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## Seismic attribute-based fault detection and structural mapping in 3D seismic data for hydrocarbon exploration

RODWAN A ELBAROUNI \*

*Department of Geology and Geophysics, Missouri University of Science and Technology, Rolla, MO, USA.*

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### Abstract

Accurate identification of subsurface fault systems is critical for hydrocarbon exploration and reservoir management. Fault structures influence hydrocarbon migration, reservoir compartmentalization, and structural trap formation. Traditional seismic interpretation techniques often rely on manual analysis of seismic sections, which may overlook subtle fault features within complex geological settings. This study proposes an attribute-based seismic interpretation approach for improved fault detection and structural mapping in 3D seismic datasets. Several seismic attributes, including coherence, variance, and curvature, are analyzed to enhance the visibility of fault structures within the seismic volume. Structural interpretation is performed to map fault networks and evaluate their impact on reservoir geometry and hydrocarbon trapping mechanisms. Results demonstrate that seismic attribute analysis significantly improves the detection of small-scale faults and structural discontinuities that are not clearly visible in conventional seismic sections. The proposed workflow enhances the accuracy of structural interpretation and supports more reliable hydrocarbon exploration strategies.

**Keywords:** Seismic Attributes; Fault Detection; Structural Interpretation; 3D Seismic Data; Hydrocarbon Exploration; Seismic Coherence; Reservoir Characterization; Structural Mapping

### 1. Introduction

The accurate identification of subsurface geological structures is essential for hydrocarbon exploration and reservoir management. Structural features such as faults, folds, and stratigraphic traps play a critical role in controlling hydrocarbon migration and accumulation within sedimentary basins. Understanding these structures allows geoscientists to identify potential hydrocarbon reservoirs and optimize exploration strategies. Seismic reflection methods have become one of the most widely used geophysical tools for imaging subsurface formations and identifying geological structures in petroleum exploration [1].

Three-dimensional seismic data provide detailed spatial information about subsurface geological formations and allow interpreters to analyze complex structural features with improved accuracy. Compared with traditional two-dimensional seismic surveys, 3D seismic datasets offer enhanced imaging of structural discontinuities and stratigraphic variations. These datasets enable geoscientists to visualize fault networks, reservoir geometry, and sedimentary structures in three dimensions, significantly improving exploration decision-making [2].

Fault detection is particularly important in petroleum exploration because faults influence hydrocarbon migration pathways and reservoir compartmentalization. Fault systems may act as either conduits or barriers for hydrocarbon movement depending on their orientation and sealing capacity. Identifying these structures is therefore essential for understanding reservoir connectivity and predicting hydrocarbon distribution within a basin [3].

\* Corresponding author: RODWAN A ELBAROUNI.

Traditional seismic interpretation methods rely heavily on manual analysis of seismic sections. Although experienced interpreters can identify major geological structures, smaller faults and subtle structural discontinuities may remain undetected due to limitations in seismic resolution and visual interpretation. As seismic datasets become increasingly large and complex, advanced interpretation techniques are required to improve the accuracy and efficiency of structural analysis [4].

Seismic attribute analysis has emerged as a powerful technique for enhancing the interpretation of seismic data. Seismic attributes are mathematical transformations applied to seismic traces to highlight specific geological features within the dataset. Attributes such as coherence, variance, curvature, and RMS amplitude can reveal structural discontinuities and stratigraphic features that may not be visible in conventional seismic sections. These attributes have been widely used to detect fault structures and improve structural interpretation in hydrocarbon exploration [5].

Among these attributes, coherence and variance attributes are particularly useful for fault detection because they measure the similarity between adjacent seismic traces. Fault planes appear as zones of low similarity or discontinuity in the seismic data, allowing interpreters to map fault networks more accurately. Similarly, curvature attributes can highlight subtle structural deformation within geological layers and provide additional insights into reservoir geometry [6].

Recent advancements in digital technologies and data-driven analytics have also expanded the capabilities of seismic interpretation. Machine learning and artificial intelligence techniques are increasingly being applied to analyze large seismic datasets and identify geological structures automatically. These approaches have demonstrated significant potential for improving structural interpretation and reservoir prediction accuracy [7-10].

