Petroleum and Coal

Article Open Access

Analysis of Fault Zones for Reservoir Modeling in Taa Field, Niger Delta, Nigeria

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Received April 18, 2017; Accepted June 19, 2017

Abstract

Fault analysis is crucial in the exploration and production of hydrocarbon because it is the fault that exerts a meaningful control on the migration, entrapment and subsequent compartmentalization of hydrocarbon. Faults' effects on hydrocarbon flow are complex. Some faults allow fluid to pass across them while some reject, which further create series of complications in the geometry of hydrocarbon reservoirs. In order to minimize the risks associated with hydrocarbons' quantification, it is imperative to carry out analysis on the complex nature of faults supporting the traps in the subsurface which this research is aimed to achieve. The fault analysis of Taa field was done using 3D and well log data. Seven reservoirs were mapped on the field with the generation of fault-polygon and fault attributes involving throw analysis, Volume of Shale (Vshale), Shale Gouge Ratio (SGR) and Hydrocarbon Column Height (HCH) estimations. It was revealed that poor (20 to 40 %) to moderate (40 to 60 %) sealing constitute the SGR of the fault plane in the study area. The supportable HCH ranged from 55.7 to 368.4 ft while the structure-supported HCH ranged from 55.7 to 123.4 ft. The difference between the supportable and the structure-supported HCH and the model from SGR confirms that the traps are liable to leak. It was concluded that the faults on Taa field are not properly sealed.

Keywords: *Fault analysis; Hydrocarbon column height; Niger delta; Shale gouge ratio; Throw; Traps.*

1. Introduction

Faults generally have sealing properties and compartmentalization. These properties are usually delineated by fault attributes' algorithms using amount of shale on the fault surface and hydrocarbon column heights [1-2]. Fault could be described as the displacement of a body of rocks by shearing or fracturing along a planar surface known as fault plane [3]. Most faults produced repeated displacements over geologic time. The fault surface can be horizontal or vertical or some arbitrary angle in between [4].

A fault can be a transmitter as well as barrier to pressure communication and fluid flow. Categorizing fault behaviour within these extremes is important for hydrocarbon drilling. In many hydrocarbon reservoirs, sealing faults may be a major determinant of trap, they may also transform large and continuous hydrocarbon reservoir into compartments that then behave as collection of smaller reservoirs. Each compartment may have these properties: fluid characteristics, reservoir's pressure, effective field development and subsequent hydrocarbon recovery. When seal is improperly formed by faults, it prevents accumulation of fluid as the fluids form and transmigrates through structures in the subsurface. The faults architecture refers to the fault shape, size, orientation and interconnectivity. It also refers to the distribution of the overall fault displacement into multiple sub-faults. The rock properties that develop within the fault zones affect a fault's ability to seal [5].

The tendency to identify leaking zones is essential tool in trap assessment. Faults do not only control the presence of hydrocarbon in a trap, it also controls the volume of hydrocarbons that have been accumulated in a trap. It does not control the volume of hydrocarbons in a trap alone but also control how hydrocarbons are distributed: vertical distribution of hydrocarbon among a series of stacked sands and distribution of hydrocarbon with single sand among series of fault compartments. The leak points in the fault dependent trap limits the volume of hydrocarbons that has been trapped. The tendency to classify leaking and sealing points is the basis in trap assessment.

A range of seal capacity has been reported for various rock types. In addition, a number of other factors suc as depth, hydrocarbon phase, seal thickness, and fault-dependent leak points affect the height of trapped hydrocarbon columns. The seal capacity of different rock tyoes are grouped into three:

i. Good shale can trap thousands of feet of hydrocarbon column,
ii. Most good sands can trap only 50 ft or less of oil column, and
iii. Poor sands and siltstones can 50 to 400 ft of oil column.

Shale has high displacement pressures and can trap large columns of oil as 1830 m (6000 ft). Sands commonly have low displacement pressures and can trap only small oil columns. Carbonates have a wide range of displacement pressure. Some carbonates can seal as much as 1500-6000 ft oil. The ability of fault to seal or leak hydrocarbon is mainly governed by the Shale Gouge Ratio (SGR) or smear-gouge ratio. SGR is an evaluation of the fault zone through which seal or leakage must occur. SGR can be determined by calculating the cumulative sand and shale that has moved past a fault zone. A fault dip-leaks or cross-leaks if the sand-shale ratio is absolutely high along a fault zone (low SGR). A fault dip-seals or cross-seals if the sand-shale ratio is outrightly low in that zone (high SGR) [6-9].

