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FLUID AND LITHOLOGY DISCRIMINATION USING CROSS PLOTS ANALYSIS OF THE ROCK PROPERTIES OF AN ONSHORE FIELD OF NIGER DELTA BASIN

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Abstract— **Cross plots of computed attributes were used to accurately delineate the lithology and discriminate the fluids, so as to further characterize the existence of fluid and lithology in the reservoir. The cross plots analysis has indicate that Lambda-rho (λρ) is more robust than (Mu-rho) μρ in the analysis of fluids in the field of study, and that μρ values are relatively low for the reservoir sand. The Acoustic impedance (Zp), Lambda-rho (λρ), Mu-rho (μρ), and Poisson impedance (PI) attributes were found to be most robust in lithology and fluid discrimination within the reservoir in the cross-plot analysis. The Lambda-Mu-rho (λ-μ-ρ) technique was able to identify gas sands, because of the separation in responses of both the λρ and μρ sections to gas sands versus shale. Many different lithologies could also be identified by the cross plot of λρ versus μρ. This is possible because each lithology has a different rock properties response subject to fluid content and mineral properties.**

Index Terms— KEYWORDS: Cross plots, Discrimination, Incompressibility, Acoustic Impedance, Lithology, Lambda-rho, Mu-rho, Attributes, Hydrocarbon zone.

1 INTRODUCTION

The cross plots analysis indicate that Lambda-rho (λρ) is more robust than (Mu-rho) μρ in the analysis of fluids in the field of study, and that Mu-rho (μρ) values are relatively low for the reservoir sand. The Acoustic impedance (Zp), Lambda-rho (λρ), Mu-rho (μρ), and Poisson impedance (PI) attributes were found to be most robust in lithology and fluid discrimination within the reservoir in the cross-plot analysis. The Lambda –mu-rho (λ-μ-ρ) technique was able to identify gas sands, because of the separation in responses of both the λρ and μρ sections to gas sands versus shale. Many different lithologies could also be identified by the cross plot of λρ versus μρ. This is possible because each lithology has a different rock properties response subject to fluid content and mineral properties.

2 LOCATION OF STUDY AREA

The study area Field is located within the onshore area of Niger Delta in Nigeria (Figure 1). The terrain is generally swampy in nature, with river channels and tributaries emptying into the Atlantic Ocean. The Field lies between longitude 6°17"55'E and latitude 4°37"27'N. The Field is located within the Central Swamp Depobelt, Onshore Niger Delta.

3 GEOLOGICAL AND STRUCTURAL SETTING

Niger Delta is a large, arcuate delta of the typical, wave- and tidal-dominated type (Doust and Omatsola, 1990). It is located in the Gulf of Guinea on the margin of West Africa, at the southern culmination of the Benue trough and extends from about latitudes 40 to 60 N and longitudes 30 to 90 E (Opara et al., 2011). The delta formed at the site of a rift triple junction related to the opening of the southern Atlantic starting in the Late Jurassic and continuing into the Cretaceous (Tuttle et al., 1999). During the tertiary, it built out into the Atlantic Ocean at the mouth of the Niger-Benue river system (Figure 2), an area of catchment that encompasses more than a million square kilometers of predominantly savannah-covered lowlands (Weber and Daukoru, 1975). It ranks amongst the world's most prolific petroleum producing tertiary deltas that together account for about 5% of the world's oil and gas reserves (Opara et al., 2011). It is also considered a classical shale tectonic province, the evolution of the Niger Delta is predominantly controlled by pre- and syn-sedimentary tectonics (Evamy et al.,1978), the formations reflect a gross coarsening-upward progradational clastic wedge (Short and Stauble, 1967), which were deposited either in marine, deltaic, and fluvial environments (Weber, 1986), as accumulation of marine sediments in the basin probably commenced in Albian time, after the opening of the South Atlantic Ocean between the African and South American continents (Doust and Omatsola, 1990). Accelerated loading of the unstable marine shale caused local shale diapir movement, and as a result, the structure is more complicated than in older portions of the delta (Reijers, 2011), where large basinward-dipping growth faults dominate an overall extensional regime and their syn-depositional formation is critical in controlling patterns of local subsidence and sedimentation.

Niger delta possess many areas which makes it extremely difficult to define in a satisfactory stratigraphic nomenclature, the

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inter-digitation of a small number of lithofacies makes it impossible to define units and boundaries of sufficient integrity to constitute separate formations in a formal sense (Doust and Omatsola, 1990). That not-withstanding, three formations exist, Akata Formation, Agbada Formation and Benin Formation (Figure 3), haven been generally accepted and are widely used (Short and Stauble, 1967).

