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Porosity-Permeability Regimes in Reservoirs for Hydrocarbon Prospectivity in Nembe Creek Field, Niger Delta

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Abstract: *Porosity and permeability regimes in hydrocarbon-bearing reservoirs of Nembe Creek Field, Niger Delta were delineated by digitizing and correlating gamma ray, resistivity, and density logs from three wells: Nembe 01, Nembe 02 and Nembe 03 respectively. Results obtained from the analyses of these composite logs reveal eight potential hydrocarbon-bearing reservoirs. These reservoir sands were observed to have very good to excellent average porosities ranging from 29 to 45%. Permeability values were excellent within these reservoirs and range from 2200 to 5789mD. Hydrocarbon saturation was observed to be high in all the reservoir sands, ranging from 64 to 81% with corresponding water saturation from 36 to19%. The regimes observed indicate that porosity and permeability increase with depth. Cross-plots indicate increase in porosity and permeability with depth and a linear increase of permeability with porosity. Petrophysicists and reservoir analysts will find these results very beneficial for better understanding of the reservoir properties, fluid distribution and in quantifying the hydrocarbon prospectivity of this Field which is observed to be very high.*
Keywords: *Porosity, Permeability, Hydrocarbon, Reservoirs, Nembe Creek, Niger Delta*

I. Introduction

Multinational hydrocarbon exploration companies may experience poor reservoir performance within few years of production due to inadequate reservoir properties description. The success of any hydrocarbon exploration program depends on the building of a reliable reservoir model.

The delineation of petrophysical properties of hydrocarbon-bearing reservoirs in the Niger Delta has been conducted by several researchers (Egbai and Aigbogun (2012); Tamunosiki et al, 2014; Ekine and Ibe, 2013; Adewoye et. al (2013); Adaeze et al., (2012); Abraham-Adejumo (2013)). Several parameters describing the characteristics of these reservoirs have been investigated. Among these, lithology, depositional environment, shale volume, porosity, permeability, Formation resistivity, water and hydrocarbon saturations received the most attention. The evaluation of reservoir rocks in terms of porosity, water saturation and permeability is useful in defining abnormally pressured zones, hydrocarbon reserves estimates, and reservoir bed thickness and in distinguishing between gas, oil and water bearing strata by observing their electrical resistivity and relative permeability values (Hilchie, 1990; Schlumberger, 1996; Uguru et al., 2002). However, porosity and permeability are the main petrophysical properties of reservoir rocks that have vital impact on the evaluation processes at all stages.

This research is geared towards maximizing hydrocarbon recovery from reservoirs, ensuring consistent reservoir description by accurate prediction of porosity and permeability regimes which helps in optimal well placement.

Location and Geology of the Study Area

The Nembe Creek Field is located in the Coastal Swamp depobelt (Oil Mining License 29) of the Cenozoic Tertiary Niger Delta Basin (Figure 1). Sediment deposition in this area started in early Miocene times and the sedimentary package is comprised of the basal holomarine shales (Akata Formation), the coastal plain sand-shale alternations (Agbada Formation), and coastal plain sands (Benin Formation) being the youngest stratigraphic unit at the shallower part of the basin. This succession is linked to the palaeo Niger and Benue system (Allen, 1965).

The Nembe Creek Field reservoir is in the middle Miocene deltaic sandstone-shale sequence. The structure is dissected by numerous growth faults steeping upwards. The shallow sandstone reservoirs are faulted such that spill points are generated at remarkable uniform depths resulting in similarity of fluid contact depth. A transgressive shale formation overlay the reservoir, which makes up the caprock (Nelson, 1980).

