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Petrophysical Evaluation Using Well Logs 3D Models and Mud Log Hydrocarbon Typing Analysis: Case Study of an Onshore Niger Delta Field

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Abstract
Petrophysical evaluation is essential to the upstream sector of every exploration company in the oil industry because accurate formation evaluation enables reserve development models for uptimal well production and management. The study was carried out on an onshore Niger Delta field using eight wells with the objectives of identifying possible reservoir units with the potential to contain hydrocarbons, delineate hydrocarbon type(oil and gas), and quantify the identified hydrocarbons for possible viable reservoir development and production using both well logs and mud logs as data sets. Formation evaluation using fluorescence and hydrocarbon typing/potential (qualitative) of the mud logs revealed oil and gas zones (SMKs 6, 13 and 14) and oil zones (SMK 12) corroborated excellently by quick look well log formation evaluation using Density-Neutron Overlays. Quantitative petrophysical evaluation for all wells was made using models from Wireline/MWD logs of the case study reservoir (SAND_O) to account for delineated hydrocarbon zones and results showed sufficient porosity (0.15 – 0.28), Volume of shale (0 – 0.2%), hydrocarbon saturation (60% to 90%) for possible well development with a STOIIP estimate of about 15MBO (million barrels oil equivalent).
Keywords: Petrophysical Evaluation, Fluorescence, Hydrocarbon potential, Stock Tank Oil Initially In Place, Niger Delta

1. INTRODUCTION
The Niger Delta is a prolific hydrocarbon province situated in the Gulf of Guinea with depobelts covering an area of around 300,000 km^2 with a basin depocenter thickness of over 10km (Kaplan et al, 1994) (Figure 1). The basin is ranked 12th richest in terms of petroleum resources (Petroconsultants Inc.1996), with exploration efforts in recent times shifting from onshore down to shallow offshore and deepwater regions as the demand for the very important energy resource increased. Due to the huge cost of exploration and exploitation of this resource, high premium is given to accuracy and precision of tools capable of identifying and quantifying the resource with minimum risk, one of which is the use of petrophysics in measuring rock properties and using the relationships between these properties to detect and evaluate hydrocarbon bearing formations (formation evaluation) (Amigun et al., 2012) (Ameloko and Owoseni, 2015). Accurate formation evaluation aids optimal well development and production as it gives clues of well potential to produce oil or gas or both (Obekezie and Bassey, 2015).A well drilled into a dry reservoir zone - due to incorrect interpretation of data - is a failure both in terms of well costs and target expectation.
This is where the formation evaluation aspect is so crucial because it determines the hydrocarbon and productivity potentials of the well for development and subsequent production. Formation evaluation for this study integrates both real time and postdrill parameters to delineate and quantify possible hydrocarbon accumulations.

This study aims at incorporating both real time (Mud and MWD – Measurement While Drilling - logs) and post drill(Wireline logs) data as well as 3D modelling to evaluate the hydrocarbon bearing (volume of shale, resistivity, Density-Neutron crossplots, Porosity etc) and hydrocarbon producibility potential (Permeability and STOIIP estimates) of the SMK field (Figure 2). Mud logs give the earliest indication of hydrocarbon presence through oil shows, samples stains, flouresence and Hydrocarbon typing analyses and it is mostly qualitative to semi quantitative. Well logs give an overview in terms of both qualitative (crossplots and overlays) and quantitative evaluations (3D Modelling of reservoir horizons and reservoir volumetrics).A comparison of results from both data sets will serve to eliminate errors and minimise risks associated with well placement, development and production in frontier, maturing and matured basins(Figure 1).

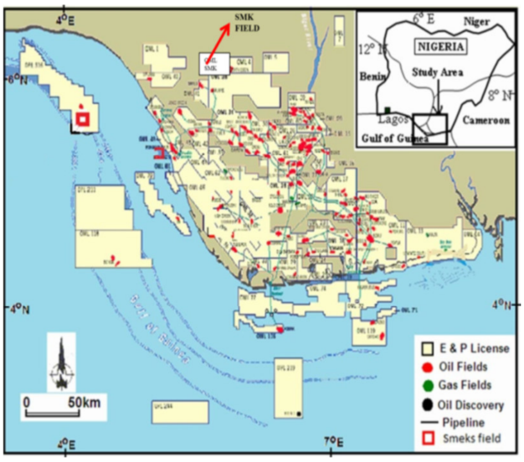

Figure 1: Concession map of the Niger Delta (inset is the map of Nigeria) showing the study area, SMK Field (Doust and Omatsola, 1990)

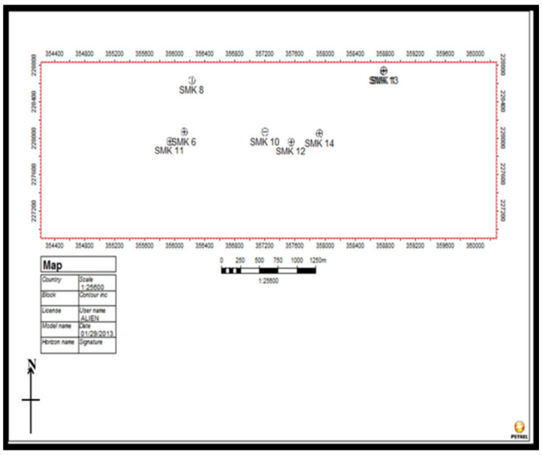

Figure 2: Base Map of the SMK Field

1.1 GEOLOGIC SETTING

SMK field is located onshore in the Northern Delta depobelt, West of the Niger Delta between Latitudes 5°N and 6°N and Longitudes 5°E and 6°E and exhibit the typical characteristics associated with the regional structural settings of the Niger Delta, a delta situated in Southern Nigeria at the apex of the Gulf of Guinea on the West coast of Africa between latitudes 4^0 N and 6^0 N and longitude 3^0 E and 9^0 E (Nwachukwu and Chukwura, 1986). It is one of the most prolific deltaic hydrocarbon provinces of the world (Figure 1). From the Eocene to the present, the delta has prograded southwestward, forming depobelts that represent the most active portion of the delta at each stage of its development (Doust and Omatsola, 1990). The Niger Delta Province contains only one identified petroleum system (Kulke, 1995; Ekweozor and Daukoru, 1994). Stratigraphically, there are three major formations corresponding to tripartite sequences from the oldest to youngest observed in the Niger Delta namely the Akata (marine shales ranging from 600 to 7000m, potential source rocks, Paleocene to Recent in age), Agbada (paralic sequence of alternating sandstone, sitstone and clays, about 300 to 3500m, potential reservoir rocks, Eocene to Recent in age) and Benin (Continental sands, about 2000m thick, Eocene to Recent in age)