Furthermore, the integration of digital technologies and advanced data analytics has transformed many engineering disciplines, including energy exploration and industrial systems. Studies have shown that artificial intelligence and digital transformation frameworks can significantly enhance data-driven decision-making and operational efficiency in complex engineering environments [11].

Despite these advancements, many exploration workflows still rely primarily on conventional interpretation methods. There is therefore a need for integrated seismic attribute-based approaches that improve the detection of faults and structural discontinuities in complex geological settings [12-13, 15].

The objective of this study is to develop an attribute-based seismic interpretation workflow for improved fault detection and structural mapping in 3D seismic datasets. The proposed methodology integrates seismic attribute analysis and structural interpretation techniques to enhance the identification of fault systems and evaluate their impact on hydrocarbon reservoir distribution.

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## 2. Background and Literature Review

### 2.1. Seismic Reflection Principles

Seismic reflection surveying is one of the most effective geophysical methods for imaging subsurface geological structures. The technique is based on the propagation of seismic waves through the Earth and the reflection of these waves at interfaces where there are contrasts in acoustic impedance between different rock layers. The recorded seismic reflections provide valuable information about subsurface stratigraphy, lithology, and structural geometry.

The travel time and amplitude of reflected seismic waves are analyzed to determine the depth and characteristics of geological formations. These reflections are recorded by arrays of geophones or hydrophones positioned across the survey area. After acquisition, seismic data undergo several processing stages including noise removal, stacking, and migration to produce interpretable seismic sections [17].

Modern seismic reflection surveys often employ three-dimensional acquisition geometries that provide detailed spatial coverage of the subsurface. Compared with traditional two-dimensional seismic surveys, 3D seismic datasets allow interpreters to analyze complex geological structures from multiple directions and improve the accuracy of structural mapping [18].

## 2.2. Structural Interpretation in Seismic Data

Structural interpretation involves identifying geological features such as faults, folds, anticlines, and stratigraphic boundaries within seismic datasets. These structures play an essential role in controlling hydrocarbon accumulation because they influence the migration and trapping of hydrocarbons within sedimentary basins.

Fault systems are particularly important in hydrocarbon exploration because they may either facilitate or restrict hydrocarbon migration. When faults act as sealing barriers, they can create structural traps where hydrocarbons accumulate beneath impermeable cap rocks. Conversely, permeable faults may serve as migration pathways that allow hydrocarbons to move through the subsurface.

Structural interpretation typically begins with horizon picking, where interpreters track continuous seismic reflections corresponding to geological layer boundaries. These interpreted horizons are then used to construct structural maps that represent the geometry of subsurface formations [19].

Advanced visualization tools and interpretation software have significantly improved the efficiency of structural interpretation by enabling geoscientists to analyze seismic data in three-dimensional space. These tools allow interpreters to identify complex structural features that may not be easily recognizable in traditional two-dimensional seismic sections [20].

## 2.3. Seismic Attributes for Fault Detection

Seismic attributes are quantitative measures derived from seismic data that enhance the visibility of geological features within seismic datasets. Attribute analysis involves applying mathematical transformations to seismic traces to highlight specific characteristics of the data such as amplitude, frequency, and phase.

Among the most widely used attributes for fault detection are coherence, variance, and curvature attributes. Coherence attributes measure the similarity between neighboring seismic traces and can reveal discontinuities in seismic reflections that correspond to fault planes. Areas with low coherence values often indicate the presence of faults or fractures within the subsurface [21].

Variance attributes are also useful for identifying structural discontinuities because they emphasize variations in seismic signal characteristics across adjacent traces. These attributes help interpreters detect subtle faults that may not be visible in conventional seismic sections.

Curvature attributes provide additional insights into structural deformation by measuring the curvature of seismic horizons. These attributes are particularly effective for identifying folds and subtle structural flexures within sedimentary formations [22].

