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Petrophysical and Reservoir Rock Property Analyses of Open-Hole Geophysical Logs for Afenmai Field, Eastern Niger Delta Basin of Nigeria

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Abstract
Petrophysical attributes and reservoir rock properties were estimated and analysed for Afenmai Field located within eastern part of the Central Depobelt of the Niger Delta Basin in Nigeria. The reservoir rock properties comprised reservoir pore volume-to-grain volume ratio (ϕ_z), reservoir quality index (RQI), reservoir flow zone (FZI) indicator, and reservoir deliverability index. The study was carried out with data-set obtained from Well 8 in the field. The data comprised subsea vertical depth to top and base of sand units, hydrocarbon-water contact depths, and a suite of gamma ray, resistivity and density logs. Total porosity estimated from the density log was corrected for shaliness effect using empirical relationship between shale volume and Gamma Ray shale index for Tertiary sandstones. The corrected porosity was utilized as effective porosity (ϕ_e). Hydrocarbon saturation (S_h) was estimated using the Nigerian saturation equation. Matrix permeability (K) was estimated using the Timur equation. Reservoir pore volume-to-grain volume ratio (ϕ_z), RQI and FZI were obtained from K and ϕ_e. The well is a multi-reservoir well with S_h values ranging from 44 to 61%. Matrix permeability (K) varied between 187 and 583 md, in conformity with values commonly reported in literature for Niger Delta reservoirs. Matrix permeability (K) appeared to be influenced by degree of sorting, rather than by shale distribution within the sandstone matrix. D6000 sand has the best petrophysical attributes and highest ϕ_e, ϕ_z, RQI, FZI and reservoir deliverability index values. The results constitute a framework for recommending multiple completions option in D6000, D3000 and 5000 sands.

Keywords: *Petrophysical Attributes, Reservoir Rock Properties, Multiple Completions.*

Introduction

Present day conventional hydrocarbon exploration is dominantly anchored on interpretation of seismic reflection data. The interpretation produces a subsurface model from which promising prospects are generated. However hydrocarbon accumulation within the prospects is only ascertainable by drilling. The first indications of penetrated hydrocarbon reservoirs come from oil shows seen in ditch cuttings, as well as increased total gas and gas chromatographic content from background values recorded at the laboratory of well-site mud-logging units. These petroleum indications are then evaluated by petrophysical analysis of geophysical logs. Alyafei (2021) called the exercise wireline petrophysics. Archie (1950) coined the name Petrophysics for the study of the physics of rocks and their fluid content. It occupies a central role in hydrocarbon reservoir development (Ellis and Singer, 2007). This is partly because it concerns the identification of hydrocarbon bearing reservoirs, distinguishing the hydrocarbon fluid content, net pay thickness determination, effective porosity and hydrocarbon saturation estimation (Cannon, 2016). Reservoir rock properties are rock attributes related to hydrocarbon deliverability of the reservoir (Ezekwe, 2011). They include pore volume-to-grain volume ratio, reservoir index quality, reservoir flow indicator, reservoir matrix permeability, and reservoir deliverability index. Some workers that have conducted petrophysical and reservoir rock properties analyses of geophysical logs acquired in clastic sedimentary basins. They are Ishwar and Bhardwaj (2013), Amigun and Odole (2013), Tamunoski *et al.*(2014), Lyaka and Malibo (2015), Unuevho *et al.*(2018), Nkwanjard *et al.*(2018), and Ramadhan (2019).

Undersaturated oil and oil with associated gas have long been found in six wells within Afenmai Field. Nevertheless, it remains an undeveloped field because the discovery has only been partially appraised. This work was conducted to generate appraisal information on the reservoirs' petrophysical attributes and reservoir rock properties. Such information is an integral part of the critical requirements for formulating optimal development strategy for the hydrocarbon fields.

Study Location

Afenmai Field is located within the eastern part of the Central Depobelt of the Niger Delta Basin in Nigeria (Fig.1). However, the name 'Afenmai Field' is a pseudo name chosen to protect data confidentiality and economic interests of the asset owners. The field's areal extent is approximately 242Km^2, and it has eight drilled wells within it. The Niger Delta Basin is a clastic sedimentary basin within the northeastern margin of the Gulf of Guinea in the West African coast. Its sedimentary succession piled up from the mouth of the Benue – Niger River system onto the Atlantic Ocean (Unuevho and Onuoha, 2017). It consists of Cenozoic sequence differentiated into Benin Formation, Agbada Formation and Akata Formation. The Benin Formation consists of a monotonous body of freshwater gravels and sands interrupted occasionally by minor shales and lignites. The Agbada Formation consists of alternating sandstone and shale bodies deposited in sedimentary environments that range from inner neritic to middle bathyal. The Akata Formation consists of continuous middle neritic to middle bathyal shales with minor sands and siltstones (Unuevho, 2014).

