Petrophysical Characterization of the Reservoirs of ‘‘Fuja’’ Field, Offshore Niger Delta, Southern Nigeria

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Abstract:- In order to have a good understanding of the rock properties of the reservoirs of ‘‘Fuja’’ Field, offshore Niger Delta, an evaluation of the petrophysical properties of this reservoir including total porosity, effective porosity, permeability, volume of shale, water saturation, hydrocarbon saturation and bulk volume of water was carried out. Bulk density and gamma ray logs from four different wells within the field were used with appropriate empirical equations to estimate these rock properties using Petrel and Ms-Excel software. Results show that the reservoir sand thickness varies from 32m to 208m with a field average of 110.9m, total porosity ranges between 0.002 (0.2%) and 0.255 (25.5%) with an average of 0.18 (18%), effective porosity ranges between 0.001 (0.1%) and 0.244 (24.4%) with an average of 0.16 (16%), permeability varies between 0.01mD and 197.18mD with an average of 28.0mD, water saturation varies between 0.11 and 0.87 with an average of 0.36, hydrocarbon saturation varies from 0.13 to 0.89 with an average of 0.64, while bulk volume of water ranges between 0.020 and 0.139 with an average of 0.053. On the average, the porosity of the reservoir sands in this field is good while the permeability is high. Apart from reservoirs E, K, Q and W with high water saturation, the other 20 reservoirs have low water saturation. Therefore, this field has good prospect for hydrocarbon exploration and production because of the low amount of water saturation and consequently high amount of hydrocarbon saturation in most of the reservoirs.

Keywords:- *Petrophysical Properties, Reservoir, Empirical Equations, Porosity, Permeability, Water Saturation.*

I. INTRODUCTION

Petrophysical properties are physical properties of rocks relating to the system of pores and its fluid distribution and flow characteristics (Crain, 1986). Petrophysical properties of rocks include total porosity, effective porosity, permeability, fractional flow, fluid saturation, lithology, etc. These properties are employed for determination of lithology, net-pay, porosity, fluid contacts, water saturation, permeability, etc.

In recent years, due to the increase in worldwide energy demand, there have been intensified efforts to prospect for hydrocarbon in plays and prospects that are unconventional. These prospects are characterized by low porosity, very low permeability, high pressure and high-stress changes during production. This has led to increased efforts at understanding the behaviour and rock properties, including petrophysical properties of these reservoir rocks to draw informed conclusions on the best practical ways of handling such reservoirs for optimal productivity.

The petrophysical properties of reservoir rocks in different hydrocarbon provinces particularly the Niger Delta had been studied by previous researchers including Adiela et al (2017), Adiela and Okumoko (2018), Kalu et al (2020), Ameloko, & Oseghe (2013), and others, each using a combination of the wireline logs applied in petrophysical analysis to provide a robust understanding of the properties of those reservoir rocks. Nevertheless, as exploration and exploitation activities continue to intensify, renewed attempts at more detailed petrophysical studies, especially in unconventional environments like deep offshore Niger Delta are made. This has led not only to a better understanding of the petrophysical properties but also has provided information of the potential of porous media and enhanced exploration and development of the reservoir rocks.

This research, therefore, is aimed at presenting a detailed study of the petrophysical properties of the reservoir of "Fuja" Field, offshore Niger Delta Nigeria. The specific objectives include: to estimate the total porosity, effective porosity, permeability, volume of shale, water saturation, hydrocarbon saturation, and bulk volume of water of ‘‘Fuja’’ reservoir rock using well log information and empirical equations.

II. LOCATION AND GEOLOGY OF THE STUDY AREA

LOCATION

‘‘Fuja’’ Field is an offshore oilfield located within the offshore depobelt of the Niger Delta Basin, Nigeria. The field is situated within longitudes 7˚43′25.971″E and 7˚53′10.372″E, and latitudes 3˚47′35.715″N and 3˚56′7.466″N.

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Fig. 1 shows the Prospectivity map of parts of the Niger Delta basin showing the location of ‘‘Fuja’’ Field.

