Petrophysical Analysis of Open-Hole Geophysical Logs Acquired In Bosso Field, Offshore Niger Delta Basin, Nigeria

Christopher Imoukhai Unuevho[1], Lewis Uchechukwu Nwokorie[2],
Emmanuel Emeka Udensi[2]

[1]Deartment of Geology, Federal University of Technology,Minna, Nigeria
[2] Deartment of Physics, Federal University of Technology,Minna, Nigeria
Corresponding Author: Christopher Imoukhai Unuevho

Abstract: *Shaly sands constitute hydrocarbon reservoirs in Bosso Field of Niger Delta basin. Its In-house petrophysical estimations based correction for shaliness effect on linear estimation of reservoirs' shale content (V_{Sh}) from gamma ray logs. The approach often results in wrong estimates of hydrocarbon saturation (S_h), bulk hydrocarbon volume per unit reservoir volume (BVH) and hydrocarbon reserve. Since Niger Delta basin consists of Tertiary sediments, this work employed Larinov's empirical formula for correcting shaliness effect in Tertiary sandstones, and thereafter estimated S_h using Indonessian formula for shaly sands. The petrophysical estimations were performed using Geographix® Discovery™ 5000.0.0.0. The data employed comprise gamma ray log, resistivity log, neutron and density porosity logs obtained in six wells (BO-1, BO-2, BO-4, BO-5, BO-6, BO-7). The wells penetrated Benin and Agbada Formations. Three hydrocarbon sands (Sands A, B, C) were identified within the Agbada Formation. V_{Sh} values range from 0.03 to 0.200. Sand B's V_{Sh} is 0.03 in BO-6 and 0.038 in BO-5, indicating that the sand is clean. The sand's net-to-gross pay ratio is 1.00 in BO-6 and 0.956 in BO-5. Effective porosity (Φ_e) ranges from 0.164 to 0.253, with Sand B having the highest Φ_e of 0.253. S_h ranges from 0.620 to 0.773 in the field. BVH values range from 69.09 to 591.21. The petrophysical attributes of each of the reservoirs vary spatially in the field. Sands A and B have better petrophysical attributes than Sand C.*

I.Introduction

Petrophysical analysis of hydrocarbon reservoir sands penetrated in a petroleum field is an integral part of the field's economic assessment exercise. It entails delineation of the geological formation associated with hydrocarbon accumulation in the field, identification of hydrocarbon reservoirs and fluid type, determination of fluid contacts; as well as estimation of effective porosity, water saturation, hydrocarbon saturation, and hydrocarbon volume per unit reservoir volume. The generated information is employed in post-discovery review seismic mapping to locate appraisal wells for ascertaining extent of the penetrated reservoirs and estimating the reserve. Uncorrected shaliness effect often results in overestimated water saturation, and this masks potential hydrocarbon bearing zones [1, 2, 3]. Shaliness effect correction was earlier performed in Bosso Field by estimating reservoirs' shale volume linearly from gamma ray log. This has been the preferred approach for effecting shaliness correction [4, 1, 5]. The approach often results in overestimation of reservoirs' shale volume and thereby exaggerates undesirable reservoir attributes [6, 7]. It ultimately results in wrong estimates of hydrocarbon saturation (S_h)and its associated derivatives such as bulk hydrocarbon volume per unit reservoir volume (BVH) and hydrocarbon reserves.

The field is located within western shallow offshore of the Niger Delta basin in Nigeria (figure 1).

