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RESEARCH ARTICLE

MITIGATION OF EXPLORATION UNCERTAINTIES THROUGH FAULT SEAL ANALYSIS: A CASE STUDY OF THE AKOS FIELD, NIGER DELTA BASIN

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ABSTRACT

Exploration success in hydrocarbon-rich provinces like the Niger Delta Basin is often constrained by subsurface uncertainties, particularly in structurally complex regions. In the onshore Niger Delta, fault seal behavior remains underexplored compared to offshore areas. This study investigates fault seal characteristics in the Akos Field, onshore Niger Delta, with the aim of mitigating exploration risk and improving hydrocarbon prospectivity. The analysis integrates 3D seismic interpretation, petrophysical data, and Shale Gouge Ratio (SGR) modelling to evaluate fault sealing capacity and the likelihood of cross-fault hydrocarbon migration. Two major faults (F1 and F2) were analyzed in detail. Fault F1 exhibited partial sealing with SGR values between 35–40%, suggesting a moderate barrier to fluid flow, while fault F2 showed enhanced sealing potential with SGR values exceeding 40%, indicating a more effective trap. These variations suggest significant implications for hydrocarbon entrapment, reservoir compartmentalization, and field development planning. Comparative insights from analogous offshore fields further highlight the structural dependence of hydrocarbon accumulation in Akos. The findings underscore the importance of incorporating fault seal analysis in exploration workflows to reduce risk and enhance predictive models in similar tectonically influenced basins.

KEYWORDS

fault seal analysis, Shale Gouge Ratio, Akos Field, Niger Delta, reservoir compartmentalization, hydrocarbon entrapment, exploration uncertainty

1. INTRODUCTION

Hydrocarbon exploration in structurally complex basins like the Niger Delta is often constrained by subsurface uncertainties, particularly in fault-bounded reservoirs. Fault seal behaviour plays a critical role in determining hydrocarbon entrapment and retention; however, its evaluation is frequently underemphasized in exploration workflows, especially in onshore regions. In recent years, Shale Gouge Ratio (SGR) modelling has become an effective tool for predicting fault seal integrity and assessing the risk of cross-fault fluid migration. A group researcher applied SGR analysis in the Gabo Field and observed spatial variations in sealing capacity that directly influenced hydrocarbon distribution (Iheaturu et al., 2022). Likewise, some researchers demonstrated the importance of Petrel-based fault seal evaluation in understanding reservoir compartmentalization in the Ikeuka Field (Onyekuru et al., 2019). Despite these advances, most studies have focused on offshore fields, leaving the fault-sealing behaviour of onshore structures underexplored.

This study addresses that gap by evaluating the fault sealing potential of the Akos Field, located in the onshore Niger Delta Basin. Through integrated interpretation of 3D seismic data, petrophysical analysis, and SGR modelling, the study aims to quantify sealing capacities and assess their implications for hydrocarbon migration and trap integrity. The analysis focuses on two primary faults to evaluate their role in reservoir segmentation and entrapment efficiency. The findings contribute to a better understanding of fault-controlled hydrocarbon systems in the onshore Niger Delta and underscore the importance of incorporating fault seal analysis in reducing exploration uncertainty and improving prospect evaluation in similar tectonically influenced basins.

2. GEOLOGY AND STRUCTURAL SETTING

The Niger Delta Basin is a prolific petroleum province located in southern Nigeria, formed during the Late Cretaceous to Recent as a result of rifting and subsequent passive margin development between the African and South American plates. The basin is characterized by a thick sequence of deltaic sediments, subdivided into three major lithostratigraphic units: the Akata, Agbada, and Benin Formations (Doust and Omatsola, 1990). The Akata Formation, composed predominantly of marine shales, serves as the primary source rock. Overlying it is the Agbada Formation, consisting of interbedded sandstones and shales that form the principal reservoirs and seals. The uppermost Benin Formation is composed of continental sands and gravels and is generally non-prospective.

