Journal of Informatics and Mathematical Sciences
Vol. 9, No. 2, pp. 257–271, 2017
ISSN 0975-5748 (online); 0974-875X (print)
Published by RGN Publications

http://www.rgnpublications.com

Proceedings of
International Conference on Science and Sustainable Development (ICSSD)
"The Role of Science in Novel Research and Advances in Technology"
Center for Research, Innovation and Discovery, Covenant University, Nigeria
June 20-22, 2017

Research Article

Trap Analysis of "Covenant" Field in Niger Delta, Nigeria

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Abstract. The tendency to identify leaking zones is essential tool in trap assessment. Faults play an important role in creation of hydrocarbon traps. For volumetric analysis of a field to be meaningful, it is essential to analyze the faults contributing to the accumulation of hydrocarbons in a trap. These faults may be sealing or act as conduit to fluid flow. Analysis of trap is therefore carried out with the aim to reduce the uncertainties associated with hydrocarbon exploration and exploitation in Niger-Delta using "Covenant" field as a case study. The aim of the study is achieved using three dimensional seismic and well log data. Three reservoirs were mapped on the field while the fault supporting the identified trap was analyzed via throw, shale volume, shale gouge ratio, and hydrocarbon column heights attributes. The volume of shale model shows the presence of shale and sandstone formations in the fault plane. The fault-horizon's intersection (throw) model reveals that the horizons were not too deviated from where the maximum fault's displacement was noticed. The estimated shale gouge ratio of the fault on the analyzed trap reveals that the shallow sand horizon is supported by moderate sealing plane while that of mid and deep sand horizons are supported by proper sealing fault plane. The hydrocarbon column height model reveals a column height of 120 m supports the shallow sand horizon while column heights $>$ 180 m support the mid and deep sand horizons respectively. It was inferred that despite the three horizons are supported by sealing fault zone, leakage still occurs at shallow sand horizon which correspond to a moderately sealed plane from SGR.

Keywords. Trap; Fault; Seismic data; Well log data; Shale gouge ratio; Reservoirs; "Covenant" field

MSC. ???

Received: June 13, 2017 **Revised:** July 20, 2017 **Accepted:** July 26, 2017

1. Introduction

A trap can be defined as the geometric arrangement of rock (irrespective of its origin) that allows substantial subsurface accumulation of hydrocarbon (oil or gas, or both). Petroleum is produced into deepwater reservoirs through variety of traps. It has been reported by Weimer and Slatt [16] that more than half (66%) of the global deepwater fields produce petroleum from structural-stratigraphic traps, one-fourth (25%) produce from four-way closure structural traps, while the remaining fields (9%) produce solely from stratigraphic or subtle traps. Hydrocarbons migrate upwardly from the source through permeable strata, until their flow is obstructed by layers of impermeable rocks. After their route is blocked by impermeable layers, the hydrocarbons accumulate beneath the sealing body known as trap or structure. Traps are divided into structural and stratigraphic as shown in Figure 1. Structural traps are developed by tectonic forces following the deposition of the sedimentary rocks. They occur in two forms: anticlines (where the rock is bent upwardly or being folded) and faults (where the movement along a fracture or joint zone has driven an impermeable layer over a permeable one). Stratigraphic traps are developed during sediments' deposition time. These are of three forms: pinchouts, conformities, and reefs (Caldwell *et al*. [7]).

At times, structural analysis is being neglected in assessment of uncertainty associated with reservoir characterization. The role of structural interpretation in the generation of the framework for the reservoir modeling cannot be overlooked (Ajisafe and Ako [4]). Fault controls the flow of fluid in sedimentary basins. It could act as pathway for vertical migration of hydrocarbon, lateral flow of hydrocarbon, or impede hydrocarbon's flow (Irving *et al.* [10]). When seal is improperly formed by faults, it prevents accumulation of fluid as the fluids form and transmigrates through structures in the subsurface. Faults do not only control the presence of hydrocarbon in a trap, it also controls its volume as well as its distributions. However, tendency to distinguish between leaking and sealing fault is the basis of trap assessment (Adagunodo *et al.* [3]).

Fracture occurs as a result of rock response to stress. Relative movement of the two fractured rocks to each other is known as fault. Fault could be vertical, horizontal, or at an arbitrary angle in between (Adagunodo and Sunmonu [1]). Impact of fault in structural analysis is significant in that it is the house at which hydrocarbon resides. Unsealed fault prevents hydrocarbon's accumulation because a leaking fault provides communication within compartments in a fault system. Thus, fault analysis and depending solely on reservoir parameters and estimated hydrocarbon contacts can lead to extremely unequal division of reserves (Adagunodo *et al.* [2]).

Analysis of fault has been facilitated by the methods developed in the time past. These methods allow behaviour of fault in siliciclastic sequence to be more represented and quantified in geocellular reservoir models (Yielding *et al.* [19]). In recent time, algorithms such as Shale Smear Potential (SSP), Shale Smear Factor (SSF), and Shale Gouge Ratio (SGR) have been developed. The algorithms are able to provide a quantitative prediction of the amount of fine-grained (phyllosilicate) material contained within a fault zone (Irving *et al.* [10]).

