Sensitivity Log Analysis of Rock Properties for Fluid & Lithology Discrimination: A Case Study of Gugu Field in the Niger Delta

Valentine Uwechie, Julius Adesun,Andrew Avwunudiogba

Abstract— To mitigate uncertainties associated with conventional approaches in determining lithology and discriminating pore fluids using well logs, a quantitative rock physics analysis has been carried out and presented in this technical paper. Density, compressional wave velocity and shear wave velocity were used as inputs and applied in an integrated approach to identify and delineate hydrocarbon charged reservoirs in Gugu oil field, Niger Delta. Shear wave velocity was derived empirically using the Castagna's mud rock line relationship. Fluid replacement modeling was used to obtain correct shear wave velocity readings over hydrocarbon bearing zone of the target reservoir. A sensitivity log analysis by means of cross plotting of P-impedance & Vp/Vs Ratio, P-impedance & S-impedance, Lambda-Rho & Mu-Rho, Lambda-Rho & Vp/Vs were carried out to discriminate lithology, pore fluids or both. Cross-plot pairs responded in a unique fashion, showing visible separation and identifiable cluster trends. A cross-plot of P-impedance vs Vp/Vs, Lambda-Rho vs Mu-Rho, Lamb-da vs Vp/Vs gave a clear distinction between of both fluids and lithology discrimination. P-impedance vs S-impedance on the other hand discriminated hydrocarbon bearing sand but failed to delineate brine sand and shale zones. Consequently making it not suitable for lithologic discrimination.

Index Terms—biot-gassmann, castagna, compressional wave velocity, density, fluid replacement,impedance, modulus, niger delta, rock physics, shear wave velocity

INTRODUCTION

With the increase in demand of oil and gas, geoscientists have been compelled to come up with new ideas for exploring new reservoirs. Thus, it is pertinent to differentiate lithology and fluids within the newly discovered reservoirs. This study is part of an effort to support conventional approaches for fluid discrimination and lithology identification, and to ultimately reduce exploration risks.

Basically, Bulk modulus, (K), Shear modulus (μ), Young modulus (E) and Lambda (λ) attributes are used for discriminating lithology (sandstones versus shale) or fluids (gas, oil, brine). On the other hand, P-wave velocity (Vp), S-wave velocity (Vs), Density (ϱ) and its derivatives such as P-impedance (Ip), S-impedance (Is) etc., are prerequisites for the computation of all said attributes.

Over the last few years, pre-stack seismic simultaneous inversion has been adopted in estimating these pre-requisites. The products of the inversion includes, P-wave impedance, S-wave impedance etc. The estimation of density from seismic volume requires a long offset noise-free data, which is barely available. In a bid to bypass this stringent requirement of estimating density from seismic, we then compute it as its product with other attributes like λϱ, μϱ etc.

The cross plotting pair of these attributes has been generated and it's to be used for the lithology identification and fluid content discrimination. These cross plots are visual representations of the relationship between two or more variables and they are used to visually identify or detect anomalies which could be possibly interpreted as the presence of hydrocarbon or other fluids and lithologies. Cross plot analysis is carried out to determine the rock properties/attributes that better discriminate fluids in the reservoir [1].

Location and Geology of Study Area

Gugu field is located onshore of the Niger Delta. The Niger Delta is a prolific hydrocarbon province with a regressive succession of clastic sediments which reaches maximum thickness of 10-12km. The province contains only one identified petroleum system known as the Tertiary Niger Delta. The Delta is divided into an upper series of massive sands and gravels (Benin formation, deposited under continental conditions. This grades downward into interbedded shallow marine and fluvial sands, silts and clays, which forms the paralic sequence of the Agbada

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formation. The Agbada formation grades into the massive and monotonous marine shales (fig 1). Most of the hydrocarbons are in the sandstones of the Agbada formation, where they are trapped by rollover anticlinal structures, forming growth faults in channels and sandstones bodies [2].