The Akos Field is located in the onshore depobelt of the central Niger Delta. This region is structurally complex and dominated by syn-sedimentary extensional faulting, which developed in response to gravitational collapse of over pressured shale sequences. Growth faults with roll-over anticlines and associated synthetic and antithetic faults are common structural features in this area. These faults often act as hydrocarbon traps, either through juxtaposition of reservoir against seal or via shale smear along fault planes. In the Akos Field, the dominant structural style includes a series of listric normal faults that sole out into deeper shales of the Akata

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Formation. The traps are primarily fault-assisted and rely on effective lateral and top seals. The integrity of these fault-related traps is controlled by fault geometry, displacement, lithological variation, and the extent of shale smear factors that directly influence seal effectiveness and hydrocarbon accumulation.

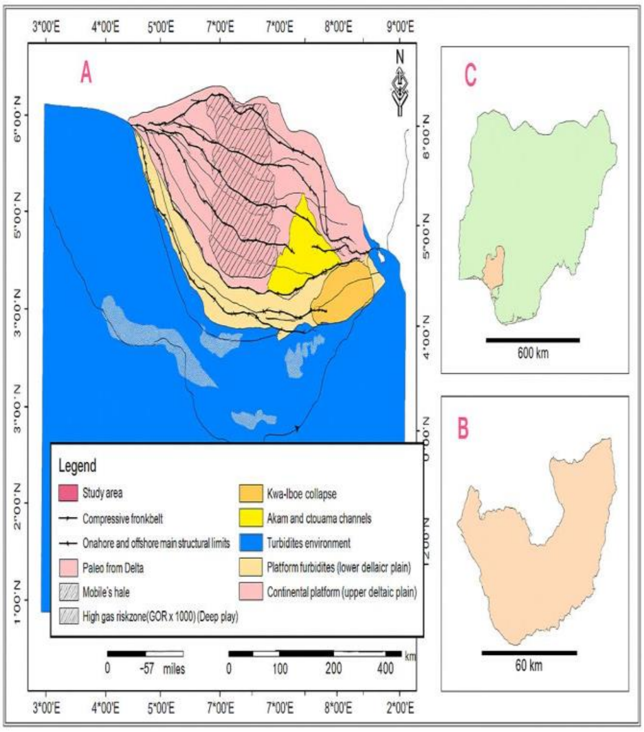

Figure 1: Location Maps of the Study Area within the Niger Delta Basin. (A) Regional map showing the study area situated in the coastal swamp depobelt of the Niger Delta; (B) Map of the Niger Delta highlighting its areal extent; (C) Map of Nigeria indicating the position of the Niger Delta within the national framework.

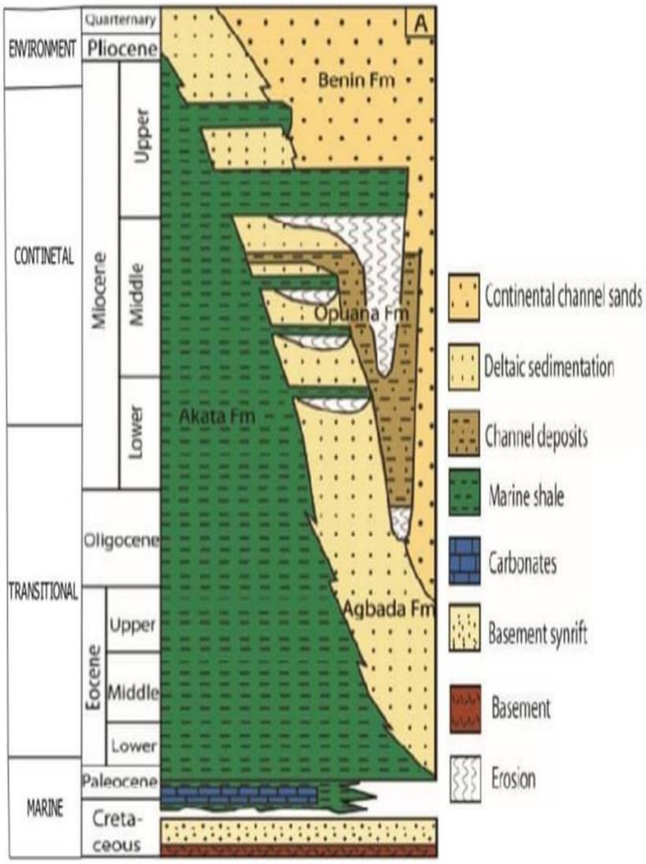

Figure 2: Stratigraphic Framework of the Niger Delta Depobelts and associated hydrocarbon bearing Formations (Lawrence et al., 2002).

