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# FLUID REPLACEMENT MODELLING ANALYSIS FOR C4 RESERVOIR CHARACTERISATION ONSHORE NIGER DELTA BASIN

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## ABSTRACT

*This study applied Gassman's fluid substitution theory to model the sensitivity of several saturations of gas and oil in the C4 reservoir using well log data, to determine the applicability of rock physics analysis to evaluate the reservoir in the undrilled area of the field. Results of fluid substitution modeling for gas revealed that P-wave velocity decreased significantly at 5% gas saturation. Upon further increments in the gas saturation, the P-wave velocity remained relatively constant, revealing the difficulty in differentiating between economical and sub- economical gas saturation on seismic. Oil substitution showed that as the saturation of oil introduced into the reservoir increases, the P-wave velocity and density decreases accordingly. The 80% oil saturation model appeared to be greater than the insitu P-wave and density. Hence it can be concluded that the insitu oil saturation may be greater than 80% oil. In both fluid substitution scenarios, the S-wave models remained constant irrespective of the fluid saturation. Cross plot of Vp/Vs ratio against P-impedance and Mu-rho against Lambda-rho technique were done to validate the modeling results. The techniques discriminated both the lithology types and fluid contrast in the reservoir. Hence, it can be applied in the evaluation and characterization of the C4 reservoir in the undrilled area of the field from inversion results.*

**Key Words:** Forward-Modelling, Fluid-Substitution, P-wave, S-wave, Fluid-Saturation, Rock Properties, Petrophysical Evaluation.

## INTRODUCTION

Fluid substitution modeling is an important part of seismic attribute studies because it provides the interpreter with a valuable tool for modeling the seismic responses for various fluid scenarios (Smith *et al.*, 2003). The modeling process on reservoir sands is done using Gassmann's equations (Batzle and Wang 1992). The application of these equations is done in two stages whereby we first determine the bulk modulus of the porous rock frame and brine, after which we calculate the bulk modulus of the rock saturated with any fluid of our choice (Smith *et al.*, 2003).

Sensitivity of the basic rock properties (P-wave velocity, S-wave velocity and Density) to variation in fluid types and saturation hints us of the applicability of quantitative interpretation techniques especially inversion and rock physics analysis of derived rock attribute for lithology and fluid discrimination. Sensitivity of these basic rock properties ultimately result to variation of their derived rock attributes such as Vp/Vs ratio, Lambda-rho, Mu-rho, and P-wave impedance to changes in lithology and fluid types and saturations suggested by Pickett (1963) and Goodway *et al.*, (1997), to be effective for lithology and pore fluid discrimination form both well data and seismic inversion results.

The technique has been adopted successfully for shear wave estimation and field evaluation across the word (Assefa *et al.*, 2003; Paul and Marianne, 2006; Veeken, 2007;Chopra and Castagna, 2014; Toshev, 2017), but just few have been recorded of the Niger Delta Basin (Ekwe et al., 2012; Uko and Emudianughe, 2014; Ohaegbuchu and Igboekwe, 2016; Adeoti, *et al.*, 2018 ; Ogbamikhumi *et al.*, 2018 ).

## Location and Geology of the Study Area

The study field is located in the Central swamp Depo-belt of the Niger Delta basin (Figure 1). The Basin is situated on the continental margin of the Gulf of Guinea in equatorial West Africa between latitude 3°N and 6°N and longitude 5°E and 8°E (Reijers, 2011).

The basin is complex and it is structurally divided into five Depo-belts (Figure 1) in the order of increasing complexity from the Northern to the shallow marine Depo-belts. Majority of the traps found in the Basin are structural in nature (Doust and Omatsola, 1990). The structural traps were formed during syn-sedimentary deformation of the Agbada paralic sequence (Evamy et al., 1978). These syn-sedimentary structures known as growth faults are usually associated with rollover anticlines, shale ridges and shale diapirs. Most of the faults are listric normal faults, while others include: structure building growth faults, crestal faults, flank faults, counter regional faults and antithetic faults.

Sediment Deposition in the basin has been divided into three large-scale litho-stratigraphic units; Basal pro-delta shale facies of the Akata Formation, paralic facies of the Agbada Formation and fluvial facies of the Benin Formation (Stacher, 1995). The depo-belts of the Niger Delta basin constitutes one of the major regressive deltas in the world with an area coverage of about 300,000 km$^2$, a sediment volume of about 500,000 km$^3$ and a maximum sediment thickness of over 10 km in the basin (Owoyemi and Willis, 2006).

The basin is a prolific oil and gas basin where hydrocarbon production has been on from the hydrocarbon bearing intercalated Agbada sands for several years, and the objective reservoir in this study is one of such sands of the Agbada Formation.