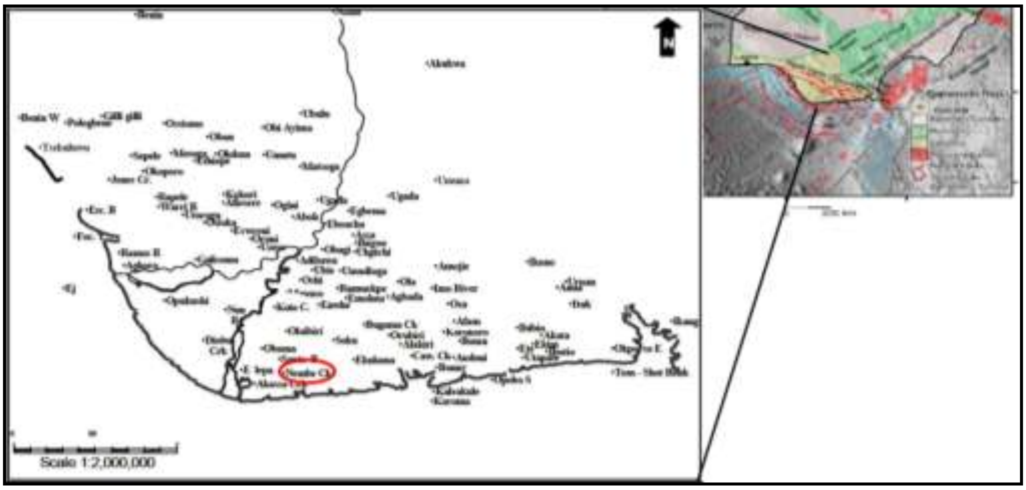

Figure 1: Map of Southern Nigeria; inset the Niger Delta Map showing Location of Nembe Creek in red coloured circle (Modified from Abrakasa, et al, 2016).

II. Methodology

Porosity and permeability regimes are evaluated by digitizing and correlating gamma ray, resistivity, and density logs from Nembe wells 01, 02 and 03 using Rokdoc software.

Lithology Delineation and Hydrocarbon-bearing Zones

Gamma ray (GR) log was digitized to define the lithologies of interest (sand and shale units). A combination of GR log and induction resistivity logs were analyzed to delineate the hydrocarbon-bearing (sand) zones. Zones of possible oil accumulations are indicated by high resistivity values whereas water zones have low resistivity values. Similar sand zones from the three wells were correlated (Figure 2). The fluid type occurring within the pore volume of the reservoirs was further ascertained using the Neutron-Density logs cross-plot. Gas zones were identified from the 'balloon effect'.

Determination of Volume of Shale

To determine the volume of shale, the gamma ray index I_{GR} was calculated applying the Equation (Schlumberger, 1996): $I_{GR} = \frac{(GR_{\log} - GR_{\min})}{(GR_{\max} - GR_{\min})}$ (1)

Where I_{GR} = gamma ray index; GR_{log} = gamma ray reading of the Formation; GR_{min} = minimum gamma ray reading (sand baseline); GR_{max} = maximum Gamma ray reading (shale baseline)

The volume of shale for tertiary rocks was then computed using the Equation (Larionov, 1969).

$$V_{sh} = 0.083(23.7 * I_{GR} - 1) \tag{2}$$

Where: V_{sh} is the percentage of shale in the Formation.

Net/Gross Reservoir Thickness

The gross reservoir thickness, H was determined by picking the tops and bases of the reservoir sands across the wells (Figure 2). Shale thickness, h_{shale} within the reservoir sands was obtained by defining shale and sand baselines respectively on the Gamma ray log. The net reservoir thickness, *h* was determined from the gross reservoir thickness as follows:

$$h = H - h_{shale} \tag{3}$$

The net-to-gross thickness was obtained thus: $\text{Net-to-Gross} = \frac{\text{h}}{\text{H}}$ (4)

Determination of Total Porosity

Porosity, the ratio of pore volume in a Formation to its total volume, was calculated from density log using the equation (Dresser, 1979):

$$\phi_T = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \tag{5}$$

Where: ρ_{ma} = Matrix density which is taken to be 2.65g/cc for sandstones; ρ_b = Bulk density determined directly from the log; ρ_f = Fluid density which is taken to be 1 for water and 0.87 for oil.

Determination of Effective Porosity
This is usually based on the adjustment of total porosity by means of estimated shale volume (content) (Dresser, 1979): $$\phi_{eff} = \phi_T - [\phi_{sh} * V_{sh}] \quad (6)$$
Where: ϕ_{eff} = effective porosity; ϕ_T = total porosity; ϕ_{sh} = log reading in a shale zone, V_{sh} = volume of shale

Computation of Permeability
Permeability, the petrophysical property that indicates the ability of fluids to flow through rocks, is measured in darcies (D) or millidarcies (mD). Permeability was calculated from the equation:

$$K = \left[\frac{250 * \phi^3}{S_{w_{irr}}}\right]^2 \quad (7)$$

Where: S_{wirr} = Irreducible water saturation determined by: $$S_{w_{irr}} = \sqrt{\frac{F}{2000}} \quad (8)$$

The Formation factor was determined by Archie (1942) equation $$F = \frac{a}{\phi^m} \quad (9)$$

Where: ϕ = porosity; *a* = Tortuosity taken as 0.62; *m* = cementation exponent taken as 2 for sands.

Determination of Water and Hydrocarbon Saturations
The water saturation, S_w for the uninvaded zone was determined using the equation by Archie, 1942

$$S_w = \left(\frac{aR_w}{R_t\phi^m}\right)^{\frac{1}{n}} \quad (10)$$

Where: S_w = water saturation of the uninvaded zone; R_w = Resistivity of the interstitial water; R_t = True resistivity of the formation; n = saturation exponent taken as 2.

