



## Depositional environment interpretation of sand reservoirs in the Niger Delta using porosity and discriminant functions

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### Abstract

The accessibility and the worth of hydrocarbons in a reservoir are determined by the sediment deposited in the reservoir. Interpreting the depositional environment of a sand reservoir plays an important role in revealing the volume of appreciable hydrocarbons in the reservoir. Three wells' data were used for this study. These data were processed and analysed with Microsoft Excel as well as the calculated parameters. The average total porosity estimated were 20.0% [indicating that the reservoir is highly porous; classified as good], 25.1% [showing that the reservoir is highly porous; belongs to the very good class] and 21.5% [signifying that the reservoir is highly porous; classified as good] respectively for wells AA, BB and CC. For well AA, the mean and standard deviation outcomes are 20.5 and 2.525 respectively. The sorting, skewness and kurtosis correspond to extremely poorly sorted, very coarse skew and extremely leptokurtic. For well BB, the mean and standard deviation results are 25.2 and 0.6 respectively. The sorting, skewness and kurtosis results for wells BB and CC correspond to poorly sorted, very coarse skew and very leptokurtic. The mean and standard deviation outcomes deduced from well CC reservoir are 21.0 and 0.75 respectively. The outcomes of the discriminant functions defined reservoir AA as one that has beach and fluvial characteristics with shallow agitated conditions. Wells BB and CC show aeolian and shallow marine with agitated conditions. The very coarse skew definition of sediment arrangement in the reservoirs points to the environment of deposition with high energy; as such the migration of hydrocarbons is faster from the reservoir to the well bore.

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## 1.0 Introduction

Sandstones are significant components of sedimentary environments on the Earth's surface. The environment of deposition of sediment is the sum of the physical, chemical and biological condition under which it was deposited (Atat et al., 2018). The availability and the quality of hydrocarbons in a reservoir is assessed by the sediment deposited in the reservoir. Therefore, a decision can be made about the transporting medium, the condition of flow at the time of deposition, and the nature of the depositional location to qualitatively predict the quality of the reservoir sand body. A high degree of reservoir heterogeneity is generally connected with the paralic successions of the Niger Delta basin (Asquith et al., 2004); this is a major challenge for explorationists to effectively model the reservoirs and evaluate hydrocarbon reserves (Mode et al., 2017; Darling, 2005, Mode et al., 2013). Sand deposited in varying environments are categorized by different log trends, geometrics and dimensions (Allen, 1970). This shows that the physical characteristics of clastic reservoir rocks reflect a response of the complex interplay of processes operating in a depositional system. The disparity in sedimentary environments may be accredited to changes in energy levels, flow velocity and climate, leading to the differences in the morphologies and qualities of sandstone reservoirs. According to Tyler and Finley (1991), the average recovery efficiency of oil could be tied closely to depositional environments and recovery mechanisms. Weber and Daukoru (1975), Evamy et al. (1978), and Ekweozor and Okoye (1980) have reported in their works on Niger Delta reservoir rocks, that the quality of the sandstones initially deposited is a function of the source area, the depositional processes and the environment in which the deposition takes place.

Although depositional environments of Niger Delta sands have been studied, few works have quantitatively classified environments using discriminant functions combined with porosity

outcomes. This study addresses that gap. From Walter's Law [or the law of facies succession] which states that the facies that occur in a given sedimentary sequence will always be found in a specific order reflecting the sequence of depositional environments in which they formed. This law suggests that the facies in a sedimentary sequence will always occur in a predictable order with each facies representing a specific depositional environment. This law is a fundamental principle in sedimentary geology and is used to reconstruct ancient depositional environments and to understand the evolution of sedimentary basins. In a simple break down, a sedimentary sequence begins with a sandstone facies (representing a beach or river depositional environment), followed by a shale facies (representing a deeper water depositional environment, after which a limestone facies occurs (representing a shallow water depositional environment, and finally, the sequence ends with a conglomerate facies (representing a high energy depositional environment).