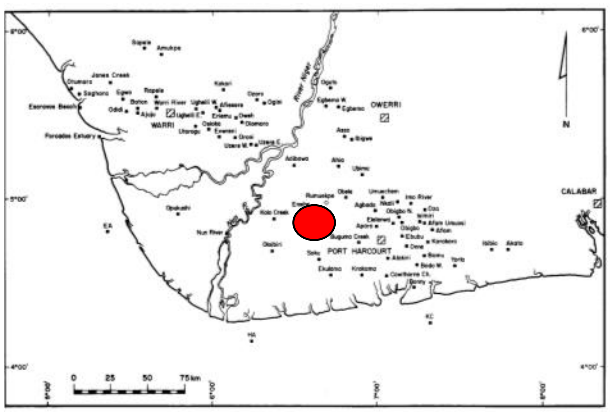

Fig 1: Map of Niger Delta Area showing the location of the Study Area.

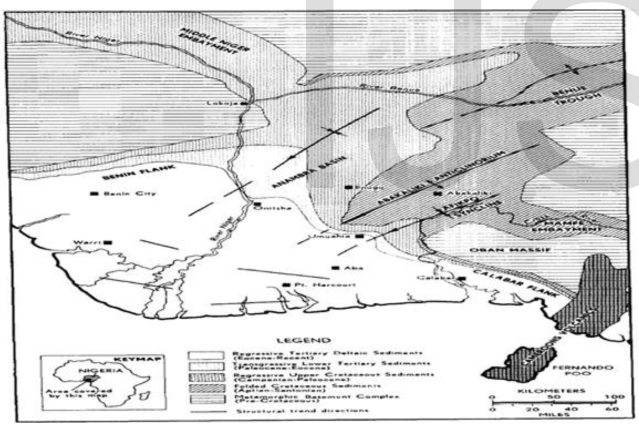

Fig. 2: Structural units of Niger Delta Area (Short and Stauble, 1967).

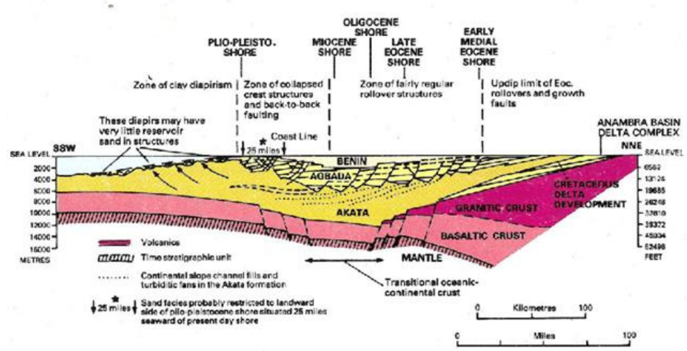

Fig. 3: Schematic dip section of the Niger Delta (Modified from Weber and Daukoru, 1975.

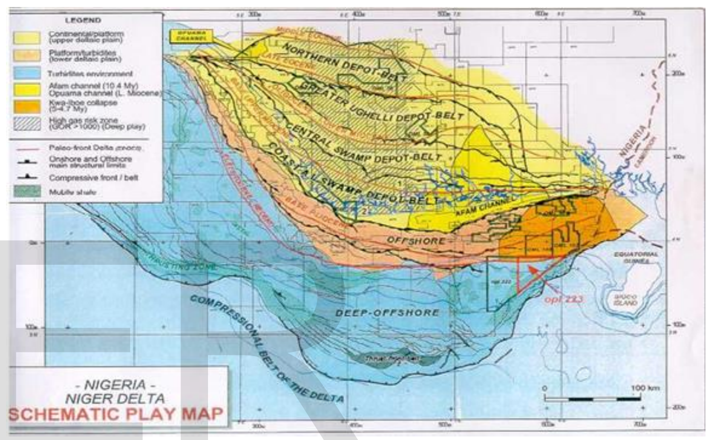

Figure 4: Map Showing the Niger Delta Depobelts (Steele et al., 2009).

4 Theoretical Background

4.1 Well Logs

A well log is a record of measurements of the subsurface formation properties in a well. Well logs data are routinely used for stratigraphic interpretation of the earth's subsurface; it is a practice of making a detailed record of the geologic formations penetrated by a borehole.

4.2 Petrophysical Properties

Petrophysics is a study of the physical and chemical properties of rock and their interactions with fluids. It is majorly applied in the study of reservoirs for the hydrocarbon industry and some of the key properties studied are Gross and Net thickness, porosity, fluid saturation, permeability, Net to Gross ration and shale volume. A key aspect of petrophysics is measuring and evaluating these rock properties by acquiring well log measurements. The petrophysical properties are as follows.

4.2.1 Gross and Net thickness
The gross thickness of the reservoir is the entire thickness of the reservoir, including the shaly sections of the reservoir while the net sand is the interval of sand in the reservoir that is clean, containing no shaly fractions. The net sand can be computed after the Volume of shale has been determined and subtracted from the total reservoir thickness.

4.2.2 Porosity
Porosity may be defined as effective or total depending on whether it includes porosity associated with clays; some tools measure total porosity and must be corrected for the clay content.
Total porosity (ΦT) and effective porosity (ΦE) were calculated based on Wyllie's equation as follows.

