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Integration of Rock Properties Crossplot and Petrophysics for Enhancement of Litho-Fluid Discrimination and Compartmentalizationto Reduce Uncertainty and Mitigate Hydrocarbon Exploration Risk. 'A Case of 'NICK' Field, Onshore Niger Delta'.

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Abstract: The main components of reservoir rocks are hydrocarbons and immiscible water in varying ratios. It is essential to precisely identify, characterize, and divide the fluids in these reservoirs into distinct groups according to the characteristics of their rock properties to conduct a successful hydrocarbon exploration. For this reason, petrophysics and rock physics analysis were combined on the "NICK" field in the onshore Niger Delta. Through precise litho-fluid discrimination in the field, this study seeks to improve field hydrocarbon production, lower uncertainty, and mitigate risks related to hydrocarbon exploration. The suites of well logs (Gamma-ray neutron, bulk density, sonic, and resistivity logs) from three wells—NICK-1, NICK-3, and NICK-6—make up the data used. Gamma-ray log signatures were used to identify and correlate lithologies throughout the field. Potential reservoirs and fluid content were identified and delineated by high resistivity and adequate neutron-porosity log signatures. Hydrocarbon-bearing sands were recorded at low values of elastic attributes (acoustic impedance, rigidity, incompressibility, and others), which were computed to aid in the characterizations. Two potentialreservoirs' Sands A and B delineated, constituted the correlated pay zones observed in three wells across the field at depths ranging from 1986.24 to 2599.82m. Petrophysics results generally revealed fair to good porosities of (11-25%) for easy accumulation of hydrocarbon. Permeability ranged from 210- 809mD for Sand A and 27 – 887mD for Sand B, showing that there are suitable permeabilitiesfor fluid movement/migration within the reservoirs. Cross plot of Lambdarho versus Murho, Lambdarho versus Velocity Ratio, and Velocity Ratio versus Acoustic Impedance gave four distinct clusters for litho-fluid zones identification given as gas-sand, oil-sand, brine-sand, and shale. This study has assisted in better characterization and distinguishing of the litho-fluid details for enhancement of hydrocarbon production in the field.

Keywords: Reservoir, Well – Logs, Petrophysics, Rock physics, Cross plotting, Lithology, Hydrocarbon

I. Introduction

Hydrocarbon exploitation is hampered by risks arising from an inadequate knowledge of reservoir and fluid properties. Consequently, the integration of sophisticated approachesis needed to understand reservoir and fluid properties that will promote higher production success rates [1], [2]. Reservoir Characterization is a method of integrating several qualities and quantities of data consistently to define reservoir properties of concentration in inter-well locations [2], [3], [4]. It is evaluated to understand the properties and efficiency of reservoirs. The objective of characterization is lithology and pore fluid determination [1], [2], [3].

After defining prospects and drilling wells, petrophysical analysis is used to determine "pay zones" and other reservoir parameters, including porosity, permeability, and so on, derived from well data. It is common practice in the industry to use petrophysical analysis to perform reservoir characterization. This yields reservoir volume and saturation properties like porosity, water permeability, hydrocarbon saturation, etc.[2],[5], [6]

However, in terms of elastic properties and litho-fluid discrimination, it fails to provide insight into the reservoir's essence. Therefore, enhancing the understanding of well-data by more extensive research is crucial [1], [3], [5]

Rock physics discourses the relationships/affinitybetween two important attributes which include the rock properties (lithology, porosity, fluid saturations etc.)and elastic properties (velocity,Impedances, etc.) [1],[3], [7].Some of the equations between any two or more of these attributes often show some distinct details that can be described in terms of lithology and

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fluids. Identification of those characteristics of the rock properties that can effectively distinguish the reservoir qualities and contents also involved the performance of cross-plot analysis [1],[3],[7],[8]. This study incorporates petrophysical evaluation and rock physics studies -to accurately identify these qualities of the reservoirs in 'NICK' field which can aid/boost its litho-fluid discrimination.

II. Location and Geology of The Area

The 'NICK' oil field is located onshore Niger Delta (Figure 1), some 55 km south of Onitsha in the south-western sector, and straddles at deeper levels to the west into the concession border with Shell. 'NICK' field is located approximately 4 km to the west of the Izombe field at an elevation of 25m above mean sea level in a drowned river valley affected by seasonal flooding which limits access to the field during the rainy season [2.], [9],[10]. The Niger Delta encompasses the whole Niger Delta Province and is located on the Gulf of Guinea (Figure 1). The Tertiary Niger Delta (Akata-Agbada) petroleum system is the only petroleum system known to exist in the Niger Delta province.[2], [9], [10}. The upper Akata Formation, the delta's marine-shale facies, is the main source rock; interbedded marine shale from the lowermost Agbada Formation may have contributed as well [9,10]. The Agbada Formation's sandstone facies is the reservoir rock; however, the higher Akata Formation's turbidite sand is a possible target in deep water offshore and potentially under presently producing intervals onshore. The delta, according [10] has prograded southwestward, forming depobelts, which are the delta's most active regions at every stage of its history, from the Eocene to the present. Approximately 5% of the world's oil and gas reserves are found in this region, which is one of the most prolific tertiary deltas in the world for producing petroleum. It originated in the location of a rift junction that was connected to the South Atlantic opening, which occurred in the late Jurassic and early Cretaceous [1], [2], [5], [9], [10]

