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Advanced 3D seismic interpretation techniques for accurate subsurface structural mapping and reservoir characterization

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Abstract

Three-dimensional (3D) seismic interpretation has become a fundamental tool in geophysical exploration for identifying subsurface structures and evaluating hydrocarbon reservoirs. Traditional interpretation techniques often face challenges such as limited resolution, structural complexity, and uncertainty in reservoir prediction. This study presents an advanced workflow for 3D seismic interpretation integrating seismic attribute analysis, structural interpretation, and petrophysical data integration to improve reservoir characterization accuracy. The proposed methodology incorporates horizon picking, fault detection, seismic attribute analysis, and inversion techniques to enhance structural mapping and reservoir identification. The results demonstrate that integrating seismic attributes and well-log data significantly improves reservoir characterization and reduces exploration uncertainty. The study highlights the importance of advanced interpretation methods for identifying structural traps and optimizing hydrocarbon exploration strategies.

Keywords: 3D seismic interpretation; Reservoir characterization; Seismic attributes; Structural mapping; Hydrocarbon exploration

1. Introduction

Accurate subsurface imaging is critical for hydrocarbon exploration, reservoir management, and geological resource assessment. Understanding the structure and stratigraphy of subsurface formations allows geoscientists and petroleum engineers to identify potential hydrocarbon reservoirs and reduce uncertainties associated with exploration and production activities. Seismic reflection methods have become one of the most widely used geophysical techniques for subsurface investigation because they provide detailed information about geological structures and stratigraphic features beneath the Earth's surface [1]. These techniques rely on the propagation of seismic waves through subsurface layers and the recording of reflected signals generated by contrasts in acoustic impedance between geological formations.

Seismic reflection surveys enable the identification of structural features such as faults, folds, anticlines, synclines, and stratigraphic traps that control the accumulation and migration of hydrocarbons [2]. Among various seismic techniques, three-dimensional (3D) seismic interpretation has emerged as one of the most powerful tools for high-resolution imaging of subsurface structures. Unlike traditional two-dimensional (2D) seismic surveys, which provide limited cross-sectional views of geological formations, 3D seismic datasets capture spatial variations in three dimensions, allowing interpreters to visualize complex geological structures with significantly greater clarity and accuracy [3]. In contrast, 3D seismic volumes provide continuous spatial coverage across an entire survey area, enabling interpreters to analyze geological structures in multiple directions and construct more reliable structural and stratigraphic models [4]. This capability significantly improves the detection of structural traps, fault systems, and reservoir compartments that may control hydrocarbon accumulation. Similarly, folds and anticlines often form structural traps where hydrocarbons

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accumulate due to buoyancy forces. High-resolution 3D seismic interpretation allows geoscientists to accurately map these structural features and evaluate their impact on reservoir potential [5]. Porosity represents the volume of void spaces within a rock formation, while permeability describes the ability of fluids to flow through those pore spaces. Accurate estimation of these properties is essential for determining reservoir quality and optimizing hydrocarbon recovery strategies [6]. As a result, integrating well-log data with seismic information is essential for extending reservoir property estimates across the entire field. Seismic interpretation can provide continuous spatial coverage, allowing geoscientists to interpolate rock properties between wells and construct comprehensive reservoir models [7].

One of the most important advancements in modern seismic interpretation is the use of seismic attribute analysis. Seismic attributes are quantitative measures derived from seismic data that highlight specific characteristics of the subsurface. Common attributes include amplitude, phase, frequency, coherence, and curvature, each of which provides valuable insights into geological structures and stratigraphic features. These attributes can reveal subtle variations in lithology, fluid content, and structural deformation that may not be apparent in conventional seismic sections [8].

For example, amplitude-based attributes are often used to identify direct hydrocarbon indicators (DHIs) such as bright spots, dim spots, and flat spots, which may suggest the presence of hydrocarbons within reservoir formations. Similarly, coherence and variance attributes are particularly useful for detecting faults and fractures because they highlight discontinuities in seismic reflections. These attributes enhance the interpreter's ability to identify complex geological features and improve the accuracy of subsurface structural mapping [9]. Machine learning models have demonstrated significant potential for improving reservoir prediction accuracy and reducing interpretation time [10].