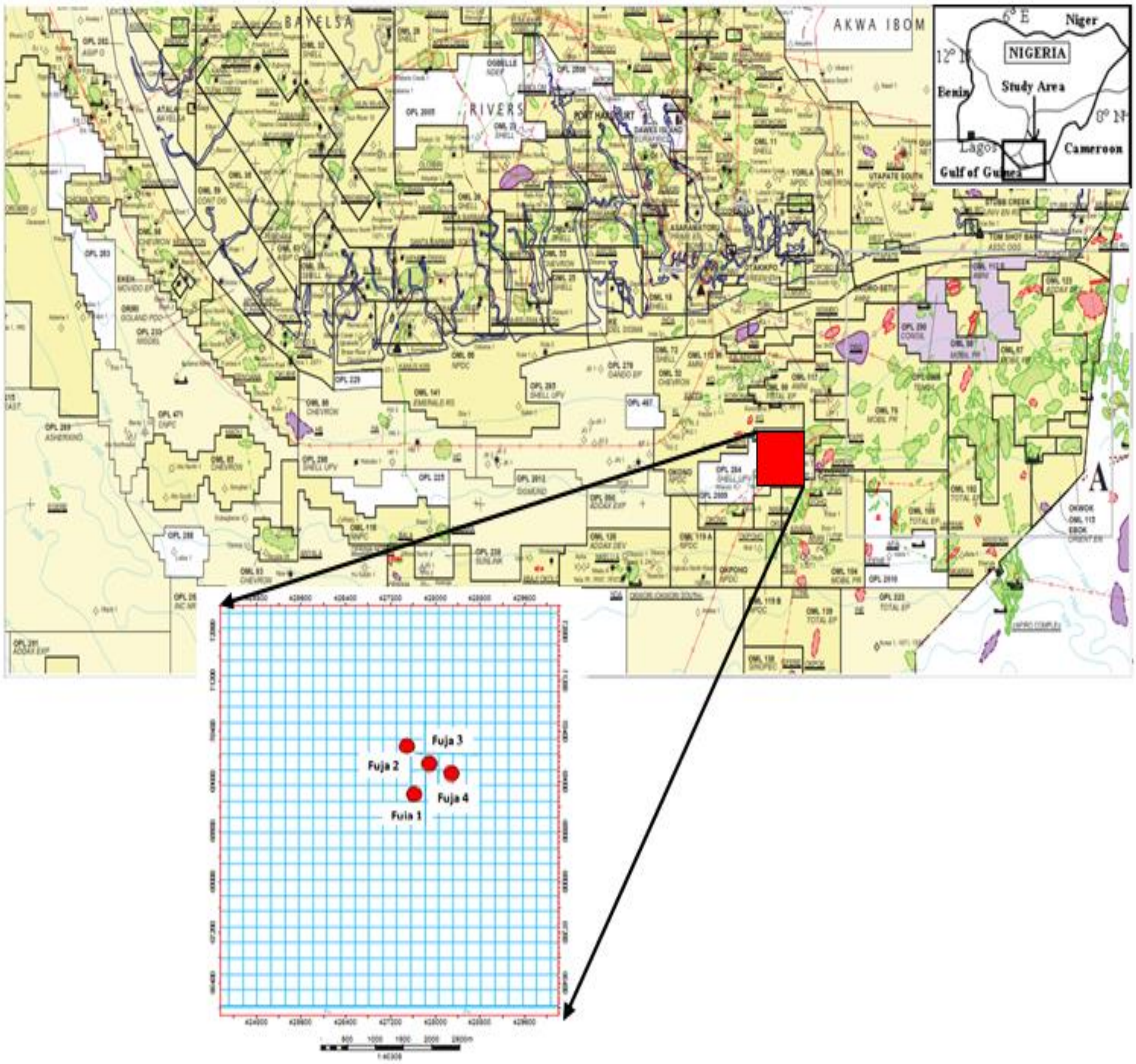

Fig. 1: Base map of ‘‘Fuja’’ Field showing the geometry of seismic inline and cross line and drilled wells. (Modified from IHS Niger Delta Licence Map, 2013).

GEOLOGY OF THE STUDY AREA

The Tertiary Niger Delta Basin is situated at the apex of the Gulf of Guinea on the coastline of western Africa (Doust and Omatsola, 1990). According to Haack, (2000), this delta is regarded as one of the highly prolific hydrocarbon provinces world over. This delta sits between longitude 4°E and 8°E and latitude 3°N and 6°N (Zorasi et al., 2017). The Niger Delta complex covers an area of about $200{,}000 km^2$, of which less than 20% is considered as prospective (Doust and Omatsola, 1990).

Three geological formations are known in the Niger Delta and they are the Akata, Agbada and Benin Formations. The Akata Formation consists of purely marine shales and is the hydrocarbon source rock in this delta; Agbada Formation consists of paralic sequence of clastics made up of sand and siltstone with intercalation of shales generated in several offlap cycles (Short and Stauble, 1967). The Agbada Formation is the reservoir of oil and gas in this delta (Short and Stauble, 1967), while the Benin Formation overlies the Agbada Formation and it consists of continental sands. Benin formation is the youngest of the three formations and the uppermost unit of the Tertiary Niger delta basin. Most of the hydrocarbon produced in the Niger Delta is from the Agbada reservoir sands where the oil and gas are trapped in mostly structures like faults and rollover anticlines (Schlumberger, 1985).

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Fig. 2 is a section showing Benin, Agbada and Akata Formations of the Niger Delta after Short and Stauble (1967) while Fig. 3 shows the regional geological map of the Niger Delta after Opara et al (2012).

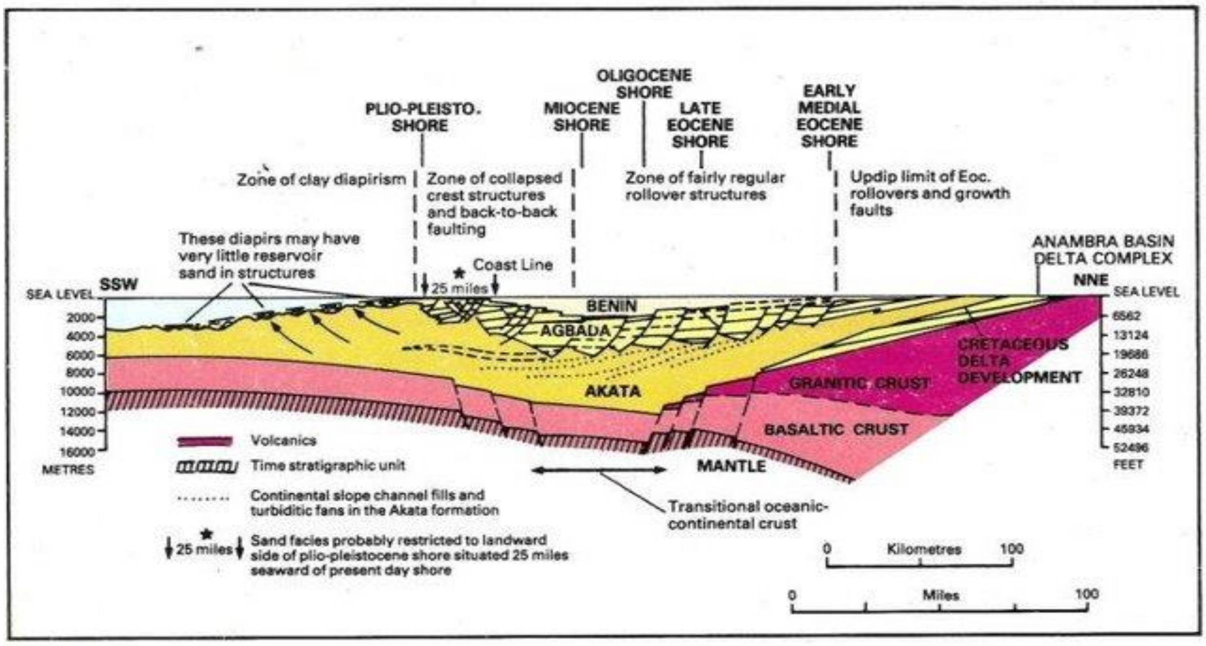

Fig. 2: Section showing Benin, Agbada and Akata Formations (after Short and Stauble, 1967)

