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Integrated seismic and petrophysical analysis for improved hydrocarbon reservoir characterization

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Abstract

Accurate reservoir characterization is essential for efficient hydrocarbon exploration and production. Seismic interpretation provides valuable information about subsurface structures, while petrophysical analysis offers direct measurements of reservoir rock properties. Integrating these two approaches significantly improves the reliability of reservoir prediction and reduces uncertainties in subsurface interpretation. This study presents an integrated workflow combining 3D seismic interpretation, seismic attribute analysis, and well-log petrophysical evaluation to enhance hydrocarbon reservoir characterization. Structural interpretation of seismic data is used to identify faults, folds, and stratigraphic traps, while petrophysical analysis of well logs is applied to estimate key reservoir properties such as porosity, permeability, and water saturation. The integration of seismic and petrophysical datasets enables the development of a comprehensive reservoir model that accurately describes the spatial distribution of reservoir properties. Results demonstrate that the integrated interpretation approach improves reservoir prediction accuracy and supports more effective hydrocarbon exploration strategies.

Keywords: Reservoir Characterization; Seismic Interpretation; Petrophysical Analysis; Well-Log Integration; Hydrocarbon Exploration.

1. Introduction

Hydrocarbon exploration relies heavily on accurate subsurface characterization to identify potential reservoirs and evaluate their production potential. Geological formations that contain hydrocarbons often exhibit complex structural and stratigraphic features that require advanced geophysical techniques for proper interpretation. Seismic reflection methods are widely used to map subsurface structures and identify geological formations that may contain hydrocarbon accumulations [1].

Three-dimensional seismic surveys provide high-resolution imaging of subsurface geological structures and allow geoscientists to identify faults, folds, and stratigraphic traps with improved accuracy. However, seismic data alone cannot directly measure reservoir properties such as porosity, permeability, or fluid saturation. These properties are typically obtained from well-log measurements recorded during drilling operations [2].

Petrophysical analysis involves evaluating well-log data to estimate reservoir rock properties that influence hydrocarbon storage and flow behavior. Commonly used well logs include gamma-ray logs, density logs, sonic logs, and resistivity logs. Each log provides valuable information about rock lithology, fluid content, and reservoir quality.

Despite the usefulness of seismic and well-log data individually, significant uncertainties can arise when these datasets are interpreted independently. Integrating seismic interpretation with petrophysical analysis provides a more

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comprehensive understanding of reservoir systems by combining spatial geological information with direct measurements of rock properties [3].

In recent years, integrated seismic–petrophysical workflows have become increasingly important in reservoir characterization studies. These approaches allow geoscientists to develop more accurate reservoir models and improve predictions of hydrocarbon distribution within sedimentary basins [4].

The objective of this study is to develop an integrated workflow that combines seismic interpretation, seismic attribute analysis, and petrophysical evaluation to improve hydrocarbon reservoir characterization.

2. Background and Literature Review

2.1. Seismic Interpretation in Hydrocarbon Exploration

Seismic interpretation is one of the most important tools used in petroleum exploration. By analyzing seismic reflection data, geoscientists can identify geological structures that influence hydrocarbon accumulation and migration. Structural traps such as anticlines, fault traps, and stratigraphic traps play a critical role in controlling hydrocarbon distribution within sedimentary basins [5].

Three-dimensional seismic data allow interpreters to visualize geological structures in multiple directions and construct detailed structural maps of subsurface formations. These maps help identify potential drilling locations and guide exploration activities.

2.2. Petrophysical Analysis

Petrophysics focuses on evaluating the physical properties of reservoir rocks using well-log measurements. Petrophysical analysis helps estimate key reservoir properties including porosity, permeability, and fluid saturation.

Porosity represents the fraction of void space within a rock formation that can store fluids. Permeability describes the ability of fluids to flow through interconnected pore spaces within the reservoir. Water saturation indicates the proportion of pore space occupied by water rather than hydrocarbons [6].

These parameters are essential for evaluating reservoir quality and estimating hydrocarbon reserves.