4.2.3 Fluid Saturation
Fluid saturation in petrophysics comprises of both water and hydrocarbon saturation contents. Water saturation (Sw) is the proportion of total pore volume occupied by formation water.
Hydrocarbon saturation is the proportion of fluid that is (oil and gas) and is derived from the relationship

$$SH = 1 - Sw. \quad (1)$$

4.2.4 Permeability
Permeability (K or k) is the measure of the capacity of a reservoir to conduct fluids or for flow to take place between the reservoir and a wellbore, it is dependent on the associated rock and fluid properties and it is also one of the most difficult to measure and evaluate without data at all relevant scales – core, log and production test. Permeability is measured in darcies (D) but usually reported as millidarcies (mD).

4.2.5 Net-To-Gross
This is the total amount of pay footage divided by the total thickness of the reservoir. One approach of determining N/G is to calculate the oil initially in place (OIIP) or Gas initially in place (GIIP) assuming that the entire reservoir interval is used to determine the total volume of hydrocarbons present within the reservoir interval. Net-To-Gross is a measure of the potential of the productive part of a reservoir.

4.2.6 Shale Volume
This is the space occupied by shale or the fraction of shale (clay) present in reservoir rocks, the volume of shale in a reservoir plays a key role in hydrocarbon production where the higher the reservoir shaliness, the poorer the reservoir productivity.

4.3 Cross Plots Analysis
In order to delineate the extent and determine the volume of hydrocarbon in-place in probable reservoirs identified in the wells, some of the attributes from well logs were estimated and cross plotted (using 3-D cross plots), where the 3rd dimension connotes the colour coding of the data points using Hampson-Russell software. Three major attributes of the well data were estimated and used to delineate the lithology and the discrimination fluid contents in the reservoir. Two lame's paraments (elastic moduli), namely Lambda-rho (incompressibility modulus - λρ) and Mui-rho (rigidity modulus - μρ) and the acoustic impedance.

$$\text{Lambda-Rho}(\lambda\rho)=(\text{P-impedance})2-Cx(\text{S-impedance})2 \quad (2)$$

$$\text{Mui-Rho}(\mu\rho)=(\text{S-impedance})2 \quad (3)$$

$$\text{P-impedance}=\text{P-wavexDensity} \quad (4)$$

5 MATERIALS AND METHODS

5.1 MATERIALS

This study was conducted using well logs obtained from the designated field, onshore Niger Delta Area (study area). Some of the available data from the well log suite includes Gamma ray (GR) logs, Caliper logs, Porosity logs (Neutron, Density and Sonic logs) and resistivity (shallow and deep) with their well header information, check shot data and well survey deviation data.
Two major industrial software were used namely: Schlumberger PETRELTM (2014 version) Software (loading of the well log data appraisal, petrophysical analysis, well correlation, generation of hydrocarbon prospect maps) and Hampson-Russell (HR) Software (Used for loading well log data, evaluation of lithology and fluid discrimination from well data).

Table 1: Well data inventory for four wells utilized in this study.

	Well logs						Well Header	Check shot	Dir, Survey
	GR	Cali	Res	Den	Neutr	Sonic			
A-002	YES	YES	YES	YES	YES	YES	YES	NO	YES
A-007	YES	YES	YES	YES	YES	YES	YES	NO	YES
A-009	YES	YES	YES	YES	YES	YES	YES	NO	YES
A-011	YES	YES	YES	YES	YES	YES	YES	YES	YES

YES = Available, No = Not Available

5.2 METHODS

In achieving our study aim, the outlined procedure below was utilized for the successful completion of the study:

1. Data sourcing, data gathering, and data loading into relevant software.
2. Data quality assurance and quality control.
3. Well logs conditioning (despiking and interpolation).
4. Well correlation.
5. Petrophysical evaluation of reservoirs.
6. Attribute cross plots from well logs
7. Hydrocarbon Prospect evaluation
8. Volumetric evaluation

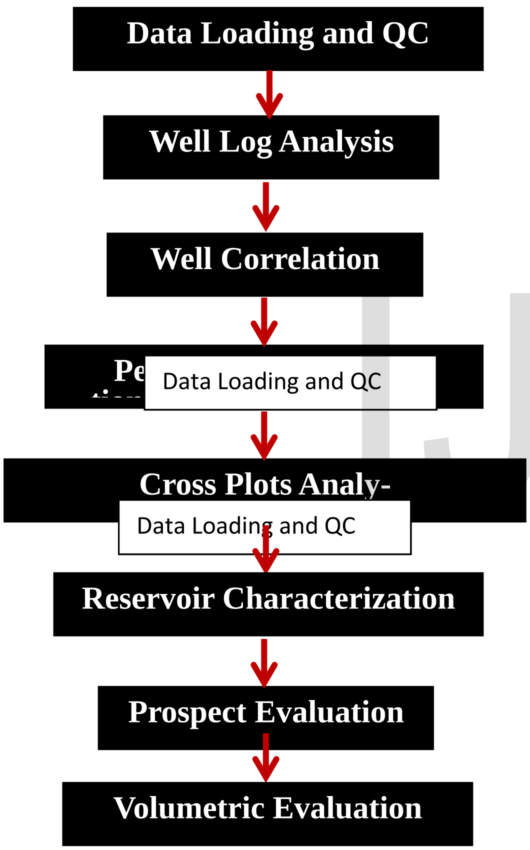

Figure 5: Workflow for the study

The data was loaded into software panel, which was the displayed in a function window for conditioning by displaying as a graph with depth on the vertical axis and two way travel time (TWT) on the horizontal axis to check for any spikes not related to geology. There was no spike (outlier), hence the checkshot was of good quality.

