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STRATEGIC DRILLING DECISIONS BASED ON SEISMIC FAULT INCLINATION ANALYSIS FOR ENHANCING HYDROCARBON RECOVERY IN THE BIJEEL AND HARIR OIL FIELDS, KURDISTAN REGION, NORTH IRAQ

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Abstract

The seismic method is a well-established technique for delineating subsurface structures and gathering information. This study focuses on the Bijeel and Harir Oil Fields to ascertain subsurface data using seismic techniques. 3D and 2D seismic profiles were employed in the Bijeel and Harir blocks, respectively. The 3D seismic profiles reveal the subsurface structure of the Bijeel block, exposing various faults and folds. Reflected lines in the profiles extend to Triassic depths, enabling an investigation into the area's geological structure. This information provides valuable insights into the geological characteristics and structural setting of the Bijeel block, aiding in the detailed drilling process and hydrocarbon recovery of this oil field's subsurface formations. The 2D seismic profile of the Harir field, particularly in the Mirawa (well-1) and Harir (well-1) area, depicts significant fluctuations in reflected lines, indicating the presence of a major anticline within the subsurface. Based on the interpretation, numerous faults and folds were identified in this oil field and subsurface formations. These identifications assist oil drilling companies in selecting suitable locations and directions for development drilling operations to enhance hydrocarbon recovery in the fields.

Keywords: Subsurface Geology; Seismic Fault Inclination; Hydrocarbon Recovery; Bijeel and Harir Oil Fields; Kurdistan Region.

1. Introduction

The Zagros Fold-Thrust belt is home to one of the world's largest petroleum-producing reservoirs (Omer & Syan, 2017). Seismic exploration is the search for commercial economic subsurface deposits of crude oil, natural gas, and minerals by the recording, processing, and interpretation of artificially induced shock waves in the earth (Milsom, 2003). Seismic exploration techniques have long been used in geophysical studies to investigate the subsurface structure and the properties of geological formations. Seismic methods provide key subsurface

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information for structural geologists and have become highly effective in imaging even complex geological settings (Abdulkareem, 2025). The seismic method is of great importance in understanding the tectonic situation. It also identifies the major anticlines, including folds, faults, and their effects on the geological sedimentary cover and formation thickness (Al-Banna et al., 2024). The influence of folds, faults, and other structural features on the sedimentary cover and formation thickness is crucial for understanding subsurface geology. These structures can cause variations in formation thickness due to compression, extension, or fault displacement. Their identification helps in delineating hydrocarbon traps, reservoir continuity, and subsurface stratigraphy, which is essential for hydrocarbon exploration and reservoir characterization.

Seismic interpretation primarily aims to provide a geological description of the subsurface. The accuracy of the interpretation depends on the quality of seismic data, where higher-quality data yield more precise interpretations (Herron, 2011). Structural interpretation involves generating time, velocity, depth, and isopach maps, which illustrate variations between two seismic events or reflections of the studied formations in the depth domain (McQuillin, 1984). Seismic reflections occur at interfaces where the acoustic properties of rocks change, serving as a key factor in understanding seismic data. The acoustic impedance of a rock layer is the product of its density and velocity, and reflections are generated by contrasts in acoustic impedance. Since impedance and lithology typically correlate, impedance boundaries generally coincide with lithological boundaries (Brown, 2011).

Numerous oilfields in Iraq have undergone extensive seismic surveys to learn more about their subsurface geology. For the most accurate picture of the stratigraphy and structure, researchers say that the seismic reflection approach provides an outstanding depiction of the subsurface geology and provides good evidence of oil deposits (Faisal & Ali, 2021). Almost all exploration activities in Kurdistan have historically relied on 2-D seismic surveys combined with exploration wells. The 2-D seismic method provides essential structural information but is often limited in its ability to capture the full complexity of subsurface geology, particularly in highly deformed regions. However, in recent years, several 3-D seismic surveys have been acquired, offering more detailed and comprehensive images of the subsurface. The enhanced resolution and spatial coverage of 3-D seismic data improve the accuracy of structural and stratigraphic interpretations, leading to better delineation of hydrocarbon reservoirs. This advancement is expected to contribute significantly to production optimization and reserve estimation, especially in geologically complex areas where subtle structures and reservoir compartmentalization play a critical role in hydrocarbon accumulation (Mackertich & Samarrai, 2015).

The analysis of the regional seismic line in Iraq has provided valuable insights into the subsurface characteristics of the Jurassic and Triassic formations (Baban et al., 2019). In a two-dimensional (2D) reflection seismic survey, both the sound source and the sound detectors (numbering up to a hundred or more per shot) are moved along a straight line. The same line contains recording cables and geophones as well as source points. The resultant product can be thought of as a vertical sonic cross-section of the subsurface beneath the survey line (Abdullah et al., 2021). The extent of this seismic activity reached the Triassic period and particularly the Kurra Chine Formation. This formation is the thickest formation within the Triassic period (Aswad et al., 2024). In three-dimensional (3D) reflection seismic surveying, the sound detectors (numbering up to a thousand or more) are spread out over an area, and the sound source is moved from one location to another. 3D seismic programs are generally a uniform and evenly spaced grid of lines. Receiver lines containing recording devices (geophones) usually, but not always, run in a direction perpendicular or diagonal to the source lines (Al-Rahim & Fadhel, 2025). The thickness of the lithology will help sonic impedance to identify the seismic lines. The Kurra Chine Formation can be easily recognized from seismic data due to its bed thickness and its lateral extension (Aswad, 2020). The resultant product can be thought of as a cube of common depth point stacked reflections. Advantages over 2D include the additional dimension, the fact that many more reflections are available for stacking at each point, which provides greatly improved resolution of subsurface features, and the elimination of the "ghost" or "side swipe" reflections from nearby offline features that 2D surveys are prone to (Alhadithi, 2021). Currently, there are more scientific approaches, such as using a combination of geological information with seismic surveys and subsurface structure, that are applied to recognize the location of the oil and gas. The direct hydrocarbon indicators technique is used for predicting the presence of hydrocarbons in many oil fields around the world (Khawaja et al., 2023). These methods will help to accurately distinguish the drilling location and increase hydrocarbon recovery (Cox et al., 2020). The current study aims to address this gap by providing a detailed analysis of the seismic interpretation to enhance the hydrocarbon recovery. Additionally, it recognizes most Jurassic and Triassic formations in the Kurdistan Region. Integrating seismic and well logging data provides a comprehensive approach to determining reservoir characteristics (Gardi et al., 2024). The primary research question of this study is to comprehensively evaluate the role of fault in drilling and hydrocarbon recovery within the oil production fields in the northern Iraq Kurdistan Region. The results of this research will contribute to filling a long-standing knowledge gap in northern Iraqi oil wells, offering insights into the enhanced production of oil in these fields. This study holds significant importance as it aims to detail the analysis of faults and folds in the Jurassic and Triassic periods in both fields, enabling a better understanding of the drilling direction within the reservoir units.

2. Location and Tectonic Setting of the Studied Area

The study area encompasses two oilfields. The first is the Harir Oilfield, located approximately 70 kilometers northeast of Erbil city within the Kurdistan Region of northern Iraq (Figure 1 green zones). The second is the Akri-Bijeel Block, situated east of the Sheikhan Block, covering an area of 889 km². Topographically, the Akri-Bijeel Block is divided into two distinct regions. The northern portion features a series of mountains with elevations reaching up to 1,500 meters above sea level, oriented approximately in an east-west direction. In contrast, the southern part consists of gently rolling hills and plateau-like terrain, with an average elevation of around 500 meters above sea level (Csontos et al., 2011).