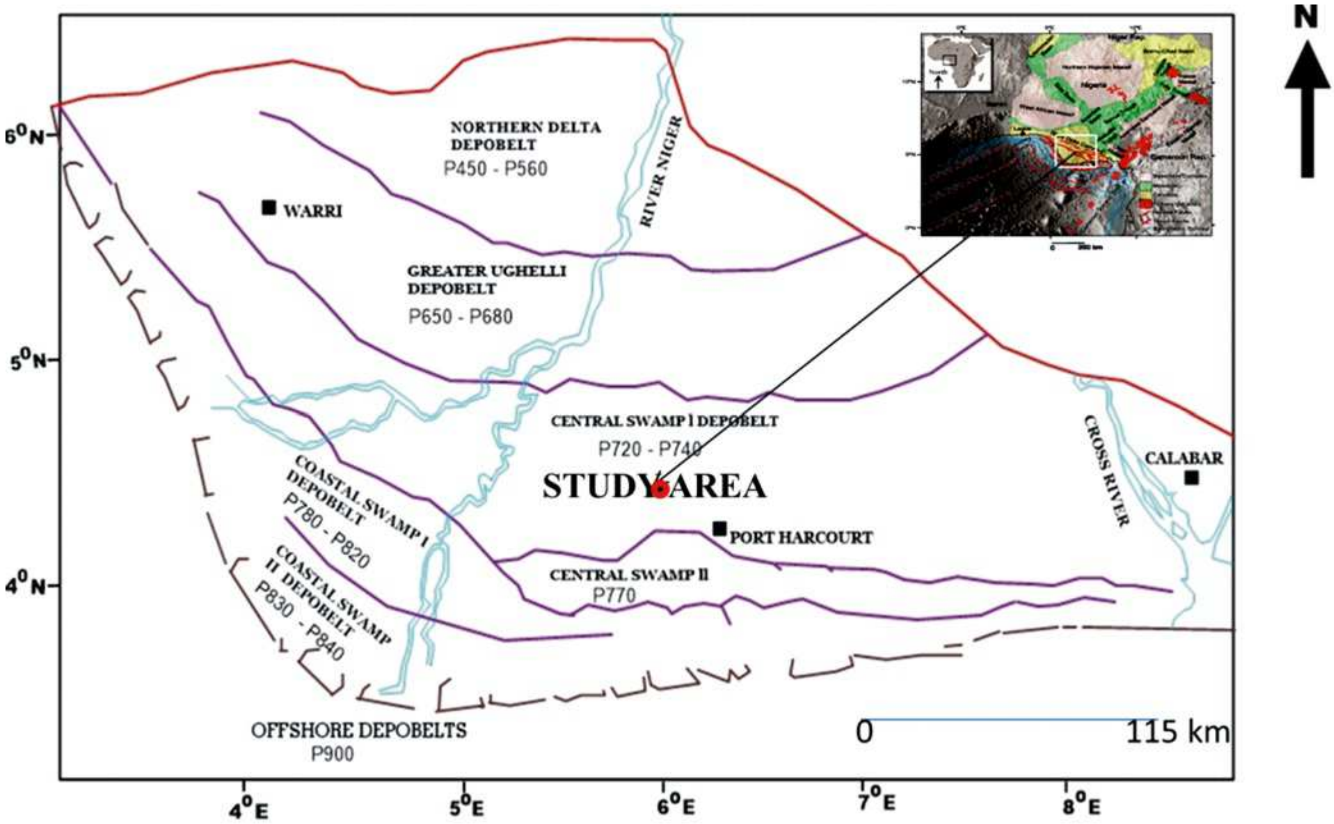

Fig. 1: Location of the Niger Delta in relation to other sedimentary basins in Nigeria (Unuevho and Onuoha, 2020)

Akata Formation has been penetrated between 12000ft and 18000ft in most onshore fields, and between 5000ft and 10000ft in many of the offshore fields (Schlumberger, 1985). The petroleum source rocks are shales in the upper part of the formation and shales in the lower part of the Agbada Formation (Evamy *et al.,* 1978; Nwachukwu and Chukwura, 1986; Weber, 1987; Haack *et al.,* 2000). Geological structures are found only within the Agbada Formation, and they comprise growth faults, rollover anticlines and mud diapirs. The growth faults are differentiated into structure building faults, crestal and flank faults. The entire basin is divided into depobelts. They are Northern Depobelt, Greater Ughelli Depobelt, Central Swamp Depobelt 1, Central Swamp Depobelt 2, Coastal Swamp Depobelt 1, Coastal Swamp Depobelt 2, Shallow Offshore Depobelt, Deep Offshore Depobelt and Ultra Deep Offshore Depobelt. Petroleum structural trapping styles are anticlinal dip closures, footwall closures and hanging wall closures. The stratigraphic traps include sand truncation against clay fills of incised valleys, sands within canyon fills above unconformity surfaces, and basin floor fans.

