JASEM ISSN 1119-8362

Full-text Available Online at www.ajol.info and www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage. *June*., 2016
Vol. 20 (2) 383 – 393

Petrophysical Evaluation of Reservoir Sand Bodies in Kwe Field Onshore Eastern Niger Delta

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ABSTRACT: Reservoir sand bodies in Kwe Field, coastal swamp depobelt, onshore eastern Niger Delta Basin were evaluated from a composite log suite comprising gamma ray, resistivity, density and neutron logs of five (5) wells with core photographs of one (1) reservoir of one well. The aim of the study was to evaluate the petrophysical properties of the reservoirs while the objectives were to identify the depositional environment and predict the reservoir system quality and performance. The study identified three reservoir sand bodies in the field on the basis of their petrophysical properties and architecture. Reservoir A has an average NTG (61.4 %), Ø (27.50 %), K (203.99 md), S_w (31.9 %) and S_h (68.1 %); Reservoir B has an average NTG (65.6 %), Ø (26.0 %), K (95.90 md), S_w (28.87 %) and S_h (71.13 %) while Reservoir C has an average NTG (70.4 %), Ø (26.1 %), K (91.4 md), S_w (25.0 %) and S_h (75.03 %) and therefore show that the field has good quality sandstone reservoirs saturated in hydrocarbon. However, the presence of marine shales (or mudstones) interbedding with these sandstones may likely form permeability baffles to vertical flow and compartmentalize the reservoirs. These reservoirs may therefore have different flow units. Integrating wireline logs and core data, the reservoir sand bodies were interpreted as deposited in an estuarine-shoreface setting thus indicating that the Kwe Field lies within the marginal marine mega depositional environment. ©JASEM

http://dx.doi.org/10.4314/jasem.v20i2.21

Key words: Estuarine, Shoreface, Reservoir, Sand, Kwe, field

Introduction

The Niger Delta Basin has been known as one of the world's most prolific petroleum producing Tertiary deltas (Selley, 1997) and has been ranked the 12th largest known accumulation of recoverable hydrocarbons, with reserves exceeding 34 billion barrels of oil and 93 trillion cubic feet of gas (Tuttle *et al.*, 1999). Ever since the commencement of commercial hydrocarbon production in this basin by Shell-BP in 1958 (Weber, 1971), there has been an overwhelming concentration of exploration activities as well as scientific researches.

Previous work by Short and Stauble (1967) outlined the general geology of the Niger Delta by dividing the stratigraphy into three distinct units (the Akata Formation, the Agbada Formation and the Benin Formation) and set the stage for more investigation into the deltaic deposits. Evamy *et al*. (1978) on their part, researched into the hydrocarbon habitat of the basin and identified two possible migration pathways; one along the structure building faults which terminate in the Akata Formation; and the other, migrating from the seaward facies and changes up dip into the roll-over structures. A more recent work by Nton and Adesina (2009) who investigated some aspects of structures and depositional environment of sand bodies within the Tomboy Field, offshore part of the basin noted that the reservoir sands were deposited in different environments consisting of distributary channels, mouth bars, barrier island and tidal channels, and were deposited across normal growth faults and anticlinal structures.

On the petrophysical evaluation of the reservoir sands, Ulasi *et al.* (2012), Omoboriowo *et al.*(2012); Rotimi *et al.* (2013); Alao *et al.* (2013), and Mode *et al*. (2015) have independently investigated the Uzek well, offshore depobelt; Amma field in onshore eastern part; Bob field, in south eastern onshore part; Apete field, in offshore part; and DC70X reservoirs of Mbakan field in the central part of the basin respectively, and noted that the petrophysical properties of the reservoirs sands of the Niger Delta are high enough to permit hydrocarbon production.

With the increasing demand of hydrocarbon products to meet global needs in the 21st century despite the fall in global oil price, there is however need for more research on the petrophysical and depositional

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environments of other fields with a view to increasingly support reservoir appraisal, development and thus optimize hydrocarbon production from the basin. This work is therefore aimed at the petrophysical evaluation of the Kwe Field, located in the coastal swamp depobelt, onshore Eastern Niger Delta Basin and thus, is a scientific contribution towards supporting hydrocarbon production programme in the basin. The objectives of the study were to identify the depositional environment, estimate and compare the porosity, permeability and water saturation distribution within the field, identify specific reservoir sand bodies, and predict the reservoir system quality and performance.