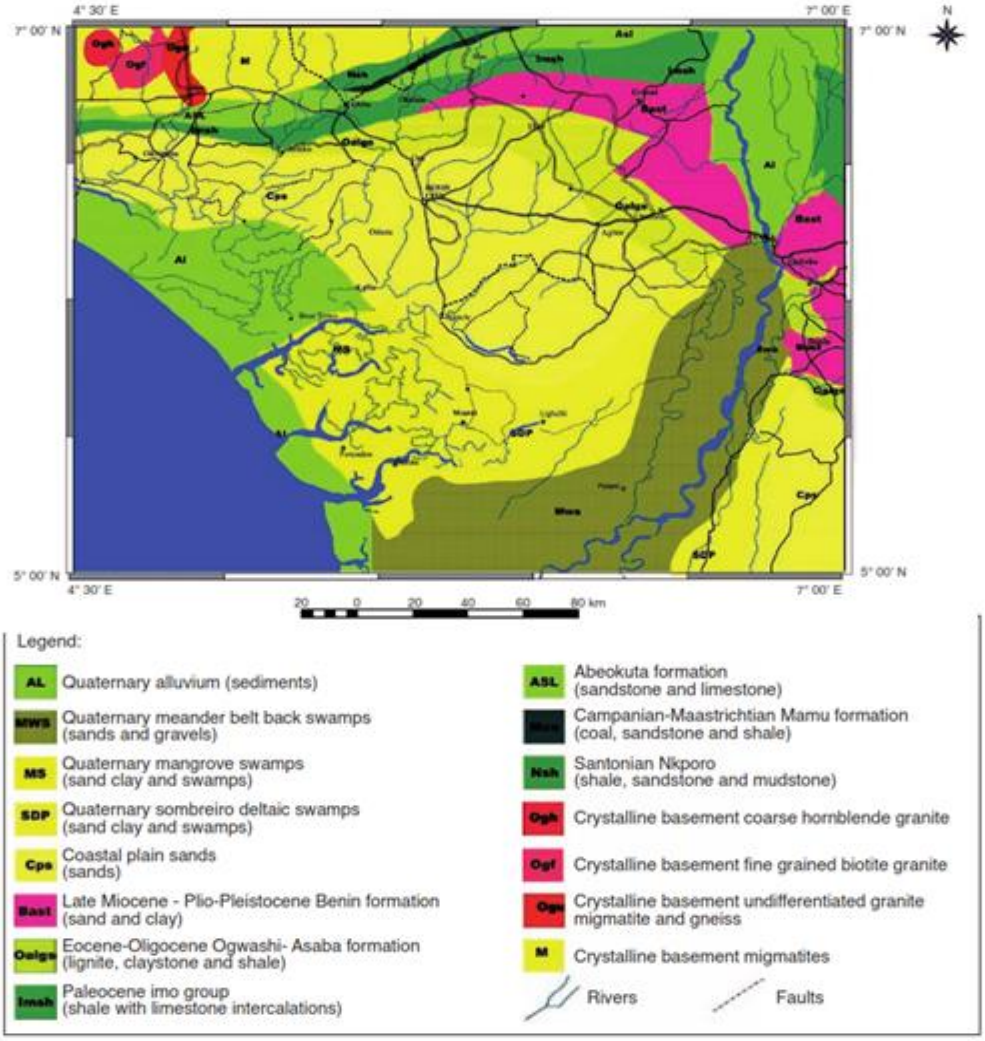

Fig. 3: Regional geological map of the Niger Delta (after Opara et al, 2012)

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III. MATERIALS AND METHOD

Well log data including bulk density and gamma-ray logs from four different wells within the study field in addition to appropriate empirical equations were used for this study. The hardware and software employed for this research include standard workstation with Petrel and Microsoft Excel software.

Importation of the well log data into the software was followed by reservoir identification for the four wells. Using appropriate empirical equations and well log data, estimation of the various petrophysical parameters including total porosity, effective porosity, permeability, volume of shale, water saturation, hydrocarbon saturation, and bulk volume of water was achieved.

Estimation of Total Porosity ($Ø_D$)

The total porosity was estimated using the equation according to Schlumberger (1989). It is the total porosity of the average density of the pore fluid and the densities of the rock. The equation is given by

$$Ø_D = \frac{(\rho_{ma} - \rho_b)}{(\rho_{ma} - \rho_{fl})} \quad (1)$$

Where $Ø_D$= total density porosity, ρ_{ma}= density of rock matrix (2.65g/cm^3), ρ_b = bulk density derived from density log, and ρ_{fl} = density of fluid occupying pore spaces (1.1g/cm^3 for water, 0.9g/cm^3 for oil, and 0.74g/cm^3 for gas).

Estimation of Effective Porosity ($Ø_{eff}$)

The effective porosity was calculated by applying the volume of shale equation by Asquith and Gibson, (1982) as stated below:

$$Ø_{eff} = \frac{(\rho_{ma} - \rho_b)}{(\rho_{ma} - \rho_{fl})} - \frac{V_{sh}(\rho_{ma} - \rho_{sh})}{(\rho_{ma} - \rho_{fl})} \quad (2)$$

Where $Ø_{eff}$= shale-corrected density porosity, V_{sh}= volume of shale, ρ_{sh} = density of shale (2.30g/cm^3), ρ_{ma}= density of rock matrix (2.65g/cm^3), and ρ_{fl} = density of fluid occupying pore spaces.

Estimation of Volume of Shale (V_{sh})

The shaliness or volume of shale was calculated using the equation according to Larionov (1969), given as:

$$V_{sh} = 0.083(2^{3.7 I_{gr}} - 1) \quad (3)$$

Where I_{gr} is the gamma ray or shale index given as

$$I_{gr} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (4)$$

GR_{log}= gamma ray reading from log, GR_{min}= minimum gamma ray reading (sand baseline), GR_{max}= maximum gamma ray reading, and V_{sh}= volume of shale.

Estimation of Permeability (K)

Permeability was calculated using the porosity equation from Adiela et al (2017) given as:

$$K = \frac{0.136Ø^{4.4}}{(Swirr)^2} \quad (5)$$

Where Ø is the effective porosity and Swirr is the irreducible water saturation.

Swirr is determined using the equation also by Adiela et al (2017) given by

$$Swirr = \left(\frac{F}{2000}\right)^{1/2} \quad (6)$$

F is the formation factor obtained from

$$F = \frac{a}{Ø^m} \quad (7)$$

where a is the tortuosity factor (0.62), Ø is the effective porosity, and m is the cementation factor (2.15).

