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Analytical Evaluation of Rock Attributes for Hydrocarbon Reservoir Characterization in an Eastern Niger Delta OnshoreX Field

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Abstract: *Well log data helps compute rock attributes, show correlations with reservoir properties and act as control datafor seismic data interpretation.The aim of this studyis to analyse and identify rock attributes robust in fluid and lithology discrimination of hydrocarbon reservoirs for seismic data interpretation and reservoir characterization. Rock physics analysis was used to determine the significance of rock attributes, establish relationship between the rock attributes and reservoir properties and identify robust attributes applicable in characterizing reservoir.The cross-plotresults show that acoustic impedance (Ip), poisson ratio (σ), compressional to shear velocity ratio (Vp/Vs), rigidity (μρ) and incompressibility (λρ) rock attributes are robust as fluid and lithology discriminators. The λρ and Vp/Vs ratio are more sensitive to fluid content, while σ and μρ to rock matrix.The μρ vs λρ cross plot was more robust in fluid and lithology discrimination.Hydrocarbon saturated sands were characterized by low λρ and Vp/Vs ratio, and low to moderate Ip, μρ and σ ratio. Low Ipcorresponded to low water saturation (Sw) and high porosity (ϕ).The petrophysical analysisdepictthe delineated reservoirs with good reservoir qualities: thickness in feet (177-324), porosity (0.28-0.29), water saturation (0.29-0.34) and net to gross (0.79-0.83) values.These rock attributes and its relation to reservoir properties are important for calibrating and interpretation of seismic data field wide and are applicable in seismic exploration for gas and oil, and monitoring changes within the reservoir during exploitation.*

Key Words*: Reservoir Characterization, Rock Physics, Elastic constants, Rock attributes, cross plots*

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I. Introduction

In characterization of a reservoir, an understanding of elastic properties of the reservoir rock is important as the reflectivity of seismic waves depends on this elastic property of the rock. Petroleum fields are found in sedimentary basins with source rock (shale), porous and permeable rock (reservoir) and impervious rock (caprock). In Niger Delta sedimentary basin, the rock formations present have been classified as Agbada (reservoir), Akata (source) and Benin deposit (Chukwu, 1991; Tuttle *et al*., 1999).Therefore, locating shale and sandstone zones, and further identifying hydrocarbon and brine sands is paramount in characterisation process. A well-defined and understood reservoir guides drilling, reduces risks and maximizes exploitation of the field.

The well logging technique measures the properties of the penetrated formations from which the rock attributes are derived relating to lithological and fluids characteristics of the formation. The well log data provide valuable information about the elastic properties of the reservoir rocks, and has been used extensively as the control basis for interpretation of seismic data(Udo *et al*., 2017; Bello *et al*., 2015). Through rock physics analysis, the measured physical propertiesrelevant rock attributes are derived and quantified. Cross plot analysis is used to identify robust rock properties or attributes that discriminate lithology and fluid content in a reservoir (Bello *et al*., 2015).

Previous studies indicate that compressional waves are more sensitive to pore fluid than shear waves, rigidity coefficient being more sensitive to rock matrix and incompressibility coefficient to fluid content (Shaocheng*et al*, 2010; Bello *et al*., 2015; Wafaa, 2018). The relationships between propagation velocities and elastic rock constants are well defined by various researchers(Goodway, et al.1997; Udo *et al*., 2017). Other quantities of importance are density, Poisson ratio etc.

The area of this study is located in the eastern part of the Niger Delta (Fig. 1.0). The Niger Delta basin is situated on the continental margin of the Gulf of Guinea in equatorial West Africa, at the southern end of Nigeria bordering the Atlantic Ocean between latitudes 3^0 and 6^0, and longitudes 5^0 and 8^0, with known large hydrocarbon province and characterized by near sea level elevation, rain forest and mangrove vegetations, high torrential rainfall and relative humidity.

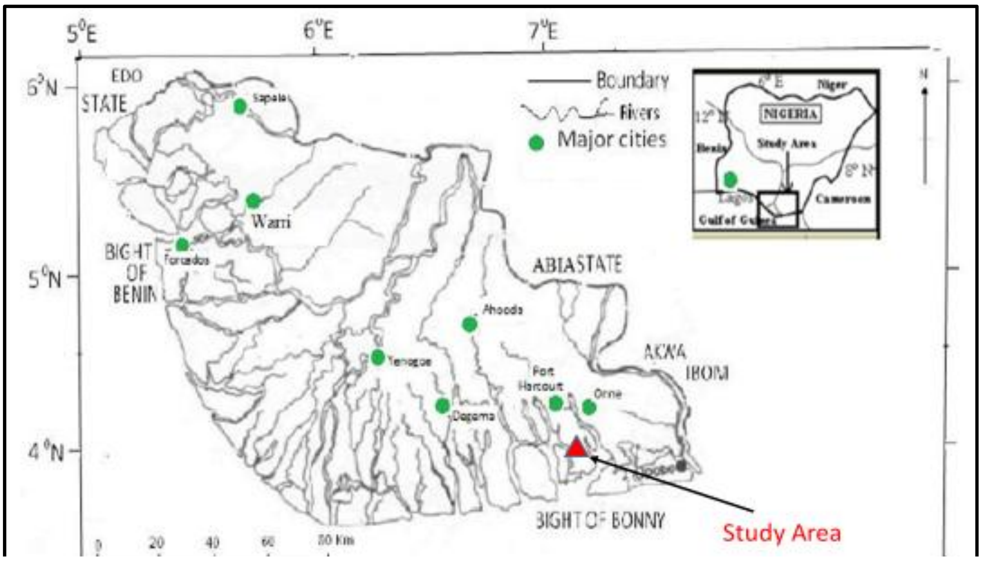


Fig. 1. Location map of the study area (Obiekezie and Bassey 2015)

The aim of this study is to analyse and identify robust rock attributes that predict and discriminate pore fluid and lithology of hydrocarbon reservoirs, for seismic data interpretation and reservoir characterization of eastern Niger delta field X.