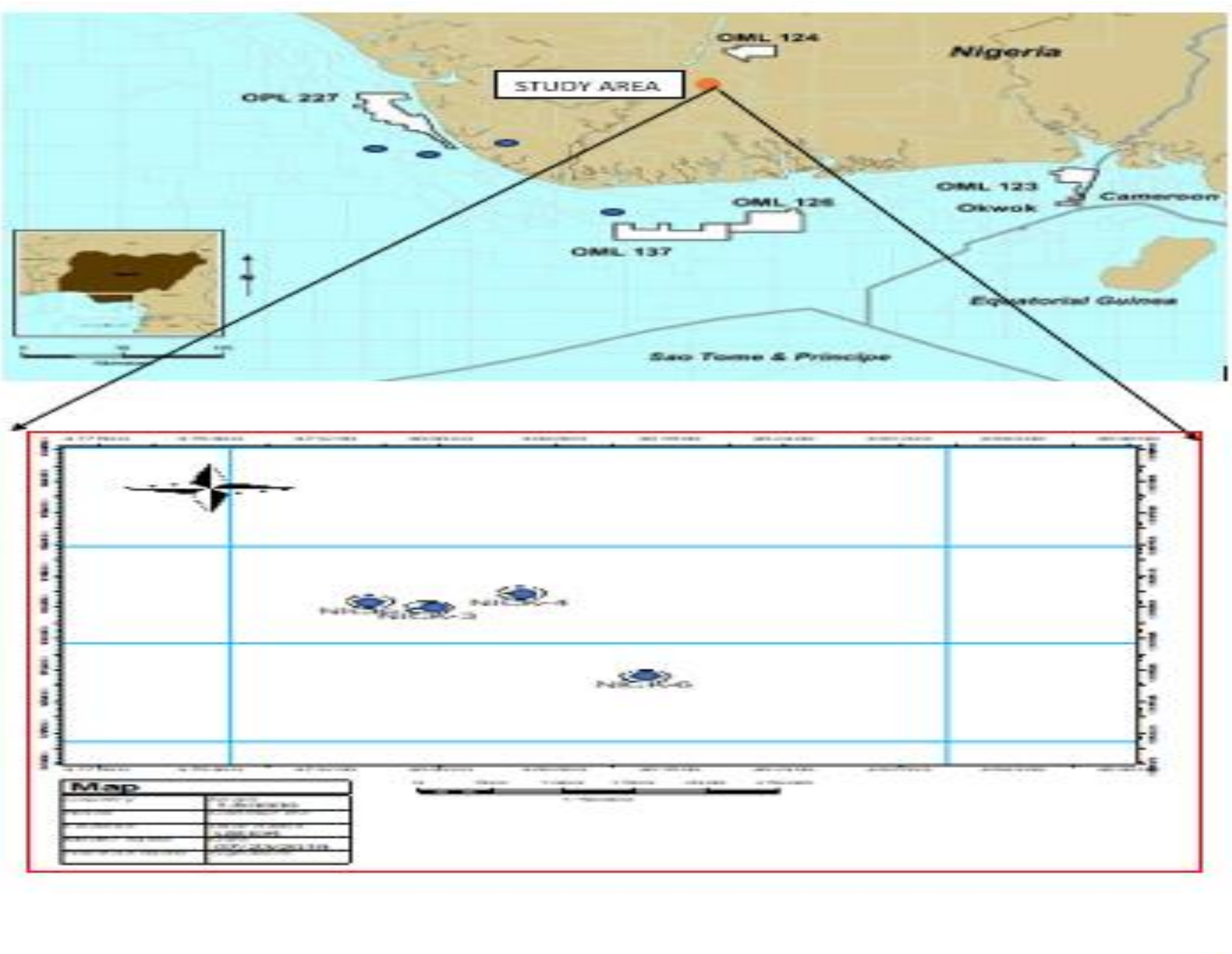

Figure 1: Location and Base Map of the Study Area (Modified after Ojo et al 2018)

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III. Materials and Methodology

Gamma-ray, neutron, bulk density, sonic and resistivity log suites are among the wireline logs used. This is shown in Table 1. The logs were utilized in the reservoir study to improve the compartmentalization of the pay zones within the "NICK" field, Onshore Niger-Delta.

The workflow for the methodology is shown in Figure 2. In the first step, well correlation is performed in a West-East direction, and petrophysical parameters of the reservoir intervals were estimated using Petrel software afterward. These parameters; volume of shale, effective porosity, and water saturation were then plottedto establish fluid contact. In the final step, these estimated petrophysical parameters along with elastic properties derivable from well log attributes were used to generate rock elastic parameters(logs),that were cross-plotted to mark the litho-fluid zones. Finally, results from the cross-plots were used to validate petrophysical findings in the characterization of the "NICK" field are the suite of well-logs in LAS format (Table 1), Check shot survey data, Well-head data, Well deviation data(LAS), Petrel 2009 software and Rokdoc 6.1.4.1089.

The various analyses and computations carried out in this study can be grouped into two broad categoriesinclude Petrophysical computation and analysis and Rock physics and cross plots (RPTs).

Petrophysical Analysis

Qualitative Petrophysical Analysis

This involved all forms of analysis done by accurate visual inspection and visual inference from the well data signatures loaded on Petrel software. [11],[12],[13]

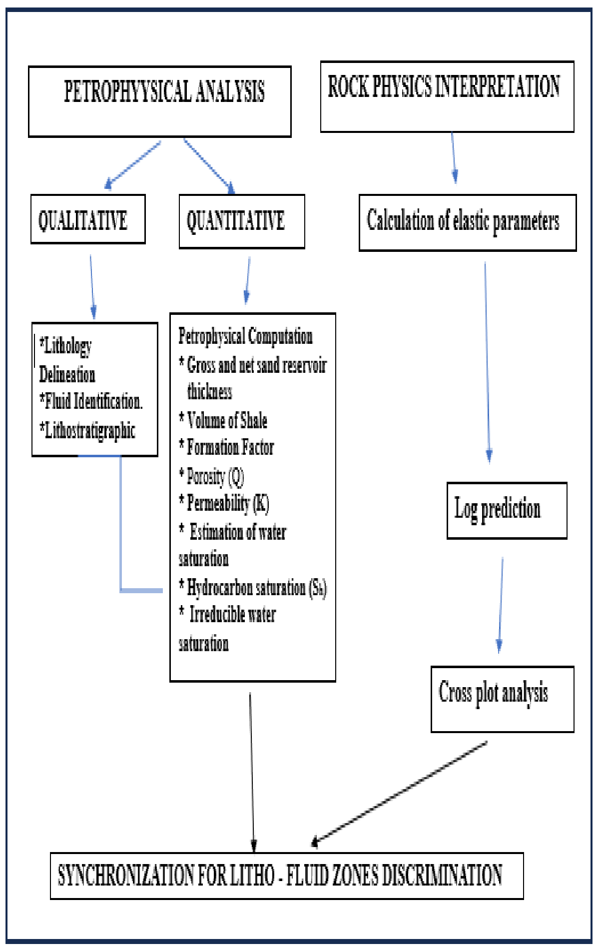

Figure 2 The workflow for the methodology

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Lithology Delineation

Lithologies were identified using the gamma-ray log as the principal lithology log. High gamma ray values depicted shaly formations and low gamma ray counts depicted sand formations. [2], [13]