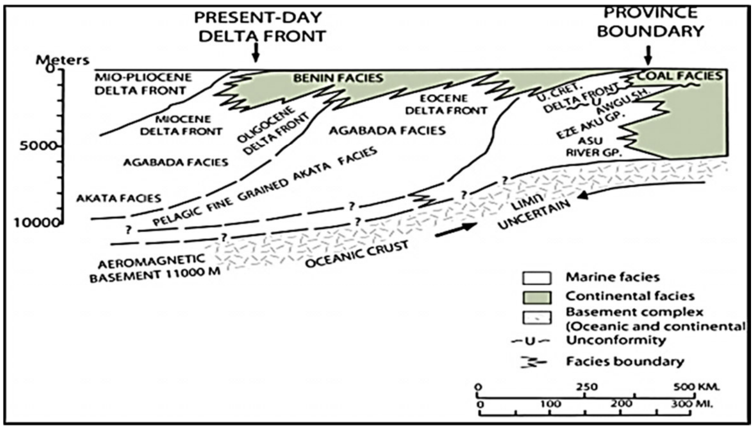

Figure 3: Geologic cross section through the Niger Delta showing the stratigraphic units (Mitchele et al., 1999)

2. MATERIALS AND METHOD

The data set was obtained from PanOcean Nigeria Limited through the Department of Petroleum Resources (DPR), Lagos state; Nigeria. Generally, there are three data categories used in this research: Mud logs, Wireline and MWD logs. Each data set is processed separately initially and the results of each analysis are integrated to realize the study objectives. Eight wells were used in this study. For the well logs (Wireline/MWD), the data include gamma ray (GR), sonic (SON) density (DENS), resistivity (LLD) and neutron (NEU) logs and were analysed using the PETREL software. The Gamma ray log was used to differentiate sand and shale units (lithology) using cutoffs. The Deep resistivity log was used to differentiate hydrocarbon bearing and non-hydrocarbon bearing zones in conjunction with the gamma ray log. The neutron and density logs were combined to identify fluid types (oil and/or gas) and fluid contact from identified log crossovers. The sonic log was combined with neutron log to identify secondary porosity (fractures) from log crossovers. Petrophysical evaluation involves the quantification of various reservoir parameters which aided in prospect risking. Reservoir porosity was calculated from bulk density using Equation 1(Wyllie et al, 1958).Since the Niger Delta consists of clastic reservoirs, the matrix density of 2.65g/cm^3 and fluid density of 1.0g/cm^3 are used in the calculation.

$$\Phi d = \frac{\rho ma - \rho b}{\rho ma - \rho f1} \qquad (1)$$

Where
ρma = matrix density
ρb = density log represents bulk density of the formation
ρfl = density of the fluid in the formation
The evaluation process continued with the estimation of volume of shale (Vshale – portion of the reservoir with shale intercalations) using Dresser Atlas, 1979 formula (Equations 2 and 3)

$$Vsh = 0.083[2^{(3.7*I_{GR})} - 1] \qquad (2)$$

$$\text{Where } I_{GR} = \frac{GRlog - GRmin}{GRmax - Grmin} \qquad (3)$$

Vsh = Volume of shale, I_{GR} = Gamma ray index, GRlog = Gamma ray reading for the depth of interest, GRmax = maximum gamma ray, GRmin = minimum gamma ray.
One of the reservoir parameters measured was water saturation (the portion of the reservoir horizon occupied by water) and to calculate this, a water resistivity Rw value is required which was calculated from porosity and resistivity logs within clean water zones (Rt) using Equations 4 and 5

$$Rw = \frac{(\Phi 2 * Rt)}{a} \qquad (4)$$

After calculating Rw, then Sw is delineated using the archie equation below

$$Sw = \frac{\sqrt{(a * Rw)}}{\Phi 2 * Rt} \qquad (5)$$

Where Rw = Formation water resistivity in a water bearing reservoir, Rt = resistivity in a hydrocarbon bearing reservoir, a is a constant and is equal to 0.81. Φ is total porosity
The hydrocarbon saturation is easily derived from the water saturation values using Equation 6.

$$Sh = 1 - Sw \qquad (6)$$

Where Sh = hydrocarbon saturation and Sw = water saturation
To estimate the volume of oil in place, calculated reservoir parameters were used in modelling the STOIIP (Stock Tank Oil Initially In Place) using Equation 7

$$STOIIP = \frac{0.1781*GRV*N/G*\Phi*(1-SW)}{Bo} \qquad (7)$$

Where STOIIP = Stock Tank Initially In Place, N/G is Net to Gross, Φ is the porosity, S_W is water saturation, Bo is the oil formation factor(taken to be 1.3 for this study)

For the mud logs (show the drilling record of a well, providing real time information on lithology, hydrocarbon presence, depth for evaluation and correlation, offering incontrovertible evidence on formation samples), a combination of Fluorescence, Bateman and Haworth Methods were used in accessing reservoir suitability and producibility for the wells with mud logs (SMK 6, 12, 13 and 14) using Origin and Microsoft Excel softwares.

To determine flourescence(oil's ability of emitting light in the visible range when exposed to ultraviolet radiation giving an idea of oil type) , different flourescing colours from sand cuttings were analysed and catalogued with,brown colour denoting heavy oils,gold to yellow/cream medium gravity oil,white colour indicative of light oil while blue white colour indicates gas(Figure 4).

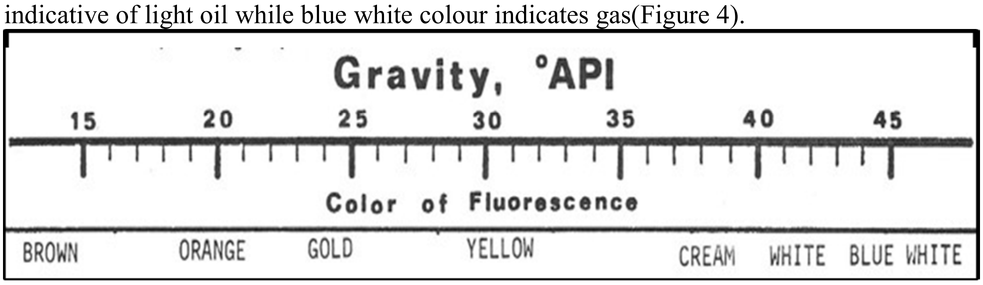

Figure 4 : Flourescence colour and API gravity scale(Crain,2012)

Haworth and Bateman methods are hydrocarbon delineators giving indications of reservoir/formation productivity through the calculation and plotting of numerical ratios of the various hydrocarbon contents encountered.

Using the Haworth et al., 1984 method, some numerical ratios are calculated and the results evaluated using three values to type formations (Table 1). These are:

Gas wetness ratio (GWR), a measure of the amount of methane encountered and calculated using the formula below

C2 + / C1+ , where C1 = Methane, C2 = Ethane values in PPM (Part Per Million)

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Light – to- Heavy ratio (LHR), a measure of the light to heavy hydrocarbons encountered and calculated using the formula

(C1 + C2) / (C3 + C4 + C5) where C3, C4, C5 represent propane, butane and pentane values respectively

Oil character Qualifier (OCQ) , a qualifier when excessive methane is present and is denoted by the formula below

(C4 + C5) /C3, where C3, C4, C5 represent propane, butane and pentane values respectively.