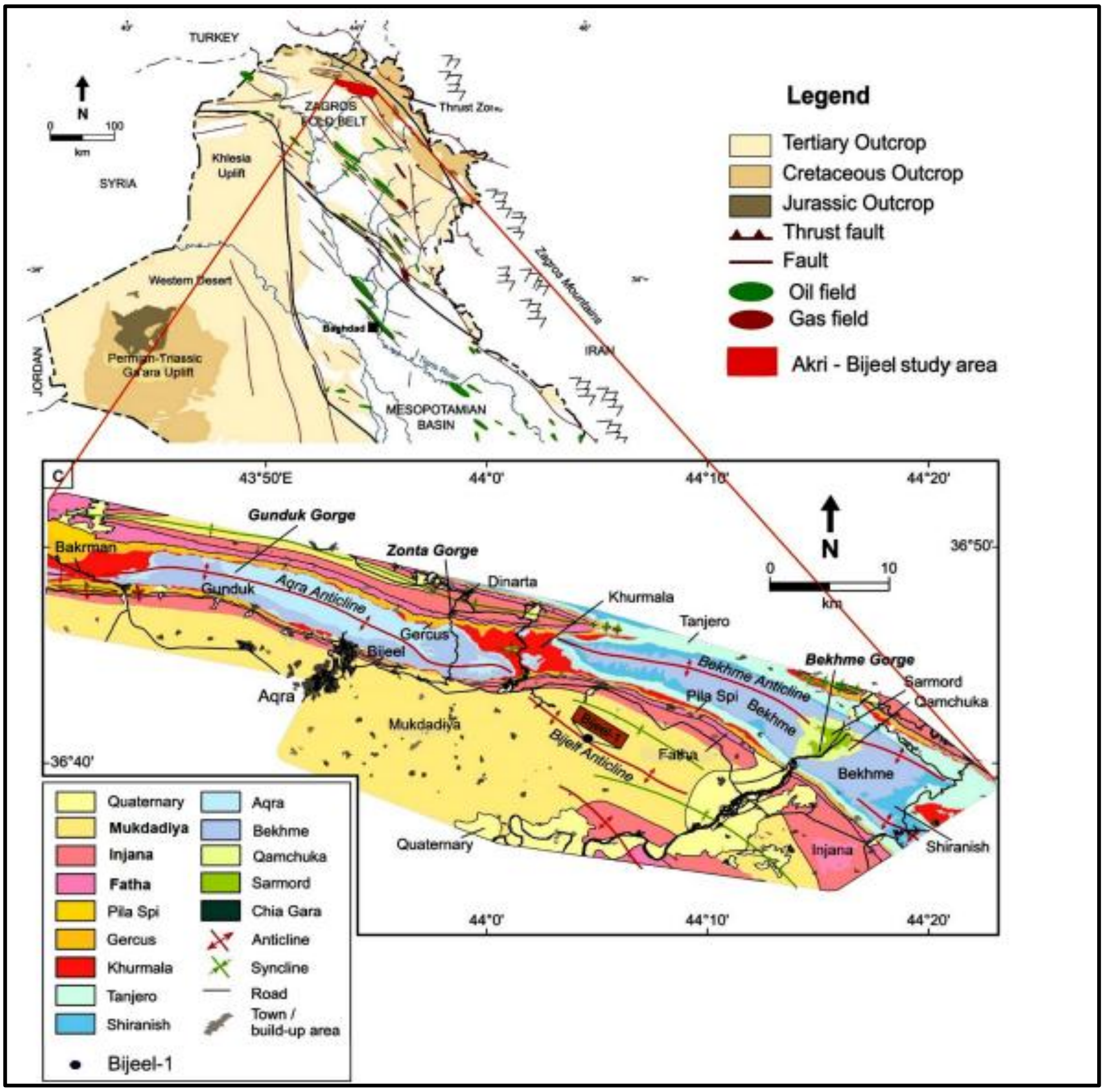

Figure 1. The geological setting of the studied area (modified after Omer & Syan, 2017, and Abdullah, 2020). The green zone delineates the High-Foldded Zone where the studied area lies.

Tectonically, both fields are located at the Unstable Shelf of the High Folded Zone. The subzone is notable for its wide and deep Anticlines (Jassim & Buday, 2006) and (Ahmed & Khawaja, 2024). The Akri-Bijeel and Harir Blocks are located in northeastern Iraq, within the tectonic collision zone between the Arabian and Iranian plates (Jassim & Buday, 2006). The region is characterized by steeply dipping Mesozoic strata, particularly along the limbs of anticlines extending from Bijeel to Akri and Bakrman. Numerous thrust faults are exposed along the southern limbs of the Aqra and Pirat anticlines (Abdula et al., 2020). A total of seven wells have been drilled in the Bijeel Block, along with two wells in the Bakrman and Bekhma areas (Figure 2). The Harir and Shakrok anticlines, located on the northern limbs of these major folds, indicate the presence of underlying thrust faults beneath the limbs (Csontos et al., 2011). The Harir area is located within the Zagros High-Folded Zone, which is characterized by relatively long and high-amplitude anticlines. Most of these anticlines are asymmetrical, associated with thrust/ reverse faults along their southern or southwestern limbs, and could be either faultpropagation or fault-bend folds. They also represent the last NW – SE trending structures in the Zagros Fold-Thrust Belt before the belt changes its trend to E – W. The High-Folded Zone was affected by the transversal fault system, which reactivated from late Jurassic time onward, resulting in the formation of transversal blocks. Many anticlines are segmented into separate domes, and their fold axis is bent at the intersection with these transversal faults (Omer & Syan, 2017).