2.3. Integration of Seismic and Petrophysical Data

Combining seismic and petrophysical datasets significantly improves the reliability of reservoir characterization. Seismic data provide large-scale spatial coverage of subsurface formations, while well logs provide detailed measurements of rock properties at specific locations.

Integrated interpretation workflows allow geoscientists to correlate seismic reflections with geological boundaries identified in well logs. This process enables the development of reservoir models that describe the spatial distribution of lithology, porosity, and fluid saturation across the entire field [7].

Such integrated approaches have become standard practice in modern hydrocarbon exploration because they reduce interpretation uncertainty and improve reservoir prediction accuracy.

3. Methodology

This study proposes an integrated workflow that combines **3D seismic interpretation, seismic attribute analysis, and petrophysical well-log evaluation** to improve hydrocarbon reservoir characterization. The methodology integrates geophysical and petrophysical datasets to reduce interpretation uncertainty and develop a comprehensive reservoir model. The workflow consists of five major stages: seismic data acquisition and processing, structural interpretation, seismic attribute analysis, well-log interpretation, and integrated reservoir modeling.

3.1. Seismic Data Acquisition and Processing

The first stage of the methodology involves acquiring and processing seismic data to produce reliable subsurface images. Seismic reflection surveys are conducted using controlled energy sources such as vibroseis trucks in land environments or air guns in offshore surveys. These sources generate seismic waves that propagate through the subsurface and reflect from geological interfaces where acoustic impedance contrasts occur between rock layers. The reflected waves are recorded by geophones or hydrophones positioned across the survey area [8].

Raw seismic data usually contain various types of noise caused by environmental conditions, acquisition geometry, and wave propagation effects. Therefore, seismic data processing is necessary to enhance signal quality and improve the interpretability of seismic reflections. The processing workflow includes noise attenuation, amplitude correction, velocity analysis, stacking, and migration.

Noise attenuation removes unwanted signals such as ground roll and multiple reflections that may obscure primary reflections. Amplitude correction compensates for energy loss caused by geometric spreading and attenuation during wave propagation. Velocity analysis determines seismic wave velocities within subsurface formations and is essential for accurate depth conversion and structural interpretation. Finally, migration algorithms reposition seismic reflections to their correct subsurface locations and enhance the clarity of geological structures [9].

3.2. Structural Interpretation

Structural interpretation is performed on the processed seismic dataset to identify geological structures that control hydrocarbon accumulation. Interpreters analyze reflection patterns within the seismic volume to detect key structural features such as faults, folds, anticlines, and stratigraphic boundaries.

Horizon picking is used to identify continuous seismic reflections corresponding to geological layer boundaries. These horizons are tracked across the seismic volume to construct structural surfaces that represent subsurface stratigraphy. Structural maps derived from these horizons provide valuable insights into the geometry and depth variation of geological formations.

Fault interpretation is conducted by identifying discontinuities in seismic reflections. Faults typically appear as offsets or breaks in seismic horizons and can be enhanced using seismic attributes such as coherence or variance. Fault interpretation is particularly important in hydrocarbon exploration because faults can influence hydrocarbon migration pathways and reservoir compartmentalization.

Structural maps generated from interpreted horizons help identify structural closures such as anticlines and fault traps that may serve as hydrocarbon accumulation zones [10].

3.3. Seismic Attribute Analysis

Seismic attributes are quantitative measures derived from seismic data that highlight specific geological features and improve interpretation accuracy. Attribute analysis enhances the visibility of structural and stratigraphic features that may not be easily recognizable in conventional seismic sections.

Several attributes are computed in this study, including RMS amplitude, instantaneous frequency, coherence, and envelope amplitude. RMS amplitude measures the average reflection energy within a specified time window and is commonly used to identify potential hydrocarbon reservoirs. High RMS amplitude values may indicate porous formations containing hydrocarbons.

Coherence attributes measure the similarity between neighboring seismic traces and are particularly useful for detecting faults and fractures within the seismic dataset. Instantaneous frequency attributes provide insights into lithological variations and stratigraphic changes within reservoir formations.