Fluid Identification

Resistivity logs were used to identify the fluids within the penetrated formation. Hydrocarbon zones are seen as having high resistivity on the resistivity logs. On the other hand, water-bearing zones exhibit moderate to low resistivity depending on the degree of salinity [11], [13].

Lithostratigraphic Correlation of wells

This process involved mapping lithologies of the same rock unit penetrated by the wells and their relative geological age. Lateral and vertical extents of pay zones are captured in the lithostratigraphic correlation. This is a major step in oil and gas exploration as it helps in the quantification of hydrocarbons [2], [3], [4], [13].Steps involved in Lithostratigraphic correlation include establishing of a reference datum which is a shale layer that is penetrated by all wells. Further establishment of a lithology presented in the wells using the gamma-ray logs. Also, it involves correlation of shale layers across all the wells. Later the key sequence stratigraphic markers will be identified and the specific correlation point on each well will be identified and traced out [13}.

Fluid Contact Point Identification

Density and neutron logs which are porosity logs (with the scale of the neutron log reversed relative to that of density) were co-plotted to discriminate reservoir fluids and estimate contact points between these reservoir fluids. [1], [2], [4], [14], [15]

Table 1: Available logs in the four wells used for the study

WELLS	DEPTH REGISTRATION	LOGS
NICK-01	308ft-13019ft	CALI, GR, DT, ILD, NPHI, SP, TMP, RHOB
NICK-03	46ft- 12996ft	CALI, GR DT, ILD, NPHI, SP, TMP, RHOB
NICK-04	51ft-13000ft	CALI, GR, DT, RHOB, SP
NICK-06	10.0ft- 11541.5ft	CALI, GR, DT, ILD, NPHI, SP, TMP, RHOB

Quantitative Petrophysical Analysis

Available wireline logs were transformed into the various physical properties of rocks (reservoir rocks). Such properties include porosity, permeability, saturations (hydrocarbon and water), volume of shale, net and gross thickness, and so on. These computations were done using the log calculator of the Petrel ™ 2009 software.

i. Porosity

Porosity (Φ) was calculated using equation 1 below [1], [2], [5], [6], [14];

$\emptyset_e = (\rho_{ma} - \rho_b)/(\rho_{ma} - \rho_f) - Vsh(\rho_{ma} - \rho_{sh})/(\rho_{ma} - \rho_f)$ (1)

Where:

ρ_{ma} = matrix density, ρ_b = bulk density, ρ_f = fluid density, ρ_{sh} = shale density

ii. Volume of Shale

The volume of shale was estimated using the equation below [1], [2], [4], [7],[13]

$V_{sh} = 0.083[2^{(3.7 * Igr)} - 1.0]$ (2)

Where:

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Igr = (GRlog - GRmin)/ (GRmax – GRmin)

GR_{log} is the log value of GR

GRmin = GR minimum value

GRmax = GR maximum value

iii. Formation Factor

The following Archie's (1942) equation was used to calculate the formation factor [1], [2], [3], [13], [14];

$$F = (\frac{a}{\phi^m}) \qquad (3)$$

For unconsolidated sand, as modified by Humble,

$$F = (\frac{0.81}{\phi^2}) \qquad (4)$$

Where: F=Formation factor

Φ=Porosity

m = Cementation factor

a tortuosity factor, which is determined by how difficult the fluid's route through the rock must be.

iv. Calculating the water saturation

Using Archie's equation [2], [12], the water saturation for the uninvaded zone was determined:

$$S_w{}^2 = \frac{F \times R_w}{R_t} \qquad (5)$$

But $F = \frac{R_o}{R_w}$ (6)

Thus,

$$S_w{}^2 = \frac{R_o}{R_t} \qquad (7)$$

wherein Sw= the uninvaded zone's water saturation, Rt is the true resistivity of the formation, Ro is its resistivity at 100% water saturation. F stands for formation factor

v. Hydrocarbon saturation (S_h)

It was calculated by deducting the water saturation value from 100%.[1], [13]

S_h = (100 – Sw) % (8)

in which, S_w denotes water saturation

and S_h denotes hydrocarbon saturation

vi. Irreducible water saturation (S_{wirr})

The equation provided by Asquith and Gibson (1982) was used to determine it. [2], [3], [4], [7], [13]

$$S_{wirr} = \sqrt{\frac{F}{2000}} \qquad (9)$$

vi. Permeability (K)

The permeability of each identified reservoir was calculated using Equation 10 [13], [15]

$$k = [\frac{250 \times \phi^3}{S_{wirr}}]^2 \qquad (10)$$

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where the irreducible water saturation is denoted by S_{wirr}

vii. Calculating the thickness of the sand reservoir (gross and net)

The interval encompassing the shale was subtracted from the gross reservoir thickness to determine the net sand thickness.