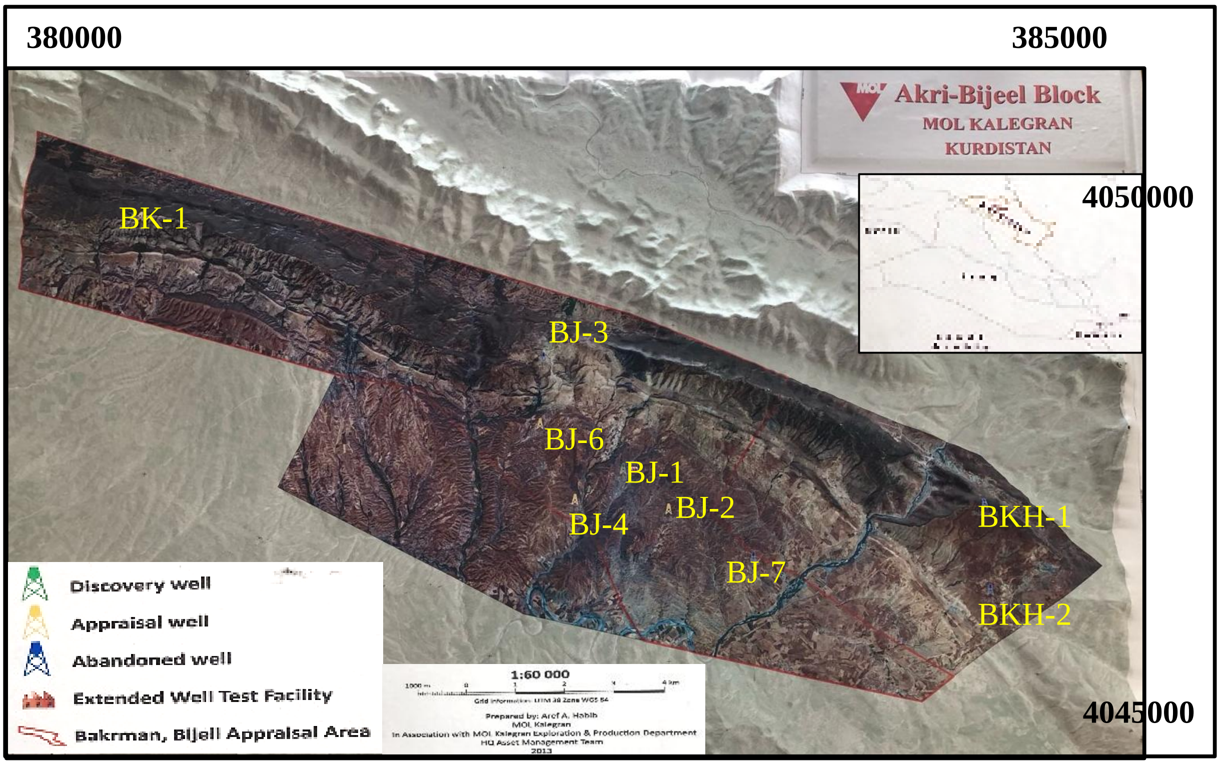

Figure 2. The Bijeel block and drilled wells are shown in yellow around the area.

3. Materials and methods

The research involved seismic interpretation and fault analysis based on the 3D and 2D seismic surveys. Seismic data acquired from two blocks within the Kurdistan region of Iraq. The study focused on subsurface geology and drilling direction by analyzing fault extensions in the area. The seismic lines penetrate Jurassic and Triassic Formations, with a 3D seismic reflection survey conducted for the Bejill oil field and 2D seismic surveys for the Harir oil field. The seismic data were obtained from international oil companies following standard acquisition and processing procedures.

3.1. Fieldwork

3.1.1. Line clearance

Before any movement begins in the field, it is essential to clear areas where vehicles or employees traverse Unexploded Ordnance (UXO) and Explosive Remnants of War (ERW). This will help the seismic process and crew avoid any injuries and explosions from the old war in the area. These areas are made safe either through core clearance or the application of two different paints, red and white. White paint indicates a safe walking path, while red paint signals that the area has not been cored and is unsafe for walking. The objective of these teams is to clear seismic lines in advance of a geophysical survey and to guarantee the safety of both the survey teams and their vehicles and equipment (Figure 3a).

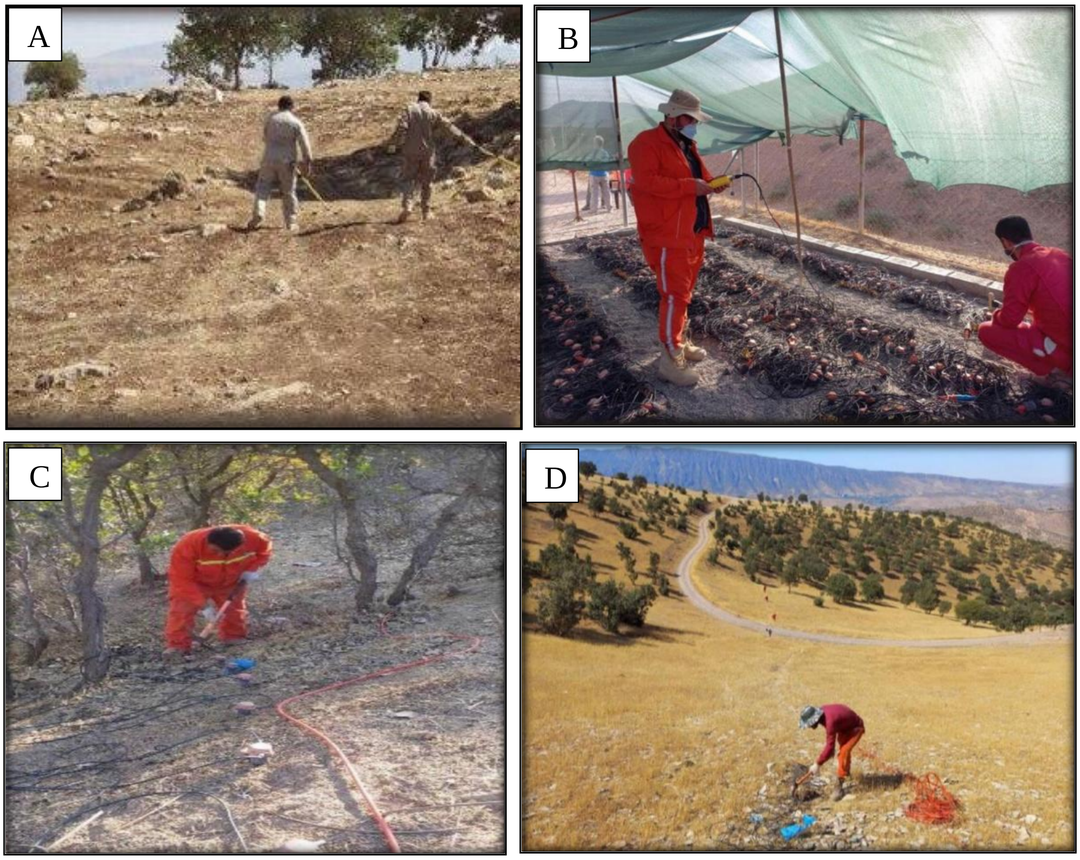

Figure 3. Geophone installation and layout crew operation in the Harir Block field.

3.1.2. Leakage Test (LT)

The first test is LT; the geophones are submerged in water and subsequently connected to a material that displays LT. If the test finds any breaks and cracks in the cable and geophones, then it will be rejected and changed with better tools. This test will show disconnectivity between lines. The second test is the Surgical Geophone Test (SGT), which was conducted by a group in the cable shop. They connected the geophones to an SGT tester and subjected each geophone to impacts using a hammer. Any issues with the geophones would be displayed on the tester's screen during this procedure (Figure 3b).

3.1.3. Installing Geophones and Layout Crew

Planting geophones along a straight line, generating seismic waves through detonation (using explosives) or vibrators, and recording the reflected waves. The crew's initial task is to lay out the geophones along the seismic receiver lines. The geophones should be positioned according to QC (Quality Control) standards. Surveyors mark the locations for geophone placement every 25 meters using blue color spray. Sensor cables are distributed across the field. These cables are linked by a connecting device. The devices' ends are attached to the FDU (Field Data Unit) device, and all the collected information is transmitted to the destination through the red cable. Secondly, a specialized device detects wave vibrations, particularly in flat areas away from mountainous regions. This device is capable of conducting both 2D and 3D surveys, utilizing a total of 6 kg of explosives (Figure 3c and d).

3.2. Field equipment

Many pieces of equipment were used during the seismic process. After using this equipment, we can do the seismic lines based on the traverse and truck systems, which are line cables, geophones, vibrators, explosives, recording truck, and crew (Figures 4a – f).

3.3. Office work

After finishing the fieldwork, we will start the conversion recorded from the FDU to computer processing. Data Processing and interpretation are the main office work in this study. The raw data of the computer processing was the job of the petrophysics to evaluate and analyze the subsurface seismic lines. 2D and 3D seismic reflection surveys are indispensable methods for oil and gas exploration and reservoir development. Their ability to provide detailed, three-dimensional images of the subsurface makes them invaluable for identifying and evaluating potential hydrocarbon reservoirs, ultimately aiding in the discovery and production of oil and gas resources. The acquisition and data processing of the survey were achieved using Petrel software by oil exploration companies. These seismic lines covered an area of 889 km^2 and 700 km^2 for the Bijeel and Harir blocks, respectively.