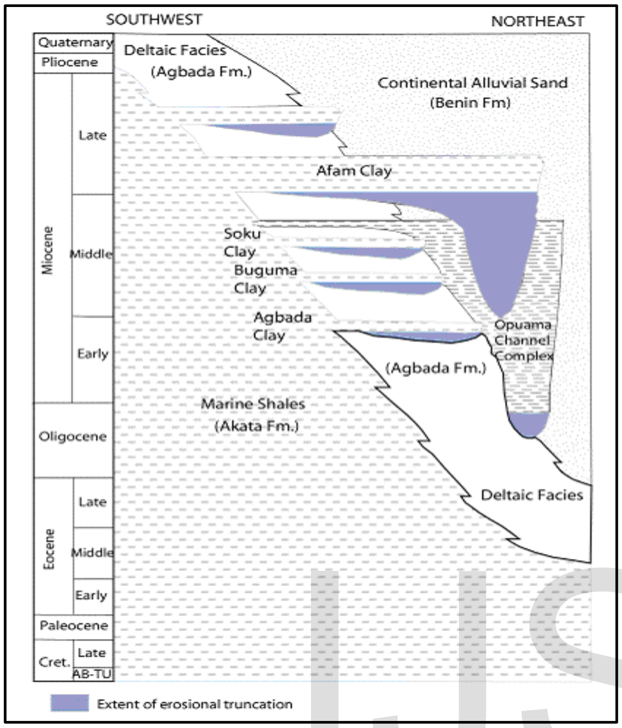

Figure 1: Stratigraphic column showing the three formations of the Niger Delta (Modified from Doust and Omatsola, 1990)

Basic Theoretical Background

Goodway[3], proposed a new approach to AVO inversion based on the Lame parameters λ-μ-ρ or Lambda-Mu-Rho (LMR). The theory is as follows;

$$Vp = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

$$Vs = \sqrt{\frac{\mu}{\rho}}$$

$$\text{Therefore; } I_s^2 = ((\rho V_s)^2) = \mu\rho$$

$$\text{And } I_p^2 = \left((\rho V_p)^2\right) = (\lambda + 2\mu)\rho$$

$$\text{So; } \lambda\rho = I_p^2 - 2I_s^2$$

where;

Vp = P-wave velocity

Vs = S-wave velocity

Ip = P-Impedance

Is = S-Impedance

The original paper by Goodway et al, gives the following physical interpretation of the lambda (λ) and mu (μ) attributes. The λ term or incompressibility, is sensitive to pore fluid, whereas the μ term or rigidity, is sensitive to rock matrix.

MATERIALS AND METHOD

Data used for this study comprises of a suite of well logs containing SP, resistivity, sonic, density and porosity logs covering the target reservoir of interest (Figure 2).The study was carried out using HampsonRussell's integrated suite of geophysical interpretation tools for reservoir characterization.. The depth of investigation ranges from 2286.45m – 2344.40m TVDss, representing the top and base limit of the reservoir of interest (reservoir A). The reservoir "A " was identified on the basis of its relatively low SP values, which is indicative of a sandstone unit. Hydrocarbon water contact was established at 2297.4m TVDss, using the induction deep resistivity log.