Geology of Area of Study

The Niger Delta sedimentary basin has largely recent deposits though southward progradation process (Fig. 1). Itis characterized by three formations: Akata (source rock), Agbada (reservoir) and Benin (topmost) (Tuttle*et al*, 1999; Osaki, 2016). The petroleum reservoir is mainly sandstone showing stratigraphic and structural trappings due to geological changes as a result of tectonic, diapiric, gravitational and compactional processes over time. Agbada Formation, part of Tertiary section of the Niger Delta, is the major oil and gas reservoir of the delta and began in the Eocene continuing into the Recent. It is the transition zone and consist of intercalation of sand and shale (paralic silica clastics) with over 3700-meter-thick and represent the deltaic portion of the Niger Delta sequence (Chukwu, 1991; Obiekezie and Bassey, 2015).

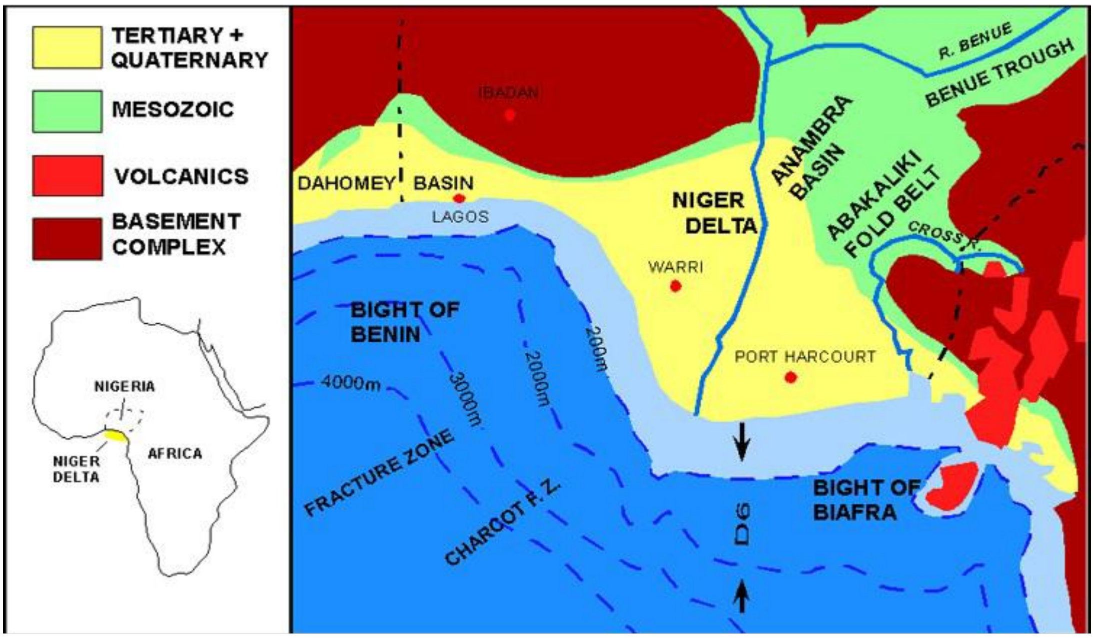


Fig 1.0: The geological map of the Niger delta (source: Ajisafe and Ako, 2013)

Theoritical background

The velocity of compressional wave in terms of elastic properties is given as

$$V_p = \sqrt{\frac{\lambda+2\mu}{\rho}} \qquad \text{-------------------------------------} \ (1)$$

And shear wave as

$$V_s = \sqrt{\frac{\mu}{\rho}} \ \text{--------------------------------------}(2)$$

Where λ, μ and ρ are incompressibility, rigidity and density of the medium the wave is passing through, respectively.

From equations (1) and (2), we can derive other physical quantities of the rock (rock attributes) that are significant in rock physics analysis.

Poisson ratio, σ, relates transversal to longitudinal changes of the media and is expressed as

$$\sigma = \frac{0.5r^2-1}{r^2-1} \qquad \text{--------------------------------------}(3)$$

where r is a Vp/Vs ratio given as

$$r = \frac{V_p}{V_s} = \sqrt{\frac{\lambda+2\mu}{\mu}} = \sqrt{\frac{2(1-\sigma)}{(1-2\sigma)}} \qquad \text{----------------------}(4)$$

LambdaRho (λρ) and MuRho (μρ)

$$\lambda\rho = (\rho V_p)^2 - 2(\rho V_s)^2 \quad \text{----------------------}(5)$$

$$\text{and} \quad \mu\rho = (\rho V_s)^2 \qquad \text{----------------------}(6)$$

where (ρV_p)and (ρV_s) are P-Impedance (Ip)and S-Impedance (Is), respectively.