Correlation was done between the wells to identify specific reservoir formations encountered within the different wells; the well correlation identification was achieved with the aid of gamma ray log measurements. The gamma ray log reading for all the four (4) wells were plotted on a histogram in order to determine and establish sand/shale baselines and cutoff for clean sand, from the histogram, the sand baseline was placed at 0 gAPI while the shale baseline was placed at 150 gAPI. Four reservoirs were identified as the reservoirs of interest for this study, Reservoir A, B, C, and D based on gross thickness and presence of significant pay thickness and the top and base of the reservoirs were picked and correlated across the field. The oil water contact (OWC) was determined with the aid of the resistivity log based on the fact that oil is more resistive than brine, there was a sharp rise in resistivity indicates the presence of hydrocarbons in the reservoir in the resistivity logs. Meanwhile, neutron and density logs were used to ascertain the type of hydrocarbon presence in the reservoirs. Oil zones were majorly identified due to the effect of the cross over between neutron and density logs which showed a small separation. The petrophysical parameters for the reservoir zones in the different wells were calculated using the relevant equations. The following petrophysical parameters were estimated namely; fluid saturation (water and hydrocarbon saturation), shale volume, permeability, porosity (total and effective). The values were plotted in the log sections.

The stock tank oil originally-in-place (STOOIP) is determined using the 3-D grid created with the boundary conditions (polygon), the zones, segment, reservoir properties (Net-to-gross, water saturation, effective porosity) and the oil-water contact (OWC) information.

6 RESULTS AND DISCUSSION

The results obtained from the Petrophysical evaluation and Cross plots analysis are presented in the figures below

Petrophysical Evaluation: The results of the petrophysical evaluation for the identified reservoirs in the field are presented in Figure 6 and the evaluated properties results tabulated in Table 2.

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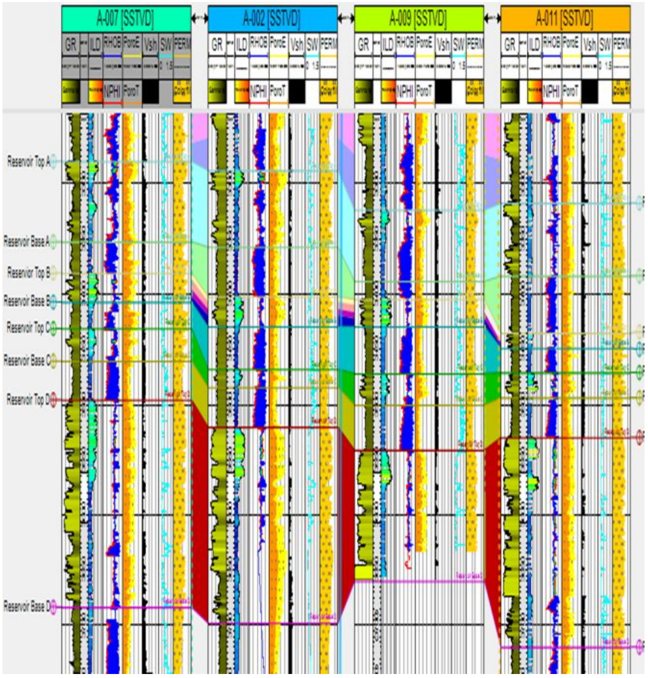

Fig. 6: The petrophysical logs derived from the availabl coventional well logs

6.1 Lithology and Fluid Discrimination

Cross plotting of some selected rock properties and rock attributes was carried out and the following results were obtained. Firstly, Vp/Vs ratio against Acoustic impedance distinguishes the A-011 reservoir into sand zone, shaly-sand zone, and shale zone (Figure 7). Secondly, lambda-rho (incompressibility) against Vp/Vs discriminates the reservoir of interest in sands and shale/sand/shale sequences (Figure 8). Next was the Mu rho against density. It observed that both mu rho and density are lithology discriminators, with density also being a fluid discriminator. Mu rho values are high for sand and low for shale. Conversely, the density of shale is higher than that of sand. Finally, cross plots of lambda-rho (λρ) against mu-rho (μρ) (Figure 9) shows separation into four zones that can be inferred to be probable shale, brine and gas zone confirmed by lowest density values.

6.2 DISCUSSION

The cross plot of Vp/Vs ratio against Acoustic impedance (Zp) (Figure 8), distinguishes the A-011 reservoir into three zones namely; hydrocarbon zone (red ellipse), brine zone (yellow ellipse) and shale zone (blue ellipse). This cross plot shows better fluid as well as lithology discrimination along the acoustic impedance axis, indicating that acoustic impedance attribute will better describe the A-011 reservoir conditions in terms of lithology and fluid content than Vp/Vs ratio. Figure 17(a) shows the variation of lambda-Rho (incompressibility) against Vp/Vs for sands and shale/sand/shale sequences.

