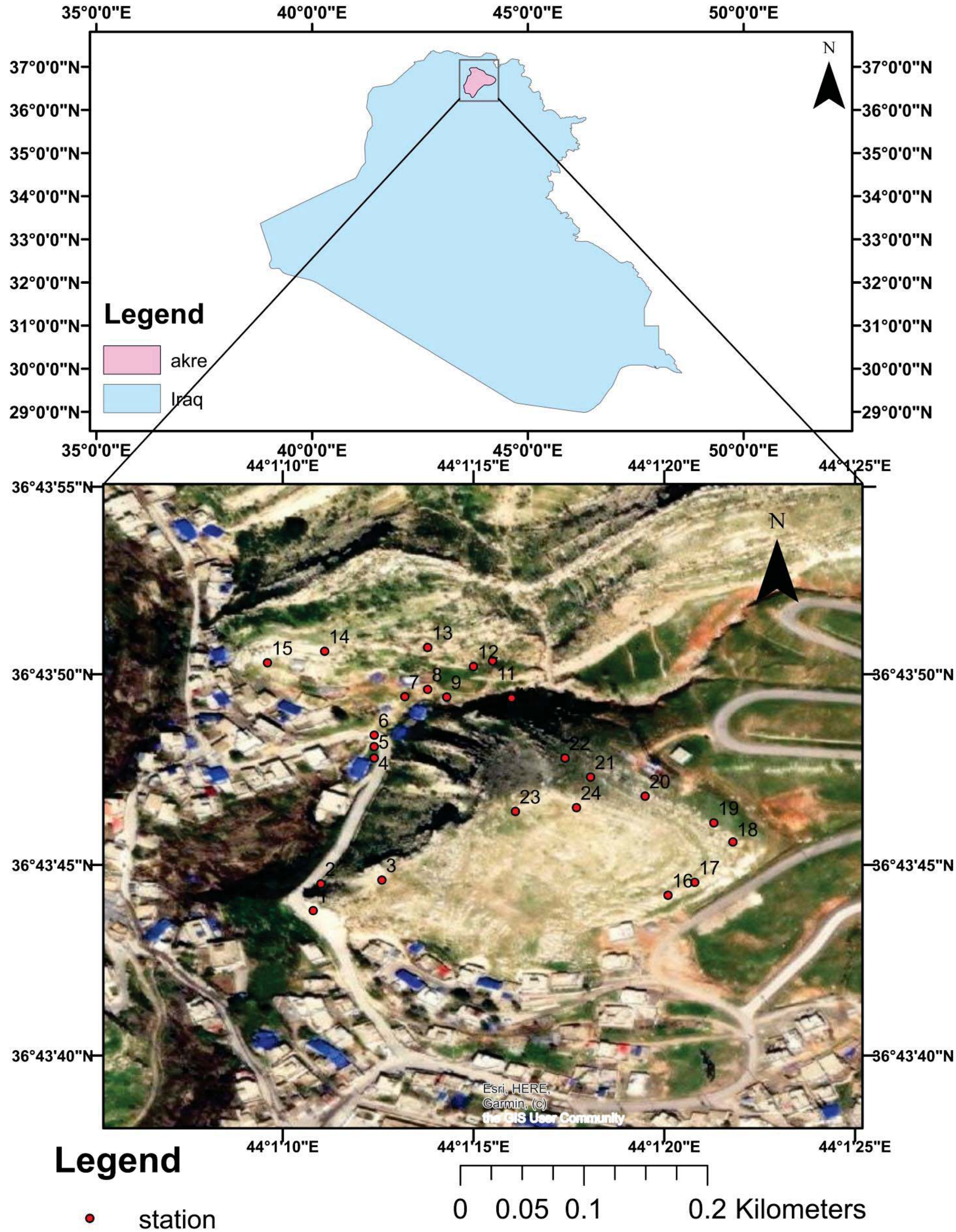

Figure (1-1): Location of the study area and distribution of the studied stations (red station)

1.3 Tectonic Setting

The Zagros Fold-Thrust Belt is a structure that arises from the convergence of the Arabian and Iranian tectonic plates, Figure (1-2). The geographical extent of this region is around 2000 kilometers, reaching from the southwestern part of Iran to the Kurdistan Region in Iraq and southeast Turkey (Alavi, 2004; Alavi,2007; Mouthereau et al., 2012).