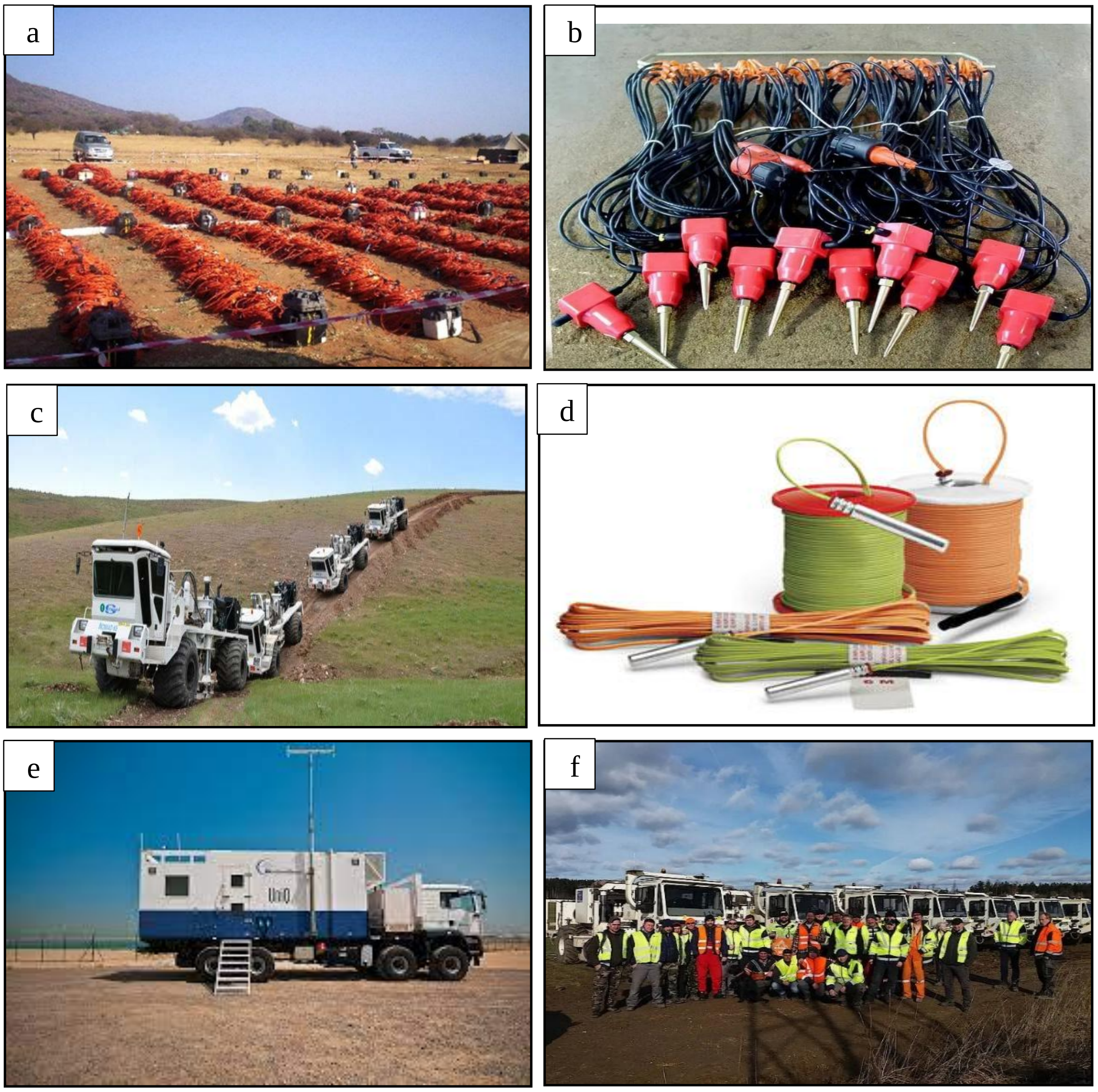

Figure 4. Seismic field equipment at the Hariri field, Erbil, Iraq, including (a- line cables, b- geophones, c- explosives cables, d- vibrators, e- dog room, f- seismic crew).

4. Results

The final and most critical step in any seismic exploration endeavor is the seismic interpretation. The final results for both fields were conducted by Petroleum Gulf Geophysics, which permits the use of the data, published in (Aswad et al., 2024) and presented in (Figures 5 – 7).

4.1. Bijeel Block

The 3D seismic profiles of the Bijeel block reveal the subsurface structure of the Bijeel block (Figure 5). The section extends to a depth of 4500 meters, enabling an investigation into the geological structure of the studied area.

Upon initial observation of the profile, a significant feature known as the major anticline is prominent within the field. This information provides valuable insights into the geological characteristics and structural composition of the Bijeel block, aiding in further exploration and understanding of the subsurface formations in the area (Figures 5 and 6).