Estimation of Water Saturation (S_w)

Water saturation was calculated using the water saturation equation from Adiela et al (2017) given as:

$$S_w = \left(\frac{R_w}{R_t}\right)^{1/2} \quad (8)$$

Where R_w is the resistivity of water-bearing rock and R_t is the true resistivity of the rock.

Estimation of Hydrocarbon Saturation (S_h)

Hydrocarbon saturation is estimated using the relationship

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

Where S_w is the water saturation and S_h is the hydrocarbon saturation.

Estimation of Bulk Volume of Water (BVW)

The bulk volume of water (BVW) is estimated by multiplying the effective porosity ($Ø_{eff}$) with the water saturation (S_w).

$$BVW = (Ø_{eff} \times S_w) \quad (10)$$

The relationship between effective porosity and depth as well as effective porosity and permeability were also investigated for this field using cross plots. These relationships were investigated for 4 different reservoirs in each case within the field and the cross plots were generated using the Ms-Excel software. Fig. 4 is a research workflow showing the key steps taken to achieve desired results.

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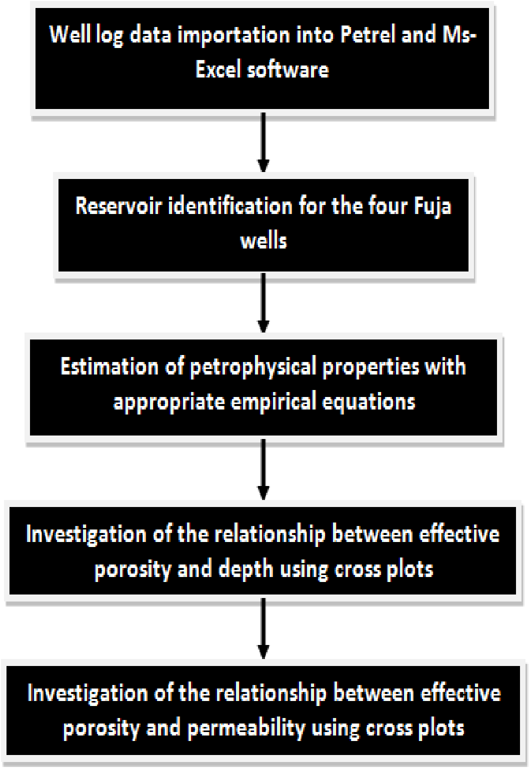

Fig. 4: Research workflow

IV. RESULTS PRESENTATION AND DISCUSSION

PRESENTATION OF RESULTS

6 different reservoirs were delineated in each of the four Fuja wells studied, hence, a total of 24 reservoirs labelled A to X were evaluated across the wells. For each of the reservoir sand units, the reservoir sand thickness, total porosity, effective porosity, permeability, volume of shale, water saturation, hydrocarbon saturation, and bulk volume of water were estimated. Gamma ray log data was used to delineate the different reservoirs in each of the wells. The depths of the reservoirs across the 4 wells lie between 7882m and 10355m, the thickness of the reservoirs ranges between 32m to 208m with a field average of 110.9m, total porosity ranges between 0.002 (0.2%) and 0.255 (25.5%) with an average of 0.18 (18%), effective porosity ranges between 0.001 (0.1%) and 0.244 (24.4%) with an average of 0.16 (16%), permeability varies between 0.01mD and 197.18mD with an average of 28.0mD, water saturation ranges between 0.11 and 0.87 with an average of 0.36, hydrocarbon saturation varies from 0.13 to 0.89 with an average of 0.64, while bulk volume of water ranges between 0.020 and 0.139 with an average of 0.053.

The following data tables (Tables 1 to 4) show the average values of the different petrophysical parameters calculated for each of the delineated reservoirs across the 4 wells.

Table 1: Average values of the different petrophysical parameters calculated for Fuja 1 well

Reservoir	Reservoir Thickness (m)	Total Porosity (%)	Effective Porosity (%)	Permeability (mD)	Volume of Shale	Water Saturation (S_w)	Hydrocarbon Saturation (S_h)	Bulk volume of water (BVW)
A	106	22	17	29.9	0.20	0.20	0.80	0.034
B	32	22	19	55.1	0.12	0.17	0.83	0.032
C	207	20	17	44.0	0.15	0. 34	0.66	0.057
D	90	16	13	5.6	0.21	0.36	0.64	0.046
E	148	16	12	6.5	0.24	0.86	0.14	0.103
F	77	16	13	7. 3	0.21	0.40	0.60	0.052

Table 2: Average values of the different petrophysical parameters calculated for Fuja 2 well

Reservoir	Reservoir Thickness (m)	Total Porosity (%)	Effective Porosity (%)	Permeability (mD)	Volume of Shale	Water Saturation (S_w)	Hydrocarbon Saturation (S_h)	Bulk volume of water (BVW)
G	208	13	10	9.9	0.26	0.21	0.79	0.021
H	48	19	17	44. 3	0.14	0.15	0.85	0.025
I	157	17	14	17.2	0.18	0.33	0.67	0.046
J	112	19	18	49.9	0.05	0. 35	0.65	0.063
K	129	14	13	10.8	0.10	0.80	0.20	0.104
L	64	18	17	29. 3	0.08	0. 36	0.64	0.061

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Table 3: Average values of the different petrophysical parameters calculated for Fuja 3 well

Reservoir	Reservoir Thickness (m)	Total Porosity (%)	Effective Porosity (%)	Permeability (mD)	Volume of Shale	Water Saturation (S_w)	Hydrocarbon Saturation (S_h)	Bulk volume of water (BVW)
M	105	22	17	30	0.20	0.18	0.82	0.030
N	34	22	19	55.2	0.12	0.11	0.89	0.020
O	206	20	17	44.2	0.15	0. 30	0.70	0.051
P	92	16	13	5.7	0.21	0. 38	0.62	0.049
Q	132	16	13	7.2	0.22	0.78	0.22	0.101
R	76	15	13	7. 3	0.20	0. 31	0.69	0.040

Table 4: Average values of the different petrophysical parameters calculated for Fuja 4 well

Reservoir	Reservoir Thickness (m)	Total Porosity (%)	Effective Porosity (%)	Permeability (mD)	Volume of Shale	Water Saturation (S_w)	Hydrocarbon Saturation (S_h)	Bulk volume of water (BVW)
S	145	19	16	41.9	0.17	0.20	0.80	0.032
T	44	20	17	51.1	0.15	0.14	0.86	0.023
U	169	16	13	12.8	0.20	0.27	0.73	0.035
V	96	20	19	66.7	0.08	0. 35	0.65	0.066
W	102	18	16	28.9	0.11	0.87	0.13	0.139
X	82	16	14	10.5	0.10	0. 34	0.66	0.047

Cross plots of depth versus effective porosity was generated for reservoirs C, L, O and V to carry out an investigation of the relationship between effective porosity and depth within the reservoirs of the field. The cross plots are shown in figures 5(a-d).

