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PETROPHYSICAL ANALYSIS OF WELL DATA FOR CLASTIC RESERVOIR EVALUATION AND DETERMINATION OF THE INVADED ZONE EFFECT: A CASE STUDY OF A FIELD IN THE ONSHORE NIGER DELTA, SOUTH-SOUTH, NIGERIA

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ABSTRACT

Two reservoirs domiciled in a well have been analysed in this study in order to obtain the quantitative reservoir properties. These quantitative reservoir properties are essential not only for well development and optimization but also for accurate decision-making prior to reservoir exploitation and production. A suite of composite logs comprising the caliper log, gamma-ray (GR) log, density log, resistivity logs and sonic transit time logs obtained from a field in the onshore Niger Delta was used for the petrophysical analysis. From our quantitative results, Reservoir 1 has the potential to produce oil and gas with a total hydrocarbon saturation of 81%. However, due to the invaded zone effect on the reservoir potential, the total hydrocarbon fluid has been partitioned into moveable hydrocarbon of 65% saturation and immoveable hydrocarbon of 16% saturation. This resulted from the mud filtrate invasion of the radially shallow zone which displaced the original fluid while the undisplaced hydrocarbon fluid remained in the pore spaces of the reservoir. The porosity of the reservoir sand is 33% and its effective porosity is 32.5%. The high effective/interconnected porosity and clean nature of the sand which is due to the extremely small volume of shale present in the sand (just 1.0%) clearly shows that the reservoir is highly porous, permeable and producible.The net pay of the reservoir (represented by the thickness TH in Mesh 1) could not be quantitatively determined due to lack of depth information on the logs. The second reservoir (Reservoir 2) has a total hydrocarbon saturation of 94.8% and water saturation of just 5.2%. The total hydrocarbon saturation is partitioned into 82.8% moveable hydrocarbon saturation and 12% immoveable hydrocarbon saturation which resulted from the invaded zone effect. The porosity of the reservoir was determined at 33% and its effective porosity at 32.5%. Again, the high effective/interconnected porosity and clean nature of the sand arising from the extremely small volume of shale present in the sand (0.4%) is a clear indication that the second reservoir is also highly porous, permeable and producible. The net pay of Reservoir 2 (represented by the thickness TH in Mesh 2) is higher compared to Reservoir 1 but could not be evaluated due to absence of depth values on the logs. In the final analysis, the overall results show that the reservoirs are commercially favourable and have the potential to pay back.

Keywords: Petrophysical, Clastic, Reservoir, Evaluation, Invaded, Zone, Effect

INTRODUCTION

Petrophysical evaluation of hydrocarbon wells and associated reservoirs is essential to exploration and production companies in the oil industry. This is because petrophysical information is required not only for well development and optimization but also for accurate decision-making prior to reservoir exploitation and production.

First, in assessing a reservoir for quality, it is important to determine qualitatively that the reservoir contains hydrocarbons (oil, gas) and is sufficiently porous, permeable and producible. This requires the application of the quick-look-log interpretation technique and use of core sample analysis etc, to obtain qualitative information that can reveal hydrocarbon presence in the reservoir (Asquith and Krygowski, 2004). Secondly, the reservoir must be further assessed to quantitatively ascertain that its hydrocarbon contents are in such a commercial quantity that can offset exploration and exploitation cost and attract profit to the investors.