Materials and Methods

This work utilised Gamma Ray (GR) logs, density logs, resistivity logs, subsea-vertical depth to top and base of sand units, and hydrocarbon fluid contact information. This data-set was available for only Well 8.

Hence the field's petrophysical and reservoir rock property estimations were performed for Well 8 and the estimations assumed to represent the petrophysical attributes of the same reservoirs in the other wells. This is a reasonable assumption because the field is approximately only 242Km[2] in total areal extent. Petrophysical estimations were performed on a workstation operating on *Geographix 5000* software. Linear estimation of shale volume (V_{sh}) from GR log is commonly the preferred approach for nullifying shaliness effect (Setyowiyoto and Samsuri, 2008; Adeoti *et al.*, 2009; Ishwar and Bhardwaj, 2013). This results in overestimation of V_{sh} and attendant under estimation of desirable reservoir petrophysical attributes (Hampson-Russel, 2008). In this study V_{sh} was obtained from GR shale index (I_{GR}) as follows:

$$I_{GR} = \frac{GR - GR_{CN}}{GR_{SH} - GR_{CN}} \quad \text{.......(1)}$$

(Western Atlas International, 1992; Islam *et al.,* 2013);

where GR is gamma ray log reading in zone of interest, GR_{CN} is gamma ray log response in clean (shale free) sand, and GR_{SH} is highest gamma ray reading for shale.

V_{sh} was obtained from I_{GR} using V_{sh} - I_{GR} empirical relationship for Tertiary sandstone reservoirs:

$$V_{sh} = 0.083(23.7^{*I_{GR}} - 1) \quad \text{.......(2)}$$

(Larionov, 1969; Islam *et al.,* 2013).

Apparent porosity (ϕ_a) and effective porosity (ϕ_e) were estimated using equations 3 and 4 respectively.

$$\Phi_a = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad \text{....... (3)}$$

(Western Atlas International, 1992; Ezekwe, 2011; Tamunoski *et al*., 2014);

Where ρ_{ma} (2.65gm/cm^3) is bulk density of matrix material, ρ_b is reservoir bulk density obtained from bulk density log and ρ_f is mud filtrate density(1.1gm/cm^3).

$$\Phi_e = \Phi a * (1 - V_{sh}) \quad \text{.......(4)}$$

(Western Atlas International, 1992; Kadhim *et al.*, *2014*)

Water saturation (S_W) was estimated using the modification of the Indonesian equation for Nigerian reservoirs as given by Ezekwe, 2011:

$$\sqrt{\frac{1}{R_t}} = \left(\sqrt{\frac{\Phi_a{}^n}{R_w}} + \sqrt{\frac{V_{sh}{}^{2.8}}{R_{sh}}}\right)^2 S_w \quad \text{.......(5)}$$

(Ezekwe, 2011) ;

Where R_t is reservoir resistivity obtained from deep resistivity log, R_{sh} is shale resistivity, R_w is apparent formation water resistivity estimated as follows:

$$R_w = \frac{R_o}{0.62} \phi_e{}^{2.15} \quad \text{.......(6)}$$

(Archie, 1942; Unuevho, 2014; Hossain and Zhou, 2015).

R_o is the deep resistivity log reading in 100% water-filled reservoir.
Hydrocarbon saturation (S_h) was obtained as follows:

$$S_h = 1 - S_w \quad \text{.......(7)}$$

(Ishwar and Bhardwaj, 2013)

Bulk hydrocarbon volume per unit reservoir volume (BVH) was estimated using equations 8.

$$BVH = \phi_e S_h \quad \text{.......(8)}$$

(Schlumberger, 1987; Western Atlas International, 1992; Ishwar and Bhardwaj, 2013)

The equations (equations 1 to equation 8) were defined in the algorithm for petrophysics in the 'PRIZM' menu of *Geographix5000* software and then executed. Matrix permeability (K) for the reservoir was estimated as follows:

$$K = \frac{(100\phi_e{}^2)^2 * \phi_e{}^{0.5}}{S_w{}^2} \quad \text{.......(9)}$$

(Schlumberger, 1985).

