COMPARATIVE ANALYSIS OF HYDROCARBON POTENTIAL IN SHALY SAND RESERVOIRS USING ARCHIE AND SIMANDOUX MODELS: A CASE STUDY OF "X" FIELD, NIGER DELTA, NIGERIA

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ABSTRACT

The comparative analyses of four wells in "X" Field within the Niger Delta were carried out with the aim of determining the hydrocarbon potential of the shaly-sand reservoirs using the Archie and Simandoux Models. The plots of effective porosity against volume of shale were used to determine the clay distribution. Composite logs comprising gamma ray, resistivity and porosity logs (density and neutron) were utilized to generate petrophysical properties in four (4) wells using Simandoux and Archie Models. Also, statistical analysis of water saturation values for both models were analysed and compared. The results of the plots of effective porosity against shale volume reveal decrease in effective porosity against increase in shale volume. The trends of the plots indicate laminated shale distribution mainly while only one hydrocarbon zone in well 3 denotes dispersed shale. Both models show very good to excellent porosity values (21-36%), and favourable hydrocarbon movability index (0.09-0.43). The statistical analyses show lower standard deviation and mean values of water saturation for Simandoux (0.008-0.2) and (0.03-0.2) when compared with that of Archie Model (0.08-0.24) and (0.15-0.5) which is indicative of higher hydrocarbon saturation than the Archie Model. At 5% error level, statistical test of difference between mean and standard deviation for both Models computed reveal t- statistics range of -20.6 to 1.8 for mean and f- statistics range of 0.005 to 11.5 for standard deviation. Their respective P (probability) - values are less than 0.05, indicating statistically significant difference between mean and standard deviation of the two models. The study reveals that the Simandoux Model has favourable petrophysical parameters indicating higher hydrocarbon potential than the Archie Model. This model could be a valuable tool in a shaly sand environment.

Keywords: Hydrocarbon Reservoir, Simandoux and Archie Models, Petrophysical Evaluation

INTRODUCTION

Petrophysics studies the physical and chemical characteristics that describe the occurrence and behaviour of rocks, soil and fluids. Petrophysics also refers to the careful and purposeful use of rock physics data and theory in the interpretation of reservoir geophysics observation (Aigbedion and Iyayi, 2007). Geophysical well logging was first introduced to the Petroleum Industry by Marcel and Conrad Schlumberger in 1927. The main purpose of well logging is the identification and evaluation of the potential hydrocarbon bearing formations. The potential of a zone is measured by estimating its water saturation, S_w and other petrophysical parameters (Ipek, 2002). The objective of the petrophysical interpretation of well log is to obtain parameters such as porosity, water saturation and hydrocarbon saturation from the composite log. In order to do this, each log on the oil well log must be distinguished, and its function must be known. The logs that will be explained are the ones that are mostly needed by petrophysicists. They include: gamma-ray, resistivity, neutron, density and sonic logs (Hamada, 1999). The aim of this study is to evaluate four wells in a typical Niger Delta field using the Archie and Simandoux models to estimate the petrophysical parameters with a view to determining the hydrocarbon potential in the shaly sand reservoirs.

The Niger Delta region is known for its proficiency in hydrocarbon production among the sedimentary basins in Nigeria. The formations in the Niger Delta Basin consist of sand and shales with sand ranging from fluvial (channel) to fluviomarine (barrier bar), while shale are generally fluviomarine holomarine or lagoonal. Three major stratigraphic units have been recognized in the Niger Delta oil and natural gas province. They are namely Akata, Agbada and Benin Formations (Short and Stauble, 1967). The study area is marked X within the western region of the Niger Delta as shown in Figure 1.

The interpretation of shaly-sands log data has long been a challenge. As a result, there are more than 30 shaly-sand interpretation models, which have been developed in the last 50 years. Interpretation difficulties arise whenever the portions of clay minerals in a shaly-sand formation are high. These clay minerals contribute to the increase of the overall conductivity. In a large quantity, their conductivity becomes as important as the conductivity of the formation water (Kurniawan, 2002). Shaliness is known to affect both formation characteristics and logging tool response.

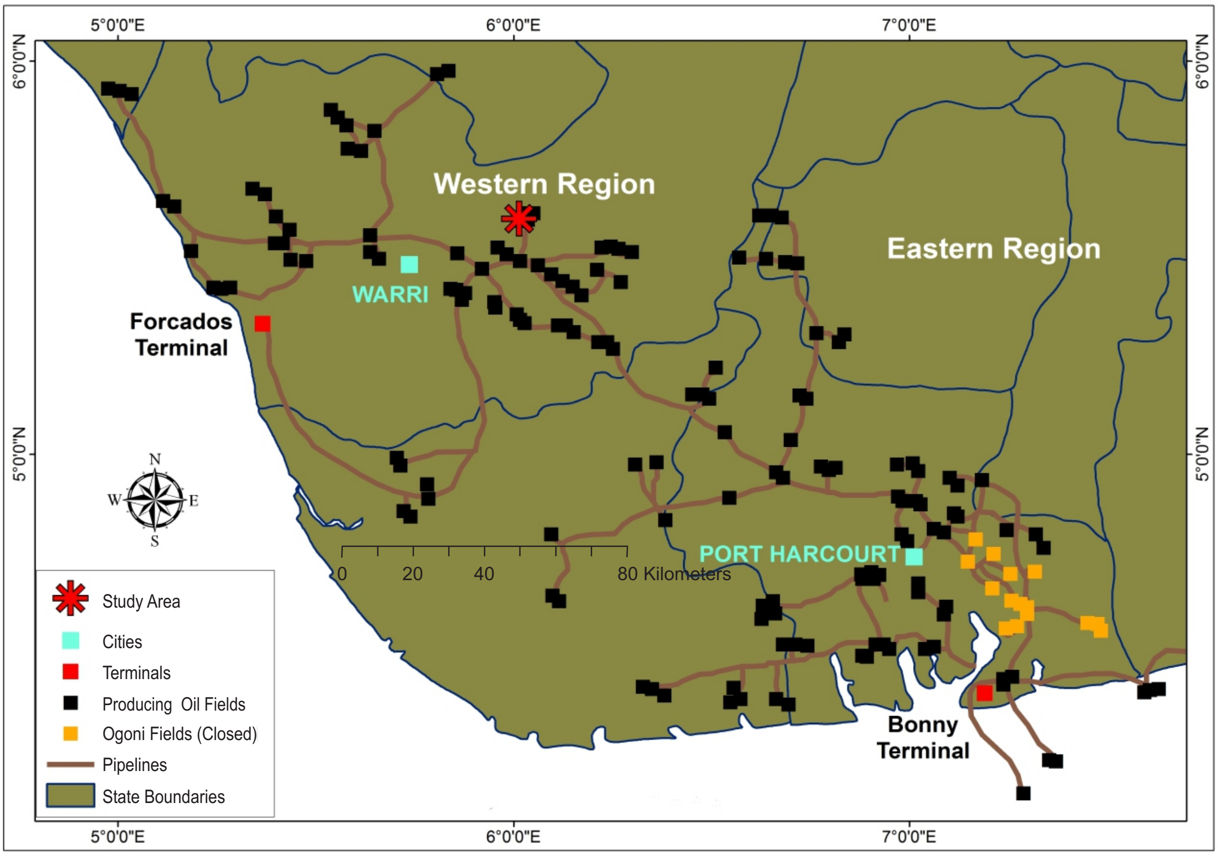

Figure 1: A Map of Niger Delta showing Oil Fields and Pipelines (After Urhobo Historical Society, 2008).

