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RESERVOIR CLASSIFICATION AND PETROPHYSICAL EVALUATION OF "BAO" FIELD, NIGER DELTA

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Abstract

Demand for hydrocarbon and its products has been the major contributor to the economic growth of any nation. The costs involved in the exploration of hydrocarbons require adoption of suitable method for its processing and interpretation. This study is aimed to evaluate the petrophysical parameters in "BAO" field in order to classify the producibility of each reservoir in the study area. A suite of well log data from four wells in the study area is used to achieve this aim. Each well comprises of Gamma ray, resistivity and porosity logs. These logs were used to delineate five hydrocarbon bearing reservoirs in the study area. The delineated reservoirs are associated with varying petrophysical parameters, which were used to evaluate the storativity and producibility of the mapped reservoirs. The true vertical depths of the delineated reservoirs are 3318, 3418, 3482, 3550 and 3744 m, respectively. The analysis across these well sections revealed that each of the sand unit extends through the field and varies in thicknesses. The porosity and permeability values across the delineated reservoirs show that the pores have ability to store and transmit appreciable quantities of hydrocarbons, which will contribute to the reserve portfolio in the study area.

Keywords: *Reservoir classification; Petrophysical evaluation; Niger delta; porosity; Permeability.*

1. Introduction

One of the basic prerequisites for a field occurrence is the presence of reservoirs [1]. A reservoir is a porous and permeable rock in the subsurface, which houses and transports hydrocarbons in commercially exploitable quantities. Initially, exploitation of hydrocarbon was through surface seeps for man's daily needs. As the search for hydrocarbon and its usage increases, man graduated from surfacial search to digging of prospective zones for hydrocarbon, till this present day which entails the use of technology for exploration and exploitation of hydrocarbon [2]. Classification of reservoirs in terms of its productivity is essential in reservoir management.

The Niger Delta province is one of the top ten hydrocarbon provinces in the world. It is the most prolific Basin in Africa. It is so promising such that most of its reserves have not been harnessed as the exploration extends towards the deep waters. The Niger Delta reservoirs are characterized by alteration of shale and sandstones, which are mainly from the Agbada Formation [3-4]. Shale serves as lateral and vertical seal to a reservoir, and it is usually used in well correlation. Sandstones are the hydrocarbon bearing reservoirs [5-7]. Classification of reservoir entails estimation and determination of reservoir properties such as porosity, permeability, fluid saturation, net pay, estimation of fluid content and lithology [8].

It is essential to evaluate the petrophysical parameters of a reservoir, because the quality of a reservoir depends on its ability to hold and transmit hydrocarbons. This quality is very essential for economic evaluation of reservoir. Reservoir characterization with respect to their petrophysical properties can contribute to the analysis of geopressure regime, volumetric analysis and estimation of reservoir depths.

The aim of this study is to utilize a suite of borehole geophysical logs to evaluate the petrophysical parameters in "BAO" field, offshore, Niger Delta with a view to classifying the producibility of each reservoir in the study area. As reported by [9], evaluation of reservoir producibility helps to understand the fluid flow through porous media, which depends on the permeability of a reservoir. Few out of numerous documented works on Niger Delta Basin have been captured in this present study [1,3-12].

2. Location and geology of the study area

The "BAO" field is an offshore field located in the western part of the Niger Delta Basin (Figure 1). The prolific Niger Delta is situated above the Gulf of Guinea. This Basin is the most inventive deltaic hydrocarbon province across the globe [7]. It is bounded by longitude 3° to 9° E and 4° to 8° N. It is one of the sedimentary terrains in Nigeria. The depth of sediments in the Niger Delta Basin depocenter is estimated as > 10 km thick [13]. The only recognized petroleum system in the study area is known as the Tertiary Niger Delta (Akata-Agbada), which represents the age of this system [14-15]. The geology of the Niger Delta Basin is directly located at the point of triple junction, which originated during the breakage of African from South American Continental plates [12].