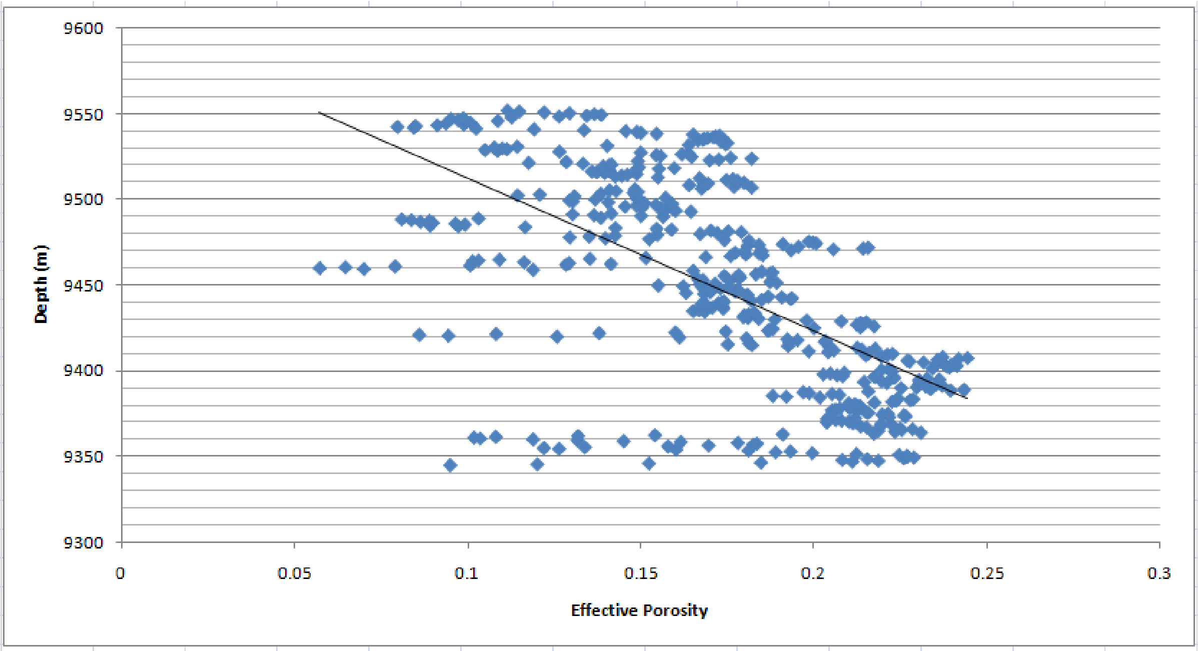

Fig. 5a: Depth-Effective Porosity plot with trend line for reservoir C.

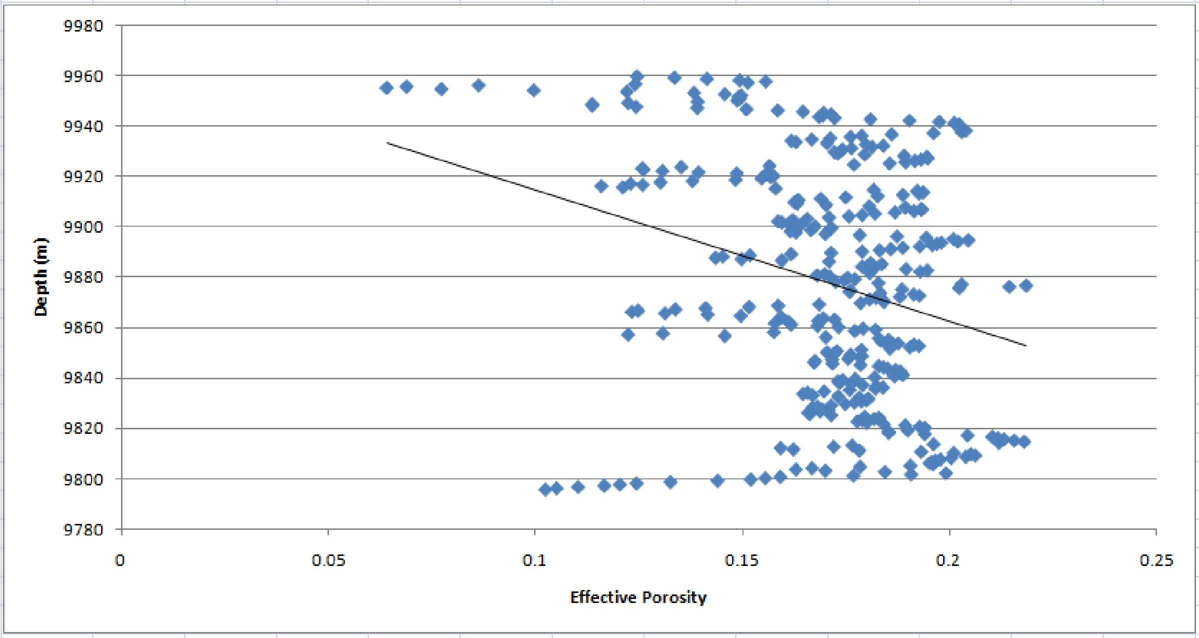

Fig. 5b: Depth-Effective Porosity plot with trend line for reservoir L.