3. Materials And Methods

This study employed an integrated approach combining 3D seismic interpretation, well log correlation, and fault seal analysis to evaluate sealing behaviour in the Akos Field, onshore Niger Delta. The dataset includes a 3D post-stack time-migrated seismic volume and three wells with gamma ray, resistivity, and density logs. These data were preconditioned for interpretation and quality checked for consistency.

Seismic interpretation was carried out using Petrel software, focusing on two key reservoir horizons and bounding faults. Faults were identified based on terminations, offset patterns, and continuity breaks. Structural elements such as fault geometry and throw were mapped to guide seal analysis.

Stratigraphic correlation across the wells was performed using gamma ray logs to delineate reservoir and seal intervals. Volume of shale (Vsh) was estimated using the linear gamma ray method (Dresser Atlas, 1982). This lithological classification was used as input for fault seal modelling.

Fault seal capacity was assessed using the Shale Gouge Ratio (SGR), which estimates the proportion of shale material along fault planes (Yielding et al., 1997). SGR was computed using juxtaposition diagrams and lithologic inputs derived from well logs. The analysis was performed using Trap Tester (T7), with results focused on the two major faults (F1 and F2). Thresholds above 20% SGR were interpreted as indicative of sealing potential (Freeman et al., 1998).

The workflow adopted follows established industry-standard practices for fault seal analysis (Knipe et al., 1997 ; Yielding et al., 1997). Software tools used include Petrel for seismic interpretation and Trap Tester for fault seal evaluation.

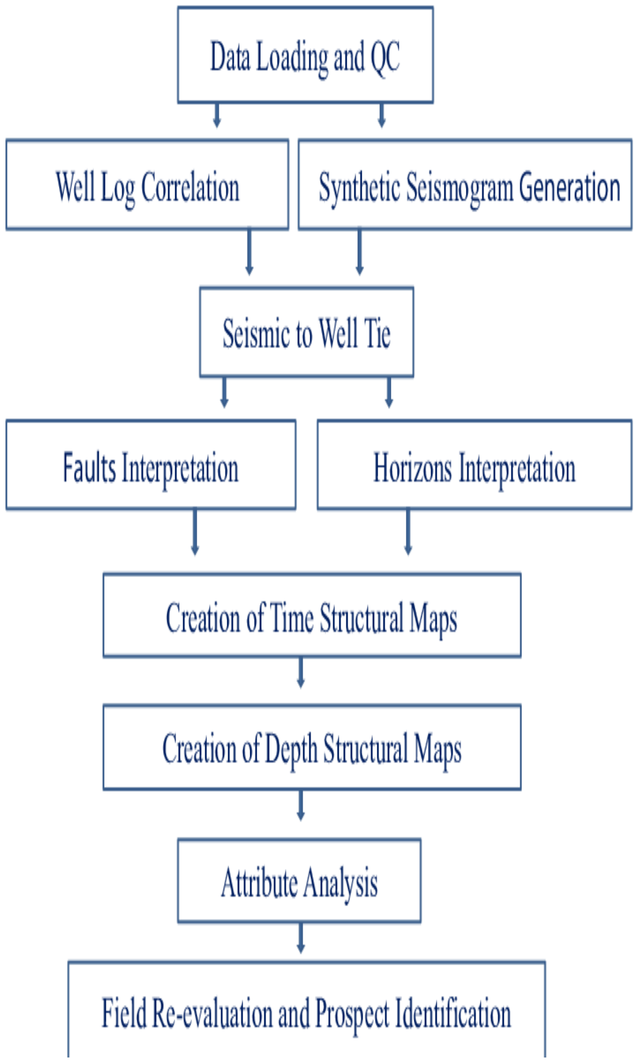

Figure 3: Presents a typical workflow for seismic interpretation, illustrating the sequential stages from data loading and quality control to horizon picking, fault interpretation, and generation of structural maps (Brown, 2011).