This has now made the volume of shale (V_{sh}) calculation from logs critical because of its further influence on the computation of important petrophysical properties such as porosity and water saturation. It is applied to most widely used shaly sand saturation equations such as Simandoux, Waxman-Smit and Dual-water to characterize excess conductivity. There are a number of ways volume of shale is derived from log measurements, using gamma ray, spontaneous potential, neutron-density combination, resistivity and combination of different methods. The most frequently used technique for deriving volume of shale in the Niger Delta, due to measurement availability, is from gamma ray and neutron density logs (Adeoti *et al.*, 2009).

The way shale affects a log response is controlled by the type of shale, shale volume and mode of shale distribution. There are two types of shale, namely, effective shale (montmorillonite and bentonite) and passive shale (kaolinite and chlorite). Apart from shale effects on porosity and permeability, the electrical properties of reservoir rocks are also affected by the existence of shale. The way shaliness affects log responses depend on the proportion of shale, the physical properties of shale, and the way it is distributed in the host layer (Hamada, 1999). Shaly material can be distributed in the host layer in three ways (laminar, structural, and dispersed).

Archie formula has been widely used by many log analysts especially when dealing with clean sand reservoir. This empirical formula provided the early basis of the quantitative petrophysical reservoir evaluation (Kurniawan, 2002). The occurrence of shale in reservoir rocks can result in erroneous values of water saturation and porosity as calculated from well logs. Derived log porosity value is computed from two terms, an effective porosity and a shale porosity (shale porosity and shale volume). Therefore, in order to obtain the effective porosity of a shaly sand, both shale volume and shale porosity should be accurately defined (Hamada, 1999). Estimation of the amount of nonconductive and conductive constituents in the pore space of sediments, using electrical resistivity logs, generally loses accuracy when clays are present in the reservoir (Lee and Collett, 2006). Many different methods and clay models have been proposed to account for the conductivity of clay.

The Simandoux Model, a volume of shale model of the shaly-sand analysis, introduced in 1963 is still widely used to some extent. This model basically uses porosity from density-neutron data and shale fraction determined from Gamma Ray, Self Potential, or other shale indicators. However, to accommodate the non-linear zone, several V_{sh} models have also been introduced by various log analysts (Kurniawan, 2002). Comparative performance of any equation model is debatable due to the typical situation of limited subsurface information and the variety of shaly sandstones, However, if models are used from the point of view of utility, then the calibration within a shaly sandstone reservoir can be made as an optimization problem based on a provisional recognition of water zones (Doveton, 2002). In the past, the Archie Model (clean sand model) was used to estimate water saturation of four wells (shaly sand reservoirs) and was later discovered that the water saturation was overestimated. The core data was not provided to establish the clay distribution in order to apply the appropriate model. This now informed the application of the Simandoux Model to estimate water saturation in shaly sand reservoir based on the plots of effective porosity against the volume of shale within the reservoirs of interest. Also, the Archie Model was applied in the study in order to compare the result of both models.

GEOLOGY OF NIGER DELTA

The Niger Delta is a prograding depositional complex within the Cenozoic Formation of Southern Nigeria. It covers an area of about 75,000 square kilometers. It extends from the Calabar Flank and the Abakaliki Trough in Eastern Nigeria to the Benin Flank in the west and it opens to the Atlantic Ocean in the southern territory. The delta protrudes into the Gulf of Guinea as an extension from the Benue Trough and Anambra Basin Provinces (Evamy *et al.*, 1978). The Niger Delta Basin is situated in the Gulf of Guinea and extends throughout the Niger Delta oil and gas province. From the Eocene to the present (Fig. 2), the delta has prograded southwestward, resulting in depobelts that represent the most active portion of the delta at each developmental stage (Doust and Omatsola, 1990). There are three major lithostratigraphic units recognized in the Niger Delta: Akata, Agbada and Benin Formations (Short and Stauble, 1967) (Fig. 2). The Akata Formation is a shale unit recognised as the major source of oil and gas. The Agbada Formation consists of sands and shales units, while the Benin Formation is composed mainly of sands. These lithostratigraphic units form one of the largest regressive deltas in the world with an area of some 500,000 km^2 (Kulke, 1995), a sediment volume of about 500,000 km^3 and a sediment thickness of more than 10 km in the basin depocenter (Kaplan *et al.*, 1994). The Niger Delta Province contains only one identified petroleum system. This system is referred to here as the Tertiary Niger Delta (Akata–Agbada) Petroleum System. The Tertiary Niger Delta is a sedimentary structure formed as a complex regressive off-lap sequence of clastic sediments ranging in thickness from 9,000 – 12,000 m (Etu-Efeotor, 1998). Starting from different depocentres, the Niger Delta Basin has coalesced to form a single united system since Miocene era. Due to the history or relative unbroken progradation throughout the Tertiary period, these three depositional lithofacies are readily identified despite local facies variations, as three regional and diachronons formations ranging from Eocene to Recent age (Short and Stauble, 1967).