Whereas the use of core samples and mud logs is a direct method of deriving the petrophysical properties of reservoirs and is essentially a qualitative approach, measurement-while-drilling (MWD) or postdrill wireline logs are used as an indirect quantitative method for obtaining the properties of the reservoirs (Jugen, 2004).The logs provide measurements of indirect parameters from which the reservoir properties can be quantitatively derived using appropriate mathematical models (Ameloko and Owoseni, 2015; Ologe, 2016). However, in addition to their application for quantification of hydrocarbon contents and other reservoir properties, the gamma ray log, resistivity logs and neutron-density overlay log are used for a quick look as an essentially qualitative technique that first helps petrophysicists to discover hydrocarbon presence in reservoir sands and delineate the associated fluid types. Though MWD or wirelinelogs can alone be used for both qualitative and quantitative reservoir assessment, the importance of core samples and mud logs cannot be overemphasized as they are needed to calibrate the results obtained from well logs. Core samples and mud logs give the earliest indication of hydrocarbon presence through oil shows and sample stains while well logs can be used thereafter to obtain both qualitative overview through crossplots and overlays and quantitative evaluations through 3D-modelling of the reservoir. A comparison of results from both techniques therefore serves to eliminate errors and minimize risks in hydrocarbon prospecting (Olugbenga et al, 2017).

To evaluate a reservoir, the hydrocarbon-bearing indicators (hydrocarbon saturation, net to gross ratio, net pay) and hydrocarbon producibility parameters (volume of shale, effective porosity and permeability) are of interest and crucial in decision-making prior to exploitation and production of the wells. This study aims to analyse two reservoirs domiciled in a well in order to evaluate their productivity potentials in terms of their hydrocarbon saturation, effective porosity and net pay, using a composite suite of petrophysical logs obtained from a field in the onshore Niger Delta of Nigeria. In addition, this study will focus on the determination of what we have termed as ‘the invaded zone effect’ on the total reservoir potential. In the clean sand zone, the water-based mud filtrate invades the radially shallow zone (called the invaded zone) and displaces the original fluid, but the undisplaced hydrocarbon fluid remains in the pores of the reservoir. This is known as the immoveable hydrocarbon. The hydrocarbon contents in the reservoir are thus partitioned into moveable and immoveabe hydrocarbon. The presence of the immoveable hydrocarbon in the reservoir is therefore a result of mud filtrate invasion. This phenomenon is what we

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have referred to as the ‘’invaded zone effect’’ and the determination of the saturation of the exploitable moveable hydrocarbon and that of the immoveable hydrocarbon shall therefore form part of this reservoir analysis.

MATERIALS AND METHODS

Study Area- The Niger Delta

The Niger Delta is a prolific hydrocarbon province, a sedimentary basin and tertiary delta situated in equatorial West Africa in the Gulf of Guinea (Fig.1). The development of the Niger Delta began, on a geologic time scale, with the formation of the delta at the site of a rift triple junction associated with the opening of the southern Atlantic. This event started in the late Jurassic and continued into the Cretaceous. The delta proper began developing in the Eocene, accumulating sediments that are now over 10km thick. The coastal sedimentary basin of Nigeria had been the scene of three depositional cycles. The first began with a marine incursion in the middle Cretaceous and was terminated by a mild folding phase in Santonian time. The second included the growth of a proto-Niger Delta during the late Cretaceous and ended in a major Paleocene marine transgression. The third cycle, from Eocene to Recent, marked the continuous growth and development of the main Niger Delta.

The delta extends throughout the Niger Delta Province and borders the Atlantic Ocean at the Southern end of Nigeria between latitudes 3^0 and 6° and longitudes 5° and 8° (Orife and Avbovbo, 1982). The onshore portion of the province is delineated by the geology of southern Nigeria and southwestern Cameroon. The northern boundary is the Benin flank — an east northeast trending hinge line south of the West African basement massif. The northern eastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High. The offshore delineation of the province is defined by the Cameroon volcanic line to the east, the eastern boundary of the Dahomey basin to the west and a sediment contour of thickness 2km. The province covers 300,000 square kilometers of area and includes the geologic extent of the tertiary delta that habours only one identified petroleum system. This system is referred to as the tertiary Akata-Agbada petroleum system (Ekweozor and Daukoru, 1994).