Previous published work in this part of the Niger Delta basin focused on seismic interpretation, paleoenvironment reconstruction and taxonomy [8, 9, 10, 11]. [12] employed wireline logs to investigate petrophysical properties of Yammne Formation in the Middle East. Their log estimated porosity values compare well with the values obtained from analysis of core samples. [13] employed Larinov, 1969's shale correction formula for Tertiary rocks to estimate shale volume contained in hydrocarbon reservoir sands in Lona Field in offshore depobelt of the Niger Delta basin.
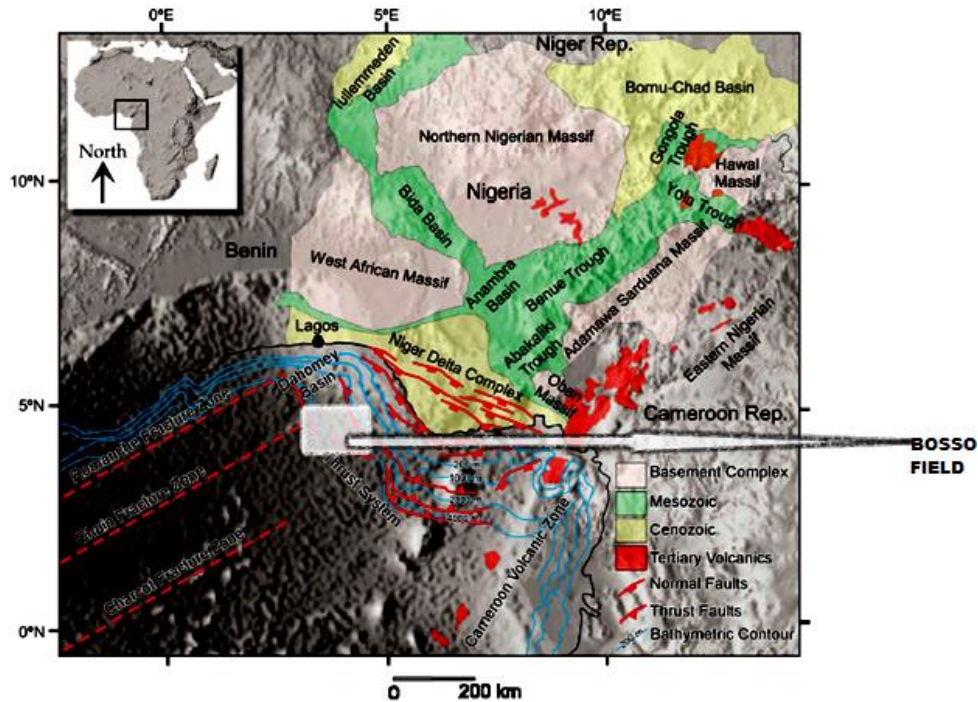

Figure 1: Location of Bosso Field within Niger Delta basin in Nigeria
(Modified after [7])

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II. Geological Overview

Intra continental Cretaceous extensional processes were responsible for the origin and evolution of the Niger Delta basin. Akata Formation, Agbada Formation, and Benin Formation are the three formal lithostratigraphic units that constitute the basin's sedimentary fill. The basin's basal formation is the Akata Formation. The sediments of the Akata Formation were deposited in shelf to bathyal environments. It is overlain by Agbada Formation, which is constituted by alternation of sandstones, siltstones, mudstones and shales deposited in inner neritic environments. But it also contains littoral, middle neritic, outer neritic and bathyal sediments. Most of the hydrocarbon reservoir sands are contained in the Agbada Formation. The uppermost lithostratigraphic unit is Benin Formation, constituted by fresh water bearing massive continental sands and gravels deposited in upper deltaic plain environment

III. Software, Data And Methodology Employed

Software employed are Geographix® Discovery™ 5000.0.0.0. and *Microsoft Paint.* The open-hole geophysical logs utilised comprise gamma ray log, deep resistivity log, density and induction porosity logs. The logs were acquired in six wells, namely BO-1, BO-2, BO-3, BO-4, BO-5 and BO-6.