Hydrocarbon saturation, S_h was computed using: $$S_h = (100 - S_w)\% \quad (11)$$

III. Results And Discussion

Lithology Identification
Figure 2 shows Gamma ray, Resistivity (LLD), Neutron and Density logs for wells NEMBE 01, NEMBE 02 and NEMBE 03 used in this study. It also shows that three reservoirs were delineated for wells NEMBE 01 and 02 respectively while two reservoirs only were delineated for well NEMBE 03. The depth and thickness of the top and base of the identified reservoirs are shown in Table 1. These wells display a shale/sand/shale sequence which is characteristic of the Niger Delta Formation (Avbovbo, 1978). Shale lithologies are defined by the high gamma ray values deflecting towards increasing API values and resistivity to the opposite direction due to high conductivity of the Formation. Zones showing low gamma ray, high resistivity, and low acoustic impedance are interpreted as sand lithologies which constitute the main hydrocarbon reservoir source rocks in the Niger Delta (Evamy et al., 1978).

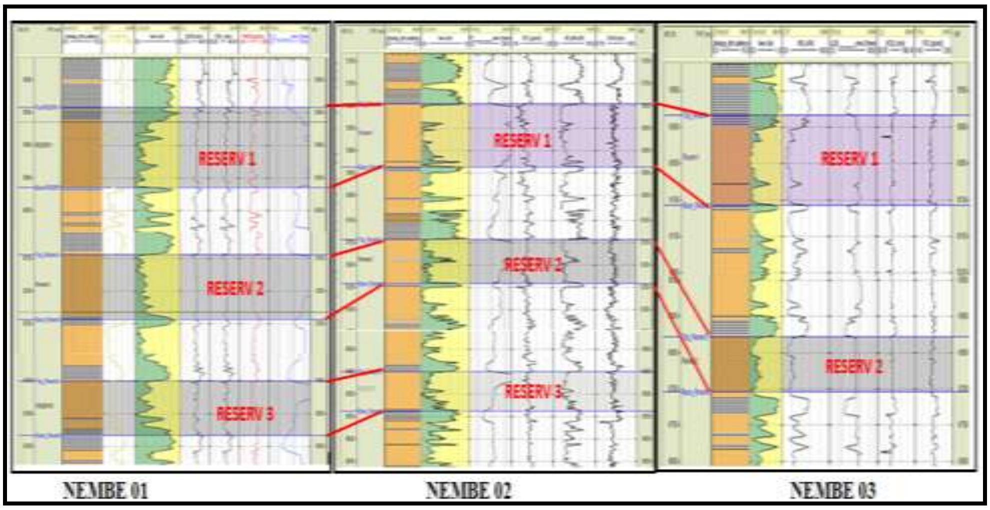

Figure 2: Wells NEMBE 01, 02 and 03 showing Suite of Logs, Delineated Lithology and Reservoirs 1, 2 and 3

Table 1: Reservoir Parameters for Wells NEMBE 01, 02 and 03

WELL NAME	RESERVOIR NAME	MEASURED DEPTH		RESERVOIR THICKNESS (ft)
		TOP (ft)	BASE (ft)	
NEMBE 01	RESERV 1	5842	5964	122
	RESERV 2	6144	6243	99
	RESERV 3	6450	6533	83
NEMBE 02	RESERV 1	5795	5936	141
	RESERV 2	6142	6241	99
	RESERV 3	6449	6537	88
NEMBE 03	RESERV 1	5938	6107	169
	RESERV 2	6629	6704	75

Petrophysical Properties

Table 2 shows the digitized and computed typical petrophysical parameters from logs within RESERV 1 in well NEMBE 01 among others. The average properties are shown in Tables 3 to 5. The results show that eight zones of interest (sand bodies) were identified as potential hydrocarbon reservoirs in the three wells. The average porosity of reservoir sands ranged from 29 to 45%. Their average permeability values within these reservoirs range from 2200 to 5789mD. Hydrocarbon saturation was high in all the reservoir sands, ranging from 64 to 81%., with corresponding water saturation from 36 to19 %.