Irving *et al.* (2010) reported several works on fault analysis. Other researchers that have reported such work include Allan [5], Yielding *et al.* [19], Soleng *et al.* [14], Freeman *et al.* [9], Adagunodo *et al.* [2], Adagunodo *et al.* [3]. The reservoir characterization and by-passed pay analysis' report of Sunmonu *et al.* [15] suggested hydrocarbons' exploitation at new prospect trap of Philus field since it has more pay than the discovery trap. Few reports on fault behaviour or its integrity have been presented on Niger Delta fields. The aim of this work is to analyze the fault supporting the structural trap in "Covenant" field in order to evaluate the sealing capability of this fault using automated approach. Manual generation of structural models may be wearisome especially when the quality of the seismic data is poor, or one looks forward to getting high density of sub-seismic faults with well noticeable effects on the flow. As a result of this, automated approach is required when simulating structural features (Soleng *et al.* [14]).

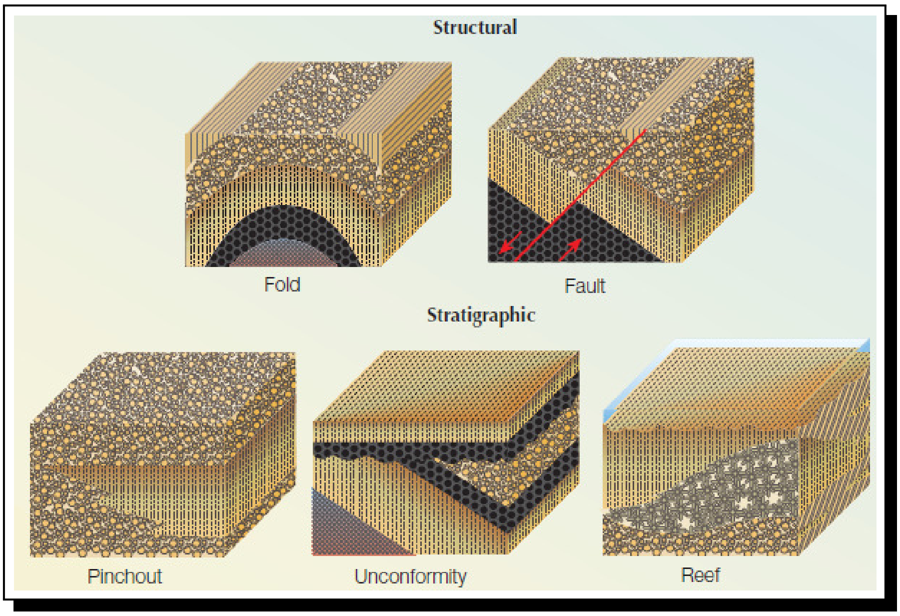

Figure 1. Types of traps (adapted from Caldwell *et al.* [7])

2. Geology of Niger Delta and the Study Area

The "Covenant" field is located in the offshore of Niger Delta, Nigeria (Figure 2). The Niger Delta basin is positioned at the top of the Gulf of Guinea on the West Coast of Africa. It is the most inventive deltaic hydrocarbon domain in the world, and extends within latitude 4° to 6° N and longitude 3° and 9° E (Ejedawe [8]). The Niger Delta is bordered on the northwest by thick outcrops of preponderant cretaceous sedimentary rocks which are defiantly resting on the immense Precambrian Basement Complex. Ajisafe and Ako [4] reported that, "a narrow step-faulted hinge zone trending Northwest-Southeast marks the transition from Niger delta Tertiary growth fault tectonics to the uniformly dipping beds of the upper Cretaceous delta".

The Niger Delta covers a distinctive offlap sequence in which the Benin, Agbada, and Akata Formations are time-equivalent, proximal to distal prograding facies' units. This progradation was influenced by synsedimentary growth faults whereby the rate of forward advance of the sandy Benin Formation was temporarily retarded when a major growth fault was activated at the delta front. The downthrown part of this active boundary fault became the new focus of Agbada rock depositions until subsidence in front of the fault was stabilized to almost sea-level. The sandstone of the Benin Formation then recommenced its rapid ocean ward approach over the newly established depobelt. Doust and Omatsola [20] reported that, "the Niger Delta Province contains only one identified petroleum system. This system is referred to as the Tertiary Niger Delta (Akata-Agbada) Petroleum System. The maximum extent of the petroleum system coincides with the boundaries of the province" (Figure 2).