### Geology of the Study Area

The Niger Delta, Nigeria is in the continental margin of West Africa, on the Gulf of Guinea. It is located within latitude  $3^{\circ}\text{N}$  -  $6^{\circ}\text{N}$ , and longitudes  $5^{\circ}\text{E}$  -  $8^{\circ}\text{E}$  (Akpabio *et al.*, 2023a; Akpabio *et al.*, 2023b; Reijers et al, 1996; Ekop et al., 2025; Eyibio *et al.* 2023; Umoren et al., 2019). The southern tip of the delta is at the Akwa Ibom State, which is at a latitude of  $5^{\circ}$  North and a longitude of  $8^{\circ}$  East. The Southern Niger Delta is located at a longitude of  $7^{\circ}$  East and a latitude of  $4^{\circ}$  North. It has some of the largest oil fields in Africa. These fields in the Niger Delta produce billions of barrels of oil every year, and they play a vital role in the economy of Nigeria. The southern Niger Delta comprises of nine states: Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo and Rivers State. Initially, the southern Niger delta was limited to the geographical area occupied mainly by the minorities of southern Nigerians

but today, the region has become synonymous with the oil producing states (Usen, 2003). The Niger Delta is the youngest Sedimentary basin within the Benue Trough system. The region began after the Eocene tectonic phase, up to 12.0km of silicic high energy deltaic deposits and shallow marine sediments have gathered in the basin (Atat et al., 2023a).

The Niger Delta province contains only one identified petroleum system (the Tertiary Niger Delta (Akata – Agbada)) (Atat et al., 2020a; kulke, 1995; Ekweozor and Daukoru, 1994). The volume of sediment is nearly 500000km<sup>3</sup> (Umoren et al., 2020). Three lithostratigraphic units are distinguished in the Tertiary Niger Delta (Atat and Umoren, 2016). The Benin Formation is the uppermost unit of the Niger Delta Complex that lays on top the Agbada Formation (Atat et al., 2023b). The Niger Delta region as other regions in Nigeria experiences wet and dry season with average rain in each month during wet season of about 135mm and falls to 65mm in dry season (George et al., 2010; Atat et al., 2020a; George et al., 2017; Ejoh et al., 2023; Benjamin et al., 2022). The three major lithostratigraphic units Akata Formation (which is where petroleum occurs in the Niger Delta basin (Udo et al., 2017; Atat and Umoren, 2016)), Agbada Formation (which lies beneath the Benin formation and comprises interbedded, fluvio-marine sands, sandstones and siltstone of several quantity (Weber, 1971) and Benin Formation (which is the uppermost unit and comprises of fluvial gravel and sands; it is the coastal plain sands which outcrop at Benin, Onitsha and Owerri province and elsewhere in the delta area).

## 2.0 Materials and Method

### 2.1 Materials

Microsoft Excel was used as the key software for the processing, analysis and computations. The data available for this research are evidence from the onshore Niger Delta Oilfield which include sonic, density, gamma ray and neutron raw wells (AA, BB and CC) data.

### 2.2 Method

Wireline logs are used to generate more information regarding the sequence of rocks penetrated by the wells (Udoh et al., 2020; Kearey et al., 2002). The data were loaded in the Excel; spurious values were removed, and sandstone lithology and shale lithology were identified. The net thickness of each reservoir was determined. The indication of the gamma ray log below 75 API (American Petroleum Institute) was taken as a sand reservoir. The step-by-step procedure is shown in Figure 1.

Porosity was estimated using Equation 3. The outcome of porosity was used to determine cumulative frequency which enables the deduction of percentiles from the ogive. The statistical and textural parameters were achieved using Equations 4. to 8. Porosity curves are in black colour; gamma ray curves in blue. Lastly Equations 9 to 12 were adequate for the findings of the discriminant functions. The mathematical expressions employed are referred to in the subsection.