In this study, we propose an advanced interpretation workflow that integrates 3D seismic data, seismic attribute analysis, and petrophysical evaluation to enhance subsurface structural mapping and reservoir characterization. The proposed methodology aims to improve the identification of geological structures, enhance the prediction of reservoir properties, and provide a more comprehensive understanding of subsurface geological systems. By leveraging modern interpretation techniques and data integration strategies, this research seeks to contribute to more efficient and reliable hydrocarbon exploration and reservoir management practices.

2. Background and Literature Review

2.1. Seismic Reflection Methods

Seismic reflection surveying is one of the most widely used geophysical methods for investigating subsurface geological structures. The technique is based on the generation of seismic waves at the Earth's surface and the recording of reflected signals from subsurface interfaces where physical properties of rocks change. These changes typically occur at boundaries where there are contrasts in acoustic impedance, which is defined as the product of rock density and seismic wave velocity. When seismic waves encounter such boundaries, part of the energy is reflected back toward the surface while the remaining energy continues traveling deeper into the subsurface [11]. These sections provide valuable information about the geometry, depth, and continuity of subsurface formations. By analyzing these reflections, geophysicists can identify stratigraphic sequences, structural traps, and potential hydrocarbon reservoirs [12].

The physical behavior of seismic wave reflection and transmission at geological interfaces is described by the Zoeppritz equations, which define how seismic energy is partitioned between reflected and transmitted waves depending on the elastic properties of the rock layers. These equations relate incident wave angles, wave velocities, and densities of the media to the amplitude of reflected and transmitted waves. Although the full Zoeppritz equations are complex, simplified approximations such as the Aki-Richards equations are often used in practical seismic analysis to estimate reflection coefficients and interpret seismic amplitudes [13]. Three-dimensional seismic datasets provide volumetric images that allow interpreters to examine geological structures in multiple directions, improving the reliability of structural interpretation and reservoir identification [14]. Convolutional neural networks such as NASNetMobile and InceptionV3 have been successfully applied to object detection in challenging environments, highlighting the potential of deep learning architectures for large-scale data interpretation and automated feature extraction [43].

2.2. Structural Interpretation

Faults are fractures in the Earth's crust where displacement has occurred between adjacent rock layers. In petroleum systems, faults can significantly influence hydrocarbon migration pathways. Depending on their orientation and sealing properties, faults may either facilitate hydrocarbon migration or act as barriers that trap hydrocarbons within reservoir formations [15].

Folds are geological structures formed by the deformation of rock layers due to tectonic forces. Among various fold structures, **anticlines** are particularly important for hydrocarbon exploration because they create structural traps that can accumulate oil and gas. In anticline traps, hydrocarbons migrate upward due to buoyancy and become trapped beneath impermeable cap rocks. Conversely, synclines represent downward-folded structures that typically serve as sediment accumulation zones rather than hydrocarbon traps [16].

With the development of 3D seismic technology, structural interpretation has become more accurate and efficient. Three-dimensional seismic volumes allow interpreters to visualize geological structures in multiple directions and identify complex fault systems that may not be visible in traditional 2D seismic profiles. Advanced visualization tools also enable interpreters to generate fault surfaces, structural maps, and reservoir models that support exploration and reservoir management activities [17].

2.3. Seismic Attributes

Seismic attributes are quantitative measures derived from seismic data that highlight specific characteristics of subsurface geological features. These attributes are calculated using mathematical transformations of seismic traces and are widely used to enhance seismic interpretation.

Common seismic attributes include RMS amplitude, instantaneous frequency, coherence, and envelope amplitude. RMS amplitude measures the average energy of seismic reflections within a specified time window and is often used to identify potential hydrocarbon reservoirs. Instantaneous frequency provides information about changes in lithology and stratigraphic features, while coherence attributes are used to detect discontinuities such as faults and fractures within seismic datasets [18].