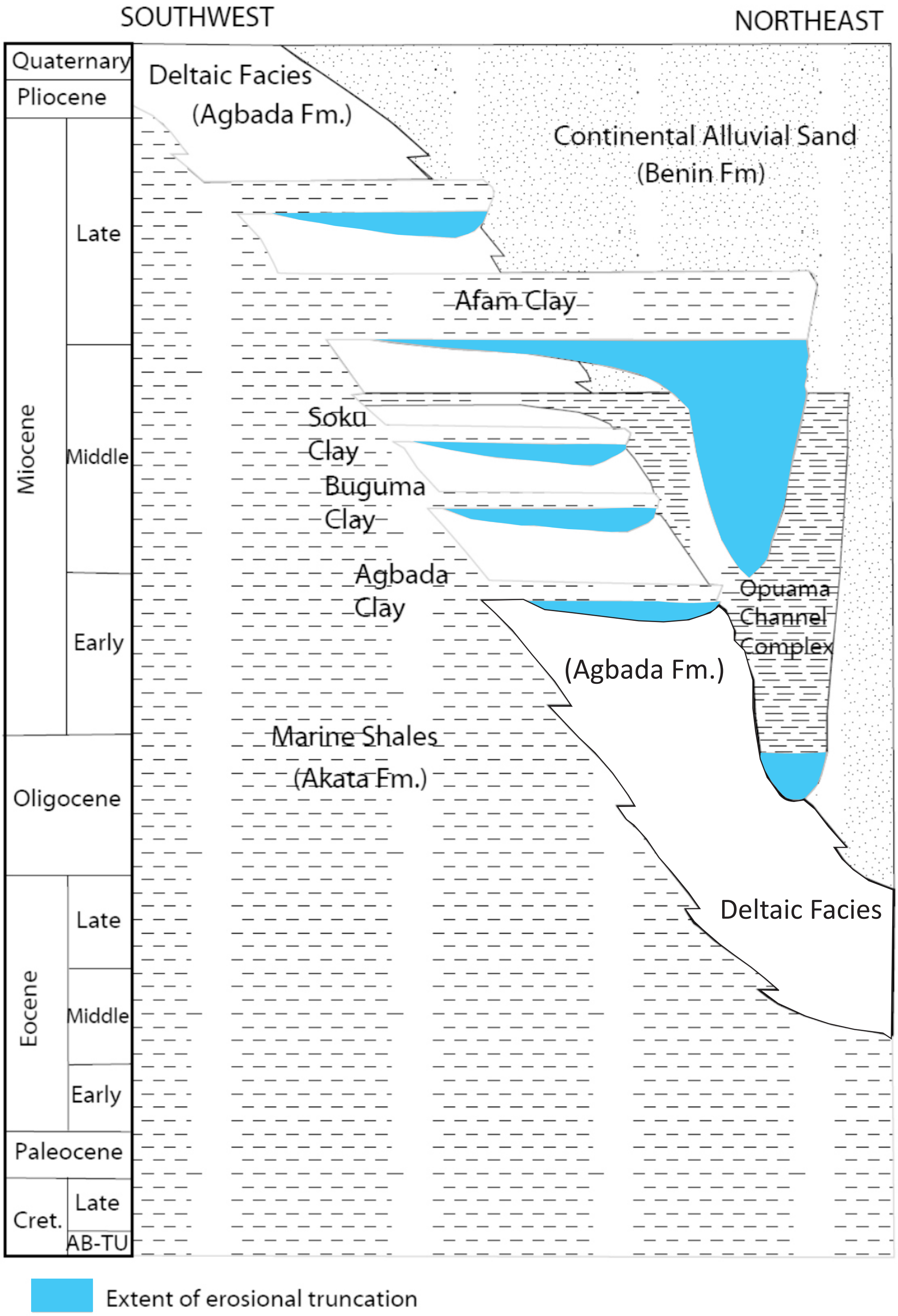

Figure 2: Stratigraphic Column Showing Formations of the Niger Delta (Modified from Doust and Omatsola,1990).

MATERIALS AND METHODS

The data used for this research were obtained from Chevron Nigeria Limited via Department of Petroleum Resources (DPR). The data consist of well logs from four wells (1, 2, 3 and 4) which comprise gamma, resistivity, neutron and density logs. In the absence of core data, the plot of effective porosity against volume of clay/shale (via Excel) was used to establish the clay/shale distribution within the zones of interest in the study area. The plots were guided using the pattern of plot of effective porosity against clay content proposed by Chevron (1996) in Figure 3.

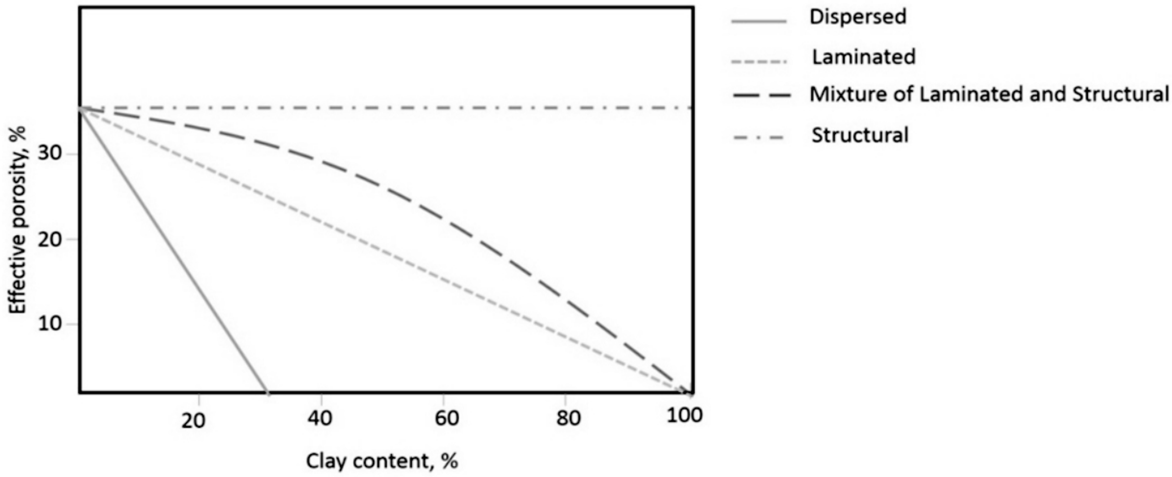

Figure 3: Graph of Effective Porosity against Clay Content (After Chevron, 1996).

The data were loaded, processed and interpreted with the use of Geolog software. After the data were loaded, the images were calibrated (on the Geolog) that is, depth and the scale axes were set and the grid was created. The reservoirs of interest were delineated using a combination of lithology, resistivity and porosity logs. The gamma ray log was used to identify the lithologies penetrated by the wells. Gamma ray is high in non–permeable beds (shale) because of the radioactive element such as potassium and thorium that accumulate in the pore spaces of the non–permeable beds (low permeability) while for permeable formations (sand) which have lower radioactivity characterized by deflection to the left (low gamma) (Schlumberger, 1972). Hydrocarbon bearing sands were identified by low gamma with high resistivity while water bearing sands were identified by low gamma with low resistivity. The clay volume analysis or volume of shale analysis was carried out using the gamma ray, resistivity and porosity logs. The clay volume and volume of shale are used interchangeably in the study. The details of the analysis are shown in equations 1-3.

The volume of shale (V_{sh}) from natural gamma ray was calculated using the formula expressed in equation (1) (Asquith and Gibson, 1982).

$$V_{sh}\ \text{linear} = \frac{GR - GR_{cl}}{GR_{sh} - GR_{cl}} \quad (1)$$

where

GR is the gamma ray log reading in the zone of interest,

GR_{cl} is the gamma ray log reading in 100% clean zone,

GR_{sh} is the gamma ray log reading in 100% shale zone.

