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Analytical Modelling of Fault Seal Effectiveness in Hydrocarbon Reservoirs: A Multi-Criteria Decision Analysis and Analytical Hierarchy Process Approach

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Abstract
Faults in hydrocarbon reservoirs significantly influence fluid flow behavior, making the prediction of fault seal effectiveness critical in reservoir management. This study introduces the FAULT-SEAL Evaluation Model (FSEM), leveraging a Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) framework. By integrating geological, geophysical, and fluid-related factors, FSEM assigns weights to key parameters, emphasizing the dominant role of clay smears and gouge composition (global weight: 0.8417) in fault-sealing potential. The Shale Gouge Ratio (SGR) and clay content emerged as the most sensitive parameters, with changes of up to 30% impacting fault seal effectiveness by as much as 0.12, underscoring their importance in fluid migration control. Fault throw and offset, with a moderate weight of 0.6262, significantly influenced the juxtaposition of rock types and sealing capacity, while stress conditions, particularly pore pressure (weight: 0.2999), moderately affected seal integrity, highlighting the need to monitor in-situ stress regimes. Validation through sensitivity analysis confirmed the model's robustness and reliability, with a Consistency Ratio (CR) of -0.0543, ensuring minimal inconsistency in the decision matrix. These findings underscore the critical role of clay-rich fault zones in hydrocarbon trapping and the importance of detailed fault rock characterization. The FSEM offers a scalable, data-driven tool capable of generating faster, more accurate fault seal predictions, advancing exploration and production strategies. By integrating machine learning techniques and decision frameworks, the model provides an innovative approach to optimizing hydrocarbon recovery in faulted reservoirs.
Keywords: *Shale Gouge Ratio (SGR), Hydrocarbon Reservoirs, Sensitivity Analysis, Clay Smears, Pore Pressure*

INTRODUCTION

Faults are a common feature in most petroleum reservoirs, representing displacements of rock layers within the stratigraphic sequence (Figure 1). These geological structures can disrupt communication between different layers within oil and gas reservoirs, making predicting fluid flow behavior difficult. As a result, faulted reservoirs present challenges in drilling and production, with unpredictable performance and complex reservoir management requirements.

Figure 1: Typical Faults representing displacements of rock layers within the stratigraphic sequence

Understanding and predicting fault behavior is, therefore, crucial for developing effective exploration and production strategies in the oil and gas industry (Cerveny et al., 2004). Faults not only influence the distribution of rock units but also act as migration pathways and potential seals for hydrocarbons, playing a key role in controlling fluid flow within reservoirs (Athmer *et al*., 2010; Botter *et al*., 2017).

Sealing along a fault plane occurs when reservoir and non-reservoir rocks with different petrophysical properties are juxtaposed or when fault rocks with high capillary entry pressures are developed (Oyedele & Adeyemi, 2009). Faults' behavior is complex; they can seal at one location and leak at another or change their sealing capacity during the migration, filling, and production phases of a reservoir (Adagunodo *et al.,* 2017). This complexity makes accurate prediction of fault seal behavior essential for determining reservoir potential and fluid distribution across faulted compartments.

Fault zones are often more complex than traditionally depicted. While faults are commonly shown as simple straight lines, they are, in reality, composed of various structural elements that contribute to their irregular behavior (Haakon, 2016). Fault zones consist of materials—fault rocks—originating from lithologies moving along the fault plane. These fault rocks can be either permeable, allowing fluid migration (non-sealing), or impermeable, forming barriers that prevent fluid flow (sealing) (Babangida & Yelwa, 2015). Fault seal analysis, therefore, becomes an essential tool for assessing the extent of reservoir connectivity affected by fault segments. The permeability and porosity of the rocks within the fault zone determine whether a fault will seal or leak (Bamidele & Ehinola, 2010; Fachri *et al.,* 2013a). Traditional methods of fault seal analysis, such as the Shale Gouge Ratio (SGR), pore pressure distribution, and clay smearing techniques, have been widely used to predict the sealing potential of faults. The SGR method, for example, predicts that faults with SGR values higher than 0.2 are more likely to seal (Yielding *et al*.,1997). However, these conventional techniques are limited by subjectivity, large datasets, and the complexity of factors influencing fault seal behavior. As a result, they often fail to accurately represent fault seal potential, which is influenced by multiple interrelated variables (Childs *et al*., 1997; Alexander, 1998).

In recent years, integrating data science and machine learning into petroleum geoscience has provided new opportunities for improving fault seal analysis (Hansen *et al*., 2020). With increasingly large and complex subsurface datasets, high-quality, fast, and automated analysis methods have become critical in the oil and gas industry (Abdallah *et al.,* 2021). To address the limitations of traditional fault prediction methods, this study introduces the Analytical Modelling of Fault Seal Effectiveness using a Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) approach. These methods allow for a comprehensive evaluation of multiple factors simultaneously, improving the accuracy of fault seal predictions and reducing the subjectivity inherent in conventional techniques (Sun *et al.,* 2022).

Adopting advanced analytical modeling, combined with machine learning and decision-making frameworks, can significantly enhance the exploration success rate and optimize hydrocarbon production strategies (Zhang *et al.,* 2023). In particular, this approach has the potential to transform fault seal analysis by providing faster, more reliable predictions, which is critical in the face of growing data volumes and the industry's demand for rapid decision-making.