The stratigraphy of the Niger Delta shows that the Niger Delta subsurface comprises an upper sandy Benin Formation, an intervening unit of alternating sandstone and shale known as the Agbada Formation and a lower shaly formation called the Akata Formation. These three delta facies extend across the whole delta and are typically environments of depositions. The depositions constitute the sequences of subsurface clastic sediments which range in thickness from 9km to12km (Ofodile, 1992). Petroleum in the Niger Delta is produced in commercial quantities from clastic sandstones and unconsolidated sands predominantly in the Agbada Formation. Recognized known reservoir rocks are of Eocene to Pliocene in age, and are often stacked ranging in thickness from about 15 meters to more than 45 meters (Evamy et al.1978). Based on reservoir geometry and quality, the lateral variation in reservoirs thickness is strongly controlled by growth faults, with the reservoirs thickening towards the fault within the down-thrown block (Weber and Daukoru, 1975). The wells analysed in this study were obtained from a field in the onshore Niger Delta.

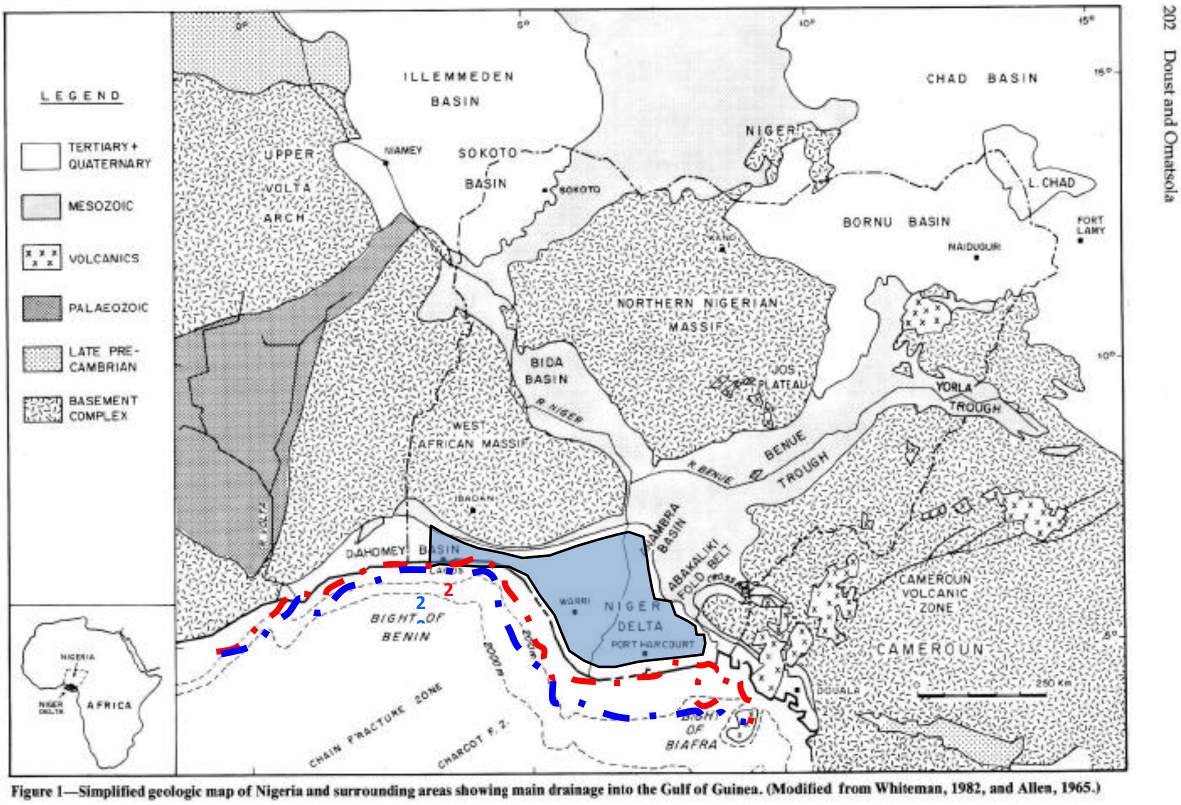

Fig.1: Location Map of the Niger Delta (Modified from Whiteman, 1982 and Allen, 1965)

Materials

The materials used for this study were obtained from SHELL Petroleum Development Company (SPDC East), Port Harcourt, Nigeria. Composite logs comprising the caliper log, gamma-ray (GR) log, density log, resistivity logs and sonic transit time logs obtained from a field in the onshore Niger Delta were manually analysed. Only one well containing two (2) reservoirs (Mesh 1 and Mesh 2, Fig.2) was analysed.