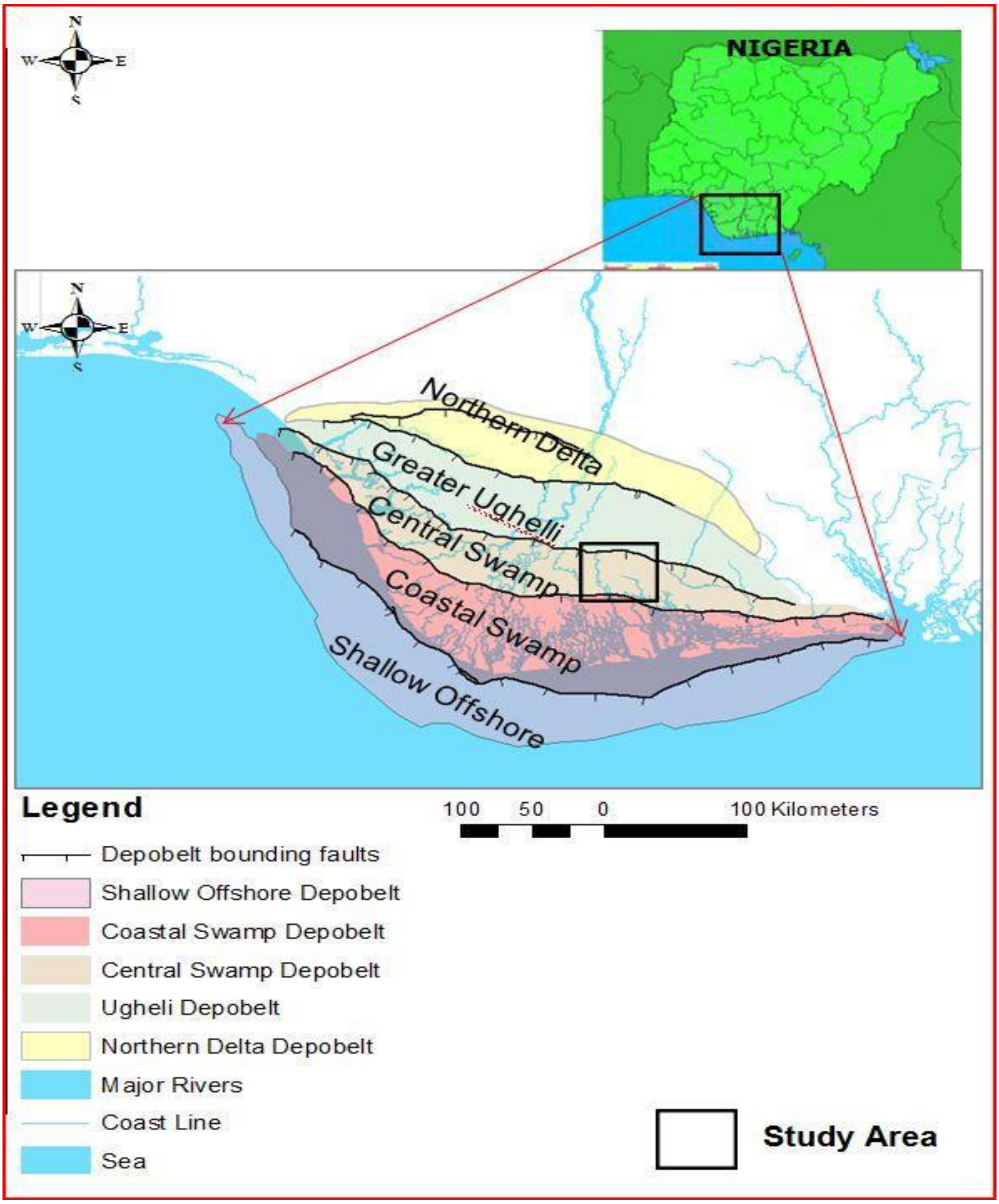

**Figure 1**: Showing the location of the study area within the Niger Delta depo belt from Doust and Omatsola (1990).

## MATERIALS AND METHOD

This study was done using well log data; Gamma ray log, Resistivity Log, Density log and P-wave velocity log (Figure 2) and the Hampson Russel subsurface software. Since Shear wave log were not available in the field, Greenberg and Castagna (1992), relationship was employed for its estimation. Petrophysical evaluation was done to estimate water saturation and porosity from the available well logs, after which derived rock physics attributes were generated for cross plot analysis (Figure 3). The fluid substitution forward modeling process was achieved using the Batzle and Wang (1992), empirical formulas and Gassmann (1951), fluid substitution theory.

The substitution process was achieved by 'Backing out' the insitu fluid in the reservoir and modeling a fluid saturation of 100% brine. After which modeling was done for four saturations of both gas and oil in the reservoir (5%, 20%, 50% and 80%), to test the sensitivity of the three basic rock properties presented by Dewar (2001); P-wave velocity, S-wave velocity and Density to changes in fluid types and saturations. Results of the modeling process was validated using the Vp/Vs ratio against P-impedance and Mu-rho against Lambda-rho cross plot techniques.