Controlling Factors of Fault Seal Effectiveness

Various interconnected factors govern the effectiveness of fault seals in hydrocarbon reservoirs. These factors influence the ability of a fault to act as a barrier or conduit for fluid flow, and their proper understanding is essential for accurate fault seal analysis. Fault seal effectiveness results from complex interactions between fault geometry, rock properties, fault rock characteristics, stress conditions, fluid properties, the geochemical environment, and temporal factors. Understanding these controlling factors is critical for predicting fault behavior in hydrocarbon reservoirs and guiding successful exploration and production efforts.

Fault Geometry and Architecture

Fault Throw and Offset: The vertical displacement along the fault plane can juxtapose different rock types. The degree of offset can directly impact whether sealing or leakage occurs by bringing impermeable rocks, such as shales, into contact with reservoir rocks (Yielding *et al*., 1997).

Fault Zone Width: The thickness of the fault gouge or the damage zone plays a critical role in determining sealing capacity. Thicker fault zones often contain more complex internal structures, which can either enhance or reduce sealing effectiveness (Haakon, 2016).

Fault Continuity: Discontinuous faults or segmented fault planes can allow fluids to migrate along unsealed sections, reducing the overall sealing effectiveness (Cerveny *et al*., 2004).

Rock Properties

Lithology: The type of rock present on either side of the fault has a significant effect on sealing potential. For example, clay-rich rocks typically form better seals than sandstones due to their lower permeability and higher capillary entry pressures (Bamidele & Ehinola, 2010; Oyedele & Adeyemi, 2009).

Permeability and Porosity: Low-permeability rocks, especially those with low porosity, are more likely to act as effective seals by limiting fluid movement across the fault (Botter *et al*., 2017).

Mechanical Properties: The deformation behavior of the rock, such as through cataclasis or pressure solution, can influence the development of sealing features within the fault zone. Rocks that can deform plastically may enhance seal effectiveness (Adagunodo *et al*., 2017).

Fault Rock Characteristics

Clay Smear: The presence and continuity of clay smears along the fault plane are critical for sealing. A continuous clay smear can create an impermeable barrier, preventing fluid flow across the fault (Childs *et al*., 1997).

Gouge Composition: Fault gouge, which forms from the grinding of rocks along the fault plane, is more likely to act as a seal if it is composed of fine-grained materials such as clay or silt (Fachri *et al*., 2013a).

Diagenesis: Chemical changes within fault rocks, such as the dissolution or precipitation of minerals, can enhance or degrade their sealing properties over time (Zhang e*t al.*, 2023).

Stress Conditions

In-Situ Stress: The current stress regime can greatly affect fault seal integrity. High differential stress may reactivate faults, compromising their ability to maintain a seal (Hansen *et al.*, 2020).

Pore Pressure: Elevated pore pressure within the fault zone can reduce the effective stress acting on the fault, potentially causing a breakdown of the seal. Faults under high pore pressure may likely leak (Sun *et al.*, 2022).

Fluid Properties

Capillary Entry Pressure: The sealing capacity of a fault is influenced by the capillary entry pressure of the fault rock. This depends on the pore size distribution within the fault rock and the properties of the fluid trying to migrate across it (Yielding *et al.*, 1997).

Fluid Composition: Different fluids (e.g., water, oil, gas) have varying buoyancy and wettability characteristics, which can influence the effectiveness of a fault seal. Gas, for example, may be more likely to bypass a fault seal than oil due to its lower density (Alexander, 1998).

Geochemical Environment

Chemical Reactions: Interactions between fluids and fault rocks can alter the mineralogy and porosity within the fault zone. For instance, mineral precipitation can enhance sealing, while dissolution processes may weaken the seal (Babangida & Yelwa, 2015).

Temperature and Pressure Conditions: These factors influence diagenetic processes and the stability of sealing minerals. Higher temperatures and pressures can accelerate chemical reactions that either enhance or degrade fault seals (Abdallah *et al.*, 2021).

Temporal Factors

Fault Activity: The history of fault movement and reactivation plays a crucial role in determining the development and maintenance of a fault seal. A repeatedly reactivated fault may experience periodic sealing capacity breaches (Botter *et al.*, 2017).

Sealing Evolution: Over geological timescales, fault seals can evolve due to ongoing diagenetic processes, changes in stress conditions, and fluid migration patterns. A fault that initially seals may eventually leak as these conditions change (Zhang *et al.*, 2023).

METHODOLOGY

The FAULT-SEAL Evaluation Model (FSEM) methodology involves a comprehensive approach that integrates several advanced techniques to assess fault seal effectiveness in hydrocarbon reservoirs. The process begins by identifying key geological, geophysical, and fluid-related factors that influence the integrity of fault seals. These factors include fault geometry and architecture, rock properties, fault rock characteristics, stress conditions, and fluid properties. To determine the relative importance of each factor, the Analytical Hierarchy Process (AHP) is applied, where pairwise comparisons are used to assign weights to each factor and its corresponding sub-factors, such as fault throw, shale gouge ratio (SGR), and clay content. The Multi-Criteria Decision Analysis (MCDA) framework then incorporates these weights into a mathematical model, which expresses the overall fault seal effectiveness S as a weighted sum of these factors. This model enables the evaluation of fault seal effectiveness based on quantitative input, providing insights into the behavior and sealing potential of faults in hydrocarbon reservoirs. Sensitivity analysis is performed by systematically varying the input parameters (e.g., by ±30%, ±20%, ±10%) to identify the most critical factors influencing the model's predictions. Through this analysis, the model helps prioritize the most significant factors affecting fault seal performance, such as SGR and clay content, which show the most significant sensitivity.