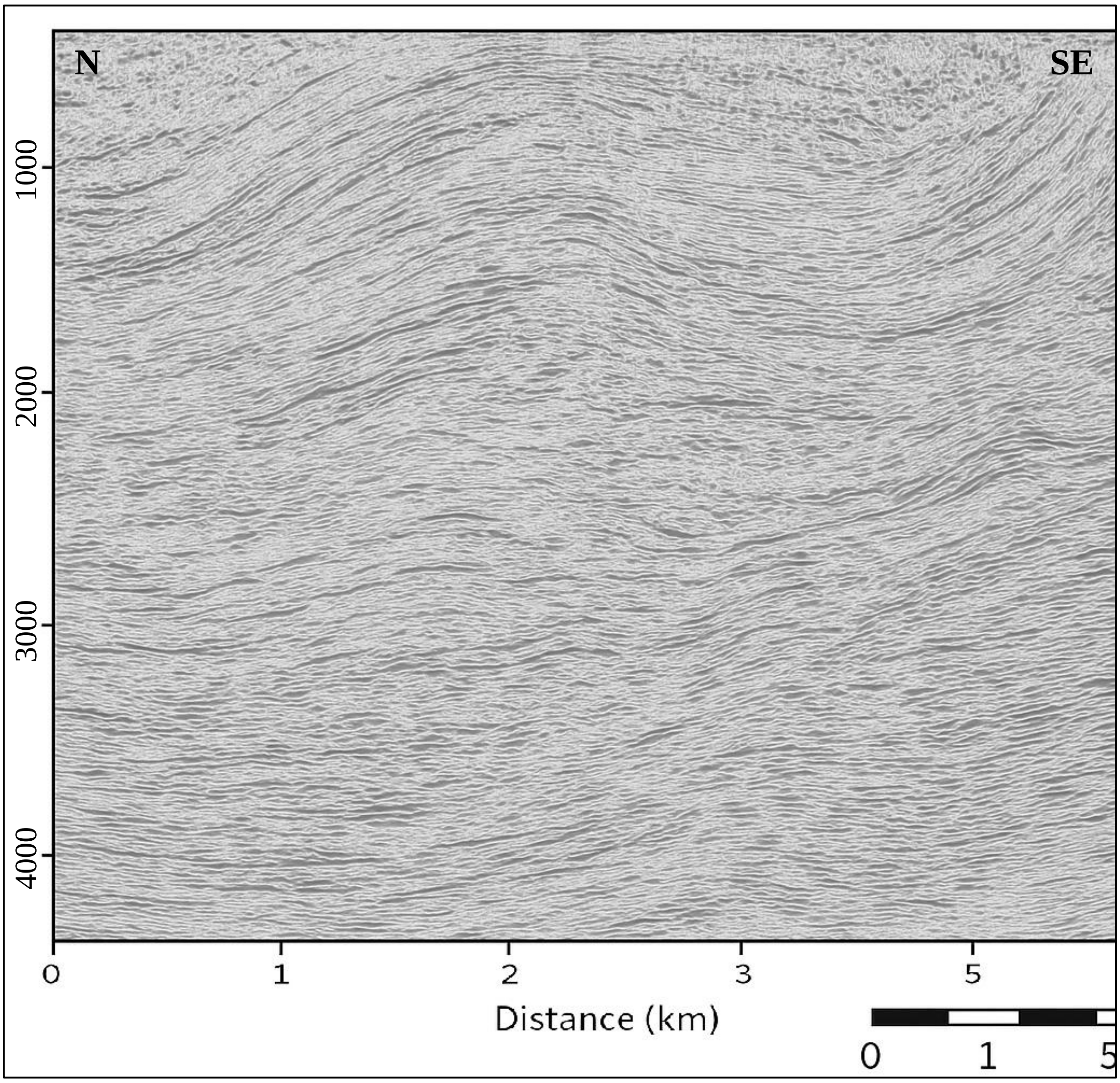

Figure 5. A seismic section obtained from the 3D seismic survey carried out in the Bijeel block. The vertical axis represents the two-way travel time (TWT) (ms), which indicates the time taken for seismic waves to travel from the source to the reflector and back to the receiver. It is typically labeled along the left side of the section, with increasing depth downward in meters on the left side. The horizontal axis represents the distance along the seismic line (km), showing the spatial extent of the survey (Aswad et al., 2024).

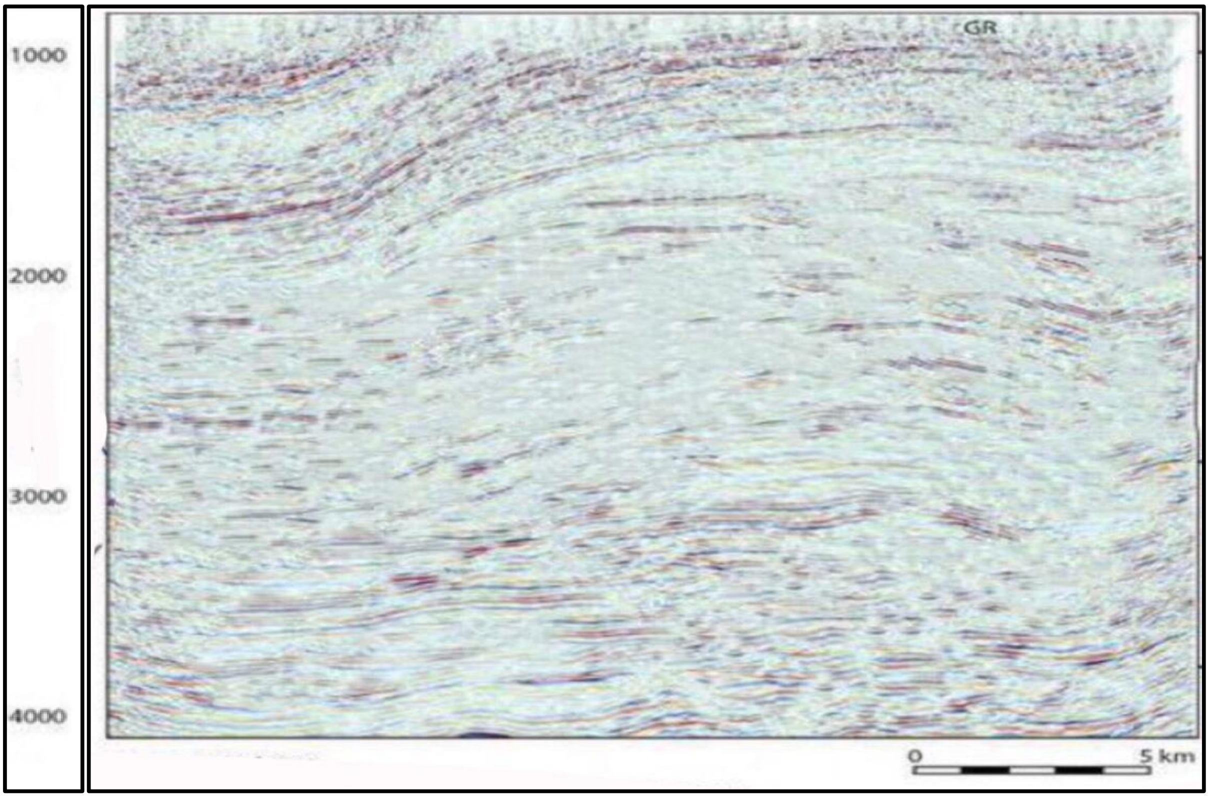

Figure 6. The 3D seismic lines of the Bijeel block by Petroleum Gulf Geophysics. The vertical axis represents the two-way travel time (TWT) (ms), which indicates the time taken for seismic waves to travel from the source to the reflector and back to the receiver. It is typically labeled along the right side of the section, with increasing depth downward. The horizontal axis represents the distance along the seismic line (km), showing the spatial extent of the survey (Aswad et al., 2024).

4.2. Harir block

The seismic 2D profile of the Harir field illustrates significant fluctuations in the reflected lines, indicating the presence of variation in the subsurface. Based on the seismic lines, which represent distinct folds and structural deformation within the subsurface. These folds likely result from complex geological processes, such as compression, extension, or lateral movement of the Earth's crust. The seismic data extends to depths exceeding about 5 km, providing valuable insights into the subsurface geology and structural architecture of the region (Figure 7).