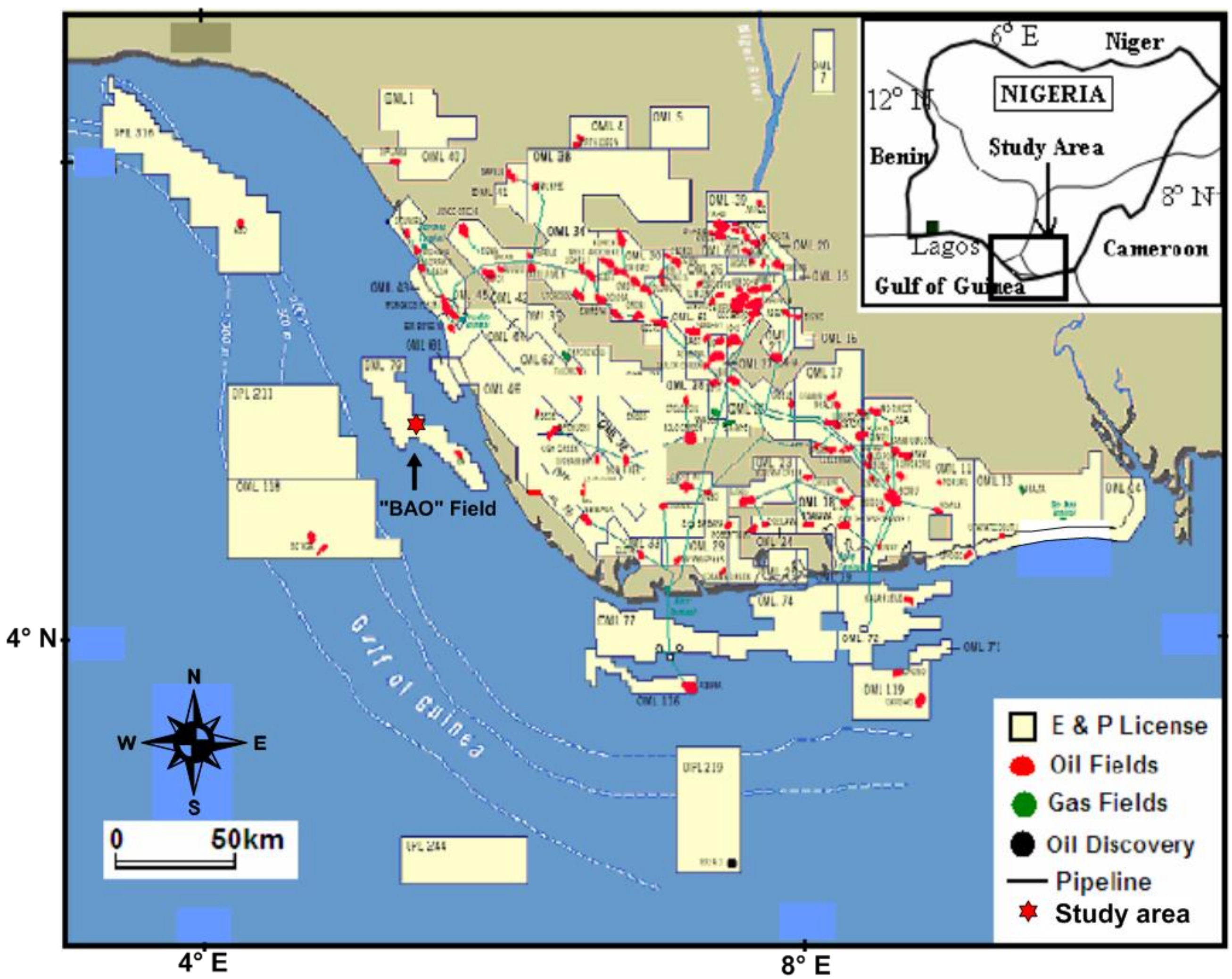

Figure 1. Hydrocarbon system in Niger Delta showing the study area (*modified after* [16])

The tertiary section of the Niger Delta is divided into three Formations, which represent the prograding depositional facies that are distinguished mostly on the basis of sand-shale ratios

(Figure 2), which are Akata, Agbada and Benin Formations (in ascending order). The depo-center of this section is about 8,535 meters thick (Figure 2) at the Central region of the Delta [6].