The shear wave velocity (Vs) is estimated from the measured compression velocity (Vp) using Castagna's equation (Castagna*et al*. 1995) expressed as:

Vs = 0.86 Vp – 1.17 ----------------------------------(7)

Petrophysical reservoir properties were estimated from the available logs using the following equations:

Reservoir Porosity, Φ,

$$\Phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \qquad \text{------------------------------------}(8)$$

where:

ρ_{ma} = matrix density (2.65 g/cc for sandstone)

ρ_b = formation bulk density (reading from density log)

ρ_f = density of the fluid saturation the rock (1.0 g/cc was used)

Water saturation, Sw:

$$S_w = \frac{2 \ x \ R_w}{\Phi R_t} \qquad \text{----------------------------------} \ (9)$$

where R_w is resistivity of formation waters, R_t is true formation resistivity, ϕ is the porosity of the rock

II. Materials And Methodology

The data used for this study consist of well logs from three wells (MUN 01, 02 and 03), which comprise gamma ray (GR), resistivity (RT), neutron (NPHI), density (RHOB) and sonic (Vp) logs. The well positions and seismic inline and crosslines in is shown in the base map of the study (Fig. 2). The sand reservoirs were identified and delineated with low GR and high RT readings while shale corresponded to high GR and low RT values. Then the reservoirs were correlated across the three wells (Fig. 3).

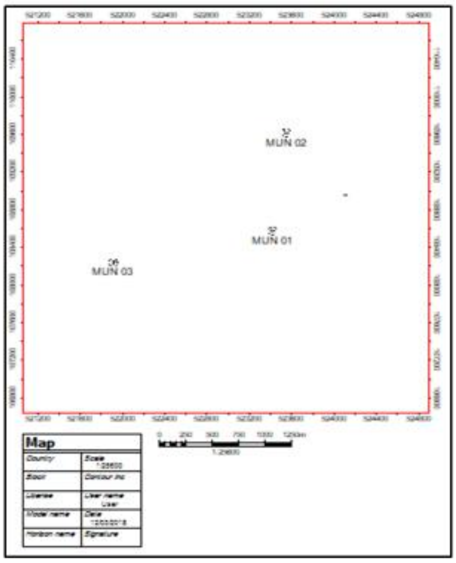


Fig. 2. Base map showing well positions

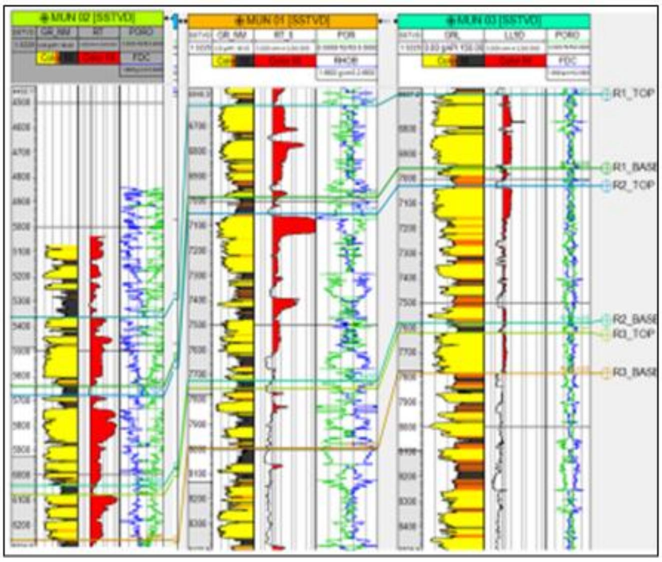


Fig.3. Reservoir identification and well correlation

Seismic to well tie was done on all wells through generation of synthetic traces and matched with seismic trace at each depth (in ms) within well depth (Fig. 4).

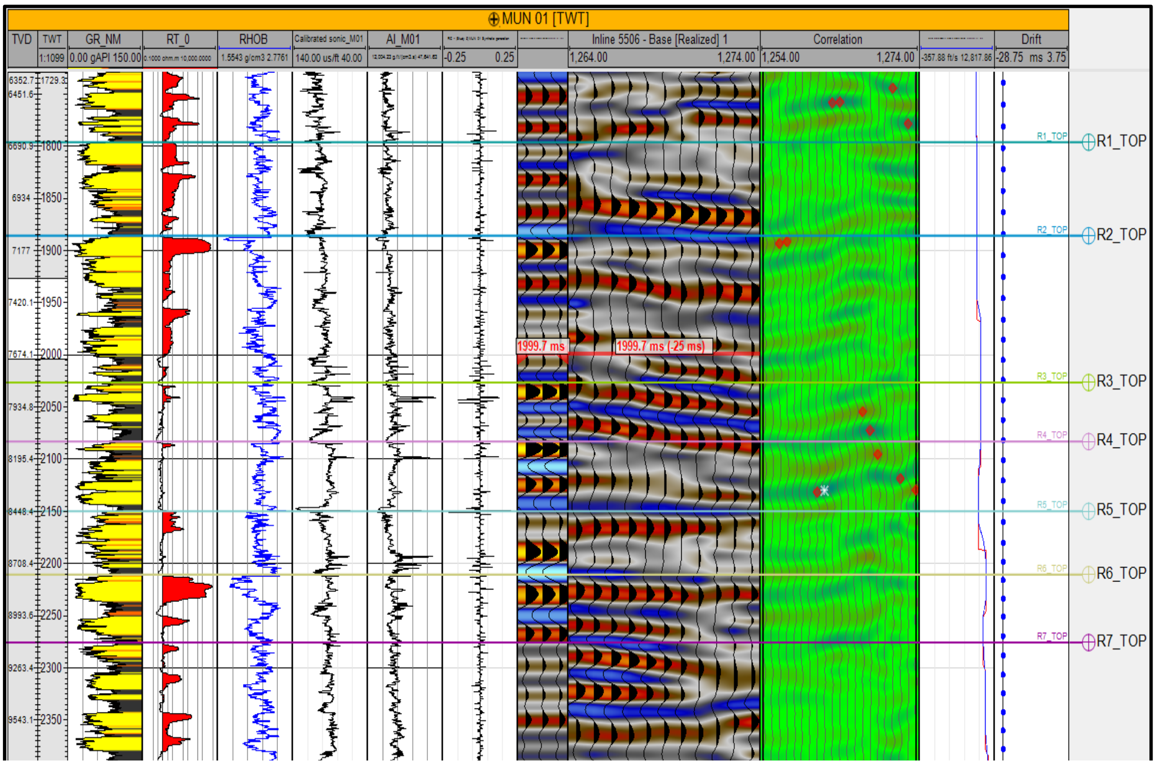


Fig. 4. Seismic-to Well tie (MUN 01)