Table 1: Hydrocarbon potential analysis from mudlogs (Hatworth et al.,1984)

HYDROCARBON	GWR(%)	LHR(%)	OCQ RATIO
LIGHT DRY GAS	< 0.5	100 +	VERY LOW
MEDIUM DENSITY GAS	0.5 – 17.5	< 100	< 0.5
LIGHT OIL GAS	5 – 10	17.5	> 0.5
MEDIUM GRAVITY OIL	17.5 – 40	< 10	> 1.0
RESIDUAL OIL	> 40	5 – 10	< 2.0
COAL BED	15 – 20	< 100	VERY LOW

Using the Bateman's method, plots of straight C-numder ratios(from chromatographic analysis) on a special logarithmic grid give an idea of the production type(oil or gas or both) predicted according to the area of the graph on which the points fall (Figure 5) using these fractions

C1/C2, C1/C3, C1/C4 and C1/C5 where C1, C2, C3, C4 and C5 are methane, ethane, propane, butane and pentane respectively

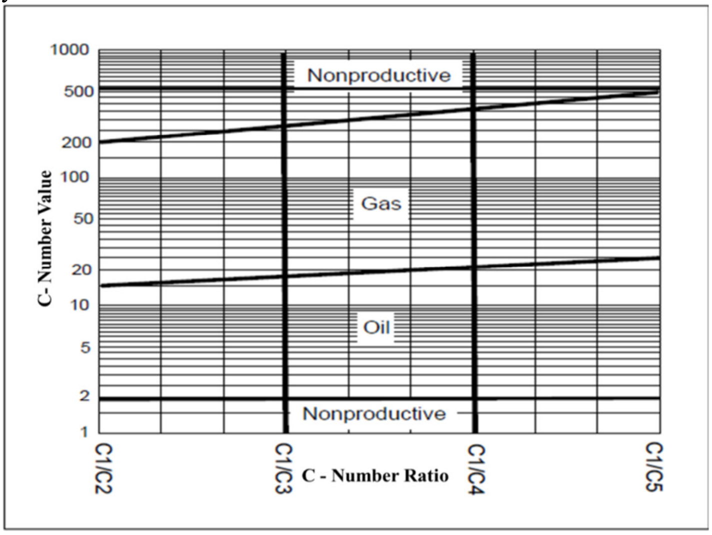

Figure 5: Semi log grid for hydrocarbon typing (Bateman, 1985)

3.0 RESULTS AND DISCUSSION

3.1 QUALITATIVE PETROPHYSICAL EVALUATION

Qualitative well log formation evaluation involved lithofacie identification, well correlation and quick look log analysis. Lithofacie identification was done using the gamma ray log with defined log signatures left and right of the shale baselines representing sands (yellow) and shales (green) respectively with resistivity logs adding further incontrovertible evidence on shale/sand presence, extent and boundaries. The correlation was done in strike direction with good reservoir connectivity and appreciable thickness observed across all the wells in the field. An abrupt change in the depositional pattern in Figure 6 (red arrow) was observed around 9000ft with consequent results of reservoir limbs being uplifted and others downthrown possibly due to an unconformity of fault system (red circle). Correlation of wells was done using good shale markers, flattening depth scales of these beds and good correlative sand/shale features marked on adjacent wells and joined together over the field (Figure 6).

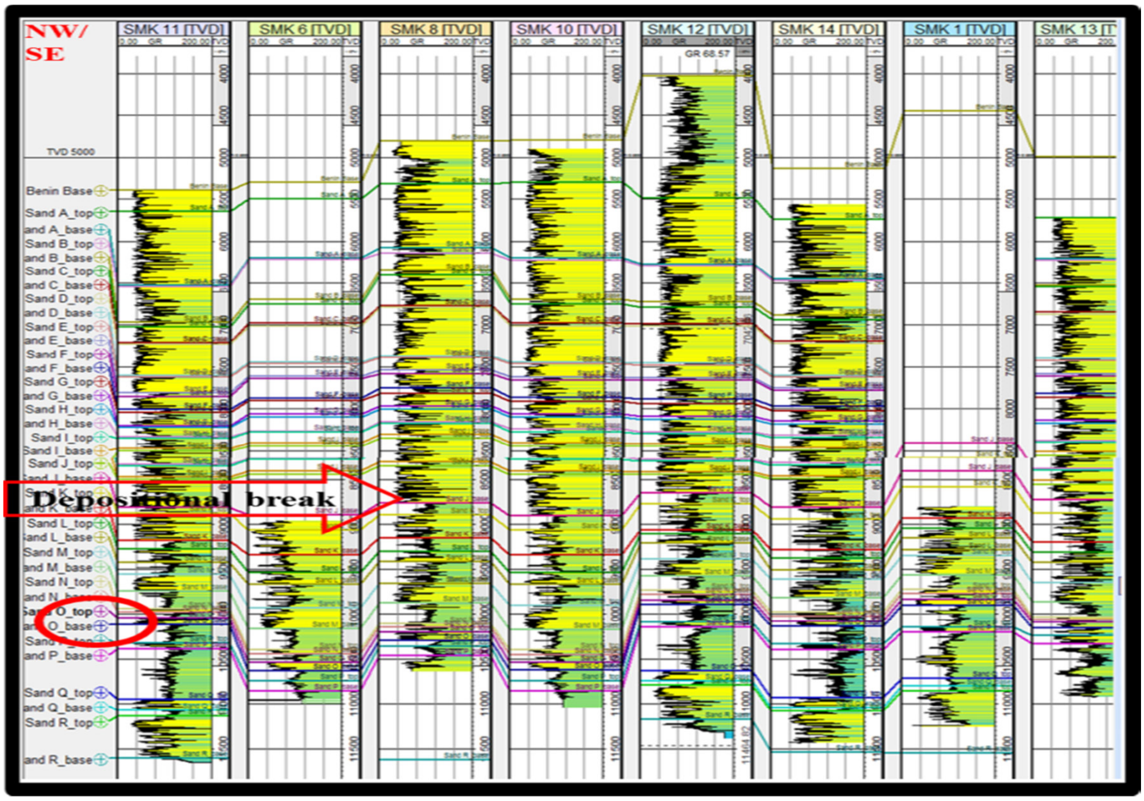

Figure 6: Well to Well correlation of the SMK field (Red circle is the case study reservoir SAND_O)

Quick look log analysis – to give first hand qualitative results on porosity and hydrocarbon presence and type - was carried out using various overlays such as Density – Neutron (hydrocarbon typing)(Figure 7) and Sonic – Density (fracture delineation)(Figure 8).