These formulae were applied in this analysis to generate rock properties based on well-log data.;

GST = Base -Top of Sand (11)

NST=(base + top of sand- shale) (12)

NTG (Net to gross) = (NST/GST) (13)

Rock physics interpretations

These involve the followings processes;

i. Calculation of elastic parameters

Adequate Elastic parameters are generated. These include acoustic impedance (AI), which is the product of density and compressional wave velocity, the shear wave and compressional wave velocities (vp and vs, respectively), Shear impedance (SI) which is the product of shear wave velocity and density.All of the equations used for these computations are listed below [1], [7], [8], [16].[17], [18], [19], [20], [21], [22]. [23]

ii. Log prediction

Vs logs were predicted from the Vp logs which were derived from sonic logs. The empirical relationship used is given below [1], [5].

$$Vs = 0.8903*Vp - 1080.61 \quad (14)$$

Using the rock physics algorithm module of the Rokdoc software package;from well data, rock attributes such as acoustic impedance, velocity ratio, lambda-rho, mu-rho, and Poisson-impedance rock property volumes were extracted. [1], [19], [22,23]

iii. Rock Physics Model

The Hashin-Shtrikman bounds for a dry rock model were adopted for this work and calibrated at 0.5 for upper and lower elastic bounds respectively [23].

b. Cross plot analysis

Crossplots from Lames petrophysical parameters were used to determine the fluid and lithology response of the rocks in this study. These include “λρ”, “μρ” and “λ/μ [1], [3], [5], [22], [23]. They include;

a) cross-plot of V_p/V_s vs acoustic impedance, using porosity and density as an indicator for reservoirs A and B

b) cross-plot of lambda-rho vs V_p/V_s, using porosity and density as an indicator for reservoirs A and B

c) cross-plot of lambda-rho vs mucho, using porosity and density as an indicator for reservoirs A and B

IV. Results and Discussion

The cross-plot analysis and petrophysics results are displayed as graphs, tables, and histograms.

Qualitative Petrophysical analysis

Two hydrocarbon-bearing sands (Sands A and B) were identified from the qualitative petrophysical analysis using Gamma Ray log as lithology tool and resistivity as reservoir fluid indicator.

Lithostratigraphic Correlation of wells

(Figure 3) shows the lithostratigraphic correlation of Sands A and Sand B across NICK- 1, NICK-3 and NICK-6. Wells in a West- East trend using gamma ray log signatures.

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Fluid Contact Point Identification

The "balloon effect" (crossover of neutron and density with large deviation) suggested the presence of gas, and the resistivity logs were used to assess the extent of hydrocarbon thickness in the reservoirs. The large discrepancies reduced until both logs coincided at the water zone [2], [4], [24], [25]. The various fluid contacts; Gas-Oil contact(GOC) and oil-water contact(OWC) estimated from the co-plotting of density and neutron logs, filled with the saturation property and visually inspected are shown in Figure 4.

Quantitative Petrophysical Analysis Petrophysical analysis

The petrophysical analysis of wells 'NICK1', 'NICK3', and 'NICK6' were carried out on compartmentalized sand intervals which constituting the pay zones are summarized in Tables 2 and 3. Reservoirs A and B have porosities that range from fair (11%) to good (23%-25%) according to [24], [25], [26], [27] classification. Sand A generally showed a higher porosity value(good) than Sand B which is averagely fair. This is a result of greater mechanical compaction at the latter sand interval.

Permeability of sands A and B have good values, except that sand B with a permeability of as low as 27 which is relatively low. Sand B was characterized by permeability values ranging from 27– 887mD, while sand A has permeability values ranging from 210 – 809mD. Results of cross plots of any two elastic properties gave four distinct litho-fluid zones; gas-sand, oil-sand, brine sand, and shale. These results have aided in further classification of the intercalation of sand and shale which is characteristic of the Niger Delta [2], [25], [26]-[31].

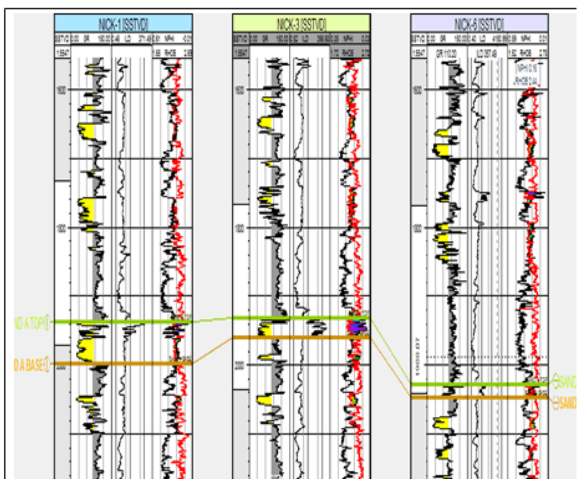

Figure 3: Lithostratigraphic Well Correlation of Sand A in West-East direction. across Nick 1,3and 6.

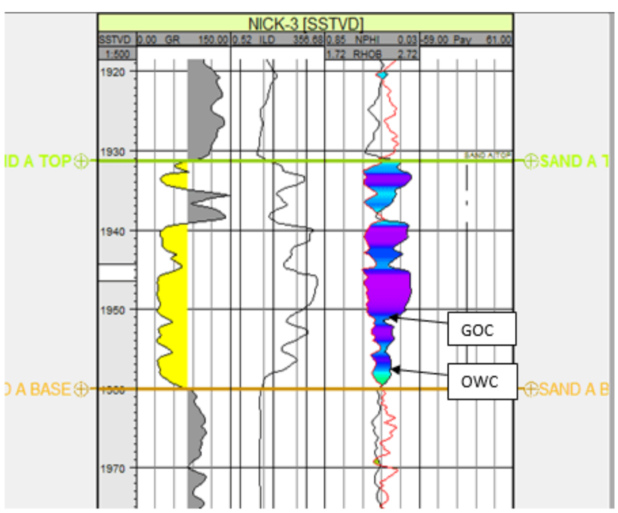

Figure 4: Fluid Contact point for Sand A

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Table 2: Summary of Petrophysical Analysis of Sand A

Wells	NICK1	NICK3	NICK6
Gross	59.94	28.79	20.07
Net	50.87	26.73	15.28
NTG(%)	85	93	76
Gamma Ray Index	0.265	0.2149	0.464
Vsh	0.1185	0.0895	0.199
Φ_d(%)	23	25	23
Φ_e(%)	20	23	19
F	38.9883	24.0864	34.3601
Sw_{irr}(%)	12	10	13
K (mD)	764.689	2101.4	809.222
S_{wc}(%)	56	24	58
Sh	44	76	42