The rock attributes: acoustic impedance (Ip), λρ, µρ, σ and Vp/Vs ratios, and petrophysical properties (Sw andϕ) were determined using rock physics and petrophysical equations, and presented as pseudo-logs (Fig. 5).

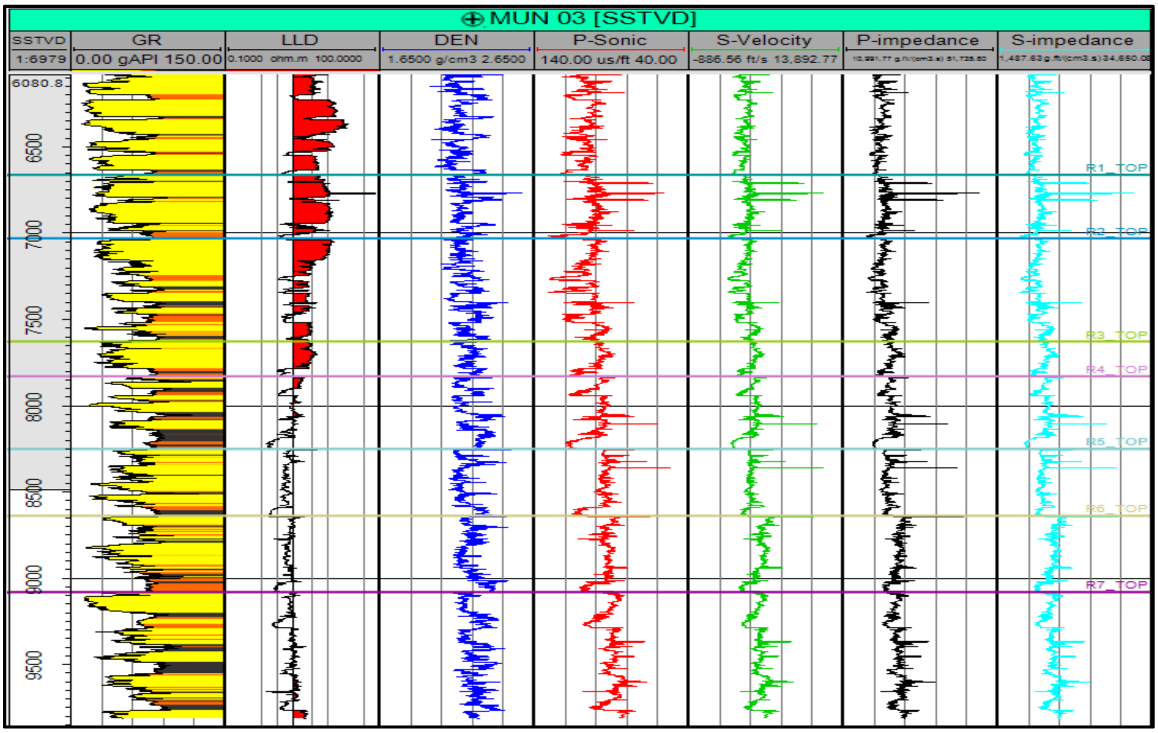


Fig. 5. Typical pseudo-log results of measured and calculated rock properties (MUN 03)

III. Results

Three reservoirs (R1, R2 and R3) were identified and delineated by low GR and high resistivity readings and correlated across the three wells for analysis. Hydrocarbon saturated sand have low radioisotope content and being non-conductive, high resistivity kicks indicate onslaught and presence of hydrocarbon. Shale were identified by relatively high GR and low resistivity readings. Therefore, GR and resistivity logs can evaluate and predict rock formation within the wellbore.

Petrophysical reservoir properties for three reservoirs across the three wells were evaluated and results show good quality values (Table 1). Range of these reservoir properties: porosity is (0.25-0.34), water saturation (0.26-0.41), Net to Gross (0.70-0.95) and thickness in ft (170-354). Except thickness, the other quantities (ϕ, Sw and N/G) average values are similar for the three reservoirs (R1, R2 and R3).

Table: Summary of petrophysical reservoir properties for three reservoirs

RESERVOIR	WELL	Thickness (ft TVD)	Porosity, ϕ	Water Saturation, Sw	Net to Gross
	MUN 01	274	0.25	0.40	0.83
	MUN 02	242	0.33	0.26	0.70
R1	MUN 03	286	0.26	0.35	0.83
	Average	**267**	**0.28**	**0.34**	**0.79**
					0.81
	MUN 01	319	0.26	0.31	
	MUN 02	354	0.32	0.28	0.81
R2	MUN 03	300	0.28	0.29	0.87
	Average	**324**	**0.29**	**0.29**	**0.83**
					0.73
	MUN 01	184	0.23	0.41	
	MUN 02	177	0.34	0.24	0.95
R3	MUN 03	170	0.26	0.31	0.74
	Average	**177**	**0.28**	**0.32**	**0.81**

The results of cross plot involving the basic well log measurements: Gamma Ray (GR), Resistivity (RT) and Density (RHOB)show fluid and lithology content within a reservoir. Cross plot between the three quantities show their interrelation in defining a reservoir. The 3D cross plot space for these quantities show hydrocarbon saturated sands (black rectangle)have low RHOB, low GR and high RT, brine sand(red oval) have higher RHOB, higher GR and lower RT while shale (blue oval) havehighest density, highest GR readings (Fig.