Envelope amplitude attributes represent the magnitude of seismic reflections and can reveal high-energy reflection zones associated with potential reservoir formations. By combining multiple attributes, interpreters can identify subtle geological features and improve the reliability of reservoir prediction [11].

3.4. Well Log Interpretation

Well-log interpretation is conducted to estimate reservoir rock properties using measurements obtained during drilling operations. Well logs provide direct information about lithology, porosity, and fluid content of subsurface formations.

The well logs analyzed in this study include gamma-ray logs, density logs, sonic logs, and resistivity logs. Gamma-ray logs are used to differentiate between shale and sandstone formations because shale typically exhibits higher natural radioactivity. Density and sonic logs are used to estimate formation porosity, while resistivity logs help identify hydrocarbon-bearing zones by measuring the electrical resistance of the formation.

Petrophysical analysis is performed using standard interpretation techniques to estimate key reservoir parameters including porosity, permeability, and water saturation. These parameters are essential for evaluating reservoir quality and determining hydrocarbon production potential [12].

3.5. Integrated Reservoir Modeling

The final stage of the methodology involves integrating seismic interpretation with petrophysical analysis to construct a comprehensive reservoir model. Integration is achieved by correlating seismic reflections with geological boundaries identified in well logs.

A well-to-seismic tie is performed using synthetic seismograms generated from sonic and density logs. This process allows interpreters to match seismic reflections with specific geological formations identified in well data. Once the correlation is established, seismic attributes and inversion results can be calibrated using petrophysical measurements.

The integrated reservoir model describes the spatial distribution of lithology, porosity, and fluid saturation across the study area. Such models are essential for estimating hydrocarbon reserves, evaluating reservoir performance, and supporting field development planning. Integrated interpretation workflows significantly reduce uncertainty in reservoir characterization and improve exploration decision-making [13].

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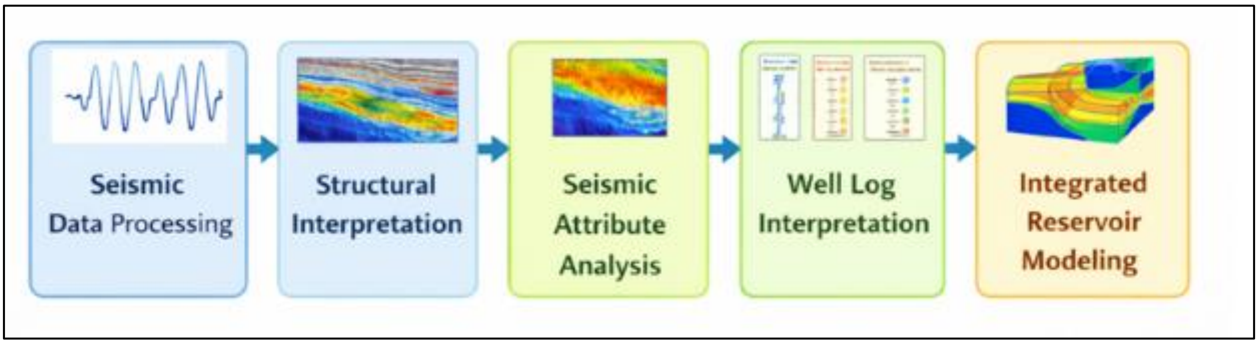

Figure 1 Integrated workflow for seismic and petrophysical data interpretation used for reservoir characterization.

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4. Results and Analysis

The integrated seismic–petrophysical interpretation workflow described in the previous section was applied to evaluate the structural framework and reservoir properties of the study area. The results demonstrate that combining seismic interpretation with petrophysical well-log analysis significantly improves the reliability of reservoir characterization. The integration of multiple datasets allows the identification of structural traps, reservoir zones, and potential hydrocarbon accumulations with greater accuracy.

4.1. Structural Interpretation Results

The structural interpretation of the 3D seismic volume revealed several important geological features within the study area. Multiple seismic horizons were identified and mapped across the seismic dataset, representing key stratigraphic boundaries within the sedimentary sequence.