Table3: Summary of Petrophysical Analysis of Sand B

Wells	NICK1	NICK3	NICK6
Gross	52.46	51.37	9.63
Net	47.17	24.88	5.32
NTG(%)	89.916	48.433	55.244
Gamma Ray Index	0.1875	0.3021	0.365
Vsh	0.079	0.122	0.146
Φ_d(%)	20	16	11
Φ_e(%)	19	14	10
F	58.36	75.85	1665.39
Sw_{irr}(%)	14	18	55
K (mD)	887.243	129.393	27.2196
S_{wc}(%)	34	59	77
Sh	66	41	23

Rock Physics Analysis

i. Vp/VS Ratio compared to Acoustic Impedance

The cross plot of Vp/Vs versus acoustic impedance with density indicator (Figures 5and6) and with porosity as an indicator (Figures 7and8) distinguished reservoir A into four zones namely; gas zone (red ellipse), hydrocarbon zone (yellow ellipse), brine zone (blue ellipse) and shale zone (purple ellipse). The crossplot showed better fluid in additionto lithology

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differentiation along the Vp/Vs axis for reservoir A NICK_1 and along the AI axis in NICK_3 and NICK_6. Also, the cross plot using the density indicator showed better fluid and lithology discrimination along the AI axis for reservoir B (Figures 9and10) across the wells ditto the porosity indicator (Figures 11and 12).

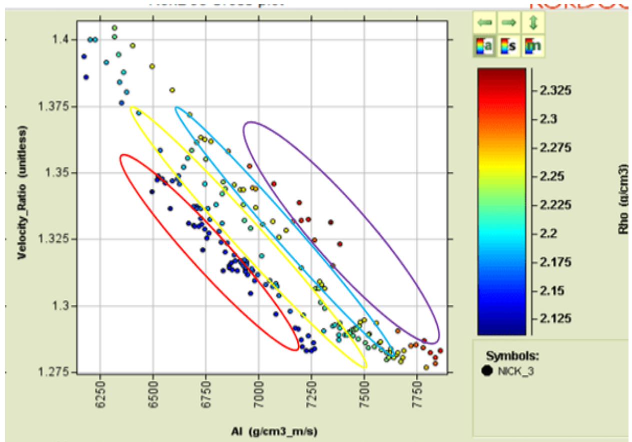

Figure 5: Cross plot of Velocity Ratio vs Acoustic Impedance for Sand-A, NICK-3 with a density as an indicator.

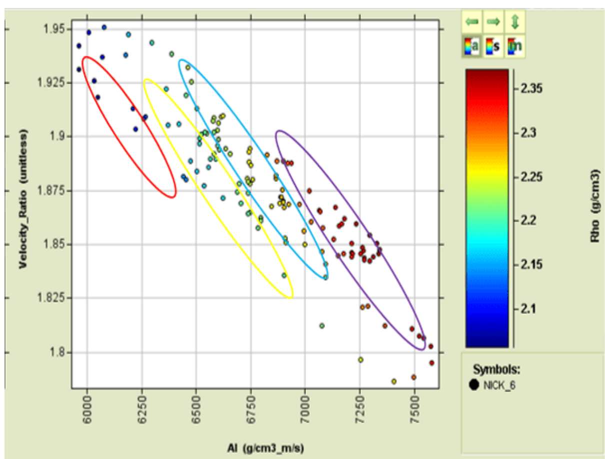

Figure 6: Cross plot of Velocity Ratio vs Acoustic Impedance for Sand-A, NICK 6 with a density as indicator.

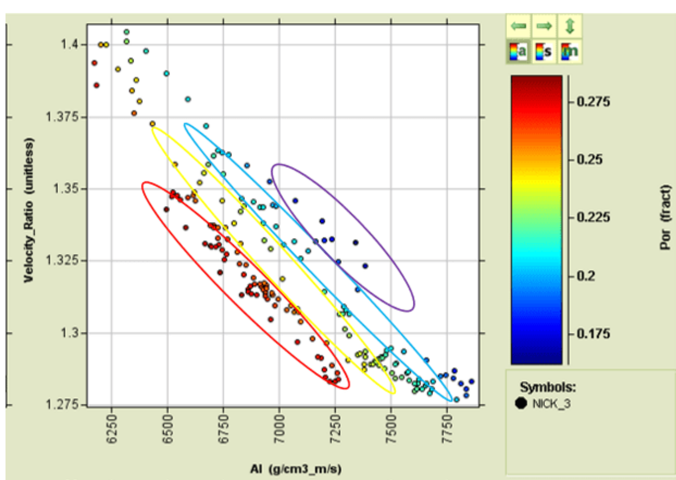

Figure 7: Cross plot of Velocity Ratio vs Acoustic Impedance for Sand-A, NICK_3 with porosity as an indicator.

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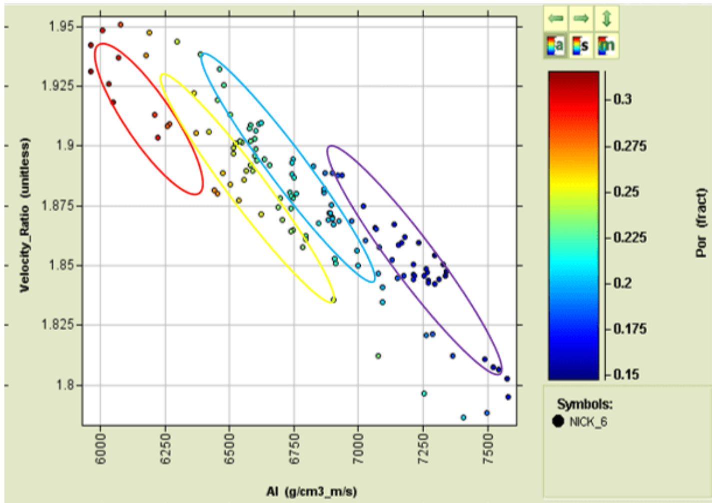

Figure 8: Cross plot of Velocity Ratio vs Acoustic Impedance for Sand-A, NICK 6 with porosity as indicator.