6). Thus, we can qualitatively identify the reservoir constituents through clustering of points defining respective constituent and expected responses of log equipment during logging measurements of basic quantities.

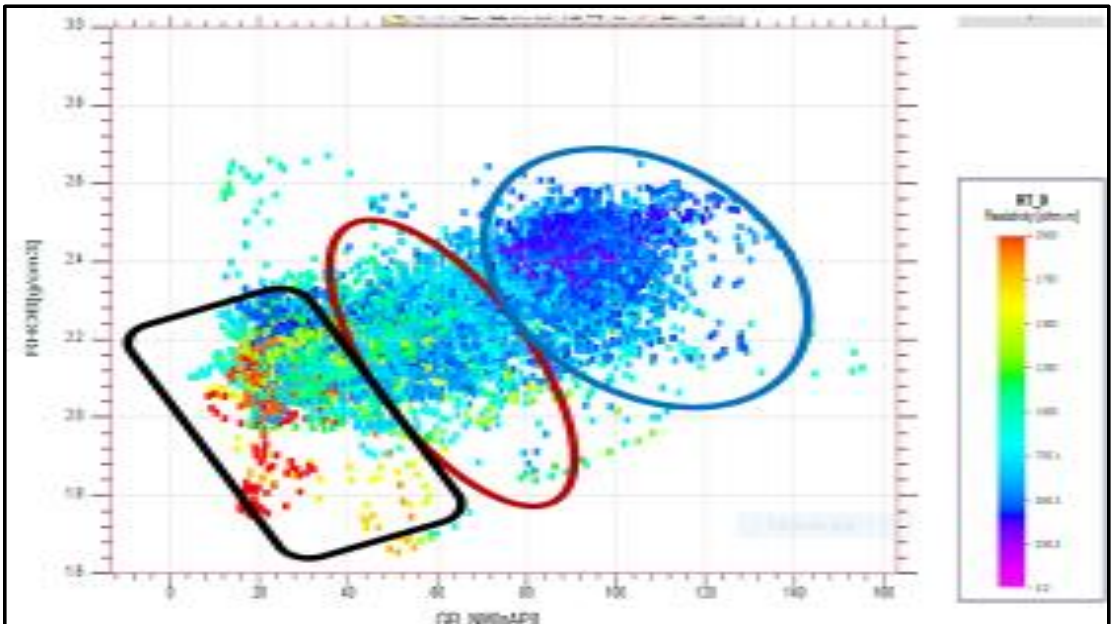


Fig. 6. Cross plot of RHOB Vs GR,color coded with RT

Results of cross plot of porosity (reservoir property) against GR, color coded with RT show that hydrocarbon saturated sands have high porosity compared to shale with low porosity (Fig. 7).

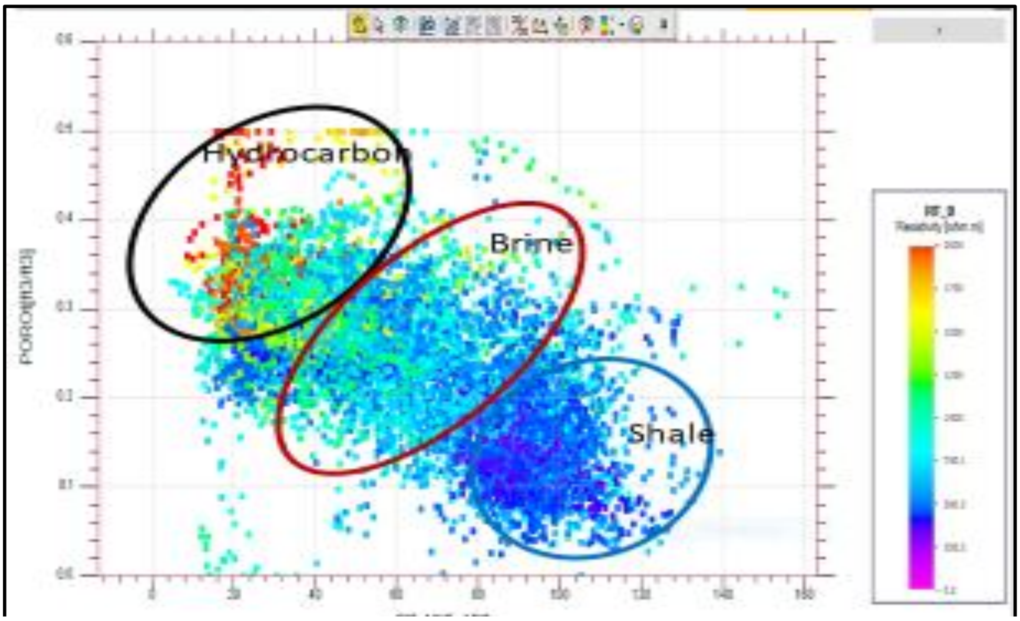
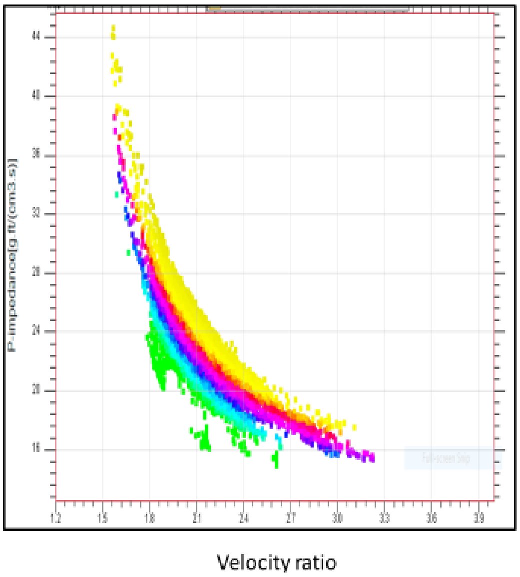