One of the most significant applications of seismic attributes is the identification of Direct Hydrocarbon Indicators (DHIs). DHIs are seismic anomalies that may indicate the presence of hydrocarbons in reservoir formations. Examples include bright spots, dim spots, flat spots, and polarity reversals. Bright spots represent unusually high-amplitude reflections caused by gas-filled reservoirs, while flat spots correspond to fluid contacts that appear as horizontal reflection events in seismic sections [19].

2.4. Reservoir Characterization

Reservoir characterization involves the quantitative evaluation of reservoir rock properties that influence hydrocarbon storage and production. Accurate characterization of reservoir properties is essential for estimating hydrocarbon reserves and optimizing production strategies.

Key reservoir parameters include porosity, permeability, water saturation, and lithology. Porosity represents the percentage of void space within a rock formation and determines the capacity of the reservoir to store fluids. Permeability measures the ability of fluids to flow through the pore network of the rock, which directly influences production rates. Water saturation represents the proportion of pore space occupied by water, while lithology describes the mineral composition and texture of the reservoir rock [20].

Traditional reservoir characterization relies heavily on well-log data, which provide direct measurements of rock properties at specific locations within the reservoir. However, well data alone cannot capture the spatial variability of reservoir properties across an entire field. Therefore, integrating well-log data with seismic information is necessary to extend reservoir property estimates beyond well locations.

Seismic attributes and inversion techniques are commonly used to estimate reservoir properties from seismic data. Seismic inversion transforms seismic reflection data into rock property models such as acoustic impedance, which can be correlated with lithology and porosity. By integrating seismic attributes, inversion results, and petrophysical data, geoscientists can construct detailed reservoir models that describe the distribution of reservoir properties throughout the subsurface [21].

Modern reservoir characterization workflows often incorporate advanced computational methods, including machine learning and statistical modeling, to improve reservoir prediction accuracy. These approaches analyze large seismic datasets and identify relationships between seismic attributes and reservoir properties, enabling more reliable prediction of reservoir quality and hydrocarbon distribution. digital twins and federated learning [44] are increasingly being used to integrate distributed industrial and sensor data for large-scale system monitoring and predictive analysis [44, 45]. These technologies enable collaborative data analysis while preserving data privacy and improving system-level decision making in complex engineering environments [45].

3. Methodology

This study proposes an integrated workflow for advanced 3D seismic interpretation and reservoir characterization. The methodology combines seismic data processing, structural interpretation, seismic attribute analysis, seismic inversion, and petrophysical data integration. The objective of this workflow is to improve subsurface structural mapping and enhance the prediction of reservoir properties. The proposed methodology follows an integrated workflow that combines seismic processing, structural interpretation, seismic attribute analysis, seismic inversion, and well-log integration, as illustrated in Figure 1.

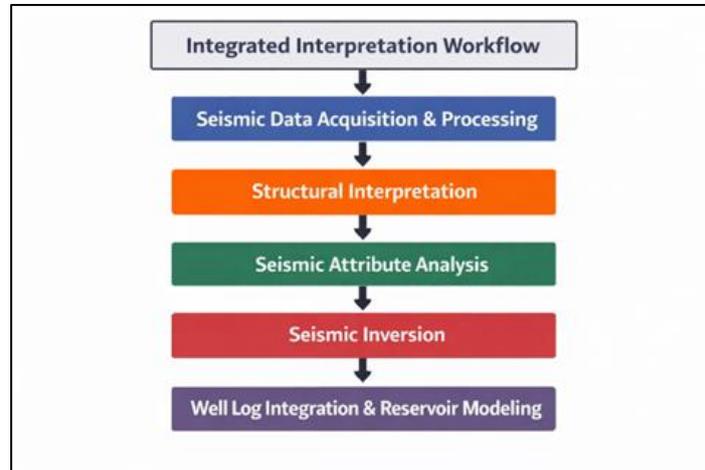


Figure 1 Integrated workflow for advanced 3D seismic interpretation and reservoir characterization

The overall workflow consists of five major stages:

- Data acquisition and preprocessing
- Seismic data processing
- Structural interpretation
- Seismic attribute analysis
- Reservoir characterization through integration with well-log data
- Each stage is described in detail in the following sections.