## 2.4. Digital Technologies in Seismic Interpretation

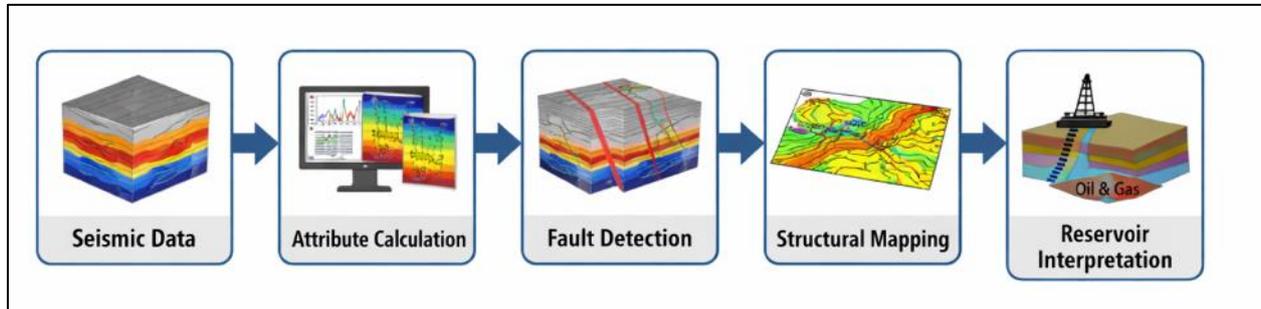
Recent advances in computational technologies have introduced new methods for seismic interpretation. Machine learning and artificial intelligence techniques are increasingly being used to analyze large seismic datasets and automatically identify geological features.

Deep learning algorithms can be trained to detect faults, horizons, and stratigraphic patterns within seismic volumes with high accuracy. These approaches significantly reduce the time required for seismic interpretation and improve the detection of subtle geological structures [23]. Advanced computational modeling and theoretical analysis have played a significant role in improving scientific understanding of complex physical systems. Recent theoretical studies on many-body quantum systems demonstrate how higher-order corrections can improve the accuracy of physical modeling and analytical predictions [14]. Machine learning-based security and monitoring frameworks have demonstrated strong potential for improving system reliability and anomaly detection in modern digital infrastructures [25].

Despite these advancements, seismic attribute analysis remains one of the most practical and widely used techniques for improving fault detection in seismic datasets. Integrating attribute-based interpretation with structural analysis provides a powerful approach for identifying fault networks and understanding their impact on hydrocarbon reservoirs.

### 3. Methodology

This study proposes an integrated seismic interpretation workflow for detecting faults and mapping structural features using three-dimensional seismic data. The methodology combines seismic data processing, seismic attribute computation, and structural interpretation techniques to enhance the identification of fault systems within complex geological environments. The workflow consists of four main stages: seismic data preparation, seismic attribute analysis, fault detection, and structural mapping.



**Figure 1** Workflow of the seismic attribute-based interpretation approach used for fault detection and structural mapping in 3D seismic data

This figure illustrates the overall methodological framework used in this study. The workflow includes seismic data preparation, seismic attribute computation, fault detection, and structural mapping. The figure provides a clear overview of how seismic attributes are integrated into the interpretation process to improve the detection of subsurface faults.

The integration of digital data processing tools and computational technologies has significantly improved seismic interpretation capabilities. Advanced analytical frameworks and artificial intelligence-based systems have demonstrated the potential to enhance large-scale data analysis and improve decision-making processes in engineering applications, inspired by these developments, the proposed workflow integrates attribute-based interpretation techniques to improve the detection of subtle geological structures in seismic datasets.

#### 3.1. Seismic Data Preparation

The first stage of the methodology involves preparing the seismic dataset for interpretation. Seismic data acquired from field surveys typically contain noise and acquisition artifacts that must be removed before interpretation can be performed. Standard seismic data processing techniques are applied to improve data quality and enhance seismic reflections.

These processing steps include noise filtering, amplitude correction, velocity analysis, stacking, and migration. Noise filtering removes unwanted signals such as ground roll and multiple reflections that can obscure geological features. Amplitude correction compensates for energy loss during wave propagation, ensuring that reflection amplitudes accurately represent subsurface structures.