Fig. 7. Cross plot of Porosity versus GR, color coded with RT

In summary, hydrocarbon saturated sands are characterized by low density and gamma ray readings, high porosity and resistivity.

The results of cross plots of well rock elastic attributes show prediction and discrimination of pore fluid and lithology within the well rock formation. Cross plot of acoustic impedance (Ip) against Poisson (σ) ratio and Vp/Vs ratio, show that Ip is a function of pore fluid as reflected by Vp/Vs ratio (Fig. 8) and rock matrix reflected by σ ratio (Fig. 9). Hydrocarbon saturated sands (green-blue) have low Vp/Vs and σ ratios, while for shale (yellow) both are high and for brine sands (purple) both are moderate. The lithology discrimination is not clear-cut.



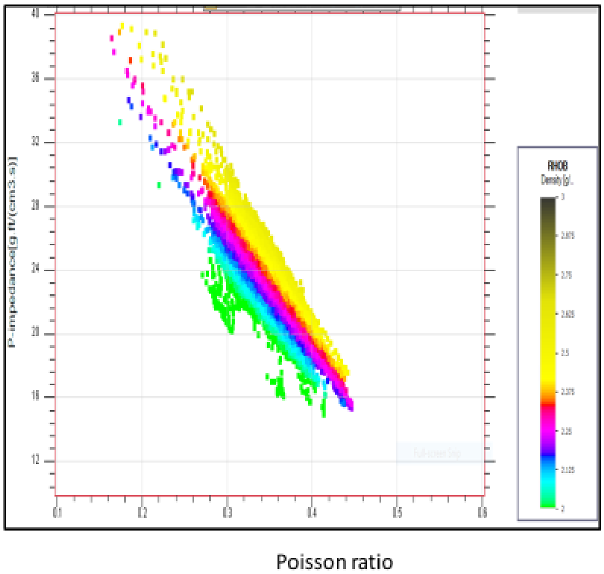


Fig. 8. Acoustic Impedance against Velocity ratio **Fig. 9.** Acoustic Impedance against Poisson ratio

Cross plot of Ip vs μρ show better lithology discrimination compared to Ip vs Vp/Vs and Ip vs σ cross plots. This shows λρ is more sensitive to fluid pore than Vp/Vs.

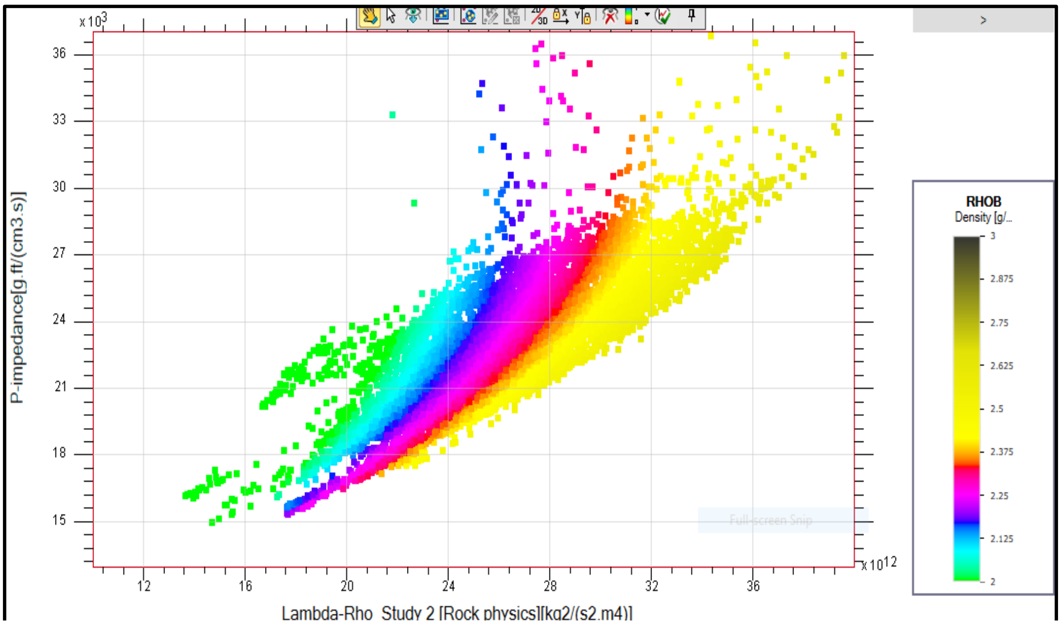


Fig. 10. Acoustic impedance against lambda-rho

Vp/Vs ratio, σ ratio and μρ cross plotted against λρshow good discrimination to Gas sands (green), Oil sands (blue),Brine sands (purple)and Shale (yellow)(Figs. 11, 12 and 13). The four zones are well discriminated on lambda-rho (λρ) axis, over a wide range. This are validated by density colour code. Therefore, λρ is a good and robust fluid discriminator when plotted with other rock attributes, either sensitive to pore fluid or rock matrix.