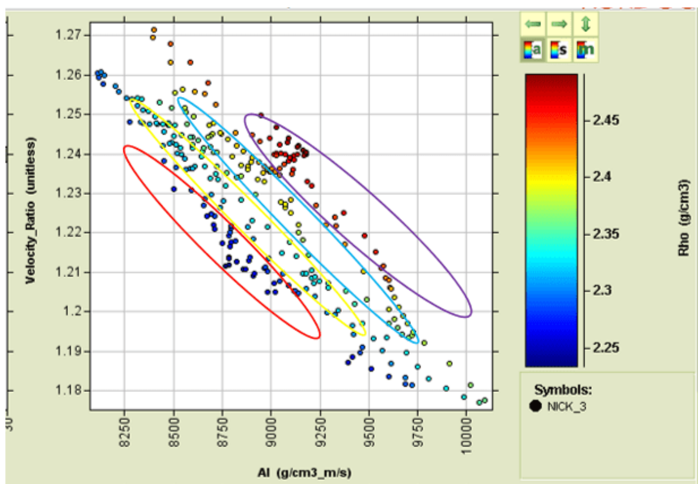

Figure 9: Cross plot of Velocity Ratio vs Acoustic Impedance for Sand-B, NICK_3 using density as an indicator.

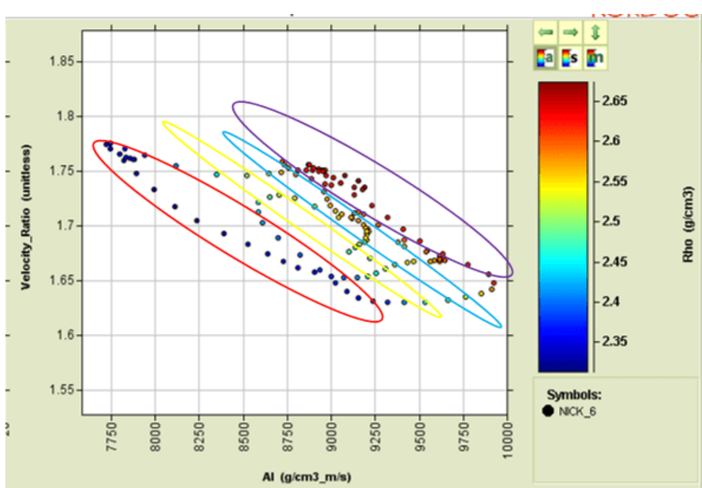

Figure 10 Cross plot of Velocity ratio vs Acoustic Impedance for Sand-B, NICK 6 with a density as indicator.

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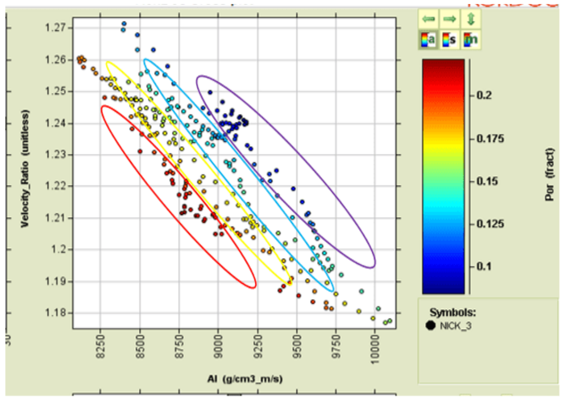

Figure 11: Cross plot of Velocity Ratio vs Acoustic Impedance for Sand-B, NICK_3 using porosity as indicator.

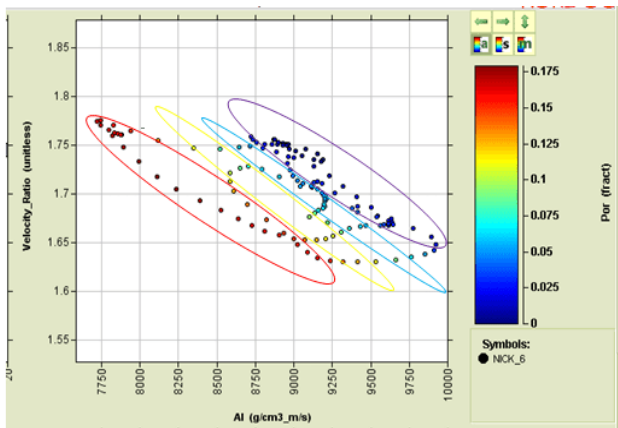

Figure 12: Cross plot of Velocity ratio vs Acoustic Impedance for Sand-B, NICK 6 with porosity as indicator.

Lambda-rho vs Vp/Vs

The cross plot of lambda-rho vs Vp/Vs using the density indicator shown in Figure 13 and14, distinguished reservoir A into four zones explicitly; gas zone (red ellipse), hydrocarbon zone (yellow colour), brine zone (blue colour) and shale zone (purple colour) ditto reservoir B shown in Figures 15 and 16. Thecross-plot showed a better litho-fluid differentiation along the lambda-rho axis.

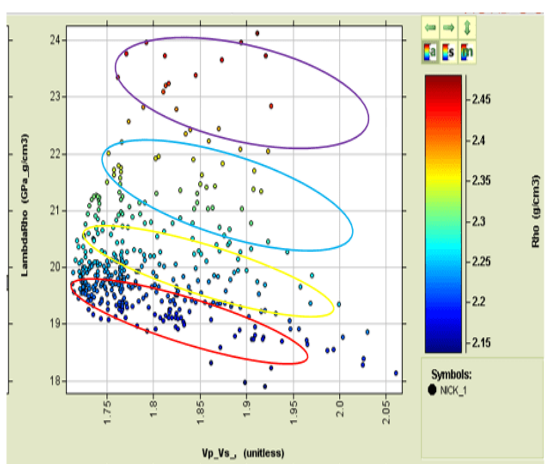

Figure 13: Cross plot of Lambdarho vs Velocity Ratio for Sand-A, NICK 1 with a density as an indicator.