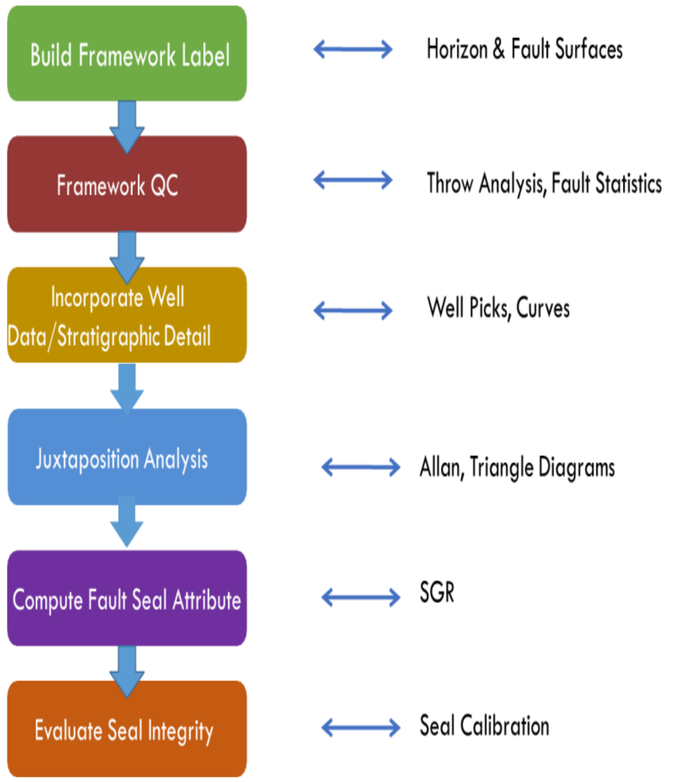

Figure 4: outlines the typical fault seal analysis workflow adopted for this study (After Yielding et al., 1997).

4. Results And Discussion

4.1 Reservoir properties from well correlation

Correlation of seven wells (AKOS 001, AKOS 002, AKOS 003, AKOS 004, AKOS 006, AKOS 010, and AKOS 011) identified three principal reservoir intervals within the study area (Figure 5a). These reservoirs are designated as Reservoir 1 (R1), Reservoir 2 (R2), and Reservoir 3 (R3). R1 is the deepest unit, occurring between 10,000 and 11,500 m, and is overlain by a thick shale sequence that provides an effective seal, enhancing its hydrocarbon potential. R2 occurs at depths of approximately 8,500–9,500 m and is similarly sealed by thick shale deposits. R3 is shallower, occurring between 7,000 and 8,000 m, and is considered to have lower hydrocarbon potential due to its shallow depth relative to deeper, mature source rocks. Consequently, this study focuses on the deeper reservoirs (R1 and R2), which are structurally controlled by faults and form fault-dependent traps. Fault seal analysis was therefore conducted on selected structures to evaluate their sealing capacity and trap integrity.

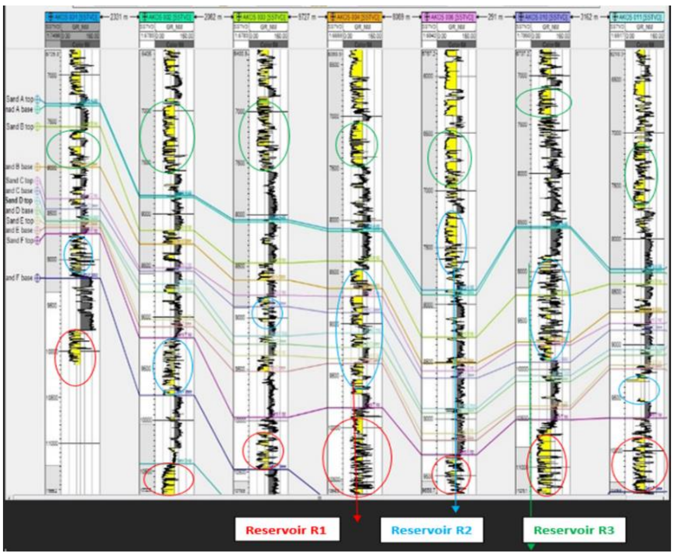

Figure 5: (a) Well correlation across seven wells – from the west to the east of the study area (b) Identified reservoirs are circled.