The volume of shale from neutron-density combination was calculated by using the relation in equation (2) (Adeoti *et al.,* 2009).

$$V_{sh}\ \text{neutron-density} = \frac{\phi_n - \phi_d}{\phi_{nsh} - \phi_{dsh}} \quad (2)$$

where

ϕ_d = density porosity in the sand

ϕ_n = neutron porosity in the sand

ϕ_{dsh} and ϕ_{nsh} are density and neutron porosities in adjacent shale respectively.

The volume of shale from Resistivity was calculated by applying the formula expressed in equation (3) (Adeoti *et al.,* 2009).

$$V_{sh}\ \text{resistivity} = \frac{\log(\text{RESD}) - \log(\text{RESD\_CLN})}{\log(\text{RESD\_SHL}) - \log(\text{RESD\_CLN})} \quad (3)$$

where
RESD = resistivity log reading from zone of interest
RESD_CLN = resistivity log reading from clean sand
RESD_SHL = resistivity log reading from shale.

The volume of shale Total (VSH) was estimated from the combination of volume of shale from the gamma, resistivity and neutron-density logs (Adeoti *et al.,* 2009). It is represented by VSH_1 as shown in track 1 of Figure 5.

Water saturation analyses were carried out using water saturation from Archie and Simandoux equations. The Archie equation (Archie, 1942) is presented in equation (4) while the water saturation from Simandoux equation (Dewan, 1983) is expressed in equation (5).

$$S_w = \sqrt{\frac{F \times R_W}{R_t}} \quad (4)$$

where
R_w = resistivity of the formation water
R_t = true formation resistivity
F = formation factor.

The Simandoux equation for water saturation is expressed in equation (5).

$$S_w = \frac{C.R_W}{\phi_e^2}\left[\sqrt{\frac{5\ \phi_e^2}{R_W \cdot R_t} + \left(\frac{V_{sh}}{R_{sh}}\right)^2} - \frac{V_{sh}}{R_{sh}}\right] \quad (5)$$

where
C = 0.40 for sand and 0.45 for carbonate
V_{sh} = lowest of the various shale indicators
R_t = deep resistivity (corrected for invasion)
R_{sh} = deep resistivity reading in adjacent scale
ϕ_e = effective porosity.

The effective porosity used in Simandoux Model was determined from equation (6).

$$\text{Effective Porosity} = \sqrt{\frac{\phi_{dc}^2 + \phi_{nc}^2}{2}} \quad (6)$$

where
ϕ_{dc} and ϕ_{nc} represent density and neutron porosities corrected for shale given by equations (7) and (8) (Dewan, 1983):

$$\phi_{dc} = \phi_d - V_{sh} \cdot \phi_{dsh} \quad (7)$$

$$\phi_{nc} = \phi_n - V_{sh} \cdot \phi_{nsh} \quad (8)$$

where
ϕ_d and ϕ_n are density and neutron porosities obtained from the zone of interest,
ϕ_{dsh} and ϕ_{nsh} are the corresponding values in adjacent shales.

Hydrocarbon Saturation (S_h) was determined using equation (9) (Asquith and Gibson, 1982).

$$S_h = 1 - S_w \quad (9)$$

Water of flushed zone (S_{xo}) was computed by applying equation (10) (Asquith and Gibson, 1982).

$$S_{xo} = S_w^{0.2} \quad (10)$$

Residual hydrocarbon saturation (S_{hr}) was obtained by using equation (11) (Asquith and Gibson, 1982).

$$S_{hr} = 1 - S_{xo} \quad (11)$$

Movable oil saturation (MOS) was calculated from equation (12) (Asquith and Gibson, 1982).

$$MOS = S_{xo} - S_w \quad (12)$$

Hydrocarbon Movability Index (HMI) was calculated from equation (13) (Asquith and Gibson, 1982).

$$HMI = \frac{S_w}{S_{xo}} \quad (13)$$

Bulk Volume Water (BVW) was determined using equation (14) (Asquith and Gibson, 1982).

$$BVW = \phi_{ND} S_w \quad (14)$$

The qualitative evaluation of porosity in reservoir rocks as presented in Table 1 was used as a guide for porosity classification

Table 1: Qualitative Evaluation of Porosity in Reservoir Rocks (Ulasi *et al.*, 2012).

Percentage Porosity (%)	Qualitative Evaluation
0 to 5	Negligible
5 to 10	Poor
15 to 20	Good
20 to 30	Very Good
Over 30	Excellent

The results of each model were then compared.
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Statistical Analysis of Water Saturation Using Both Models

The statistical analysis was carried out to determine various statistics of water saturation from Simandoux and Archie models. The mean and standard deviation were estimated via interval data of each hydrocarbon zone as shown in equations (15 and 16) (Black, 2009).

$$\overline{x} = 1/n\,(x_1 + x_2 + ... + x_n) \quad (15)$$

$$\text{Standard Deviation} = \left\{\sqrt{\frac{\sigma^2}{n_1} + \frac{\sigma^2}{n_2}}\right\} \quad (16)$$

where

σ = variance of the two set of values i.e. Simandoux and Archie.

The variance was computed by using the relation expressed in equation (17).

$$\sigma = (x - \overline{x})^2 \quad (17)$$

x = each of the values

$\overline{x}$ =mean of the given values.

The density distribution of standard deviation for water saturation of both models was done using statistical software called statgraphics.

RESULTS AND DISCUSSION

The sample results of the clay distribution analyses are presented in Figures 4 (a - c). The sample log display of well 1 is shown in Figure 5. The summary of petrophysical analyses of wells (1-4) for Simandoux is shown in Table 2 while the summary of petrophysical analysis of wells (1-4) for Archie is presented in Table 3. The results of the statistical analyses of the four wells (1 – 4) for Simandoux are presented in Table 4 while the results of the statistical analysis of the four wells (1-4) for Archie are shown in Table 5. Summary of Statistical Test is shown in Table 6 while Sample of the variations of standard deviation of water saturation for both Models is displayed in Figure 6.

Clay Distribution

Samples of the plots of effective porosity against volume of shale for zone 1 and zone 2 in wells (1-4) are shown in Figures 4 (a and b) while zone 4 in well 3 is displayed in Figure 4c. The plots reflect decrease in effective porosity with increase in volume of shale. The sampled patterns as shown in Figures 4 (a and b), when compared with Figure 3, reflect laminated shale. Laminated shale is distributed in discrete thin beds sandwiched in between the sandstone. However, Figure 4c shows increase in effective porosity with decrease in volume of shale, reflecting dispersed shale when also compared with Figure 3. Dispersed shale is as a result of clay overgrowths on the sand grains.