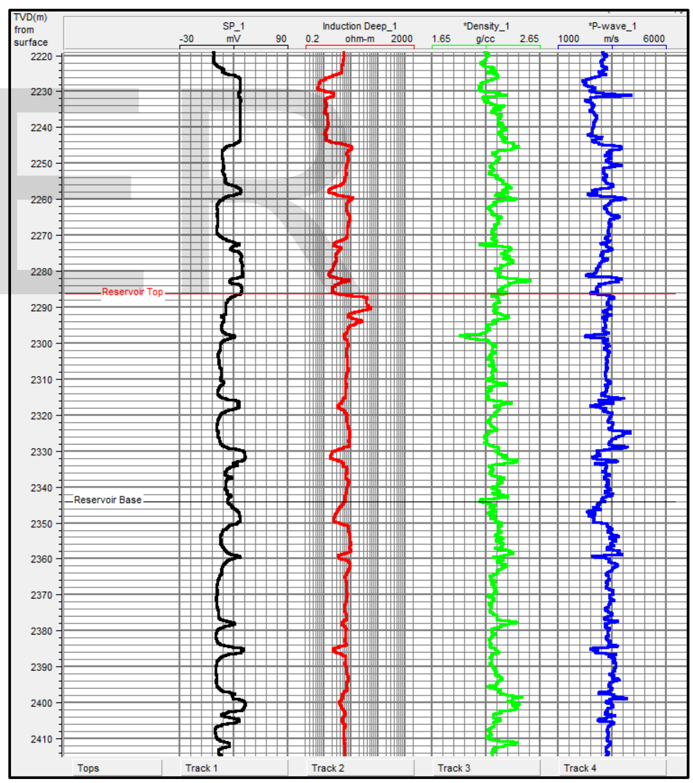

Figure 2: Wireline logs used for the study

S-wave velocity, Vs which was unavailable was derived using the empirical linear relationship with P-wave velocity, Vp by Castagna's mud rock line equation. (Figure 3)

$$Vp = 1.16Vs + 1360ms^{-1}$$

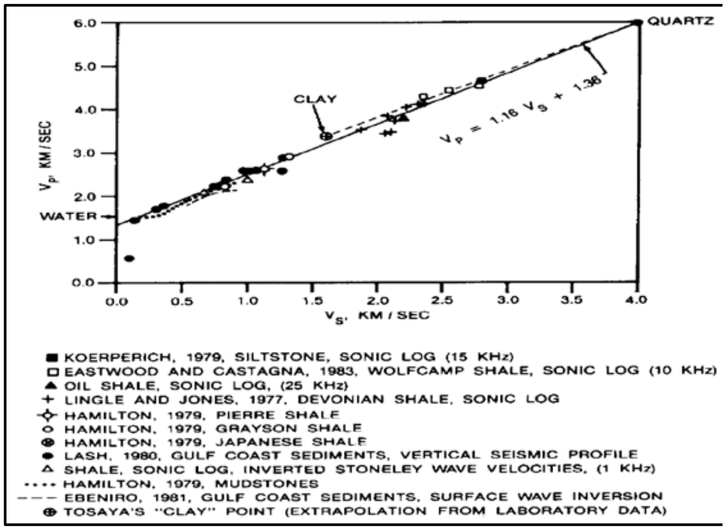

Figure 3: Castagna's Mudrock line (Castagna et al, 1985)

The derived shear velocity, Vs using the Castagna's equation is limited to brine saturated rocks [4]. Owing to this limitation, a Fluid Replacement Model, FRM was done using Biot-Gassmann's equation implemented in the HampsonRussell's AVO module software. P-wave velocity, Density and PVT parameters for the reservoir were served as inputs to generate a Fluid Replacement Model of two fluid phase composition (brine+gas), with the assumption of 50% water saturation at the target zone. New elastic and density logs were generated after the Fluid Replacement Modeling.

It is worth mentioning that the use of Castagna's equation first to create an S-wave velocity, Vs log is accurate everywhere except the target zone, where it assumes for it to be saturated with brine. Biot-Gassmann's equation, gives a corrected S-wave velocity, Vs values within the target zone.

Subsequently, P-wave impedance, S-wave Impedance, Incompressibility modulus, λϱ and rigidity modulus, μϱ were transformed from existing P-wave velocity, S-wave velocity, and density logs. Cross plots were then generated to aid in the litho-fluid discrimination using the well log data.

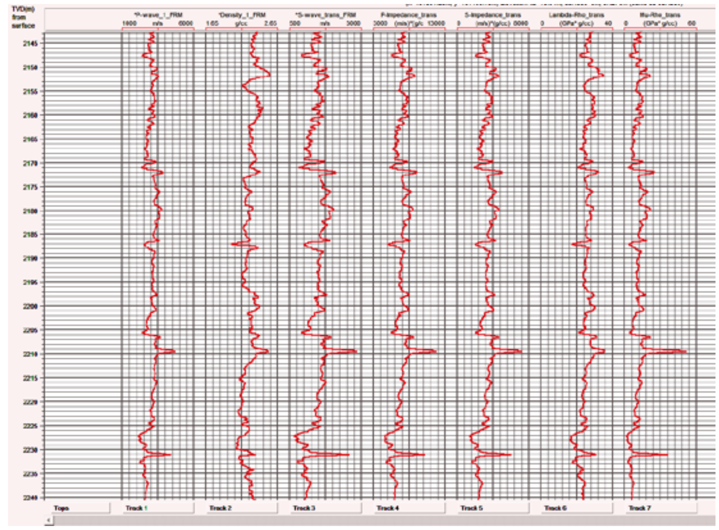

Figure 4: Biot-Gassmann's corrected density, p-wave, s-wave and their derivatives