4.2 Structures

Structural interpretation of the study area (Figures 6a–d) reveals fault geometries mapped on time-structure maps at varying depths (Figure 6e). At the deepest level (3000 ms TWTT), three major faults (F1, F2, and F3) are identified. Faults F2 and F3 exhibit an east–west orientation, while Fault F1 trends NE–SW and intersects Fault F2. These faults persist at a shallower level of 2800 ms. At 2200 ms, an additional fault (F4) emerges in the eastern part of the study area, intersecting Fault F2 and sharing a similar NE–SW trend with Fault F1. No faults are observed at the shallowest levels, suggesting that fault activity had ceased prior to the deposition of the younger stratigraphic units.

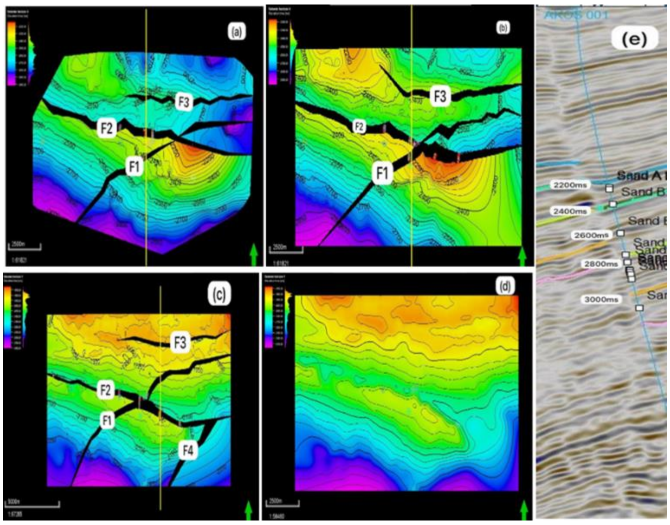

Figure 6: (a) Shows structures mapped on a time structure map within the study area at (3000ms) deeper level (see position on Figure 4e). (b) Shows structures mapped on a time structure map within the study area at (2800ms) intermediate depth (see position on Fig 4e). (c) Shows structures mapped on a time structure map within the study area at (2200ms) shallow depth (see position on Fig 4e). (d) Shows time-structure map close to the surface with no structures.

The Seismic analysis of the Akos Field revealed a structurally complex setting dominated by extensional faulting. From the seismic section presented in figure 3.1a and 3.1b, two major listric normal faults (designated F1 and F2) define the structural framework, forming roll-over anticlines and fault-bounded compartments. Fault F1 trends northeast–southwest with moderate displacement, while F2 displays greater vertical throw and more pronounced stratigraphic juxtaposition. These structural features form the primary traps in the field, with potential for hydrocarbon accumulation, in order to assess the potentials associated with these traps, fault seal analysis was carried out on selected major faults and presented in section 3.1 below.

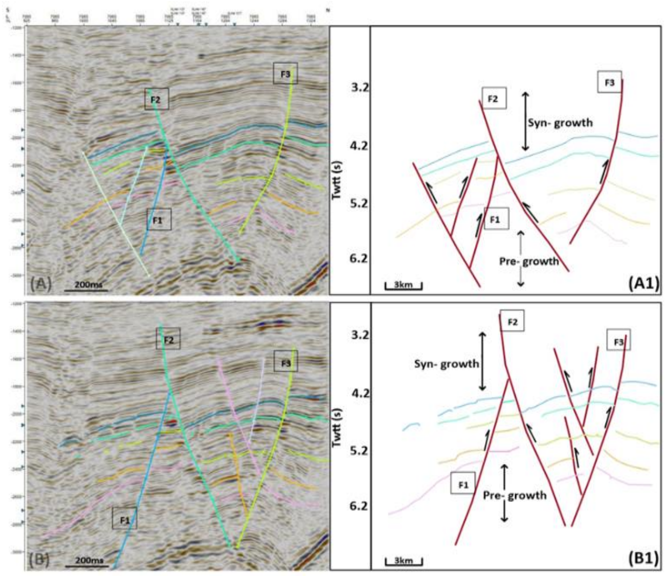

Figure 7: (a and b) Shows seismic sections across the study area revealing the nature of faults at depth. Note that the faults are generally

listric and also associated with roll-over anticlines that form potential traps.