However, this study was aimed to assess the fault zones in Taa field, Niger Delta, Nigeria in order to minimize the risks and uncertainties associated with exploration of hydrocarbons through cross sealing or leaking: one of the faults' behaviours in trap assessment. Cross-leaking refers to the lateral communication across the fault between juxtaposed sands. A cross-leaking fault allows lateral communication of hydrocarbons between juxtaposed reservoirs. A cross sealing fault prevents communication of hydrocarbons between juxtaposed sands. The main objective of this study is to determine the fault attributes (throw, volume of shale, SGR, and Hydrocarbon Column Heights (HCH)) in order to confirm the sealing nature of the faults in Taa field, Niger Delta, Nigeria. In Geophysics, the rate at which a fluid flows through a permeable medium is governed by Darcy's law. The law states that this rate is directly proportional to the drop in vertical elevation between two places in the medium and indirectly proportional to the distance between them. This study shall also provide answers to whether or not hydrocarbons have migrated out of the trap, and the likely height of hydrocarbons that a fault can support in the study area. The natures of the individual fault that support the traps in Taa field are tested by Trap Tester software ™.

Winprut and Zoback [10] evaluated the fault reactivation, leakage potential, and hydrocarbon column heights on the major faults in four oil and gas fields in the Northern North Sea. However, migration of fluids in petroleum reservoirs was investigated by them. They reported that the leakage potential of reservoir bounding faults seems to exert a significant influence on potential hydrocarbon column heights.

Richard and Richard [11] investigated on approach to assessing fault-seal risk in Dampier Subbasin, North West Shelf, Australia. The fault-seal risk for the Apollo prospect was conducted on 10 ft to 100 ft oil columns to allow integration with volumetric probabilistic statements. They concluded that a quantitative assessment of fault-seal risk that integrates parameters from different aspects of fault-seal analysis in a consistent framework may be determined if the risks associated with juxtaposition sealing, deformation process sealing, and reactivation are known.

Maunde *et al*. [2] carried out fault seal analysis of A and B fields in Nile Delta, Egypt. Five traps were mapped in A field while two traps were mapped in B field. In A field, faults in the investigated traps were sealing with potential of over 200 m HCH. The last trap in A field was interpreted as a fault leak trap which would not trap hydrocarbons. In B field, the main trap was interpreted as structural spill controlled trap. The leak point on this trap was in the oil leg. The second trap on B field was interpreted as a fault leak controlled trap which would not trap hydrocarbons.

2. Location and geology of the study area

The Taa field (Figure 1) is one of the onshore fields of Niger Delta Nigeria. The Niger-Delta-a sedimentary terrain is situated in southern Nigeria between latitudes 3^0 N to 6^0 N and longitude 5^0 E to 8^0 E [12].

Figure 1. Map of Niger-Delta showing the Study

The Niger Delta is the largest delta in Africa with a sub-aerial exposure of about 75 000 km^2 and a clastic fill of about 9 000 to 12 000 m (30 000 to 40 000 ft) and terminates at different intervals by transgressive sequences [13]. The geology of the Niger Delta basin has been reported and studied extensively by several authors and the geology is therefore sufficiently understood [12-19]. The Onshore Niger Delta is situated on the Gulf of Guinea on the West Coast of Africa and its province is delineated by the geology of southern Nigeria and southwestern Cameroon (Figure 2). The northern boundary is the Benin flank; an east-northeast trending hinge line south of the West African basement massif. The northeastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High and further east-south-east by the Calabar flank – a hinge line bordering the adjacent Precambrian. The tectonic framework of the Niger Delta is related to the stresses that accompanied the separation of African and South American plates, which led to the opening of the South Atlantic [20].

The Niger Delta is a regressive of clastic sediments developed in a series of offlap cycles. All deep wells in the basin document a tripartite lithostratigraphic succession in which the regressive sequence is demonstrated. The base of the sequence consists massive and monotonous marine shales. These grade upward into interbedded shallow-marine and fluvial sands, silts, and clays, which form the typical Paralic facies portion of the Delta. The uppermost part of the sequence is a massive non-marine sand section (Figure 3). The overall thickness of this composite sequence is inexact, but may be up to 12 km in the basin center. Previous reports from magnetic and gravity data proposed that the maximum thickness at this region could be found between Warri and Port-Harcourt. Pre-delta basement indication is seen on seismic data only along the northwestern and northeastern basin flanks, and below the continental rise offshore. The interdigitation of a small number of lithofacies makes it impossible to define units and boundaries. However, three formation names are in use in Niger-

Delta [13, 21]. In ascending order, the established Tertiary sequence in the Niger Delta consists of the Akata, Agbada and Benin formations. The strata compose of an estimated 8,535 meters of section at the approximate depocentre in the central part of the Delta.