Velocity analysis is performed to estimate seismic wave velocities within subsurface formations. Accurate velocity models are essential for proper depth conversion and structural interpretation. After velocity estimation, seismic stacking is applied to enhance the signal-to-noise ratio of the recorded data. Finally, migration algorithms reposition seismic reflections to their correct spatial locations and improve the accuracy of structural imaging.

The result of this processing workflow is a three-dimensional seismic volume that accurately represents the geometry of subsurface geological formations.

#### 3.2. Seismic Attribute Computation

Once the seismic dataset has been processed, seismic attributes are computed to enhance the interpretation of structural features. Seismic attributes are mathematical transformations applied to seismic data that reveal specific characteristics of the subsurface that may not be visible in conventional seismic sections.

Several attributes are computed in this study, including coherence, variance, curvature, and RMS amplitude attributes. Coherence attributes measure the similarity between adjacent seismic traces and are widely used for detecting structural discontinuities such as faults and fractures. Fault planes appear as zones of low coherence because seismic reflections become discontinuous across fault boundaries.

Variance attributes emphasize changes in seismic amplitude and waveform characteristics across neighboring traces. These attributes help identify subtle structural features that may not be easily detected in standard seismic sections.

Curvature attributes measure the bending or deformation of seismic horizons and are useful for identifying folds and structural flexures within sedimentary formations. These attributes provide valuable insights into the structural geometry of the subsurface.

By combining multiple seismic attributes, interpreters can improve the visualization of structural discontinuities and enhance the detection of fault networks within the seismic dataset.

### **3.3. Fault Detection and Interpretation**

Fault detection is performed by analyzing seismic attribute maps and identifying zones where seismic reflections exhibit discontinuities or abrupt changes. Fault planes typically appear as linear features within coherence or variance attribute maps.

The interpretation process begins by examining vertical seismic sections to identify potential fault zones. These zones are then verified using seismic attribute slices to confirm the presence of structural discontinuities. Interpreters map fault planes throughout the seismic volume by tracking these discontinuities across multiple seismic sections.

Fault interpretation is further refined by analyzing the displacement of seismic horizons across fault planes. The magnitude and orientation of these displacements provide valuable information about the structural evolution of the basin and the role of fault systems in controlling hydrocarbon migration.

### **3.4. Structural Mapping**

After identifying fault structures, structural mapping is performed to analyze the geometry and spatial distribution of geological formations within the study area. Horizon picking is used to track continuous seismic reflections that correspond to geological layer boundaries.

The interpreted horizons are used to generate structural maps that represent the depth and geometry of reservoir formations. These maps help identify structural traps such as anticlines and fault-bounded closures that may contain hydrocarbon accumulations.

Structural maps also provide insights into reservoir compartmentalization caused by fault systems. Understanding reservoir compartmentalization is essential for evaluating hydrocarbon distribution and designing effective reservoir development strategies.

The integrated interpretation workflow developed in this study enables the identification of both major fault systems and subtle structural discontinuities, improving the accuracy of subsurface structural mapping and hydrocarbon exploration.

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## **4. Results and Analysis**