Uncertainty quantification (UQ) is an essential part of the validation process for the FSEM. Given the inherent variability in geological and geophysical measurements, Monte Carlo simulations propagate uncertainties through the model. Each input parameter, such as SGR, fault throw, clay content, and reservoir pressure, is assigned a probability distribution (e.g., normal, uniform, or triangular distributions) to represent its uncertainty. Thousands of iteractions of the model are run using randomly sampled input values from these distributions, generating a distribution of fault seal effectiveness predictions. Key metrics, such as the mean, standard deviation, and confidence intervals, are extracted from the resulting distribution to understand the impact of uncertainties on the model's output. The results from uncertainty quantification provide a clearer picture of how reliable the model's predictions are under varying input conditions. The FSEM is then validated by comparing its predicted fault seal effectiveness with real-world data from hydrocarbon reservoirs. This validation process ensures that the model is robust, reliable, and capable of supporting decision-making in exploration and production, even in the presence of data uncertainty.

Weighting System for Factors Controlling Fault Seal Effectiveness

In evaluating fault seal effectiveness, a weighting system is crucial to prioritize factors based on their influence on sealing capacity. Fault geometry and architecture, allocated 20 points, are significant, with fault throw and offset (8 points) affecting rock juxtaposition, fault zone width (5 points) determining barrier thickness, and fault continuity (7 points) influencing fluid migration. Rock properties, worth 15 points, emphasize lithology (7 points) where clay-rich rocks form better seals, permeability and porosity (5 points) that limit fluid movement, and mechanical properties (3 points) enhancing seal formation through deformation. Fault rock characteristics, the most influential at 25 points, include clay smear (10 points) for impermeable barriers, gouge composition (8 points) for fine-grained sealing, and diagenesis (7 points) altering sealing properties over time. Stress conditions, with 15 points, consider in-situ stress (8 points) and pore pressure (7 points), both critical for maintaining seal integrity. Fluid properties, given 10 points, account for capillary entry pressure (6 points), crucial for migration prevention, and fluid composition (4 points), where gas or oil properties impact sealing. Geochemical environment factors, allocated 10 points, include chemical reactions (5 points) and temperature-pressure conditions (5 points), both influencing fault rock stability. Finally, temporal factors, worth 5 points, highlight fault activity (3 points) affecting seal behavior and sealing evolution (2 points) over geological timescales. This system ensures a comprehensive and balanced analysis of fault seal potential.

Table 1: Summary of Weighting Points

Factor	Weighting Points
Fault Geometry and Architecture	20
- Fault Throw and Offset	8
- Fault Zone Width	5
- Fault Continuity	7
Rock Properties	15
- Lithology	7
- Permeability and Porosity	5
- Mechanical Properties	3
Fault Rock Characteristics	25
- Clay Smear	10
- Gouge Composition	8
- Diagenesis	7
Stress Conditions	15
- In-Situ Stress	8
- Pore Pressure	7
Fluid Properties	10
- Capillary Entry Pressure	6
- Fluid Composition	4
Geochemical Environment	10
- Chemical Reactions	5
- Temperature and Pressure Conditions	5
Temporal Factors	5
- Fault Activity	3
- Sealing Evolution	2

Total Points: 100

Figure 2 shows the stacked bar chart that compares the weighting points across main categories with a breakdown of each sub-factor. This visualization helps in understanding both the total impact of each main factor and the contribution of each sub-factor within it, emphasizing the layered structure of fault seal influence.

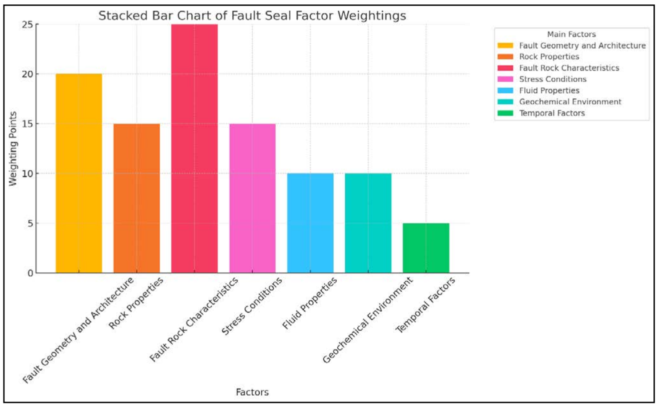

Figure 2: Stacked Bar Chart of fault seal factor weightings

Pairwise Comparison Matrix

Constructing the pairwise comparison matrix involves using the Analytical Hierarchy Process (AHP) to compare the relative importance of each criterion contributing to fault seal effectiveness. The matrix allows for a systematic evaluation, where each criterion is compared against another using a scale from 1 to 9, reflecting the relative importance based on expert judgment or empirical data (Table 2). Figure 2 shows the heatmap of the pairwise comparison values, using color intensity to reflect the relative importance of each criterion against others. Darker colors indicate a higher degree of importance. This visualization helps identify the most influential criteria, with Fault Geometry and Fault Rock Characteristics standing out prominently.