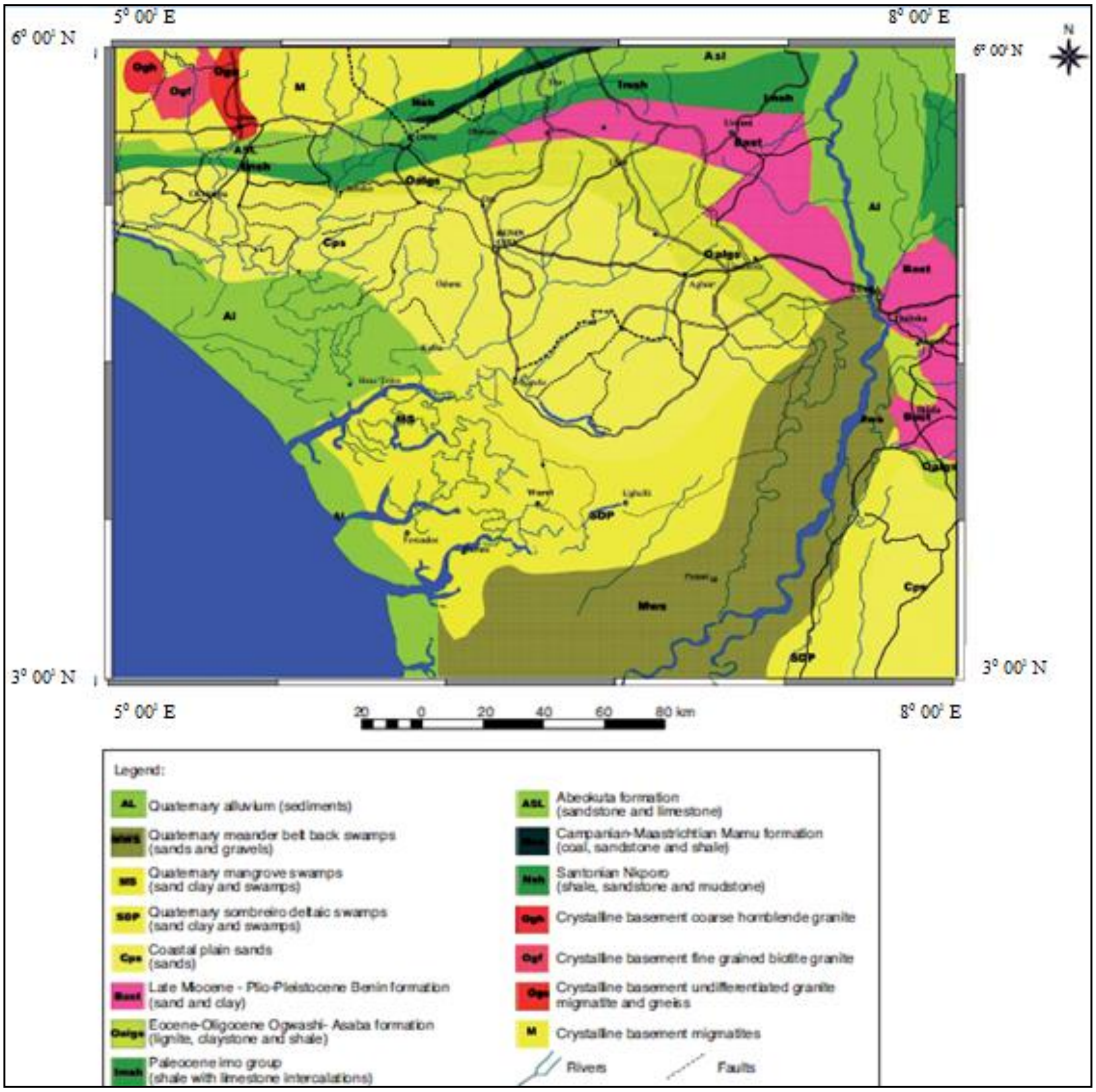

Figure 2. Regional geological map of Niger Delta, Nigeria

The common traps in Niger-Delta fields are structural traps although stratigraphic traps still exist. Figure 4 showed that simple rollover structure with clay filled channel, structure with multiple growth faults, structure with antithetic fault and collapsed crest structure are the pronounced structures in Niger-Delta fields. The structural traps developed during synsedimentary deformation of the Agbada paralic sequence. Structural complexity originates from the initially formed depobelts (i.e. from north) to the newly formed depobelts (i.e. to south) in reaction to the instability or uncertainty of the under-compacted, overpressured shale. Series of structural trapping elements, in addition to the one associated with clay filled channels, multiple growth faults structures, antithetic faults structures, simple rollover structures, as well as collapsed crest structures have been described by Doust and Omatsola [18]. Stratigraphic traps are highly important as structural traps on the Delta's flanks [22].