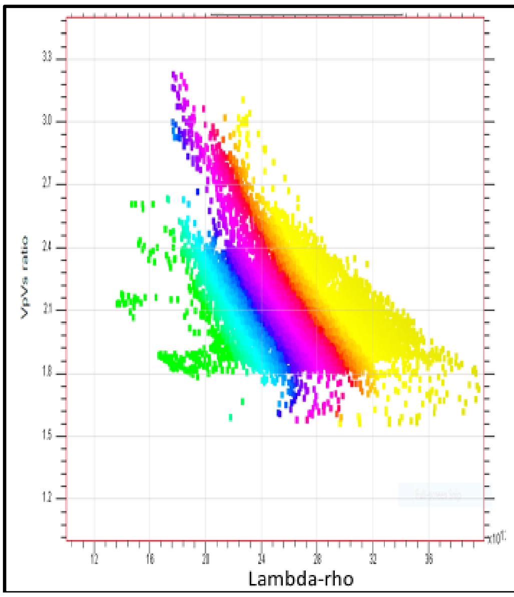


Fig. 11. Velocity ratioagainst lambda-rho

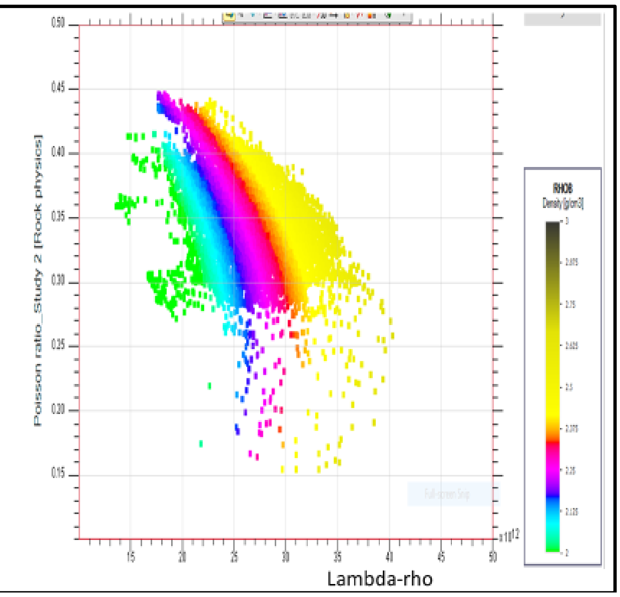


Fig. 12. Poisson ratio against lambda-rho

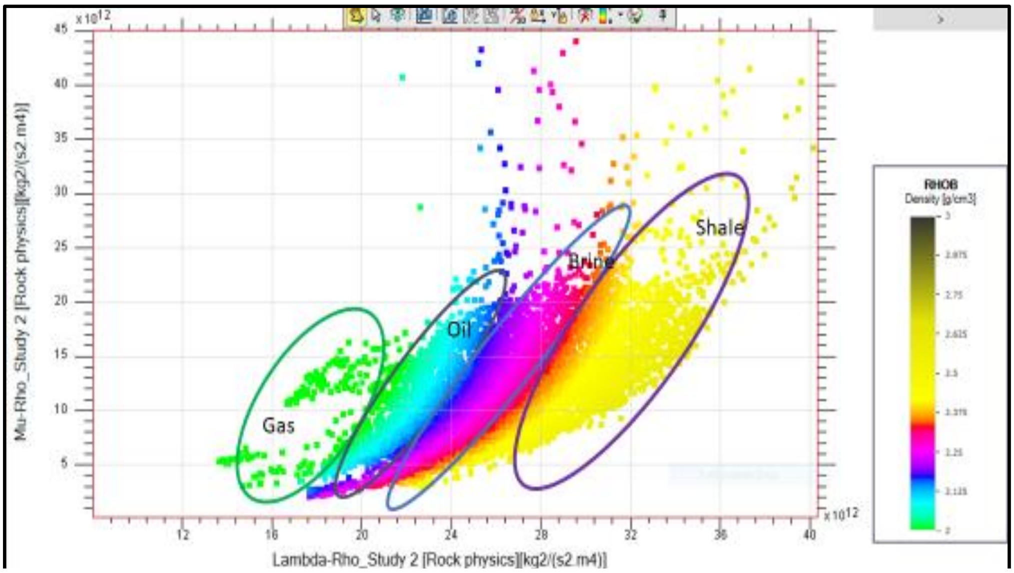


Fig. 13. Cross plot of mu-rho (μρ) against lambda-rho (λρ)

Generally, results of above cross plots suggest Vp/Vs and λρ are sensitive to fluid and σ and μρare sensitive to rock matrix and Ip sensitive to both.

The results of acoustic impedance (Ip) against porosity (ϕ) and water saturation (Sw), color coded with density show that the hydrocarbon saturated sand zones (green-blue) have lower Ip, highϕ and low Sw, compared to low ϕ and high Sw of shale (yellow) (Fig. 14). Middle zone (purple) is brine sands. Within a reservoir, Ip is almost constant across, from hydrocarbon saturated sands to shale, but ϕ and Sw vary significantly.