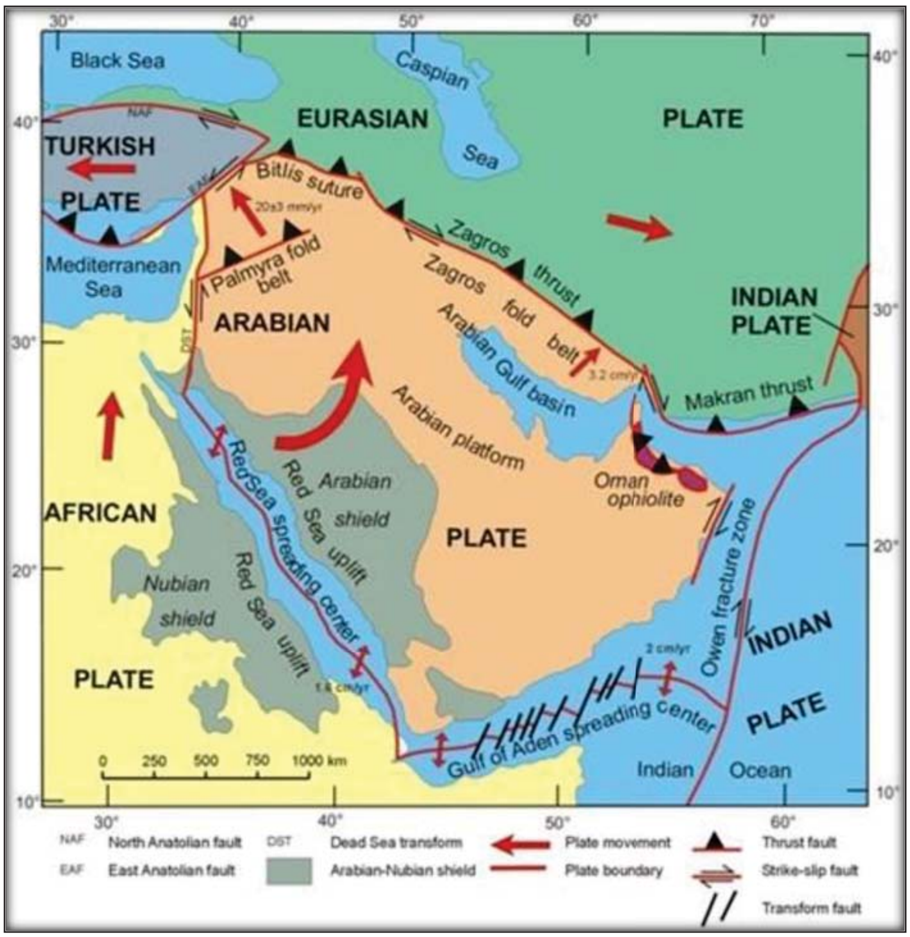

Figure (1 – 2) Boundaries of the Arabian Plate (Johnson,1998).

The Western Zagros Fold and Thrust Belt in Iraq is an essential region of the main Zagros Fold and Thrust Belt. The area is partitioned into four sub-parallel zones that exhibit variations in structural properties. The zones mentioned are the low-folded zone, the high-folded zone, the imbricate zone, and the suture zone, Figure (1-3) (Fouad, 2014).

The High Folded Zone covers approximately 400 km within the Kurdistan Region of Iraq. Its width ranges from 25 to 50 km. It is bordered by the Imbricate Zone in the north and northeast, which runs along the high Zagros reverse fault. In the south and southwest, it is bound by the Low Folded Zone, which runs along the mountain front flexure fault (Buday and Jassim, 1987; Jassim and Guff, 2006).