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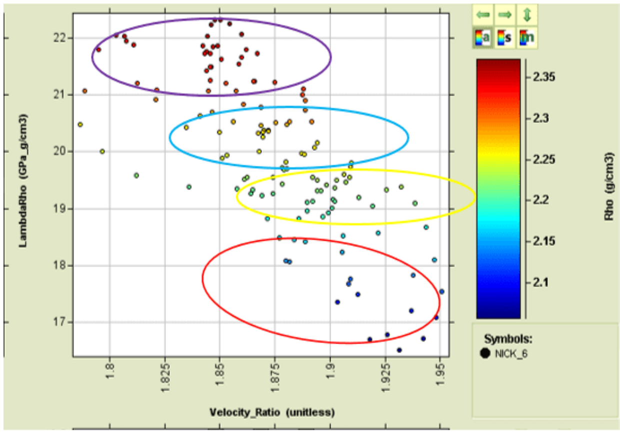

Figure 14 Cross plot of Lambdarho vs Velocity Ratio for Sand-A, NICK 6 with a density as an indicator.

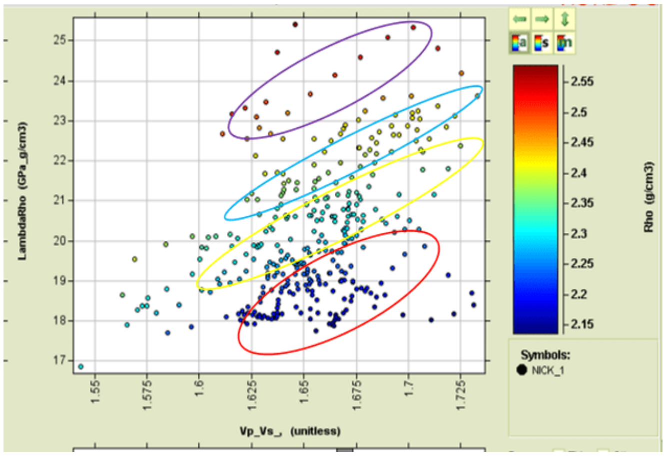

Figure 15: Cross plot of Lambdarho vs Velocity Ratio for Sand-B, NICK 1 with a density as an indicator.

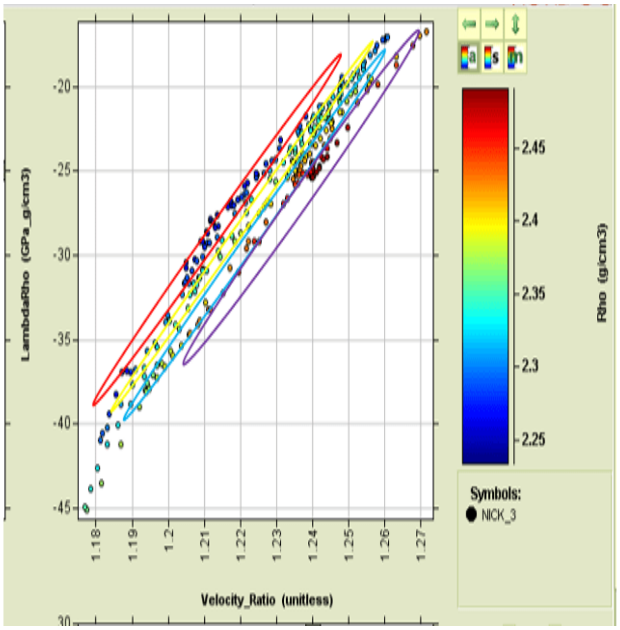

Figure 16: Cross plot of Lambdarho vs Velocity Ratio for Sand-B, NICK_3 using density as an indicator.

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Lambda-rho vs Mu-rho

The cross plot of lambda-rho vs Mu-rho using density indicator shown in Figures 17and 18 for sand A and Figures 19 to 21for sand B, distinguished the reservoirs into four zones namely; gas zone (red ellipse), hydrocarbon zone.

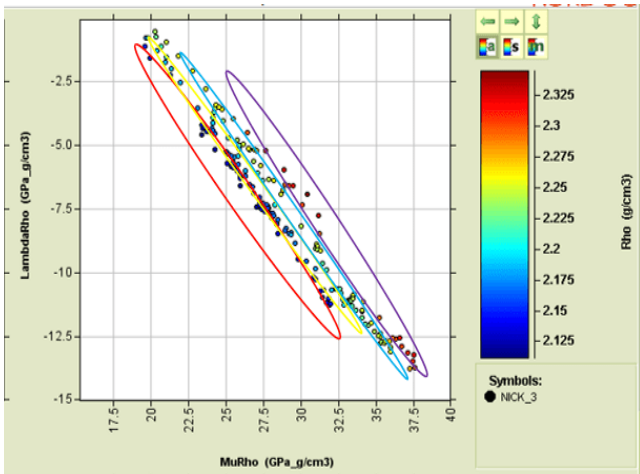

Figure 17: Cross plot of Lambdarho vs Murho for Sand-A, NICK_3 with a density as an indicator.

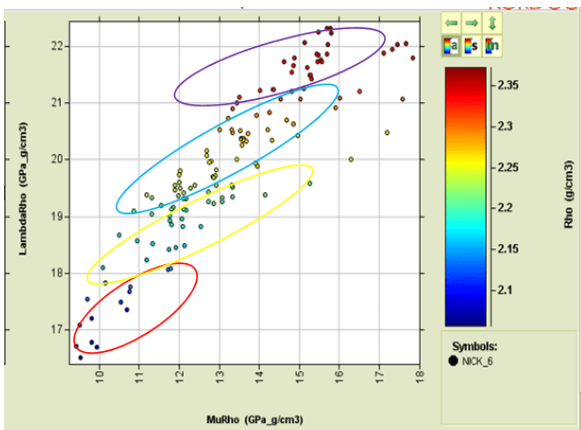

Figure 18: Cross plot of Lambdarho vs Murho for Sand-A, NICK 6 with a density as an indicator.