Density – Neutron overlay across the field (Figures 7 and 8) compared with resistivity logs showed various hydrocarbon zones(red colour) in the five wells examined and an attempt to differentiate these into either oil or gas or both was made based on the relative separation of both logs with a wide separation/crossover(balloon shape) indicating gas zones and a narrower crossover(Funnel shape) mainly indicative of oil zones.Of the wells examined (SMKs 1,10,11,12 and 13) only SMK 12 gave indications of a preference for oil zones while oil and gas zones were identified in the rest.

Sonic – Density overlays were carried out mainly for secondary porosity identification manifesting in form of reservoir fractures which could improve primary porosity and permeability.Five wells(SMKs 1,10,11,12 and 13) were analysed and it was discovered that the degree of reservoir fracturing is common throughout the well (Figure 8) Other wells show a preference for specific depth related reservoir fracturing which is not observable throughout the well.

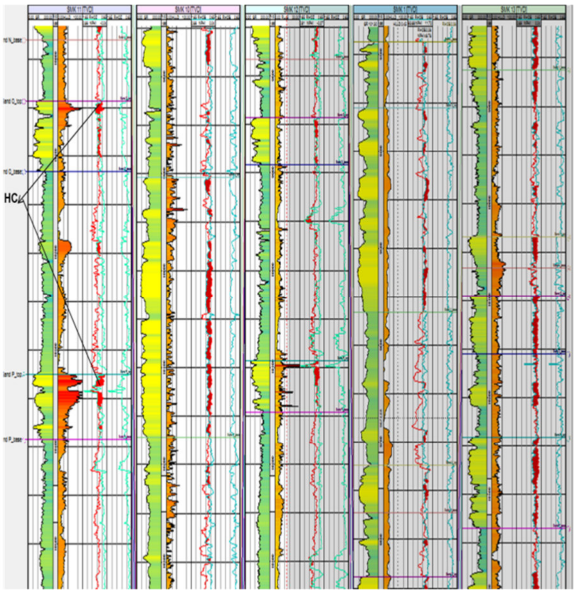

Figure 7: SMK Field Neutron – Density Overlay(enclosed red colours)

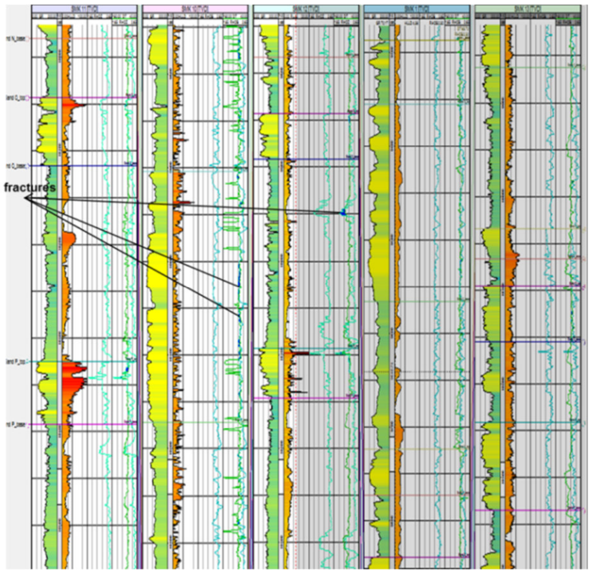

Figure 8: SMK Field Sonic – Density Overlay (enclosed blue colours)

A comparison of results for both well (wireline/MWD) logs and Mud logs is presented in Table 4 and Figure 10 with relatively good correlation observed for the datasets employed.

Flourescence analysis from sand cuttings for the SMK field carried out using the four mud logs (SMKs 6,12,13 and 14) showed that SMK 6 has yellow to milky white crushed cuts(oil and gas typed), SMK 12 has light yellow crushed cut (oil typed) ,SMK 13 has yellow, no visible cuts(oil and gas typed) and SMK 14 has yellow to milky white cut(oil and gas typed)(Table 4) (Figure 9).

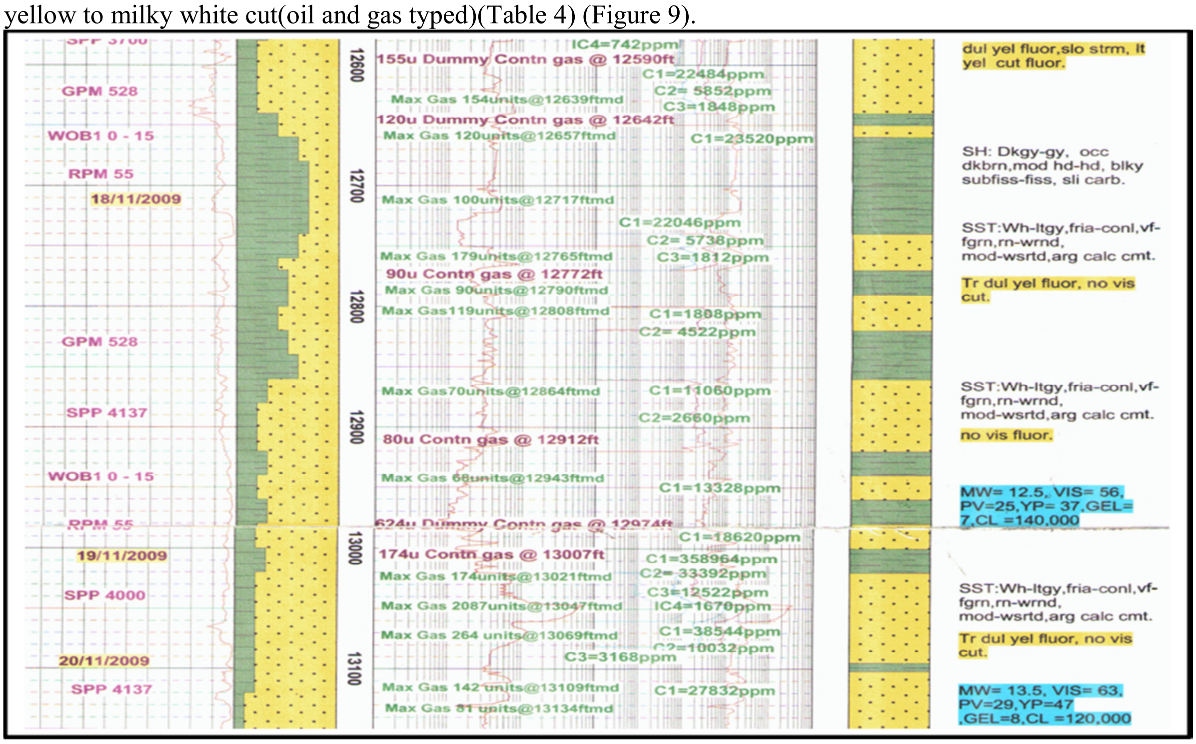

Figure 9: SMK 12 MudLog (Track 1:ROP data;Track 2: Strip log depth;Track 3: gas data,Track 4:Litholog, Track 5: cuttings flourescence and drilling data

Haworth method analytical results, showed that for SMK 6 the GWR suggest medium gravity oil, LHR suggests medium gravity gas, thus showing the well to be oil and gas windowed (Table 3).

