Derisking Hydrocarbon Exploration through Fault Seal Analysis in Fault-Assisted Traps

Ukam Ekpei*[1], Danlami Bawa [1], Ejike Okolo[1], Ifeoma Oputa-Ikpo[1], Justine N. Daboer[2], Clement Onyekwelu[2], Valentine Uwechie[2], Tunbosun A. Owolabi[2] and Ehi Bazuaye[3]

[1]NNPC E & P Limited
[2]Juvicle Energy Resources Limited
[3]Oando Energy Resources Nigeria Limited

ABSTRACT

Trap integrity is a crucial component of petroleum systems, and the ability of faults to act as effective seals is a vital aspect of trap assessment. This study focuses on several fault-bounded structural traps with hydrocarbon accumulations within a specific field in Niger Delta, Nigeria, emphasizing the importance of fault seal integrity in these contexts. The structural framework of the field is characterized by NW-SE trending micro- and macro-structural listric faults, notably lacking a counter-regional fault that typically defines the Niger Delta Northern Depobelt. Therefore, this study assesses the fault-sealing integrity of the major bounding faults associated with the identified prospects. A multi-disciplinary approach was employed to achieve the study objectives, incorporating structural mapping and geo-cellular modeling enhanced by geostatistical algorithms. This methodology facilitated the creation of a robust geometrical model, providing a three-dimensional representation of the fault surfaces and estimating the throw on these faults for seal analysis. Understanding the subsurface structural framework is essential for evaluating potential fluid connections across fault surfaces. Juxtaposition analysis was performed to identify zones adjacent to sealing or non-sealing units, such as sand or shale. Subsequently, the study assessed whether the fault deformation processes resulted in a membrane seal (fault rock seal) through the shale gouge ratio (SGR) algorithm. Hydrocarbon column heights and threshold pressures were also utilized to evaluate the fault-sealing capacities. In conclusion, the integration of juxtaposition analysis, the presence of fault rock seals, and threshold capillary entry pressures culminated in developing a chance adequacy matrix. This matrix serves as a valuable tool for defining prospects based on their fault risk assessment.

Keywords: Fault seal, Geocelluar modeling, Geostatistical, Geometrical Models, Shale Gouge Ratio (SGR).

INTRODUCTION

In fault-assisted structural plays, faults can either trap or act as flow conduits for fluids (hydrocarbon) in the subsurface, making them economically significant. Therefore, assessing trap integrity, a crucial component of a petroleum play system becomes essential. Fault Seal Analysis (FSA) plays a critical role in measuring the risk posed by the sealing and non-sealing potential of faults that define hydrocarbon reservoirs. FSA evaluates hydrocarbon permeability through faults in siliciclastic sequences, enhances the prediction of fault behavior in the subsurface, and reduces uncertainty in exploiting faulted siliciclastic reservoirs.

The authors wish to thank NNPC E & P Limited, NNPC Upstream Investment Management Services (NUIMS), Juvicle Energy Resources Limited, Oando Energy Resources Nigeria Limited and NAPE for providing the platform to present the paper during the Annual Conference.

Previous researchers (Freeman *et al.,* 1990; Knipe, 1992; Needham *et al.,* 1996; Watts, 1987; Yielding, 1997) have identified various mechanisms that allow fault planes to act as seals or barriers to hydrocarbon flow. These mechanisms include juxtaposition (where a reservoir is juxtaposed against a relatively low-permeability unit), the entrainment of low-permeability gouge materials (such as clay or shale) into the fault plane, the crushing of sand grains to produce a fault gouge of finer-grained material (cataclasis), and the creation of a hydraulic seal through preferential cementation along an originally permeable fault plane, which may partially or eliminate porosity (diagenesis).

However, the literature suggests that membrane seals, where the critical capillary entry pressure of the sealing rock is the dominant control on fault seal behavior, are key in determining seal failure, particularly in siliciclastic sequences such as the Agbada Formation of the Niger Delta. Fault zones with higher clay content, corresponding to higher Shale Gouge Ratio (SGR) values, can support higher capillary threshold pressures. This study utilizes fault seal analysis, combining juxtaposition and fault membrane seals, to help derisk hydrocarbon exploration in fault-assisted traps within a field in the Niger Delta.

BACKGROUND GEOLOGY

The prospect area is geologically situated within the Northern Depo-Belt of the Niger Delta Province. Its structural framework is defined by NW-SE trending micro and macro-structural listric faults, with the notable absence of a counter-regional fault that typically defines the Niger Delta Northern Depobelt.