The study area is situated in the High-Folded Zone. This zone is characterized by the presence of large anticlines with significant amplitudes. The cores of these anticlines include exposed Palaeogene or Mesozoic carbonates. The area experienced uplift during the Cretaceous, Palaeocene, and Oligocene periods and seen significant deformation in the Late Tertiary (Fouad, 2014).

Numan (1997) discussed the occurrence and origin of several listric normal faults within the underlying basement rocks during his study of the plate tectonic scenario for the Phanerozoic succession in Iraq. He stated that these faults were formed because of the extensional stresses in the Early Triassic period due to the opening of the Neo-Tethys Ocean.

In the Cretaceous period, there was a change in the regional tectonic system from stretching to squeezing. This change occurred due to the subduction of the oceanic crust of the Neo-Tethyan, resulting in the formation of a compressive tectonic setting. Consequently, the normal displacement was prevented on the listric normal faults of the passive continental edges. Instead, these faults experienced renewed movement characterized by strike-slip and dip-slip reversal displacement. This movement led to the formation of a phase known as "block folding" in the foreland fold belt (Numan, 2000).

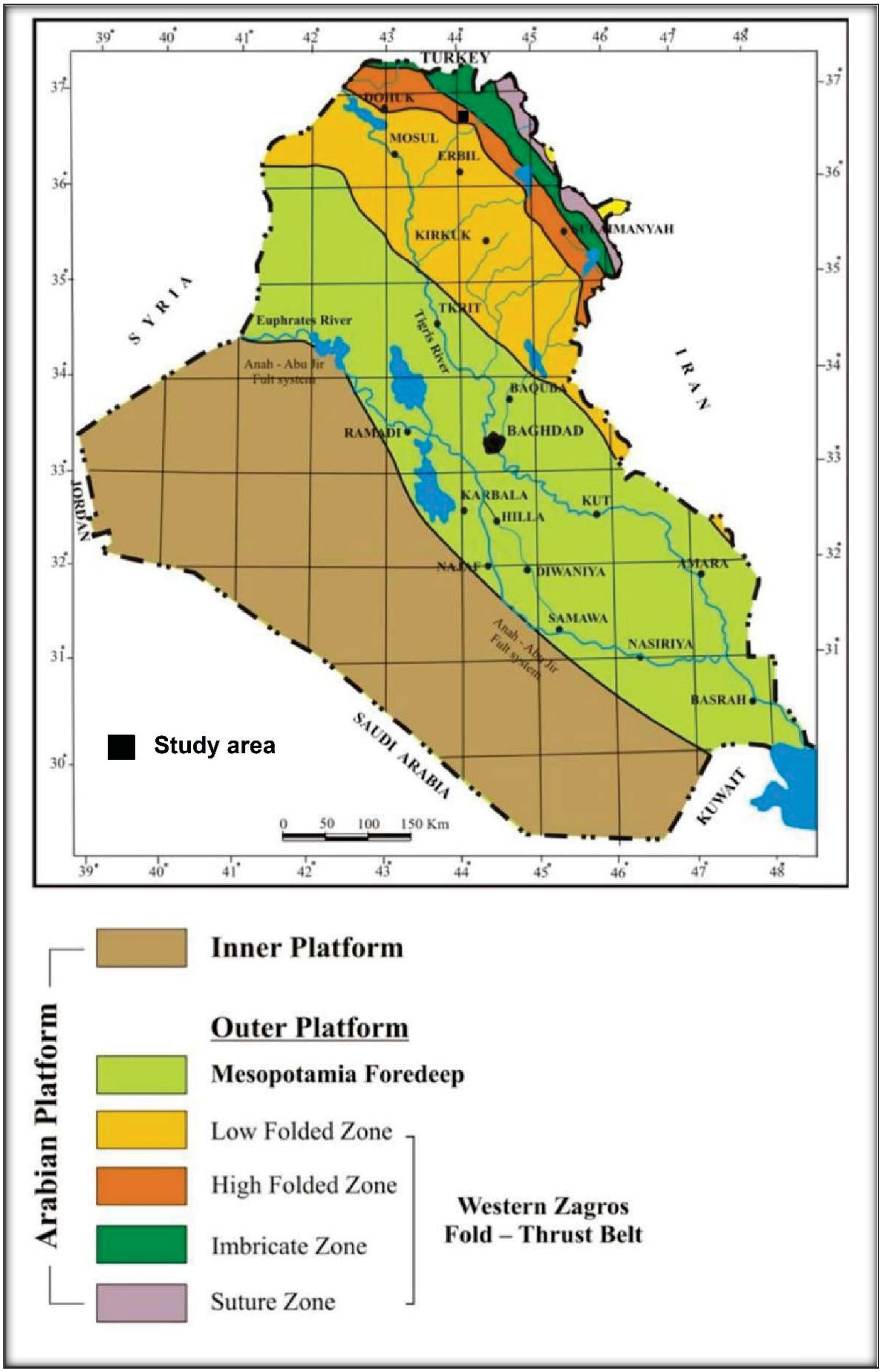

Figure (1-3): Tectonic map of Iraq (after Fouad, 2015)

1.4 Stratigraphic setting

The exposed rocks, in the studied region are represented by one formation, which is Pila Spi Formation, Figure (1-4).