MATERIALS AND METHODS

Geological Setting: The Kwe Field (Figs.1 and 2) is located in the eastern Niger Delta province which comprises the eastern (or Atlantic) session of the coastal south-south Nigeria and stretches from the Akassa River eastwards to the Cross River area.

The Niger Delta is a marginal sag basin located in the continental margin of the Gulf of Guinea in equatorial West Africa, covering an area of about 75,000 km^2, with an average thickness of about 12 km and lies between latitudes 3° and 6° N and longitudes 5° and 8° E (Knox and Omatsola, 1989).

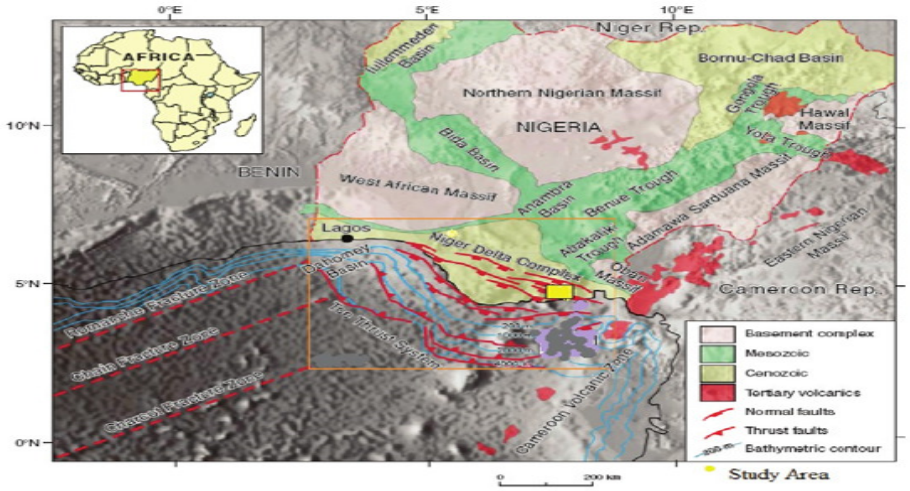

Figure 1: Location map of study area (after Corredor *et al.*, 2005)

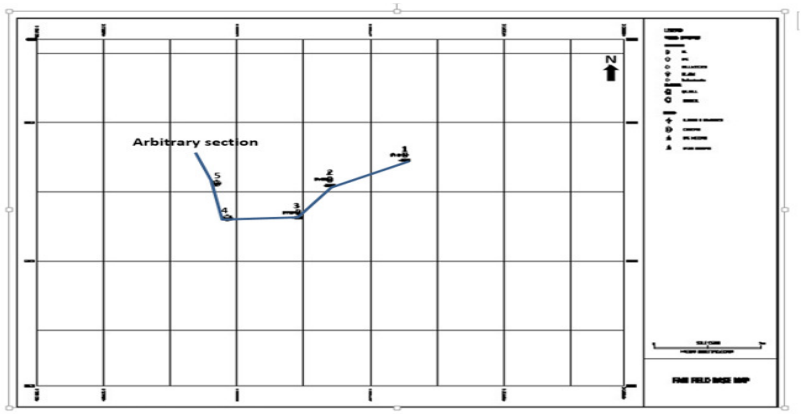

Figure 2: Base Map of the study Area

It is bounded in the western –north western part by the Okitipupa Hinge line; in the north by the Benin Flank; in the north eastern part by the Abakaliki High; and in the eastern – south eastern part by the Calabar Flank. The offshore boundary of the province towards the east is bounded by the Cameroon volcanic line while the southern to south western flank is defined by the 4000 – metre bathymetric contour in areas with great sediment thickness

(Corredor *et al.*, 2005). The formation of the basin has also been related to the separation of Africa from South America and the consequent opening of the South Atlantic in Mid Cretaceous times (Evamy *et al*., 1978; Doust and Omatsola, 1990).

METHODOLOGY

The following materials: field map, base map and a composite log suite comprising gamma ray, resistivity, density and neutron logs of five (5) wells with core photographs of one (1) reservoir of one well were provided by Shell Petroleum Development Company for which the authors are grateful.