Table 2: Typical Petrophysical Parameters from Logs within RESERV 1 in Well NEMBE 01

DEPTH (ft)	*DIGITIZED LOG PARAMETERS*			*COMPUTED PARAMETER*						
	GR (API)	*RESIS (Ωm)*	*DEN (g/cm³)*	I_{GR}	V_{Shale}	Φ_T	Φ_{eff}	S_w	S_h	*K (mD)*
5842	92.5209	3.6936	2.2222	0.67120726	0.2320845	0.25927	0.1991	0.32012623	0.6798738	2077.72
5842.5	86.672	3.8211	2.193	0.61186974	0.199322	0.27697	0.2218	0.29967177	0.7003282	2329.83
5843	82.0013	4.2844	2.1571	0.56448514	0.1765135	0.29873	0.2460	0.2778454	0.7221546	2662.58
5843.5	79.3193	4.528	2.099	0.53727605	0.164616	0.33394	0.2790	0.24854809	0.7514519	3254.32
5844	76.2774	4.9523	2.0717	0.50641575	0.1520896	0.35048	0.2972	0.2368148	0.7631852	3555.1
5844.5	73.6629	5.9839	2.0536	0.47989145	0.1420877	0.36145	0.3101	0.22962777	0.7703722	3762.52
5845	73.2829	6.9902	2.04	0.47603632	0.1406898	0.3697	0.3177	0.2245082	0.7754918	3922.58
5845.5	73.5787	7.3792	2.0518	0.47903723	0.1417768	0.36255	0.3112	0.22893681	0.7710632	3783.5
5846	72.0198	7.641	2.1628	0.46322208	0.1361413	0.29527	0.2551	0.28109606	0.7189039	2608.07
5846.5	72.5414	7.9802	2.1937	0.46851375	0.1380015	0.27655	0.2384	0.30013149	0.6998685	2323.6
5847	76.7816	8.3486	2.2214	0.51153089	0.1540979	0.25976	0.2197	0.3195287	0.6804713	2084.41
5847.5	80.7305	8.9715	2.3214	0.55159278	0.1707726	0.19915	0.1651	0.41676811	0.5832319	1345.35
5848	89.8017	9.6217	2.3704	0.64362078	0.216232	0.16945	0.1328	0.48980687	0.5101931	1054.34
5848.5	96.014	10.6124	2.3976	0.70664502	0.2541658	0.15297	0.1141	0.54259113	0.4574089	912.975
5849	100.2027	10.952	2.4284	0.7491397	0.2834315	0.1343	0.0962	0.61800542	0.3819946	770.289
5849.5	111.7715	11.5093	2.4623	0.86650604	0.3829764	0.11376	0.0702	0.72962174	0.2703783	634.572
5850	115.3318	12.0071	2.4822	0.90262555	0.420148	0.1017	0.0590	0.81615018	0.1838498	565.305
5850.5	116.9504	12.5064	2.4985	0.91904636	0.4382198	0.09182	0.0516	0.9039604	0.0960396	514.294
5851	116.718	13.2441	2.5109	0.91668865	0.435578	0.0843	0.0476	0.98454349	0.0154565	478.937

Table 3: Average Petrophysical Properties for NEMBE 01

NEMBE 01										
Reservoir Name	**Top MD (ft)**	**Base MD (ft)**	**Gross Thickness ft**	**Net Thickness (ft)**	**Net/Gross Thickness (ft)**	Φ_T	Φ_{eff}	**S_w (frac)**	**S_h (frac)**	**K (mD)**
Reserv 1	5842	5964	122	111.5	0.91	0.30	0.28	0.30	0.70	2804
Reserv 2	6144	6243	99	93.3	0.94	0.29	0.28	0.31	0.69	2601
Reserv 3	6450	6533	83	76.2	0.92	0.25	0.23	0.36	0.64	2200

Table 4: Average Petrophysical Properties for NEMBE 02

NEMBE 02										
Reservoir Name	**Top MD (ft)**	**Base MD (ft)**	**Gross Thickness ft**	**Net Thickness (ft)**	**Net/Gross Thickness (ft)**	Φ_T	Φ_{eff}	**S_w (frac)**	**S_h (frac)**	**K (mD)**
Reserv 1	5795	5936	141	131.3	0.93	0.45	0.42	0.19	0.81	5789
Reserv 2	6142	6241	99	91.3	0.92	0.38	0.35	0.22	0.78	4232
Reserv 3	6449	6537	88	80.4	0.91	0.35	0.32	0.24	0.76	3691

Table 5: Average Petrophysical Properties for NEMBE 03

NEMBE 02										
Reservoir Name	**Top MD (ft)**	**Base MD (ft)**	**Gross Thickness ft**	**Net Thickness (ft)**	**Net/Gross Thickness (ft)**	**Φ_T**	**Φ_{eff}**	**S_w (frac)**	**S_h (frac)**	**K (mD)**
Reserv 1	5938	6107	169	154.8	0.92	0.29	0.27	0.29	0.71	2677
Reserv 2	6629	6704	75	71.7	0.96	0.33	0.31	0.26	0.74	3136