RESULTS AND DISCUSSION

The rock physics relations of λ-μ-ϱ, Poisson's ratio, P-impedance and S-Impedance were most effective in discriminating hydrocarbon bearing sands. Their cross plots generated clusters of points that are well separated from the mainstream scatter plot. The sensitivity log analysis of these rock physics properties includes cross plots of;

1. P-Impedance vs Vp/Vs Ratio
2. P-Impedance vs S-Impedance
3. Lambda-Rho vs Mu-Rho
4. Lambda-Rho vs Vp/Vs

Property attributes of SP, density, porosity and resistivity were plotted on the z-axis for each cross plots. Asides the notable separation observed in discriminating the hydrocarbon bearing sand from neighboring brine sand and shale, these properties highlighted trends and reaffirmed the occurrence of hydrocarbon bearing sands (black ellipse), brine sand (blue ellipse) and shale (red ellipse) with their diagnostic fluid and lithology discriminating potentials. Consequently, this gave more credence to our interpretation.

P-IMPEDANCE vs VP/VS CROSSPLOT ANALYSIS

The cross plot clearly distinguishes the hydrocarbon bearing zone from brine sand and shale zones. This zone is associated with low P-impedance and low Vp/Vs ratio as seen in (Figure 5-8). Introducing SP on the z-axis aids in highlighting the shale zone, which is further supported with high density and low porosity values when the z-axis is interchanged with density and porosity attributes

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respectively (Figure 5, 6 & 7). A plot of resistivity on the z-axis further validated the presence of hydrocarbon with the HC zone. This was characterized by high resistivity value clusters within this zone as seen in Figure 8