The cross plots analysis shows the variation of lambda-rho (incompressibility) against Vp/Vs for sands and shale/sand/shale sequences. The plots are better aligned towards the lambda rho axis, thus making lambda rho a better lithology discrimination tool (Figure 7a). The black ellipse describes the shale zone, the yellow describes brine sand, and the red ellipse describes hydrocarbon sand. The cross plot of Vp/Vs ratio against Acoustic impedance (Zp) (Figure 7b), distinguishes the A-011 reservoirs into two zones namely; hydrocarbon sands (red ellipse), and shale zone (blue ellipse). This cross plot shows better fluid as well as lithology discrimination along the acoustic impedance axis, indicating that the acoustic impedance attribute will better describe the A-011 reservoir conditions in terms of lithology and fluid content than Vp/Vs ratio. In the cross plot of Mu-rho against density (Figure 7c), furthermore, brine is denser than hydrocarbon (oil and gas). Thus, the red ellipse in the Figure 7c indicates hydrocarbon bearing sand, the yellow ellipse shows the brine saturated sand region, while the black section describes the shale region. Cross plots of lambda-rho (λρ) against mu-rho (μρ) in Figure 7d, shows separation into four zones that can be inferred to be probable shale (black eclipse), brine (yellow eclipse), oil (red eclipse) and gas zone (blue eclipse) confirmed by lowest water saturation values. The cross plot indicates that Lambda-rho (λρ) is more robust than Mu-rho (μρ) in the analysis of fluids in the field of study and that μρ values are relatively low for the reservoir sand. The Acoustic impedance (Zp), Lambda-rho (λρ), Mu-rho (μρ), and Poisson impedance (PI) attributes were found to be most robust in lithology and fluid discrimination within the reservoir in the cross-plot analysis. The Lambda- Mu-Rho (λ-μ-ρ) technique was able to identify hydrocarbon sands, because of the separation in responses of both the λρ and μρ sections to hydrocarbon sands versus shale. Many different lithologies could also be identified by the cross plot of λρ versus μρ. This is possible because each lithology has a different rock properties response subject to fluid content and mineral properties. The cross plots for computed attributes to discriminate for lithology discrimination from Vp/Vs ratio against lambda-rho (λρ), acoustic impedance (Zp) against Vp/Vs ratio, Mu-rho (μρ) against density and mu-rho against lambda-rho (λρ) in Figure 8a-d, for well 11 depicts that in the reservoirs the lithologies are majorly sands and shale predominantly found in Niger Delta. The cross plots of Vp/Vs ratio against lambda-rho (λρ), Vp/Vs ratio against acoustic impedance (Zp), mu-rho (μρ) against density and mu-rho (μρ) against lambda-rho (λρ) (Figure 9a-d) depicts that in the reservoirs the fluid discriminates the blue eclipse as shale area, yellow eclipse as brine sands and red eclipse as oil.

Vp/Vs ratio against Lambda-rho

The cross plots of Vp/Vs ratio against Lambda-rho from petrophysical properties (gamma ray, water saturation and density) clearly show the distinct discrimination of probable hydrocarbon zones from the brine/shale zones within well A-011 (Figure 7a, 8a and 9a). From the cross plot, it was observed

Table 2: Petrophysical Evaluation of the Reservoir Units in the Four Wells in the Field

Wells	Reservoir sands	Top (m)	Base (m)	Gross thickness (m)	Shale volume (%)	Shale volume (m)	Net sand (m)	Net-to Gross (%)	Total Porosity (%)	Effective Porosity (%)	Water saturation (%)	Permeability (mD)	Hydrocarbon saturation (%)	Fluid type
Well-2	A	3289	3358	69	14%	9.66	59.34	86%	22%	20%	59%	1744.303	41%	Oil/water
	B	3402	3431	29	12%	3.48	25.52	88%	19%	17%	56%	1155.55	44%	Oil/water
	C	3469	3485	16	12%	1.92	14.08	88%	13%	11%	82%	691.9105	18%	Oil/Water
	D	3521	3698	177	13%	23.01	153.99	87%	20%	19%	78%	1636.715	22%	Oil/Water
Well-7	A	3280	3352	72	17%	12.24	59.76	83%	24%	22%	42%	1540.439	58%	Oil
	B	3381	3407	26	14%	3.64	22.36	86%	25%	21%	52%	1821.868	48%	Oil/Water
	C	3431	3460	29	13%	3.77	25.23	87%	28%	25%	41%	2019.133	59%	Oil
	D	3496	3684	188	14%	26.32	161.68	86%	26%	22%	82%	2214.002	18%	Oil/Water
Well-9	A	3325	3389	64	23%	14.72	49.28	77%	25%	23%	35%	2037.376	65%	Oil
	B	3404	3430	26	13%	3.38	22.62	87%	19%	17%	66%	1254.444	34%	Oil/Water
	C	3472	3501	29	14%	4.06	24.94	86%	15%	14%	56%	1001.586	28%	Oil/Water
	D	3542	3660	118	13%	15.34	102.66	87%	15%	14%	76%	995.2449	24%	Oil/Water
Well-11	A	3318	3384	66	30%	19.8	46.2	70%	19%	16%	78%	1313.773	22%	Oil/Water
	B	3435	3449	14	15%	2.1	11.9	85%	19%	16%	51%	991.2469	49%	Oil/Water
	C	3471	3494	23	14%	3.22	19.78	86%	29%	24%	44%	2276.725	56%	Oil
	D	3531	3720	189	16%	30.24	158.76	84%	19%	17%	81%	1434.346	19%	Oil/Water