METHODOLOGY

A critical aspect of Fault Seal Prediction involves building a geometrically consistent structural framework for all the prospect-bounding faults. The geometrical model, including the evaluation of structural style, fault throw, and lithotype juxtaposition along the fault plane, was built following the structural interpretation of the prospect areas. Since most of the prospect-bounding faults were intersecting, effective quality control (QC) of the horizon interpretation at fault branch lines was performed using the master fault and splay fault principle. According to this principle, if the downthrown polygon on the master fault steps upward, then the splay fault is on the downthrown side of the master fault. If the upthrown polygon of the master fault steps downward, the splay fault is on the upthrown side of the master fault. In both cases, the size of the step must match the offset of the splay fault at the branch line.

Seismic picks and their depth-converted equivalents are rarely available for every reservoir interval. A key step in the fault seal analysis workflow using T7 is the incorporation of the thinnest layers, which may lead to a potentially weak juxtaposition. This is achieved by integrating well-based picks and Vshale curves mapped onto the fault surface at the same resolution as the cells on the fault. Well picks (e.g., top and base reservoir picks) are used to subdivide seismic-scale stratigraphy into reservoir and non-reservoir intervals, while well curves (Vshale) provide estimates of the wall rock composition adjacent to the faults. Stratigraphic scaling rules are then applied with quality control to define the distance between marker horizons and adjacent seismic horizons within the model.

The Allan Fault plane diagram was used to assess faults sealed by juxtaposition, a process in which sealing units are juxtaposed against reservoirs. This method helps describe the geometry of reservoirs and seals on either side of the fault—an essential first step in characterizing the fault (Bouvier *et al.,* 1989; Clarke *et al.,* 2005). After establishing self-juxtaposition, it becomes necessary to measure the fault seal membrane and fault rock clay content, which correlates with seal capacity and inversely correlates with permeability (Yielding *et al.,* 2010). This is typically estimated using algorithms such as Shale Gouge Ratio (SGR) (Yielding *et al.,* 1997), Clay Smear Potential (CSP) (Bouvier *et al.,* 1989), and Shale Smear Factor (SSF) (Smith, 1966). The SGR algorithm was adopted for this study because it performs well in both exploration and production scenarios, and also takes into cognizance, the intercalation of sands and shales associated with the Agbada Formation. According to empirical data, hydrocarbon column heights can be estimated using calibrated shale gouge ratio ranges (Bretan, Yielding, and Jones, 2003) to determine whether a fault is sealing or leaking. When planning future wells, fault seal membranes are calibrated to pressure data. Therefore, SGR is plotted against buoyancy pressure to establish that fault rock sealing capacity directly correlates with shale/clay content (Yielding *et al.,* 2010). Faults in the study area are assumed not to have been reactivated or critically stressed, as they are considered potential hydrocarbon exploration sites. Therefore, fault reactivation was not factored into the fault seal risk assessment criteria or workflow (Figure 1).

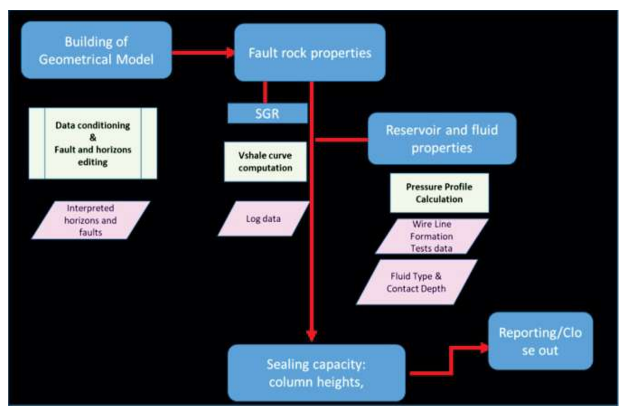

Figure 1: Simplified Fault Seal Analysis Workflow.

RESULT AND DISCUSSION

Geometrical Model

A geologically viable faulted framework model, consisting of a 3D consistent set of intersecting fault and horizon surfaces, was constructed using fault and horizon interpretations derived from the Ogh prospect interpretation. This subsurface structural framework is crucial for determining the first-order control of potential connections across fault surfaces. The Ogh Geometrical Model illustrates a classic downthrown splay fault scenario, with Fault Y intersecting and building into Fault X. Two target levels, interpreted as horizons Ogh1 and Ogh2, were identified in the prospect. The fault throw distribution of Faults 4 and 8 was consistent with the overall interpretation (Figure 2). Consequently, fault throw distribution analysis was conducted on both faults, confirming that the geological model aligns with the interpretation.