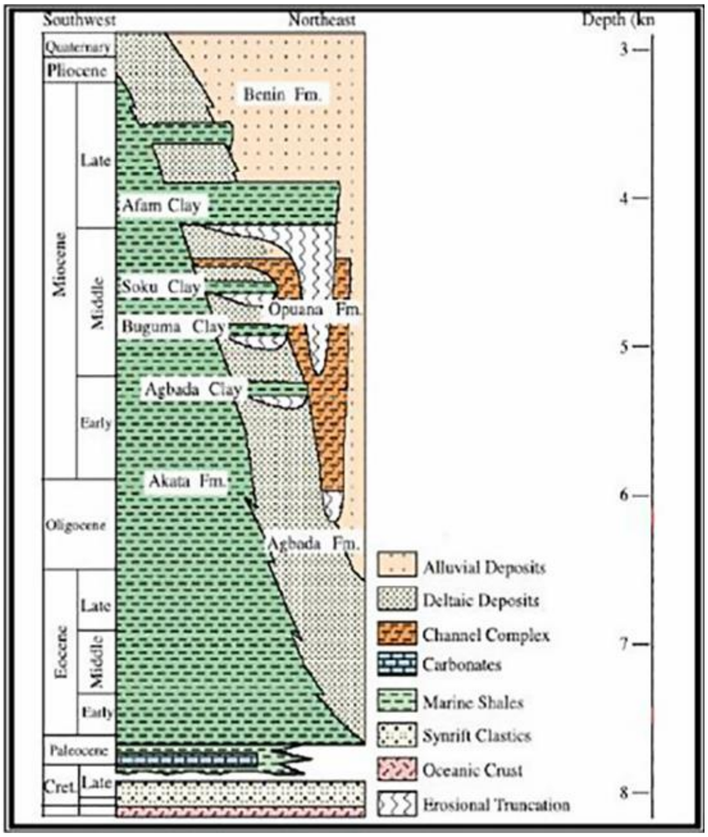

Figure 2: The three Formations in the Tertiary Niger Delta (*adapted from* [6, 12])

The Akata Formation is Paleocene in age. It is composed of thick shales, turbidite sands, and small amounts of silt and clay. It is the mobile formation that is squeezed into shale diapirs in the basin that are formed from being over pressured and not being dehydrated properly. The Akata formation formed during lowstands in sea level and in oxygen deficient conditions. This formation is estimated to be up to 7000 meters thick.

The Agbada Formation is Eocene in age. It is a marine facie, which is defined by both fresh water and deep sea characteristics. This is the major oil and natural gas bearing formation in the basin. The hydrocarbons in this layer are formed when the rock formation became subaerial and was covered in a swamp type of environment that contained lots of organics. It is estimated to be 3700 meters thick.

The Benin Formation is Oligocene and younger in age. It is composed of continental flood plain sands and alluvial deposits. This formation is estimated to be up to 2000 meters thick.

3. Materials and Method

The data used for this study is a suite of well log from "BAO" field, Niger Delta. The data are well log records from four wells in the study area. Each well consists Gamma Ray, Resistivity and Porosity logs. As contained in the backup document attached to the data, the "BAO" field is an oil field, which falls on one of the offshore oil fields in Niger Delta.

The Gamma ray is a log of the natural radioactivity of the formation used to distinguish between sands and shales in a siliclastic environment. Sandstones are usually nonradioactive quartz, while shales are highly rich in radioactive compositions, because of thorium and uranium adsorption ability and high concentration of potassium isotopes in clay. The Gamma ray is a better indicator of shaliness, and it is used for lithologic mapping. In addition, Gamma ray log is required when one needs to estimate the volume of shale in a reservoir [17].

The resistivity log contains information about subsurface electrical resistivity (ability to impede the flow of electric current). It is used to differentiate between brine and hydrocarbon formations. It is one of the required parameters (in addition to porosity log) in estimation of Water Saturation in a reservoir [17].

Porosity log measures the fraction or percentage of pore volume in a volume of rock. The basic three logs used for porosity are neutron, density and sonic logs. Acoustic (that is, sonic) log measures characteristics of sound waves propagated through the well-bore environment. Nuclear logs utilize nuclear reactions that take place in the downhole logging instrument or in the formation. Nuclear logs include density logs and neutron logs, as well as gamma ray logs which are used for correlation. The basic principle behind the use of nuclear technology is that a neutron source placed near the formation whose porosity is being measured will result in neutrons being scattered by the hydrogen atoms, largely those present in the formation fluid. Since there is little difference in the neutrons scattered by hydrocarbons or water, the porosity measured gives an image close to the true physical porosity whereas the figure obtained from electrical resistivity measurements is that due to the conductive formation fluid. The difference between neutron porosity and electrical porosity measurements therefore indicates the presence of hydrocarbons in the formation fluid [17].