that the hydrocarbon zones correspond to low Lambda-Rho and high Vp/Vs ratio while brine/shale zones correspond to high Lambda-rho and low Vp/Vs ratio.

Vp/Vs ratio against P-impedance
The cross plots of P-impedance against Vp/Vs ratio from petrophysical properties (gamma ray, water saturation and density) clearly show the distinct discrimination of probable hydrocarbon sand zones from the shale zones within well A-011 (Figure 7b, 8b and 9b). From the cross plot, it was observed that the hydrocarbon sand zones correspond to high P-impedance and low Vp/Vs ratio while shale zones correspond to low P-impedance and high Vp/Vs ratio.
Mu-rho against Density
The cross plots of Mu-rho against density from petrophysical properties (gamma ray, water saturation and density) clearly show the distinct discrimination of probable hydrocarbon sand zones from the shale zones within well A-011 (Figure 7c, 8c and 9c). From the cross plot, it was observed that the hydrocarbon sand zones correspond to high mu-rho and low density while shale zones correspond to low mu-rho and high density.
Mu-rho against Lambda-rho
The cross plots of Mu-rho against Lambda-rho from petrophysical properties (gamma ray, water saturation and density) clearly shows the distinct discrimination of probable hydrocarbon zones from the brine/shale zones within well A-011 (Figure 7d, 8d and 9d). From the cross plot, it was observed that the hydrocarbon zones correspond to high mu-rho and low lambda-rho while brine/shale zones correspond to low mu-rho and high lambda-rho.