The study was anchored in the *Geographix Discovery* software's data base by setting it up in the form of a project. The wells' geographic coordinates, measurement datum, well top and bottom depths were fed into software's data base. The values of the log content were fed into the data base using the *Prizm* menu. The gamma ray and resistivity logs' framework was created in the well section menu. Lithology was added to well tracks from Prizm menu, using log template properties based on American Petroleum Institute (API) units for gamma ray (GR) values. The value 50 API unit was taken as the upper limit for Sand line. The base of the Benin Formation (or top of Agbada Formation) was identified and correlated on the basis of shale thickness and resistivity values. Hydrocarbon reservoir sands were identified as sands characterised by low gamma ray values and high resistivity values within Agbada Formation. Porosity logs were unavailable for wells BO-1 and BO-3. This constrained numerical petrophysical estimations to be confined to wells BO-2, BO-4, BO-5 and BO-6. The petrophysical estimations comprise effective porosity (ϕ_e), water saturation (S_W), hydrocarbon saturation (S_h), bulk hydrocarbon volume per unit reservoir volume (BVH), gross pay, and net pay, net-to- gross pay ratio.
First step in estimation of V_{sh} was determination of GR shale index(I_{GR}) as follows:

$$I_{GR} = \frac{GR - GR_{CN}}{GR_{SH} - GR_{CN}} \ldots\ldots\text{Equation 1} ^{[7, 14, 15,]}$$

where GR is gamma ray log reading in zone of interest, GR_{CN} is gamma ray log response in clean (shale free) sand, and GR_{SH} is highest gamma ray reading for shale.

V_{sh} was then obtained from I_{GR} using V_{sh} - I_{GR} empirical relationship for Tertiary sandstone reservoirs:

$$V_{sh} = 0.083(23.7 *{}^{I}_{GR}{}^{-1})$$ ------------ Equation 2 [7, 14, 15].

Equations 3 and 4 respectively were employed to estimate apparent porosity (ϕ_a) and effective porosity (ϕ_e):

$$\Phi_a = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$ ....Equation 3 [16, 17, 18]

Where $\rho_{ma}(2.65 gm/cm^3)$ is bulk density of matrix material, ρ_b is reservoir bulk density obtained from bulk density log and ρ_f is mud filtrate density($1.1 gm/cm^3$).

$$\Phi_e = \Phi_a *(1- V_{sh})$$ ----- Equation 4 [12, 16]

Water saturation (S_W) was estimated using Indonesian method:

$$S_w = \left\{ \left[\left(\frac{V_{sh}^{2-V_{sh}}}{R_{sh}} \right) + \left(\frac{\Phi_e^m}{R_w} \right)^{1/2} \right]^2 R_t \right\}^{-1/n}$$ .... Equation 5;

where R_{sh} is shale resistivity, R_w is resistivity of water zone, R_t is deep resistivity of hydrocarbon reservoir pay, n is saturation exponent and m is cementation factor. R_w was obtained as follows:

$$R_w = \frac{R_o}{0.62} \phi_e^{2.15}$$ ....Equation 6 [7, 19, 20]. R_o is the deep resistivity log reading in 100% water-filled reservoir.

Hydrocarbon saturation (S_h) was obtained as follows:

$$S_h = 1- S_w$$ ......Equation 7 [5]

Bulk hydrocarbon volume per unit reservoir volume (BVH) was estimated using :

$$BVH = \phi_e S_h$$ ....Equation 8 5. [21,]

Equations 1 to 7 were defined in petrophysics algorithm in 'PRIZM' of *Geographix5000* software and then run. The algorithm generates values for the 'subject of the formula' in the equation, in addition to automatically calculating N/G pay.

IV. Results
Figure 2 shows lithostratigraphic differentiation of the penetrated lithologic fill into Benin Formation and Agbada Formation. The shallower part of the wells is dominantly sand, while the lower part is dominated by frequent intercalation of sand and shale. Three hydrocarbon reservoir sands (sand A, sand B and sand C) were penetrated in the field. The subsurface intervals occupied by the sands in the wells are shown in figure 3. Well BO-2 penetrated hydrocarbon reservoir sands A and B only. Wells BO-1, BO-4, BO-5, BO-6 and BO-7 penetrated the hydrocarbon reservoir sands A, B and C. All the sands were barren of hydrocarbon in wells BO-2 and BO-7.