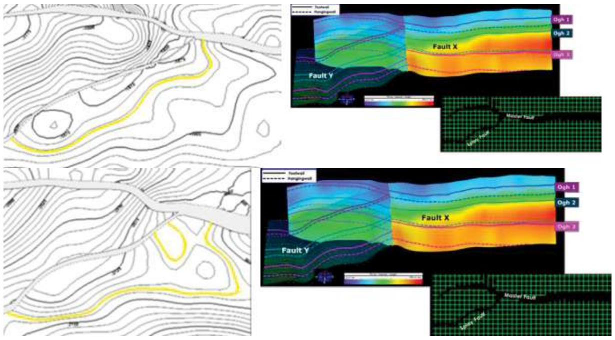

Figure 2: Depth Maps and Geometrical Models for Faults X and Y Juxtaposition Analyses.

A fault is considered to be leaking when a reservoir (sand) is juxtaposed against another reservoir unit (sand-on-sand/self-juxtaposition). The Allan diagram was used to analyze the juxtaposition seal across the two target levels (Ogh1 and Ogh2). Zones where the fault juxtaposes sealing rock (shale) against reservoir (sand) are classified as definitely sealing, while zones where the fault juxtaposes reservoir (sand) against reservoir (sand) are classified as potential leakage points, pending the estimation of the Shale Gouge Ratio (SGR). The results indicated evidence of reservoir juxtaposition at the Ogh1 and Ogh2 prospect levels, with the exception of Ogh3 (Figure 3).

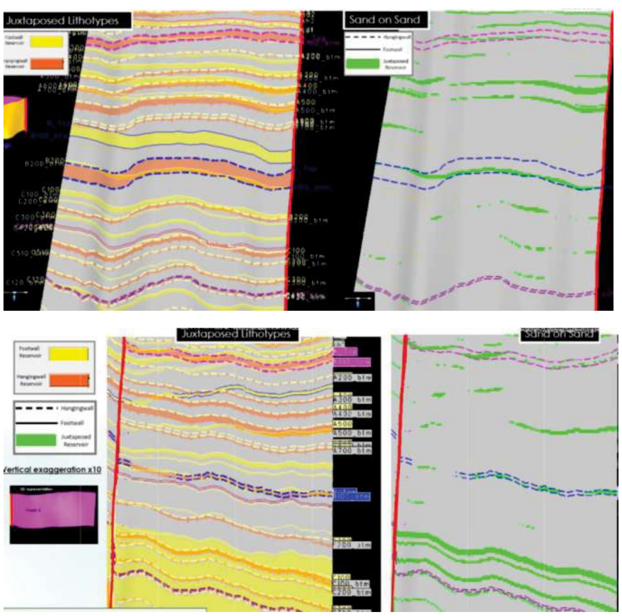

Figure 3: Faults X and Y Juxtaposition Analyses Fault Seal Algorithm.

It was assumed that at depths less than 3 km, the fault-zone composition, indicated by the Shale Gouge Ratio (SGR), is the dominant control on seal capacity. Where SGR is low (<15-20%), it is assumed that the cataclastic gouge can only support minimal pressure differences (e.g., up to approximately 1 bar, or a few tens of meters of hydrocarbon column). In such cases, clay smears are discontinuous, creating zones of high risk (definitely leaking). However, as the SGR increases from 20 to 50%, it suggests that phyllosilicate-framework fault rock can support progressively larger pressure differences (e.g., 1-40 bars), and these zones are classified as moderate to medium risk. The SGR scale tends to saturate around 50%, at which point well-developed clay smears can support geological pressure differences of many tens of bars, equivalent to hydrocarbon columns of hundreds of meters. These areas are categorized as low-risk zones (most likely sealing).

SGR at sand-sand juxtaposition (red = high; green = low) was used to analyze the impact of fault rock sealing in areas where sand-on-sand juxtaposition occurred along the faults defining the Ogh prospect (Figure 4). Faults Y and X showed SGR values greater than 50% in zones with sand-on-sand juxtaposition, except in Ogh2 on Fault Y, where the SGR is approximately 45%, classifying it as low risk.