Reservoir deliverability index (D) was estimated using equation 10:

$$D = K * h \quad \text{.......(10)}$$

(Western Atlas International, 1992), where H is reservoir thickness.

Reservoir quality index (RQI), reservoir pore-to-grain volume ratio (ϕ_z) and reservoir flow zone indicator (FZI) were estimated following Ezekwe (2011), using equations 11, 12, and 13 respectively.

$$RQI = 0.0314\sqrt{\frac{K}{\Phi_e}} \quad \text{.......(11)}$$

$$\Phi_z = \frac{\Phi_e}{1 - \Phi_e} \quad \text{.......(12)}$$

$$FZI = \frac{RQI}{\Phi_z} \quad \text{.......(13)}$$

Results

Identified hydrocarbon reservoirs in Well 008 are D3000, D4000, D5000, D6000 and E7000 sands. Some of the estimated petrophysical parameters for these sands are shown in Table 1.

Table 1: Some estimated petrophysical parameters for reservoirs in Well 008

Sand	GR (API unit)	GR_{Sh} (API unit)	GR_{CN} (API unit)	I_{GR} (API unit)	V_{Sh} (%)	ρ_b (g/cc)	Φ_t (%)	Φ_e (%)	R_{Sh} (ohm-m)	R_w (ohm-m)	R_t (ohm-m)	S_w (%)	S_h (%)
D3000	35.50	98.50	20.00	0.197	1.10	2.15	32.25	31.20	2.00	0.65	37.65	40.00	60.00
D4000	22.53	114.00	19.00	0.037	0.70	2.192	29.50	29.30	1.50	0.35	23.26	45.50	55.00
D5000	37.65	75.00	27.00	0.22	1.10	2.196	29.30	29.00	2.00	0.34	29.53	40.00	60.00
D6000	34.81	55.60	30.00	0.188	1.00	2.10	35.50	35.00	2.00	0.33	23.15	39.00	61.00
E7000	47.50	92.50	24.00	0.343	1.50	2.15	32.25	32.00	2.5	0.34	12.293	56.00	44.00

Graphical illustrations of hydrocarbon saturation in D3000, D4000, D5000 and D6000 sands are Figs. 2, 3 and 4 respectively. Similar illustration of hydrocarbon saturation in E7000 sand is given in Fig. 5.

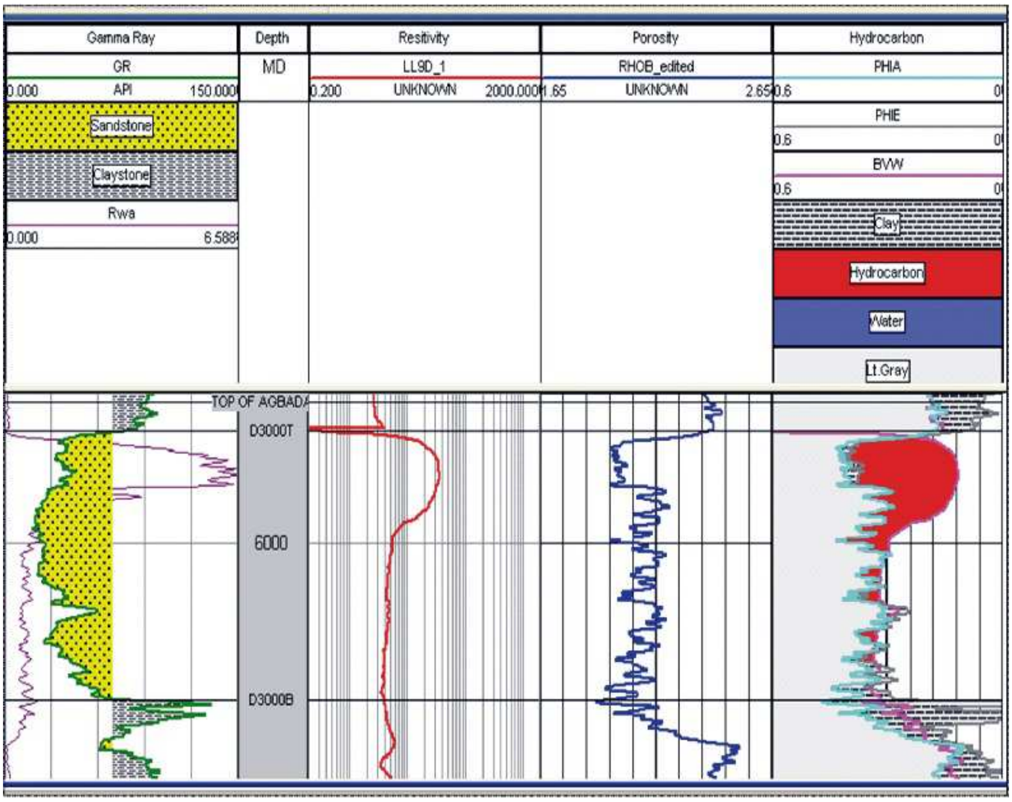

Fig. 2: Hydrocarbon saturation oil D3000 reservoir

The characterisation of the reservoirs in terms of BVH, K, RQI, ϕz, and FZI, is presented in Table 2.