Bateman method results for SMK 6 showed that C1/C2 = 5.7(oil section), C1/C3 = 16.4(oil section), C1/C4 = 82.75(gas section) showing the well to be oil and gas typed (Table 2) (Fig 10)

Table 2: Calculated carbon number values used for hydrocarbon typing analysis

FIELD WELL	CARBON NUMBER (PPM) C1	C2	C3	C4	C1/C2	C1/C3	C1/C4
SMK 6	529600	92950	33370	6400	5.7	16.4	82.75
SMK 12	298958	64106	25671	NIL	4.66	11.65	NIL
SMK 13	2077201	186902	89042	19872	11.11	23.33	104.53
SMK 14	615386	79392	36176	124084	7.75	17.01	73.4

Table 3 showing Haworth Method results

FIELD WELL	LHR (%)	GWR (%)	OCQ	DEDUCTIONS
SMK 6	15.6	19.9	0.22	LHR (Medium Gravity Oil) GWR (Medium Density Gas) OCQ(Medium density Gas) C5 presence = further proof
SMK 12	14.4	18	NIL	LHR (Medium Gravity Oil) , GWR(Medium Density Gas?) ,OCQ(no C4 and C5) C4 and C5 presence = further proof
SMK 13	20	12	0.22	LHR (Medium Gravity gas), GWR (Light Oil Gas) OCQ(Medium density Gas) C5 presence = further proof
SMK 14	14.4	17.2	0.33	LHR (Medium Gravity Oil) GWR(Medium Density Gas) OCQ(Medium density Gas) C5 presence = further proof

For SMK 12 using the Haworth method, the GWR suggests medium gravity oil, LHR is inconclusive on gas presence, thus showing the well to be oil window. No OCQ (no C4 available)(Table 3).

Bateman results include C1/C2 = 4.66 (oil section), C1/C3 = 11.65 (oil section) showing the well to be oil typed which agrees with Haworth method results (Table 2) (Figure 11).

For SMK 13 using the Haworth method, the GWR suggest medium density gas, LHR suggests light oil gas, thus showing the well to be oil and gas windowed. No OCQ (no C5 available)(Table 3)

Bateman results include C1/C2 = 11.11(oil section), C1/C3 = 23.33(gas section), C1/C4 = 104.53(gas section) showing the well to be oil and gas typed (Table 2) (Figure 12).

For SMK 14 using the Haworth method, the GWR suggests medium gravity oil, LHR suggests medium gravity gas, thus showing the well to be oil and gas windowed. No OCQ (no C5 available)(Table 3)

Bateman results include C1/C2 = 7.75(oil section), C1/C3 = 17.01(oil section), C1/C4 = 73.4 (gas section) showing the well to be oil and gas typed (Table 2)(Figure 13).

A comparison of SMK 12 and 13(both well and mud logs) show agreeable matches (Figure 14).