The gamma ray log motif for the cored section was used to calibrate and constrain the interpretation for the uncored section. The gamma ray log was thereafter integrated with other logs in the composite suite to evaluate the hydrocarbon bearing reservoir sands.

The core photographs of the reservoir of the well (well 4) provided were studied and described from bottom to top. The visible facies characteristics observed on the photos, particularly, the lithology, sedimentary structures (cross bedding, lamination and bioturbation) and geological succession were studied. Based on these, lithofacies types and associations were determined and interpreted. From the composite log suite provided, the shapes of gamma ray log were noted and further used to constrain the character of the sedimentary facies and depositional environment based on the views of Scholle and Spearing (1998) and Coleman and Prior (1980).

For the petrophysical parameters, equations 1- 11 were used to evaluate the values obtained from logs and thereafter compared with the standard values so as to characterize the reservoirs.

The porosity values of the reservoirs were estimated from the density and neutron porosity logs via equations 1 – 5 and thereafter, results obtained from the calculations were compared with standard values which have been used to characterize the porosity of reservoir rocks in parts of the Niger Delta Basin as excellent (>30%), very good (20-25%), good (15-20%), poor (5-10%) and negligible (0-5%) (Etu-Efeotor, 1997).

$$IGR = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad \text{……Equation 1}$$

$$V_{sh} = 0.083\,[2^{(3.7 \times 1GR)} - 1] \quad \text{…….Equation 2,}$$

$$\Phi_{D\,corr} = \left[\frac{\rho ma - \rho b}{\rho ma - \rho f}\right] - V_{sh} = \left[\frac{\rho ma - \rho sh}{\rho ma - \rho f}\right] \quad \text{…Equation 3}$$

$$\Phi_{N\,cor} = \Phi_N - \left[\frac{\Phi N\ clay}{0.45} \times 0.30 \times V_{sh}\right] \quad \text{…… Equation 4,}$$

$$\Phi_{N-D} = \sqrt{\frac{\Phi N_{corr}{}^2 + \Phi D_{corr}{}^2}{2}} \quad \text{…… Equation 5}$$

Where: IGR = Gamma Ray Index
GR_{max} = maximum gamma ray reading (100% shale)
GR_{min} = minimum gamma ray reading [clean sand or Carbonate]
GR_{log} = gamma ray reading of formation
ρma = matrix density (sand matrix = 2.648g/cm^3)
ρf = density of formation fluid (fresh mud = 1.0)
ρb = bulk density (read from log)
ρsh = bulk density of adjacent shale
Vsh = volume of shale,
Φ_N = neutron porosity of adjacent shale
Φ_{N-D} = neutron – density combination
$\Phi_{N\,corr}$ = neutron porosity corrected for the effect of shale
$\Phi_{D\,corr}$ = density porosity corrected for the effect of shale.

The permeability values of the reservoirs were derived from equation (6) and thereafter, results obtained from the calculations were also compared with standard values which have been used to characterize the permeability of reservoir rocks in parts of the Niger Delta Basin as excellent (>1000 md), very good (250-1000 md), good (50-250 md), moderate (15-50 md) and poor to fair (< 10-15 md) (Etu-Efeotor, 1997).

$$(K) = \frac{0.136 \times \Phi^{44}}{s_{wirr^2}} \quad \text{……. ……Equation 6}$$

Where: Φ = porosity
s_{wirr^2} = irreducible water saturation

The Net to Gross (NTG) thickness of each of the units was calculated from equation 7

$$NTG = \frac{\sum hi}{\sum H,} \quad \text{…… Equation 7}$$

Where: $\sum$hi = summation of individual sand units only
$\sum$H = the whole unit/reservoir consisting of both sand and non-sand unit

The Fluid saturation of the reservoir rock was determined as follows:

$$S_w = \sqrt{\frac{FxRw}{Rt}} \quad \text{…….. Equation 8}$$

(Archie, 1942)

$$F = a \Big/ \Phi^m = \frac{0.62}{\Phi\ 2.15} \quad \text{… … … … … … … … … … …. Equation 9}$$

$S_h = 1-S_w$ ……Equation 10

Where R_w = resistivity of the formation water
R_t = The true resistivity of the zone of interest
F = formation factor.
S_w = water saturation
S_h = hydrocarbon saturation
m = cementation factor = 2
Φ = porosity
a = constant

The bulk volume of water (BVW) was calculated as the product of the formation's water saturation (S_w) and its porosity (Φ)

$BVW = S_W \times \Phi$ ……Equation 11

Finally, from the thickness of the reservoirs obtained (by subtracting the base from the top of the reservoir), isopach map was constructed from which the geometry of the reservoirs as well as the dip and strike directions were inferred.