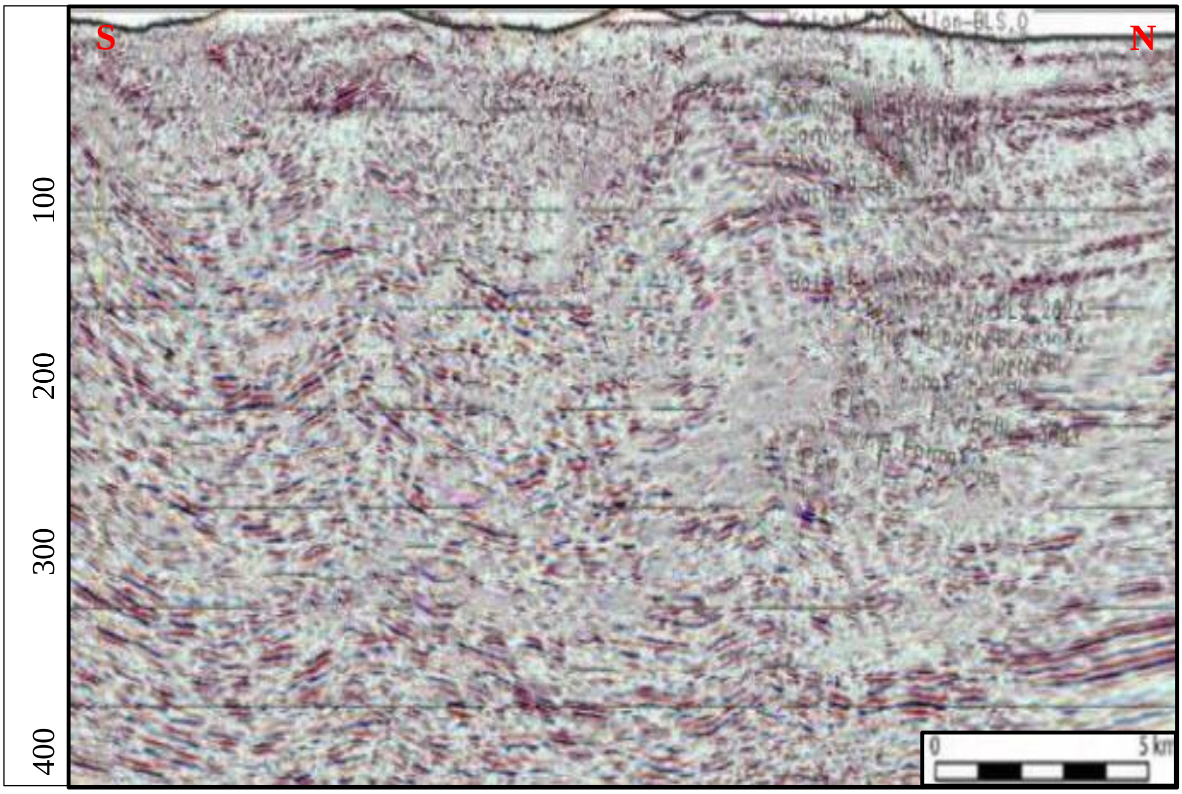

Figure 7. The 2D seismic survey of the Harir block by Petroleum Gulf Geophysics. The vertical axis represents the two-way travel time (TWT) (ms), which indicates the time taken for seismic waves to travel from the source to the reflector and back to the receiver. It is typically labeled along the right side of the section, with increasing depth downward. The horizontal axis represents the distance along the seismic line (km), showing the spatial extent of the survey. (Aswad et al., 2024).

5. Results and Discussion

5.1. Bijeel Block

The interpretation of seismic lines begins by analyzing the intensity and continuity of the reflections corresponding to each geological bed. Firstly, we observed the main anticline with some curved lines. The curved lines show the extending curved bed from NW to SE. Upon examination of the seismic lines, it becomes evident that the fold has a wide hinge line and is asymmetrical. This curved anticline holds significance in hydrocarbon accumulation and the identification of reservoir zones. If we look at the green line that represents the Barsarin Formation during the Jurassic Period, it depicts the upward curvature in the middle of the formation, with both sides declining due to tectonic activity during the respective periods. This anticline serves as an indicator for selecting an appropriate location for hydrocarbon drilling. The fault direction is also important for selecting an appropriate location to be drilled. Most hydrocarbons in Kurdistan are located in anticlines. The Bijeel Anticline can be seen clearly from the seismic lines shown in Figure 8.

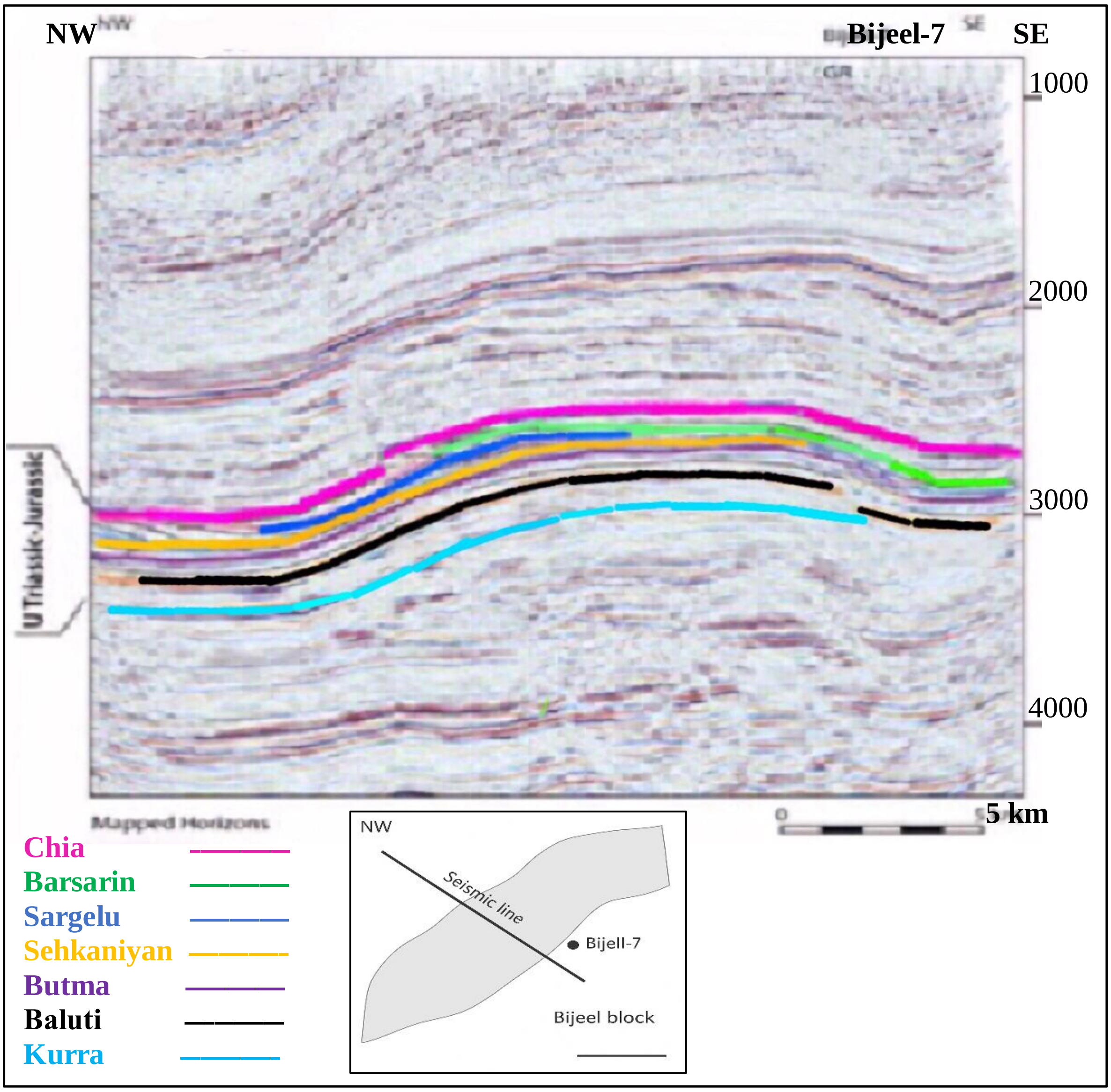

Figure 8. Bijeel Anticline and Jurassic and Triassic Formations based on the intensity of the seismic lines. The seismic interpretation is tied to borehole data, specifically Bijeel-7. Mapped horizons are colored in different lines (pink, yellow, blue, black) corresponding to changes in lithology observed in the well (Aswad et al., 2024).

The displacement is the main key to fault characterization. Some faults have long displacement, while others have less. The displacement is related to the tectonic stress applied to the area. This prominent fault toward the northwest and southeast is attributed to high stress in that direction. The fault is shown in Figure 9. The compressional stress results in the formation of the anticline, indicating the folding of geological layers due to tectonic activity from both sides of the area. The important location to be drilled needs to be analyzed for the fault direction, and then decide to drill. Many locations were previously identified to be drilled, but we disagree because the hydrocarbon control should be the fault, and it needs to be drilled with an inclined well. Fault extension and direction highly influence the hydrocarbon recovery because they can increase the reservoir zone and fracture lines (Figure 9).