The method employed in accomplishing the aim of this study is presented in workflow diagram as shown on Figure 3. The data were loaded into the workstation as a new project. Quality assessment and possible review of the database were done in order to check for missing parameters (if any) for possible correction prior to data processing. Hydrocarbon bearing sands were mapped in each well, while the shale in each well was used as marker for well correlation across the four wells. The petrophysical parameters of all the identified reservoirs were estimated and evaluated quantitatively and qualitatively.

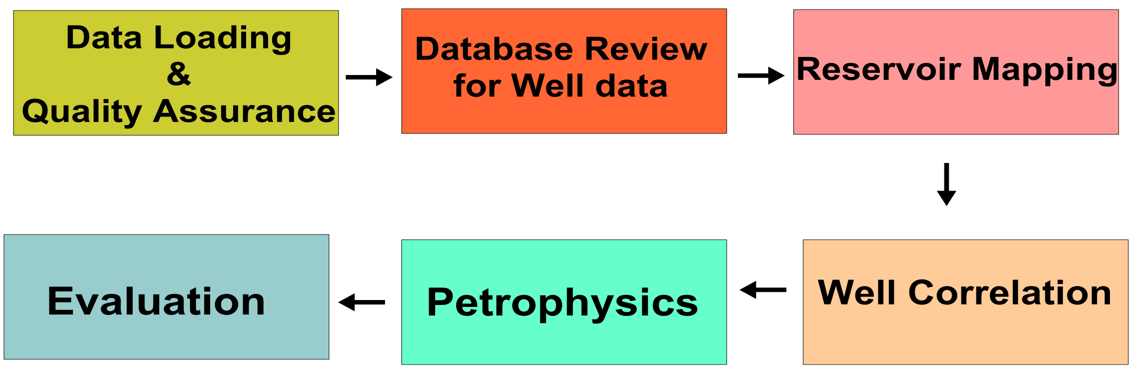

Figure 3. Workflow diagram

Quantitatively, the volume of shale (V_{Sh}) is estimated using Equation (1). It is measured in fraction.

$$V_{Sh} = \frac{GR - GR_{clean}}{GR_{Sh} - GR_{clean}} \qquad (1)$$

where, GR= Gamma ray reading from log, API; GR_{Sh}= Gamma ray reading from shale, API; and GR_{Clean}= Gamma ray reading from sandstone formation, API.

Average and effective porosities were calculated based on Equations (2) and (3).

$$\emptyset_A = \frac{\emptyset_D + \emptyset_N}{2} \qquad (2)$$

where, $\emptyset_A$= Average porosity; $\emptyset_D$= Density derived porosity; $\emptyset_N$= Neutron porosity (from log).

$$\emptyset_E = \emptyset_A \times (1 - V_{Sh}) \qquad (3)$$

where, $\emptyset_E$= Effective porosity.

$$S_{hc} = 1 - S_w \qquad (4)$$

where, S_w = water saturation.

In order to determine the permeability in the mapped reservoirs, Poroperm relationship as presented in Equation (5) was adopted. It is measured in millidarcy.

$$K = 10^{(K_a + K_b \times \phi)} \qquad (5)$$

where, K_a and K_b are the fitted constants, which are usually -2 and 20, respectively [17].

Qualitatively, Table 1 shows the classification of porosity and permeability of reservoir according to their values. Porosity defines the quantity of hydrocarbon a reservoir can hold, while permeability explains the producibility of a reservoir.