3.1. Data Acquisition

The first step in the workflow involves acquiring seismic and well-log datasets required for subsurface interpretation. The dataset used in this study includes a **3D seismic volume**, well-log data from multiple wells, and check-shot survey information for time-depth calibration.

Seismic data are typically acquired using controlled energy sources such as vibroseis trucks on land or air guns in marine environments. These sources generate seismic waves that propagate through the subsurface and reflect from geological boundaries where contrasts in acoustic impedance occur. The reflected waves are recorded by arrays of geophones or hydrophones placed on the surface or seabed [22].

Well-log data used in this study include:

- Gamma ray logs
- Density logs
- Sonic logs
- Resistivity logs

These logs provide direct measurements of rock properties and are essential for calibrating seismic interpretations and estimating reservoir parameters [23].

3.2. Seismic Data Processing

Raw seismic data contain noise and distortions caused by environmental conditions, acquisition geometry, and wave propagation effects. Therefore, seismic data processing is required to enhance signal quality and produce interpretable seismic images. Accurate interpretation of geophysical datasets depends heavily on the quality and completeness of sensor measurements. Data imputation techniques have been shown to improve parameter estimation and measurement reliability in industrial monitoring systems by reconstructing missing or corrupted sensor data [46].

The seismic processing workflow used in this study includes several key steps.

3.2.1. Noise Attenuation

Noise attenuation removes unwanted signals such as ground roll, multiples, and random noise. Filtering techniques and signal processing algorithms are applied to improve the signal-to-noise ratio of seismic reflections.

3.2.2. Amplitude Correction

Amplitude correction compensates for energy loss caused by geometric spreading and attenuation as seismic waves propagate through the subsurface. Proper amplitude balancing is necessary for reliable seismic attribute analysis and amplitude interpretation.

3.2.3. Velocity Analysis

Velocity analysis determines the propagation velocity of seismic waves through subsurface formations. Accurate velocity models are essential for converting seismic travel time into depth and improving structural interpretation accuracy [24].

3.2.4. Migration

Migration is a critical step in seismic processing that corrects the position of reflected seismic events to their true subsurface locations. Migration algorithms reposition seismic reflections that have been displaced due to dipping geological layers.

Modern seismic processing often uses pre-stack time migration (PSTM) or pre-stack depth migration (PSDM) to produce high-resolution seismic images [25].

3.3. Structural Interpretation

Structural interpretation involves identifying geological structures within the seismic dataset. This step is crucial for mapping subsurface formations and identifying potential hydrocarbon traps. Horizon picking is the process of identifying continuous seismic reflections corresponding to geological boundaries such as formation tops or stratigraphic layers.

Interpreters track reflection events across the seismic volume to construct surfaces representing subsurface horizons. Faults appear as discontinuities or offsets in seismic reflections. Interpreters identify faults by analyzing breaks in reflection continuity and variations in seismic attributes. Fault interpretation is essential because faults can influence hydrocarbon migration pathways and reservoir compartmentalization. After identifying horizons and faults, structural maps are generated to visualize the geometry of subsurface formations. These maps illustrate depth variations of geological layers and help identify structural traps such as anticlines and fault blocks.

Structural maps are widely used in hydrocarbon exploration to determine optimal drilling locations [26].

3.4. Seismic Attribute Analysis

Seismic attribute analysis is used to enhance the interpretation of geological features and improve reservoir prediction accuracy. Attributes are mathematical transformations applied to seismic data to highlight specific characteristics of subsurface formations.

The attributes used in this study include:

RMS amplitude measures the average reflection energy within a specified time window. High RMS amplitudes often indicate potential hydrocarbon reservoirs due to the presence of gas or porous formations. By combining multiple seismic attributes, interpreters can identify subtle geological features and improve reservoir prediction reliability [27].