The summary of the petrophysical estimation results is presented as table 1. Graphical illustration of the pay zones within hydrocarbon reservoir sands A, B, C penetrated in well BO-5 are figures 4, 5 and 6. Pay zones within hydrocarbon reservoir sand penetrated in well BO-4 are shown in figure 7. Figure 8 is a graphical illustration of pay zones within hydrocarbon reservoir sand B penetrated in well BO-6.
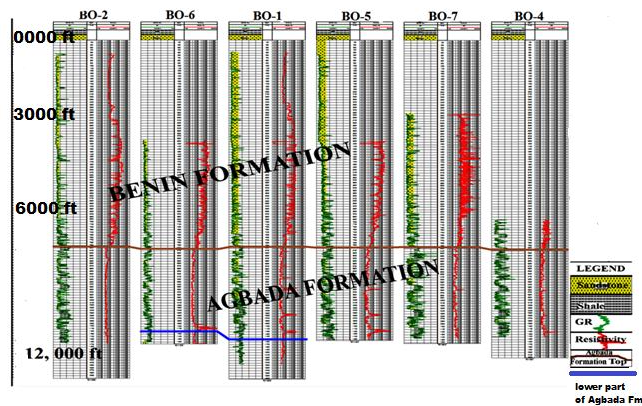

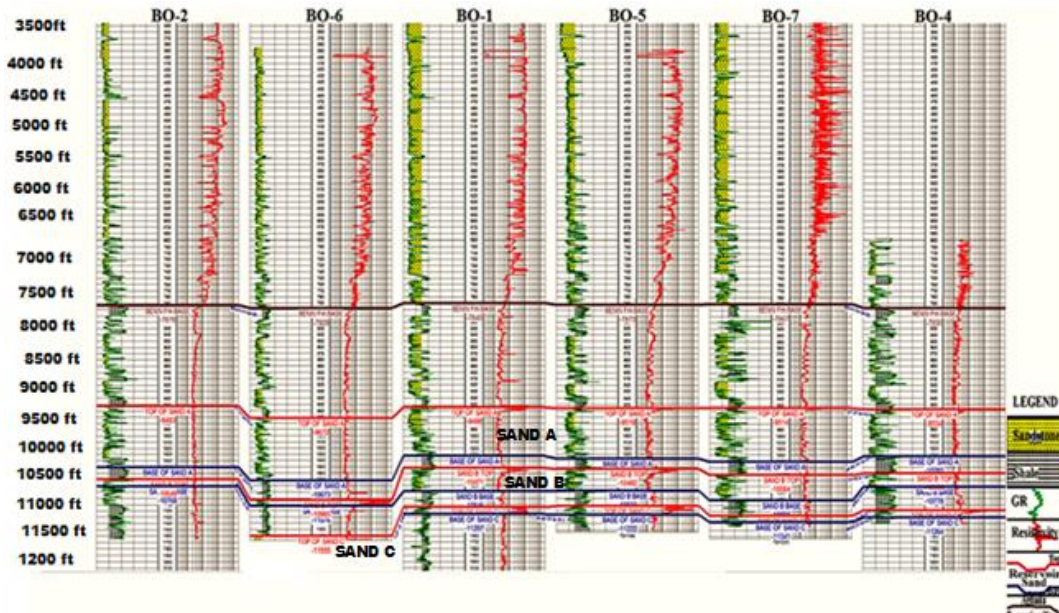**Figure 2:** Differentiation of penetrated lithologic fill into Benin Formation and Agbada Formation

Figure 3: Subsurface intervals occupied by the sands in the wells

Table 1: Summary of Petrophysical estimations

WELL BVH	RESERVOIR	GROSS PAY Thickness in Ft	NET PAY Thickness in Ft	N/G PAY	V_{SH}	Φ_e	S_h
BO-4 69.09	SAND C	103.50	97.99	0.947	0.200	0.206	0.705
BO-5 501.21	SAND A	783.96	702.96	0.897	0.124	0.236	0.713
BO-5 199.76	SAND B	337.20	322.20	0.956	0.038	0.176	0.620
BO-5 149.98	SAND C	235.40	202.40	0.860	0.152	0.164	0.741
BO-6 0.773	SAND B 69.80	90.30	90.30	1.000	0.030	0.253