Table 6: Summary of Porosity and Permeability Parameters for NEMBE 01, 02 and 03

WELL NAME	RESERVOIR	Φ_T (frac)	K (mD)
NEMBE 01	RESERV 1	0.30	2804
	RESERV 2	0.29	2601
	RESERV 3	0.25	2200
NEMBE 02	RESERV 1	0.45	5789
	RESERV 2	0.38	4232
	RESERV 3	0.35	3691
NEMBE 03	RESERV 1	0.29	2677
	RESERV 2	0.33	3136

Table 6 is a summary of the petrophysical parameters of well NEMBE 01 which was delineated to contain three hydrocarbon-bearing reservoirs with porosity ranging from 0.25 to 0.30 and permeability from 2200 to 2804mD. This also illustrates that both porosity and water saturation decreases with an increasing depth. Similarly, well NEMBE 02 was delineated to contain three hydrocarbon bearing reservoirs which have porosities ranging from 0.35 to 0.45 and permeability from 3691 to 5789mD. More so well NEMBE 03 was delineated to have two hydrocarbon bearing reservoirs. NEMBE 03 has porosity ranging from 0.29 to 0.33 and permeability from 2677 to 3136mD.

Porosity Trend

The trend in Figures 3, 4 and 5 among others show that porosity decreases as the depth increases in all the reservoirs except for reserve 1 of NEMBE 01 where the trend tends to slightly increase with increase in depth. This is as a result of low compaction or more interconnected pore spaces in the reservoir.