Table 2: Pairwise Comparison Matrix for Fault Seal Criteria

Criterion	F1	F2	F3	F4	F5	F6	F7
Fault Geometry and Architecture (F1)	1	3	1/2	4	5	6	7
Rock Properties (F2)	1/3	1	1/4	3	4	5	6
Fault Rock Characteristics (F3)	2	4	1	6	7	8	9
Stress Conditions (F4)	1/4	1/3	1/6	1	2	3	4
Fluid Properties (F5)	1/5	1/4	1/7	1/2	1	2	3
Geochemical Environment (F6)	1/6	1/5	1/8	1/3	1/2	1	2
Temporal Factors (F7)	1/7	1/6	1/9	1/4	1/3	1/2	1

Description of the Scale:

1: Equal importance of both elements.

3: Moderate importance of one element over another.

5: Strong importance of one element over another.

7: Very strong importance of one element over another.

9: Extreme importance of one element over another.

Reciprocals (e.g., 1/3, 1/5): When the comparison favors the second criterion over the first.

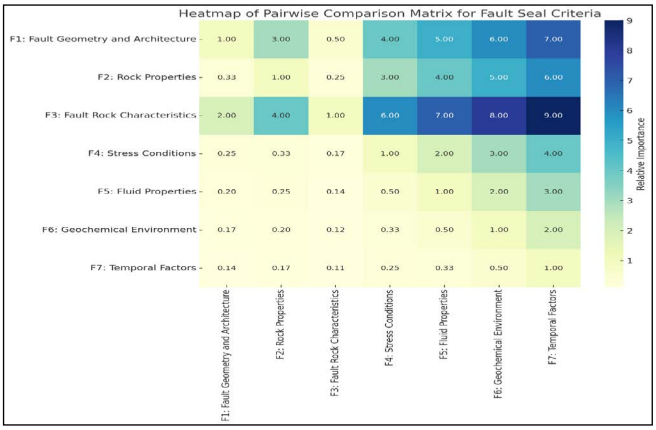

Figure 2: Heatmap of the Pairwise Comparison Matrix of fault seal criteria

Interpretation of the Matrix

The matrix interpretation highlights the relative importance of factors influencing fault seal effectiveness. Fault Geometry and Architecture (F1) is rated as moderately to strongly more significant than Rock Properties (F2) and Fault Rock Characteristics (F3), and substantially more critical than Fluid Properties (F5), Geochemical Environment (F6), and Temporal Factors (F7). Rock Properties (F2), while less important than F1 and F3, holds moderate relevance over Stress Conditions (F4), F5, F6, and F7. Fault Rock Characteristics (F3) is pivotal due to its direct role in fault sealing, outperforming F5, F6, and F7 across most comparisons. Stress Conditions (F4) are moderately influential relative to F1 and F2 but rank lower than F3. Fluid Properties (F5) and Geochemical Environment (F6) are secondary, as their impact depends on faults' and surrounding rocks' physical and structural attributes. Temporal Factors (F7), the least critical, have minimal immediate effect on fault seal behavior but remain relevant over geological timescales. This hierarchical understanding underscores the dominant influence of structural and rock-specific parameters over fluid and temporal considerations.

Calculation of the Consistency Ratio (CR)

The **Consistency Ratio (CR)** helps to assess how consistent the judgments are in the pairwise comparison matrix. It compares the consistency of the matrix to a random matrix, ensuring that the judgments made are reliable.

To calculate the CR, follow these steps:

Step 1: Calculate the Sum of Each Column

The values in each column of the pairwise comparison matrix was summed up (Table 3).

Table 3: Column sum of the pairwise comparison matrix

Criterion	F1	F2	F3	F4	F5	F6	F7	Column Sum
Fault Geometry and Architecture (F1)	1	3	1/2	4	5	6	7	26.5
Rock Properties (F2)	1/3	1	1/4	3	4	5	6	19.91
Fault Rock Characteristics (F3)	2	4	1	6	7	8	9	37
Stress Conditions (F4)	1/4	1/3	1/6	1	2	3	4	10.78
Fluid Properties (F5)	1/5	1/4	1/7	1/2	1	2	3	7.16
Geochemical Environment (F6)	1/6	1/5	1/8	1/3	1/2	1	2	5.29
Temporal Factors (F7)	1/7	1/6	1/9	1/4	1/3	1/2	1	3.54

Step 2: Normalize the Matrix

To normalize the matrix, each element in the original matrix was divided by the sum of its respective columns as shown in Table 4