The Pila Spi Formation deposited during the AP10 epoch, extending from the Early Paleocene to the Late Eocene, within the stratigraphic mega sequence of the Arabian plate (Sharland et al., 2001). This period is dominated by the ultimate convergence of the Neo-Tethys Ocean and the Arabian continental margin with the continental margins of the Turkish and Iranian Plates (Jassim and Goff, 2006).

In 1930, Less initially described this geological formation in the Pila Spi area within the High Folded Zone. Subsequently, Wetzel (1947) revised the definition, and Bellen (1957) made more modifications. The original type section was submerged by the waters of the Derbendikhan Dam. Thus, a supplemental type section was identified at Kashti, located on the Barand Dagh. This section is composed of dolomitic chalky limestone, including chert nodules. It was formed in a shallow lagoon environment (Jassim and Goff, 2006).

The thickness of Pila Spi Formation ranges from 100 to 200 m (Jassim and Goff, 2006). The lithology within the typical section of the formations has two distinguishable sections: The lower section has well-bedded limestones that possess a hard and chalk-like appearance (Bellen et al., 1959). The upper section consists of well-bedded, bituminous limestone, which exhibits a white, chalky, and crystalline weathering appearance. The formation also includes layers of light green marl with folded bedding planes or chalky marl with folded bedding planes and strips of chert nodules located in the upper section.

Within the High Folded Zone, the Pila Spi Formation is prominently visible and is characterized by high scarps. It serves as an edge separating the High-

Folded from Low-Folded zones in several regions of Iraq (Sissakian and Al Jiburi, 2014).