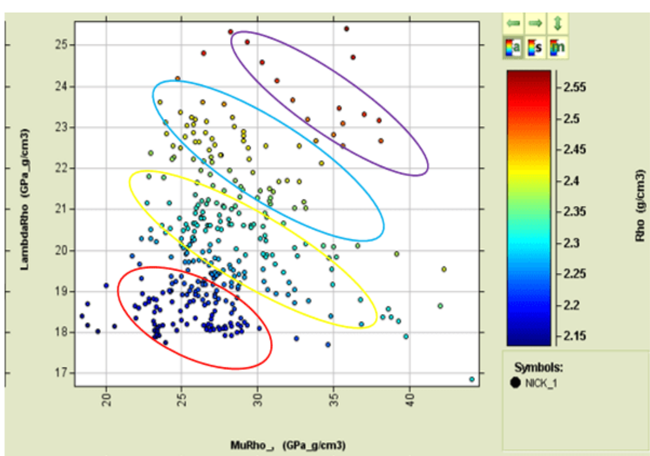

Figure 19: Cross plot of Lambdarho vs Murho for Sand-B, NICK 1 with a density as an indicator.

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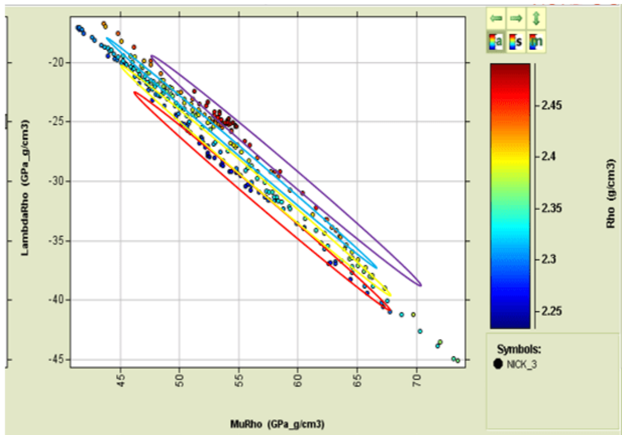

Figure 20: Cross plot of Lambdarho vs Murho for Sand-B, NICK_3 using density as an indicator.

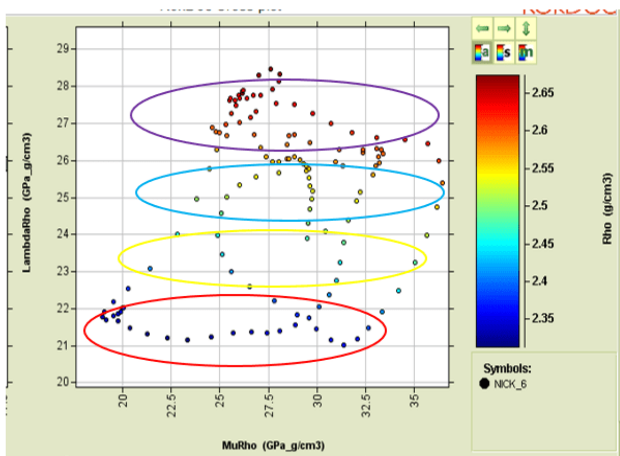

Figure 21: Cross plot of Lambdarho vs Murho for Sand-B, NICK 6 with a density as an indicator.

V. Conclusion

Reservoir characterization through petrophysical evaluation can be enhanced and improved by complementing it through integration with other characterization techniques like rock physics cross-plot analysis as demonstrated in this study.Accurate lithology and fluid property characterization of the hydrocarbon reservoir is essential for successful hydrocarbon exploration and exploitation to reduce uncertainty and mitigate exploration risk.

Lithological correlation using gamma ray log of three wells (NICK1, 3, and 6) confined within the study area revealed two hydrocarbon-bearing sand intervals A and B. Also, these sands were intercalated by shales which is peculiar to the Agbada formation of the Niger Delta.

The petrophysical evaluation revealed the reservoir properties. Sand A has an average porosity of 24% and an effective average porosity of 21% suggesting a better interconnectivity than Sand B whose average porosity and effective porosity values are 16% and 15% respectively. Also, sand B was characterized by permeability values ranging from 27 – 887 mD, while sand A has permeability values ranging from 210– 809 mD across the wells. Hydrocarbon saturations were averaged at 54% for sand A and 43% for sand B. In the crossplot analysis, it was discovered that the attributes of Acoustic impedance (AI), Lambda-rho ($\lambda\rho$), Mu-rho ($\mu\rho$), and Velocity ratio (Vp/Vs) were robust in lithology and fluid discrimination within the reservoir. The ability to differentiate between gas and oil sands was achieved through the cross-plotting of these characteristics, This is so because each lithology has a unique response of its rock properties to fluid content and mineral properties. Additionally, a wide variety of lithologies could be recognized. by the crossplot of incompressibility ($\lambda\rho$) versus rigidity ($\mu\rho$). It was found that the most robust properties for litho-fluid discrimination in the region were Lambda-rho ($\mu\rho$) and Mu-rho ($\mu\rho$). These results assist in better delineation and identification of the lithology types and the types of fluid present in the selected reservoirs with accuracy. The most promising reservoir is reservoir A, whose sands were found to be moderately saturated with hydrocarbons, having good pore interconnectivity and sufficient saturation for commercial production, according to the results of the petrophysical evaluation of the delineated potential reservoirs.

Additionally, this study has demonstrated that combining rock physics (cross plot) analysis with petrophysics aids in a better understanding of the subsurface and also aids effective litho-fluid discrimination for enhancement of hydrocarbon production.

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