3.5. Seismic Inversion

Seismic inversion converts seismic reflection data into quantitative rock property models. This process transforms seismic amplitude information into estimates of acoustic impedance, which can be related to lithology and porosity.

Acoustic impedance is defined as:

$$AI = \rho V$$

where:

ρ = rock density

V = seismic wave velocity

Changes in acoustic impedance correspond to geological boundaries and lithological variations.

Seismic inversion techniques include:

Post-stack inversion

Pre-stack inversion

Simultaneous inversion

These techniques allow geoscientists to estimate subsurface rock properties and improve reservoir characterization accuracy [28].

3.6. Integration with Well Log Data

Integration of seismic data with well-log information is a critical step in reservoir characterization. Well logs provide direct measurements of rock properties and are used to calibrate seismic interpretations.

The integration process includes:

Well-to-seismic tie involves matching seismic reflections with geological boundaries identified in well logs. Synthetic seismograms are generated using sonic and density logs to correlate seismic data with well observations. Petrophysical analysis uses well-log data to estimate reservoir properties such as porosity, permeability, and fluid saturation. After integrating seismic and well data, reservoir models are constructed to describe the spatial distribution of reservoir properties. These models help estimate hydrocarbon reserves and support reservoir management decisions [29].

4. Results and Analysis

The proposed interpretation workflow was applied to the 3D seismic dataset to evaluate its effectiveness in improving subsurface structural mapping and reservoir characterization. The results demonstrate that integrating seismic interpretation, attribute analysis, and petrophysical data significantly enhances the identification of geological structures and reservoir properties.

4.1. Structural Interpretation Results

Several major fault systems were detected within the seismic dataset. These faults are characterized by discontinuities and offsets in seismic reflections and appear clearly in coherence and variance attribute maps. The identified faults show normal fault geometry, indicating extensional tectonic activity within the basin. The interpreted seismic section reveals several major fault systems and folded geological layers that control hydrocarbon migration and accumulation within the study area, as shown in Figure 2.

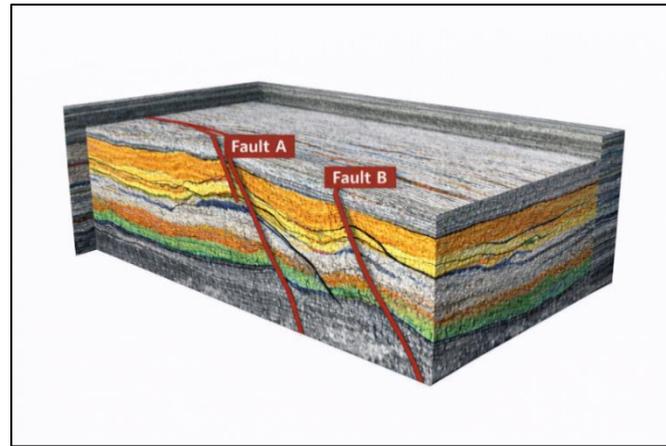


Figure 2 Interpreted 3D seismic section showing fault structures and stratigraphic layers

The interpreted fault network divides the reservoir into several structural compartments. Such compartmentalization can significantly influence hydrocarbon migration and accumulation patterns. Faults may either act as conduits that facilitate hydrocarbon migration or as barriers that trap hydrocarbons within structural closures [30].

The structural analysis suggests that the identified anticlines and fault blocks provide favorable conditions for hydrocarbon accumulation within the reservoir formation.

4.2. Horizon Mapping

Three major seismic horizons were interpreted within the study area. These horizons represent key geological layers that define the stratigraphic framework of the reservoir system.

Table 1 summarizes the interpreted horizons and their approximate depth ranges.

Table 1 Interpreted Seismic Horizons

Horizon	Depth Range (m)	Geological Interpretation
H1	2100–2300	Upper sandstone reservoir
H2	2600–2800	Primary hydrocarbon-bearing formation
H3	3100–3300	Lower reservoir unit

The structural maps generated from these horizons reveal subtle variations in depth across the survey area. These variations are associated with structural deformation caused by faulting and folding within the sedimentary basin.