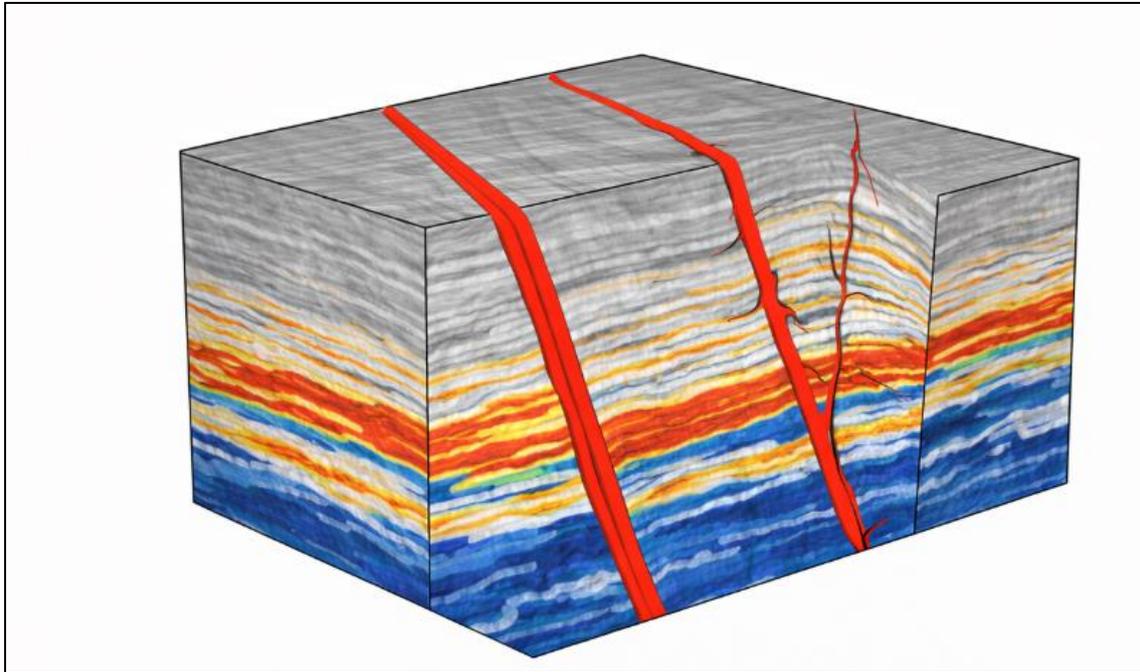
The proposed seismic attribute-based interpretation workflow was applied to the three-dimensional seismic dataset to evaluate its effectiveness in identifying fault structures and mapping the structural framework of the study area. The integration of seismic attribute analysis with conventional seismic interpretation significantly enhanced the visualization of structural discontinuities and improved the accuracy of fault detection. The results obtained from the attribute analysis and structural interpretation are discussed in the following subsections.

### **4.1. Fault Detection Using Seismic Attributes**

The application of seismic attributes played a crucial role in improving the detection of fault systems within the seismic volume. Conventional seismic sections often provide limited visibility of subtle faults due to complex reflection patterns

and noise within the dataset. However, attribute-based analysis enhances the identification of structural discontinuities by highlighting variations in seismic trace characteristics.

Among the attributes analyzed in this study, coherence and variance attributes were particularly effective for detecting fault planes. The coherence attribute measures the similarity between neighboring seismic traces. Fault zones typically appear as areas of low coherence because seismic reflections become discontinuous across fault boundaries. When coherence attributes were applied to the seismic dataset, several previously indistinct structural discontinuities became clearly visible.



**Figure 2** Interpreted 3D seismic section showing major fault planes within the seismic volume. The discontinuities in seismic reflections represent fault structures that control the structural configuration of the reservoir