Method

The Gamma ray log was first used to differentiate the subsurface lithology into clean sand and shale units with cut-off values of 50 API as the clean sand baseline and 80 API as the clean shale baseline. A quick look interpretation was then carried out using the deep resistivity log, GR log, model-calculated porosity log and density log. Whereas the deep resistivity log was used to differentiate hydrocarbon-bearing from non-hydrocarbon-bearing zones in conjunction with the gamma ray log, the sonic-porosity and density logs were combined to identify fluid types (oil, gas) (Fig.2). Generally water-bearing zones have very low resistivity since they are conductive while the hydrocarbon-bearing zones have relatively high resistivity as they are non-conductive.

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Petrophysical evaluation involves the quantification of various reservoir parameters which assists in assessment of prospect risks. These parameters were determined as follows.

Evaluation of Porosity

The average reservoir porosity was calculated from the sonic and bulk density logs by taking the mean of the porosities from both logs (Kearey et al. 2003; Asquith and Krygowski 2004). Porosity from the density logs was determined using the equation:

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

where ρ_{ma} is the matrix density, ρ_b is the bulk density and ρ_{fl} is the fluid density. For the clastic sediments of the Niger Delta, a matrix density of 2.65g/cm^3 and fluid density of 1.00g/cm^3 were used (Olugbenga et al, 2017). Porosity from sonic log (sonic transit time) was model-calculated using the Wyllie et al (1956) average time equation because of its critical importance in this analysis. This is given by

$$\Delta t_p = (1 - \phi).\Delta t_{ma} + \Delta t_{fl} \quad (2)$$

where Δt_p is the compressional wave slowness of the porous rock, Δt_{ma} is the compressional wave slowness of the rock matrix, t_{fl} is the compressional wave slowness of the fluid (mostly water), all measured in μs/ft. Equation (2) can be re-arranged as

$$\Phi_t = \frac{\Delta t_p - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} \quad (3)$$

where for the clastic sandstone of the Niger Delta, the values of $\Delta t_{ma} = 55.5$μs/ft. and $t_{fl} = 189$μs/ft were used.

To evaluate the effective porosity which gives an indication of the permeability of the reservoirs, the volume of shale present in the reservoir sands was determined. The shale volume V_{sh} and effective porosity ϕ_{eff} are given by Dresser Atlas (1979) as

$$V_{sh} = 0.083\left[2^{(3.7*I_{GR})} - 1\right] \quad (4)$$

where

$$I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (5)$$

GR_{log} is the GR reading from the zone of interest, GR_{max} is the maximum GR reading obtained from the shale zone and GR_{min} is the minimum GR reading obtained from clean sand zone. The effective porosity was then obtained by using the equation given by

$$\phi_{eff} = \phi(1 - V_{sh}) \quad (6)$$

where ϕ is the average porosity obtained from the combination of sonic and density logs.