### 2.3 Determination of porosity

Porosity is defined as the percentage of void space in a rock that can contain fluid. It is a measure of the rock's ability to hold fluid (Atat et al., 2023c; Umoren et al., 2024) and is expressed as a percentage of the rock's total volume. It may be seen as the openings between grains that oil and gas can move through the rock, contained, and pass from the rock into the well (Fraser, 1935). The amount of void space interconnected, and able to transmit fluids is called Effective Porosity while a void space that is connected and not connected is called Total Porosity. Porosity can be primary or secondary. Primary porosity is that which a rock possesses at the end of its depositional phase. Secondary porosity is that which is due to post depositional processes such as solution and fracturing (Pettijohn, 1975). Porosity of the formation is important in evaluation of fluid content, potentiality of fluid flow. It may be determined by the use of Equation 1 (Atat et al., 2024a;

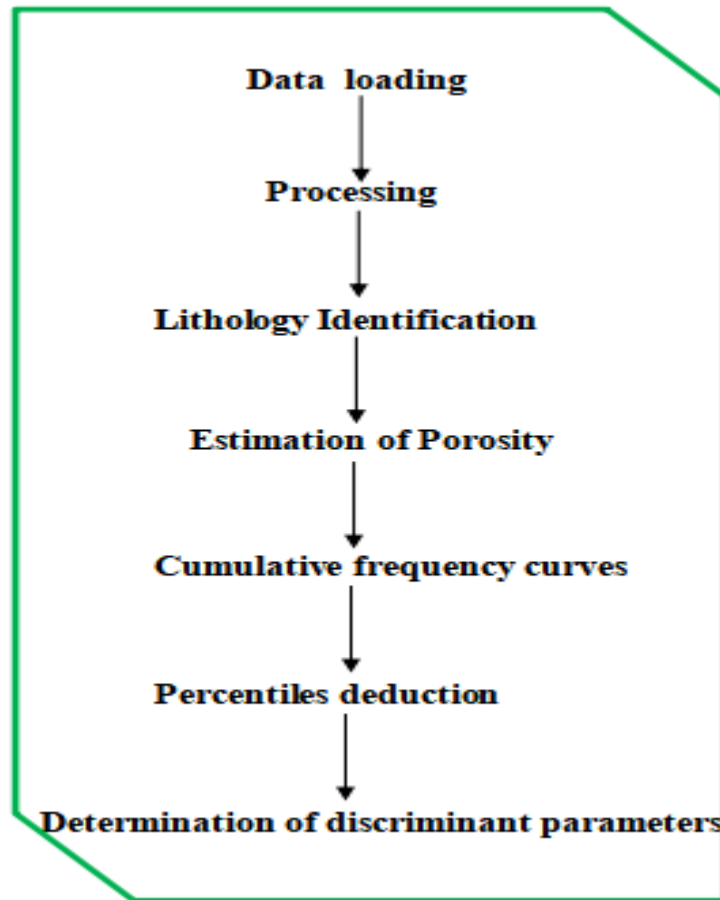
Umoren et al., 2023). Equations 2 and 3 (Atat et al., 2023c) are also recommended (Atat et al., 2022). However, if there is no precision in the estimation of fluid density, porosity outcome may not be better (Atat et al., 2020b) as the mud filtrate fluid is recorded by the formation density device. A zone with higher density defines the number of electrons with greater densities (Atat et al., 2024b). Density of oil is the fraction of the mass of oil to its volume (Atat et al., 2020c), and aids in identification of reservoir rock by

lithology description (Umoren et al., 2024; Ekop et al., 2025).

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad (1)$$

where:  $\phi$  = Total porosity;  $\rho_{ma}$  = grain matrix density = 2.65g/cm<sup>3</sup> for sandstone;  $\rho_b$  = bulk density recorded;  $\rho_f$  = fluid density which is taken as taken as 0.85 for oil and 0.2 for gas (Atat et al., 2024a).

$$\phi = \frac{C_r(t - t_{ma})}{t} \quad (2)$$



**Figure 1:** The workflow for determination of discriminant parameters

The value  $C_r$  of can vary between 0.625 and 0.700 as the case may be. The most widely accepted value is 0.670 (and 0.60 for gas reservoirs).

$$\phi = \frac{t - t_{ma}}{t_f - t_{ma}} \quad (3)$$

$t$  is the sonic response in microsec/ft,  $t_{ma}$  is the matrix travel time in microsec/ft,  $t_f$  is the fluid travel time in microsec/ft,  $\phi$  is the porosity. The fluid velocity ( $t_f$  of 189  $\mu$ sec/ft) of 5,300 ft/sec

is generally assumed for fresh drilling fluids (Umoren et al., 2023). A slightly lower value, 185  $\mu$ sec/ft, is used for salt muds.