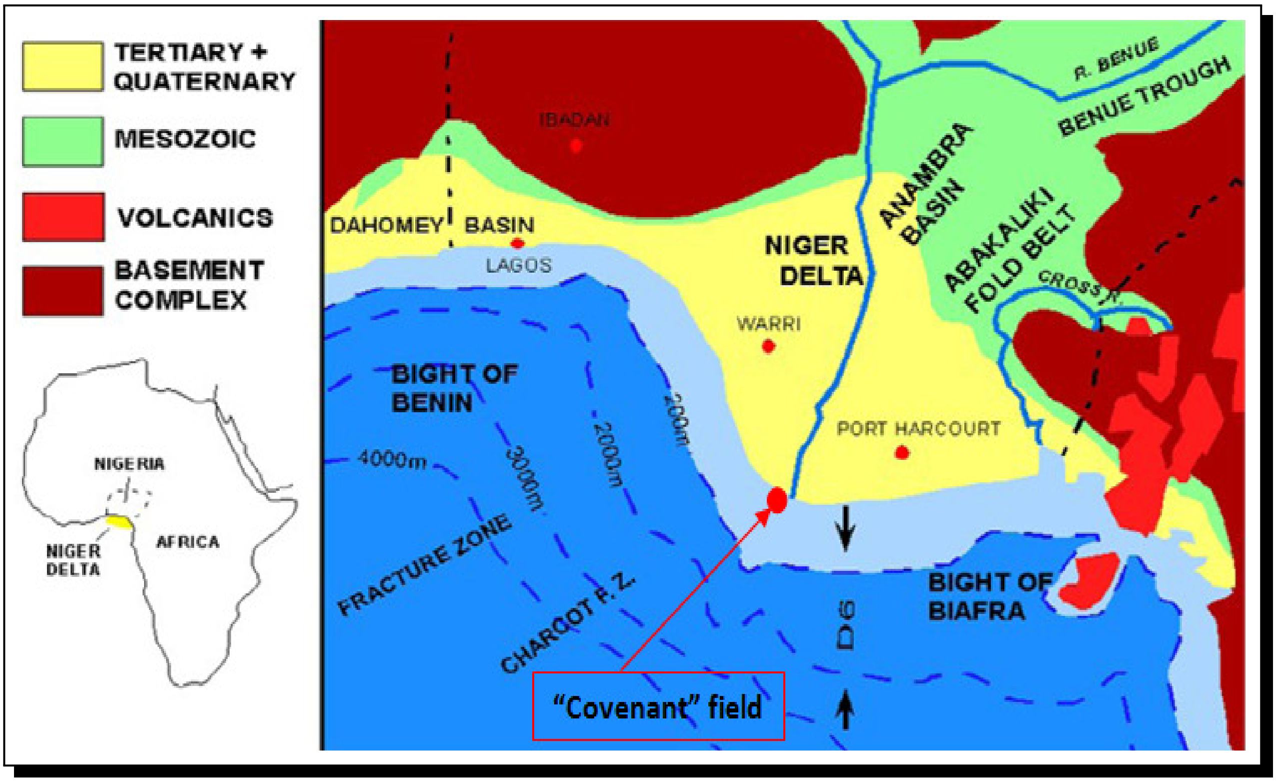

Figure 2. Niger Delta geological map (Ajisafe and Ako [4])

3. Materials and Methods

The data used comprises three-dimensional seismic (SGY format) with a total coverage of 100 km^2 and three well log (LAS format) data in order to create a clearer image of the subsurface geology. Check shot data was used to tie well log and seismic data at the reservoir of interest together as well as to convert time values to depth. Faults were identified and picked on the seismic section. Three structural maps were generated in order to visualize the possible identifiable trap(s) on "Covenant" field. The velocity model generated from the check shot data of each well was used to convert the time structure map to its respective depth structure map. Reservoirs were mapped and correlated across the wells along their corresponding horizon. The fault supporting the identified trap was analysis for its sealing capability via deterministic approach of Shale Gouge Ratio (SGR) and Hydrocarbon Column Height (HCH) as prepared by Badley Geoscience Limited [21]. The mathematical models used for this deterministic approach have been reported by Adagunodo *et al.* [2], [3].

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 "Covenant" field.

The SGR is calculated based on equation (1).

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

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).

$$H_{\max} = \frac{FZP}{g\left(\rho w - \rho h\right)}, \tag{2}$$

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

4. Results and Discussion

4.1 Well Correlation and Seismic Interpretation

Three reservoirs were correlated at shallow, mid and deep reservoirs in a flexible two-dimensional environment across the three available wells on "Covenant" field (Figure 3). The correlation panel shows the gamma ray log and resistivity log as a tool to determine the hydrocarbon presence in a reservoir. Low gamma ray implies a sandstone formation while high value of resistivity is a yardstick for determining hydrocarbon formation in a resistivity log. However, high gamma ray log implies a shale formation. The use of shale in reservoir mapping is that it acts as marker that seals the head or top and bottom of the reservoir.

Furthermore, two major faults and a minor fault were mapped in NW-SE strike orientation (Figure 4) which dips towards the south (Figure 5). The structural trap on "Covenant" field is constituted by fault. "Fault gives rise to an effective hydrocarbon traps closed by an anticlinal structure" (Sunmonu *et al.* [15]). Three horizons were mapped on the seismic section. The mapped horizons were used to generate the structural maps.

At the completion of the seismic interpretation, fault heaves were calculated and the fault polygons were generated via GeoGraphix software (Landmark [11]). Three time maps were gridded via Seisvision gridding algorithm, which were exported to Geoatlas for the structure map generation. Three depth structure maps were generated using the time structure map and check shots velocity data. The velocity model that was used to generate the depth map was based on the velocity-time relationship. Depth map generation is essential because the drillers are curious to know the depth at which the hydrocarbon could be exploited. The plot of the True Vertical Depth (TVD) against the Two-Way-Travel time (TWT) was plotted such that the models gotten from the graph is used for time-to-depth conversion. The regression analysis of the graph was done basically in order to determine the level of acceptance of the model. For the three wells, three equations gotten were: $y = -0.0007x^2 - 2.2583x - 366.97$, $y = -0.0006x^2 - 2.3957x - 301.11$, and $y = -0.0006x^2 - 2.6529x - 14.61$ with R-square of 0.9999 and 1 respectively (Figure 6a to 6c).