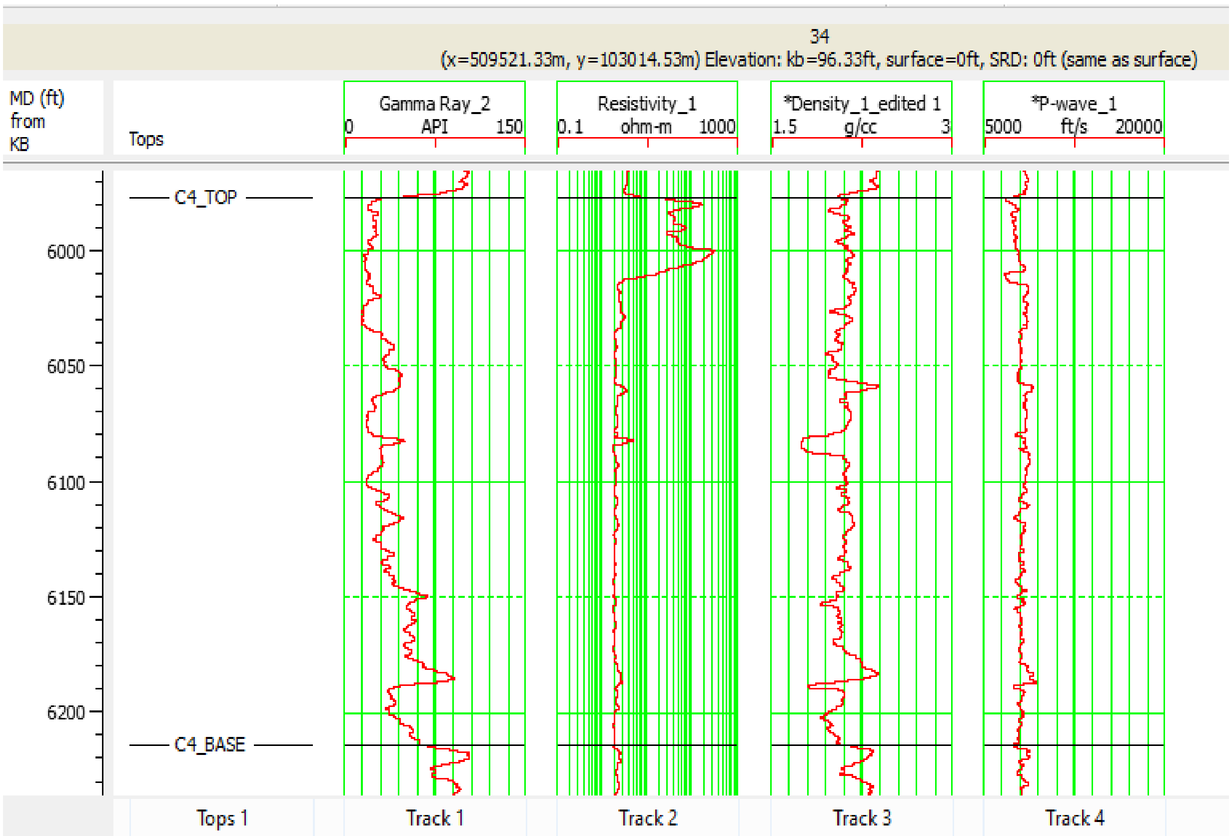

**Figure 2:** Raw well logs with the C4 Reservoir top and base defined

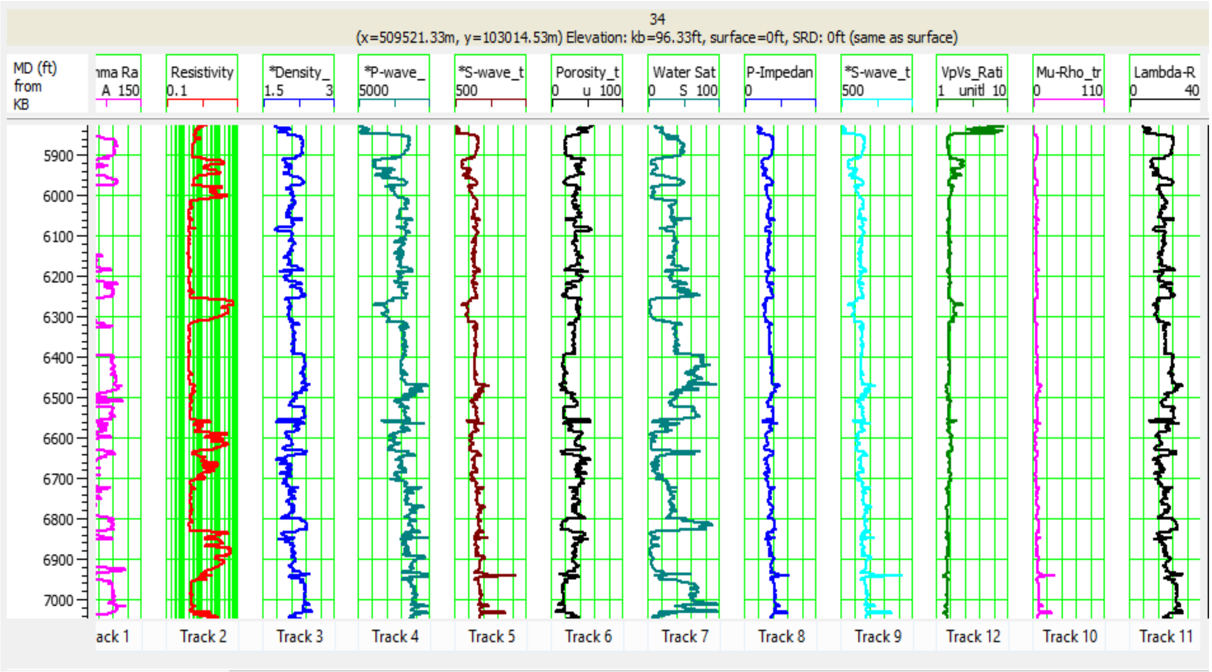

**Figure 3:** Display of Raw well logs, estimated shear wave log, derived logs and petrophysical logs.

## RESULTS

### Fluid Substitution Modelling Results

Fluid substitution modeling performed on the C4 reservoir is vital to proceed with its characterization in the undrilled area of the studied field on seismic since the observed amplitude on seismic data is as a result of contrast or variation in rock properties at the boundary between two geological or geophysical interfaces. i.e changes in lithology or fluid in the subsurface (Brown, 1987).

The Fluid substitution modeling in this study was done to test both gas and oil scenarios at various saturations of 5%, 20%, 50% and 80% after 100% brine saturation was initially determined. The results of gas substitutions are presented in figures 4-6. In each of these figures, three tracks are displayed that shows the hydrocarbon bearing interval of the C4 reservoir. In tract 1 is the gamma ray log that defined the top of the sand. In tract 2 is the resistivity log that indicated hydrocarbon presence and the hydrocarbon water contact. Tract 3 houses the five models and the insitu log (Figure 4). From the base of this tract are; the brine saturated model (yellow curve), 5% model (blue curve), 20% model (Orange curve), 50% model (Purple curve), 80% model (Green curve) and the insitu reservoir curve (Black curve).