An integrated workflow combining caprock and fault seal

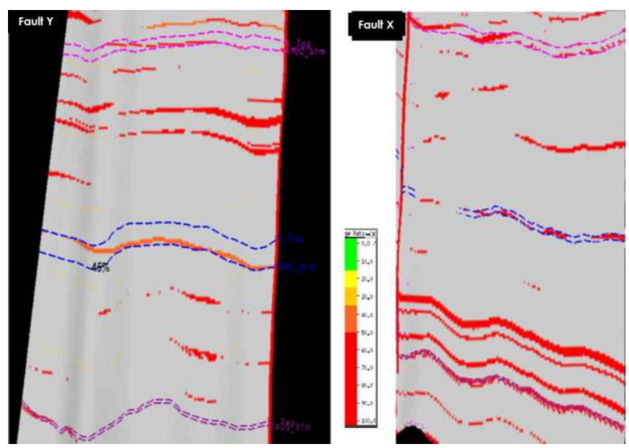

Figure 4: Faults X and Y Fault Rock Seal Fault Seal Risk Assessment of Ogh Prospect.

analyses to predict trap integrity in prospect evaluation, as developed by Mildren *et al.* (2003) and Jones and Hillis (2003), was adopted for this study. This framework provides a structured approach for quantifying the risks associated with hydrocarbon trapping. The Fault Seal Risk categorization for the Ogh prospect was based solely on juxtaposition and fault rock seal. This approach assumes that sealing by juxtaposition is a perfect seal and assigns it a value of 1. It further assumes that the deformation processes have created a membrane seal. Seal prediction based on the Shale Gouge Ratio (SGR) is categorized into four risk subgroups, in line with fault-seal calibration derived from a comparison between core samples, outcrop samples, and our experience with fault seal behavior in the Onshore Niger Delta Basin.

A Chance Adequacy Matrix (modified after Rose, 2001) was generated, based on the probability that the fault is sealing, with values ranging between 0 and 1 (Figure 5). A value of 0 indicates that a breach is certain, while a value of 0.5 suggests significant uncertainty, implying a "toss-up" between sealing and leaking. A value of 1 means that the seal will remain uncompromised. Subjective expressions of confidence for each critical parameter are used to determine risk modifiers. For example, sealing by juxtaposition (considered a perfect seal) with a value of 1 is classified as "Definitely Sealing." For membrane seals, the subjective expression considers the relationship between the proportion of juxtaposition or its position (whether up-dip or down-dip in relation to the trap) and the four risk subcategories based on the SGR described earlier.

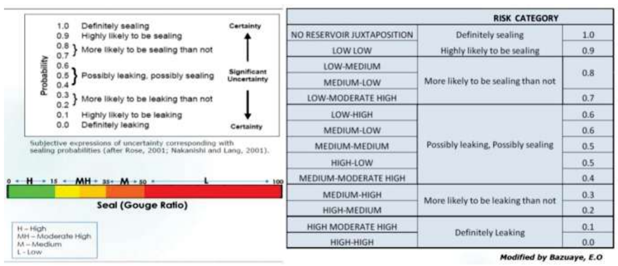

Figure 5: Fault Seal Categorization of the OGH Prospect.

The Risk Assessment for Faults Y and X, which define the Ogh prospect, is summarized in Table 1 below. The results indicate that all prospective levels, except Ogh3, have sand-on-sand juxtaposition (Table 1). As a result, Ogh3 falls into the lowest risk category of 1, classified as "Definitely Sealing." In Fault Y, although prospective levels Ogh1 and Ogh2 exhibit similar distributions of sand-on-sand juxtaposition, Level A is placed in the 0.8 risk category ("More likely to be sealing than not") due to an SGR >50% (Figure 4). Ogh2 is assigned a risk category of 0.5 ("Possibly leaking, possibly sealing") because of its lower SGR value. Meanwhile, for Fault X, both Ogh1 and Ogh2 are classified as "Possibly leaking, possibly sealing" (risk category 0.5), as indicated in Table 1 below.

CONCLUSION

Table 1: Ogh Prospect Risk Assessment.