Key: N/G PAY, V_{Sh}, Φ_e, S_h BVH respectively represents ratio of net pay to gross pay, amount of shale content within reservoir, reservoir's effective porosity, reservoir's hydrocarbon saturation and bulk hydrocarbon
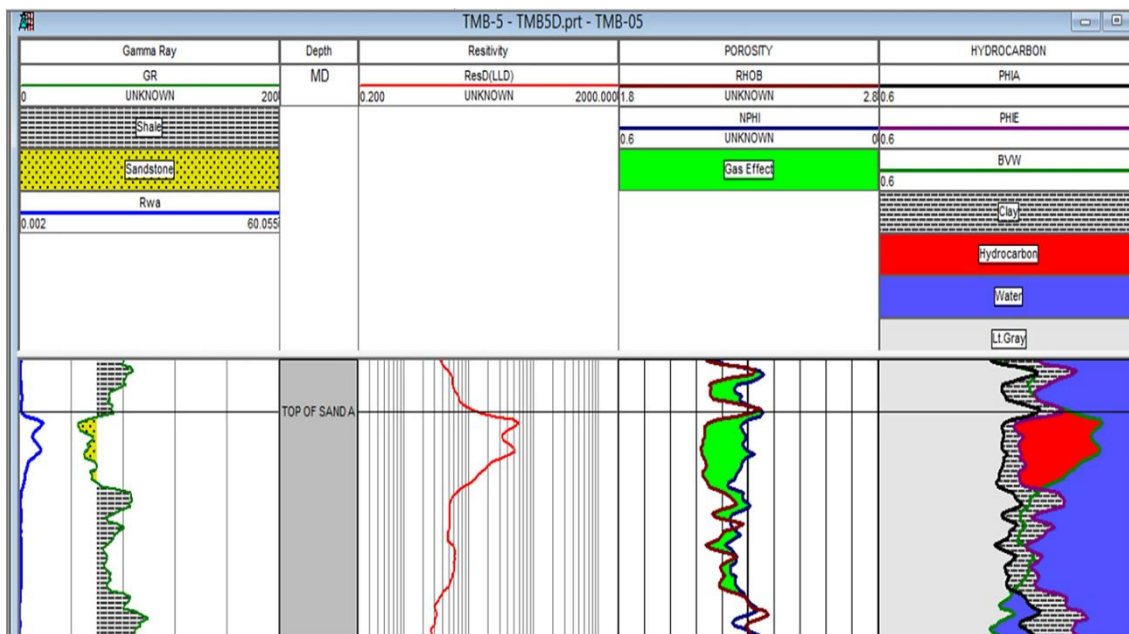   per unit reservoir volume