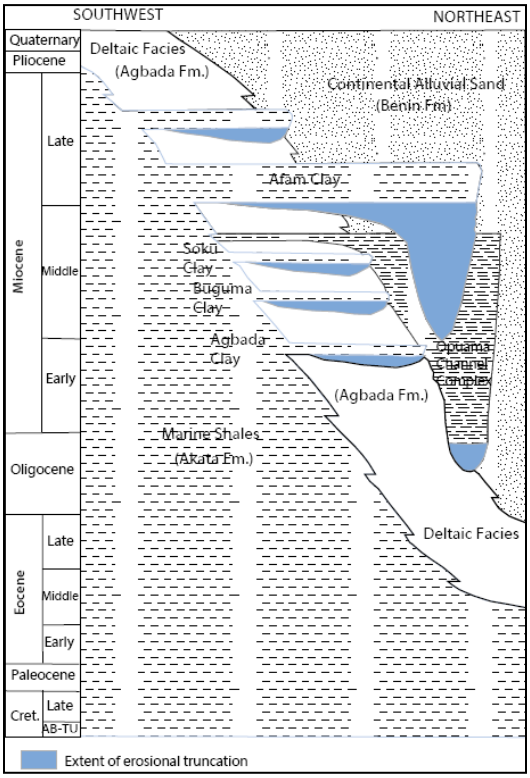

Figure 3. Stratigraphic column showing the three Formation of the Niger Delta [22]

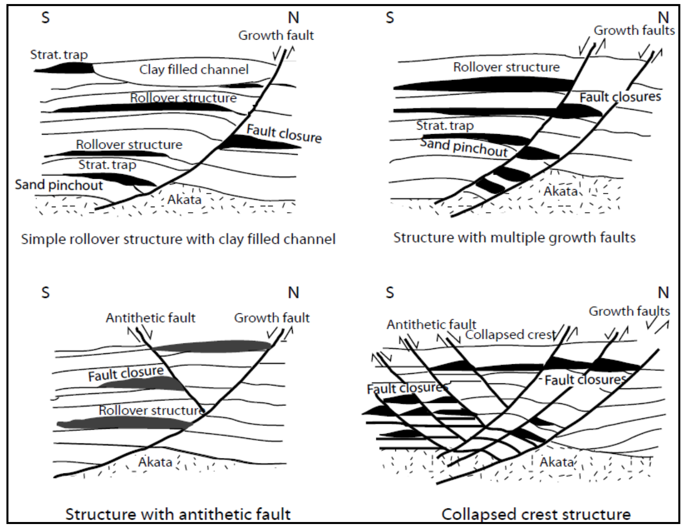

Figure 4. Niger Delta oil field structures and associated trap types [22]

3. Materials and methods

Taa field, one of the onshore fields in Niger Delta which comprises three-dimensional seismic data and well log data were used for the sealing analysis. Faults were identified and picked on the seismic section. Structural traps were mapped and correlated across the wells along their corresponding horizon.

A Trap Tester project was created on Trap Tester software [23]. The horizons, the fault segments, and the well data (i.e. well picks and Vshale curve) were imported into the Trap Tester project. The interpreted horizons and fault segments were further loaded into the volume editor for 3-D visualization and to build structural model. Some faults were linked together (fault-fault intersection) hence a branch line (line of intersection between two faults) was created to generate a relationship between the master and the splay. Fault polygons were created by synchronizing the fault surface with the horizons in the volume editor. This step modeled the intersection between the horizon raw data and the fault surfaces. The quality of the fault-horizon intersection lines (fault polygons) were assessed and edited because abrupt irregularities in the polygons geometry may reflect anomalies in the interpretation. V-Shale (well data) were loaded into the well editor after removing the errors in the seismic polygons; hence marker horizons were picked and the horizon-fault intersection polygons for the horizon picks made in the well were then created on the fault surfaces. The essence of Vshale is to show the distribution of the sand and shale layers at the fault plane. These picks were used to create the reservoir-scale polygons and this provides the extra stratigraphic details that will be used for fault seal analysis. Psedo wells were generated where wells have not been in existence before on the hanging wall.

The quality control of the study known as throw analysis was done. However, the faults attributes such as SGR and HCH were estimated in order to predict the sealing potential of faults supporting the traps in Taa field.

The SGR is calculated based on Equation 1.

$$SGR = \frac{\sum(V - sh \times \Delta Z)}{t} \times 100\% \qquad (1)$$

where, V-sh is the volume of shale; ΔZ is the thickness of the bed; and t is the throw.

However, HCH is calculated based on Equation 2.

$$H_{\max} = \frac{FZP}{g(\rho w - \rho h)} \qquad (2)$$

where, H_{max} is the maximum hydrocarbon column height (m); Fault Zone Capillary Entry Pressure (FZP); ρ w is the pore water density (kg/m^3); ρ h is the hydrocarbon density (kg/m^3); and g is the acceleration due to gravity.