The interpreted horizons indicate the presence of several structural features including anticlines and normal faults. These structures are clearly visible in the seismic sections and are interpreted as potential hydrocarbon traps. Faults appear as discontinuities in seismic reflections and can significantly influence hydrocarbon migration and reservoir compartmentalization.

The interpreted fault network divides the reservoir into several structural compartments. Such compartmentalization is common in sedimentary basins and can influence hydrocarbon distribution and production performance. Depending on their sealing properties, faults may either facilitate hydrocarbon migration or act as barriers that trap hydrocarbons within structural closures [14].

Structural maps generated from interpreted seismic horizons indicate the presence of several anticline structures. These structures form when sedimentary layers are folded upward due to tectonic compression, creating closures where hydrocarbons may accumulate beneath impermeable cap rocks.

4.2. Well Log Interpretation

Well-log analysis was performed to estimate the petrophysical properties of the reservoir formation. The interpretation focused on four key well logs: gamma-ray, density, sonic, and resistivity logs.

The gamma-ray log was used to distinguish between shale and sandstone formations. Low gamma-ray values indicate clean sandstone reservoirs, while high gamma-ray values correspond to shale-rich intervals. The interpreted gamma-ray log indicates that the primary reservoir interval consists predominantly of sandstone formations with relatively low shale content.

Density and sonic logs were used to estimate formation porosity. The calculated porosity values indicate that the reservoir interval exhibits moderate to high porosity, suggesting favorable storage capacity for hydrocarbons.

Resistivity logs provide important information about fluid content within the reservoir. High resistivity values observed in the reservoir interval suggest the presence of hydrocarbons rather than formation water. These results support the interpretation that the identified reservoir zones contain hydrocarbon accumulations [15].

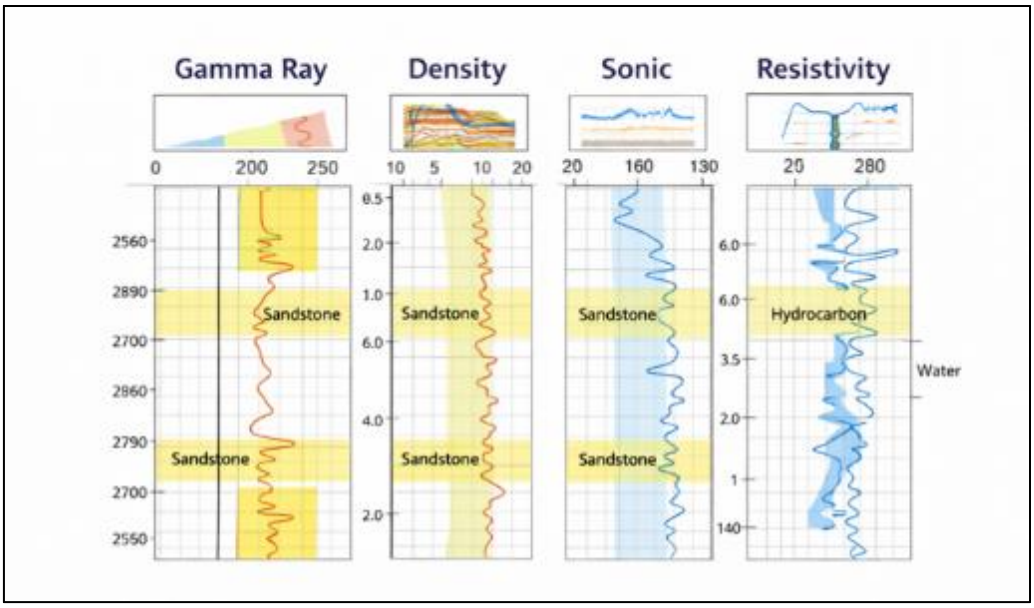

Figure 2 Well-log interpretation showing gamma-ray, density, sonic, and resistivity logs used for reservoir evaluation [32-33].