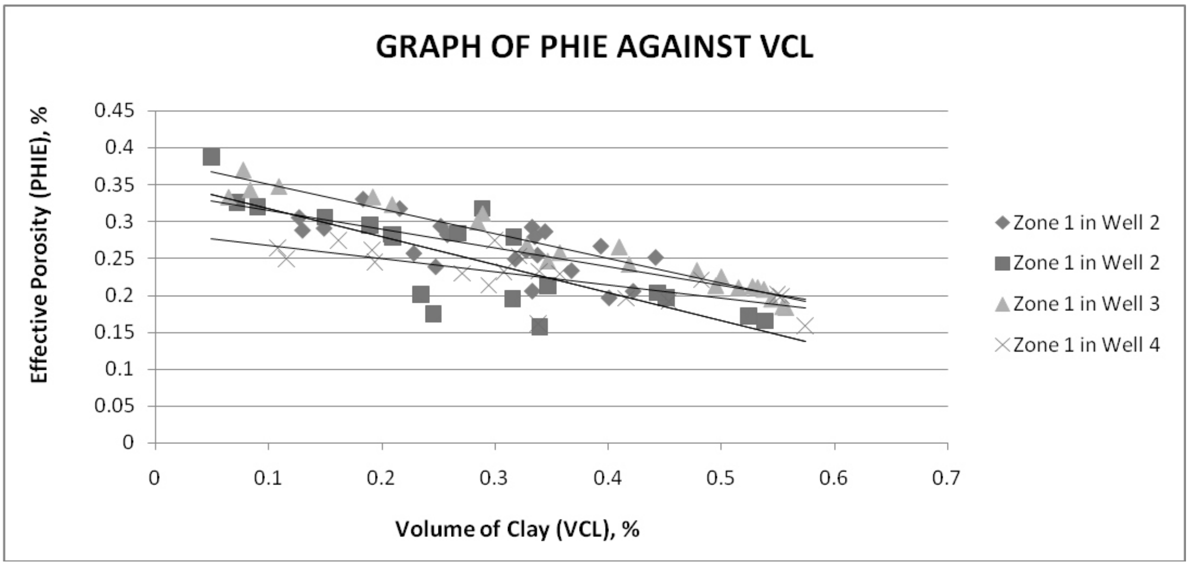

Figure 4a: Graph of Effective Porosity (PHIE) against Volume of Clay (VCL) for Zone 1 of Wells (1-4).

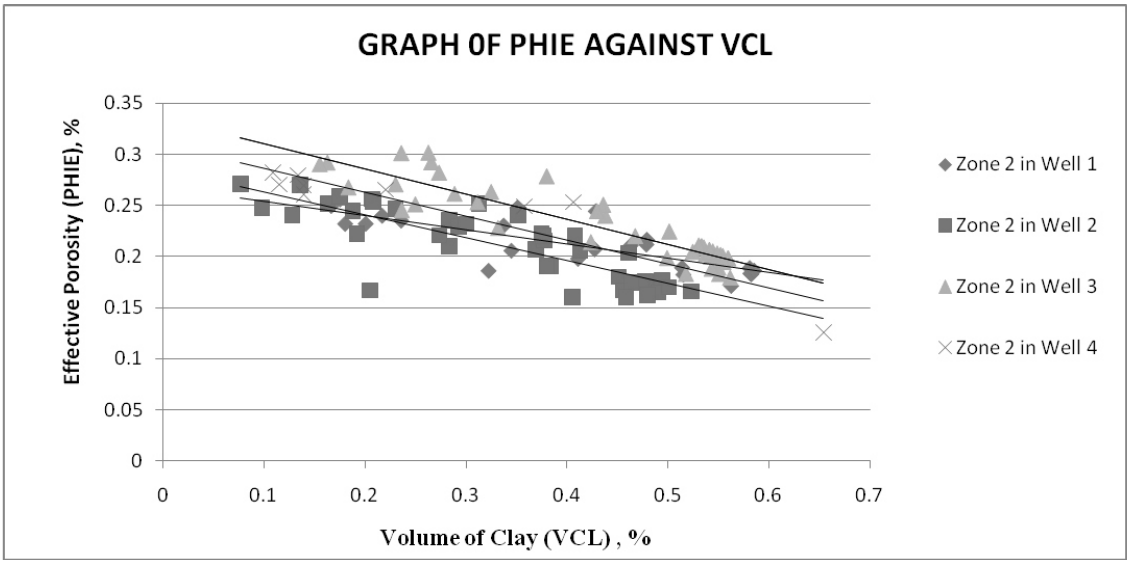

Figure 4b: Graph of Effective Porosity (PHIE) against Volume of Clay (VCL) for Zone 2 of Wells (1-4).

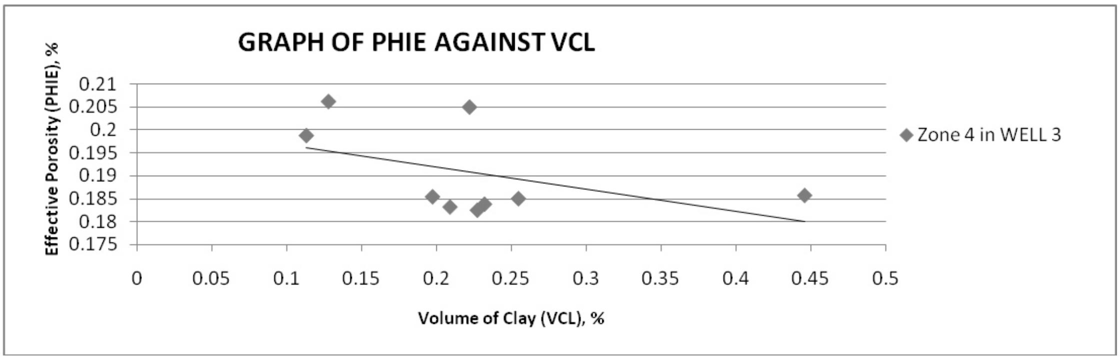

Figure 4c: Graph of Effective Porosity (PHIE) against Volume of Clay (VCL) for Zone 4 of Well 3.

Petrophysical Analysis of Simandoux and Archie Models

A sample log displaying some petrophysical parameters for well 1 is shown in Figure 5. The petrophysical parameters generated for Simandoux Model are shown in Table 2 while the petrophysical parameters generated for Archie are presented in Table 3. The zones in all the wells are not laterally correlated due to different fault compartments. However, results of petrophysical analyses (Tables 2 and 3) for wells (1-4) show that porosity values in zone 1 falls within very good to excellent porosity values (25-31%) as shown in Table 1. This shows that the grain sizes of various sands are spherical and very porous to accommodate hydrocarbon. The Simandoux Model gave lower estimation of water saturation values (5-13%) than Archie Model (1-21%), higher hydrocarbon saturation values range for Simandoux Model (87-95%) than for Archie (79-90%) , lower range of bulk volume water values (0.02-0.04) for Simandoux than Archie (0.03-0.07) revealing that the hydrocarbon produced by Simandoux Model would be more water free than that produced by Archie. Also, the analysis shows higher movable hydrocarbon saturation values (0.53-0.535) for Simandoux than for Archie (0.5-0.53) and lower hydrocarbon movability index (0.09-0.2) for Simandoux than for Archie (0.15-0.33**).**

The results of petrophysical values shown in Tables 2 and 3 reveal the same trend in Zones 2-4 in wells 1-4 and Zone 5 of wells 2 and 4 when compared with Zone 1 in the four wells except variation in their values. The analysis underscores that Simandoux Model has more favourable petrophysical values than Archie Model.