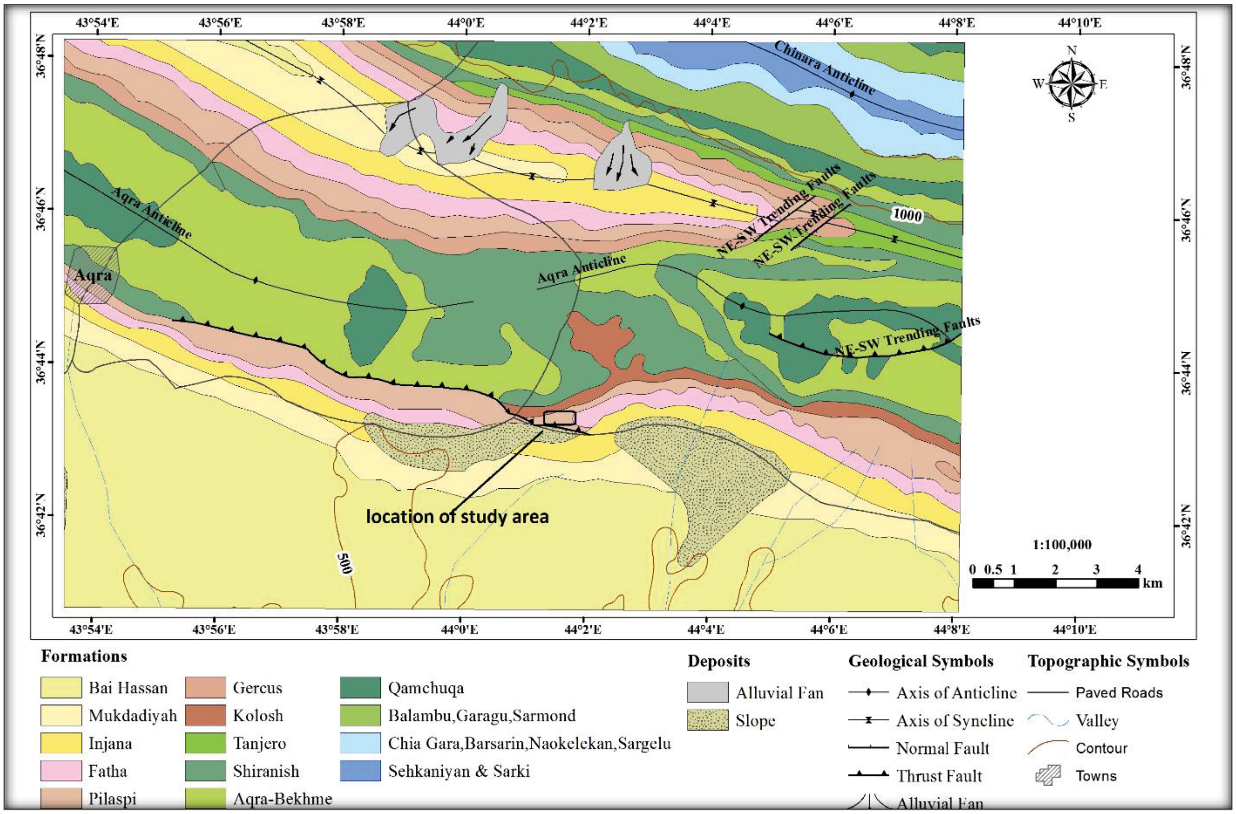

Figure (1-4): Stratigraphic map of the study area(Geological Survey After Sissakian and Fouad, 2012)

1.5 Objectives of the study

The study aims to conduct a structural analysis of the Bijeel anticline-syncline couple and to improve the understanding of fracture patterns in the folds. The specific objectives can be listed as follows:

1. Geometrical analysis of the Bijeel anticline-syncline couple.
2. Determine the direction of the stresses that formed the Bijeel anticline and the syncline as well as their relationship with the Aqra anticline as the major structure in the region.
3. Investigating the type of folding mechanism associated with the stress exerted on layered rocks.

4. Making fracture analyses of the joints, faults, and stylolites to find their geometrical relationships also their genetic relationships with principal tectonic axes of the anticline and syncline in the study area.

1.6 The Previous Studies

Extensive geological (tectonic, stratigraphic, and structural) studies have been conducted in the north and northeast parts of Iraq. This section is dedicated to reviewing the main findings of these studies.

Marouf (1983) conducted a thorough examination of the fractures and minor structures in the Aqra structure, analyzing their geometric and mechanical correlation with the overall geometry of the Aqra structure. Within this examination of the minor structures, the existence of the Bijeel fold was identified ,and characterized by the presence of both an anticline and a syncline. However, there was not a comprehensive study of the Bijeel fold.

Taha et al, (1995). the microtectonics of the Dokan area in NE Iraq was examined, and the area experienced two significant tectonic phases of compression, with one occurring in the NNE-SSW direction and the other in the E-W direction.