4.3. Seismic Attribute Analysis

Seismic attribute analysis was conducted to enhance the identification of reservoir zones within the seismic dataset. Several seismic attributes were computed, including RMS amplitude, coherence, and instantaneous frequency.

The RMS amplitude attribute highlights zones with strong seismic reflections that may correspond to porous reservoir formations. High-amplitude anomalies were observed within the main reservoir interval, indicating potential hydrocarbon accumulations.

Coherence attributes were particularly effective in identifying fault structures within the seismic volume. Fault planes appear as low-coherence zones because seismic reflections become discontinuous across fault boundaries.

Instantaneous frequency attributes provide additional information about lithological variations within the reservoir formation. Variations in instantaneous frequency may indicate changes in depositional environments or lithological composition.

The integration of multiple seismic attributes allows interpreters to identify subtle geological features that may not be visible in conventional seismic sections. This improves the accuracy of reservoir prediction and structural interpretation [16].

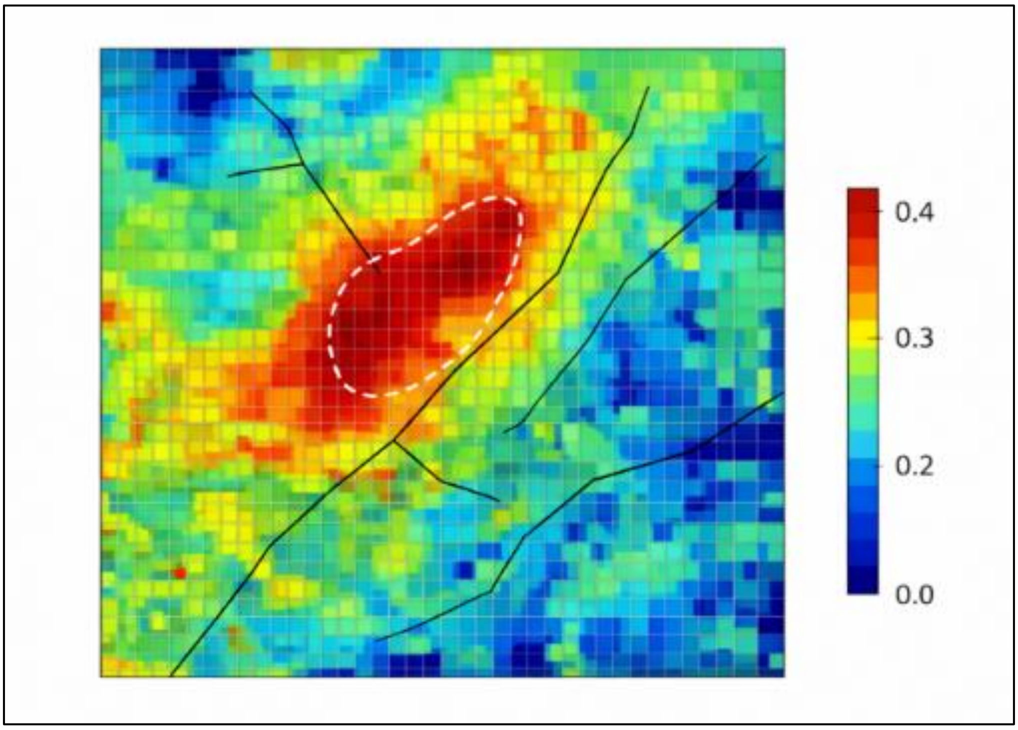

Figure 3 RMS amplitude seismic attribute map highlighting high-amplitude anomalies associated with potential hydrocarbon reservoirs.

4.4. Integrated Reservoir Properties

By integrating seismic interpretation and petrophysical analysis, several key reservoir properties were estimated for the primary reservoir interval. These properties provide important insights into the hydrocarbon storage capacity and production potential of the reservoir.