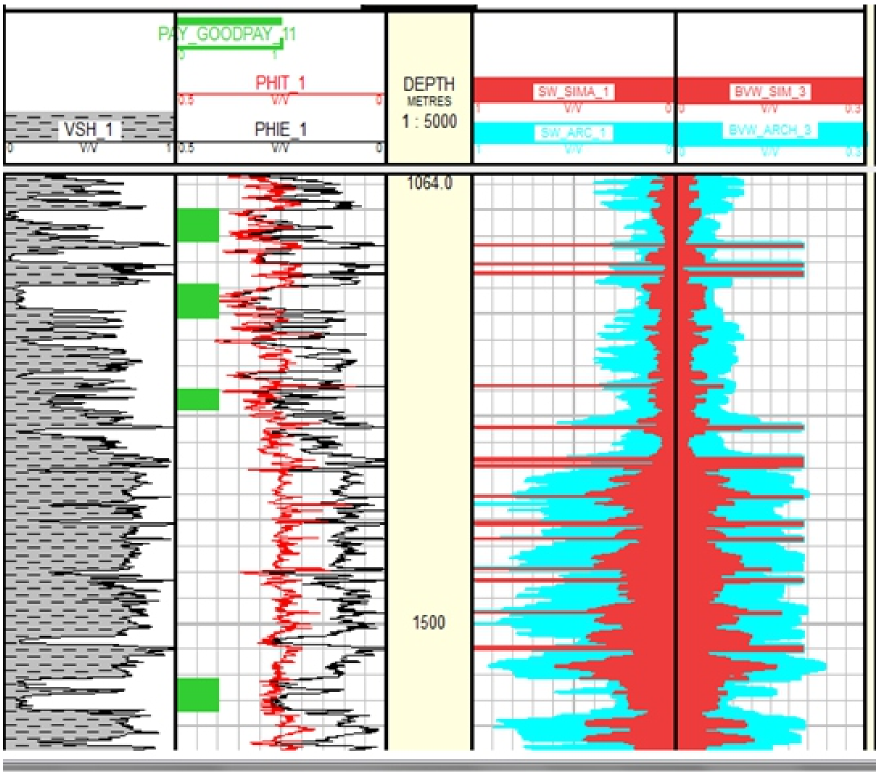

Figure 5: Porosity and Water Saturation Analysis for Well 1.
VSH - Volume of shale log, CAL – Caliper log, PHIT – Total porosity log, PHIE – Effective porosity log, SW_SIMA – Water saturation (Simandoux) log, SW_ARC - Water saturation (Archie) log, BVW_SIMA – Bulk volume water (Simandoux) log and BVW_ARC – Bulk volume water (Archie) log are meanings of petrophysical symbols displayed in Figure 5.

Table 2: Petrophysical analysis (Simandoux) of Wells (1- 4).

WELL	ZONE	TOP DEPTH (m)	BASE DEPTH (m)	NET (m)	PHT AVG	VSH AVG	PHIE AVG	BVW_SIMA AVG	SW_ SIMA AVG	F	Sh_ SIMA	Sxo_ SIMA	MOS_ SIMA	HMI_ SIMA
1	1	1099.57	1128.52	28.96	0.31	0.22	0.27	0.02	0.07	13.7	0.93	0.5875	0.53	0.1191
	2	1172.57	1203.05	30.48	0.32	0.17	0.29	0.03	0.11	11.9	0.89	0.6431	0.5331	0.171
	3	1274.37	1291.59	17.22	0.31	0.35	0.24	0.03	0.09	17.4	0.91	0.6178	0.5278	0.1457
	4	1554.18	1583.89	29.72	0.27	0.21	0.23	0.06	0.22	18.9	0.78	0.7387	0.5187	0.2978
2	1	1074.27	1138.13	63.86	0.32	0.3	0.28	0.03	0.1	12.8	0.9	0.631	0.531	0.158
	2	1144.68	1236.27	91.59	0.38	0.14	0.36	0.06	0.15	7.72	0.85	0.684	0.534	0.219
	3	1295.71	1357.89	62.18	0.32	0.2	0.29	0.05	0.17	11.9	0.83	0.702	0.532	0.242
	4	1465.03	1486.06	21.03	0.27	0.4	0.21	0.05	0.17	22.7	0.83	0.702	0.532	0.242
	5	1570.79	1593.96	23.16	0.3	0.19	0.27	0.03	0.11	13.7	0.89	0.643	0.533	0.171
3	1	1086.42	1127.11	40.69	0.34	0.28	0.31	0.02	0.05	10.41	0.95	0.549	0.53	0.09
	2	1153.78	1215.35	61.57	0.32	0.27	0.29	0.03	0.09	11.89	0.91	0.618	0.53	0.15
	3	1304.81	1341.23	36.42	0.3	0.21	0.27	0.04	0.14	13.72	0.86	0.675	0.53	0.21
	4	1548.65	1584.92	36.27	0.32	0.3	0.28	0.05	0.15	12.76	0.85	0.684	0.53	0.22
4	1	1311.6	1329.1	17.5	0.29	0.29	0.25	0.04	0.13	16	0.87	0.66	0.535	0.196
	2	1426.3	1436.8	10.5	0.27	0.37	0.22	0.05	0.19	20.7	0.81	0.72	0.527	0.265
	3	1534.5	1572.2	37.6	0.29	0.23	0.26	0.04	0.15	14.8	0.85	0.68	0.534	0.219
	4	1587.7	1593.2	5.49	0.3	-0.2	0.32	0.05	0.16	9.77	0.84	0.69	0.54	0.231
	5	1620	1630.9	11	0.3	-0	0.31	0.05	0.17	10.4	0.83	0.7	0.532	0.242

PHT – Total porosity, VSH AVG – Average volume of shale, PHIE AVG – Average effective porosity, BVW_SIMA AVG – Average bulk volume water from Simandoux, SW_SIMA AVG – Average water saturation from Simandoux, F- Formation Factor, Sh_SIMA – Hydrocarbon saturation from Simandoux, Sxo_ SIMA- Water saturation of flushed zone from Simandoux, MOS_SIMA - Movable hydrocarbon saturation from Simandoux and MHI_SIMA Movable hydrocarbon index from Simandoux Model are the meanings of the petrophysical symbols presented in Table 1. The same is applicable to Archie Model with the inclusion of ARC to differentiate it from Simandoux Model which has SIMA attached to the petrophysical symbols as shown in Table 3.

Table 3: Petrophysical analysis (Archie) of Wells (1 – 4).