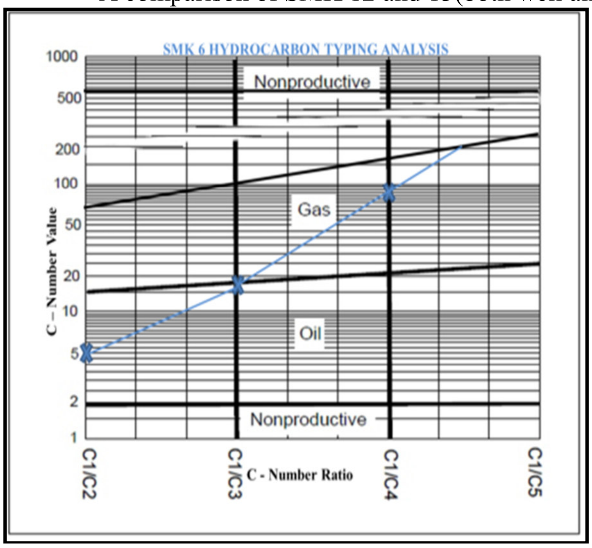

Figure 10: SMK 6 Bateman Method Result

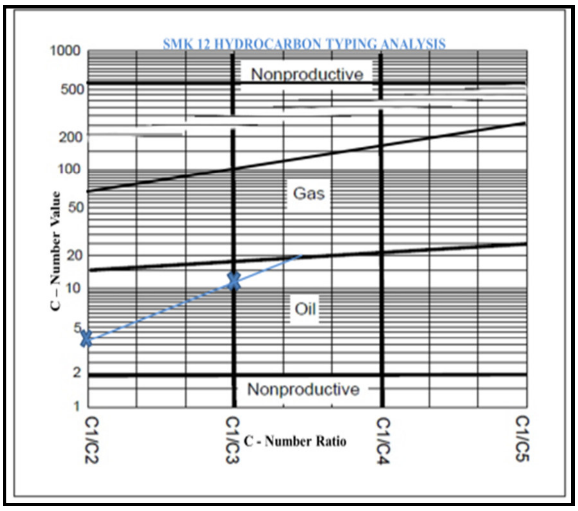

Figure 11: SMK 12 Bateman Method Result

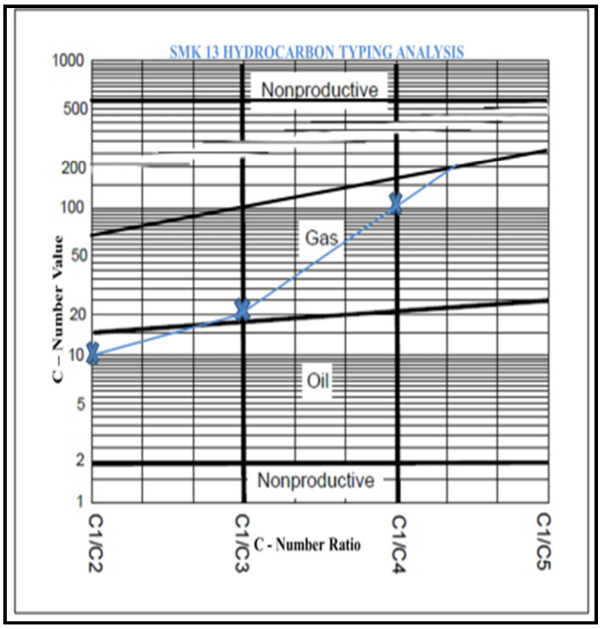

Figure 12: SMK 13 Bateman Method Result

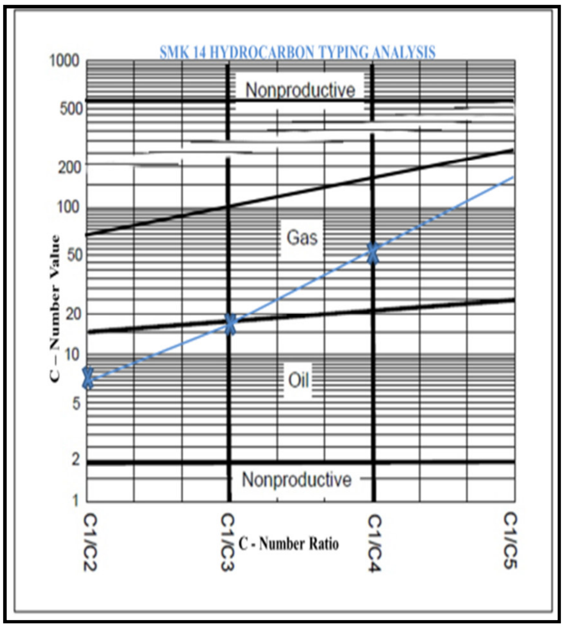

Figure 13: SMK 14 Bateman Method Result

Table 4: Well and Mud log Qualitative Petrophysical Evaluation Results

FIELD WELL	WELL LOGS (NEUTRON – DENSITY CROSSPLOT)	FLOURESCENCE	HC TYPING C-NUMBER RATIO	HC TYPING HAWORTH METHOD	POSSIBLE MATCH
SMK 6	NOT AVAILABLE	Yellow to milky white crushed cut	Oil and Gas typed	Oil and Gas typed	Good
SMK 12	OIL	Light yellow crushed cut	Oil typed	Oil typed	Excellent
SMK 13	OIL AND GAS	Yellow, no visible cuts	Oil and Gas typed	Oil and Gas typed	Excellent
SMK 14	NOT AVAILABLE	Yellow to milky white cut	Oil and Gas typed	Oil and Gas typed	Good

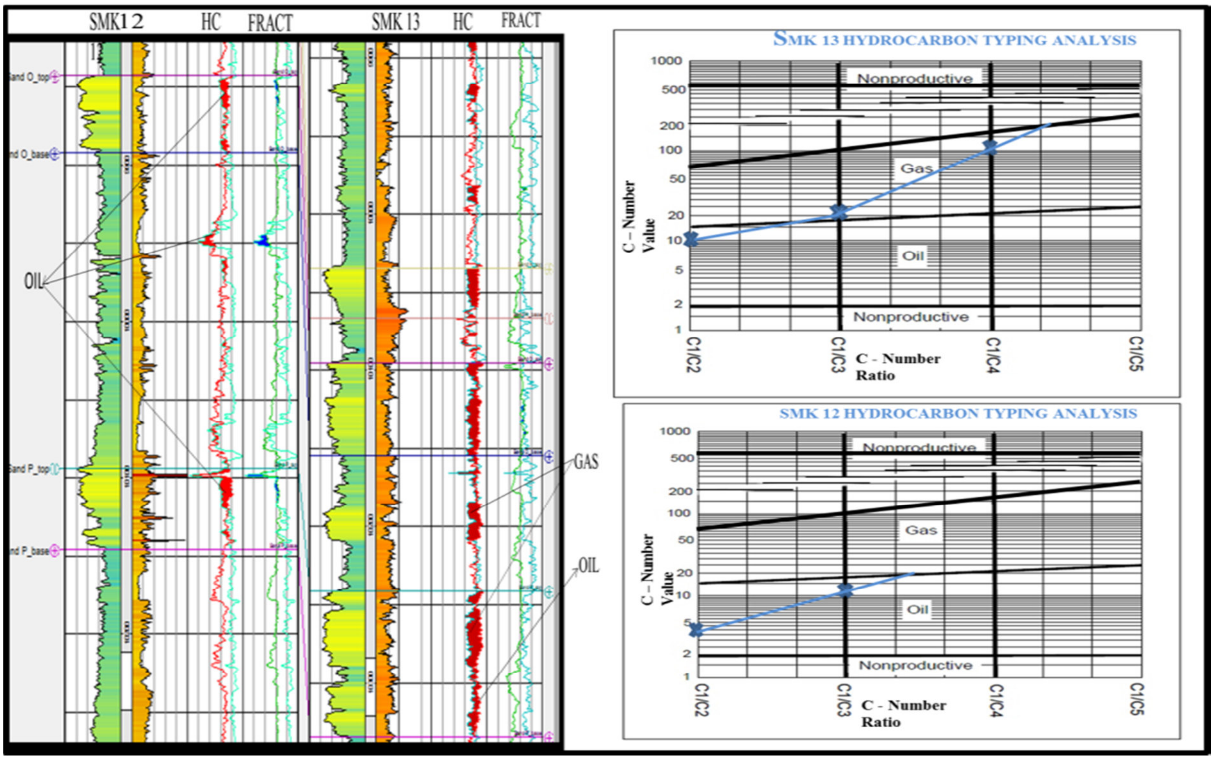

Figure 14: Well and Mud log Formation Evaluation(SMK 12 and 13) showing excellent matches

3.2 QUANTITATIVE PETROPHYSICAL EVALUATION

For the SMK field study, a case study reservoir(SAND_O) was chosen for quantitative estimates of porosity, water saturation, volume of shale, permeability(where possible) and a possible reserve estimate which were carried out through modelling and presented in this section. Modelling gives precise and concise information of the subsurface horizon through the measurement of the insitu peoperties of the reservoir of interest (Figure 6). SAND_O was chosen to provide information on how producible a marginal reservoir will be (no extensive thickness of sand units) (Figure 15). For porosity estimation, figures 16 and 18 show the variation of porosity values across the case study reservoir of the SMK field. From the map and model, porosity is observed to be highest around the southwestern part (0.28), southernmost and northeastern corner of the field (0.24) with the lowest values recorded around the southeastern corner of the field (0.08).Generally, porosity values across the case study reservoir horizon is favourable for reservoir development and production except probably SMK 14 but several productive horizons were identified in the same well at 10200ft TVD downwards.