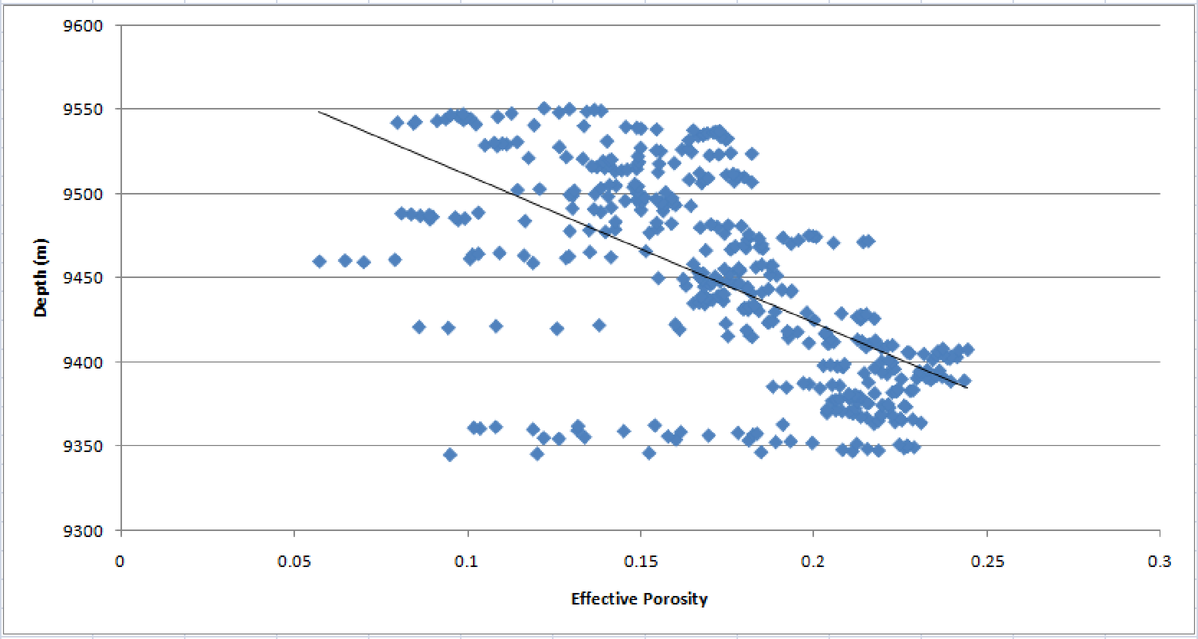

Fig. 5c: Depth-Effective Porosity plot with trend line for reservoir O.

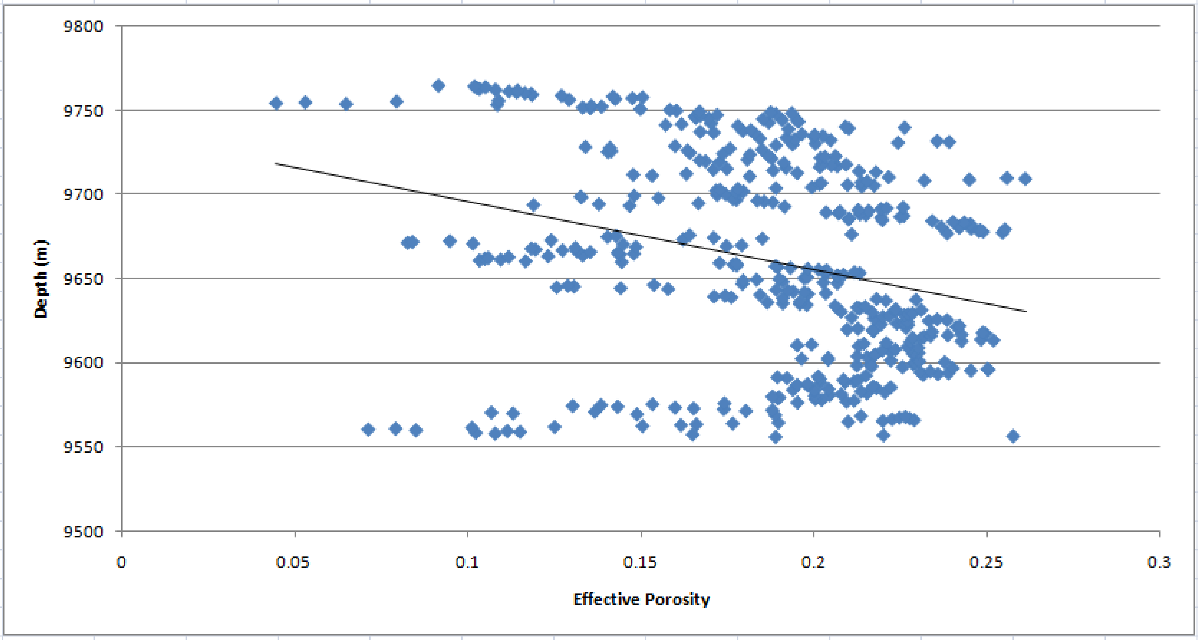

Fig. 5d: Depth-Effective Porosity plot with trend line for reservoir V.

Also, cross plots of permeability against effective porosity was obtained for reservoirs E, J, P and T to similarly carry out an investigation of the relationship between permeability and effective porosity within the reservoirs of the field. The cross plots are shown in figures 6(a-d).