Table 1 Estimated Reservoir Properties

Property	Estimated Range
Porosity	18–25%
Permeability	150–450 mD
Water Saturation	20–35%
Net-to-Gross Ratio	0.60–0.75

The relatively high porosity and permeability values indicate that the reservoir formation has good storage capacity and fluid flow potential. Low water saturation values suggest that a significant portion of the pore space is occupied by hydrocarbons.

These results are consistent with the seismic attribute anomalies identified in the RMS amplitude map and support the interpretation of potential hydrocarbon reservoirs within the study area.

The integration of seismic interpretation and petrophysical analysis enabled the development of a comprehensive reservoir model describing the spatial distribution of reservoir layers, fault structures, and hydrocarbon traps within the study area, as illustrated in **Figure 4**.

Integrated seismic–petrophysical interpretation significantly improves reservoir prediction accuracy by combining spatial geological information from seismic data with direct rock property measurements obtained from well logs. Such integrated approaches are widely used in modern hydrocarbon exploration to reduce uncertainty and improve exploration success rates [17].

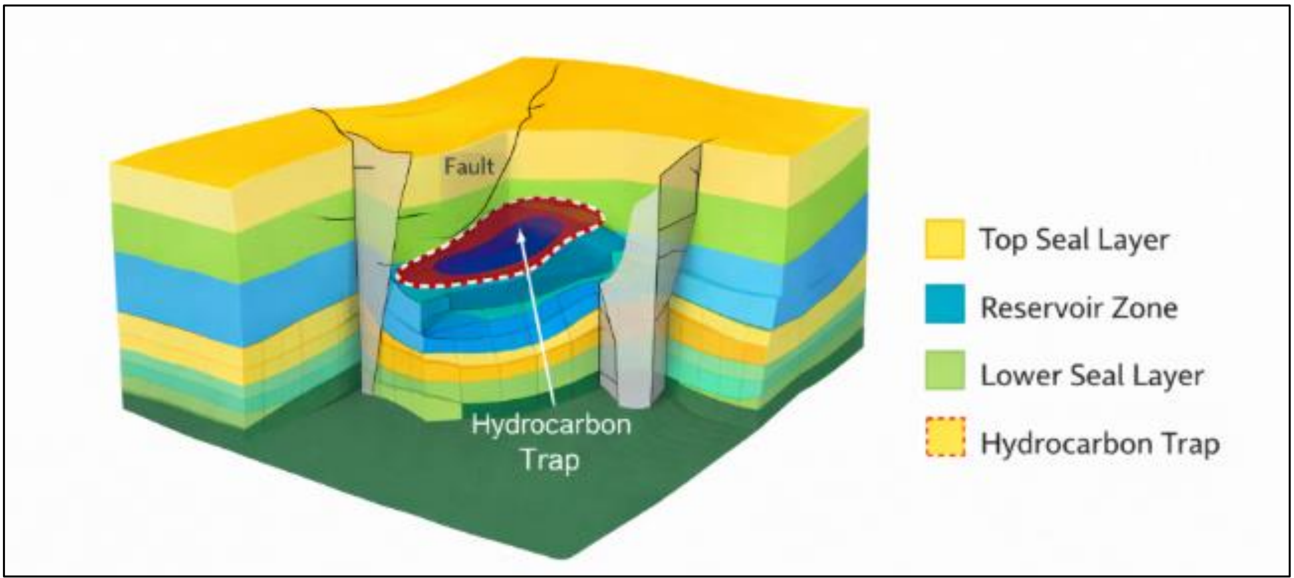

Figure 4 Integrated reservoir model derived from seismic interpretation and petrophysical analysis showing structural traps and reservoir zones [30-31].

5. Discussion

The results obtained from the integrated seismic and petrophysical interpretation workflow highlight the importance of combining multiple datasets for accurate reservoir characterization. Traditional seismic interpretation alone may not provide sufficient information about reservoir properties because seismic data primarily reveal structural and stratigraphic features rather than direct rock properties. However, when seismic interpretation is integrated with well-log petrophysical analysis, it becomes possible to obtain a more comprehensive understanding of the subsurface reservoir system.