## 2.4 Textural Parameters

Statistical and textural parameters include mean ( $M$ ) (Equation 4 was used to determine it), standard deviation ( $S_d$ ) (appropriate expression is Equation 5), sorting (which was obtained using Equation 6), skewness ( $S$ ) (it was achieved by the use of Equation 7) and kurtosis ( $K$ )

(Equation 8 was considered) (Adedoyin *et al.*, 2022; Oladipo *et al.*, 2018; Gandhi and Raja, 2014; Atat *et al.*, 2024c; Folk and Ward, 1957).

$$M = \frac{1}{3}(\phi_{16} + \phi_{50} + \phi_{84}) \quad (4)$$

Standard deviation is a measure of sorting. The sorting is a measure of the range of grain-size present and the magnitude of these sizes around the mean sizes.

$$S_d = \frac{1}{4}(\phi_{84} - \phi_{16}) \quad (5)$$

$$S = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \quad (6)$$

Skewness measures the symmetry of a curve by marking the position of the mean in relation to the median. A given size population that has a tail of excess fine particles is said to be positively skewed while one with tail excess is said to be negatively skewed. Negatively skewed (which is coarse skewed) defines a high energy environment and positively skewed (which is finely skewed) corresponds to a low energy environment.

$$K = 0.5 \left( \frac{\phi_{84} + \phi_{16} - \phi_{50}}{\phi_{84} - \phi_{16}} + \frac{\phi_5 + \phi_{95} - \phi_{50}}{\phi_{95} - \phi_5} \right) \quad (7)$$

Kurtosis is defined as platykurtic, its value is negative excess kurtosis (that is, opposite situation to the case of leptokurtic); if it is mesokurtic, kurtosis curve is observed to have uniform sorting in both tails and central position and finally leptokurtic, if its value is positive excess kurtosis (tail is better sorted than central portion). It is a quantitative measure used to describe the departure from normality of distribution. It signifies the ratio between sorting in tails and the central portion of the curve.

$$K_S = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})} \quad (8)$$

(Gandhi and Raja, 2014; Oladipo *et al.*, 2018; Atat *et al.*, 2024c)

## 2.5 Discriminant Functions

A discriminant function is a statistical tool used to classify sedimentary rocks into different depositional environments (Ghosh and

Chatterjee, 1994). It is a method that combines numerous variables (like grain size, sorting, skewness and kurtosis). Sahu (1964) and Atat *et al.* (2021) articles contained that the fluctuation in the energy and fluidity effects correlate better with different processes and the environment of deposition. Equations 9 to 12 are adequate for the computation of different discriminant functions.

$$Y_1 = -3.5688M + 3.7016S_d^2 - 2.0766S + 3.1135K \quad (9)$$

$$Y_2 = 15.6534M + 65.7091S_d^2 + 18.1071S + 18.5043K \quad (10)$$

$$Y_3 = 0.2852M - 8.7604S_d^2 - 4.8932S + 0.0482K \quad (11)$$

$$Y_4 = 4.5129M - 1.2837S_d^2 + 3.5904S + 4.1038K \quad (12)$$

where M is the mean,  $S_d$  is the standard deviation, S is skewness, K is kurtosis. If  $Y_1 \geq -2.7411$ , it points to the beach environment;  $Y_1 < -2.7411$  shows the aeolian condition;  $Y_2 \geq 65.36$  signifies shallow agitated condition;  $Y_2 < 65.36$  characterizes the beach deposition;  $Y_3 \geq -7.41$  defines shallow marine environment;  $Y_3 < -7.41$  specifies the deltaic environment;  $Y_4 \geq 9.81$  characterizes the fluvial or deltaic deposit;  $Y_4 < 9.81$  denotes the influence of turbidity current (Atat *et al.*, 2021). Therefore, the above expressions (Equations 9 to 12) are used to interpret the process and environment of deposition.