Discussion

The estimated ϕ_e and K values for reservoirs in Well 008 follow the trend commonly reported in literature. Whiteman (1982) and Schlumberger (1985) reported that ϕ_e of sands within Agbada Formation are often between 28 and 32%, and sometimes up to 40%. They also presented many examples of wells in the Niger Delta where reservoir K varies from 10 darcy to less than 1 millidarcy. D6000 sand has the highest ϕ_e and K values. D5000 sand has the least ϕ_e value. E7000, D3000 and D4000 sands have intermediate ϕ_e values. D3000, D5000, and D4000 sands have intermediate K values, while E7000 sand has the least K value. The V_{sh} values can all be approximated to 0.02. Although V_{sh} is approximately constant, ϕ_e and K vary widely. The very low values of V_{sh} and moderate Φ_Z values indicate that observed variation in ϕ_e and K are unlikely to be due to shale distribution within the matrix of the sands. The variation is probably due to varying degree of sorting, as reflected by the variation in RQI and FZI values. Higher

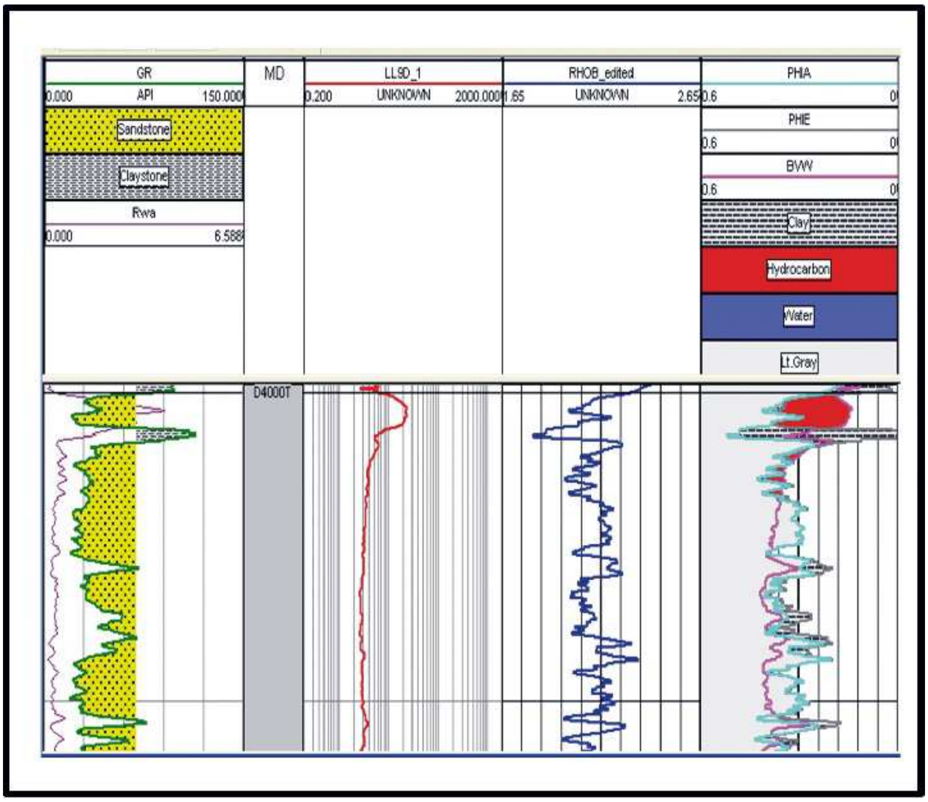

Fig. 3: Hydrocarbon saturation in D4000 reservoir

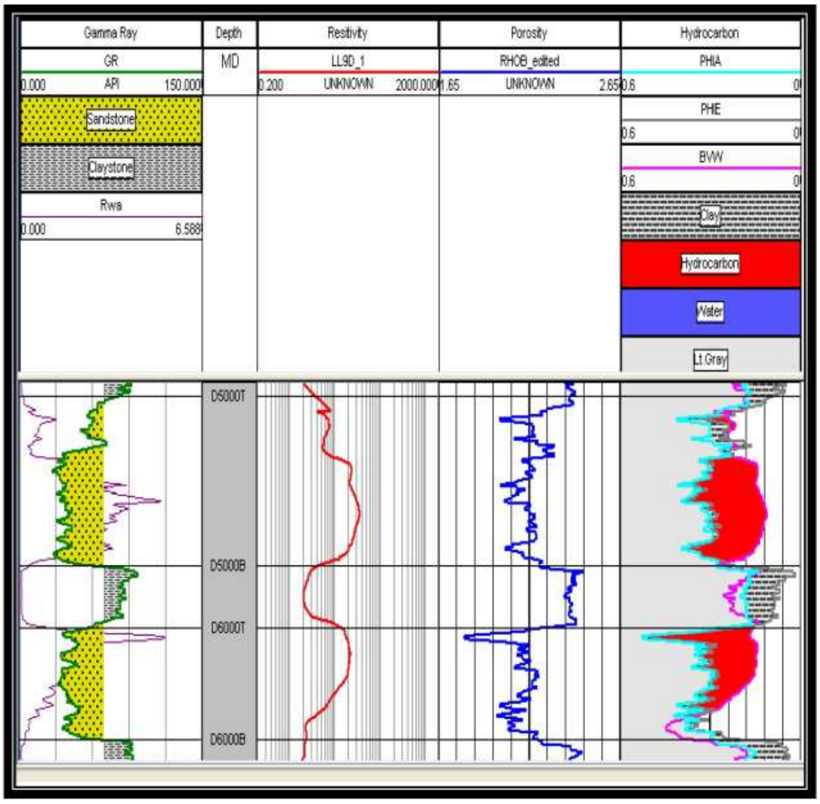

Fig. 4: Hydrocarbon saturation in D5000 and D6000 sands

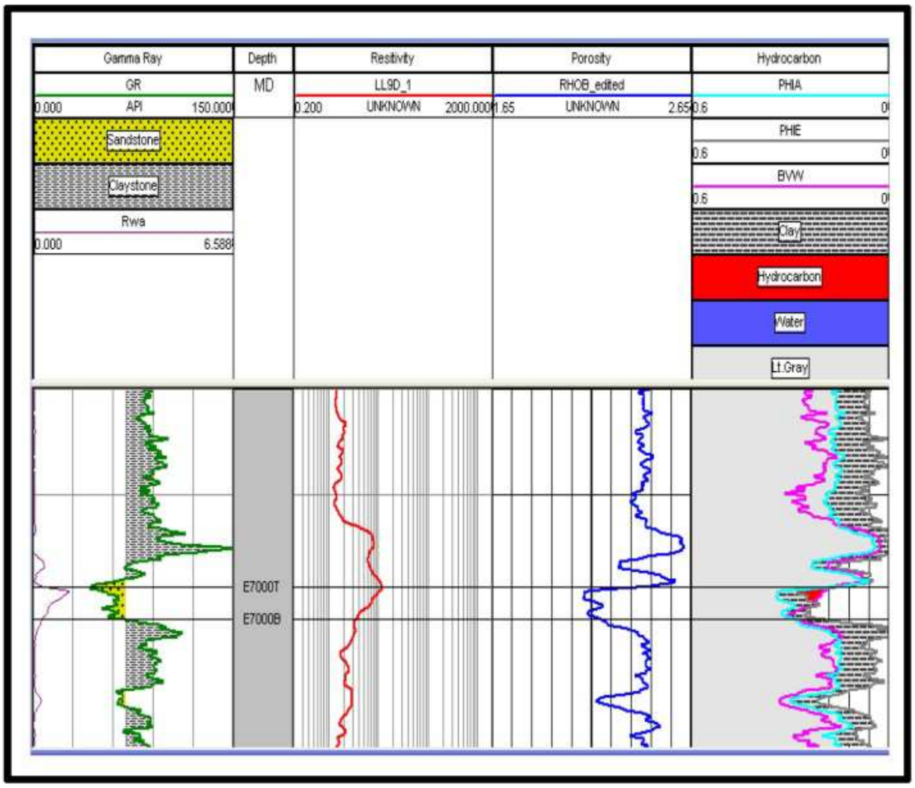

Fig. 5: Hydrocarbon saturation in E7000 sand

Table 2: Estimated BVH($\phi_e S_h$), K, RQI, FZI and KH values

Sand	HWC (depth in ft)	Depth to top (in ft)	HYcolumn thickness (T) in ft	ϕ_e (%)	S_h (%)	$\phi_e S_h$ (per $_{10}{}^2$)	$\phi_e S_h$ T (per 10^2ft)	K (md)	RQI (μm)	Φ_Z	FZI (μm)	KH (md-ft
D3000	5992.00	5962.00	30.00	31.20	60.00	21.52	645.6	331.06	1.02	0.45	2.25	9930.00
D4000	6106.00	6086.00	20.00	29.30	55.00	16.12	322.40	197.00	0.81	0.41	1.97	3940.00
D5000	6418.00	6408.00	10.00.	29.00	60.00	17.40	174.00	238.00	0.90	0.41	2.20	2380.00
D6000	6522.00	6488.00	34.00	35.00	61.00	21.35	725.9	583.68	1.23	0.54	2.28	19845.12
E7000	7844.00	7810.00	34.00	32.00	44.00	14.08	478.72	187.25	0.76	0.47	1.62	6366.65