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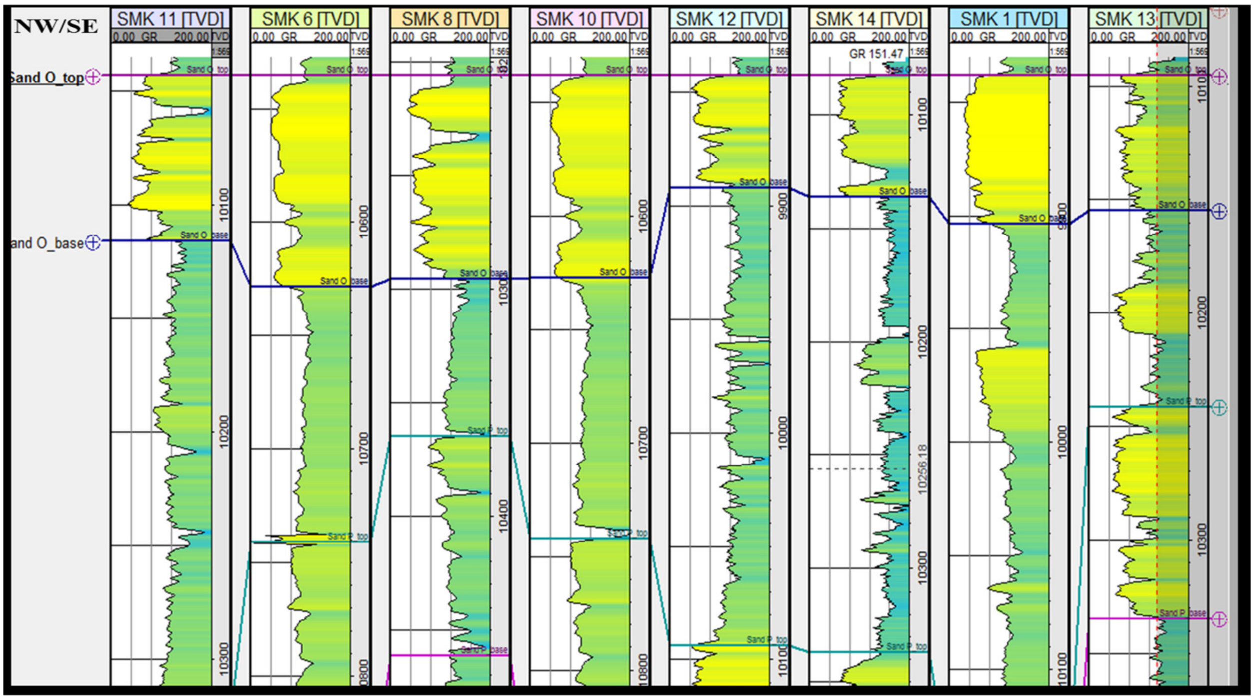

Figure 15: Case Study Reservoir (SAND_O) for petrophysical evaluation showing well section flattened on the well top

Depth/Elevation 3D grid models across the case study reservoir horizon showed results corroborating with the 2D map models (Figures 17 and 19.) with matching crests and troughs. Resistivity derived hydrocarbon zones (yellow/red colours) are depth displayed for each well (Figure 17 to 22).

Quantitative estimates of water saturation which represent the reservoir pore volume fraction occupied by water are depicted in Figure 21 showing reservoir depths of the wells and their relationship with the blue parts being water wet reservoirs having the highest values (0.9) indicating that wells with reservoirs at these depths are hydrocarbon barren (SMKs 6, 8, and 10) compared to the rest with lower values (+0.1 - 0.3) showing promising hydrocarbon saturation prospects for SMKs 1,11,12,13 and 14.