4. Results and discussion

A major and minor fault were analyze for this study. The fault dips towards the south while its strike ranged from NW-SE direction. The fault plane on Taa field constitutes the structural trap in all the reservoirs. Seven horizons were mapped from the seismic section. Generally, fault is resulted to a gap on a structure map between the formations in the hanging walls and the downthrown blocks. This gives rise to effective hydrocarbon traps closed by an anticlinal structure. The shallow to the deep horizons were mapped as follow: 9050 ft, 9180 ft, 9250 ft, 9300 ft, 9900 ft, 10300 ft and 11859 ft respectively.

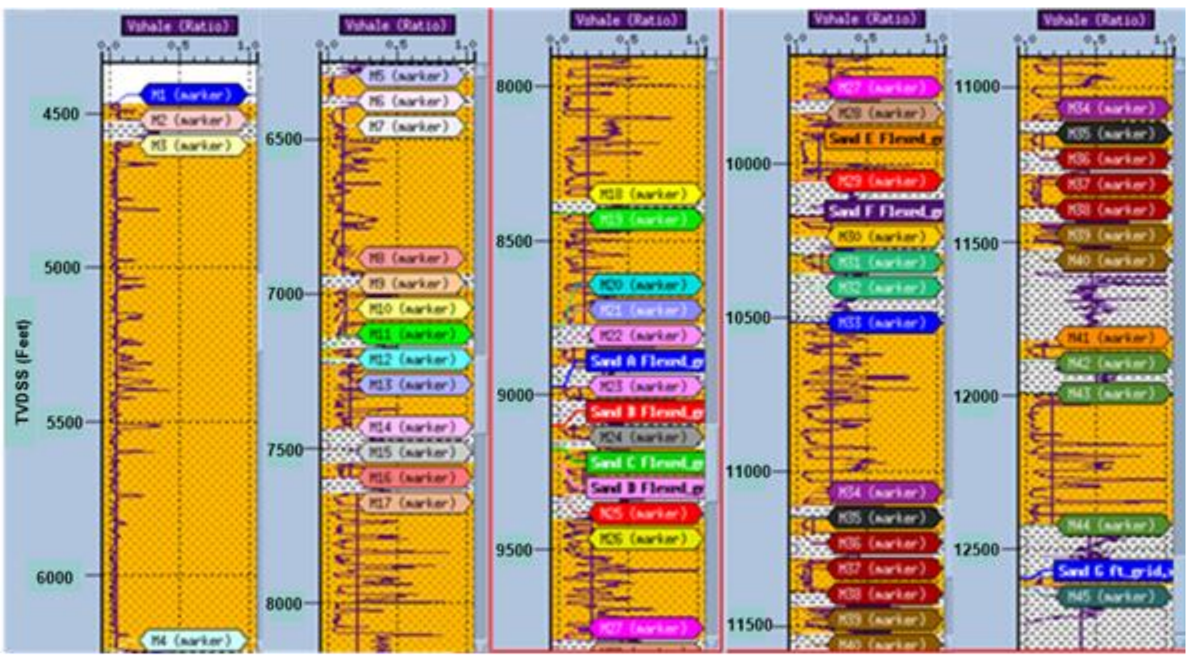

Figure 5a. V-shale log Strip of Taa Field

Horizon and fault interpretations were used to build the structural model. The raw fault segments were automatically modeled into 3-D fault surface. Figure 5a showed the V-shale log strip of Taa field. The log consists forty-five shale markers from depth 4500 to 12750 ft. The 3-D map of volume of shale along the footwall (Figure 5b) was generated in order to determine how shaly the plane is (part of measure to know if the plane is sealing or leaking). High V-Shale rating ($\geq$ 0.4) indicates sealing while low V-Shale rating indicates leaking zone [24]. Low V-Shale intercalates with some regions of high V-Shale on Figure 4b, this indicates that regions with low V-Shale are leaking zone. Hydrocarbon entrapped along such plane with low V-Shale would simply migrate out of the trap. V-Shale analysis was carried out along the hanging wall showed high V-Shale from the base of the plane to about two-third to the top of the hanging wall plane (Figure 5c). This indicates sealing towards the base of the plane to about two-third to the top of the hanging wall plane.