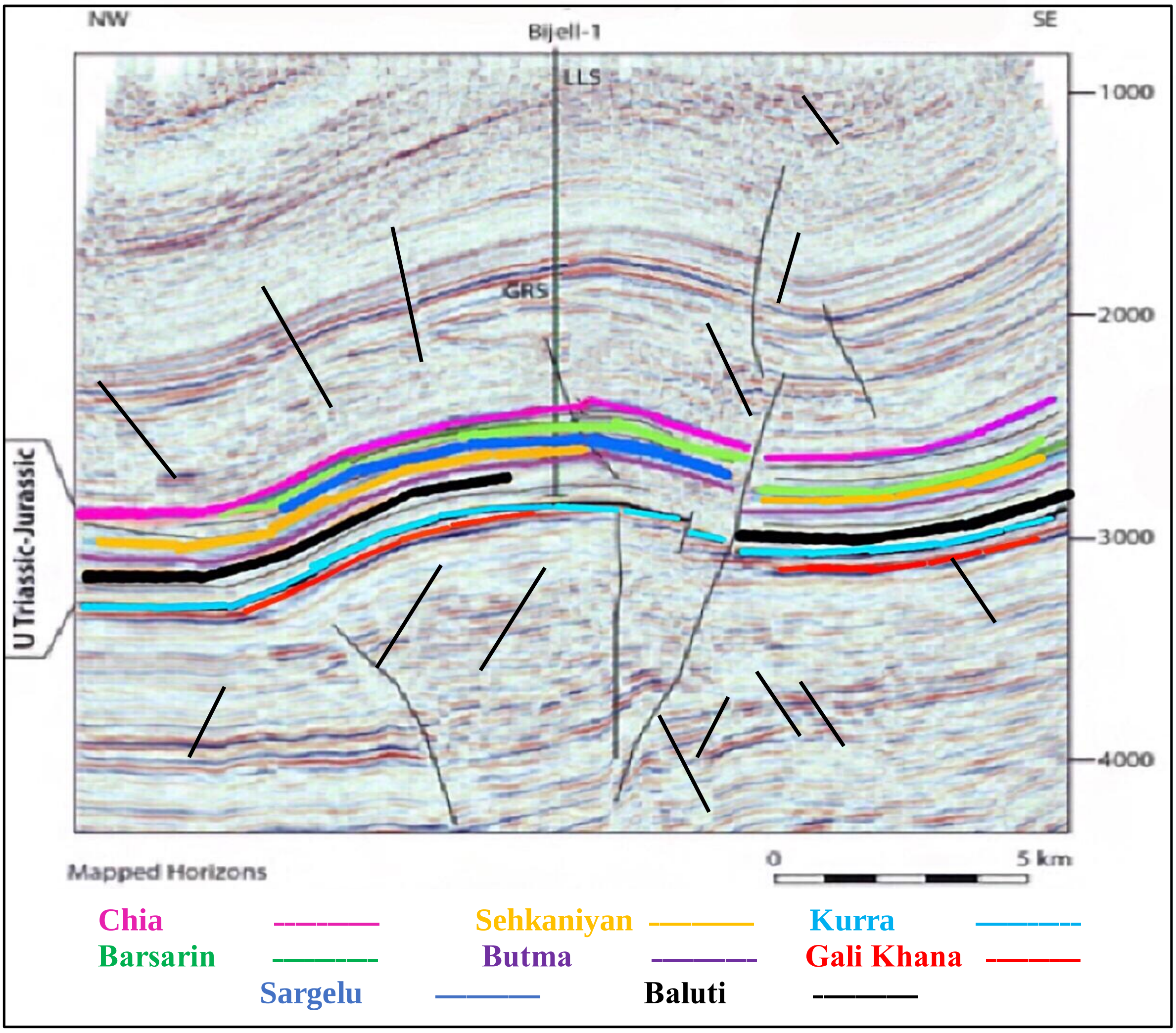

Figure 9. Interpreted the seismic section in the Bijeel block showing the main anticline and other structures. The main formations are from the Late Triassic and to the Late Jurassic periods (Aswad et al., 2024).

Wells drilled within the anticline structure can access reservoirs at shallower depths than those drilled on the anticline limbs or those that are affected by faults. This is because the beds are bent upwards at the anticline's hinge line, allowing easier access to hydrocarbons at shallower depths, while the sides are more inclined. The fault directions significantly impact the ability to recover hydrocarbons. The study suggests that hydrocarbon recovery is better when wells are drilled in a direction aligned with these faults and fractures. In comparison, Csato et al. (2014) primarily focused on fault structures but did not address the specific drilling directions and their impact on recovery. This research highlights the importance of drilling direction for maximizing hydrocarbon yield, with inclined wells generally producing more hydrocarbons than vertical wells. A critical factor when drilling near faults is the presence of seal or cap rock. If a fault intersects the seal rock, hydrocarbons could migrate away from the reservoir, reducing recovery efficiency. Therefore, it's crucial to ensure faults do not intersect seal rocks during drilling operations. Many of the wells drilled in Kurdistan are located within structural traps, which occur in areas where anticlines and faults intersect. These traps are favorable for hydrocarbon accumulation. Wells drilled in these zones, especially those aligned with fault and fracture directions, tend to have higher hydrocarbon recovery. The geological bed directions, particularly in anticline and faulted areas, are essential for understanding the best locations for drilling. The study (as shown in Figure 10) illustrates how these directions affect the potential for hydrocarbon recovery.