4.3 Fault Seal Analysis

SGR values were computed along the fault planes of F1 and F2 to evaluate their sealing behaviour (Figure 7). Fault F1 exhibited SGR values ranging between 35% and 40%, indicating moderate sealing potential and the likelihood of partial hydrocarbon leakage (Figure 7a). In contrast, Fault F2 recorded higher SGR values exceeding 40%, suggesting stronger sealing capacity and a more effective trap (Figure 7b). The spatial distribution of SGR along the fault planes highlights variability in seal efficiency, which has direct implications for fault-bounded reservoir compartmentalization and trap integrity.

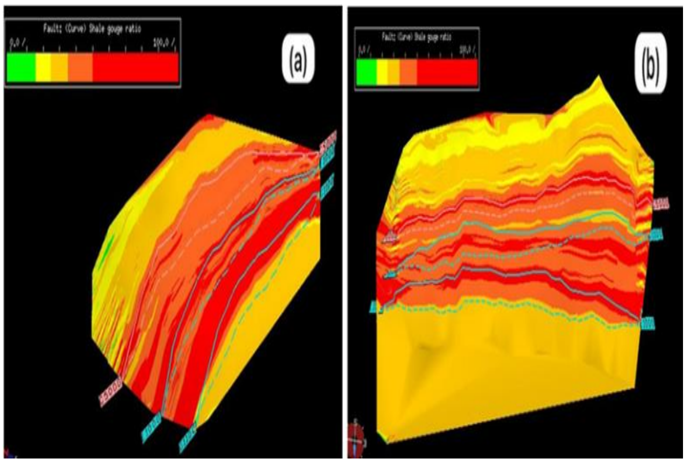

Figure 8: (a) F1 SGR result, showing high values at the middle zone, indicating potential sealing of the fault, while the green and yellow represent low SGR. (b) F2 SGR result, showing high values along the fault planes. Generally, they are both sealing, but F1 exhibits a partial sealing capacity.

4.4 Implication for Hydrocarbon Accumulation

The variation in sealing capacity between the two faults suggests differential effectiveness in retaining hydrocarbons. Fault F2 likely contributes to hydrocarbon entrapment by forming a reliable lateral seal, whereas Fault F1 may allow limited cross-fault migration depending on pressure conditions and juxtaposed lithologies. These findings underscore the importance of integrating fault seal analysis into exploration workflows, particularly in structurally complex onshore settings.

4.5 Comparison with Established Fields

When compared with documented offshore fields such as Bonga, Agbami, and Okan, which exhibit well-defined fault-assisted traps with robust sealing characteristics (e.g., Iheruturu et al., 2018; Oyekuru et al., 2019), the Akos Field presents a more variable sealing regime. This suggests that onshore fault systems may require more detailed seal analysis due to higher compartmentalization and greater lithologic heterogeneity.

4.6 Ranking of Prospect and Risk Management

One significant risk is the potential reactivation of faults due to production activities, which could compromise sealing integrity and lead to hydrocarbon leakage. Real-time reservoir monitoring using 4D seismic imaging and pressure surveillance could help mitigate these risks but this is beyond the scope of this study.

To rank the three prospects labelled in different shapes (oval, rectangular, and triangular) based on their economic potential and their relationship to Faults F1 and F2, their structural positioning, fault dynamics, and potential impact on hydrocarbon trapping was analysed (Figure 8).

Oval-shaped prospect ranks highest due to its intersection with faults F1 and F2, enhancing structural closure and migration pathways.

Triangular-shaped prospect ranks second, benefiting from fault F2 trapping, but its deeper position increases drilling costs and operational risks.

Rectangular-shaped prospect ranks lowest due to its lack of direct fault influence, making it more dependent on stratigraphic trapping and increasing geological uncertainty.

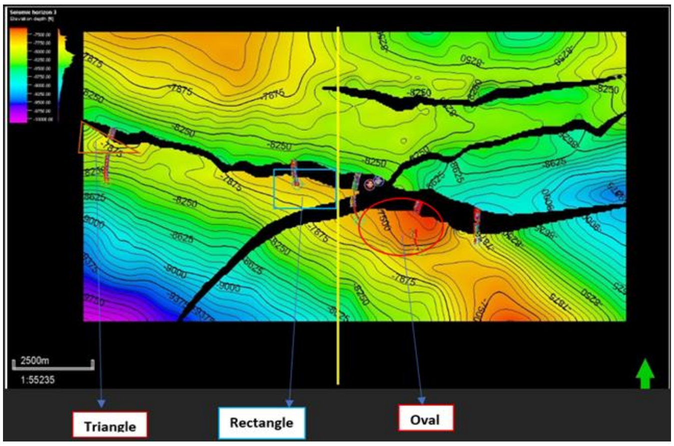

Figure 9: Shows the three-prospect labelled in different shapes (Oval, Triangle and Rectangle) identified within the study area on a time structure map.