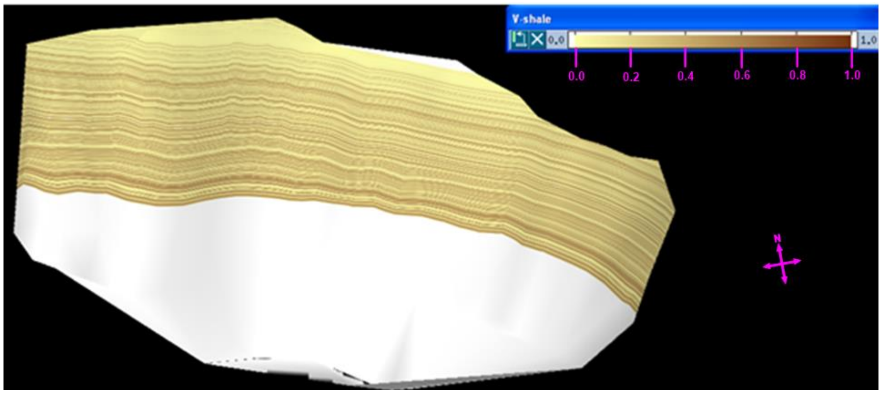

Figure 5b. 3-D of V-Shale along footwall of Taa Field

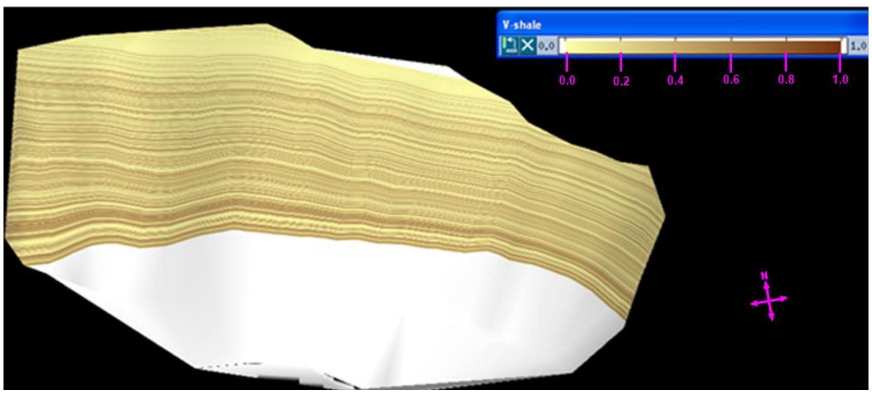

Figure 5c. 3-D of V-Shale along hanging wall of Taa Field

The throw of a fault is the generalized elevation difference between two points offset by the fault. The fault-polygons were used to produce the throw model. This is the quality control aspect of fault analysis and a very sensitive aspect because the results gotten from this stage will be integrated into Equation 1 in order to calculate the SGR of the fault plane. The initially generated fault-polygons were used to produce the unedited throw (Figure 6a) while the filtered fault-polygons were used to produce the edited throw (Figure 6b) which would be integrated in the calculations of the SGR in the study area.

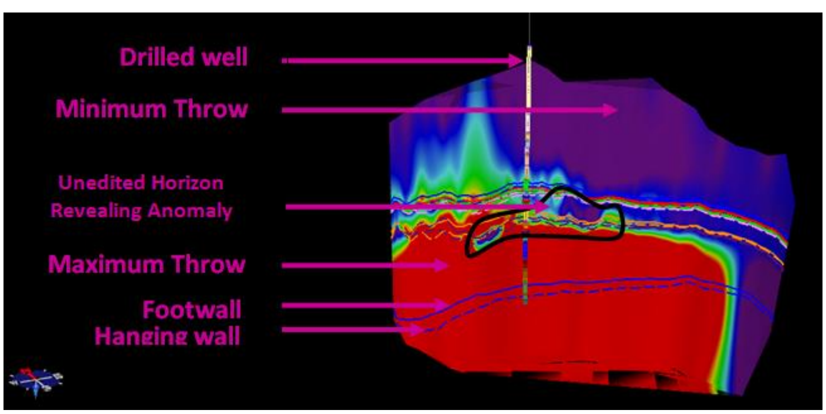

Figure 6a. Unedited throw of Taa Field

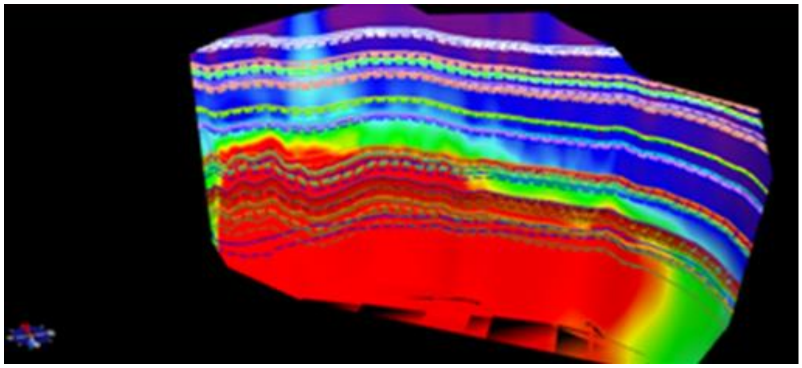

Figure 6b. Edited throw of Taa Field

The major contributor to hydro-carbons' accumulation is the hanging wall because it is the part which movement always takes place. The maximum displacement is always at the centre of the throw which is depicted by red colour. A throw that extends towards Akata formation always takes different shape apart from the generalized model because the seismic sections' resolution might not be able to image the Akata formation clearly during interpretation. The base of the Taa field started from the peak of the throw (red colour) to the minimum displacement (blue colour) at its apex. The reason is that Taa's major fault extends downward to Akata formation. Therefore, no reason-nable horizon could be mapped further after the seventh (deep) horizon due to poor resolution of the seismic section at this formation.