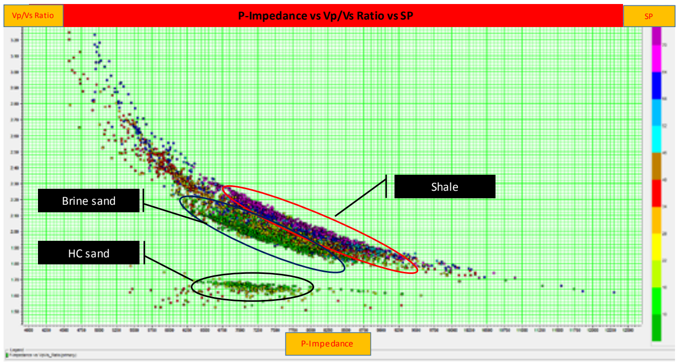

Figure 5: CROSSPLOT OF P-IMPEDANCE vs VP/VS vs SP

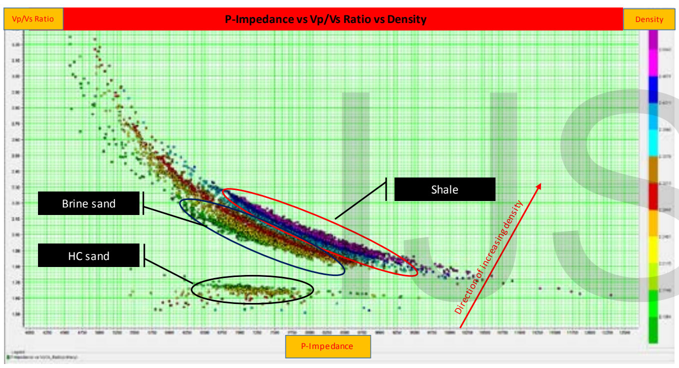

Figure 6: CROSSPLOT OF P-IMPEDANCE vs VP/VS vs DENSITY

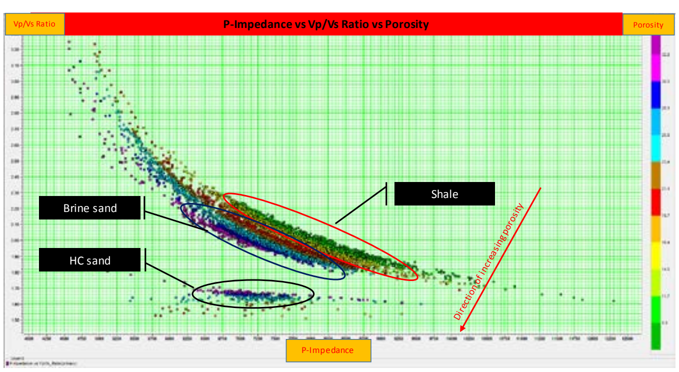

Figure 7: CROSSPLOT OF P-IMPEDANCE vs VP/VS vs POROSITY

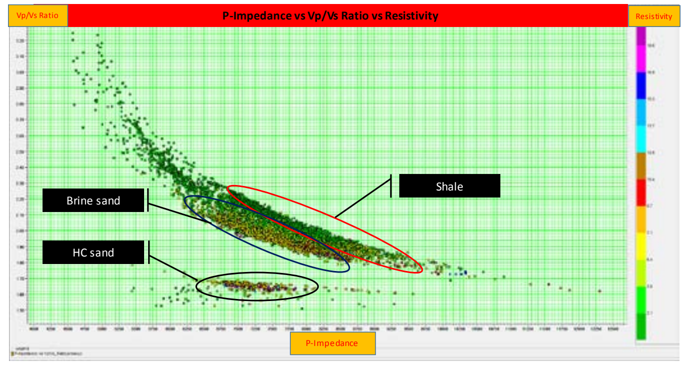

Figure 8: CROSSPLOT OF P-IMPEDANCE vs VP/VS vs RESISTIVITY

P-IMPEDANCE vs S-IMPEDANCE CROSSPLOT ANALYSIS

The cross plot shows a good discrimination between hydrocarbon bearing sand and the shale. However, the brine sand and shale is difficult to delineate, as overlapping values of brine sand and shale is observed. SP attribute on the z-axis struggles to narrow out a borderline between brine sand and shale as seen in fig 9. The boundary between the brine sand and shale were seen with a marked increasing density from north to south direction, peaking towards the shale and a decline in porosity from south to north, having lowest porosity values with the HC sand zone (Figure 10 & 11). This zone is also associated with high resistivity value clusters, being indicative of the presence of hydrocarbon (Figure 12).