Table 1 Qualitative evaluation of porosity and permeability [8]

Porosity value (%)	Interpretation	Permeability value (md)	Interpretation
0-5	Negligible	<10.5	Poor to Fair
5-10	Poor	15-50	Moderate
15-20	Good	50-250	Good
20-30	Very Good	250-1000	Very Good
>30	Excellent	>1000	Excellent

4. Results and discussion

The results of the four well data used for this study are presented in Figure 4 and Tables 2 to 6. The well identities (ID) as uploaded to the workstation were WELL 5, WELL 7, WELL 10 and WELL 11, respectively. Wireline logs for these four wells were used to delineate five hydrocarbon bearing reservoirs in "BAO" field (Figure 4) by identifying subsurface layers with gamma ray log curves deflecting to the left (low gamma ray values) and high resistivity log readings juxtaposed against them. Figure 4 shows a correlation across the four wells. Five reservoirs (S1 to S5) were identified within well 5. These reservoirs are mapped at depths 3318, 3418, 3482, 3550 and 3744 m, respectively. In well 7, S1, S2, S3, S4, and S5 occur at 3314, 3422, 3476, 3532 and 3788 m, respectively. In Well 10, only S5 could be delineated at a depth of 3758 m. In well 11, reservoirs S2, S3, S4 and S5 occur at depths 3381, 3502, 3553 and 3778 m, respectively. The analysis across these well sections revealed that each of the sand unit extends through the field and varies in thickness with some units occurring at greater depths than their adjacent units possibly indicating the presence of a fault, which can be verified using seismic data.

4.1. Reservoir 1

Table 2 shows the results of some computed petrophysical parameters for reservoir 1 which cut across Well 5and 7. The reservoirs were penetrated at depths of 3318 -3333 m and from 3314 -3335 m in Wells 5 and 7 respectively. It has a gross thickness ranging from 15 to 20 m. The net thickness varies from 15 to 19 m, while the net/gross thickness (N/G) varies from 0.95 to 0.98 m. Reservoir 1 also has an average porosity value ranging from 0.22 to 0.32 with permeability value ranging from 676 to 13696 md. The water and hydrocarbon saturations (S_w and S_h) vary from 17 to 49% and 51 to 83%, respectively.

Table 2. Summary of the computed petrophysical parameters obtained for reservoir 1

Well ID	Sand top (m)	Sand base (m)	Gross sand (m)	Net thick. (m)	NGR	V_{Sh} (%)	S_w (%)	S_h (%)	$Φ_E$ (%)	K (md)
5	3318.27	3333.79	15.52	15.42	0.99	1.00	49.00	51.00	13.00	5511.00
7	3314.59	3335.31	20.72	19.72	0.95	2.00	17.00	83.00	-	-

The porosity values obtained across the two wells within resevoir1 depict a good to excellent rating, while the high permeability value obtained in well 5 indicates an excellent value that permits free flow of fluid within the reservoir. The hydrocarbon saturation indicates a high proportion of hydrocarbon to the quantity of water within the reservoir. Hence reservoir 1 is a fair to good reservoir.

4.2. Reservoir 2

Table 3 shows the petrophysical characteristics of reservoir 2 which cuts across well 5, 7 and 11. The reservoir penetrates at depths of 3418 to 3439 m, 3422 to 3440 m and 3381 to 3408 m in Wells 5, 7 and 11, respectively. It has a gross thickness which varies from 17 to 27 m. The net thickness also varies from 17 to 23 m, net/gross ratio from 0.72 to 0.87, while the water saturation (S_w) and hydrocarbon saturation (S_h) vary from 14 to 70%, and 30 to 86%, respectively. The estimated volume of shale for this reservoir varies from 6 to 11%. The ratio of the hydrocarbon to water saturation indicates that this reservoir contains both water and hydrocarbon, with hydrocarbon slightly higher than water saturation.

Table 3. Summary of the computed petrophysical parameters obtained for reservoir 2

Well ID	Sand top (m)	Sand base (m)	Gross sand (m)	Net thick. (m)	NGR	V_{Sh} (%)	S_W (%)	S_h (%)	Φ_E (%)	K (md)
5	3418.47	3439.46	20.99	17.39	0.83	6.00	20.00	80.00	19.00	5511.00
7	3422.57	3440.43	17.86	12.88	0.72	3.00	14.00	86.00	-	-
11	3381.53	3408.97	27.44	23.89	0.87	11.00	70.00	30.00	21.00	5612.00