RESULTS AND DISCUSSION

Geological Core Analysis: Three reservoir sands labeled A, B and C were identified in the Kwe Field from the data set provided. These were correlated across five wells (Fig. 3) of which only reservoir C of well 4 which lies within 12900 – 13300 ft. (3931.9 – 4053.8 m) was cored and is described on the basis of lithofacies and sedimentary structures.

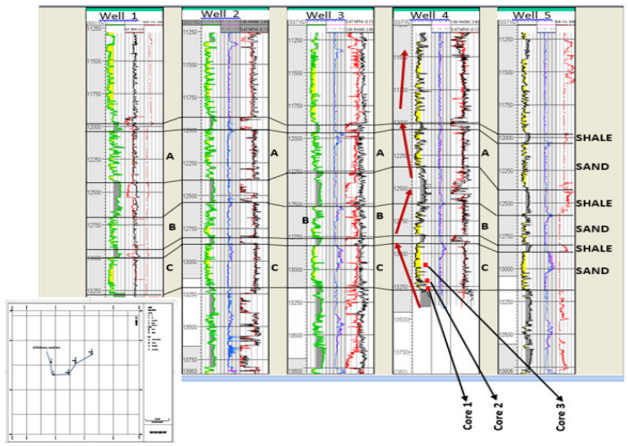

Figure 3: Correlation of Reservoir sands in Kwe Field

Core 1, Reservoir C, Well 4 (13250.0 – 13256.0ft.or 4038.6 – 4040.4m):
This core (Fig. 4[1]) is characterized by bioturbated, hummocky and swaley cross bedded sandstone. The hummocky and swaley cross bedding, though has been strongly obliterated by bioturbation, relicts can however be observed at a closer look, particularly at the upper section of the core. The intensity of the burrows increases upsection and are somewhat mottled with dark organic material. On the gamma-ray log (Fig. 3), this section shows a serrated funnel shape and exhibits a coarsening-upward grain-size profile.

The presence of hummocky and swaley cross bedding is indicative of deposition by storm waves in the outer shoreface and transition zone between fair weather wave-base and storm wave-base (Yagishita *et al.*, 1992; Monaco, 1994; Tucker, 2003). Additionally, the presence of *Ophiomorpha* reflects a well-oxygenated and nutrient-rich setting and such setting are commonly found within the shoreface environment, particularly at the lower-middle shoreface environment (Frey*et al.*, 1978; Boggs, 2001; Mude, 2011).

Core 2, Reservoir C, Well 4 (13195.0-13201.0ft. or 4021.8– 4023.7 m)
This core (Fig. 4[2]) is characterized by parallel, ripple cross laminated sandy heteroliths to low angle cross bedded sandstone. On the gamma-ray log, this section shows a serrated funnel shape and exhibits a coarsening-upward grain-size profile thus indicative of interbedded sand and shale deposition with sand to shale ratio increasing upwards.

The presence of parallel to ripple laminated sandy heteroliths suggests deposition in tidally influenced subaqueous environments under fluctuating flow conditions (Nwachukwu, *et al.,* 2011). Such environments are often characterized by high flow velocity (caused by high tidal action) alternating with slack water stage during period of low tidal influence. Deposition of sand is favoured during period of high tidal current with high flow conditions whereas, at low

tide, energy is weak and therefore favours shale or clay deposition (Archer and Kvale, 1989; Hettinger, 1995; Shanley *et al.,* 1992). Although such settings may range from coastal to deep marine (Boggs, 2001; .

sheikh *et al.*, 2006; Roberts, 2007), however, the presence of low angle cross-bedding, couple with its association with core 1 and 3, suggests its deposition in upper to middle shoreface environment.