Prospect	Fault		Reservoir Juxtaposition	Sand - Sand Juxtaposition: Reservoir Juxtaposition *Increasing Risk*			Shale Gouge Ratio *Increasing Risk*				Risk Category	
				Low	*Medium*	*High*	*Low*	*Medium*	*Med - High*	*High*	*0 - 1*	*Definition*
Ogh	Fault Y	Ogh1	Yes		•		•				0.8	More likely to be sealing than not
		Ogh2	Yes		•			•			0.5	Possibly leaking, possibly sealing
		Ogh3	No								1	Definitely sealing
	Fault X	Ogh1	Yes			•	•				0.5	Possibly leaking, possibly sealing
		Ogh2	Yes			•	•				0.5	Possibly leaking, possibly sealing
		Ogh3	No								1	Definitely sealing

Trap integrity is one of the four key components in assessing geological success when evaluating prospects. Fault Seal Analysis was conducted on the faults defining the Ogh Prospect to evaluate its trapping potential. This analysis utilized the Allan diagram for juxtaposition and the Shale Gouge Ratio (SGR). A risk assessment was also performed for the faults at various prospect levels. The risk parameters were defined by the likelihood of fault juxtaposition and deformation, and these were quantified by assigning a range of values as previously reported.

REFERENCES CITED

Bouvier, J.D., Kaars-sijpesteijn, C.H., Kluesner, D.F., Onyejekwe, C.C. & Van der pal, R.C. (1989). Three-dimensional seismic interpretation and fault sealing investigations, Nun River field, Nigeria. AAPG Bulletin, 73, 1397–1414, https://doi.org/10.1306/44B4AA5A170A-11D7-8645000102C1865D

Bretan, P., Yielding, G., and Jones, H. (2003). Using calibrated shale gouge ratio to estimate hydrocarbon column heights. AAPG Bulletin, 87, pp.397-413.

Clarke, S.M., Burley, S.D. & Williams, G.D. (2005). A three-dimensional approach to fault seal analysis: fault-block juxtaposition and argillaceous smear modelling. Basin Research, 17, 269–288, https://doi.org/10. 1111/j.1365-2117.2005.00263.x

Freeman, B., Yielding, G. and Badley, M. (1990). Fault correlation during seismic interpretation. First Break, vol. 8 (3).

Jones R.M. and Hillis R.R. (2003). An integrated, quantitative approach to assessing fault-seal risk. AAPG Bulletin vol. 87 (3), pp. 507–524, https://doi.org/10.1306/10100201135

Knipe, R. J. (1992). 'Faulting processes and fault seal'. R. M. Larsen, H. Brekke, B. T. Larsen, and E. Talleras, eds., Structural and tectonic modelling and its application to petroleum geology: Amsterdam, Elsevier, pp. 325–342.

Mildren S.D., Hillis, R.R., Kivior1, T. and Kaldi, J.D. (2003). Integrated seal assessment and geologic risk with application to the Skua Field, Timor Sea, Australia. Timor Sea Petroleum Geoscience: Proceedings of the Timor Sea Symposium, Ellis, P.W. Baillie and T.J. Munson (eds.): pp.275-294

Needham, D.T., Yielding, G. and Freeman, B. (1996). Analysis of fault geometry and displacement patterns. In: P.G. Buchanan and D.A. Nieuwland (Editors), Modem Developments in Structural Interpretation Validation and Modelling. Geol. Soc. Special Publication No. 99, pp. 189-200.

Smith D.A. (1996). Theoretical Considerations of Sealing and Non-Sealing Faults. American Association of Petroleum Geologists Bulletin, Vol. 50, pp. 363 - 374

Watts, N.L. (1987). Theoretical aspects of cap-rock and fault seals for single and two-phase hydrocarbon columns. Marine and Petroleum Geology, 4, 274–307, https:// doi.org/10.1016/0264-8172(87)90008-0

Yielding, G., Freeman, B. and Needham, D.T (1997). Quantitative Fault Seal Prediction. AAPG Bulletin, 81(6), pp.897-917.

Yielding, G. (2002). Shale gouge ratio – calibration by geo-history. Koestler, A. G. & Hunsdale, R. (eds) Hydrocarbon Seal Quantification. Norwegian Petroleum Society, Special Publications, 11, pp.1–15.

Yielding, G., Bretan, P.G. & Freeman, B. (2010). Fault seal calibration: a brief review. Jolley, S.J., Fisher, Q.J., Ainsworth, R.B., Vrolijk, P.J. & Delisle, S. (eds) Reservoir Compartmentalization. Geological Society, London, Special Publications, 347, pp.243–255.