Figure 4: Pay zones in hydrocarbon reservoir sand A penetrated in well BO-5
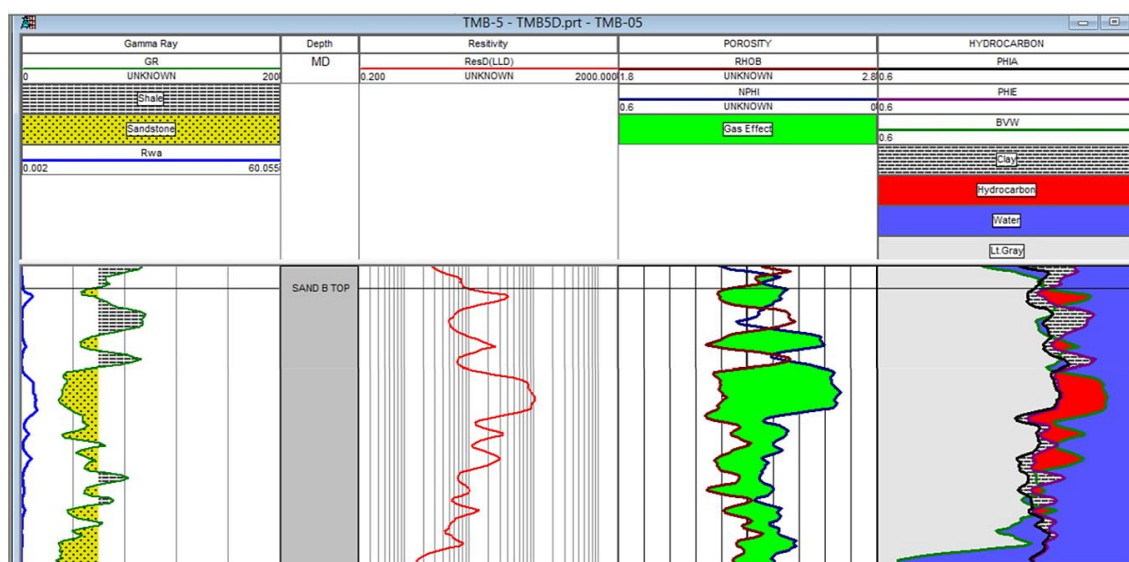