SGR is the net shale or clay content of the rocks that have slipped past a fault surface. It is a mathematical algorithm that tends to foretell the fault rock types for simple fault zones developed in sedimentary sequences dominated by sandstones and shales. SGR is used in exploration and production companies in order to permit quantitative predictions to be made concerning the hydrodynamic behaviour of faults. Hydrocarbon exploration involves identifica-tions of hydrocarbons' traps in the subsurface. Many times, the structures are segmented or lith by faults. In a comprehensive trap evaluation, it is paramount to foretell the leaking or sealing potential of fault supporting a trap. SGR is used to estimate the shale content of the fault zone. Generally, a fault zone with high clay content corresponds to a high SGR which could support higher capillary threshold pressures and vice versa. On a broader scale, other factors also exert a control on the threshold pressure, such as depth of rock sequence at the time of faulting, and the maximum depth of burial. As the maximum depth of burial exceeds 3km, the fault seal effective strength increases in all fault zone compositions [9].

This section's analysis adopts the SGR threshold of Sahoo *et al*. [25]. SGR less than 20 % is associated with leaking fault, SGR of 20 to 40 % is associated with poor sealing, SGR of 40 to 60 % is associated with moderate sealing, while SGR greater than 60 % is associated with sealed fault. The SGR on Figure 7a ranged from leaking (low SGR) to sealing (high SGR) fault plane. Low SGR constitutes the upper part of the fault plane of Taa field. Therefore, migration of hydrocarbon from trap is certain in this zone. However, in order to know the locations of the shallow (sand A) to the deep (sand G) horizons on Taa field, the polygons were displayed with their respective SGR on Figure 7b. It was revealed that none of the horizons is associated with the leaking fault but most of the horizons belong to the poor and moderate sealing. The implication is that SGR estimation showed that no hydrocarbon has escaped from the trap on Taa field which is general believe of fault supporting structures in Niger-Delta but gradual leakage of hydrocarbon is possible from the plane because the clay minerals in phyllosilicate are very small. Phyllosilicates are important group of minerals that include: micas, chlorite, serpentine, talc, and the clay minerals.

HCH is an important parameter in the prediction of prospect volumes. In order to provide an estimate of how competent the fault seal might be, the strength of a fault seal can be quantified in terms of subsurface pressure, arising from the buoyancy forces within the hydrocarbon column that the fault can support before it starts to leak. When dealing with a fault zone, this subsurface pressure is known as capillary threshold pressure. A fault that is developed in sandstone and shale sequence, composition is the first order control on its capillary threshold pressure, especially the content of the clay or shale in the fault surface.