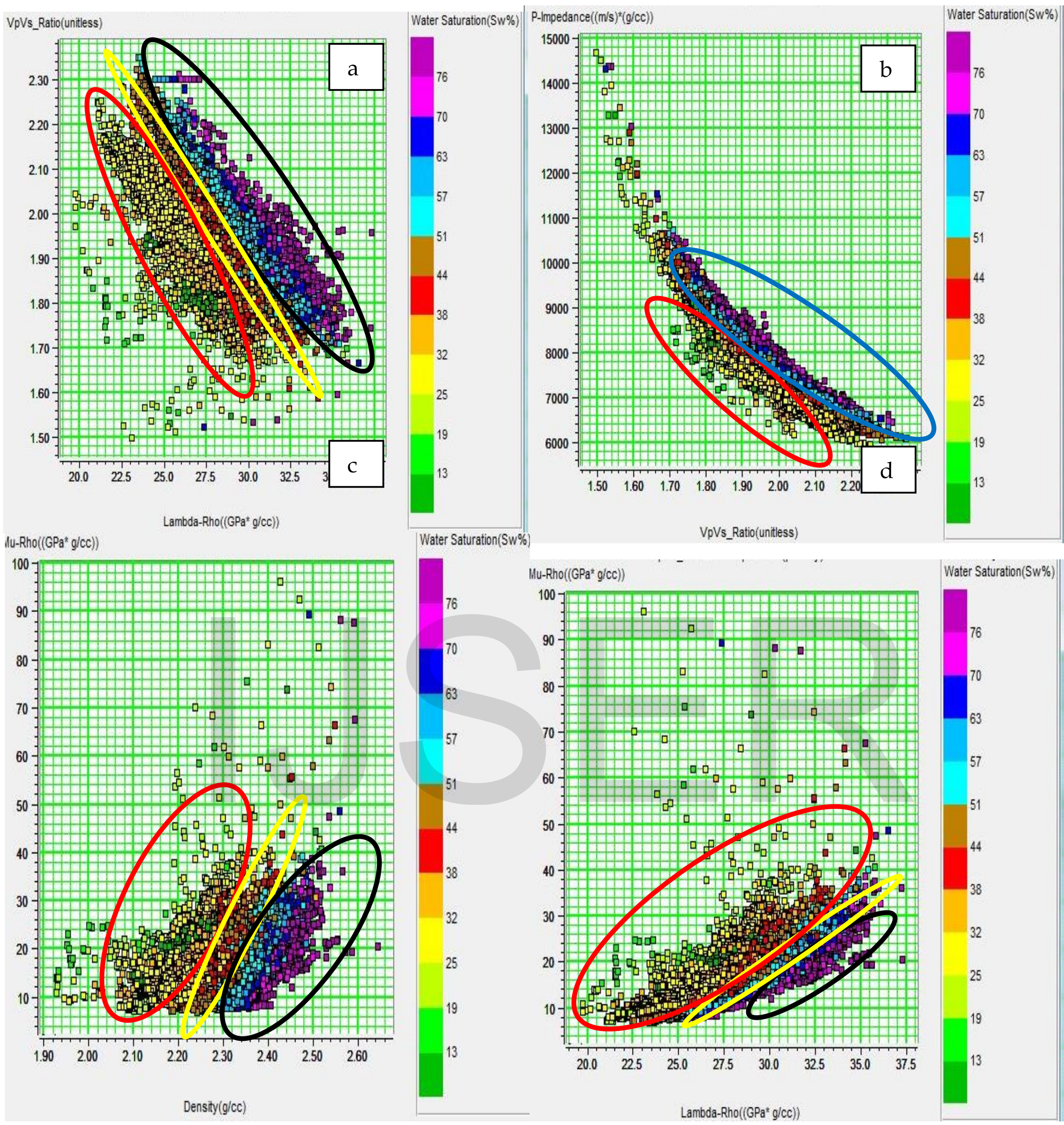

Figure 7: Cross plots for attributes computed to identify lithology and fluid discrimination using water saturation colour for Well 11.

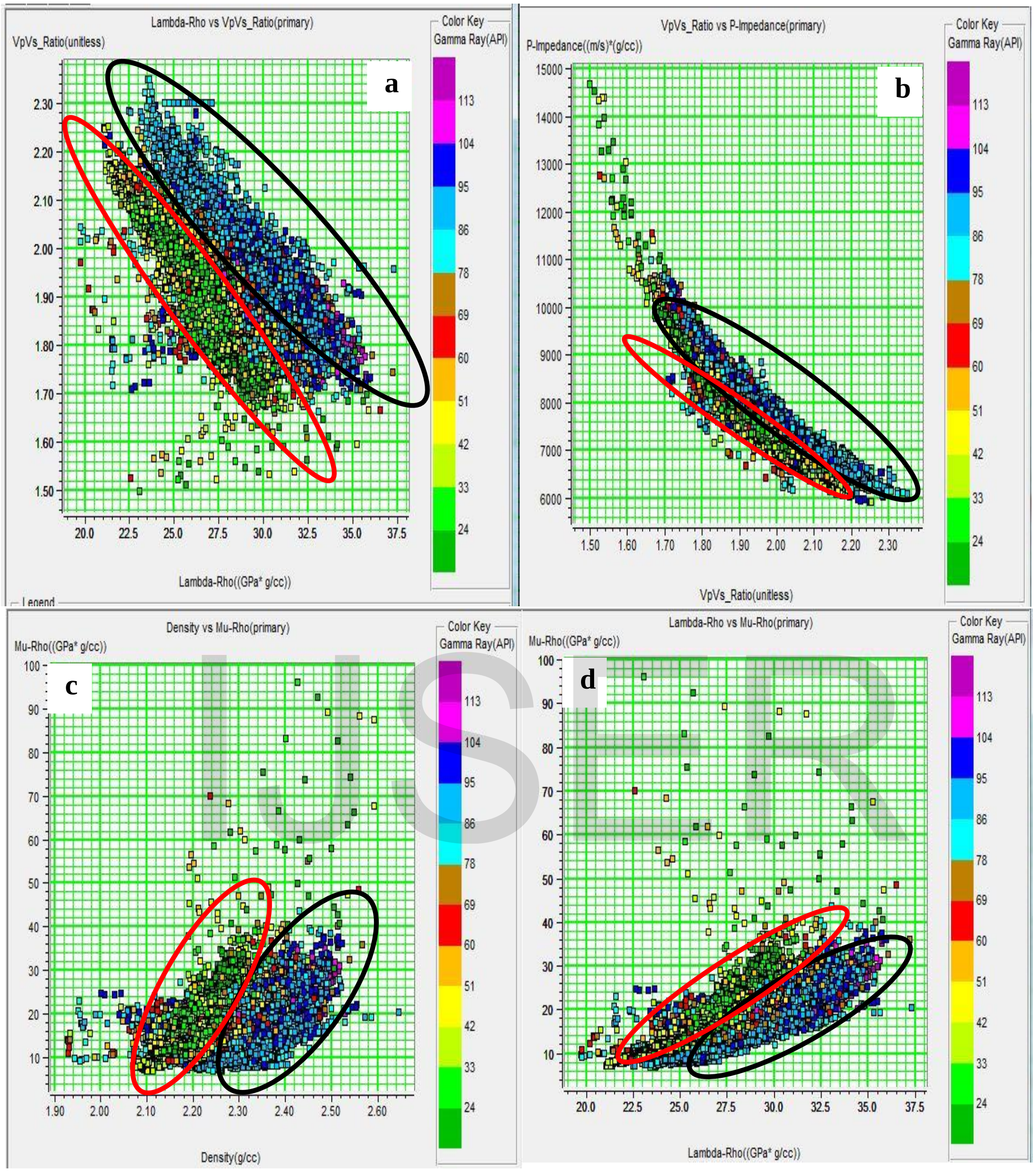

Figure 8: Cross plots for attributes computed to identify lithology discrimination using gamma ray colour key for Well 11.