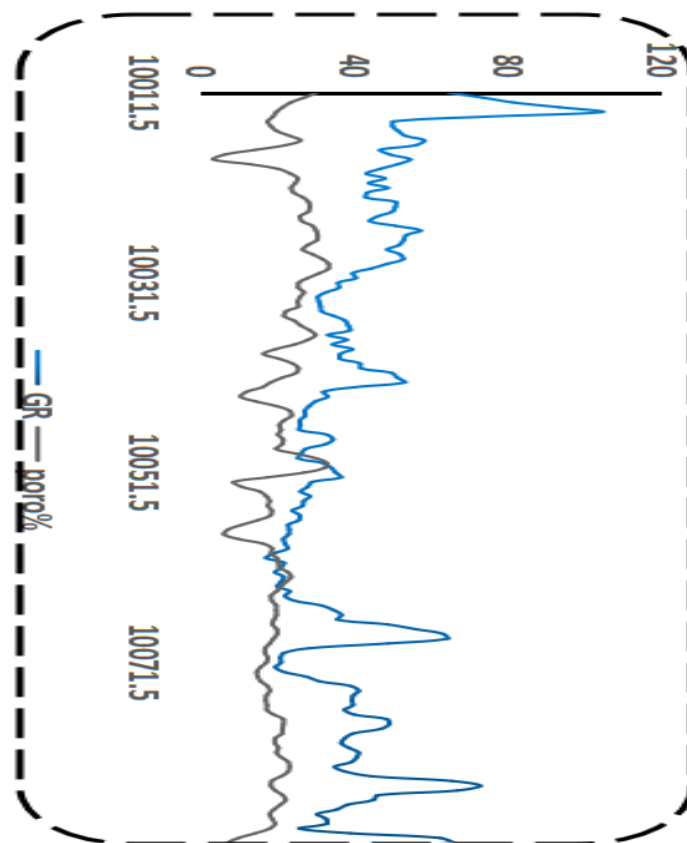
## 3.0 Results and Discussion

### 3.1 Results

Discriminant functions have been determined to interpret the environment of deposition of the studied wells reservoirs. The wells data (AA, BB and CC) have been analysed using Microsoft Excel. The result of investigation of the textural and discriminant parameters are displayed in Table 1. The porosity and gamma ray curves are presented in Figures 2 to 4. The ogive outcomes are highlighted in Figure 5.

**Table 1: The outcome of textural and linear discriminant parameters**

WELLS	AA	BB	CC
Mean	20.5	25.16666667	20.96666667
Standard Deviation	2.525	0.6	0.75
Sorting	5.343181818	1.190909091	1.446969697
Skewness	- 42.225	- 6.795	- 1.96
Kurtosis	57.93442623	2.557377049	2.827868852
Y1	119.7227982	- 82.99287238	- 67.3464576
Y2	1908.616811	486.4855581	443.6891474
Y3	- 73.35924318	- 1.680301457	- 5.892040509
Y4	341.2655185	127.8833219	110.6985969