Al-Kubaisi, 2000. A morphotectonic investigation was conducted on the Tigris River and its tributary basins within the folded region of Iraq. The investigation of longitudinal cross sections of the basin revealed a link between structural variables and lithology that influences the type of drainage pattern. Linear structural analysis revealed that the overall trend of the tributaries aligns with the general orientation of the transversal faults.

Omar (2005) carried out an extensive investigation of the Bina Bawi-Safin-Bradost Area in Iraqi Kurdistan, examining both its structural and tectonic aspects. The study revealed the occurrence of multiple phases of deformation in the region. A detailed structural map, drawn for the folds in the area, suggested that the majority of the folds are fault-propagation folds, fault-bend folds, or a combination of both.

Zebari (2013) conducted a study on the geometric characteristics and development of fold structures in northeast Iraq, and explained the deformation style within the zone, depending on the field data and seismic section interpretation. the depth of the detachment level to be within the Triassic units of the sedimentary cover was estimated, also the seismic sections was interpreted, one of them near the Bekhme Gorge. Moreover, constructed two geological cross-sections, one of which passed through Akre and Piris Anticlines. The degree of shortening along the Akre section was quantified to be between 20% and 29% through the process of balancing and restoring this specific cross-section.

Barno (2014) performed the structural geology study in Sulaimaniyah Province, Iraq. the fold geometry and the paleostress direction and categorized the fractures was discussed. Furthermore, the development of the Kosrat Anticline was impacted by the tectonic inversion that occurred during the Zagros Orogeny was determined.

Fouad (2014) studied the High Folded Zone within the Western Zagros Fold and Thrust Belt. The folds were generated by the presence of more than one type of folding mechanism, based on the different geometries and sizes of the folds in the zone, and the fault-propagation folds appear to dominate fold types in the high-folded zone were concluded.

Shihab and Al-Obaidi, (2016) analyzed the geometry and structural properties of the High Folded Zone between Harir and Bradost folds in the Duhok Province of Iraq using several techniques. Satellite images, GIS, and fieldwork were used to analyze fold types and thrust systems. Attitudes of bedding planes were extracted using the Structural Contour Lines (SCL) method and compared with attitudes measured in the field. The study aimed to determine geometric and structural deformation analyses and modify the geological and structural map of the studied zone. The investigation revealed that faults were created sequentially as the deformation front moved from the impact zone toward the northeast.

Awdal et al., (2016) studied the fracture patterns and petrophysical properties of carbonates that were experiencing regional folding processes in Kurdistan, N Iraq. They found fracturing processes consist of three stages: pre folding fractures, early folding fractures, and post folding fractures. The study also revealed that the petrophysical characteristics, specifically porosity and permeability, of both the Kurra Chine and Sehkaniyan formations were highest in the hinges and backlimbs of the Gara Anticline.

Ward and Al-Kubaisi (2018a) studied the structural evolution in the Khalakan anticline and the formation of the Dokan conglomerate, NE Iraq. Their study revealed that the growth of this anticline took place during the Late Miocene and expanded further during the Late Pliocene as a fold associated with the back thrust fault. The study determined that the Conglomerate of Dokan was deposited above this anticline due to back-thrusting resulting from the structural evolution of the anticline. As a result, in the Pliocene epoch, boulders from the Pila Spi Formation were deposited by rivers on the southwestern side of the anticline, while clay was deposited on the northeastern side.

In their study, Ward and Al-Kubaisi (2018b) explored the geometry of the Khalakan anticline in northeastern Iraq. Field data from the Qamchuqa and Kometan formations and characterized the anticline as an asymmetrical and overturned fold with northeastern vergency was analyzed. The average orientation of the NE and SW limbs was found to be 220°/89° and 219°/55°, respectively. The axis of the fold has a trend of 130° and a plunging of 1°. Its axial plane has a dip direction of 220° and a dip amount of 72°. The interlimb angle measures 34°.