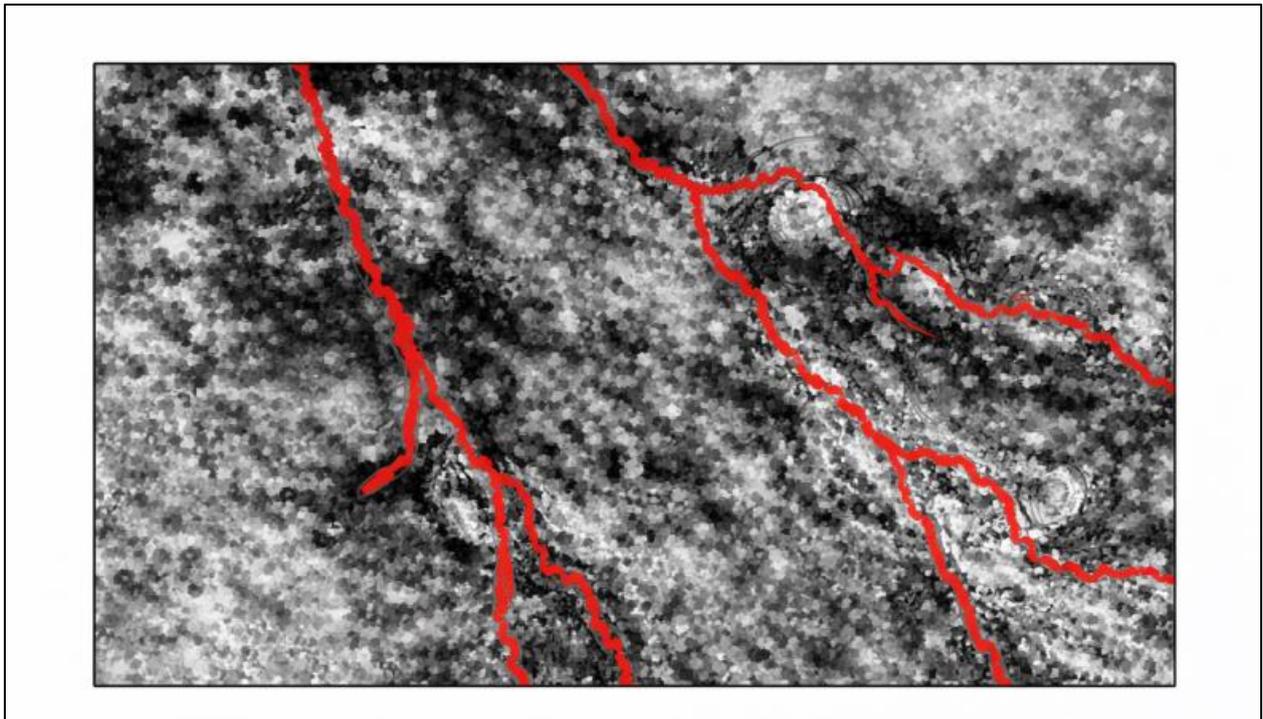
Figure 2 illustrates a representative seismic section from the study area with interpreted fault planes. The discontinuities observed in the seismic reflections indicate the presence of multiple fault structures that extend across the reservoir interval. These faults exhibit varying orientations and displacement magnitudes, suggesting a complex structural deformation history within the basin.

The variance attribute further enhanced fault detection by emphasizing abrupt changes in seismic amplitude and waveform characteristics. Attribute maps generated using variance analysis revealed additional secondary faults that were not easily visible in conventional seismic sections. The identification of these smaller faults is particularly important because they may significantly influence reservoir compartmentalization and hydrocarbon migration pathways.

Previous studies have demonstrated that attribute-based interpretation techniques significantly improve fault detection in complex geological environments, enabling interpreters to identify both major and minor structural discontinuities within seismic datasets

#### 4.2. Seismic Attribute Visualization

Seismic attribute slices extracted from the seismic volume provided valuable insights into the spatial distribution of structural features within the study area. Attribute visualization enables interpreters to analyze structural patterns across horizontal slices of the seismic volume, which can reveal fault networks and stratigraphic variations.



**Figure 3** Coherence attribute map highlighting structural discontinuities associated with fault systems within the seismic dataset. Zones with low coherence values indicate potential fault planes and structural breaks in the subsurface

Figure 3 presents a coherence attribute map that highlights the distribution of structural discontinuities within the seismic dataset. The low-coherence zones correspond to fault traces that extend across the seismic volume. These faults form interconnected networks that segment the reservoir interval into multiple structural compartments.

The coherence attribute map clearly illustrates the orientation and continuity of the fault systems. Several faults appear as linear discontinuities that intersect at different angles, forming complex fault networks within the basin. These structural features play a critical role in controlling hydrocarbon migration and accumulation.

In addition to coherence attributes, RMS amplitude attributes were analyzed to identify potential reservoir zones. High-amplitude anomalies observed within the reservoir interval may correspond to porous formations containing hydrocarbons. These anomalies were found to coincide with structural closures identified during the structural interpretation stage.

The integration of multiple seismic attributes provides a more comprehensive understanding of subsurface structural features. By combining coherence, variance, and amplitude attributes, interpreters can identify subtle geological features that may not be visible in conventional seismic sections.

#### **4.3. Structural Interpretation Results**

Following the identification of fault structures using seismic attributes, structural interpretation was performed to map the geometry of subsurface formations within the study area. Several seismic horizons corresponding to key stratigraphic boundaries were interpreted across the three-dimensional seismic volume.

The interpreted horizons revealed the presence of several anticline structures within the reservoir interval. These anticlines form potential hydrocarbon traps because hydrocarbons can accumulate beneath impermeable cap rocks in folded geological formations.