Three depth maps generated were presented on Figure 7a to 7c. Each map portrays the depth to the top of each reservoir. In accordance with the petroleum system of Niger-Delta, close contours (basically anticlines) represent trap for hydrocarbon accumulation. Fault dependent structure and the anticlinal structure are the points of interest that would be subjected to further analysis, hence mapping of the structural trap on the depth maps. The anticlinal structure on these maps justifies the reason for drilling the producing three wells at the structural trap of "Covenant" field bounded by the contour line of 7350 ft on shallow sand depth map (Figure 7a), 8250 ft on mid sand depth map (Figure 7b), and 8450 ft on deep sand depth map (Figure 7c). Two major faults trending in NW-SE direction were present on the shallow depth map (Figure 7a). Syncline and a minor fault were the added features on the mid and deep sand depth maps respectively. These features might be due to the depth variations in each horizon. The structural analysis would further be carried out on the fault dependent structure (structural trap) of "Covenant" field in order to ascertain the sealing potential of the fault.

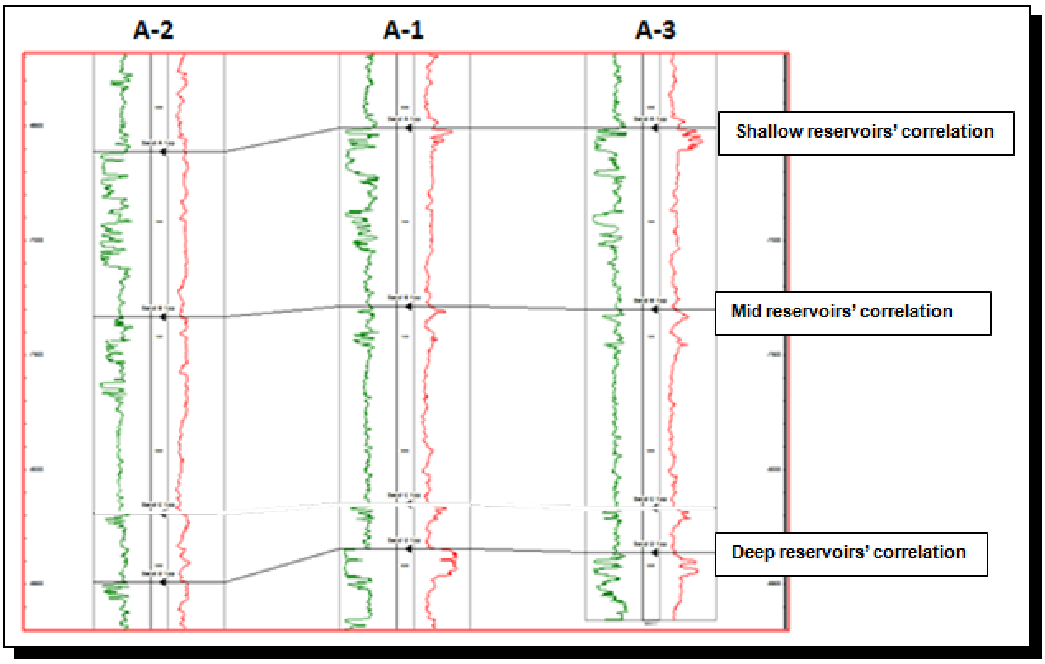

Figure 3. A flexible two-dimensional well log correlation panel of "Covenant" field

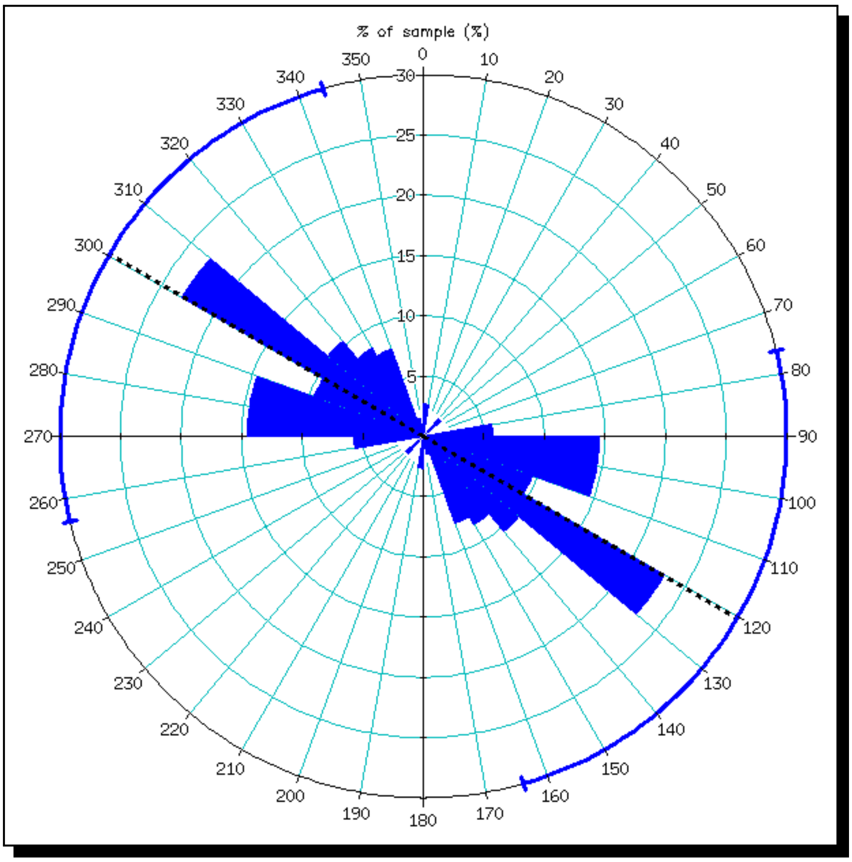

Figure 4. Fault orientation plot of "Covenant" field which strikes in NW-SE direction