values of RQI and FZI are associated with higher degree of sorting and vice-versa (Tiab and Donaldson, 2010). Though E7000 has higher ϕ_e value than D4000 and D5000 sands, the latter sands possess higher K value than E7000 sand because they are better sorted, as reflected by their higher RQI and FZI values. The values of BVH (a measure of movable hydrocarbon) do not trend parallel with S_h values. In D6000 sand, S_h is 60.00% while BVH is 21.35 per 10^2ft. In D3000 sand, S_h is 60.00% while BVH is 21.52 per 10^2ft. Furthermore, D5000 sand has 60.00 % S_h and 17.40 per 10^2ft BVH values. The D6000 reservoir has the best petrophysical characteristics in Well 008. It possesses the highest hydrocarbon column, bulk hydrocarbon volume per unit reservoir volume, best reservoir quality indicator, flow zone indicator and deliverability index. It is followed by D3000 sand in ranking of petrophysical attributes and desirable rock property. E7000 sand has the least S_h and BVH values, though its KH and $\phi_e S_h$ T are much higher than corresponding values for D4000 and D5000 sands. Its least S_h value gives it the highest potential to produce greater volume of undesirable water in early production phase than the rest sands. It is thus considered the least in the order of petrophysical ranking. D5000 sand is ranked petrophysically higher than D4000 sand in terms of S_h, K, BVH, RQI and FZI. Being a multi-reservoir well, completion options available for Well 8 are sequential reservoir depletion completion and multiple reservoir completion. In sequential reservoir depletion completion, profit return is usually delayed in early production phase. Work over and recompletion required on depletion of each reservoir increases development expenditures in the long term (Schlumberger, 1985). Since multiple completion is practically limited to three reservoir zones (Schlumberger, 1985), D6000, D3000 and D5000 sands constitute choice zones for initial completion for early profit returns.

Conclusion and Recommendations

Analysis of a suite of GR, resistivity and density logs established that Well 8 is a multi-reservoir well. Petrophysical estimations showed that D6000, D3000 and D5000 sands possess the best petrophysical attributes. Estimations and analyses of shale volume, pore volume-to-grain volume ratio, reservoir quality index and flow zone indicator established that degree of sorting influenced matrix permeability, rather than shale distribution within sand matrix. The study serves as a framework for recommending multiple completion option, and for selecting D6000, D3000 and D5000 sands as completion zones in well 8.

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References

Adeoti, L., Ayolabi, E.A. and James, P.L. (2009). An integrated approach to volume of shale analysis: Niger Delta example, Orire Field. World Applied Sciences Journal, 7 (4), pp.448-452

Amigun, J.O. and Odole, B.N, (2013). Reservoir evaluation of "Dana" Field, Niger Delta using petrophysical analysis and 3D seismic interpretation. Petroleum and Coal, 55(2), pp.119-127.

Archie, G.E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. AIME, 146, pp. 54-62.

Archie, G.E. (1942). Introduction to petrophysics of reservoir rocks. AAPG Bulletin, 34, pp.943 – 961

Castagna, J.P., Batzle, M.L. and Eastwood, R.l. (1985). Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks. Geophysics, 50, pp. 571-581.

Craft, B.C. and Hawkins, M.F. (1959). Applied Petroleum Engineering, Prentice Hall, Boston, 650p.

Doust, H. and Omatsola, A.E. (1990). Niger Delta. In: J.D. Edward, and M.Santagrossi (eds) Divergent / passive Margin Basins. AAPG Memoir 45, Tulsa Oklahoma: 201 – 238.

Evamy, B.J., Hareboure,J., Kamerling,P., Knaap, W.A., Melloy, F.A. and Rawlonds, P.H. (1978). The hydrocarbon habitat of Delta. AAPG Bull.64 , pp.1-37.

Ezekwe,N.(2011). Petroleum reservoir engineering practice. Prentice Hall, Boston, 770pp.