Hydrocarbon Detection

The hydrocarbon fluids in the reservoirs under study were identified and delineated. This was achieved by the use of the deep resistivity log. The deep resistivity log reveals the resistivities of the radially deep-lying uninvaded zone in the depth region of interest. The use of the resistivity log becomes necessary for hydrocarbon detection because hydrocarbon-bearing reservoirs have relatively high deep resistivity due to their non-conductivity, whereas water- bearing reservoirs have relatively low deep resistivity because of the non-conductivity of water (Maju-Oyovwikowhe and Njoku, 2019). The hydrocarbon-water contacts were also delineated with the aid of the resistivity, sonic and density logs (Fig. 2)

Evaluation of Hydrocarbon Saturation

Hydrocarbon saturation S_{hy} is a very important parameter in reservoir evaluation. This was obtained by first calculating the water saturation S_w in the reservoir, as some portion of the reservoir horizon is occupied by water. For the clean water-saturated sand zone (with S_w =1), the classical Archie's (1942) equations were applied. The measured resistivity of the formation R_o in the water-saturated zone is given by

$$R_o = F.R_w \qquad (7)$$

where F is the formation factor and R_w is the resistivity of water in this zone (with S_w =1). Given that F = 1/ϕ^m, we have

$$R_o = \frac{R_w}{\emptyset^m} \qquad (8)$$

Therefore, the water saturation in the reservoir is

$$S_w = (\frac{R_o}{R_t})^{\frac{1}{n}} \qquad (9)$$

where R_t is the measured formation resistivity in the hydrocarbon zone (the zone of interest).Using Equations (7) and (8), we re-write

$$S_w = (\frac{1}{\emptyset^m}\frac{R_w}{R_t})^{\frac{1}{n}} \qquad (10)$$

The value of the constants m and n = 2 is accepted for the clastic sandstone of the Niger Delta. So we have

$$S_w = \sqrt{\frac{R_o}{R_t}} (11)$$

or $$S_w = \sqrt{\frac{1..R_w}{\emptyset^2\ R_t}} \qquad (12)$$

The hydrocarbon saturation S_{hy} was then obtained using the equation

$$S_{hy} = 1 - S_w \qquad (13)$$

In our analysis, we have also assessed the mud filtrate invasion of the radially shallow zone (called the invaded zone) and its effect on the reservoir potential. We have termed this "the invaded zone effect''. With the mud filtrate invasion of the shallow zone, the original fluid in this zone is displaced but the undisplaced hydrocarbon remains in the pore spaces of the reservoir. This is known as the immoveable hydrocarbon. The total hydrocarbon fluid in the reservoir is thus partitioned into moveable and immoveable hydrocarbon and their saturations have been determined in this analysis.

The mud filtrate saturation S_{xo} using the Archie's equation is given by

$$S_{xo} = \sqrt{\frac{F.R_{mf}}{R_{xo}}} (14)$$

where R_{xo} is the formation resistivity in the mud filtrate zone. This is obtained by the use of shallow microlog to measure this resistivity which is low compared to the resistivity of the deeper zone. Equations (7) and (8) allow us to re-write

$$S_{xo} = \sqrt{\frac{1.R_{mf}}{\emptyset^2\ R_{x0}}} (15)$$

The temperature of the mud filtrate is noted and its resistivity evaluated at this temperature using the Arps equation (Arps 1953; Jugen 2004), given by

$$R_{mf},\theta = 0.336.\ \frac{90+6.77}{\theta+6.77} (16)$$

Net Pay

The net pay is one of the important petrophysical parameters that determine whether a reservoir can pay back. The total thickness of the reservoir that contains hydrocarbon is known as the net pay. This pay back parameter was determined using a

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combination of the GR log, resistivity log and porosity-density log which were correlated to the depth axis of the logs. The absence of depth information on the logs, however, placed some limitation on the evaluation of the net pay. Because of the absence of depth values, the net pay (represented by the thickness TH for both reservoirs in Mesh 1 and Mesh 2) could not be quantitatively determined.