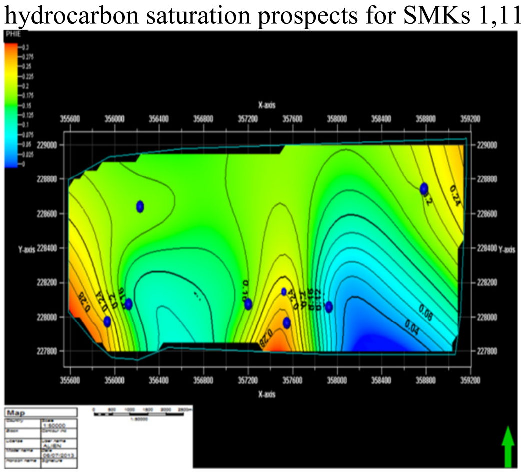

Figure 16: Porosity map for SAND_O reservoir

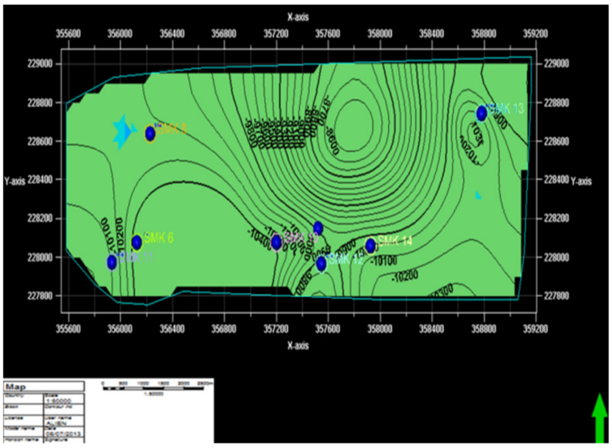

Figure 17: Elevation Map for SAND_O reservoir

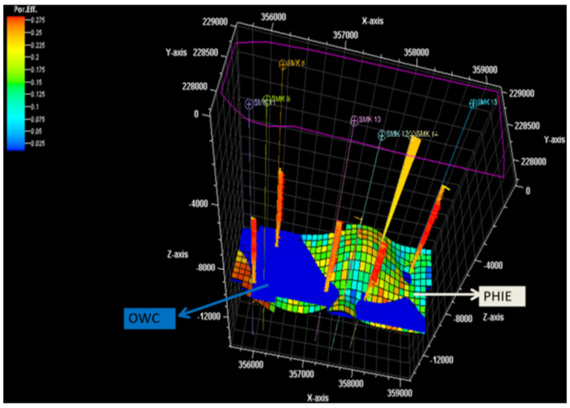

Figure 18: Porosity Model for SAND_O reservoir

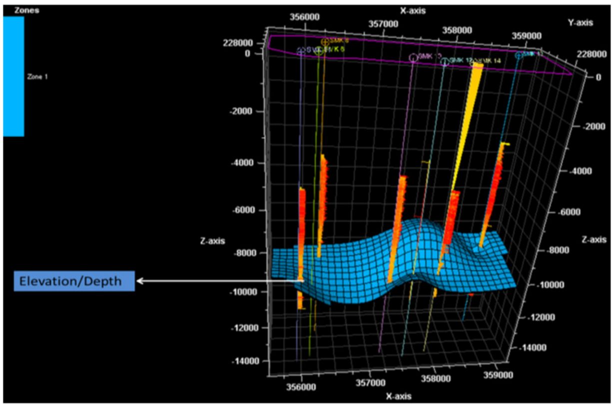

Figure 19: Elevation Model for SAND_O reservoir

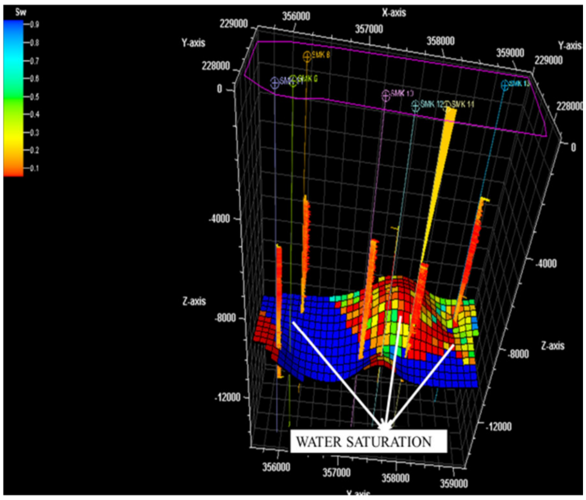

Figure 20: Water Saturation Model for SAND_O reservoir

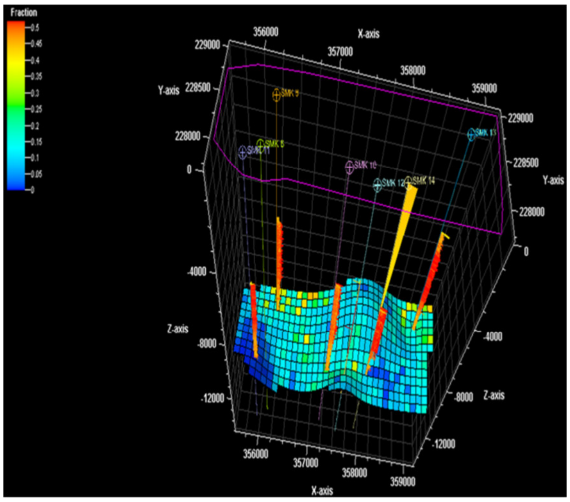

Figure 21: Vshale Model for SAND_O reservoir

A volume of shale (Vshale) model showing sand/shale ratio is shown in Figure 21 using a shale cutoff of 0.5 for the analysis. The model shows generally very low shale values of around 0 – 0.2 for the wells under consideration indicating good reservoir potential across the field and ultimately its potential producibility.

Reserve estimation for the case study reservoir was modelled so as to adequately evaluate its hydrocarbon potential. The model was for oil only identified in Figure 22 as the oil-water contact (a zone below which only water is found, above which there is oil) identified as 10067ft based on visual inspection extending and probably beyond. For the volumetric analysis, a Formation Volume Factor (Bo) of 1.3 (RB/STB) was adopted. RV model (Figure 22) for prospect reservoir shows volume estimates to be less than 15 million stock barrels of oil equivalent (MBOE), a result which could have been much higher but for the water wet reservoir portions of SMK 6, 8 10 and 14(Table 5)(Figure 23).

Table 5: SAND_O reservoir average petrophysical values for STOIIP

WELL	SMK 11	SMK 6	SMK 8	SMK 10	SMK 12	SMK 14	SMK 1	SMK 13	AVERAGE OVERALL
POROSITY	0.275	0.16	0.18	0.16	0.24	0.06	0.2	0.2	0.18
WATER SAT.	0.05	0.9	0.9	0.9	0.05	0.9	0.05	0.05	0.475
HC SAT.	0.95	0.1	0.1	0.1	0.95	0.1	0.95	0.95	0.525
VSHALE	0.0	0.05	0.15	0.15	0.2	0.1	0.2	0.2	0.13

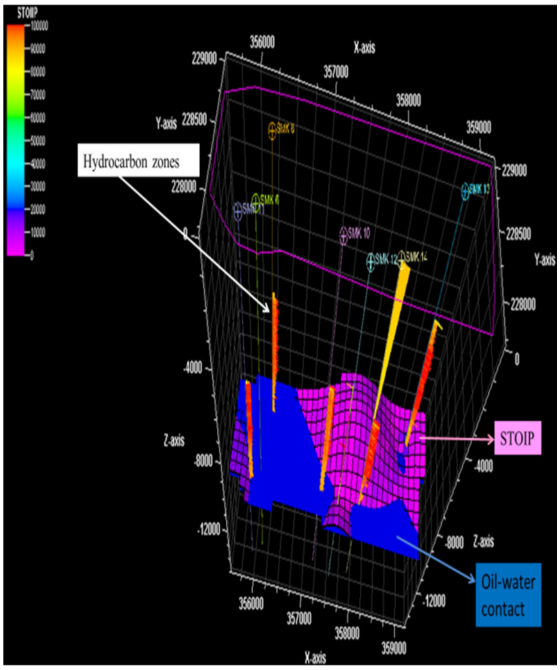

Figure 23:STOIIP Model for SAND_O reservoir

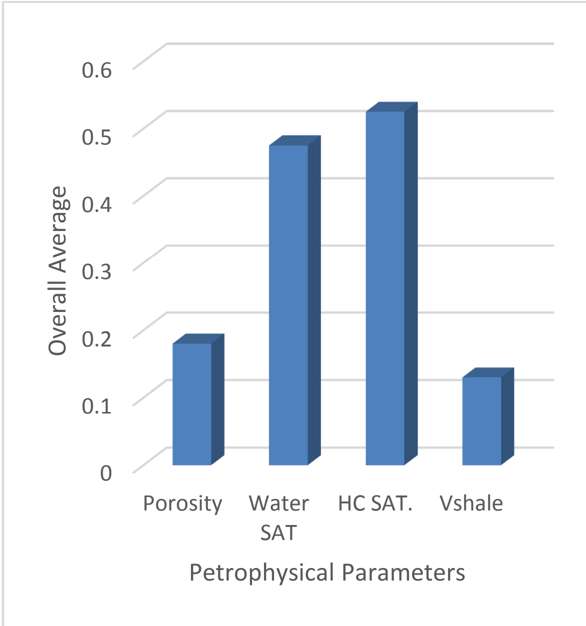

Figure 24: Average petrophysical values for STOIIP

4.0 CONCLUSION AND RECOMMENDATIONS

Qualitative petrophysical evaluation of the SMK Field from mud logs using fluorescence, Bateman and Haworth methods revealed SMKs 13, 14 and 6 to be oil and gas typed using while SMK 12 is oil typed, results corroborated excellently by wireline logs overlays (density-neutron/sonic-density) particularly SMK 12 and 13. Fracture delineation in some wells may contribute positively to secondary porosity and permeability.

Quantitative petrophysical evaluation of a Case study Horizon (Sand_O Prospect reservoir) across the field using maps and models yielded average values of porosity (0.18),water saturation (0.48),HC saturation(0.52) and Vshale (0.13) giving sufficient evidence exist to attest to the productivity potential of the Prospect reservoir. A STOIIP estimate of 15MBOE was calculated for the horizon.

I would recommend the use of 3D Seismic data to compliment this work by its use in characterizing the reservoir and other prospects in the wells as well as to give clues on fault controls on porosity and permeability. Complete log suites for all wells (especially SMKs 11, 6 and 14) will help in providing a better estimate of petrophysical parameters. More Mud logs would have been useful in the work.

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