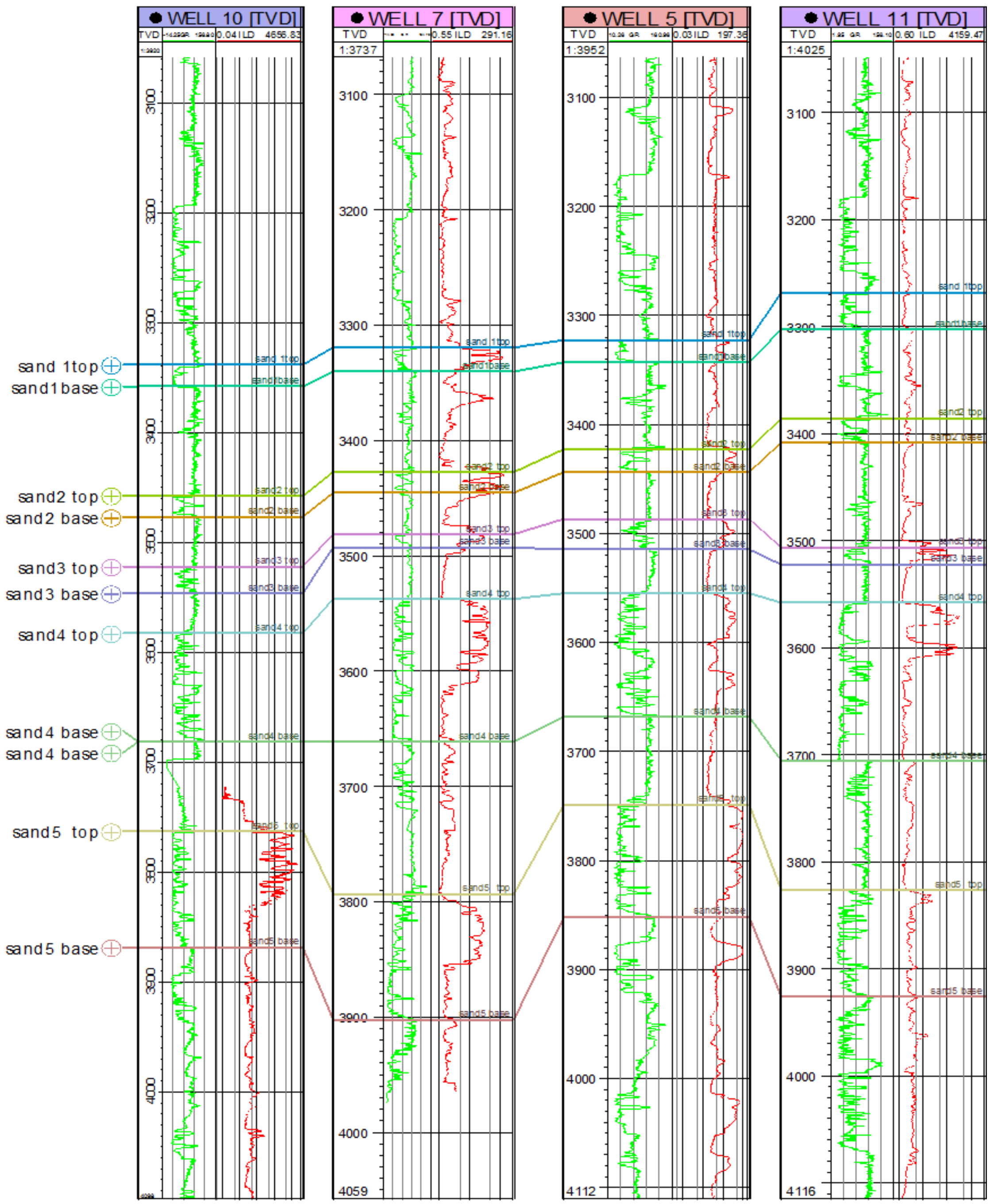

Figure 4: Stratigraphic correlation of the four wells

4.3. Reservoir 3

Table 4 shows petrophysical parameters for reservoir 3. This reservoir cuts across Wells 5, 7 and 11. The reservoir penetrates between 3476 to 3502 m, with gross thickness varying from 11 to 27 m. The net thickness varies from 11 to 26 m, while Net/Gross ratio varies from 0.96 to 1. Reservoir 3 has porosity and permeability values varying from 0.23 to 0.27 and 961 to 3481 md, respectively. The water saturation (S_w) and hydrocarbon saturation (S_h) values vary from 9 to 23% and 77 to 91%, respectively. The volume of shale (V_{sh}) for reservoir 3 varies from 3 to 9%. Hence reservoir 3 is a good hydrocarbon bearing unit.