WELL	ZONE	TOP DEPTH (m)	BASE DEPTH (m)	NET (m)	PHIT AVG	VSH AVG	PHIE AVG	BVW_ARC AVG	SW_ARC AVG	F	Sh_ ARC	Sxo_ ARC	MOS_ ARC	HMI_ ARC
1	1	1099.57	1129	28.96	0.31	0.2	0.27	0.05	0.15	13.7	0.85	0.684	0.52	0.219
	2	1172.57	1203	30.48	0.32	0.2	0.29	0.06	0.18	11.9	0.82	0.71	0.50	0.254
	3	1274.37	1292	17.22	0.31	0.4	0.24	0.07	0.23	17.4	0.77	0.745	0.5153	0.309
	4	1554.18	1584	29.72	0.27	0.2	0.23	0.09	0.33	18.9	0.67	0.801	0.4711	0.412
2	1	1074.27	1138.13	63.86	0.32	0.3	0.28	0.07	0.21	12.8	0.79	0.73	0.522	0.287
	2	1144.68	1236.27	91.59	0.38	0.14	0.36	0.07	0.2	7.72	0.8	0.72	0.525	0.276
	3	1295.71	1357.89	62.18	0.32	0.2	0.29	0.08	0.25	11.9	0.75	0.76	0.508	0.33
	4	1465.03	1486.06	21.03	0.27	0.4	0.21	0.09	0.35	22.7	0.65	0.81	0.461	0.432
	5	1570.79	1593.96	23.16	0.3	0.19	0.27	0.05	0.18	13.7	0.82	0.71	0.52	0.254
3	1	1086.4	1127.1	40.69	0.34	0.28	0.31	0.03	0.1	10.4	0.9	0.63	0.5	0.158
	2	1153.8	1215.4	61.57	0.32	0.27	0.29	0.05	0.15	11.9	0.85	0.68	0.52	0.219
	3	1304.8	1341.2	36.42	0.3	0.21	0.27	0.06	0.21	13.7	0.79	0.73	0.522	0.287
	4	1548.7	1584.9	36.27	0.32	0.3	0.28	0.06	0.21	12.8	0.79	0.73	0.522	0.287
4	1	1311.6	1329.1	17.5	0.29	0.29	0.25	0.06	0.2	16	0.8	0.72	0.525	0.276
	2	1426.3	1436.8	10.5	0.27	0.37	0.22	0.07	0.28	21	0.72	0.78	0.495	0.361
	3	1534.5	1572.2	37.6	0.29	0.23	0.26	0.06	0.2	15	0.8	0.72	0.52	0.276
	4	1587.7	1593.2	5.49	0.3	-0.2	0.32	0.04	0.13	9.8	0.87	0.66	0.53	0.196
	5	1620	1631	11	0.3	-0	0.31	0.05	0.18	10	0.82	0.71	0.50	0.254

Statistical Analyses of Water Saturation Using Simandoux and Archie Models

Table 4 reflects the standard deviation and mean of water saturation for the Simandoux while Table 5 shows the standard deviation and mean of water saturation for Archie Model in wells (1-4). Figure 6 displays the sample of variation in standard deviation of water saturation for both models in Zone 1. The results of statistical analyses (Tables 4 and 5) for Zone 1 reveal higher standard deviation and mean range values for Archie Model (0.0093-0.24) and (0.15-0.21) which implies higher values of water saturation than the Simandoux Model with relative standard deviation and mean range of (0.0086-0.2) and (0.03-0.13). At 5% error level, the confidence intervals for mean and standard deviation using Simandoux are (0.0552604, 0.0685174) and (0.00862329, 0.0165202) respectively while the confidence intervals for mean and standard deviation using Archie are (0.141756, 0.156022) and (0.006268, 0.017778). Result of test of the specific hypothesis about the difference between mean and standard deviation for Simandoux and Archie Models computed reveal t- statistics to be -20.6 for mean and f-statistics to be 0.863548 for standard deviation while their respective P- values are 0 and 0.012247. Since the computed P-values are less than 0.05 for both mean and standard deviation of the two Models, then the null hypothesis of equal result is rejected, indicative of statistically significant difference between mean and standard deviation of the two Models at 95% confidence level. Hence, the two models are not the same which imply that Simandous Model with lower values of mean and standard deviation is more favourable than Archie Model. Also, the results of statistical analyses (Tables 4 and 5) reflect the same pattern in Zones 2-4 in wells 1-4 and Zone 5 of wells 2 and 4 when compared with Zone 1 in the four wells except variation in their values.

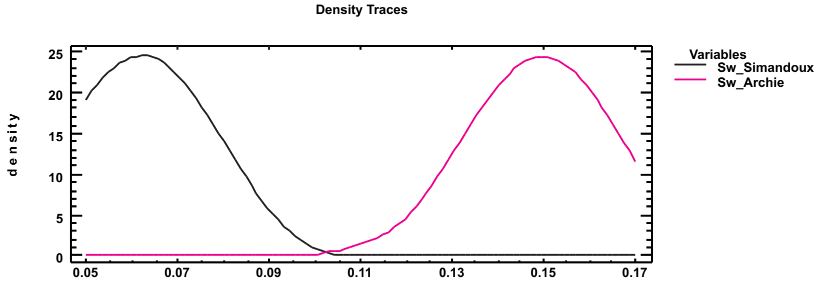

Figure 6: Density Distribution of Standard Deviation for Sw_Simandoux and Sw_Archie Zone 1.

Table 4: Statistical Analyses of Water Saturation Using Simandoux Model

Model	Wells	Zones	Mean	95% Confidence Interval For Mean		Standard Deviation	95% Confidence Interval For Standard Deviation	
				Lower Bound	Upper Bound		Lower Bound	Upper Bound
SIMANDOUX	1	1	0.0618889	0.0552604	0.0685174	0.00862329	0.00582466	0.0165202
		2	0.112222	0.102216	0.122228	0.0130171	0.00879248	0.0249377
		3	0.216667	0.0443577	0.388976	0.224165	0.151414	0.429448
		4	0.207778	0.0326721	0.382883	0.0187824	0.0126867	0.0359827
	2	1	0.0888889	0.0737847	0.103993	0.0196497	0.0132725	0.0376443
		2	0.105556	0.0740703	0.137041	0.0409607	0.0276672	0.0784712
		3	0.163333	0.15002	0.176647	0.0173205	0.0116993	0.0331821
		4	0.166667	0.155137	0.178197	0.015	0.0101319	0.0287365
		5	0.0966667	0.0880727	0.105261	0.0111803	0.00755184	0.0214189
	3	1	0.03	0.0172531	0.0427469	0.0165831	0.0112012	0.0317694
		2	0.0955556	0.0827444	0.108367	0.0166667	0.0112576	0.0319295
		3	0.124444	0.101671	0.147218	0.0180278	0.012177	0.034537
		4	0.15	0.102929	0.197071	0.0180278	0.012177	0.034537
	4	1	0.13	0.119129	0.140871	0.0141421	0.0095524	0.0270931
		2	0.193333	0.182463	0.204204	0.0141421	0.0095524	0.0270931
		3	0.148889	0.141756	0.156022	0.00927961	0.00626798	0.0177776]
		4	0.133333	0.118953	0.147714	0.0187083	0.0126366	0.0358407
		5	0.177778	0.15789	0.197666	0.0258736	0.0174765	0.0495679