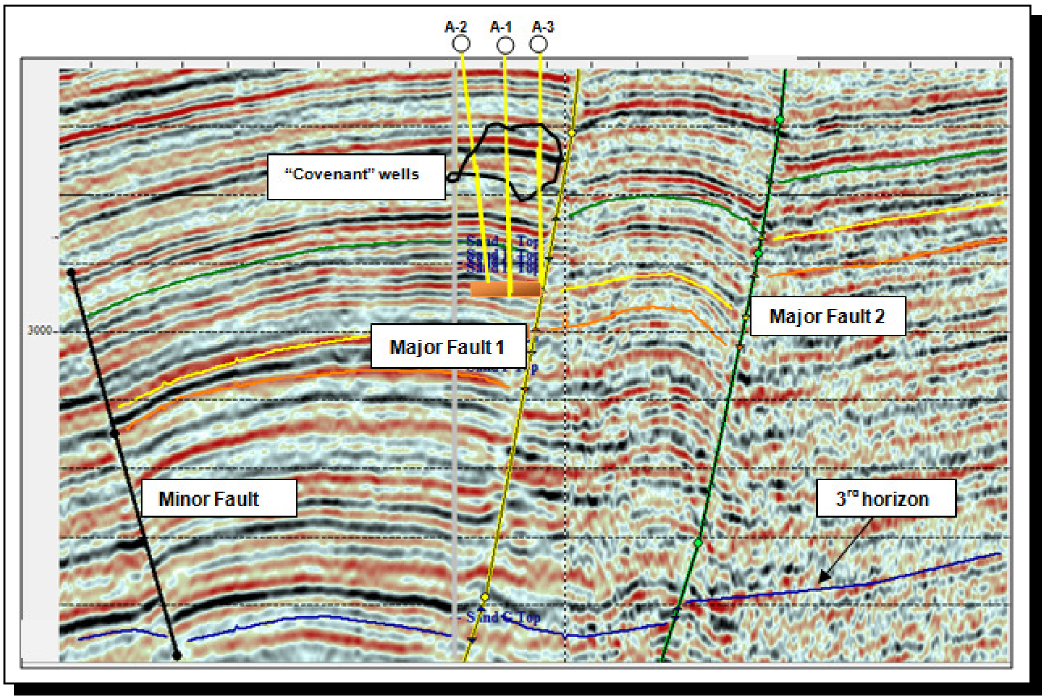

Figure 5. Interpreted horizon of inline 10926

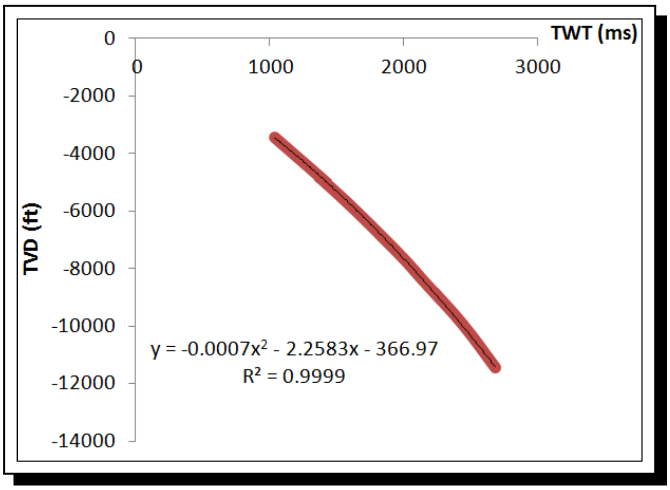

Figure 6a. Velocity plot of "Covenant" field-well 1

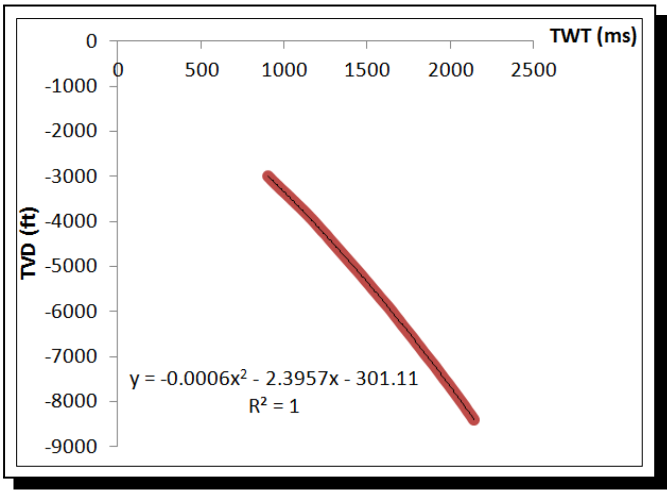

Figure 6b. Velocity plot of "Covenant" field-well 2

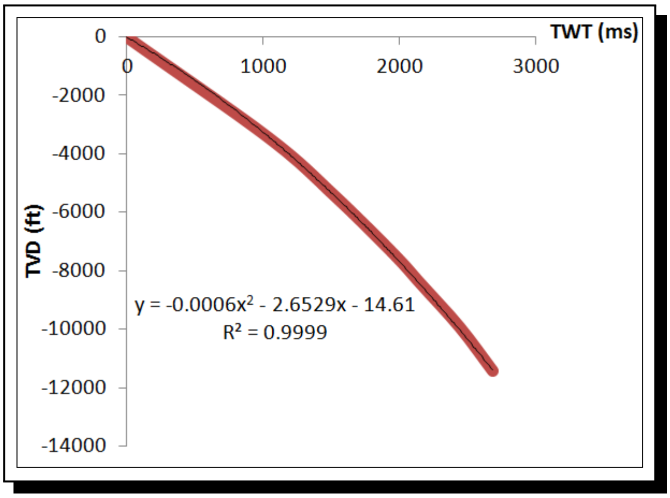

Figure 6c. Velocity plot of "Covenant" field-well 3

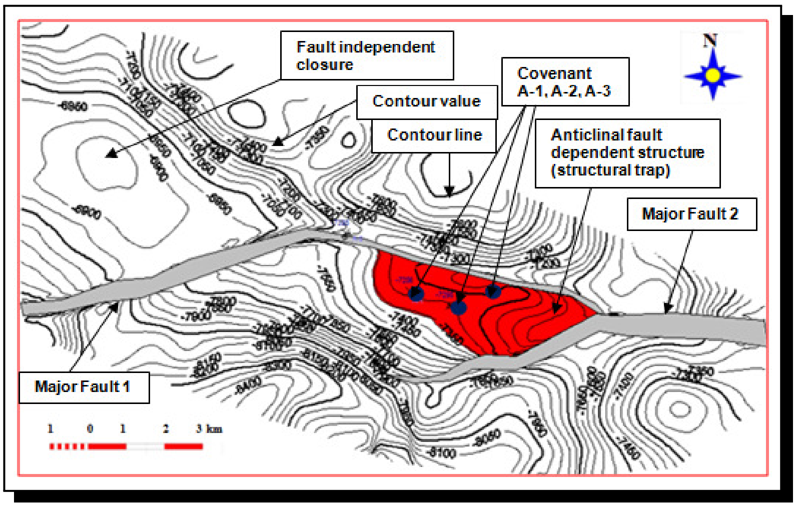

Figure 7a. Shallow sand depth map

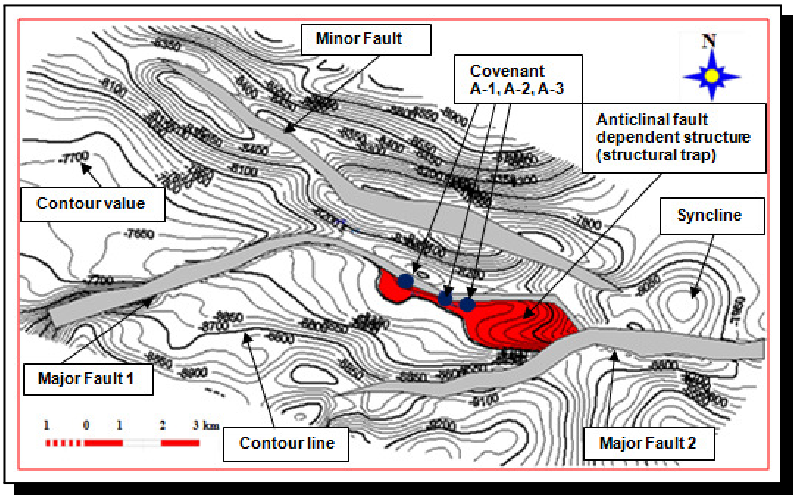

Figure 7b. Mid sand depth map

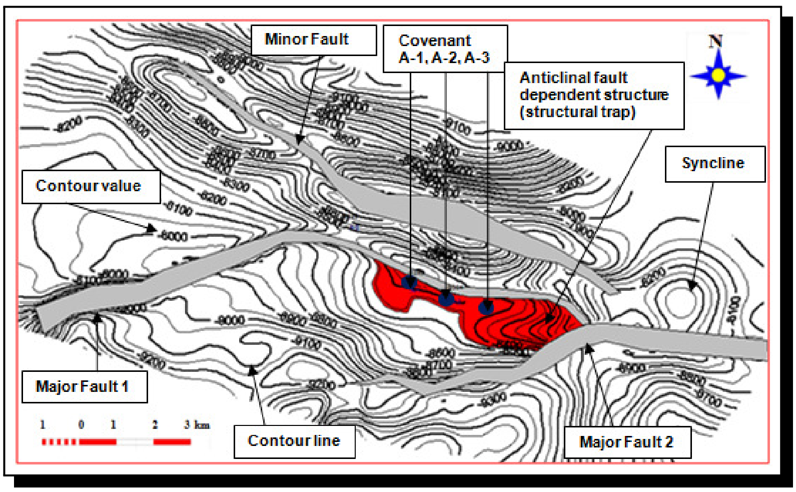

Figure 7c. Deep sand depth map

5. Structural Analysis

Framework model refers to a steady 3-D set of intersecting fault with its respective horizons. Fault and horizon's interpretations were used to build the structural model. The fault segments were automatically modeled into a three-dimensional fault surface. Faults' intersections were created in order to establish a 3-D relationship between the master and the splay faults so as to produce a fault network of "Covenant" field. The structural model of the study area was presented on Figure 8. The model revealed a 3-D display of the two major faults and the three horizons mapped on "Covenant" field. In order to confirm the status of the fault supporting the trap on "Covenant" field, fault attributes which involve generation of Volume of Shale (Vshale), SGR and HCH models were established. The 3-D model of Vshale on Figure 9 was derived from gamma ray log. The major assumption of using Vshale as reported by Rider (2000) is that, "sand and shale material are incorporated into the fault, fault gouge in