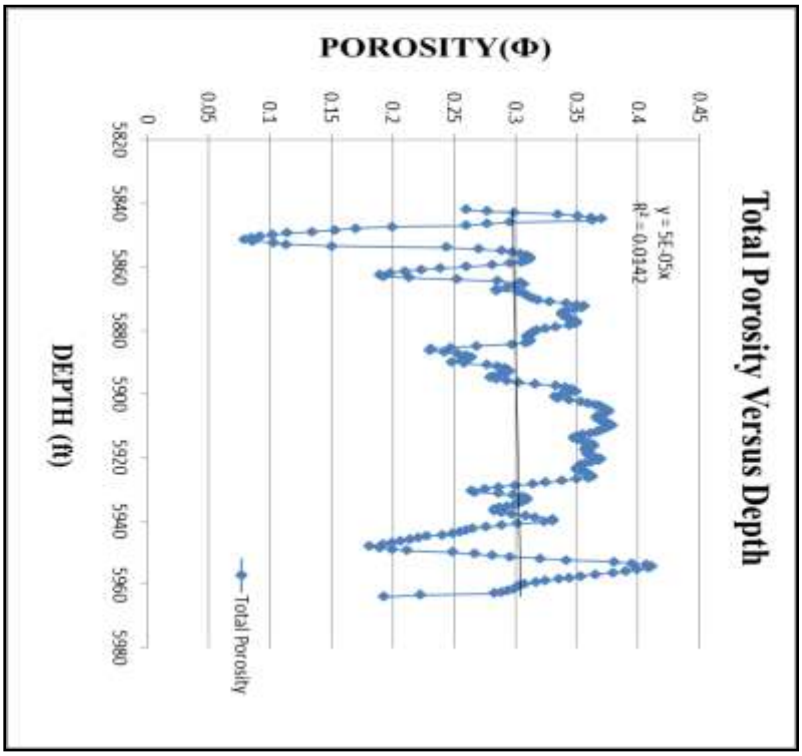

Figure 3: Total Porosity versus Depth for Reserv 1 of NEMBE 01

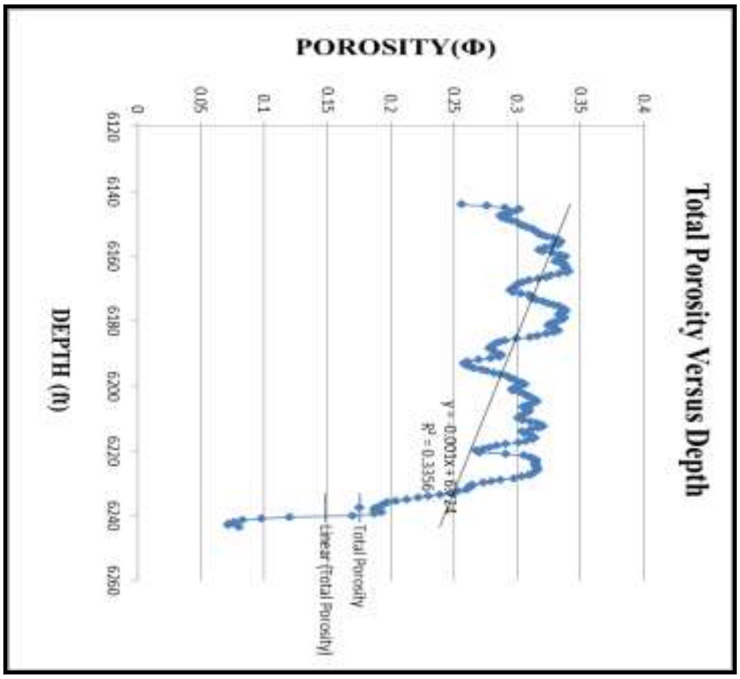

Figure 4: Total Porosity versus Depth for Reserv 2 of NEMBE 01

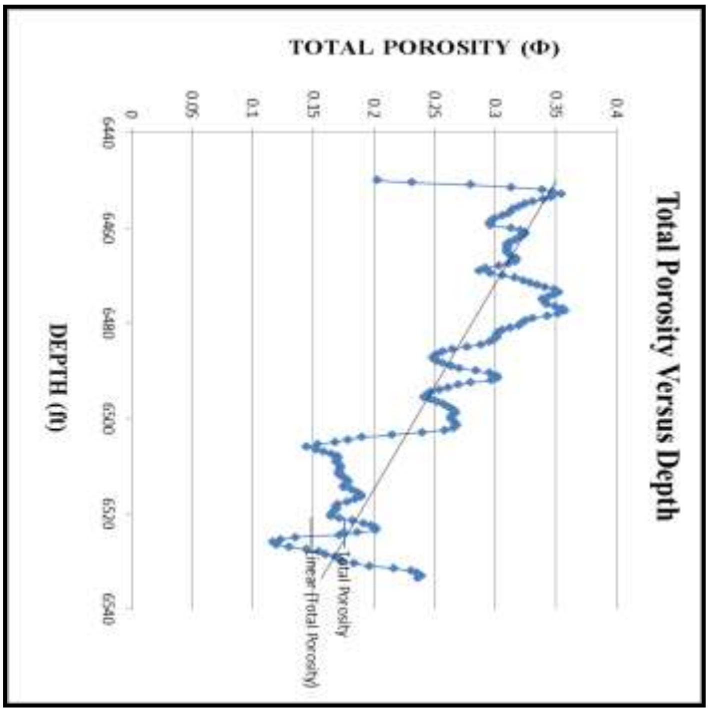

Figure 5: Total Porosity versus Depth for Reserv 3 of NEMBE 01

Permeability Trend

Figures 6, 7 and 8 among others show typical permeability trend in well NEMBE 01. There is a normal linear decrease of permeability with increase in depth, but within the Reserv 1 of NEMBE 01 there is an increase of permeability with an increase in depth (Figure 6) as shown in the trend line of the permeability-depth cross-plot. This indicates an excellent permeability which is a property of highly prolific reservoirs.