4.3. Seismic Attribute Analysis

Seismic attribute analysis was performed to enhance the interpretation of geological features within the seismic dataset. Several attributes were computed, including RMS amplitude, coherence, instantaneous frequency, and envelope amplitude.

4.3.1. RMS Amplitude

The RMS amplitude attribute highlights zones with high seismic reflection energy. These zones often correspond to porous formations or hydrocarbon-bearing reservoirs. RMS amplitude attributes were computed to identify high-energy reflection zones that may correspond to potential hydrocarbon reservoirs, as illustrated in Figure 3.

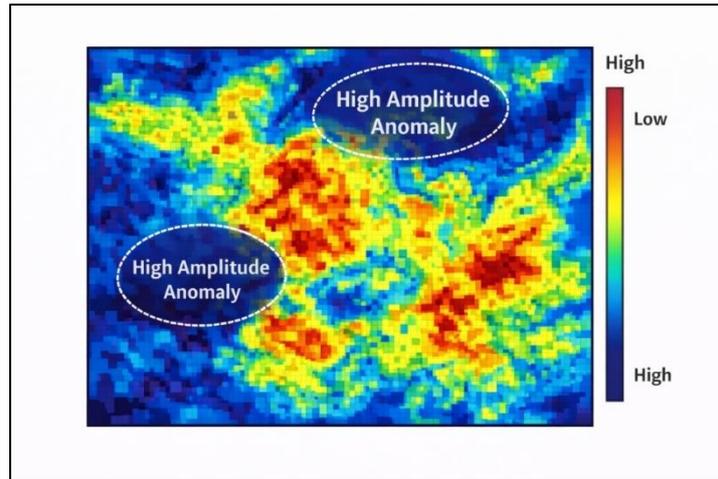


Figure 3 RMS amplitude attribute map highlighting high-amplitude anomalies associated with potential hydrocarbon reservoirs

In the study area, high RMS amplitude anomalies were observed within the H2 horizon. These anomalies may indicate the presence of gas-filled or oil-filled reservoir zones. The coherence attribute was particularly effective in identifying fault structures. Fault planes appear as low-coherence zones due to the discontinuity of seismic reflections across fault boundaries. The coherence map clearly reveals several fault trends within the study area. These faults correspond closely with those identified during structural interpretation. Instantaneous frequency attributes provide insights into lithological variations within the reservoir. Variations in frequency may indicate changes in rock composition or depositional environments.

Analysis of instantaneous frequency maps suggests that the reservoir interval contains heterogeneous lithological units, which may influence reservoir performance. Envelope amplitude attributes highlight high-energy reflection zones associated with reservoir formations. The envelope attribute maps reveal several amplitude anomalies within the primary reservoir horizon.

These anomalies may correspond to direct hydrocarbon indicators (DHIs) such as bright spots and flat spots, which are commonly associated with hydrocarbon accumulations [31].

4.4. Seismic Inversion Results

Seismic inversion was performed to estimate acoustic impedance variations within the reservoir interval. The inversion results provide valuable insights into subsurface rock properties and lithological variations.

The acoustic impedance model shows clear contrasts between sandstone reservoir units and surrounding shale formations. Low acoustic impedance zones within the H2 horizon correspond to porous sandstone formations that may contain hydrocarbons. Seismic inversion was applied to estimate acoustic impedance variations within the reservoir interval, allowing identification of porous sandstone formations as shown in Figure 4.

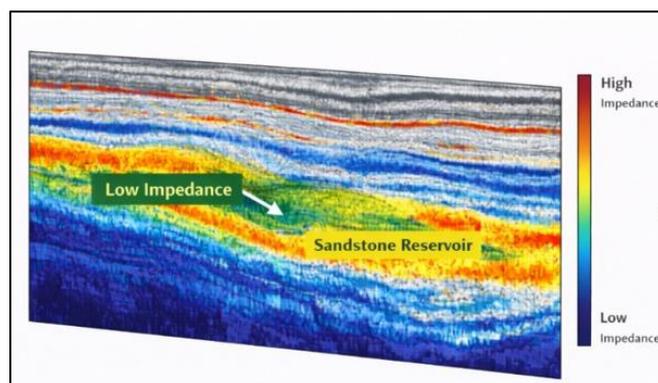


Figure 4 Acoustic impedance section derived from seismic inversion highlighting potential reservoir zones

This correlation supports the interpretation that these zones represent potential hydrocarbon reservoirs.