the same proportions as they occur in the wall rocks of the slipped interval". Vshale scale ranges between 0 and 1 such that Vshale ≥ 0.4 composed of shale formation (which are rated as a sealed plane) while those < 0.4 are composed of sand formation and could be leakage in the trapped hydrocarbon in such plane (Adagunodo *et al*. [2, 3]). The Vshale model revealed that the middle of the plane is sealed while a leaking plane is suspected at the top and bottom of the plane (Figure 9). It was revealed on Figure 9 that the Vshale of the three horizons ranged from shale to sandstone formations. The quality control of the analysis was done by assessing and editing the fault-polygons. The edited fault-polygons were used to model the elevation difference of the fault which is known as throw. This is one of the sensitive stage in the fault attributes' estimation because the established results from this stage would be incorporated in the SGR analysis. In order to avoid recurring error, it is essential to edit the throw before proceeding to the next stage of fault attributes. From Figure 10, the minimum displacement of the throw is indicated by blue colour while the maximum is indicated by red colour with the scale ranging from 0 to 378. Fault throw analysis is an effective method to check the quality of the intersection model. The three seismically mapped horizons (solid lines for footwalls and dashed lines for hanging walls) were displayed on the strike view of the modeled throw in order to correlate the throw attributes of each horizon.

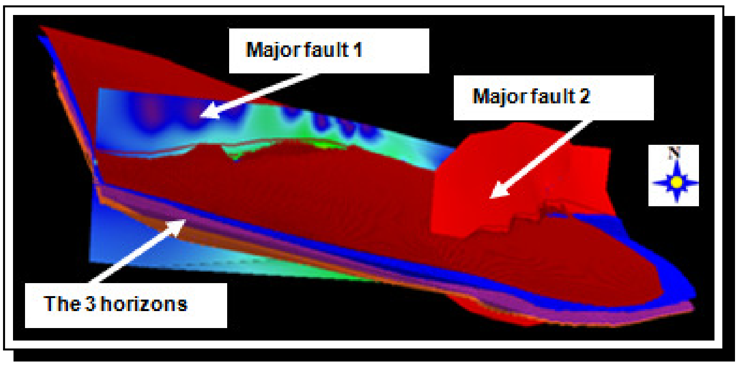

Figure 8. Structural model of "Covenant" field