Therefore, the fold is classed as a close fold.

Al-Sumaidaie and Al-Azzawi (2018) made the structural and tectonic study of Brifka anticline, northern Iraq. The geometrical analysis of this fold revealed that the anticline is asymmetrical, mostly overturned and verged towards the southwest in all traverses, except in the fourth traverse it appears verging towards the south. The axis of the anticline is oriented NE -SW in the first three traverses whereas it trended toward E- W in the fourth one.

Ghafur et al. (2019) studied the Aqra anticline north of Iraq by employing satellite images to interpret geomorphological features; these features include water gaps, wind gaps, forked-shaped valleys, curved valleys, and inclined valleys. They reveal the lateral growth of the anticline.

Hameed and Alkubaisi (2019) study examined the structural factors influencing rock slope stability in the Bammo Anticline, northeastern Iraq. The research identified various types of rock failures, ranked from most to least abundant: rock falls, toppling, plane sliding, and occasionally rolling. The study identified a range of hazard classifications in the examined area, spanning from "very low hazard" to "high hazard."

Hussien et al. (2020) examine the influence of geological structures on rock slope stability in the northwest plunge of the Surdash anticline, Sulaimaniya, northeastern Iraq. The stability was assessed using kinematic analysis with DIPS software. This analysis indicates that planar sliding is feasible at certain stations, whereas wedge sliding is viable at others. The remaining stations generally stable. The geological structure was determined to have a negative effect, contributing to the failure in the research area. Nevertheless, in certain locations, it facilitated a transition from unstable to stable conditions.

Shakir and Barno (2020) studied and classified rock joint analysis to determine the main stress field in the Bustanah structure in northeast Iraq. They discovered two prevailing joint systems, hko>a (first) and hko>b (second), which were observed in the majority of the surveyed locations. The main orientation of the stress field, as determined by the joint's categorization, is in the northeast-southwest direction, which aligns with the convergence of the Arabian and Iranian tectonic plates. The northwestern orientation, ranking second, is likely attributed to the Arabian plate rotation and the impact of localized stress within the area.

Ahmed and Salman (2020) studied the geology and structural description of the Shakrok anticline in northern Iraq. and they classified this anticline as asymmetrical, double-plunging, and verging toward the northeast. It has a trending direction of NW-SE, which is parallel to the main Zagros orogenic trends. The Shakrok Anticline, characterized by Cretaceous successions, was formed as a result of the Cretaceous and Tertiary folding periods. The anticline's fold axis had a 16-degree anticlockwise rotation from Merawa to Sork anticlines, which was caused by the rotation of the Arabian plate that arose due to its impact on the Iranian and Anatolian tectonic plates.

Based on the literature review, the fractures within Bijeel anticline and syncline have not been described and classified. Consequently, a structural analysis, involving geometric and genetic analyses, was conducted to determine the type and origin of the folds and fractures in addition to determining their relevance to the primary regional tectonic events.

1.7 Thesis Organization

The current study consists of five chapters. Chapter One presents a brief introduction to the current thesis. It describes the location and geological background of the study area and High Folded Zone. Furthermore, this chapter provides a literature review of the previous studies, the objectives of the study, and the thesis layout and organization.

Chapter Two discusses the theoretical background and main methods employed in this work. In addition, the nature of the fieldwork and office work carried out are described.

Chapter Three shows the main findings related to fold characterization. The stereographic projection drawn of the Bijeel anticline and syncline as well as their classification based on several geometric classifications are discussed. Furthermore, the type of folding mechanism that determines how layers fold is identified and discussed.

Chapter Four, the fractures, such as joints, faults, veins, and stylolites, are discussed and analyzed in relation to the principle tectonic axes of the anticline and syncline. Additionally, drawing a stereographic projection for these fractures and discussing them.

Finally, Chapter Five summarizes the main conclusions of the current study and suggests recommendations to be considered for future work.