4.5. Petrophysical Analysis

Petrophysical analysis was conducted using well-log data to estimate reservoir properties. The analysis focused on key reservoir parameters including porosity, permeability, and water saturation.

The results indicate that the primary reservoir interval exhibits favorable reservoir properties.

Table 2 Estimated Reservoir Properties

Property	Estimated Range
Porosity	20–24%
Permeability	200–500 mD
Water Saturation	15–30%
Net-to-Gross Ratio	0.65–0.75

The relatively high porosity and permeability values suggest that the reservoir formation has good storage capacity and fluid flow potential. Low water saturation values further indicate the presence of hydrocarbons within the reservoir interval.

4.6. Integrated Reservoir Model

By integrating structural interpretation, seismic attributes, inversion results, and petrophysical data, a comprehensive reservoir model was developed for the study area.

The integrated interpretation indicates that hydrocarbon accumulations are likely controlled by a combination of structural and stratigraphic trapping mechanisms. Anticlinal structures and fault closures provide structural traps, while lithological variations within the reservoir formation contribute to stratigraphic trapping. Similar integrated interpretation approaches have been widely used in modern hydrocarbon exploration because they allow geoscientists to combine multiple datasets and generate more reliable geological models [32].

5. Discussion

The results obtained from the integrated seismic interpretation workflow demonstrate the importance of combining multiple datasets and analytical techniques for accurate subsurface characterization. Traditional seismic interpretation methods often rely on visual inspection of seismic sections, which can lead to uncertainties when identifying subtle geological features. The integration of structural interpretation, seismic attribute analysis, and petrophysical evaluation significantly improves the reliability of subsurface interpretation and reservoir prediction. Such structural compartmentalization is common in sedimentary basins and must be carefully considered when planning drilling operations and reservoir development strategies [33-37]. Recent advances in computational geophysics have further improved the efficiency of seismic interpretation. Machine learning algorithms are increasingly being used to automate the detection of faults, horizons, and stratigraphic features within large seismic datasets. These techniques can significantly reduce interpretation time while improving the accuracy of subsurface models [41,42].

Despite these advancements, several challenges remain in seismic interpretation and reservoir characterization. Seismic data quality, acquisition limitations, and processing uncertainties can affect the accuracy of interpretation results. Additionally, the resolution of seismic data may not always be sufficient to detect very thin geological layers or subtle stratigraphic features.

Future research should focus on integrating advanced machine learning techniques with seismic interpretation workflows to improve automated feature detection and reservoir prediction. Such approaches have the potential to enhance the efficiency of seismic interpretation and support more accurate decision-making in hydrocarbon exploration.

6. Conclusion

This study presents an integrated workflow for advanced 3D seismic interpretation and reservoir characterization. The methodology combines structural interpretation, seismic attribute analysis, seismic inversion, and petrophysical evaluation to improve subsurface structural mapping and reservoir prediction.

The results demonstrate that the proposed workflow significantly enhances the identification of geological structures and potential hydrocarbon reservoirs. Structural interpretation of the 3D seismic dataset revealed several fault systems and anticline structures that form favorable hydrocarbon traps within the study area. Seismic attribute analysis further improved the interpretation by highlighting subtle geological features and amplitude anomalies associated with reservoir formations. Overall, the integrated interpretation workflow presented in this study provides a robust framework for improving subsurface characterization and reducing uncertainties in hydrocarbon exploration. By combining multiple geophysical and petrophysical datasets, geoscientists can generate more reliable reservoir models and optimize exploration and production strategies.

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