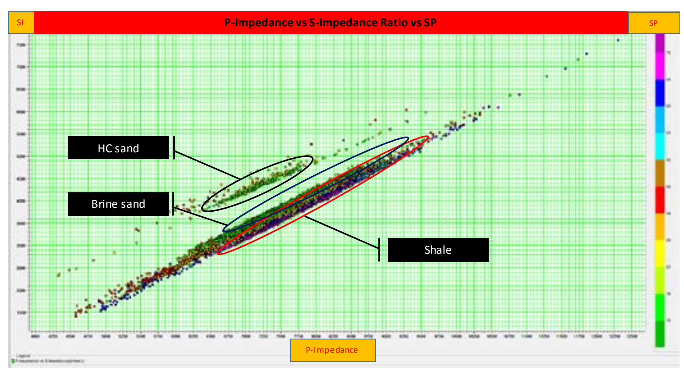

Figure 9: CROSSPLOT OF P-IMPEDANCE vs S-IMPEDANCE VS SP

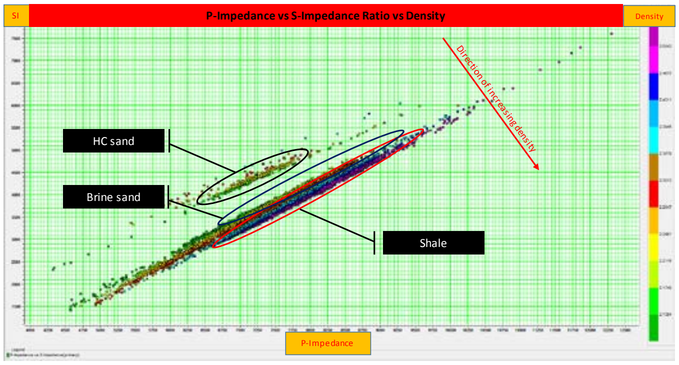

Figure 10: CROSSPLOT OF P-IMPEDANCE vs S-IMPEDANCE vs DENSITY

LAMBDA vs MU-RHO CROSSPLOT ANALYSIS

A cross plot of lambda-Rho (incompressibility modulus) and Mu-Rho (rigidity modulus) gave a very good discrimination for fluid and lithology. SP, density and porosity attributes plotted on the z-axis showed defining trends which helped in establishing boundaries between the brine sand zone and shale zone (Figure 13, 14 & 15). Density increasing from west to east, peaking at the shale zone (Figure 14) while porosity increasing from east to west, peaking at the HC sand (fig 15). High resistivity value cluster is visibly noticed within the HC sand zone (fig 16).