4.7 Summary Report

Table 1: Summary report for F1

Interval	Minimum SGR (%)	Supportable Hydrocarbon Column Height (ft.)	Structural Supported Hydrocarbon Column Height (ft.)
Prospect A			
Sand A	48.4	495.9	200
Sand B	44.2	564.1	200
Sand C	36.0	480.1	200
Sand D	47.9	671.7	200
Sand E	48.5	853.9	50

Table 2: Summary report for F2

Interval	Minimum SGR (%)	Supportable Hydrocarbon Column Height (ft.)	Structural Supported Hydrocarbon Column Height (ft.)
Prospect A			
Sand A	48.4	495.9	300
Sand B	44.2	564.1	500
Sand C	39.0	480.1	550
Sand D	47.9	671.7	600
Sand E	48.5	853.9	750

4.7.1 For Prospect A

Fault seal analysis for Prospect A indicates effective sealing across all evaluated sand units (A–E), based on minimum shale gouge ratio (SGR) values ranging from 39.0% to 48.5%. These SGR values correspond to high fault-sealing capacities, with maximum supported hydrocarbon column heights between approximately 480 ft and 854 ft. However, in all cases, the actual hydrocarbon column heights are constrained by structural spill points rather than fault seal capacity. Structurally supported column heights are estimated at ~200 ft for Sands A–D and ~50 ft for Sand E, calculated from the crest of closure to the spill point. Overall, the results demonstrate that the faults are sufficiently sealing and capable of supporting significantly larger hydrocarbon columns than those structurally permitted.

4.7.2 For Prospect B

Fault seal analysis for the evaluated sands (A–E) indicates effective sealing capacity across the prospect, with minimum shale gouge ratio (SGR) values ranging from 39.0% to 48.5%. These SGR values correspond to high fault-supported hydrocarbon column heights, varying from approximately 480 ft to 854 ft. However, for most sands, the maximum hydrocarbon column heights are constrained by structural spill points rather than fault seal capacity. Structurally supported column heights are estimated at ~300 ft for Sand A, ~500 ft for Sand B, ~600 ft for Sand D, and ~750 ft for Sand E, calculated from the crest of closure to the spill point. In contrast, Sand C is structurally capable of supporting a column height (~550 ft) that exceeds the fault-supported capacity, indicating that fault seal may be the limiting factor for this reservoir.

Hydrocarbon column height estimation was performed using the Yielding algorithm due to the absence of pressure (RFT) data in this greenfield. The workflow integrates calibrated SGR values, fluid density, and other fault-related parameters within the software to estimate maximum supportable hydrocarbon columns. An oil density of 0.8 g/cm^3 was assumed. Overall, higher SGR values correspond to greater supported column heights, confirming a strong relationship between fault gouge composition and sealing efficiency.

5. Conclusions

This study applied fault seal analysis to assess the structural and sealing characteristics of the Akos Field in the onshore Niger Delta Basin, with the goal of reducing exploration uncertainty. Integrated interpretation of 3D seismic data and well logs, combined with Shale Gouge Ratio (SGR) modelling, revealed significant variability in fault sealing capacity across the field. Fault F2 demonstrated high SGR values (>40%), indicating strong sealing potential and effective hydrocarbon trapping, while Fault F1 exhibited moderate SGR values (35–40%), suggesting partial seal behaviour and increased risk of cross-fault leakage. These differences directly influenced the definition and ranking of prospects within the field. Three prospects were identified and ranked based on fault seal integrity, lithologic juxtaposition, and trap geometry, with oval prospect emerging as the most viable drilling target. The findings confirm that fault seal analysis is a critical tool for evaluating trap reliability, reservoir compartmentalization, and hydrocarbon retention, especially in structurally complex onshore settings. Overall, the study highlights the importance of incorporating fault seal evaluation into early exploration workflows to enhance prospect de-risking and improve decision-making in fault-controlled petroleum systems.

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