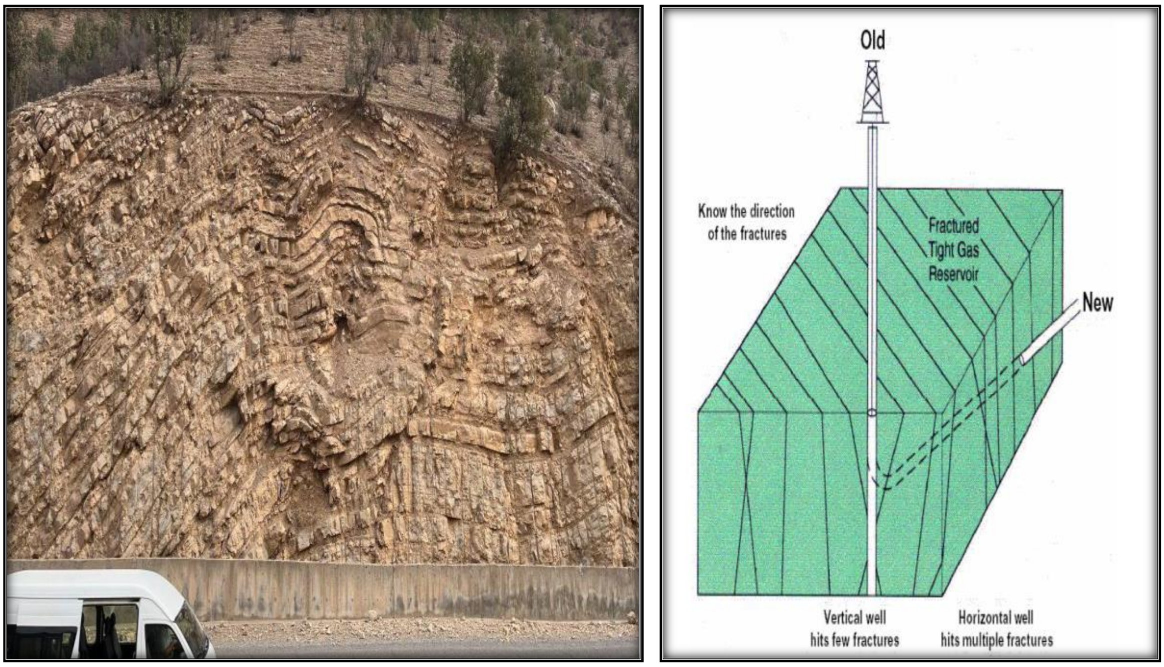

Figure 10. Different directions of the drilling to enhance oil hydrocarbon recovery. a) *Left Photo:* This is an outcrop showing well-developed folded and fractured carbonate strata. b) *Right Diagram:* A block diagram illustrating a fractured reservoir. It compares traditional vertical drilling, which intersects fewer fractures, with modern horizontal drilling, which is oriented to intersect more fractures, significantly improving hydrocarbon recovery. The diagram emphasizes the importance of knowing the fracture direction to optimize well placement.

5.2. Harir Block

In the Harir seismic survey, three main folds can be observed from the seismic section. Three distinct folds with numerous faults are present between the Hariri Anticline and Shakrok Anticline. The Miraw Well-1 and Harir Well-1 are the primary drilling sites due to the clear exposure of these folds (Aswad, 2020). The faults extend back to the Early Triassic period. Drilling at Harir occurs on surfaces ranging from the Tertiary to the Cretaceous based on location, with drilling reaching down to the Early Triassic (Figure 11). These wells are directed towards the northeast, leading to the Hariri Anticline, and towards the southwest, extending to the Shaqlawa area. Numerous faults are visible on both sides. The selection of drilling locations depends on the presence of folds and faults. The direction of the faults significantly controlled the drilling location and hydrocarbon recovery. One fault can control the direction of the fracture and control the fluid movement. Those wells that were drilled based on the fault expansion and fracture distributions have contained more hydrocarbon recovery (Figure 11). This can be seen in Mirawa-1 and Jisk-1. The Jisk-1 contains 11000 bp/d while Miraw-1 contains 6100 bp/d, which is due to fracture and fault directions.

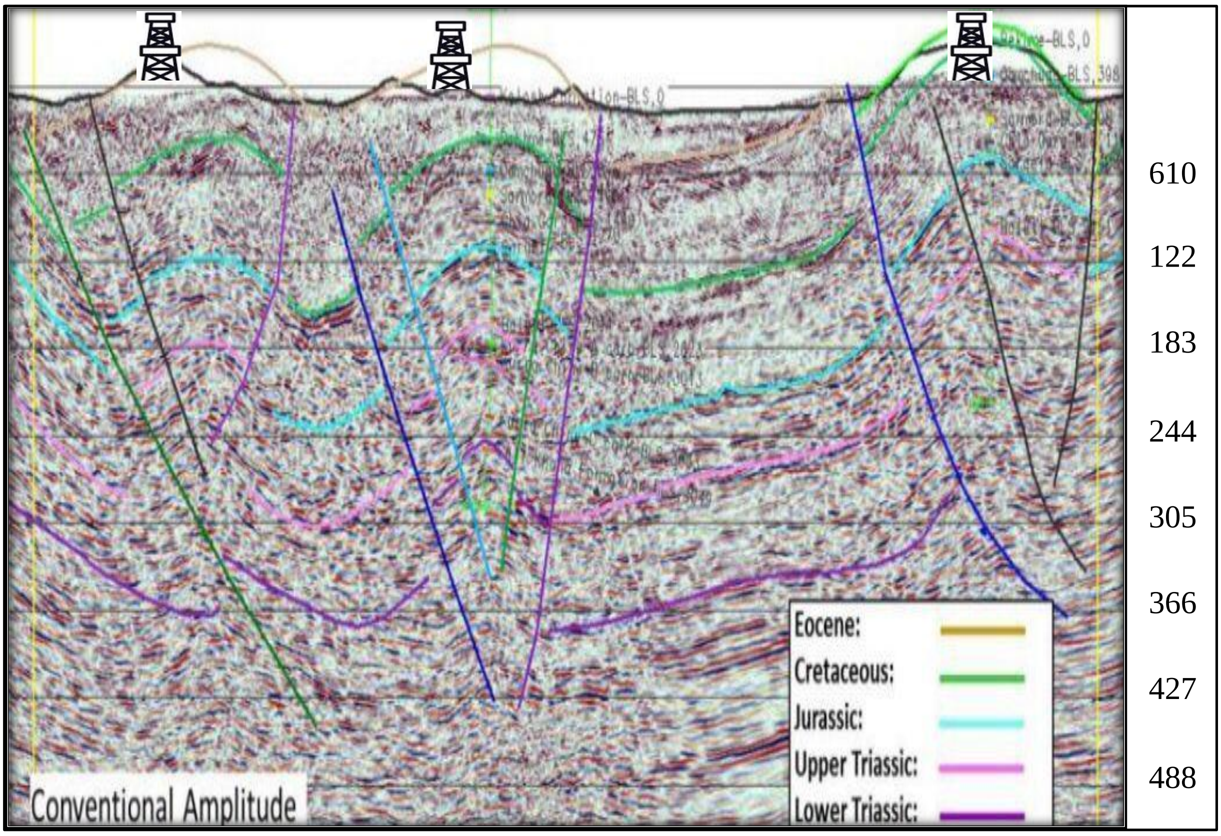

Figure 11. Interpreted a 2D seismic section from the Harir Block. A detailed interpretation of the 2D seismic section from the Harir Block is presented. The section reveals key structural features, including anticlines, synclines, and fault systems, which play a crucial role in hydrocarbon accumulation within the region. The seismic data show the stratigraphic layers' continuity, providing insights into the depth, thickness, and lateral extent of the formations (Aswad et al., 2024).

A comparison of the fault systems between the Bijeel and Harir areas reveals that the faults in the Harir region are more complex than those in Bijeel. This complexity is attributed to the increased tectonic activity and greater tectonic forces in the Harir area. The Triassic and Jurassic formations are primarily targeted for hydrocarbon accumulation and drilling. Many of the reservoirs within these formations are fault-controlled, and to optimize hydrocarbon recovery, wells should be drilled using inclined directional drilling techniques that align with the fault structures.

6. Conclusions

Based on the results of seismic interpretation, we may conclude the following. The seismic interpretation conducted across various oil fields in the Kurdistan Region has provided valuable insights into the subsurface structure and hydrocarbon potential of the area. Through detailed analysis, several key findings were revealed that could significantly influence future drilling operations. The study identified many faults within both fields, which play a crucial role in controlling hydrocarbon recovery. In addition, the main folds in the two fields were delineated, offering valuable guidance for the placement of initial exploration wells. The interpretation also highlighted the importance of drilling techniques, particularly those aligned with fault and fracture directions, to optimize hydrocarbon recovery. These findings will pave the way for more efficient drilling strategies and improve reservoir management in the Kurdistan Region.

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Author Contributions

Mahdi Aswad: Supervision; Conceptualization, methodology, data curation, formal analysis, and writing—original draft preparation. Shokhan Azad: software, validation, resources, and review & editing. Helin Mohammed: Data collection, visualization, and writing—review & editing.

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