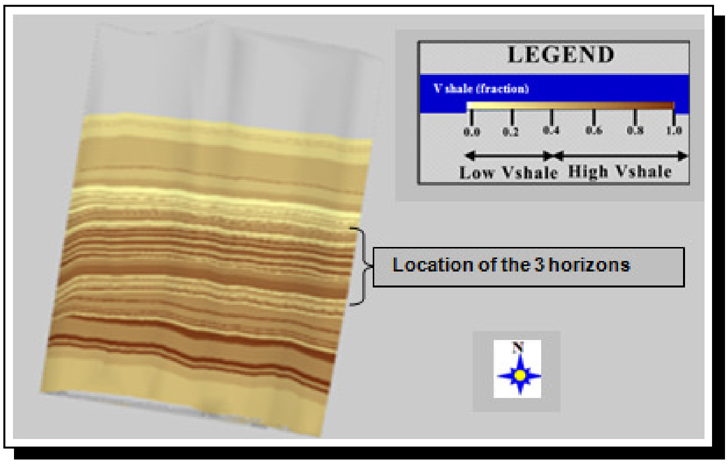

Figure 9. Vshale model of "Covenant" field

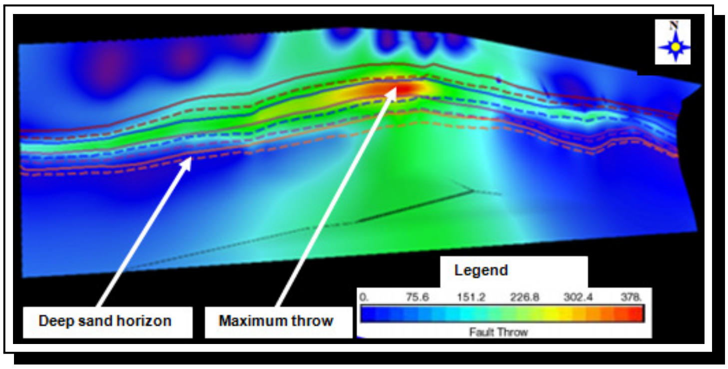

Figure 10. Fault throw of "Covenant" field

The "Covenant" field SGR was estimated based on the models from bed thickness, Vshale and the throw distribution across the fault plane based on Equation (1). SGR is the percentage of clay or shale content in the slipped interval. It is used in oil and gas settings to predict quantitatively the hydrodynamics behaviour of faults. In another words, it is used to estimate the content of shale in a fault plane. The standard SGR algorithm (Yielding *et al.* [18]; Yielding [19]) was used to estimate the fault rock shale content. "In a comprehensive trap evaluation, it is paramount to foretell the sealing potential on the fault supporting such trap" (Adagunodo *et al.* [3]). Figure 11 shows the SGR of "Covenant" field which ranged from 0 to 100%. Taditionally, a fault plane with high clay content corresponds to a high SGR which is viable to support higher capillary threshold pressure. SGR < 20% correspond to a a leaking fault, while those > 20% correspond to a sealing fault. Sealing a further are subdivided into three viz: 20 to 40% correspond to poor sealing, 40 to 60% correspond to moderate sealing > 60% correspond to proper sealing (Sahoo *et al.* [13]; Adagunodo *et al.* [2]; Adagunodo *et al.* [3]). The SGR mechanism shown on Figure 11 revealed that the horizons are supported by moderate and proper sealing fault. Shallow horizon is on moderate sealing plane while the mid and deep horizons are on properly sealing fault plane.