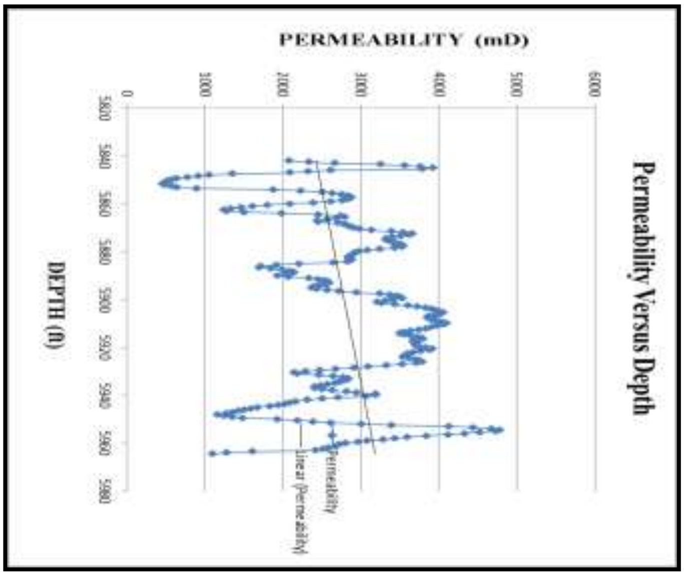

Figure 6: Permeability versus Depth for Reserv 1 of NEMBE 01

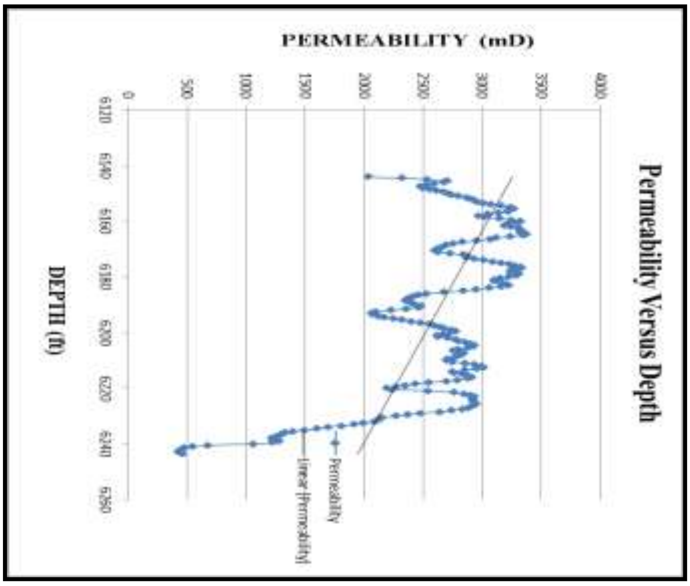

Figure 7: Permeability versus Depth for Reserv 2 of NEMBE 01

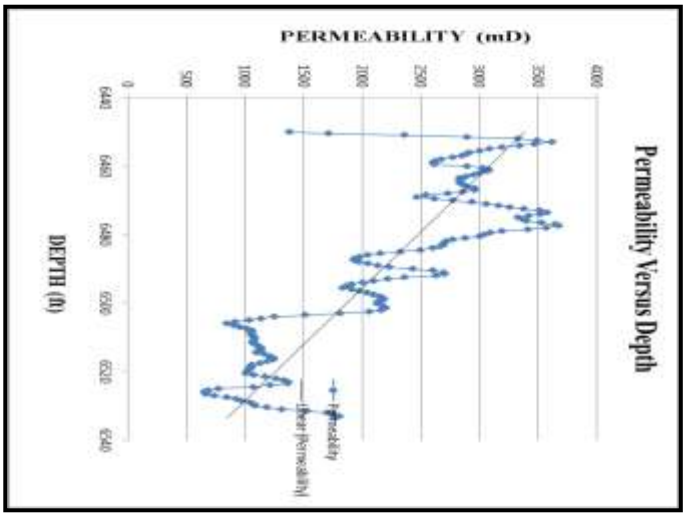

Figure 8: Permeability versus Depth for Reserv 3 of NEMBE 01

Porosity-Permeability Cross-Plot

Permeability is related to porosity but not always dependent on it. It is controlled by the connected passages of the pores space (pore throats). The cross-plot of permeability against porosity indicates a linear increase of permeability with porosity (Figure 9) which is an indication that the reservoirs are highly porous.

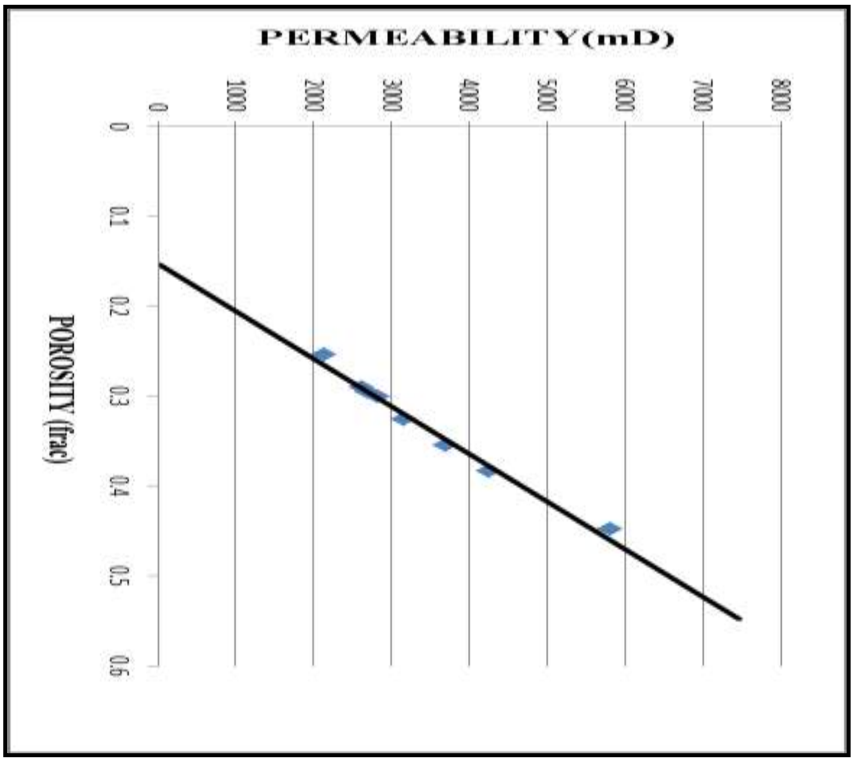

Figure 9: Permeability-Porosity Cross-plot

Hydrocarbon Prospectivity of Wells NEMBE 01, 02 & 03

Figure 10 is a clustered-column bar chart showing some reservoir properties for the reservoirs of interest in the three wells. The chart shows total porosity (BLUE), effective porosity (RED), and hydrocarbon saturation (GREEN). Hydrocarbon saturation was high in all the reservoir sands, ranging from 64% to 81%, with corresponding water saturation from 36 to 19%. Figure 11 is a bar chart displaying the different permeabilities of the reservoirs.