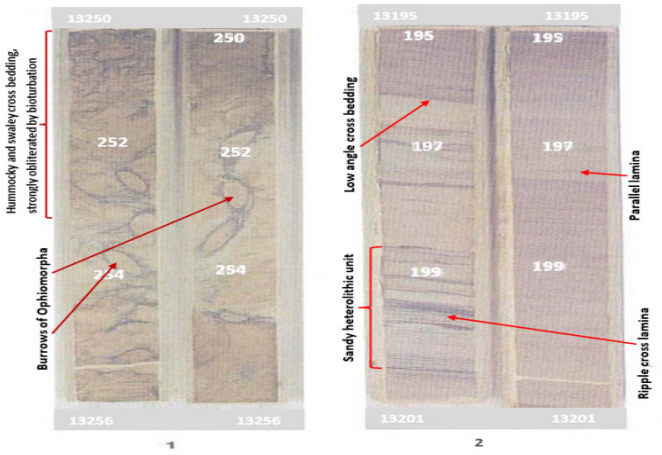

Figure 4: Cores 1 & 2, reservoir C, well 4

Core 3, Reservoir C, Well 4 (13075.0-13081.0ft. or 3985.3–3987.1m)

This core (Fig. 5) is characterized by unidirectional planar cross bedded sandstone with bed sets bounded by sharp erosional surface at the base and at the top by argillaceous laminae/bands. On the gamma-ray log, this section shows serrated blocky-bell shape suggestive of tidally influenced stacked channel fill with sand to shale ratio decreasing upwards in a finning upward succession that is characteristic of channel fills.

It should however be noted that though unidirectional paleocurrent pattern is indicative of fluvial channel (Boggs, 2001), tidally influenced channel such as a tidal channel or estuarine channel dominated by ebb flow or flood current could produce a unimodal paleocurrent pattern as the ebb and flood often find different dominant pathways (Bjørlykke, 2010).

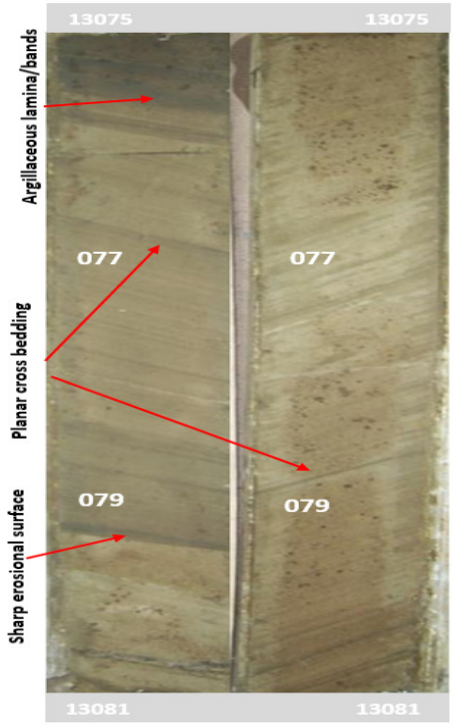

Figure 5: Core 3, reservoir C, well 4

Reservoir Architecture and Depositional Model of Reservoir 'C' in Kwe Field

As shown on Figure 6, a fluvially dominated estuarine-shoreface depositional setting has been proposed by this research as the reservoir architecture and depositional model for the reservoir 'C' in Kwe Field based on core description and interpretation of well logs. Furthermore, by using similar gamma ray log motif in cored section as calibration for the uncored section, the Gross Depositional Environment (GDE) of the Kwe field was interpreted as ranging from coastal setting to shallow marine. The gamma ray log motif of the five wells presented for the Kwe Field shows successions of stacked channels interbedded by marine shales and are indicative of deposition by transgressive and regressive phases of the delta build up. With regards to reservoir 'C' however, its lithofacies and associations were deposited in a shallow marine (shoreface) depositional setting incised by fluvial dominated estuarine channels. Estuarine channel genetic units have been described by Boggs (2001) and Scholle and Spearing (1998) as consisting of a mixture of marine (shoreface)-reworked sand (lower part) and subordinate fluvial sand (upper part) filling channels near the mouth of the estuary; and a sharp erosive base with interbedded silts and muds indicative of fluctuating flow conditions. On the log motif, Scholle and Spearing (1998) further noted that estuarine channel units are characterized by stacked log profiles typically blocky to bell-shaped and often reflects the hybrid of marine and fluvial depositional environments.