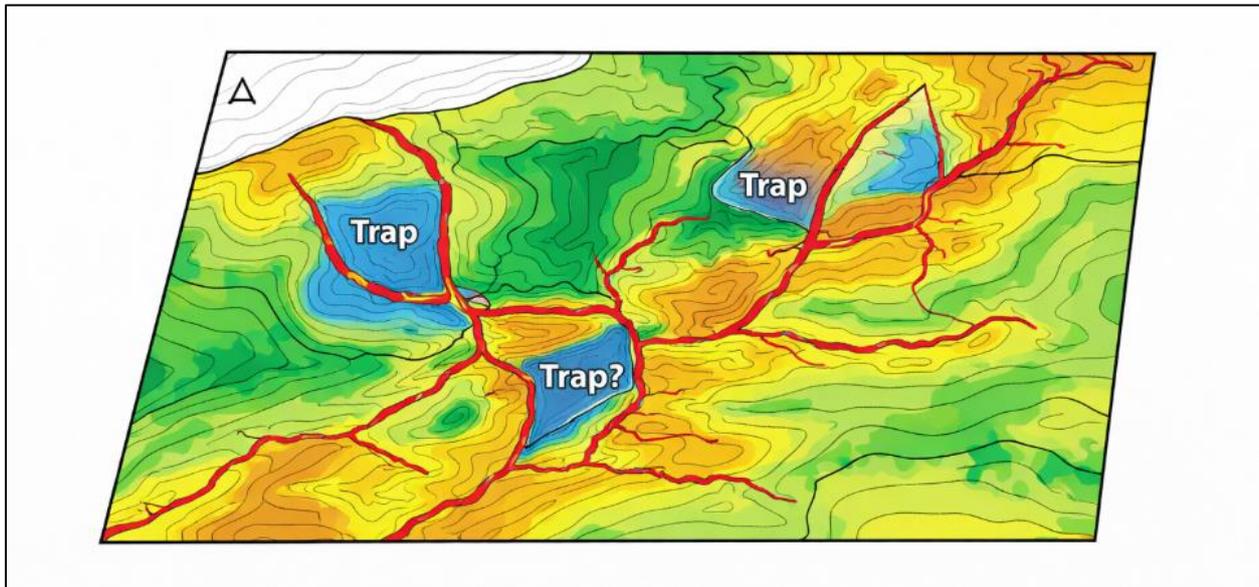
Fault interpretation indicated that the identified faults predominantly exhibit normal faulting characteristics, suggesting that the basin has experienced extensional tectonic activity. The displacement of seismic horizons across fault planes indicates significant structural deformation that has influenced the geometry of the reservoir.

Structural maps generated from the interpreted horizons indicate that the reservoir interval is segmented into multiple compartments by fault systems. These compartments may influence reservoir connectivity and hydrocarbon distribution. In some areas, faults appear to act as sealing barriers that trap hydrocarbons within structural closures.

Understanding the structural framework of the reservoir is therefore essential for evaluating hydrocarbon accumulation and designing effective exploration strategies

#### 4.4. Structural Mapping and Reservoir Implications

The final stage of the analysis involved integrating the results of seismic attribute analysis and structural interpretation to generate structural maps of the reservoir interval. These maps provide a comprehensive representation of the spatial distribution of geological formations and fault systems within the study area.



**Figure 4** Structural map of the interpreted reservoir horizon showing the spatial distribution of fault networks and potential hydrocarbon trap zones. Fault systems divide the reservoir into several structural compartments that may influence hydrocarbon accumulation and migration pathways

Figure 4 presents the final structural map showing the interpreted fault network and potential hydrocarbon trap zones. Several structural closures are observed within the reservoir interval, many of which are bounded by fault systems. These fault-bounded structures may serve as potential hydrocarbon traps if suitable source rocks and migration pathways are present.

The structural map also highlights the influence of fault systems on reservoir compartmentalization. In some areas, faults divide the reservoir into isolated compartments that may contain separate hydrocarbon accumulations. This structural segmentation can significantly impact reservoir performance and production strategies.