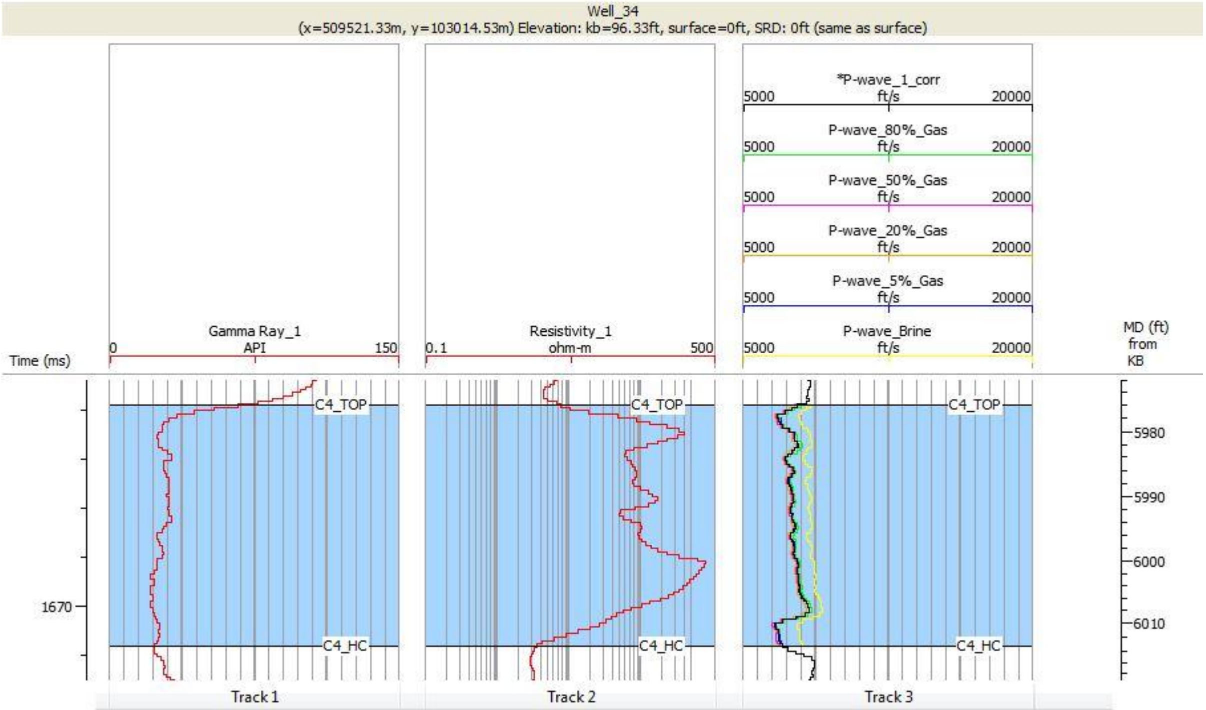

**Figure 4:** Fluid substitution models for gas in C4 reservoir at 5%, 20%, 50% and 80% gas saturations with the insitu and brine filled response on P-wave Velocity.

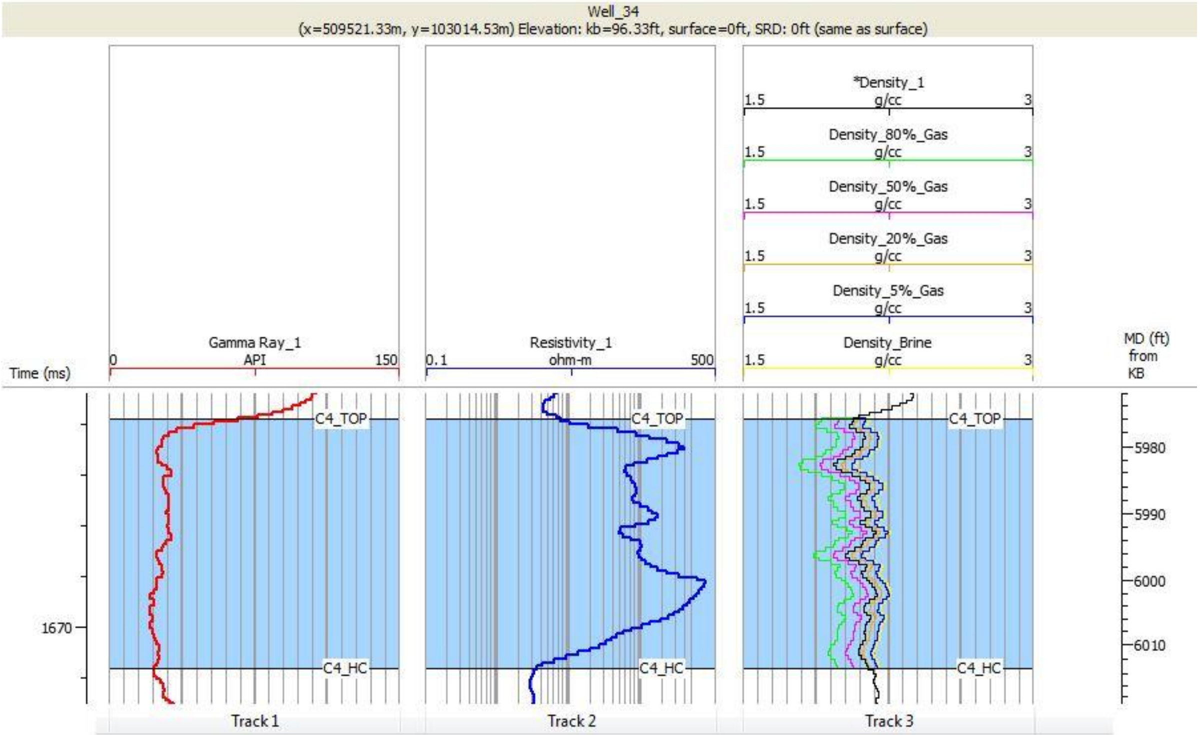

**Figure 5:** Fluid substitution models for gas in C4 reservoir at 5%, 20%, 50% and 80% gas saturations with the insitu and brine filled response on density.