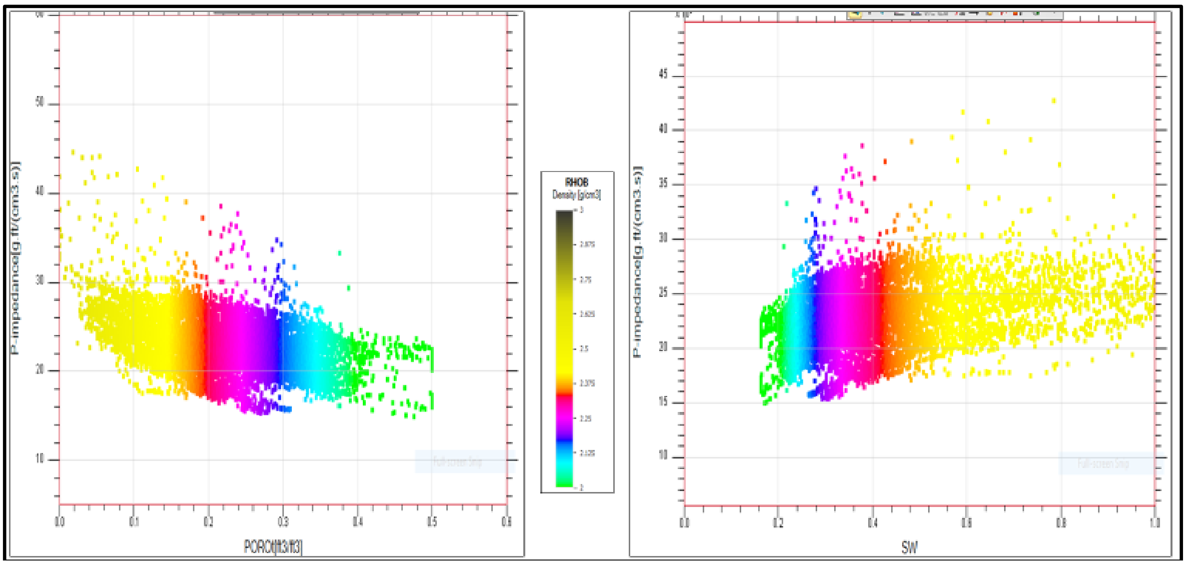


Fig. 14. Acoustic impedance against a) porosity and b) water saturation

IV. Discussion

Well log data in conjunction with rock physics modewere used to generate `rock attributes and evaluate their sensitivity to lithology, pore fluid and establish relations with reservoir properties. The well evaluation identified and delineated three sand reservoirs for petrophysical analysis out of 7 reservoirs identified and correlated them across three wells. Hydrocarbon saturated sands are delineated by low GR and high RT readings due to its low radioisotopic content and non-conductivity.

The petrophysical evaluation of the three reservoirs (R1, R2 and R3) showed average petrophysical properties (thickness in ft, porosity, Water saturation, Net to Gross) as follows: R1 (267, 0.28, 0.34, 0.79), R2 (324, 0.29, 0.29, 0.83) and R3 (177, 0.28, 0.32, 0.81). These quantities indicate relatively good reservoir qualities worth further consideration. Reservoirs are relatively thick, porosity is within the Niger Delta values, water saturation is slightly high and net to gross values are good. In the Niger Delta basin, the porous hydrocarbon reservoir rock (Agbada) at depth, is considered to be a mainly sandstone formation with shale acting like seal (Chukwu, 1991).

The cross plots between pairs of rock attributes (Ip, Vp/Vs, σ, λρ, μρ) were done to predict pore fluid and discriminate lithology and obtain most robust attribute. The cross plots ofIp vs Vp/Vs and Ip vs λρshow that Ip attribute is sensitive to both reservoir matrix and pore fill. The results also show that Vp/Vs and λρ are good fluid discriminators with λρ being more robust, supported by Vp/Vs vsλρ cross plot(Hamada, 2004; Close *et al.*, 2016;Wafaa, 2018). Cross plot of Ip vs σ show that there is direct relationbetween Ip and σ,and σ is a good lithology discriminator, supported by σ vs λρ cross plot. Use of velocity and poisson ratios has proven to be a good tool in discriminating fluid type and lithology (Johnston and Christensen, 1993; Hamada, 2004; Close *et al*., 2016). Cross plot of μρ vs λρshow good prediction of pore fill and discrimination of lithology compared to the other cross plotted pairs (Goodway *et al.* 1997; Close *et al.* 2016; Dagogo*et al.* 2016). The cross plots of acoustic impedance and reservoir properties (Ip vs ϕ and Ip vs Sw) showed that hydrocarbon saturated sands are characterized with low Sw and high ϕ, contrary to shale.

The cross plots analysis suggest that hydrocarbon sands are characterized by low λρ andVp/Vs, and low to moderate Ip, μρ and σ, while shale has high Ip, λρ, μρ, Vp/Vs and σ (Hamada, 2004; Close *et al.*, 2016). This has been validated by studies made in Niger Delta fields (Ekwe*et al* 2012; Abe *et al.* 2018). These attributes play great role in interpretation of seismic data field wide and are used in seismic exploration for gas and oil and 4D studies exploitation (Hamilton, 1979; Dagogo*et al*, 2016; Wafaa, 2018).

V. Conclusion

The well petrophysical analysis obtained the average reservoir properties of three delineated reservoirs in the following ranges: thickness in feet (177-324), porosity (0.28-0.29), water saturation (0.29-0.34) and net to gross (0.79-0.83). This indicates is good quality reservoirs.

The rock physicscross plot analyses established robust fluid and lithology discriminators, (Vp/Vs, λρ) and (σ, μρ), respectively. Best discrimination occurs when pair of attributes with almost independent sensitivity to fluid or rock matrix are cross plotted, for instance μρ vs λρ. Relationship between petrophysical properties (ϕ, Sw) and rock attributes (Ip, λρ, μρ, Vp/Vs, σ) are used for seismic data interpretation over the entire field.

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