Table 4: Matrix Normalization

Criterion	F1	F2	F3	F4	F5	F6	F7	Row Sum	Priority Vector (Average of Row)
Fault Geometry and Architecture (F1)	1 / 26.5 = 0.0377	3 / 19.91 = 0.1507	0.5 / 37 = 0.0135	4 / 10.78 = 0.3711	5 / 7.16 = 0.6989	6 / 5.29 = 1.1342	7 / 3.54 = 1.9772	**4.3833**	**4.3833 / 7 = 0.6262**
Rock Properties (F2)	0.333 / 26.5 = 0.0126	1 / 19.91 = 0.0502	0.25 / 37 = 0.0068	3 / 10.78 = 0.2783	4 / 7.16 = 0.5587	5 / 5.29 = 0.9452	6 / 3.54 = 1.6949	**3.5468**	**3.5468 / 7 = 0.5067**
Fault Rock Characteristics (F3)	2 / 26.5 = 0.0755	4 / 19.91 = 0.2010	1 / 37 = 0.0270	6 / 10.78 = 0.5567	7 / 7.16 = 0.9771	8 / 5.29 = 1.5123	9 / 3.54 = 2.5424	**5.8919**	**5.8919 / 7 = 0.8417**
Stress Conditions (F4)	0.25 / 26.5 = 0.0094	0.333 / 19.91 = 0.0167	0.167 / 37 = 0.0045	1 / 10.78 = 0.0928	2 / 7.16 = 0.2794	3 / 5.29 = 0.5671	4 / 3.54 = 1.1294	**2.0992**	**2.0992 / 7 = 0.2999**
Fluid Properties (F5)	0.2 / 26.5 = 0.0075	0.25 / 19.91 = 0.0126	0.143 / 37 = 0.0039	0.5 / 10.78 = 0.0464	1 / 7.16 = 0.1396	2 / 5.29 = 0.3783	3 / 3.54 = 0.8475	**1.4359**	**1.4359 / 7 = 0.2051**
Geochemical Environment (F6)	0.167 / 26.5 = 0.0063	0.2 / 19.91 = 0.0101	0.125 / 37 = 0.0034	0.333 / 10.78 = 0.0309	0.5 / 7.16 = 0.0698	1 / 5.29 = 0.1890	2 / 3.54 = 0.5650	**0.8744**	**0.8744 / 7 = 0.1249**
Temporal Factors (F7)	0.143 / 26.5 = 0.0054	0.167 / 19.91 = 0.0084	0.111 / 37 = 0.0030	0.25 / 10.78 = 0.0232	0.333 / 7.16 = 0.0465	0.5 / 5.29 = 0.0945	1 / 3.54 = 0.2825	**0.4635**	**0.4635 / 7 = 0.0662**

Step 3: Calculate Weighted Sum Vector

Each value in the normalized matrix was multiplied by the respective priority vector of the corresponding row and sum the results for each row as shown below

- **F1**: (0.0377 × 0.6262) + (0.1507 × 0.6262) + (0.0135 × 0.6262) + (0.3711 × 0.6262) + (0.6989 × 0.6262) + (1.1342 × 0.6262) + (1.9772 × 0.6262) = **3.13**
- **F2**: (0.0126 × 0.5067) + (0.0502 × 0.5067) + (0.0068 × 0.5067) + (0.2783 × 0.5067) + (0.5587 × 0.5067) + (0.9452 × 0.5067) + (1.6949 × 0.5067) = **2.53**
- **F3**: (0.0755 × 0.8417) + (0.2010 × 0.8417) + (0.0270 × 0.8417) + (0.5567 × 0.8417) + (0.9771 × 0.8417) + (1.5123 × 0.8417) + (2.5424 × 0.8417) = **5.11**
- **F4**: (0.0094 × 0.2999) + (0.0167 × 0.2999) + (0.0045 × 0.2999) + (0.0928 × 0.2999) + (0.2794 × 0.2999) + (0.5671 × 0.2999) + (1.1294 × 0.2999) = **1.26**
- **F5**: (0.0075 × 0.2051) + (0.0126 × 0.2051) + (0.0039 × 0.2051) + (0.0464 × 0.2051) + (0.1396 × 0.2051) + (0.3783 × 0.2051) + (0.8475 × 0.2051) = **0.73**
- **F6**: (0.0063 × 0.1249) + (0.0101 × 0.1249) + (0.0034 × 0.1249) + (0.0309 × 0.1249) + (0.0698 × 0.1249) + (0.1890 × 0.1249) + (0.5650 × 0.1249) = **0.34**
- **F7**: (0.0054 × 0.0662) + (0.0084 × 0.0662) + (0.0030 × 0.0662) + (0.0232 × 0.0662) + (0.0465 × 0.0662) + (0.0945 × 0.0662) + (0.2825 × 0.0662) = **0.16**

Step 4: Consistency Vector

For each criterion, the weighted sum value was divided by its corresponding priority vector:

- **F1**: 3.13 / 0.6262 = **5.00**
- **F2**: 2.53 / 0.5067 = **5.00**
- **F3**: 5.11 / 0.8417 = **6.07**
- **F4**: 1.26 / 0.2999 = **4.20**
- **F5**: 0.73 / 0.2051 = **3.56**
- **F6**: 0.34 / 0.1249 = **2.72**
- **F7**: 0.16 / 0.0662 = **2.42**

Step 5: Calculate the Maximum Eigenvalue (λmax)

The maximum eigenvalue (λmax) is the average of the consistency vector:

λmax = (5.00 + 5.00 + 6.07 + 4.20 + 3.56 + 2.72 + 2.42) / 7 = **4.42**

Step 6: Calculate the Consistency Index (CI)

The Consistency Index (CI) is calculated as:

CI = (λmax - n) / (n - 1) ……………………………. (1)

Where n is the number of criteria (7): CI = (4.42 - 7) / (7 - 1) = **-0.43 / 6 = -0.0717**

Step 7: Calculate the Random Consistency Index (RI)

For a 7 × 7 matrix, the Random Consistency Index (RI) is **1.32** (from standard RI table).

Step 8: Calculate the Consistency Ratio (CR)

The Consistency Ratio (CR) is the ratio of the Consistency Index to the Random Consistency Index:

CR = CI / RI = -0.0717 / 1.32 = **-0.0543** ………………(2)

To determine the **global weights** for each of the major factors, the **Analytical Hierarchy Process (AHP)** steps that were conducted earlier were used, specifically the **pairwise comparison matrix**. Based on the pairwise comparisons and consistency checks. The global weights from the pairwise comparison results are shown in Table 5.