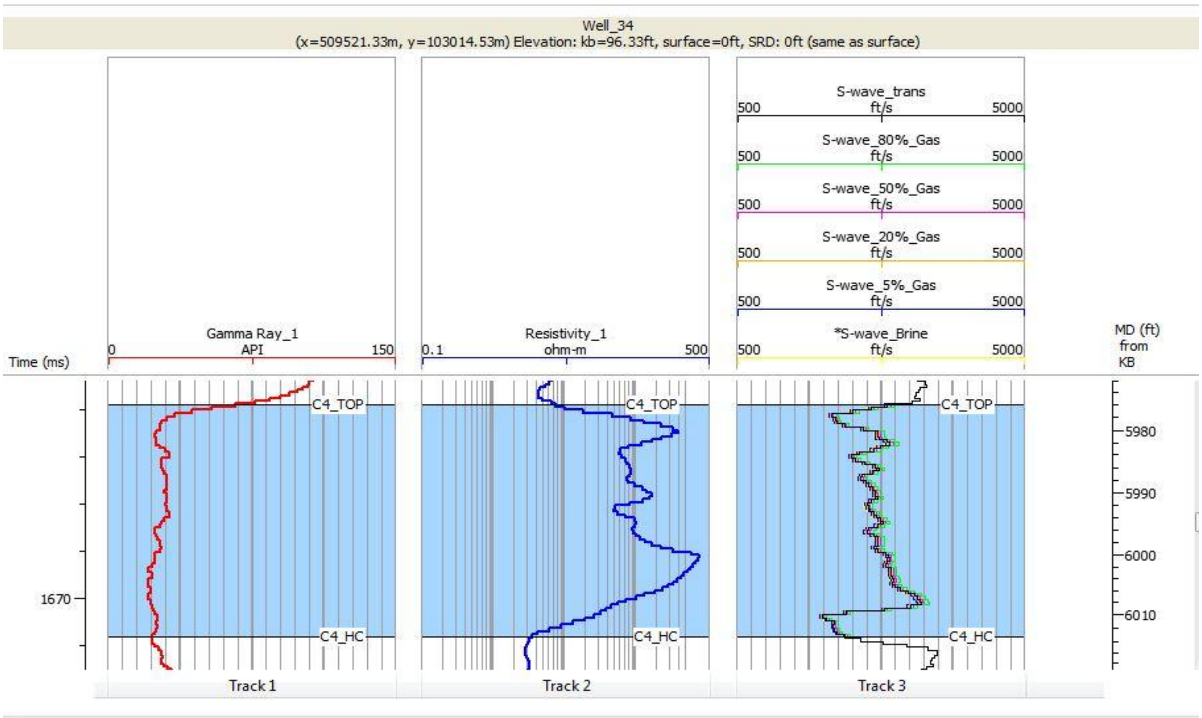

**Figure 6:** Fluid substitution models for gas in C4 reservoir at 5%, 20%, 50% and 80% gas saturations with the insitu and brine filled response on S-wave Velocity.

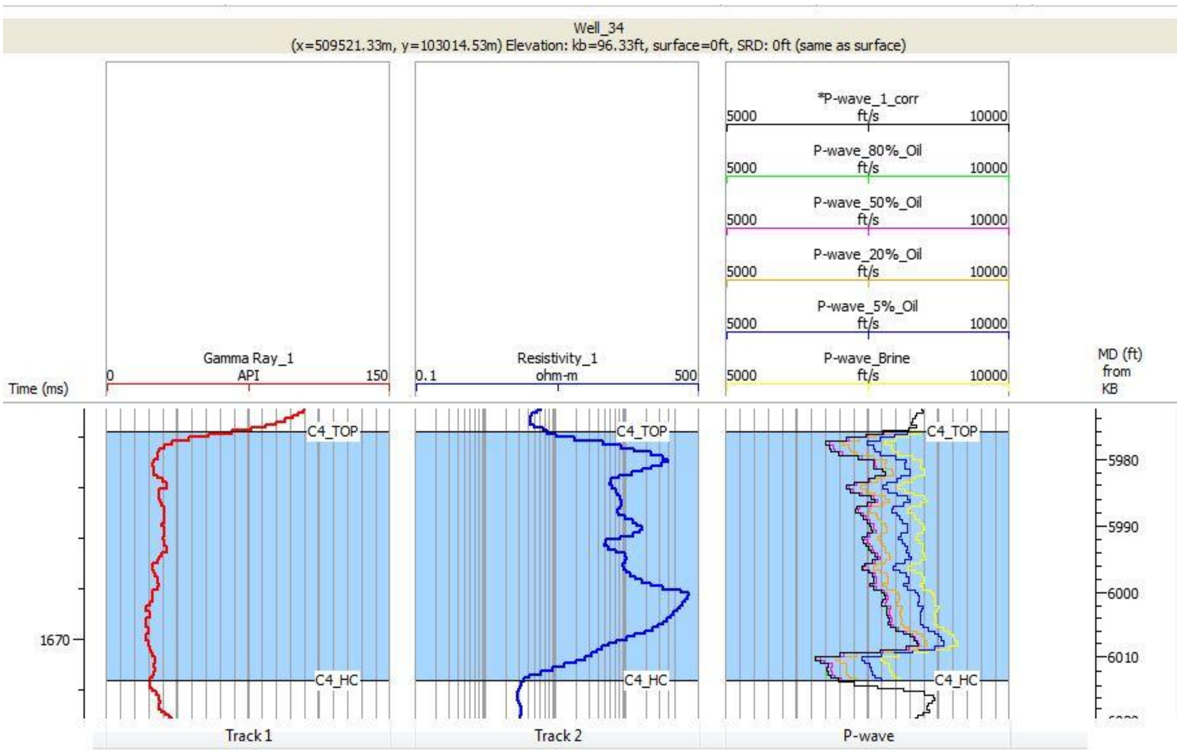

**Figure 7:** Fluid substitution models for oil in C4 reservoir at 5%, 20%, 50% and 80% oil saturations with the insitu and brine filled response on P-wave Velocity.