Table 4. Summary of the computed petrophysical parameters obtained for reservoir 3

Well ID	Sand top (m)	Sand base (m)	Gross sand (m)	Net thick. (m)	NGR	V_{Sh} (%)	S_W (%)	S_h (%)	Φ_E (%)	K (md)
5	3482.43	3510.41	27.98	26.98	0.96	3.00	23.00	77.00	19.00	5511.00
7	3476.37	3488.00	11.63	11.63	1.00	9.00	22.00	78.00	-	3476.37
11	3502.22	3518.18	15.96	15.96	1.00	8.00	9.00	91.00	20.00	5562.00

4.4. Reservoir 4

Table 5 shows petrophysical parameters for reservoir 4. This reservoir cuts across three wells which are Well 5, 7 and 11 respectively. The reservoir penetrates between 3532 and 3553 m. The gross thickness varies from 113 to 147 m, the net thickness varies from 104 to 135 m, while the Net/Gross ratio varies from 0.86 to 0.92 m, respectively. The water saturation (S_w) and hydrocarbon saturation (S_h) vary from 7 to 22% and 78 to 93%, respectively. The volume of shale (V_{sh}) for this reservoir varies from 3 to 4%. Hence reservoir 4 is a very good hydrocarbon bearing unit.

Table 5. Summary of the computed petrophysical parameters obtained for reservoir 4

Well ID	Sand top (m)	Sand base (m)	Gross sand (m)	Net thick. (m)	NGR	V_{Sh} (%)	S_W (%)	S_h (%)	Φ_E (%)	K (md)
5	3550.57	3664.00	113.43	104.33	0.92	4.00	22.00	78.00	19.00	5511.00
7	3532.56	3656.37	123.81	106.80	0.86	3.00	18.00	82.00	-	3532.56
11	3553.77	3701.34	147.57	135.46	0.92	3.00	7.00	93.00	20.00	5562.00

4.5. Reservoir 5

Table 6 shows petrophysical parameters for reservoir 5. This reservoir cuts across Wells 5, 7, 10 and 11. The reservoir penetrates between 3744 and 3834 m. The gross thickness varies from 87 to 108 m, the net thickness varies from 81 to 105 m, while the Net/Gross ratio ranges from 0.89 to 0.97 m, respectively. The water saturation (S_w) and hydrocarbon saturation (S_h) vary from 11 to 32% and 68 to 89%, respectively. The volume of shale (V_{sh}) for reservoir 4 varies from 68 to 83%. Hence reservoir 5 is a very good hydrocarbon bearing unit.

Table 6. Summary of the computed petrophysical parameters obtained for reservoir 5

Well ID	Sand top (m)	Sand base (m)	Gross sand (m)	Net thick. (m)	NGR	V_{Sh} (%)	S_W (%)	S_h (%)	Φ_E (%)	K (md)
5	3744.33	3847.42	103.79	93.12	0.89	2.00	17.00	83.00	19.00	5511.00
7	3788.51	3897.39	108.88	105.28	0.97	2.00	21.00	79.00	-	3788.51
10	3758.54	3864.23	105.69	99.53	0.94	6.00	11.00	89.00	17.00	5400.00
11	3834.83	3921.97	87.14	81.49	0.94	4.00	32.00	68.00	17.00	5400.00

5. Conclusion

Classification and evaluation of reservoirs in "BAO" field, offshore Niger Delta has been carried out. Well-bore data from four wells comprising of Gamma ray, resistivity and porosity records were used for this study. Five hydrocarbon bearing sands (reservoirs) were mapped and correlated for better classification of each reservoir. The delineated reservoirs are associated with varying petrophysical parameters, which were used to evaluate the storativity and producibility of the mapped reservoirs. The identified reservoir sands possess hydrocarbon and water saturation varying from 30 to 93% and 9 to 70%, respectively. Reservoirs in "BAO" field are characterized by varying porosities, which vary from good to excellent in rating. The permeability values are rated as excellent. This shows that the pores in the delineated reservoirs have ability to store and transmit appreciable quantities of hydrocarbons that can contribute to the economic status of the field.

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