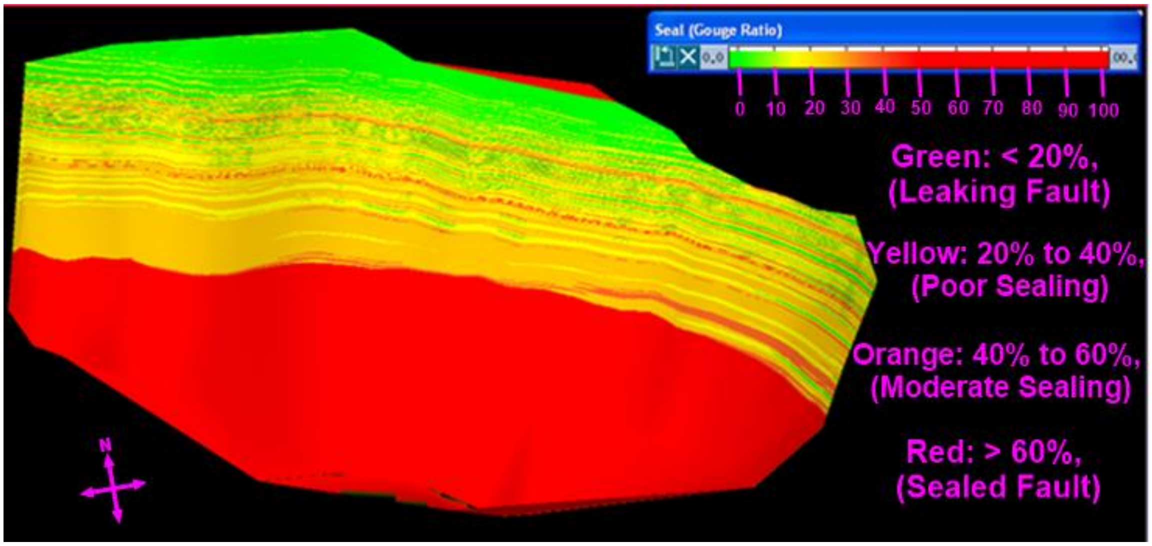

Figure 7a. SGR of Taa Field

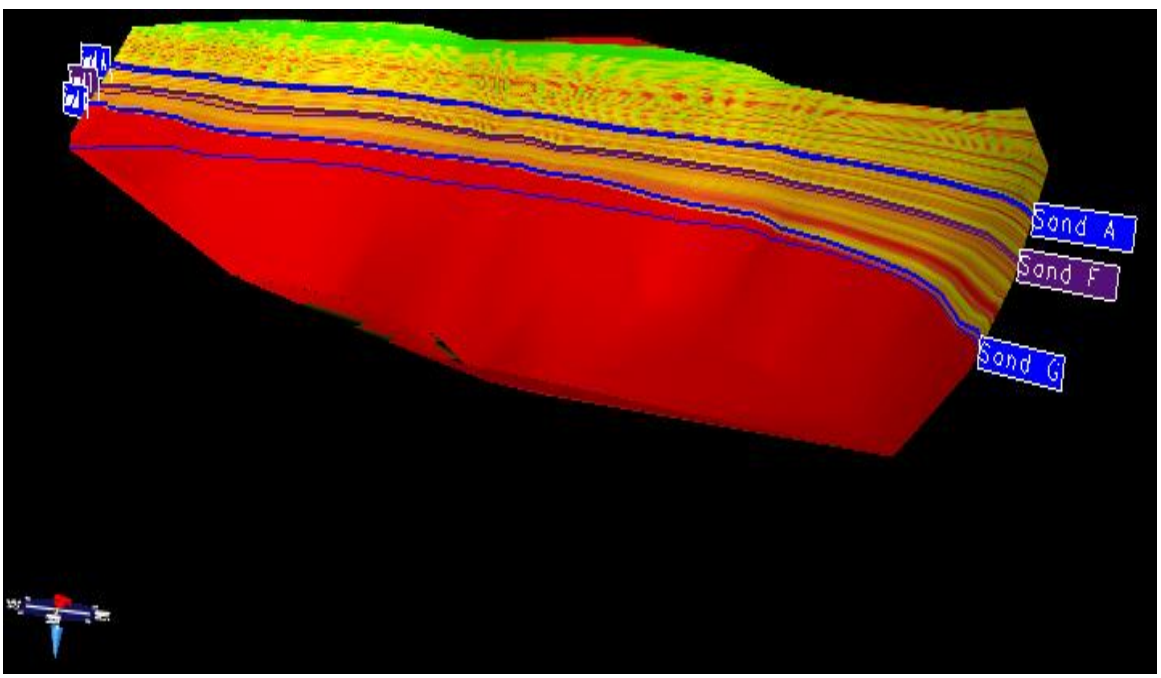

Figure 7b. SGR and some Polygons of Taa Field

Hydrocarbons' leakage along a water-wet fault zone is chiefly by capillary action. The supportable and structure-supported HCH based on the relationship between SGR and the H_{max} of the hydrocarbon column in Taa field are presented in Table 1. The supportable HCH ranged from 55.7 to 368.4 ft while the structure-supported HCH ranged from 55.7 to 123.4 ft. The difference between the supportable and the structure-supported HCH further confirmed that there are traps' leakages in Taa field. The leakages might have not been pronounced presently, but will become appreciable in the future. However, No Hydrocarbon (NH) was found on sand E and G of Taa field. This might have been the results of the migration predicted from this study.

Table 1. Supportable and structure-supported hydrocarbon column heights.

Interval	Supportable HCH (ft)	Structure-supported HCH (ft)	Δ HCH
Sand A	368.4	82.4	286.0
Sand B	185.6	80.0	105.6
Sand C	102.4	100.0	2.4
Sand D	55.7	55.7	0
Sand E	NH	NH	NH
Sand F	223.6	123.4	100.2
Sand G	NH	NH	NH

5. Conclusion

The fault attributes of Taa field have been assessed. Reservoirs' models have been used to arrive at a reasonable conclusion. The trap assessment on E (5th) and G (7th) sands showed that no hydrocarbon was present in the two reservoirs. However, hydrocarbon bearing horizons were supported by poor to moderate sealing (SGR from 20 to 40 and 40 to 60 %). It has been established that the faults supporting the traps in Taa field were not properly sealed and as such could serve as leaking zones for hydrocarbons from the traps.

Acknowledgements

The authors are grateful to Badley Geoscience Limited for creating the automated links used for the study.

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