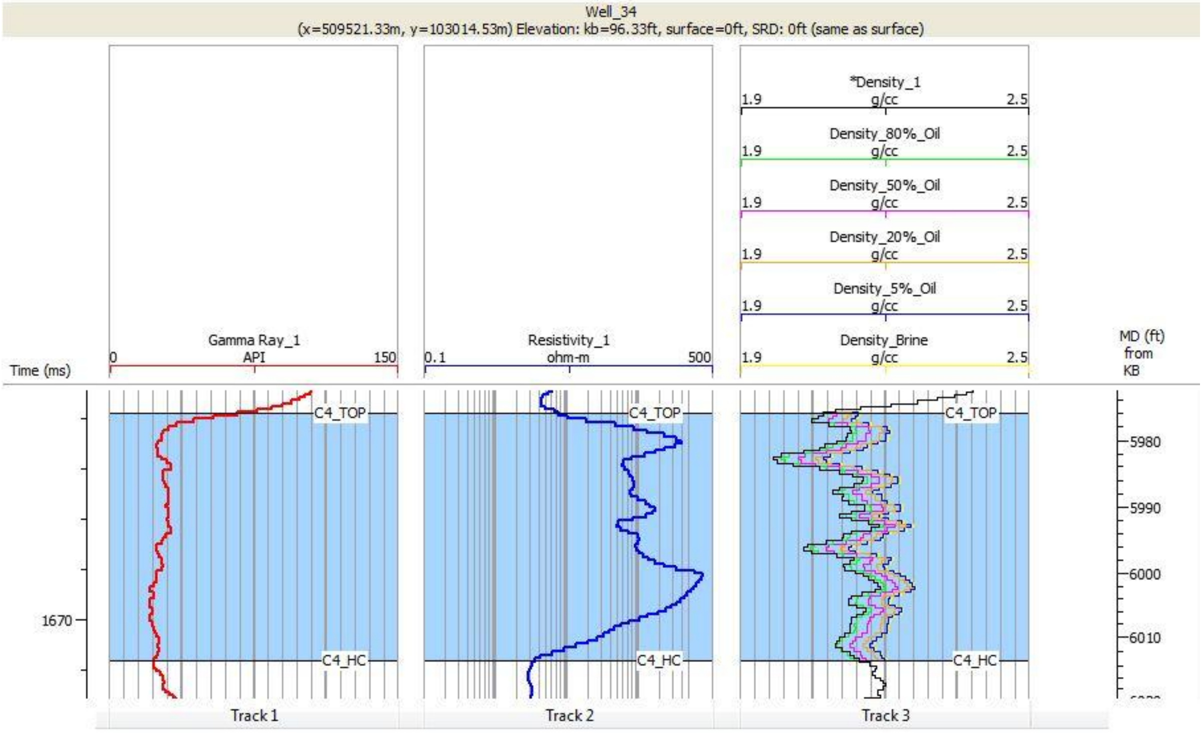

**Figure 8:** Fluid substitution models for oil in C4 reservoir at 5%, 20%, 50% and 80% oil saturations with the insitu and brine filled response on density.

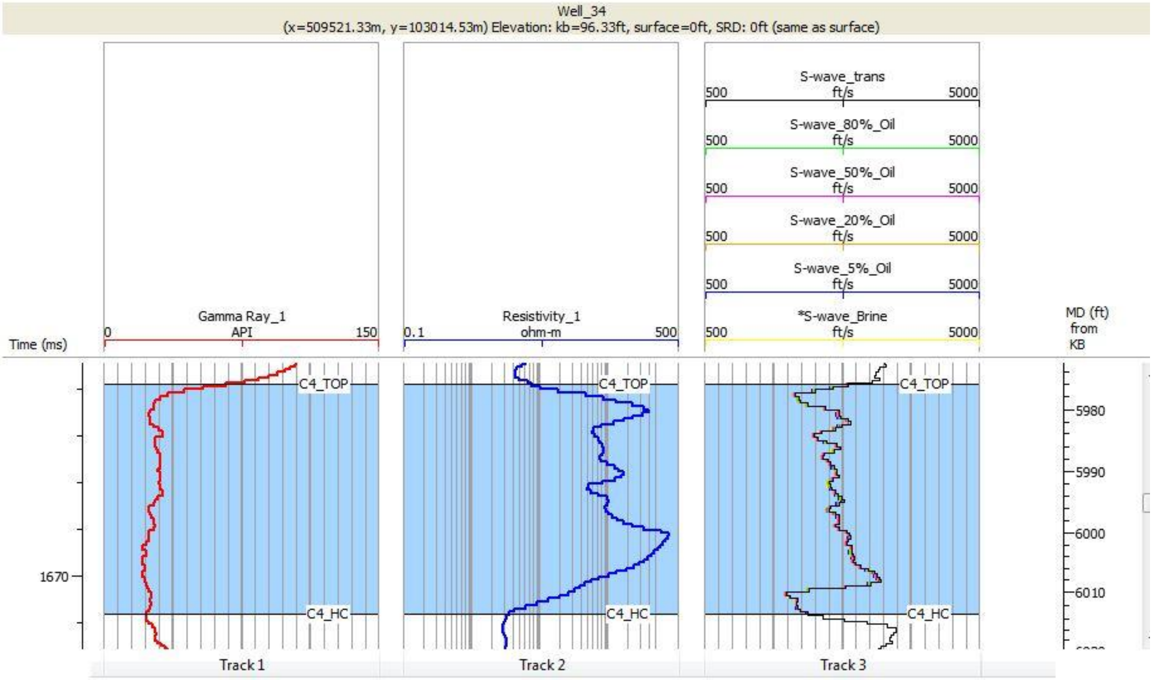

**Figure 9:** Fluid substitution models for oil in C4 reservoir at 5%, 20%, 50% and 80% oil saturations with the insitu and brine filled response on S-wave velocity.

## Rock Physics Cross Plot Results

The cross plot results of derived rock physics attributes from the three basic rock properties were to validate the fluid substitution modeling sensitivity results. Two cross plot techniques were selected; the Vp/Vs ratio against P-impedance technique and Mu-rho against Lambda-rho technique. The result of cross plot of Vp/Vs ratio against P-impedance is presented in figure 10, while the cross plot of Mu-rho against Lambda-rho is presented in figure 11. The cross plot space is divided into two panels; the well log panel (left) and the cross plot panel. The cross plotted attributes are displayed in tract 1 and 2 of the well log panel while gamma ray and resistivity logs are housed in tract 3 and four for lithology discrimination, indication of the cross plotted interval of the C4 reservoir and hydrocarbon presence indication. In the cross plot space, cluster zones of the plotted attributes are visibly defined by colour ellipse. The points in each colour ellipse corresponds to intervals in the well log panel with the same colour, while the colour bar to the right of the cross plot space houses a given well log to validate the define cluster zones.