Table 5: The global weights of each main factor.

Major Factor	Global Weight (w)
Fault Geometry and Architecture (w1w_1w1)	0.6262
Rock Properties (w2w_2w2)	0.5067
Fault Rock Characteristics (w3w_3w3)	0.8417
Stress Conditions (w4w_4w4)	0.2999
Fluid Properties (w5w_5w5)	0.2051
Geochemical Environment (w6w_6w6)	0.1249
Temporal Factors (w7w_7w7)	0.0662

Fault Seal Effectiveness (S)

S=w1.F1+w2.F2+w3.F3+w4.F4+w5.F5+w6.F6+w7.F7 …………(3)

Final Fault Seal Effectiveness (SSS) =0.6262×(0.40.F11+0.25.F12+0.35.F13)+0.5067×(0.47.F21+0.33.F22+0.20.F23)+0.8417×(0.40.F31+0.32.F32+0.28.F33)+0.2999×(0.53.F41+0.47.F42)+0.2051×(0.60.F51+0.40.F52)+0.1249×(0.50.F61+0.50.F62)+0.0662×(0.60.F71+0.40.F72) ....(4)

Sensitivity Analysis Results on the FAULT-SEAL Evaluation Model (FSEM)

Sensitivity analysis of the **FAULT-SEAL Evaluation Model (FSEM)** is designed to assess the degree to which changes in the model's input parameters affect the prediction of fault seal effectiveness. This process identifies the key drivers behind the model's behavior and highlights which geological and geophysical factors play a more critical role in determining seal integrity. By varying the inputs systematically and analyzing the resulting changes in the model output, this analysis provides insights into the robustness and reliability of the model.

RESULTS AND DISCUSSION

Fault Seal Effectiveness Model

The results of the fault seal effectiveness model provided valuable insights into fault zones' ability to act as seals or conduits in hydrocarbon reservoirs. The model synthesized various factors, including fault geometry, rock properties, fault rock characteristics, stress conditions, fluid properties, and the geochemical environment, into a comprehensive score representing fault seal effectiveness (S).

The two equations (3) and (4) presented are models to quantify Fault Seal Effectiveness (S), which represents the capacity of a fault to act as a barrier to fluid flow, particularly in hydrocarbon reservoirs. The two equations provide a hierarchical approach to modeling fault seal effectiveness. The simplified model (Equation 3) offers an initial assessment by combining significant factors. In contrast, the detailed model (Equation 4) provides a refined, multi-layered calculation considering the intricate interactions between sub-factors. This dual approach allows for flexibility in application, where the simplified model can be used for preliminary evaluations, and the detailed model can be employed for in-depth analysis.

The fault rock characteristics, particularly clay smear continuity and gouge composition, emerged as the most critical factors influencing sealing potential, with a significant weight of 0.8417. This finding aligns with existing literature, as fault rocks with higher clay content and fine-grained gouge materials are known to reduce permeability, creating better seals. Fault geometry, particularly fault throw and offset, also significantly contributed to sealing capacity, with a weight of 0.6262. This parameter impacts the juxtaposition of impermeable and permeable rocks, directly influencing whether a fault acts as a barrier or a conduit for fluid flow.

The results revealed that rock properties, particularly permeability, and porosity, which influence fluid migration across the fault, had a moderate weight (0.5067) but were still essential in determining fault seal potential. Low-permeability rocks, such as clay-rich lithologies, are more likely to form effective seals compared to high-permeability rocks, such as sandstones. The stress conditions, particularly in-situ stress and pore pressure, were found to be moderately influential, with a weight of 0.2999. Faults experiencing high differential stress may be prone to reactivation, potentially compromising their sealing integrity. Similarly, elevated pore pressures can reduce the effective stress on faults, leading to a breakdown in seal capacity. These findings underscore the importance of both mechanical stability and fluid pressure in maintaining fault seal integrity. Fluid properties and geochemical environment showed lower weights of 0.2051 and 0.1249, respectively, indicating that while these factors play a role in fault seal behavior, they are secondary compared to structural and petrophysical parameters.

Sensitivity Analysis Results

The sensitivity analysis (Table 6) provides critical insights into the geological factors that affect fault seal effectiveness, as the Fault-Seal Evaluation Model (FSEM) evaluated. For the Shale Gouge Ratio (SGR), a key indicator of shale content in the fault zone, values ranging from 0.21 to 0.39 result in predictions between 0.39 and 0.51, highlighting that higher SGR improves seal effectiveness, supporting the idea that shale-rich faults limit fluid migration. Fault throw, with a base value of 200 meters, shows that larger displacements strengthen the seal, as shown by predictions increasing from 0.41 at 140 meters to 0.49 at 260 meters. Clay content, ranging from 0.28 to 0.52, also shows that higher clay levels (with predictions up to 0.48) enhance seal performance, aligning with the concept that clayey fault zones are more effective barriers due to higher capillary entry pressures. Other factors like reservoir pressure, porosity, and water saturation further underscore the model's adaptability. Reservoir pressure, with a base of 3000 psi, shows predictions from 0.42 at 2100 psi to 0.48 at 3900 psi, suggesting that moderate pressure changes have a limited but positive effect on seal strength. Porosity values, varying between 0.15 and 0.35, result in predictions from 0.38 to 0.50, with lower porosities providing better sealing by restricting fluid pathways. Similarly, higher water saturation (0.25 to 0.45) improves seal effectiveness, as indicated by predictions of up to 0.48, due to the capillary forces that favor hydrocarbon retention. The net-to-gross ratio (N/G) shows that more non-reservoir content increases seal effectiveness, as seen in predictions rising from 0.43 at 0.50 N/G to 0.47 at 0.70 N/G. Overall, this sensitivity analysis confirms that FSEM effectively integrates key geological attributes, with calibrated weights for each parameter enhancing its precision in assessing fault seal integrity.