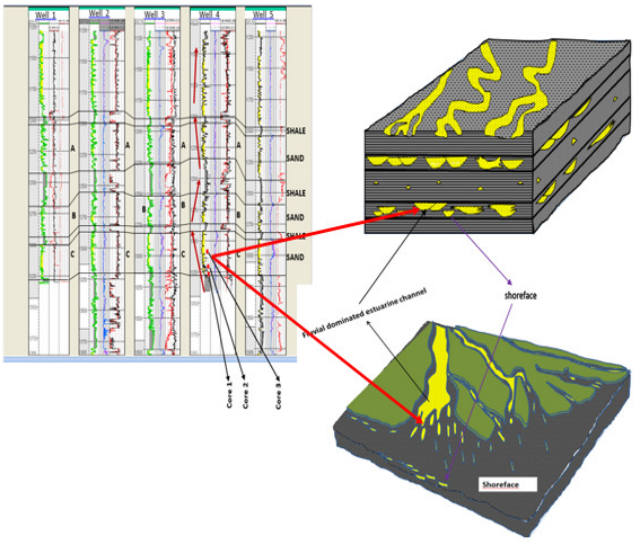

Figure 6: Conceptual Depositional model of reservoir 'C', Kwe Field

Petrophysical Evaluation: Results of petrophysical evaluation of the three reservoir sands labeled A, B and C based on the available dataset are shown on Table 1 and are discussed:

Reservoir A

This occurs at a depth range of 11950 - 12425 ft. (3642.4 –3787.1 m) with an average gross thickness of 101.6 m, average net sand thickness of 62.3 m and average net to gross thickness of 61.4 %. The porosity of the reservoir ranges from 25 – 32 % with an average value of 27.50 % while permeability rages from 169.36 - 269.76 md with an average value of 203.99 md. These values, when compared with the qualitative evaluation of reservoir porosity and permeability on standard charts (Etu-Efeotor, 1997) show that the reservoir has very good to excellent porosity with good permeability. Furthermore, the water saturation ranges from 21.7 - 45.2 % with an average value of 31.90 % while the hydrocarbon saturation ranges from 54.8 - 78.2 % with an average value of 68.10 % and therefore shows that the reservoir has a good hydrocarbon saturation. However, the presence of marine shales (mudstones) as indicated by high gamma spikes on gamma log (Fig 3) and heterolithic unit (Fig 4^2) interbedding with the sandstones are likely to form permeability baffles to vertical flow and compartmentalize the reservoirs. Reservoir 'A' may therefore have different flow units arising from the interbedding of the reservoir sandstones with the shale (or mudstones).

Table 1: Results of Petrophysical Analysis of Reservoir sands in Kwe Field

Reservoir B

This occurs at a depth range of 3817.6 – 3947.2 m with an average gross thickness of 78.7 m, average net sand thickness of 52.0 m and average net to gross thickness of 65.6 %. The porosity of the reservoir ranges from 22.8 – 30.0 % with an average value of 26.0 % while permeability rages from 39.44 – 179.02 md with an average value of 95.90 md. These values, in comparison with qualitative evaluation of reservoir porosity and permeability on standard charts (Etu-Efeotor, 1997) also show that this reservoir has very good porosity with good permeability. Furthermore, the water saturation ranges from 23.3 - 24.7% with an average value of 28.87% while the hydrocarbon saturation ranges from 61.4 - 76.7% with an average value of 71.13% and also shows that the reservoir has a good hydrocarbon saturation. However, like reservoir A, the presence of marine shales (mudstones) interbedding with the sandstones may likely form permeability baffles to vertical flow and compartmentalize the reservoirs. Reservoir 'B' may therefore have different flow units arising from the interbedding of the reservoir sandstones with the shale (or mudstones).