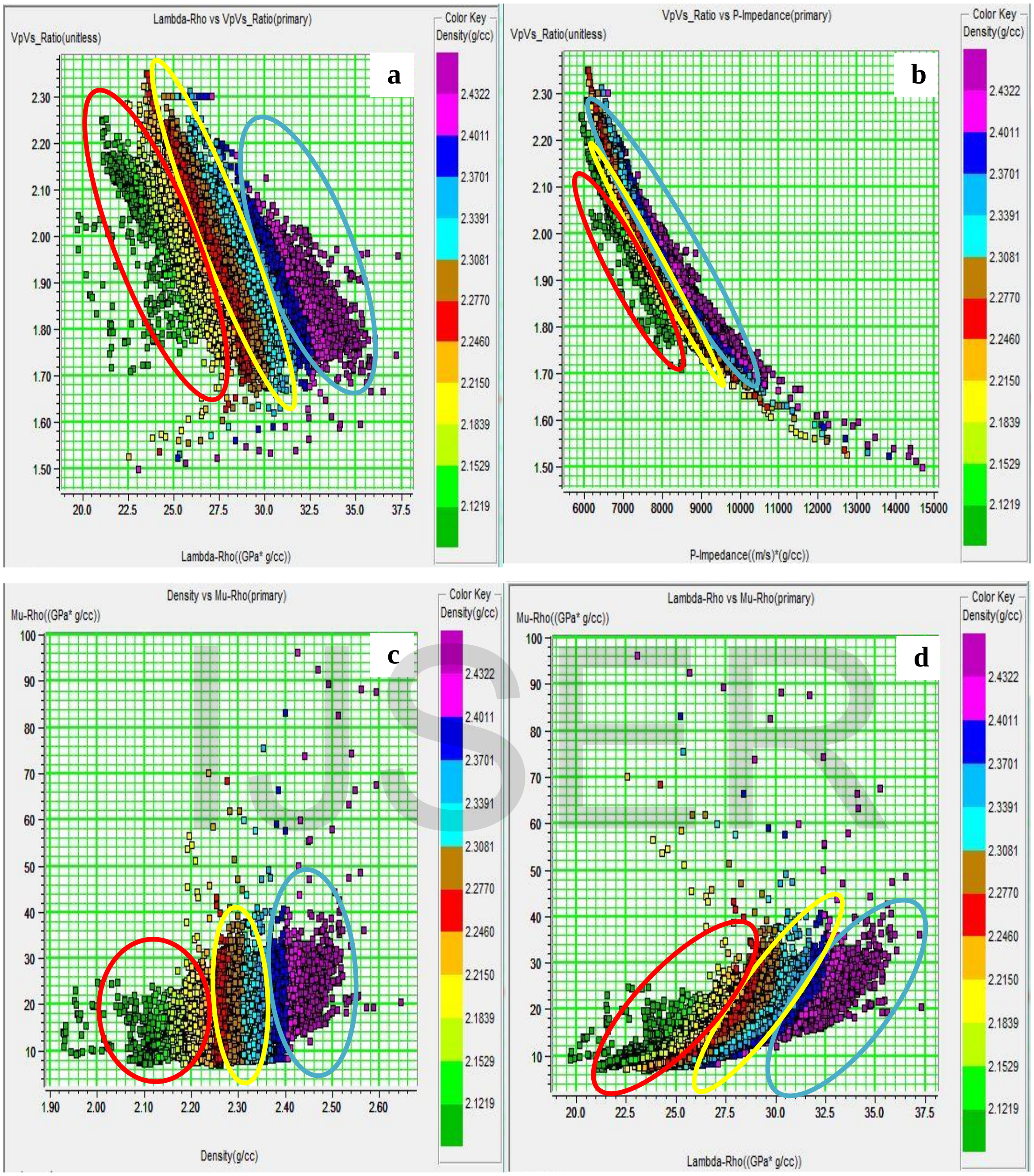

Figure 9: Cross plots for attributes computed to identify fluid and lithology discrimination using density colour key for Well 11.

4 Conclusion

The cross plots analysis indicate that Lambda-rho (λρ) is more robust than (Mu-rho) μρ in the analysis of fluids in the field of study, and that Mu-rho (μρ) values are relatively low for the reservoir sand. The Acoustic impedance (Zp), Lambda-rho (λρ), Mu-rho (μρ), and Poisson impedance (PI) attributes were found to be most robust in lithology and fluid discrimination within the reservoir in the cross-plot analysis. The Lambda – mu-rho (λ-μ-ρ) technique was able to identify gas sands, because of the separation in responses of both the λρ and μρ sections to gas sands versus shale. Many different lithologies could also be identified by the cross plot of λρ versus μρ. This is possible because each lithology has a different rock properties response subject to fluid content and mineral properties.

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