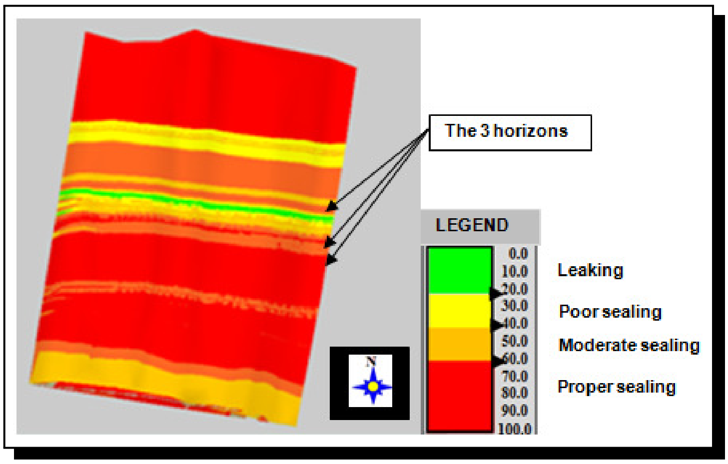

Figure 11. Shale gouge ration of the "Covenant" field

A major step to predict HCH is the transformation of the shale content of the fault zone, as estimated from SGR algorithm, to threshold capillary pressure" (Bretan [6]). It is a crucial parameter when predicting the prospect volume. For meaningful HCH predictions, all faults contributing to hydrocarbon sealing must be analyzed as one coherent structural element. As the capillary threshold pressure of the fault zone material which has been estimated through SGR varies in strike and dip, HCH analysis will converge on a single point, which represents the weakest point on the fault seal (Bretan [6]).

Equation (2) was used to estimate the HCH of "Covenant" field. The relationship between the SGR and the threshold pressure has been presented by Adagunodo *et al.* [2]. In HCH analysis, at any point on the sealing interface, if the buoyancy pressure is less than the capillary threshold pressure, the buoyancy force would be insufficient to overcome the capillary threshold pressure, the seal remains undefiled. When the two pressures are equal, the trap becomes saturated to its sustainable maximum column height (h_{max}). Furthermore, if the buoyancy pressure becomes greater than the capillary threshold pressure, the buoyancy is able to overcome the surface tension and force hydrocarbon through the pore-throat. Flow through the seal is initiated and is then controlled by permeability in the seal lithology which is governed by Darcy's law. As the hydrocarbon begins to leak, the column height will decrease and so will the buoyancy of the column. Note that the capillary seal maintains its structural integrity when it leaks-fluid is forced through intact rock and no fracturing occurs (Yielding [19]).

Figure 12 shows a 3-D model of HCH of "Covenant" field which ranged from 0 to 200 m. The weakest of short column height corresponds to a red colour while the tallest column height corresponds to purple colour. Column height of 120 m supports the shallow sand horizon while column heights >180 m support the mid and deep sand horizons respectively. It was inferred that despite the three horizons are supported by sealing fault zone, leakage still occurs at shallow sand horizon which correspond to a moderately sealed plane from SGR.

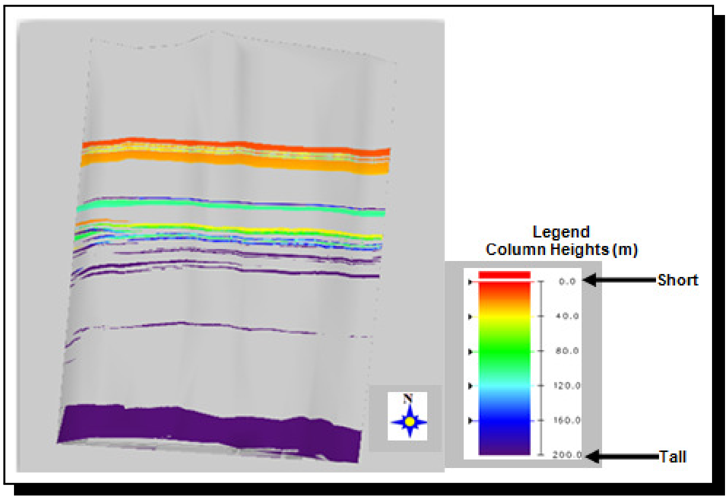

Figure 12. Hydrocarbon column height of "Covenant" field

6. Conclusion

The analysis of derived fault-surface attributes in a single 3-D geometrical model of the faulted subsurface in "Covenant" field has been established. The approach in another word which is regarded a "Trap Analysis" has been able to determine the sealing potential of the structural trap in the study area. The chief-automated analysis from SGR and HCH suggest hydrocarbon leakage at shallow sand horizon while the mid and deep sand horizons' fault are properly sealed and suggest no leakage.

Acknowledgement

The support received from the management of Covenant University, Ota, Ogun State, Nigeria is highly appreciated. The reviewer's contribution in order to improve the quality of this work is also appreciated. Also, the authors from Covenant University thank the management of Covenant University for allowing this collaborative work with a view to actualizing vision 10:2022.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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