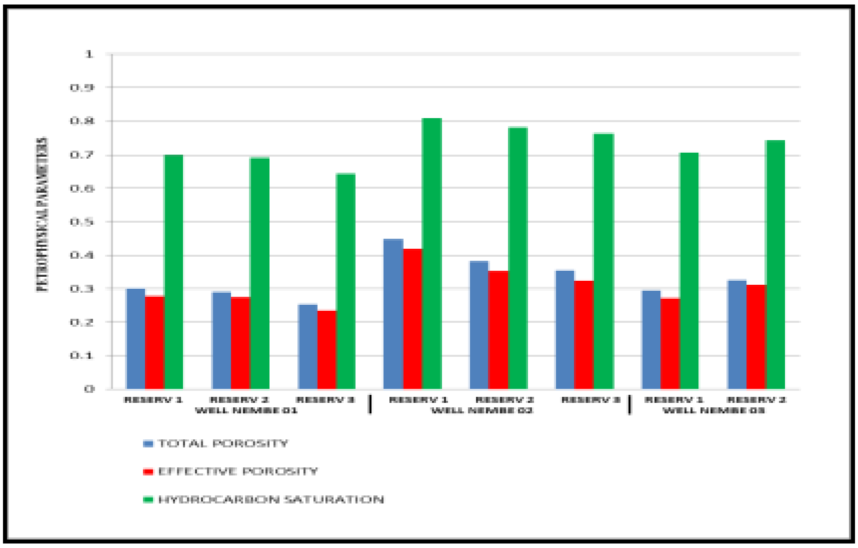

Figure 10: Combined Bar chart showing Variations of Reservoir Properties in Well NEMBE 01, 02 & 03

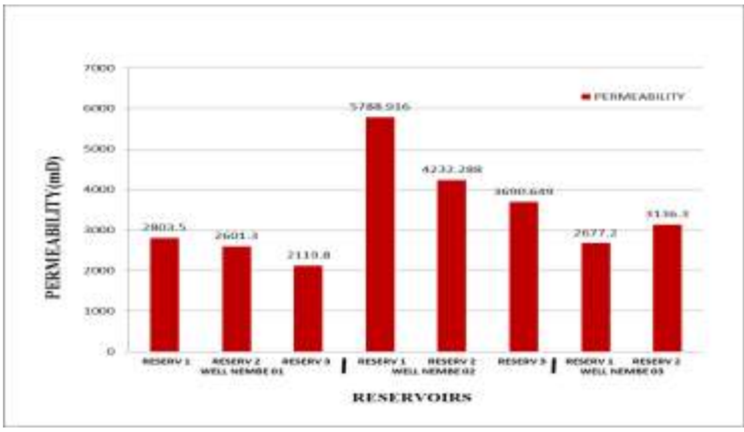

Figure 11: Bar chart showing Variations of Reservoir Permeabilities of Wells NEMBE 01, 02 & 03

IV. Conclusion And Recommendation

The three wells investigated reveal eight reservoirs consisting of sandstones and shaly-sands in alternating sequence. Porosity, permeability, hydrocarbon saturation, reservoir thickness (pay zone) and volume of shale were estimated in order to characterize the reservoirs' potential of this field. In all the wells, it was observed that high porosity corresponds to high permeability. Reserv 1 of NEMBE 02 has the highest porosity value of 45% which is very good to excellent (Rider, 1986) and the highest permeability value of 5789 mD which was also excellent (Rider, 1986). It can be concluded from the results that NEMBE 02 reservoirs are more prolific than NEMBE 01 & 03 in terms of hydrocarbon prospectivity.

A quick look evaluation through porosity-depth, permeability-depth and permeability-porosity cross-plots generally reveals decrease in porosity and permeability with depth due to increase in compaction with depth of burial of materials. Permeability was also noticed to increase with increasing porosity which is in agreement with the results of previous researches in Niger Delta. Further research should be conducted with geostatistical and other geoscientific techniques employing more wells, core and seismic data for unbiased estimation of the petrophysical parameters in this field. With more data, the results can be verified and uncertainties reduced.

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