The results demonstrate that the integrated seismic attribute-based interpretation workflow provides a reliable method for detecting fault structures and mapping the structural framework of sedimentary basins. By improving the accuracy of structural interpretation, this approach helps reduce exploration uncertainty and supports more effective hydrocarbon exploration decisions.

Overall, the integration of seismic attribute analysis with conventional structural interpretation significantly enhances the detection of subsurface faults and improves the reliability of reservoir characterization in three-dimensional seismic datasets.

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## 5. Discussion

The results of this study demonstrate that seismic attribute analysis significantly enhances the detection of subsurface fault systems compared with conventional seismic interpretation techniques. Traditional interpretation methods rely

primarily on visual examination of seismic sections, which may limit the identification of subtle structural discontinuities. By incorporating attribute-based analysis, interpreters can highlight structural variations that are otherwise difficult to detect in raw seismic data. Among the attributes evaluated in this study, coherence attributes proved to be the most effective for identifying fault planes. The coherence attribute clearly revealed zones of low trace similarity that correspond to fault structures within the seismic volume. These results are consistent with previous studies that have shown coherence attributes to be highly effective in identifying structural discontinuities in seismic datasets.

Variance attributes also contributed to improving fault detection by emphasizing abrupt changes in seismic reflection patterns. These attributes allowed the identification of several secondary faults that were not clearly visible in conventional seismic sections. The detection of such small-scale faults is particularly important because they may significantly influence reservoir compartmentalization and hydrocarbon migration pathways. The integration of multiple seismic attributes provided a more comprehensive understanding of the subsurface structural framework. By combining coherence, variance, and amplitude attributes, the interpretation workflow was able to identify both major and minor structural discontinuities. Similar integrated attribute analysis approaches have been widely used in modern seismic interpretation to improve structural mapping accuracy and reduce exploration uncertainty.

Another important observation from this study is the role of fault systems in controlling the structural configuration of the reservoir. The interpreted faults divide the reservoir into several compartments that may influence hydrocarbon distribution and reservoir connectivity. In some cases, faults may act as barriers that trap hydrocarbons within structural closures, while in other cases they may facilitate hydrocarbon migration through permeable fault zones. The structural mapping results indicate that several fault-bounded closures exist within the study area, suggesting favorable conditions for hydrocarbon accumulation. Understanding these structural features is essential for improving reservoir characterization and optimizing hydrocarbon exploration strategies. In industrial systems, safety management and risk mitigation remain critical considerations for operational reliability and worker protection. Studies on industrial hazard control and chemical exposure management show the importance of structured safety frameworks in modern engineering operations [24].

Despite the effectiveness of seismic attribute analysis, some limitations remain. The resolution of seismic data may restrict the detection of very small faults or thin geological layers. Additionally, interpretation results may vary depending on the quality of seismic data and the selection of seismic attributes. Future studies may benefit from incorporating advanced computational techniques such as machine learning algorithms to further enhance the detection of structural features in seismic datasets.

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## 6. Conclusion

This study presented an integrated seismic interpretation approach for fault detection and structural mapping using three-dimensional seismic data. The proposed methodology combines seismic attribute analysis with structural interpretation techniques to improve the identification of subsurface fault systems and reservoir structures.

The results demonstrate that seismic attributes such as coherence, variance, and RMS amplitude significantly enhance the visualization of structural discontinuities within seismic datasets. The application of these attributes enabled the detection of several fault structures that were not clearly visible in conventional seismic sections.

Structural interpretation of the seismic dataset revealed a complex fault network that divides the reservoir interval into multiple structural compartments. Several structural closures identified within the study area may serve as potential hydrocarbon traps, indicating favorable conditions for hydrocarbon accumulation.

The integration of seismic attribute analysis and structural mapping provides a powerful workflow for improving the accuracy of subsurface interpretation. This approach enhances the detection of fault systems, reduces uncertainty in structural mapping, and supports more reliable hydrocarbon exploration strategies.

Future research may focus on integrating machine learning algorithms and automated seismic interpretation techniques to further improve the detection of structural features in large seismic datasets. Such advancements will contribute to more efficient exploration workflows and improved reservoir characterization in complex geological environments.

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