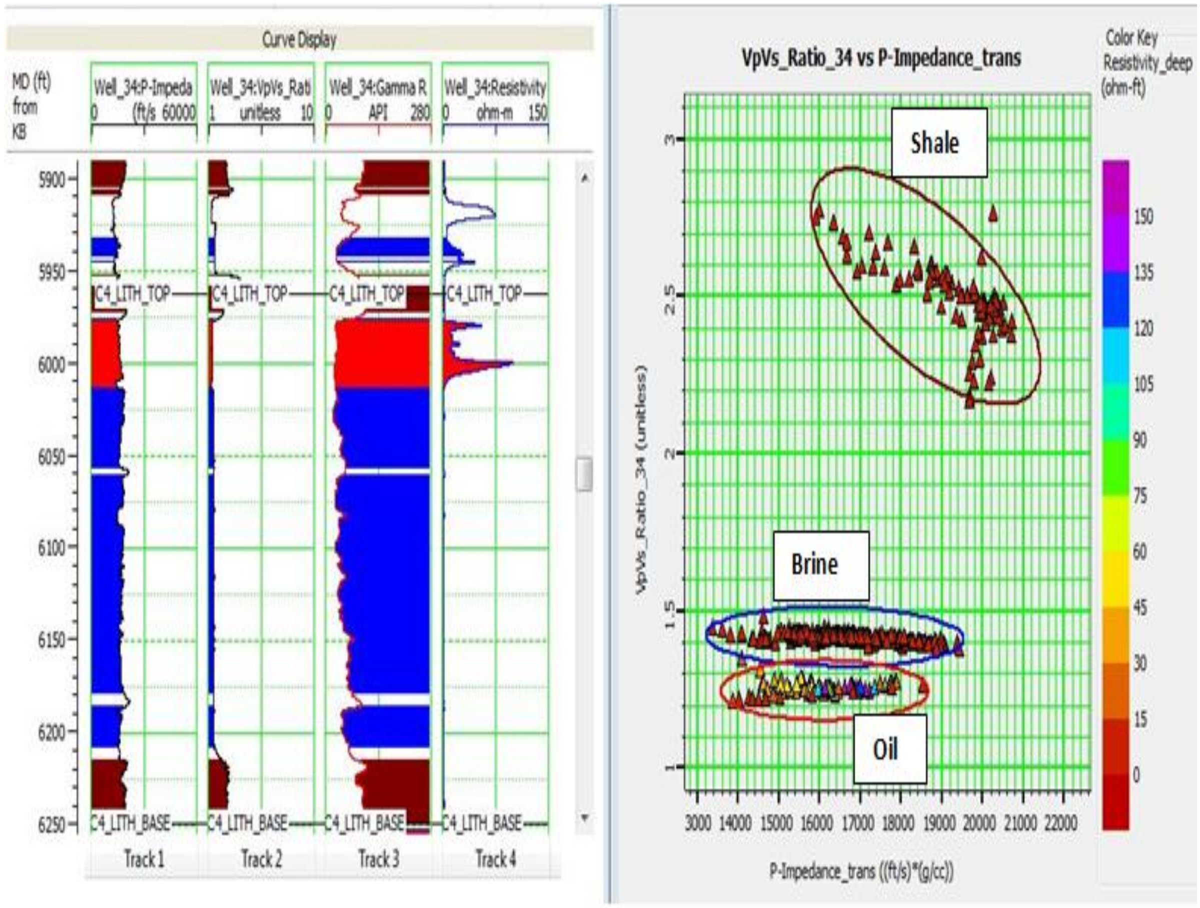

**Figure 10:** Cross plot of Vp/Vs ratio against P-impedance for the validation of fluid substitution results on primary rock properties derived attribute for lithology and fluid discrimination.

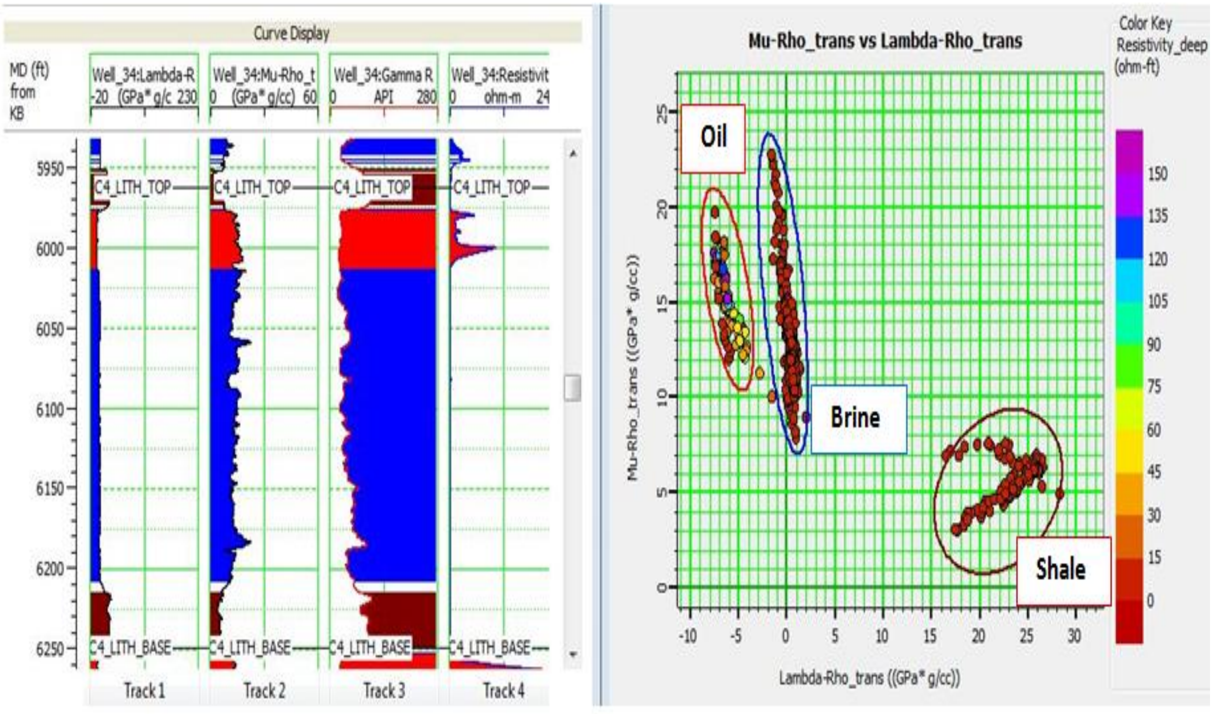

**Figure 11:** Cross plot of Mu-rho against Lambda-rho for the validation of fluid substitution results on primary rock properties derived attribute for lithology and fluid discrimination.