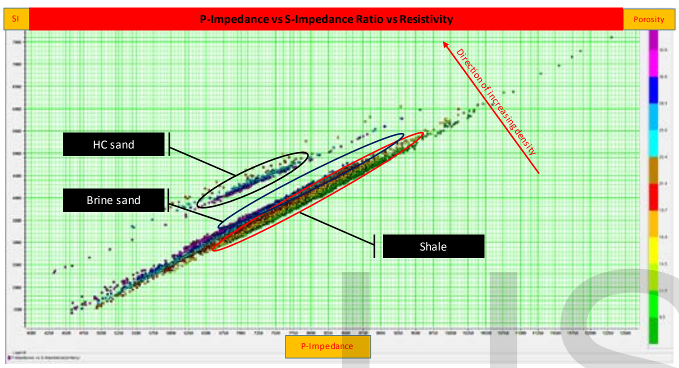

Figure 11: CROSSPLOT OF P-IMPEDANCE vs S-IMPEDANCE vs POROSITY

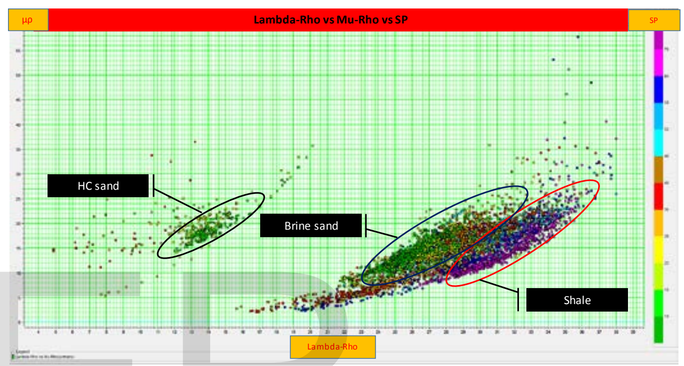

Figure 13: CROSSPLOT OF LAMBDA vs MU-RHO vs SP

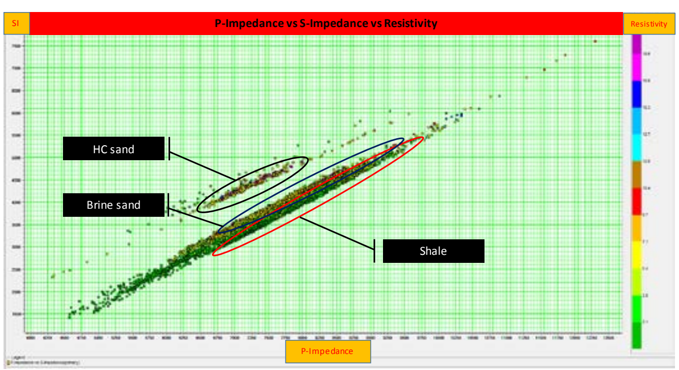

Figure 12: CROSSPLOT OF P-IMPEDANCE vs S-IMPEDANCE vs RESISTIVITY

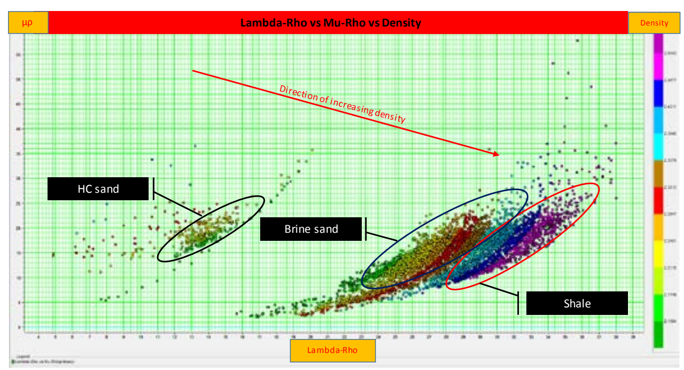

Figure 14: CROSSPLOT OF LAMBDA vs MU-RHO vs DENSITY

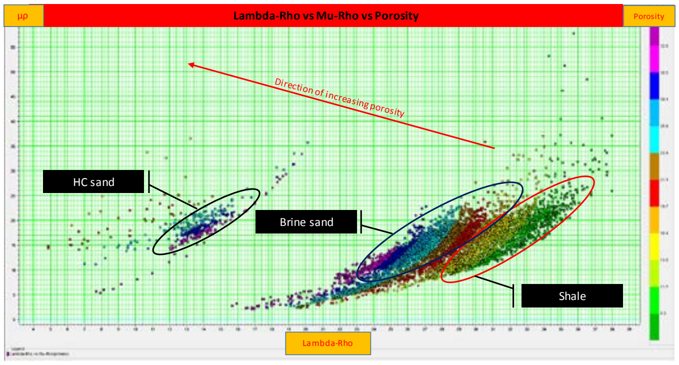

Figure 15: CROSSPLOT OF LAMBDA vs MU-RHO vs POROSITY

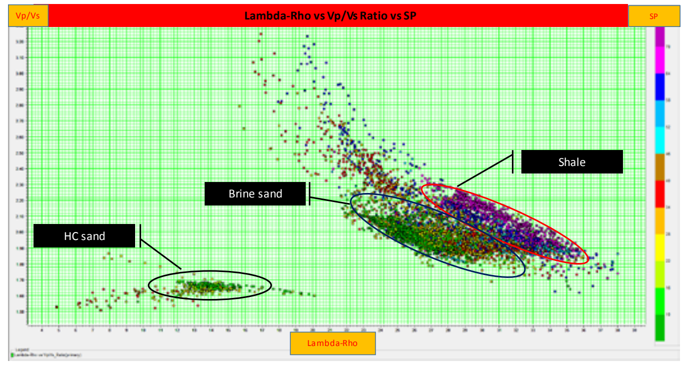

Figure 17: CROSSPLOT OF LAMBDA-RHO vs VP/VS RATIO vs SP

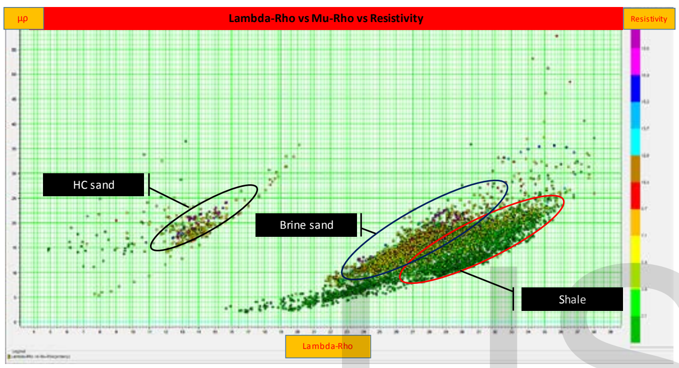

Figure 16: CROSSPLOT OF LAMBDA vs MU-RHO vs RESISTIVITY

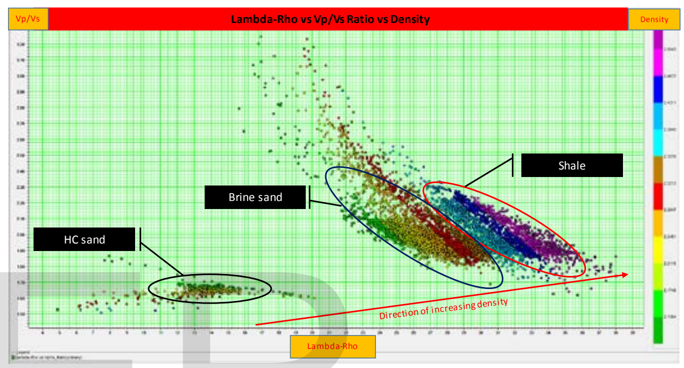

Figure 18: CROSSPLOT OF LAMBDA-RHO vs VP/VS RATIO vs DENSITY

LAMBDA-RHO vs VP/VS RATIO CROSSPLOT ANALYSIS

Hydrocarbon sand zone is marked by with a decrease in both Vp/Vs ratio and Lambda-Rho. This cross plot discriminates for both fluid and lithology. The Hydrocarbon sand zone shows good reservoir quality, showing high porosity values in the ranges of 0.23 – 0.33 (Figure 19) and the presence of hydrocarbon marked by high resistivity value clusters (Figure 20). The shale zone is clearly highlighted using SP attribute on the z-axis (Figure 17) and characterized with decrease porosity (Figure 19) and increased density (Figure 18).

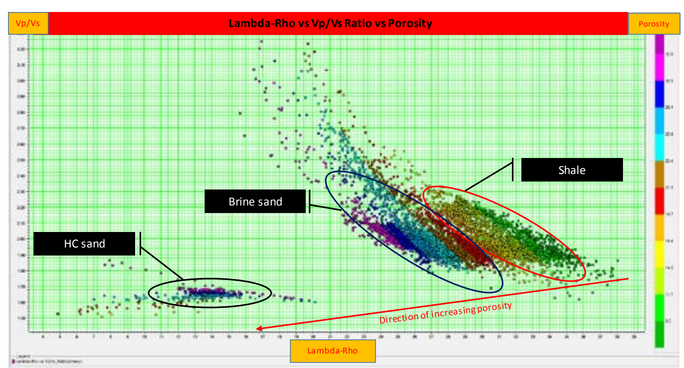

Figure 19: CROSSPLOT OF LAMBDA-RHO vs VP/VS RATIO vs POROSITY

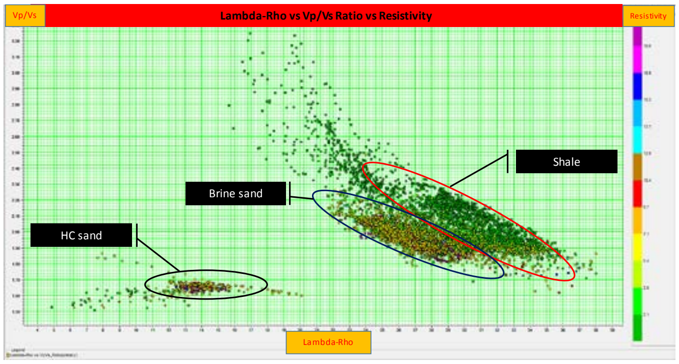

Figure 20: CROSSPLOT OF LAMBDA-RHO vs VP/VS RATIO vs RESISTIVITY

CONCLUSION

The Lambda-Mu-Rho (λ-µ-ϱ), Vp/Vs ratio, P-wave impedance and S-wave impedance analysis reveals that for the reservoir under investigation, the technique is quite sensitive to fluid and lithology discrimination. The cross plot of P-wave impedance vs Vp/Vs and Lambda-Rho vs Mu-Rho, gave a better sensitive response to discriminate for both fluid and lithology compared to a cross plot of P-wave impedance vs S-wave impedance which showed overlapping brine sand zones and shale zones, making it not so suitable for lithology discrimination.

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