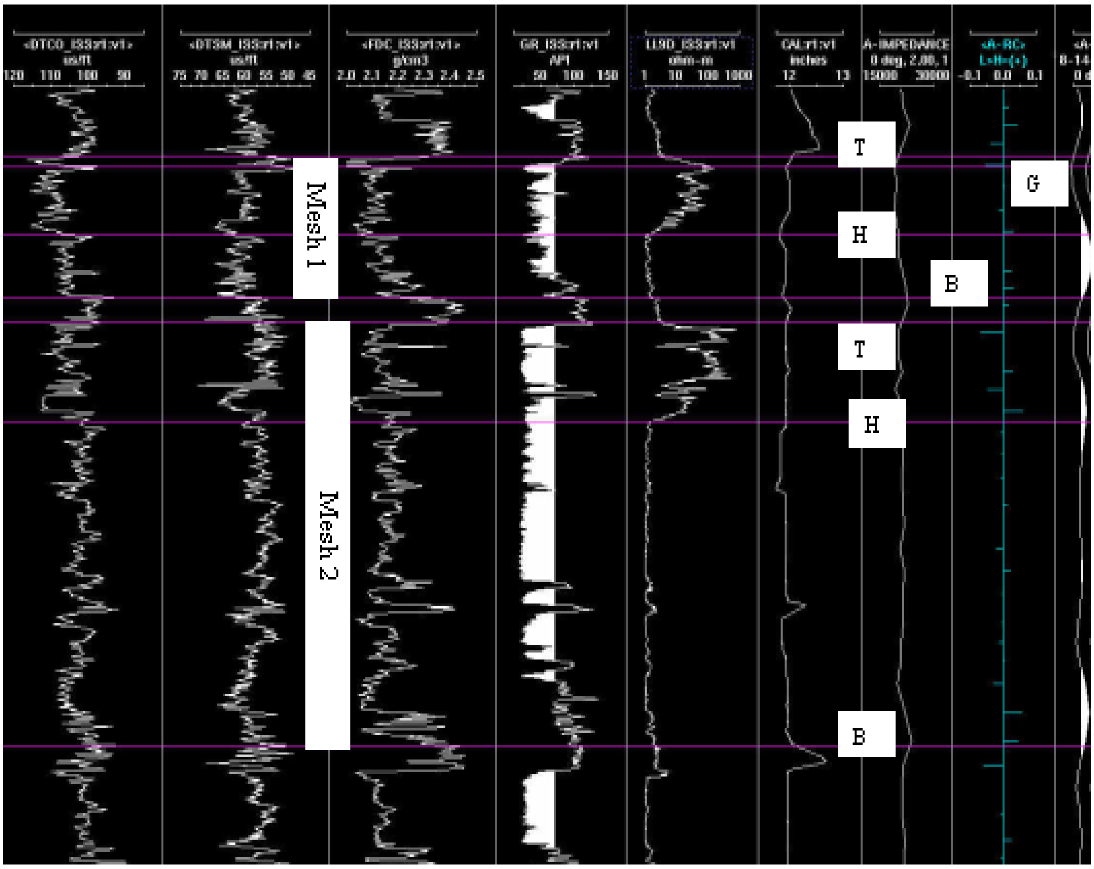

Fig.2: The Suite of Well Logs Used for the Interpretation. T – Top, G – Gas-Oil-Contact (GOC), H – Hydrocarbon-Water-Contact (HCWC), B - Base

RESULTS

Table 1 shows the input parameters used in the models for the quantitative interpretation of Reservoir 1 (Mesh 1) and Reservoir 2 (Mesh 2). The top and base of the reservoirs are shown. The Gas-Oil Contact (GOC) in Reservoir 1 is clearly shown and indicates that reservoir 1 contains oil and gas. The Hydrocarbon-Water Contact (HCWC) in Reservoir 2 is also shown. This reservoir is also predominantly a gas and oil sand.