## DISCUSSION

### Fluid Substitution Modelling Analysis

Modeling of fluid substitution process is an important aspect of seismic attribute studies as it provides the interpreter with a valuable tool to model the seismic responses for various fluid scenarios (Smith *et al.,* 2003). Although the study reservoir in the well-used for this study is oil bearing, there exist the possibility for the same reservoir to be mix oil and gas in undrilled area of the field within the same structure or within a neighbouring structure. Hence, modeling was carried out for both gas scenario and oil scenario. Both the brine case (100% water), economical (50% and 80%) and un economical saturations (5% and 20%) were modeled not just to test for the sensitivity of the three basic rock properties identified by Dewar (2001), to changes in fluid type in the pore space of the reservoir, but also to test for variation of a particular hydrocarbon fluid saturation, and if possible determine the insitu saturation of the hydrocarbon in the reservoir by comparing the insitu curve to each modeled saturations.

Results of the modelling process performed for the gas scenario was presented in figures 4-6. In figure 3, the effect of changes in gas saturation on P-wave velocity was tested. It was observed that the brine case model has the highest value for P-wave velocity as expected. But as little as a 5% increase in gas saturation, the value of P-wave velocity dropped significantly. Every further increment in gas saturation had no effect on P-wave velocity. The implication is that the presence of just small saturation of gas will be evident on seismic, but it will be almost impossible to differentiate between economical and uneconomical gas saturation. The effect of the substitution on density presented in figure 5 reveals that an increase in gas saturation result into a corresponding decrease in the bulk density of the reservoir as expected.

Since rigidity (μ) of the pore space remained unchanged during shearing regardless of pore-fluid type, S-wave which is mainly defined by this parameter is expected to remain unchanged irrespective of the fluid type or variation in saturation. This was demonstrated in Figure 6, where the S-wave curves remain unchanged irrespective of the variation of gas saturation. The combined effects of the sensitivity of these three rock attribute to gas saturation have shown that quantitative interpretation technique such as rock physic analysis can be used to evaluate and characterize gas sands.

The results for the oil scenario modeling were presented in figures 7-9. The effect of various saturation of oil on P-wave in figure 7 revealed that the brine case has the highest P-wave velocity. Increments in oil saturation from5% to 80% lead to a corresponding decrease in P-wave velocity due to the negative effect an increase in pore fluid has on incompressibility. One vital observation made here was that the insitu P-wave curve overlies the 80% oil saturation model. The implication of this is that it is possible the insitu saturation is about 80% oil saturation. A similar effect was observed for the modeling done for density in figure 8, but the in this case, a clear separation between the insitu density curve and 80% saturation is obvious. Since the insitu density log has a lesser value than the 80% oil saturation, we can confirm here that the insitu saturation could be greater than 80% oil saturation. The effect of variation of oil saturation on S-wave velocity in figure 9 is similar to observation in figure 6, where the S-wave log remains relatively constant irrespective of the fluid type or variation in fluid saturation.

This sensitivity analysis just like the gas scenario has also demonstrated that the combine effect of oil sensitivity on the basic rock attribute is an indication that rock physics analysis can be employed to characterize the C4 reservoir in both the drilled and undrilled area of the field from seismic data.

## Rock Physics Cross Plot Analysis

Pickett (1963) and Goodway *et al.,* 1997 suggested four attributes for lithology and pore fluid discrimination; Vp/Vs ratio, Lambda modulus and density, shear rigidity and P-wave impedance. These attribute were cross plotted in two cross plot techniques (Figure 10 and 11).

The cross plot of Vp/Vs ratio against P-impedance in figure 10 defined three cluster zones of shale, brine sand and oil sand. The shale cluster is defined by very high values of Vp/Vs ratio and a slightly higher value of P-impedance than the sand due to the negative effect of hydrocarbon presence on incompressibility. As demonstrated by the fluid substitution results, the obsereved separation is due to the sensitivity of the basic rock properties to lithology and fluid variations.

Goodway *et al.,* (1997) affirmed that lambda-rho (λ***ρ***) is a pore-fluid indicator since the introduction of hydrocarbon into pore space will reduce incompressibility (λ). Thus, we expect a hydrocarbon bearing reservoir to have low incompressibility. Mu-rho (μ***ρ***) was identified as a good lithology indicator since lithological variations tend to be characterized better by rigidity (μ). The pore space remained unchanged during shearing regardless of pore-fluid type.

Therefore, rigidity which measures a rock resistance to shearing is lower in shales than sands, and should be able to characterize lithology than pore fluid. As observed in the cross plot in figure 10, the shale cluster ellipse is defined by high lambda-rho and low Mu-rho values, while the sand is define by higher values for Mu-rho and lower values for Lambda-rho due its lower incompressibility than shale. Both brine and oil sands have similar range of values for Mu-rho, confirming that variation of pore fluid does not affect rigidity. A good separation was achieved along the Lambda-rho axis due to the effect of pore fluid change on incompressibility. Therefore, it is concluded that the fluid substitution result was consistent with the cross plot analysis, which it is vital for sensitivity analysis to test for the applicability of quantitative interpretation techniques for both well and seismic base study.

Fluid replacement modeling analysis carried out on C4 reservoir to analyze the possibility of applying quantitative interpretation technique such as rock physics analysis for the evaluation and characterization of the reservoir in the undrilled areas of the study field reveals that as little as 5% gas saturation will be visible on seismic data, but it will be impossible to differentiate between economical and sub-economical gas saturation in the field. The fluid substitution modeling done for oil at various saturation shows that oil saturation of both economical and sub-economical saturation can be differentiated on seismic. It also reveals that the technique can be adopted to determine hydrocarbon saturation in a reservoir. Due to the observed sensitivity of the evaluated basic rock properties to fluid type and saturation variation, it was concluded that quantitative interpretation techniques such as rock physics analysis can be employed to characterize the reservoir both on seismic and well logs. This was demonstrated by generating and analyzing derived rock attributes from the basic rock properties and performing cross plot analysis that adopted the Vp/Vs ratio against P-impedance and Mu-rho against Lambda-rho technique. Both techniques were able to discriminate both lithology types and fluid contrast in the reservoir accordingly.

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