**Figure 2: Porosity/gamma-ray logs from well AA**



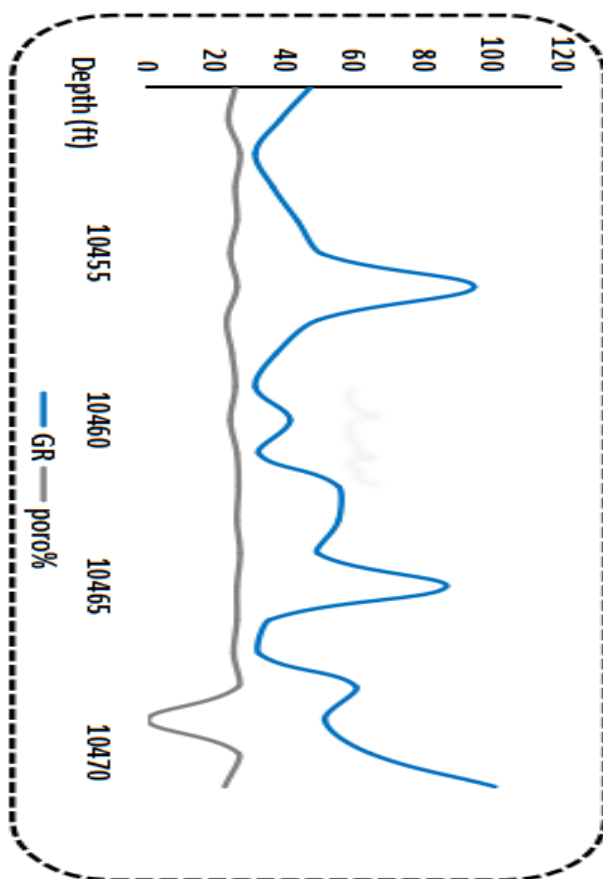


Figure 3: Porosity/gamma-ray logs from well BB

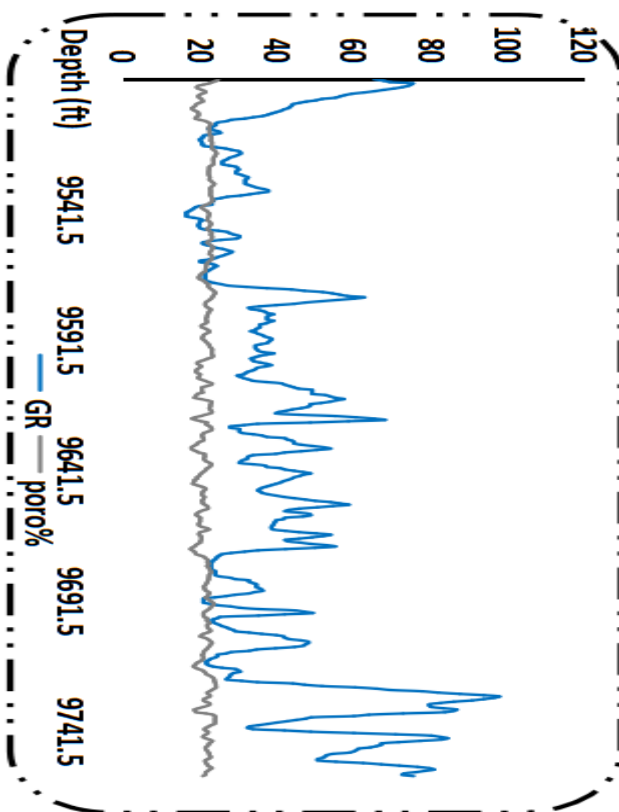
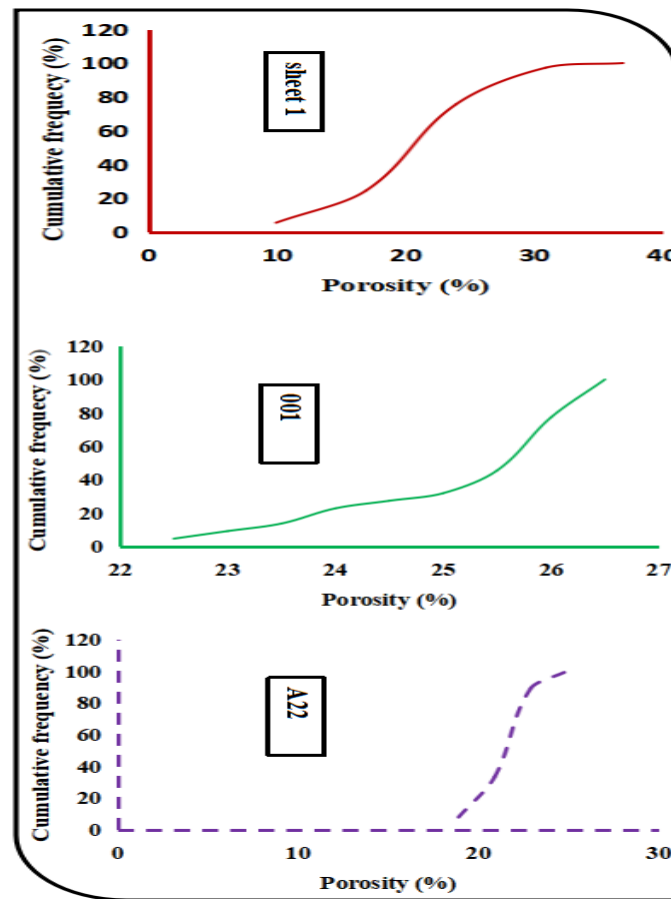