One of the key findings of this study is the strong correlation between seismic attribute anomalies and reservoir properties estimated from well-log analysis. The RMS amplitude anomalies identified within the reservoir interval correspond closely with zones exhibiting higher porosity and permeability values in the well logs. This relationship suggests that seismic attributes can serve as useful indicators of reservoir quality when properly calibrated with petrophysical measurements.

Structural interpretation also revealed several anticline structures and fault systems that may serve as hydrocarbon traps. These structural traps are essential components of petroleum systems because they create conditions where hydrocarbons can accumulate beneath impermeable cap rocks. The interpreted fault systems divide the reservoir into several compartments, which may influence hydrocarbon migration pathways and reservoir performance during production [18-23].

Another important observation is the presence of lithological heterogeneity within the reservoir formation. Variations in instantaneous frequency attributes and well-log responses indicate that the reservoir consists of multiple depositional units with different rock properties. Such heterogeneity is common in sedimentary reservoirs and must be carefully considered when developing reservoir models and planning field development strategies [23-26].

The integration of seismic interpretation and petrophysical analysis significantly reduces uncertainty in reservoir characterization. By combining spatial geological information with direct rock property measurements, geoscientists can construct more reliable reservoir models and improve predictions of hydrocarbon distribution. Similar integrated workflows have been widely applied in modern hydrocarbon exploration because they enhance exploration success rates and reduce drilling risks [26-29].

Despite these advantages, several limitations remain. Seismic data resolution may not always be sufficient to detect very thin reservoir layers or subtle stratigraphic features. Additionally, well-log data are typically available only at discrete locations, which introduces uncertainty when extrapolating reservoir properties across the entire field.

Future research should focus on incorporating advanced computational techniques such as machine learning and seismic inversion to further improve reservoir prediction accuracy. These methods can analyze large seismic datasets and identify complex relationships between seismic attributes and reservoir properties.

6. Conclusion

This study presents an integrated approach for hydrocarbon reservoir characterization using seismic interpretation and petrophysical analysis. The proposed workflow combines 3D seismic interpretation, seismic attribute analysis, and well-log evaluation to improve subsurface structural mapping and reservoir prediction.

Structural interpretation of the seismic dataset revealed several geological features including faults and anticline structures that may serve as hydrocarbon traps. Seismic attribute analysis further enhanced the interpretation by highlighting high-amplitude anomalies associated with potential reservoir formations.

Petrophysical analysis of well-log data provided quantitative estimates of reservoir properties such as porosity, permeability, and water saturation. The results indicate that the primary reservoir interval exhibits favorable reservoir properties, suggesting significant hydrocarbon production potential.

The integration of seismic and petrophysical datasets enabled the development of a comprehensive reservoir model that accurately describes the spatial distribution of reservoir properties. This integrated interpretation approach significantly reduces uncertainty in reservoir characterization and improves the reliability of exploration decisions.

Overall, the methodology presented in this study provides an effective framework for improving hydrocarbon exploration and reservoir evaluation in sedimentary basins.

Future Work

Future research should focus on expanding the integrated interpretation workflow by incorporating additional advanced techniques and datasets. Several promising research directions include:

- **Machine Learning for Seismic Interpretation**

Machine learning algorithms can be applied to automatically detect faults, horizons, and stratigraphic features within seismic datasets.

- **Seismic Inversion for Reservoir Property Estimation**

Seismic inversion techniques can be used to estimate acoustic impedance and lithological variations within reservoir formations.

- **Integration with Geological and Geomechanical Models**

Combining seismic interpretation with geological and geomechanical modeling can provide deeper insights into reservoir behavior and structural deformation.

- **Time-Lapse (4D) Seismic Monitoring**

Time-lapse seismic surveys can be used to monitor changes in reservoir properties during hydrocarbon production.

- **Improved Reservoir Simulation**

Advanced reservoir simulation models can be integrated with seismic and petrophysical data to improve predictions of reservoir performance.

These research directions will further enhance the accuracy and efficiency of reservoir characterization and support more sustainable hydrocarbon exploration practices.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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