Figure 5: Pay zones in hydrocarbon reservoir sand B penetrated in well BO-5
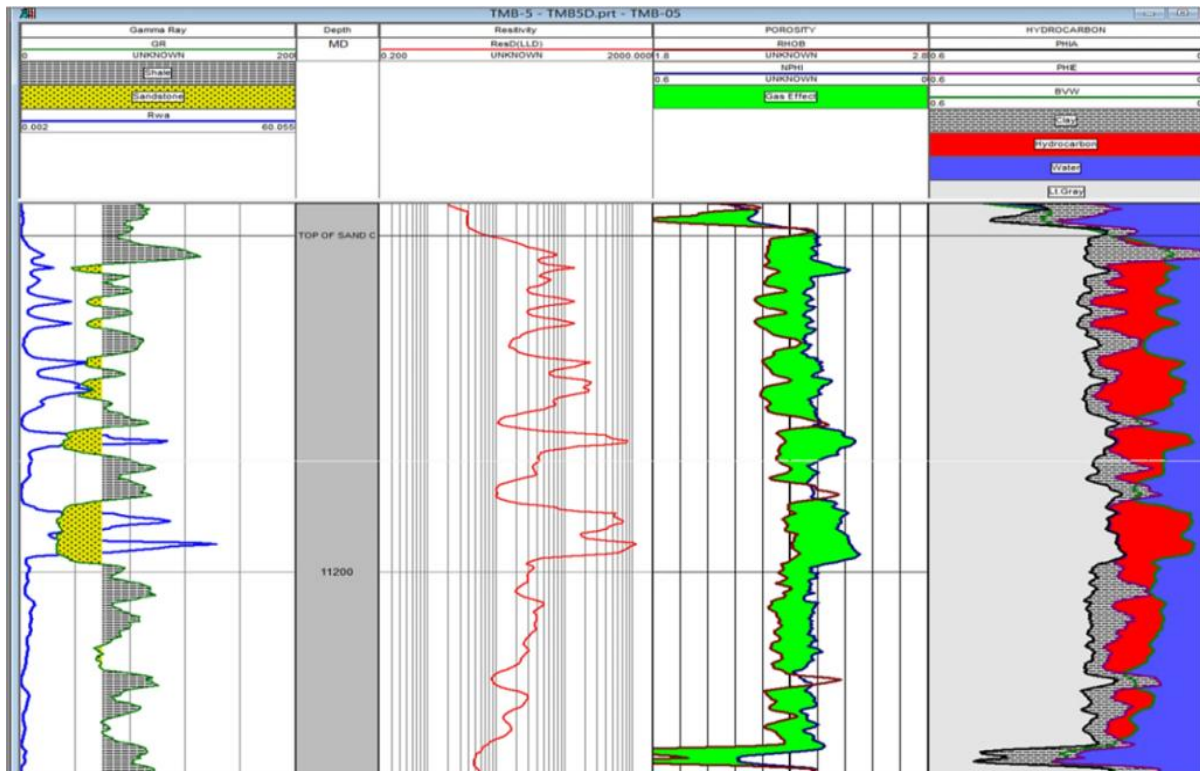
Figure 6: Pay zones in hydrocarbon reservoir sand C penetrated in well BO-5
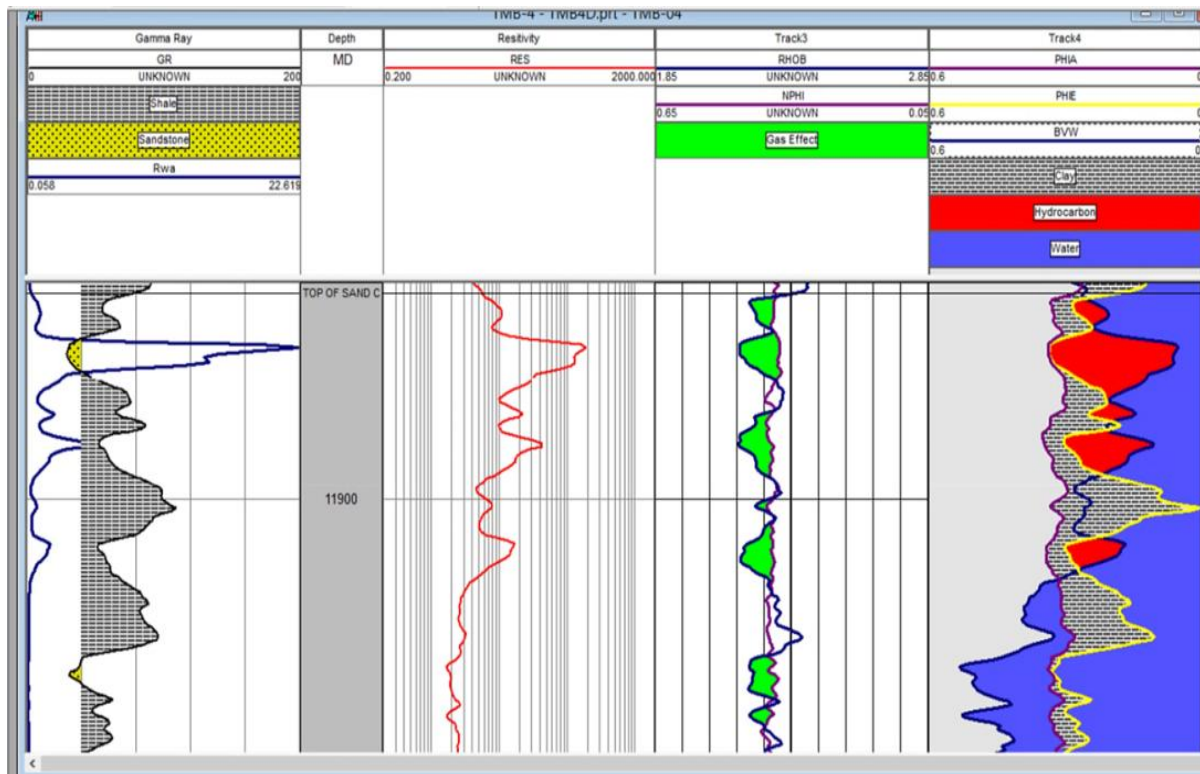