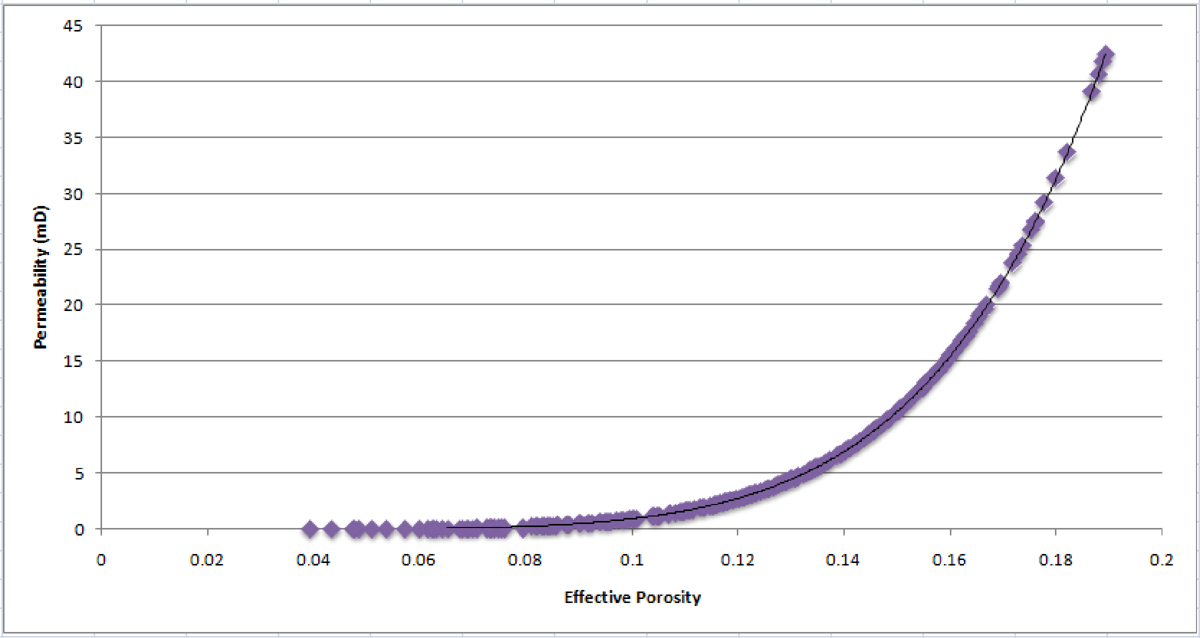

Fig. 6a: Permeability-Effective Porosity plot with trend line for reservoir E.

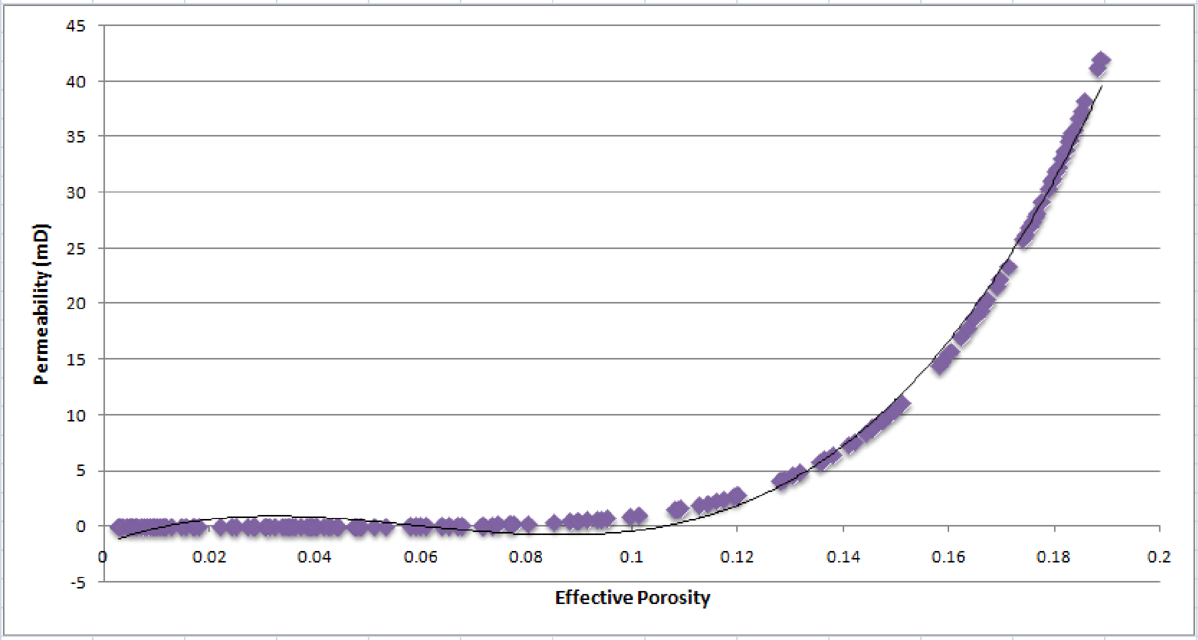

Fig. 6b: Permeability-Effective Porosity plot with trend line for reservoir J.

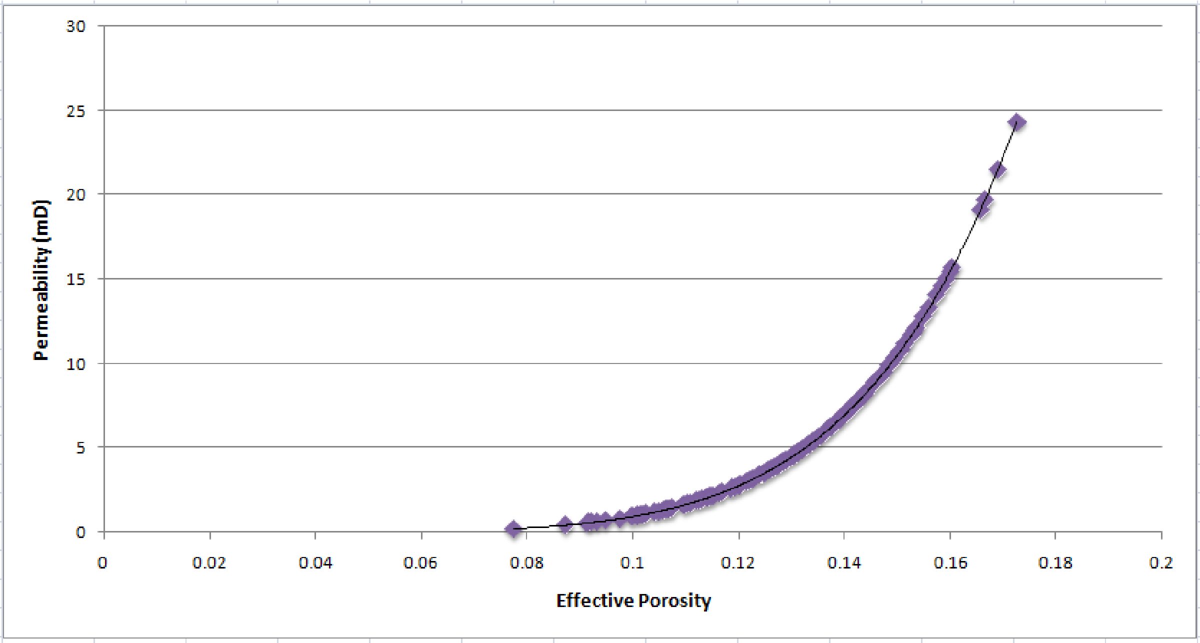

Fig. 6c: Permeability-Effective Porosity plot with trend line for reservoir P.