Figure 4: Porosity/gamma-ray logs from well CC



**Figure 5:** The Ogive outcomes of wells AA (red), BB (green) and CC (purple)

## 4.0 Discussion

### 4.1 For well AA

The net thickness of the reservoir was obtained as 91.5ft (Figure 2). The average total porosity estimated is about 20.0% indicating that the reservoir is highly porous and it is classified as good. In order to determine the discriminant functions, the statistical and textural parameters were investigated from the ogive. The mean and standard deviation outcomes for this reservoir were determined as 20.5 and 2.525 respectively (Table 1). From Figure 5, the values of sorting, skewness and kurtosis correspond to 5.34 (extremely poorly sorted), - 42.23 (very coarse skew) and 57.93 (extremely leptokurtic). The discriminant functions were determined as  $Y_1 = 119.722$  (beach environment);  $Y_2 = 1908.62$  (shallow agitated conditions);  $Y_3 = - 73.359$  (fluvial environment) and  $Y_4 = 341.27$  (fluvial deposit) (Atat et al., 2021).

### 4.2 For well BB

The net thickness of the reservoir obtained is about 21.0ft (Figure 3). The average total porosity estimated is about 25.1% showing that

the reservoir is highly porous and it belongs to the very good class of porosity. From the discriminant functions findings, the statistical and textural parameters were determined. The mean and standard deviation results for this reservoir are 25.2 and 0.6 respectively (Table 1). From Figure 5, sorting, skewness and kurtosis correspond to 1.19 (poorly sorted), -6.80 (very coarse skew) and 2.56 (very leptokurtic). The discriminant functions were determined as  $Y_1 = - 82.99$  (aeolian condition);  $Y_2 = 486.49$  (shallow agitated conditions);  $Y_3 = - 1.68$  (shallow marine environment) and  $Y_4 = 127.88$  (fluvial deposit).

### 4.3 For well CC

The net thickness of the reservoir was obtained as 267.0ft (Figure 4). The average total porosity estimated is about 21.5% signifying that the reservoir is highly porous and it is classified as good. In order to assess the discriminant functions, the statistical and textural parameters were examined. The mean and standard deviation outcomes for this reservoir are 21.0 and 0.75 respectively (Table 1). From Figure 5,



sorting, skewness and kurtosis correspond to 1.45 (poorly sorted), - 1.96 (very coarse skew) and 2.83 (very leptokurtic). The discriminant functions were determined as  $Y_1 = - 67.35$  (aeolian condition);  $Y_2 = 443.69$  (shallow agitated conditions);  $Y_3 = - 5.89$  (shallow marine environment) and  $Y_4 = 110.70$  (fluvial deposit).

### 5.0 Conclusion

Porosity is an important parameter which accounts for the ability for the transmission and storage of fluid in the reservoir. The studied reservoirs are highly porous and good in all the wells. The pore spaces thicknesses information shows poorly sorted, very coarse skewed and very leptokurtic possibility for both wells BB and CC reservoirs but for AA, it is observed as extremely poorly sorted, very coarse skewed and extremely leptokurtic. The sorting disparity could be due to constant deposition of coarse or fine materials. The outcomes of the discriminant functions defined reservoir AA as one with fluvial characteristics with shallow agitated conditions. Wells BB and CC show aeolian and shallow marine with agitated conditions which point to high energy of deposition. Therefore, development and hydrocarbon production are strongly encouraged as the transmission of hydrocarbons to the well bore would be faster as due to the influence of energy of deposition.

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