Table 5: Statistical Analyses of Water Saturation Using Archie Model

Model	Wells	Zones	Mean	95% Confidence Interval For Mean		Standard Deviation	95% Confidence Interval For Standard Deviation	
				Lower Bound	Upper Bound		Lower Bound	Upper Bound
ARCHIE	1	1	0.148889	0.141756	0.156022	0.0372567	0.00626798	0.0177776
		2	0.195111	0.169305	0.220917	0.0335725	0.0226768	0.0643171
		3	0.350069	0.00166014	0.457216	0.3413852	0.201615	0.571832
		4	0.496958	0.291118	0.319993	0.227804	0.153871	0.436419
	2	1	0.208889	0.18385	0.233928	0.071743	0.0220028	0.0624056
		2	0.257111	0.108174	0.174049	0.080157	0.0289432	0.0820904
		3	0.233333	0.205619	0.261048	0.081429	0.0243539	0.069074
		4	0.341111	0.314361	0.367862	0.034801	0.0235066	0.0666707
		5	0.137778	0.106371	0.169185	0.0408588	0.0275984	0.0782761
	3	1	0.214667	0.0312256	0.344559	0.244438	0.165107	0.468287
		2	0.155221	0.102929	0.197071	0.0612372	0.0413631	0.117316
		3	0.213333	0.199476	0.227191	0.068801	0.020012	0.0567591
		4	0.213333	0.199476	0.227191	0.0612372	0.0413631	0.117316
	4	1	0.196667	0.17864	0.214694	0.0607551	0.0158409	0.0449287
		2	0.26	0.231239	0.288761	0.0374166	0.0252733	0.0716815
		3	0.213333	0.185619	0.241048	0.0360555	0.0243539	0.069074
		4	0.162222	0.141605	0.18284	0.0522239	0.0181174	0.0513856
		5	0.206667	0.15789	0.197666	0.0618568	0.0191048	0.0541861

Table 6: Summary of Statistical Test

WELL	ZONE	MEAN		STANDARD DEVIATION	
		P- VALUE	**T -VALUE**	**P-VALUE**	**F-VALUE**
1	1	0.00001	-20.6035	0.012247	0.863548
	2	3.50E-06	-6.90593	0.014697	0.150335
	3	4.47E-06	0.089296	0.035551	1.77302
	4	4.22E-06	-1.2833	1.43E-07	1.47102
2	1	5.89E-08	-9.46313	0.017146	0.363874
	2	3.88E-06	1.79943	0.01633	1.09437
	3	7.93E-05	-5.25	0.020412	0.230769
	4	2.62E-10	-13.8097	0.028296	0.18578
	5	0.010195	-2.91149	0.001388	0.074875
3	1	1.94E-06	-1.55102	3.05E-08	0.004603
	2	0.020405	-2.57361	0.001336	0.074074
	3	9.24E-07	-7.68911	0.018145	2.70085
	4	0.008907	-2.97639	0.002325	11.5385
4	1	1.77E-06	-7.30297	0.016394	0.363636
	2	1.31E-04	-5.0	0.012478	0.142857
	3	8.88E-05	-5.19287	8.96E-04	0.066239
	4	0.017463	-2.65017	0.010614	0.486486
	5	0.038057	-2.26087	0.014697	0.836806

CONCLUSION

The plots of effective porosity against volume of shale were used to determine the clay distribution. Composite logs comprising gamma ray, resistivity and porosity logs (density and neutron) were utilized to generate petrophysical properties in four (4) wells using Simandoux and Archie Models. Also, statistical analysis of water saturation values for both models were estimated and compared.

Well 1 has four hydrocarbon zones at depth intervals 1099.6 -1128.5 m in zone 1, 1172.6 - 1203.1 m in zone 2, 1274.4 -1291.5 m in zone 3 and 1554.2 -1583.9 m in zone 4. Well 2 has five hydrocarbon zones at depth intervals 1074.3-1138.1 m in zone 1, 1144.7-1236.3 m in zone 2, 1295.7-1357.9 m in zone 3, 1465 -1486.1 m in zone 4 and 1570.8 - 1593.9 m in zone 5. Well 3 has four hydrocarbon zones at depth intervals 1086.4 - 1127.1 m in zone 1, 1153.8-1215.4 m in zone 2, 1304.8 -1341.2 m in zone 3 and 1548.6 -1584.9 m in zone 3. Well 4 has five hydrocarbon zones at depth intervals 1311.6 -1329.1 m in zone 1, 1426.3 -1436.8 m in zone 2, 1534.5 -1572.2 m in zone 3, 1587.7 - 1593.2 m in zone 4 and 1620 -1630.9 m in zone 4.

The results of the plots of effective porosity against shale volume show decrease in effective porosity against increase in shale volume and these reflect shale distribution in thin beds sandwiched in between sandstones. The results of the petrophysical analyses of the four wells having a total of 18 hydrocarbon zones using both Archie and Simandoux Models show very good to excellent porosity values (21-36%) which reveal enough pore spaces to accommodate hydrocarbon, water saturation of (5-35%) which indicates high hydrocarbon saturation, bulk volume water (0.02-0.09) which shows high tendency of producing free water hydrocarbon, movable hydrocarbon saturation (0.49-0.54) and favourable movable hydrocarbon index (0.09-0.43). The statistical analyses show lower standard deviation and mean values of water saturation for Simandoux (0.008-0.2) and (0.03-0.2) when compared with that of Archie Model (0.08-0.24) and (0.15-0.5). This is indicative of higher hydrocarbon saturation than the Archie Model. At 5% error level, the confidence intervals for mean using Simandoux and Archie are (0.017, 0.4) and (0.0017, 0.46) while that of standard deviation for both Models are (0.0058, 0.42) and (0.006, 0.57) respectively. Tests of the specific hypothesis about the difference between mean and standard deviation for both Models computed reveal t-statistics range of -20.9 to 1.8 for mean and f-statistics range of 0.005 to 11.5 for standard deviation while their respective P- values are less than 0.05, indicative of statistically significant difference between mean and standard deviation of the two models. Hence, the two models are not the same which signifies that Simandoux Model with lower values of mean and standard deviation is more favourable than Archie Model in shaly sand reservoir.

The study reveals that the Simandoux Model has favourable petrophysical parameters indicating higher hydrocarbon potential than Archie Model. This implies that the Simandoux Model could be a valuable tool in a shaly sand environment.

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