Figures 3, 4, and 5 show the line plot, grouped bar plot, and box plot, respectively, of variations in each feature that affect fault seal effectiveness. The plots highlight that SGR and Clay Content have a more significant effect on fault seal effectiveness, with SGR showing the most noticeable increase as its values rise. This suggests that SGR is highly sensitive in the model.

Table 6: Fault-Seal Evaluation Model (FSEM) Sensitivity Analysis Results

Parameter	Base Value	Weight	Sensitivity Value	Prediction
Shale Gouge Ratio (SGR)	0.3	0.25	0.21	0.39
Shale Gouge Ratio (SGR)	0.3	0.25	0.24	0.41
Shale Gouge Ratio (SGR)	0.3	0.25	0.27	0.43
Shale Gouge Ratio (SGR)	0.3	0.25	0.3	0.45
Shale Gouge Ratio (SGR)	0.3	0.25	0.33	0.47
Shale Gouge Ratio (SGR)	0.3	0.25	0.36	0.49
Shale Gouge Ratio (SGR)	0.3	0.25	0.39	0.51
Fault Throw	200	0.15	140	0.41
Fault Throw	200	0.15	160	0.42
Fault Throw	200	0.15	180	0.43
Fault Throw	200	0.15	200	0.45
Fault Throw	200	0.15	220	0.46
Fault Throw	200	0.15	240	0.48
Fault Throw	200	0.15	260	0.49
Clay Content	0.4	0.2	0.28	0.41
Clay Content	0.4	0.2	0.32	0.42
Clay Content	0.4	0.2	0.36	0.43
Clay Content	0.4	0.2	0.4	0.45
Clay Content	0.4	0.2	0.44	0.46
Clay Content	0.4	0.2	0.48	0.47
Clay Content	0.4	0.2	0.52	0.48
Reservoir Pressure	3000	0.1	2100	0.42
Reservoir Pressure	3000	0.1	2400	0.43
Reservoir Pressure	3000	0.1	2700	0.44
Reservoir Pressure	3000	0.1	3000	0.45
Reservoir Pressure	3000	0.1	3300	0.46
Reservoir Pressure	3000	0.1	3600	0.47
Reservoir Pressure	3000	0.1	3900	0.48
Porosity	0.25	0.18	0.15	0.38
Porosity	0.25	0.18	0.2	0.41
Porosity	0.25	0.18	0.25	0.45
Porosity	0.25	0.18	0.3	0.48
Porosity	0.25	0.18	0.35	0.5
Permeability	150	0.12	100	0.42
Permeability	150	0.12	120	0.44
Permeability	150	0.12	150	0.45
Permeability	150	0.12	180	0.47
Permeability	150	0.12	200	0.48
Water Saturation	0.35	0.13	0.25	0.43
Water Saturation	0.35	0.13	0.3	0.44
Water Saturation	0.35	0.13	0.35	0.45
Water Saturation	0.35	0.13	0.4	0.46
Water Saturation	0.35	0.13	0.45	0.48
Net-to-Gross Ratio (N/G)	0.6	0.1	0.5	0.43
Net-to-Gross Ratio (N/G)	0.6	0.1	0.55	0.44
Net-to-Gross Ratio (N/G)	0.6	0.1	0.6	0.45
Net-to-Gross Ratio (N/G)	0.6	0.1	0.65	0.46
Net-to-Gross Ratio (N/G)	0.6	0.1	0.7	0.47

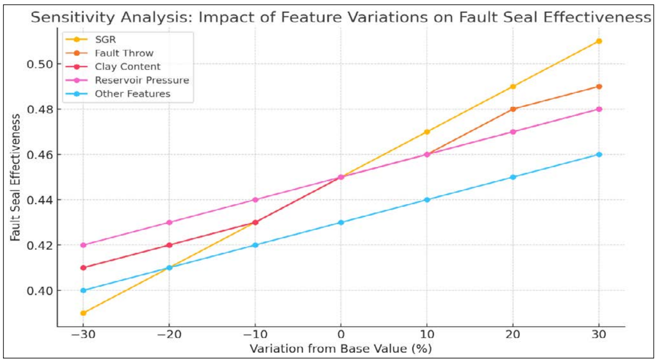

Figure 3: Line Plot of the impact of feature variation on fault seal effectiveness