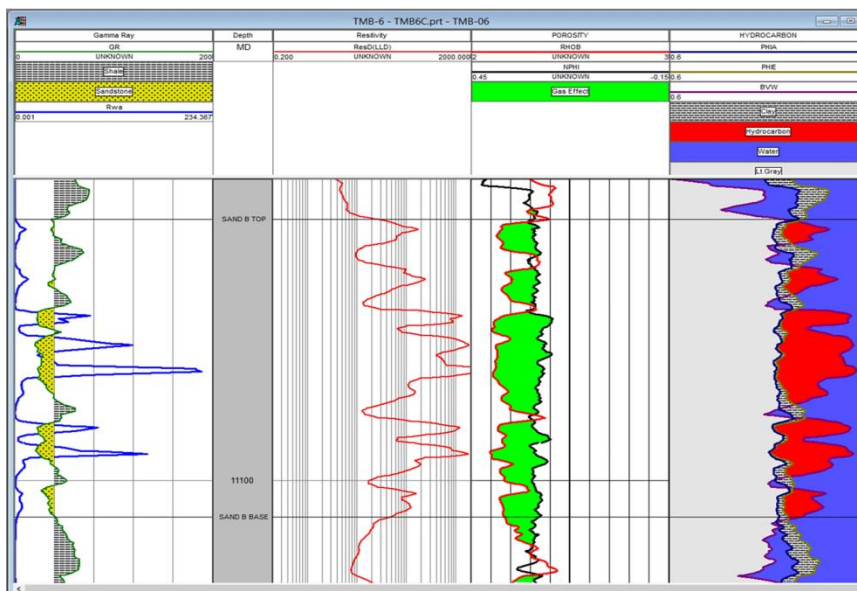**Figure 7:** Pay zones in hydrocarbon reservoir sand C penetrated in well BO-4

Figure 8: Pay zones in hydrocarbon reservoir sand B penetrated in well BO-6

V. Discussion

Table 1 reveals that V_{Sh} ranges from 0.03 to 0.200. V_{Sh} for Sand B is 0.03 in BO-6 and 0.038 in BO-5. This implies that the sand is very clean. The net-to-gross pay ratio for Sand B is 1.00 in BO-6 and 0.956 in BO-5. V_{Sh} for Sand C is 0.152 in BO-5, while its net-to-gross pay ratio is 0.860. In the same well, V_{Sh} for Sand A is 0.124, while its net-to-gross pay ratio is 0.897. Φ_e ranges from 0.164 to 0.253. Sand B in BO-6 has the highest value of Φ_e (0.253). Φ_e value for Sand B is low (0.176) in BO-5. Sand C also possesses different values of Φ_e at different well-sites. Its Φ_e value is 0.104 at BO-5 and 0.206 at BO-4. S_h values ranges from 0.620 to 0.773. Value of S_h for Sand B is highest (0.773) in BO-6 and lowest (0.62) in BO-5. Its BVH value is 199.76 in BO-5 and 69.80 in BO-6. Similarly, values of S_h and BVM are different for the same sand at different well-sites. Thus the petrophysical attributes of the same reservoir sand do vary spatially in Bosso Field.

Sand A in BO-5 has the highest value of estimated BVH (501.2). Its hydrocarbon saturation is 0.713, net pay thickness is 702.10, and net-to-gross pay ratio is 0.897. Though it contains hydrocarbon only in BO-5, it possesses very good petrophysical attributes. Sand C in BO-4 has the lowest bulk hydrocarbon volume per unit reservoir volume (69.09), the least net pay thickness (90.3) in BO-6, and the poorest petrophysical attributes in Bosso Field.

VI. Conclusions

Three hydrocarbon reservoir sands were identified within Agbada Formation from the suite of gamma ray, resistivity neutron porosity and density porosity logs. Larinov(1969)'s shale correction equation for Tertiary reservoir sands gave V_{Sh} values that range from 0.03 to 0.200. sand B's V_{Sh} values of 0.03 in BO-6 and 0.038 in BO-5 indicates that is clean sand. Its N/G pay ratio value is 1.00 in BO-6 and 0.956 in BO-5. Sand B has the highest value of S_h (0.773) in BO-6. Sand A has the highest net pay thickness (702.96ft) and highest BVH value (502.10ft), but contains hydrocarbon only in BO-5. The petrophysical attributes of Sands B and A are better than those of Sand C, and the value of the attributes for each reservoir vary spatially within the field.

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