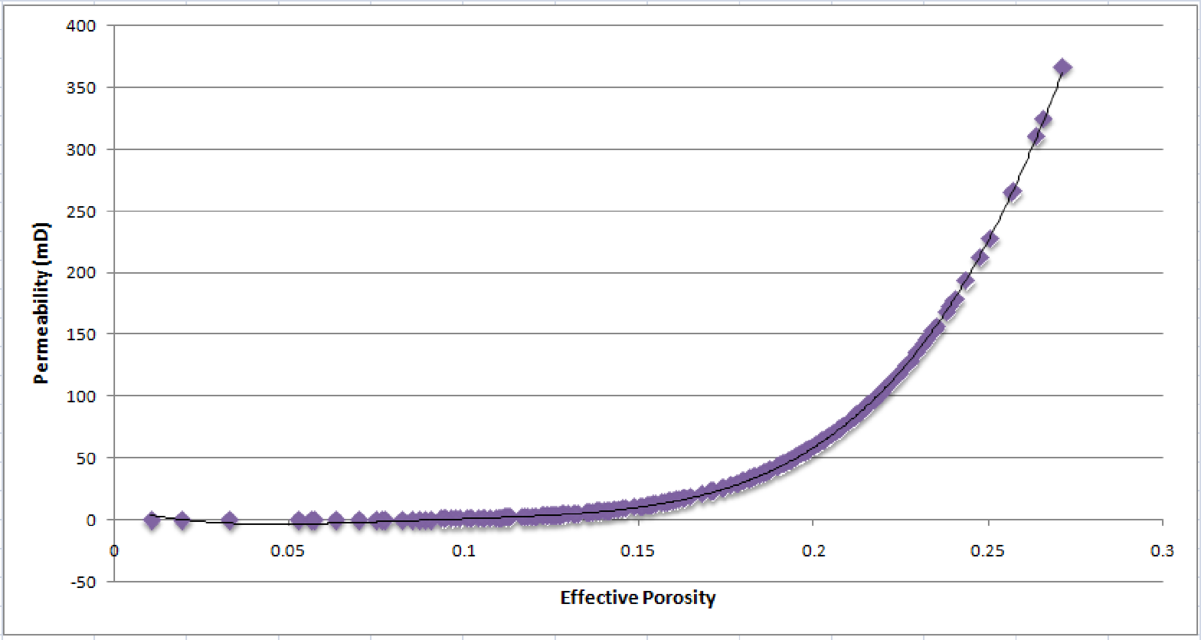

Fig. 6d: Permeability-Effective Porosity plot with trend line for reservoir T.

V. DISCUSSION

Reservoir delineation shows that the reservoirs fell within the lower Agbada Formation of the Niger Delta basin with a paralic sequence of sand intercalated by shale. The depth interval of the reservoir fell between 7882m and 10355m. The reservoirs of this field are also comparatively thick with the least reservoir having a thickness of 32m and the thickest having a thickness of 208m.

From porosity estimates of the reservoirs, the porosity ranges between negligible and very good according to porosity classification by Rider (2002). The highest total porosity values of 22% were recorded in reservoirs A, B, M and N while the least total porosity value of 13% was observed in reservoir G. The highest effective porosity values of 19% were observed in reservoirs B, N and V, while the least of 10% was recorded in reservoir G. On the average, the porosity of the reservoir sands in this field is good.

Results of permeability analysis show that permeability varies from fair to very high within the reservoirs of the field according to the classification by Glover (1997). The highest permeability of 66.7mD was seen in reservoir V while the least of 5.6mD was recorded in reservoir D. This comparatively higher permeability observed in this reservoir is attributable to the low shale volume of 0.08 in addition to the higher effective porosity recorded in this reservoir. The average permeability value of the reservoirs of this field shows that the permeability is high.

Water saturation was observed to be high in reservoirs E, K, Q, and W with values of 0.86, 0.80, 0.78, and 0.87 respectively. This directly implies that hydrocarbon saturation is low in these reservoirs and hence, they do not have good prospect for hydrocarbon exploration and production. However, water saturation in the other reservoirs are comparatively low with reservoir N recording the lowest water saturation of 0.11 and consequently the highest hydrocarbon saturation of 0.89.

Reservoir W recorded the highest bulk volume of water with a value of 0.139 while reservoir N recorded the lowest with a value of 0.020. The bulk volume of water recorded almost a constant value throughout each studied reservoir. According to Dewan, (1983), this implies that the reservoirs are at irreducible water saturation and therefore should produce water-free hydrocarbons because through capillary pressure or surface tension, the formation's water is held by the reservoir grains.

From the cross plot between depth and effective porosity for 4 reservoirs namely reservoirs C, L, O and V shown in figures 5(a-d), it is observed that effective porosity and by extension total porosity varies inversely with depth in all the 4 reservoirs investigated. This implies that as reservoir depth increases, the volume of pore spaces contained within the reservoir rock decreases due mainly to pressure and compaction.

Similarly, from the cross plot between permeability and effective porosity for reservoirs E, J, P and T shown in figures 6(a-d), it is observed that effective porosity varies directly with permeability in all the 4 investigated reservoirs. This shows that as the porosity of the reservoir rock in this field increases, the ability of the rock to transmit fluids contained in its pore spaces also increases and vice versa.

VI. CONCLUSION

From the results obtained from the estimation of the petrophysical reservoir properties including total and effective porosity, permeability, volume of shale, water and hydrocarbon saturation as well as bulk volume of water from the four wells within the field in addition to the appreciable thicknesses of the reservoirs, it can be concluded that Fuja Field has considerable prospect for hydrocarbon exploration and production. The quality of most of the studied reservoirs is good. The porosity of the reservoir sands is good, the permeability is high and water saturation is comparatively low in most of the studied reservoirs. Also, the reservoirs are at irreducible water saturation and this should guarantee water-free completions.

RECOMMENDATION

It is therefore recommended from the results of this study that this work should be incorporated into other reservoir characterization techniques like volumetrics and fluid flow characterization to further characterize geology, estimate reserve and fluid flow within the field.

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