Table1: Input Values

Input	ρ_{ma}	ρ_{fl}	Δt_{ma}	Δt_{fl}	GR_{log}	GR_{max}	GR_{min}	V_{sh}	m	n	F	R_w	R_o	R_t	R_{xo}	R_{mf}
	g/cm^3	g/cm^3	µs/ft	µs/ft	API	API	API	%	-	-	-	Ωm	Ωm	Ωm	Ωm	Ωm
Reservoir 1	2.65	1.0	55.5	189	25	130	20	1.0	2	2	9.18	0.087	0.80	10-100	6.02	0.46
Reservoir2	2.65	1.0	55.5	189	22	130	20	0.4	2	2	9.77	0.082	0.80	300	6.02	0.48

Table 2 shows the average values of the petrophysical properties obtained for Reservoir 1(Mesh 1) and Reservoir 2 (Mesh 2)

Table 2: Values of the Reservoir Properties

	Lithology	Fluid Type	Net Pay	ϕ_{av}	V_{sh}	ϕ_{eff}	S_w	S_{HY}	S_{MHY}	S_{IMHY}	S_{xo}
			(m)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Reservoir 1	Clean Sand	Gas,Oil	-	33	1.0	32.5	19	81	65	16	84
Reservoir 2	Clean sand	Gas, Oil	-	33	0.4	32.5	5.2	94.8	82.8	12	88

S_{MHY} – Saturation of the moveable hydrocarbon fluid
S_{IMHY} – Saturation of the immoveable hydrocarbon fluid (the invaded zone effect)
S_{xo} – Saturation of water-based mud filtrate in the invaded zone

DISCUSSION OF RESULTS

Two reservoirs domiciled in a well have been analysed in this study. From our quantitative results, Reservoir 1 (Mesh 1) will produce oil and gas, and has a total hydrocarbon saturation of 81%. However, due to the invaded zone effect on the reservoir potential, the total hydrocarbon fluid is partitioned into moveable hydrocarbon and immoveable hydrocarbon. This resulted from the mud filtrate invasion of the radially shallow zone which displaced the original fluid while the undisplaced hydrocarbon fluid remained in the pore spaces of the reservoir. The moveable hydrocarbon has a saturation 65% , while the immoveable hydrocarbon is left with a saturation of 16%.With a total hydrocarbon saturation of 81%, the water zone was found to be as small as 19% saturated. The average porosity of the reservoir sand was determined at 33% and its effective porosity at 32.5%. The high effective/interconnected porosity and clean nature of the sand arising from the extremely small shale intercalation present in the sand (with a shale volume of just 1.0%) clearly shows that the reservoir is highly porous, permeable and producible.The net pay (represented by the thickness TH in Mesh 1) could not be quantitatively determined due to lack of depth information on the logs used for the analysis. Reservoir 2 has a total hydrocarbon saturation of 94.8% and water saturation of just 5.2%. The total hydrocarbon saturation is partitioned into 82.8% moveable hydrocarbon saturation and 12% immoveable hydrocarbon saturation. The average porosity of the reservoir is 33% and the effective porosity is 32.5%. This again indicates a reservoir sand that is highly porous, permeable and producible owing to the high effective/interconnected porosity and clean nature of the sand arising from the extremely small volume of shale present in it (0.4%).The net pay (represented by the thickness TH in Mesh 2) could not be evaluated due to absence of depth information on the logs used, which placed some limitation on this petrophysical analysis. Overall, the results obtained are quite consistent with the results of petrophysical reservoir evaluation documented in the literature for the Niger Delta (e.g Ologe 2016; Olugbenga et al. 2017; and Maju-Oyovwikowhe et al. 2019).

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The results obtained also show that the reservoirs analysed are commercially favourable and have the potential to pay back.

CONCLUSION

This work had focused on petrophysical analysis of two reservoirs. Our results show that reservoir properties can be quantitatively derived from well logs which can help to minimize prospect risks. Using the logs, the reservoirs' interconnected porosity, volume of shale present, formation factor, and hydrocarbon saturation were determined. The effect of the mud filtrate invasion of the shallow zone on the total reservoir potential was also successfully determined. However, core and mud log analyses may be combined with well logs in order to compare and calibrate the petrophysical results.

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