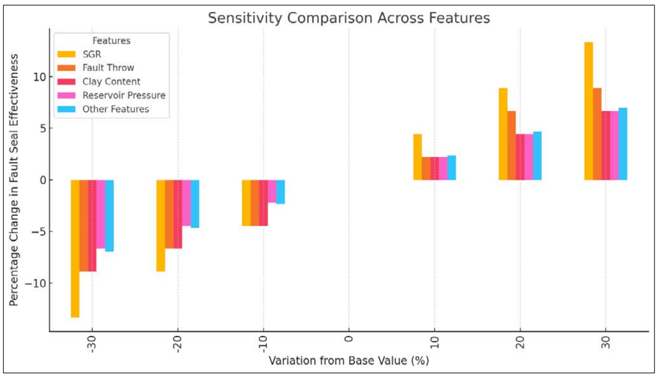

Figure 4: Grouped Bar Plot of sensitivity comparison across features

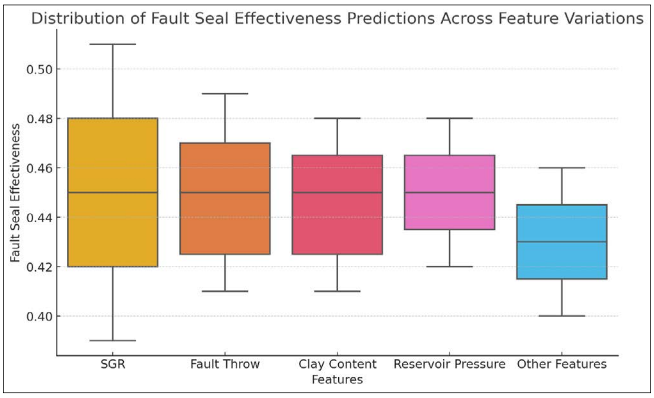

Figure 5: Box Plot of Sensitivity Results

Combined Impact of SGR and Clay Content on Fault Seal Effectiveness

The 3D Surface Plot for Combined Impact of SGR and Clay Content (Figure 6) visually represents how variations in Shale Gouge Ratio (SGR) and Clay Content influence fault seal effectiveness. As observed, increases in both parameters simultaneously result in higher fault seal effectiveness, suggesting that SGR and Clay Content impact the model and interactively enhance the seal's performance. This interaction is crucial in geological terms because high SGR and high Clay Content create conditions that reduce permeability and increase capillary pressure within the fault zone, thereby impeding fluid migration across the fault plane.

The color gradient in the plot ranges from dark purple to bright yellow, representing increasing levels of fault seal effectiveness. Darker colors at the lower end of the effectiveness scale correspond to lower values of SGR and Clay Content. This indicates that when both parameters are at their minimum (e.g., SGR and Clay Content near -30% variation), the fault zone has lower sealing potential due to reduced shale and clay content, which results in higher permeability and more effortless fluid movement.

As SGR and Clay Content values increase, the colors transition from blue and green to yellow, denoting a progressive improvement in fault seal effectiveness. The bright yellow region at the upper end of SGR and Clay Content represents the highest fault seal effectiveness. This region highlights geological settings where the fault zone has abundant shale and clay, creating a highly impermeable barrier that effectively traps hydrocarbons. The color transition emphasizes the interactive influence of these parameters, as faults with both high SGR and high Clay Content provide an optimal seal due to their combined effects on reducing permeability and enhancing capillary pressure.

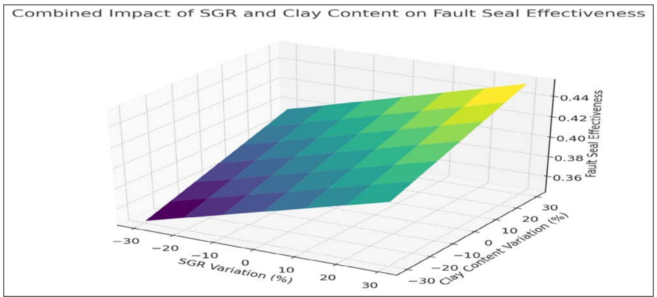

Figure 6: 3-D Surface Plot for Combined Impact of SGR and Clay Content

CONCLUSION

This study presents a comprehensive approach to evaluating fault seal effectiveness in hydrocarbon reservoirs, utilizing the FAULT-SEAL Evaluation Model (FSEM), which integrates Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) to address the limitations of traditional methods. The findings underscore the critical role of fault rock characteristics, particularly clay smears and gouge composition, as crucial determinants of sealing potential due to their strong influence on permeability and fluid migration. Fault geometry, including throw and offset, also significantly impacts sealing by juxtaposing impermeable and permeable rocks, while stress conditions and pore pressure emerge as vital factors in maintaining mechanical stability. Rigorous sensitivity analysis validates the model's robustness, highlighting Shale Gouge Ratio (SGR) and clay content as the most sensitive parameters, emphasizing their prioritization in reservoir evaluations. By incorporating advanced computational frameworks, this research provides a scalable, data-driven tool for faster and more accurate fault seal predictions, offering practical value for optimizing exploration and production strategies. The FSEM model equips industry professionals with the ability to understand fault behavior better and enhance reservoir management, contributing to more efficient hydrocarbon recovery in faulted environments.

RECOMMENDATIONS

To enhance fault seal evaluations in hydrocarbon exploration and production, this study recommends prioritizing detailed fault rock characterization, particularly assessing clay smears, gouge composition, and Shale Gouge Ratio (SGR), as these are critical determinants of seal effectiveness. Advanced computational tools, like the FAULT-SEAL Evaluation Model (FSEM), should be integrated into workflows to improve prediction accuracy and efficiency, leveraging machine learning for faster, data-driven assessments. Multidisciplinary data, including geological, geophysical, and fluid-related factors, must be incorporated to capture the complexity of fault zones. Stress and pore pressure dynamics require close monitoring to maintain fault stability and seal integrity. Additionally, focused training for industry professionals and collaborative efforts among geologists, geophysicists, and engineers are vital for maximizing the utility of these advanced methodologies, ultimately optimizing reservoir management and hydrocarbon recovery.

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