Haack, R.C., Sundaraman, P., Diedjomahor,J.O., Xia,H.,Grant,N.J., May, E.D. and Kelsch, K. (2000). Niger Delta petroleum systems, Nigeria . In: M.R. Mello and B.J. Katz,(eds.), Petroleum Systems of South Atlantic margins. AAPG Memoir 73, Tulsa, pp. 213-321.

Hampson-Russel Inc.(2008). Shale volume calculation. CE8R2, Irfan, Saputra, HRS, Jarkata.

Hossain, Z. and Zhou, Y. (2015). Petrophysics and rock modeling of diagenetically altered sandstone. Interpretation, 3(1), pp. SA107-SA120.

Ishwar, N.B. and Bhardwaj, A. (2013). Petrophysical well log analysis for hydrocarbon exploration in parts of Assqin Arakan Basin, India. Kochi10th biennial international conference and exposition, pp.153-157.

Islam, A.R.M., Habib, M.A., Islam, M.T. and Mita, M.R. (2013). Interpretation of wireline log data for reservioir charaterisation of Rashidpor Gas Field, Bengel Basin, Bangledesh. IOSR-JAGG, 1(4), pp 47-54.

Kadhim, F.S., Samsuri, A. and Idris, A. (2014). Calculation of petrophysical properties for Mishrif carbonate reservoir. 3rd International Conference on Fundamental and Applied Sciences. AIP Conf. Proc. 1621, pp. 756-762.

Larionov, V.V. (1969). Borehole radiometry. National Electric Drag Racing Association, Moscow.

Lyaka, A. and Mulibo, G. (2018). Petrophysical analysis of the Mpapai well logs in the East Pand Exploration Block, southern coast of Tanzania: Geological implication on the hydrocarbon potential. Open Journal of Geology, 8, pp.781 – 802.

Nkwanjard ,L., Ehinola, O., Taken, J., Nguema, P., Makuube, S. and Chongwairu, G. (2018). Depositional setting and petrophysical evaluation of reservoir of the K – Field in the Western Offshore Depobelt, Rio Del Rey Basin, Cameroon. International Journal of Geosciences, 9, 528 – 546.

Nwachukwu, J.I. and Chukwura, P.I. (1986). Organic matter of Agbada Formation, Niger Delta, Nigeria. AAPG Bull. 70 (1), pp.48-55.

Ramadhan, A.A. (2019). Evaluation of petrophysical properties using imaging techniques. IOP conference series: materials science and engineering. doi:10.1088/1757 – 889X/579/1/012024

Schlumberger, (1985). Well Evaluation Conference, Nigeria Edition, Schlumberger, Paris, 292p.

Schlumberger, (1987). Log Interpretation: Principles/Applications. Schlumberger educational services, Texas, 198p.

Serra, O. (1985). Sedimentology Environments from Wireline Logs. Second edition. Schlumberger educational services, Texas, 243p.

Setyowiyoto, J. and Samsuri, A.(2008). Formation evaluation: correlation between clay volume and porosity based on well logging data. Scientific conference (1), Universiti Kebangsaan Malasia (UKM).

Tamunoski,D., Ming, G.A., Wang, L., Uko, E.D., and Tamunonengiyeofori, W. (2014). Petrophysical characteristics of Coastal Swamp Depobelt reservoir in the Niger Delta, using well-log data. IOSR-JAGG, 2(2), pp 76-85.

Thomas, E.C. and Steiber, S.J. (1975). The distribution of shales in sandstones and its effect upon porosity. Transactions of the 16th annual SPWLA logging symposium. Paper T.

Tiab,D. and Donaldson, E.E.(2010) . Petrophysics (2nd edition). Gulf professional publishing, Burlington, 920p.

Unuevho, C. (2014). Facies analysis of 3D seismic data from eastern Niger Delta, Nigeria. unpublished Ph.D thesis, University of Nigeria, Nsukka, 220p.

Unuevho, C.I. and Onuoha, K.M. (2020). Facies Analysis of Afenmai Field in Eastern Niger Delta Basin of Nigeria, using combined geophysical logs, lithologic and paleontological data. Journal of Natural and Applied Sciences, 9 (1), 44 – 61.

Unuevho, C.I.,Nwokorie, L.U. and Udensi, E.E (2018). Petrophysical Analysis of Open-Hole Geophysical Logs Acquired In Bosso Field, Offshore Niger Delta Basin, Nigeria. IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG), 6(3) ,Ver.II, pp. 13 – 20.

Western Atlas International (1992). Introduction to Wireline Log Analysis, Western Atlas International Inc., Houston-Texas, 312p.

Whiteman, A.J. (1982). Nigeria: Petrolum Geology, Resources and Potential. Graham and Trotmam, London, 2, 394pp.