Well Name	Reservoir zone	Depth (m)	Gross thickness (m)	Net Thickness (m)	Net- Gross Thickness (%)	Porosity Φ (%)	Permeability k (md)	Water saturation (%)		HC saturation (%)
								Average	Irreducible	
2	A	3657.6-3771.9	114.3	72.0	63.0	25.0	169.4	45.2	8.2	54.8
	B	3825.2-3909.1	83.9	64.2	76.5	22.8	39.4	38.6	8.9	61.4
	C	3924.3-4023.4	99.1	64.4	65.0	22.2	25.4	32.4	8.9	67.6
3	A	3642.4-3741.4	99.0	51.4	51.9	25.4	172.9	21.7	8.3	78.3
	B	3817.6-3893.8	76.2	45.5	59.7	25.2	69.2	23.3	7.9	76.7
	C	3909.1-4000.5	91.4	58.7	64.2	25.9	60.1	16.2	7.7	83.8
4	A	3672.8-3764.3	91.5	63.4	69.3	32.1	269.8	28.8	6.0	71.2
	B	3871.0-3947.2	76.2	46.2	60.6	30.0	179.0	24.7	6.5	75.3
	C	3935.7-4046.2	110.5	90.7	82.1	30.1	188.8	26.3	6.4	73.7

Reservoir C

This occurs at a depth range of 3909.1 - 4046.2 m with an average gross thickness of 100.3 m, average net sand thickness of 71.3 m and average net to gross thickness of 70.4 %. The porosity of the reservoir ranges from 22.2 – 30.1% with an average value of 26.1 % while permeability ranges from 25.4 – 188.8 md with an average value of 91.4 md. These values, also when compared with qualitative evaluation of reservoir porosity and permeability on standard charts (Etu-Efeotor, 1997) also show that this reservoir has very good porosity with good permeability. The water saturation ranges from 16.2 - 32.4 % with an average value of 25.0 % while the hydrocarbon saturation ranges from 67.6 - 83.8% with an average value of 75.03% and therefore shows that the reservoir has a good hydrocarbon saturation. Further contouring of the top of this reservoirs (fig. 7) shows that this reservoir has good anticlinal trap. However, like the other two reservoirs, the presence of marine shales interbedding with the sandstones may likely form permeability baffles to vertical flow and compartmentalize the reservoirs. Reservoir 'C' may also have different flow units arising from the interbedding of the reservoir sandstones with the shale.

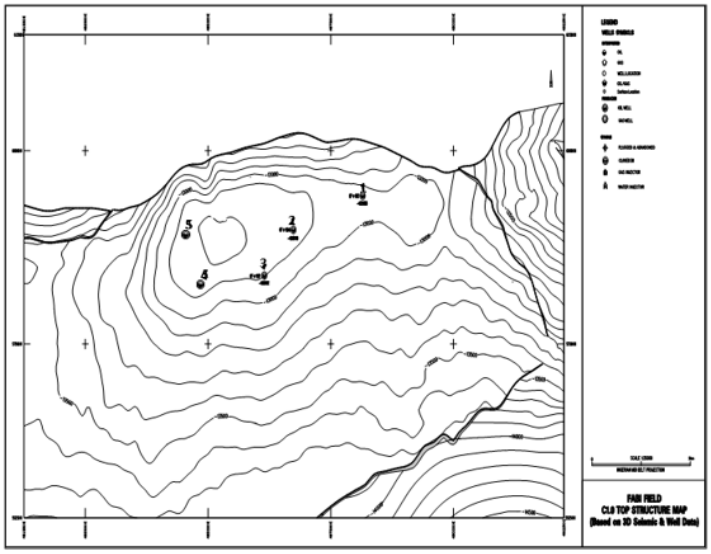

Figure 7: Contour Map of the top of Reservoir 'C'

*Conclusion***:** Three reservoir sand bodies labeled A, B, and C were identified and evaluated in the Kwe Field. These reservoir sand bodies were interpreted as deposited in an estuarine-shoreface setting thus indicating that the Kwe Field lies within the marginal marine mega depositional environment. These reservoir sand bodies have good reservoir characteristics as shown by their petrophysical properties. Contour map of the top of reservoir 'C' shows that the reservoir has good anticlinal trap. However, the presence of marine shales (or mudstones) interbedding with the sandstones are likely to form permeability baffles to vertical flow and compartmentalize the reservoirs. These reservoirs may therefore have different flow units. The study however recommends that the interpreted depositional environment should further be constrained with biostratigraphic data as they were not made available for this study. Additionally, thin-section petrographic characterization and clay mineral studies of the identified lithofacies should be studied so as to further determine the reservoir quality of these reservoir sandstone as well as accessing the seal potentials.

Aknowledgement: The dataset for this research were provided by the Shell Petroleum Development Company (SPDC) through the Department of Petroleum Resources (DPR) for this research for which the authors are grateful

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