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Enhanced Hydrocarbon Reservoir Delineation and Evaluation using AVO Reconnaissance studies in the Coastal Swamp of Niger Delta

Dagogo, Tamunonengiyeofori1 ,Balogun, Ayomide Olumide 2

1Geophysics Research Group Department of Physics, University of Port Harcourt, Choba, Rivers State, Nigeria
nengi.dagogo@uniport.edu.ng
2Department of Physics, University of Port Harcourt Rivers, Nigeria
ayomide.balogun@uniport.edu.ng

Abstract: *Amplitude versus offset (AVO) analysis was applied as a reconnaissance tool, in this field of the coastal swamp depobelt of the Niger Delta, known for its lithofacies diversity and heterogeneous reservoirs, which resulted from multi-process influenced depositional environments and abnormal pressures. Some of the specific challenges encountered in the field include paucity of data and geologic complexity. The objective was to effectively delineate and characterize reservoirs and highlight prospects with high fidelity, particularly for one of the two (2) wells, W-4, which had no neutron porosity log and the available resistivity log did not show any reliable contrast to indicate hydrocarbon saturation at depth intervals that are considered charged in the other well. AVO scenario modeling showed that density and Poisson's ratio were more sensitive to pore fluid changes. The modeled logs highlighted a high correlation between the in-situ and 100% oil saturation, AVO curve and intercept-gradient plots done on generated synthetics revealed the sands to exhibit class 1 and 2p anomalies. Further petrophysical evaluation showed the sands of interest to have excellent reservoir properties, with porosities, net to gross and hydrocarbon saturation having average values of 26%, 70% and 57% respectively. This finding underscores the robustness of AVO analysis to enhance reservoir delineation and evaluation when applied at different stages of the exploration workflow.*

Keywords—Reservoir delineation, Lithofacies, AVO Reconnaissance and Depositional environments

1. INTRODUCTION (*Heading 1*)

The global demand for energy has continued to rise steadily, driven by rapid population growth and accelerating technological advancement (Chu & Majumdar, 2012; Joshi et al., 2025; Noorollahi et al., 2025). Although contemporary discourse increasingly emphasizes the transition toward renewable energy sources to mitigate carbon emissions and enhance environmental sustainability (Rahman et al., 2022; Chirambo, 2024; Anas et al., 2025), fossil fuels are expected to remain a dominant source of reliable, versatile, and affordable energy in the coming decades (Abbasi et al., 2024; Joshi et al., 2025). This reality places a significant burden on the hydrocarbon industry to ensure that global energy demands continue to be met (IEA, 2023). This responsibility is further compounded by the fact that most easily identifiable and economically viable hydrocarbon reservoirs have already been discovered and exploited. Consequently, hydrocarbon exploration is increasingly shifting toward more complex geological settings and unconventional resources, including deep, tight reservoirs, high-temperature and high-pressure environments, and deep offshore systems (Zhang et al., 2024; Wang et al., 2026). In such settings, reservoir characterization is often challenged by sparse well control and geological heterogeneity, necessitating the application of advanced and integrated prediction techniques (Wang et al., 2026). Therefore, reservoir delineation and evaluation methods must be continuously refined to improve accuracy and reduce uncertainty in subsurface interpretation. This is critical to prevent the misallocation of scarce investment capital to non-productive wells and to minimize operational risks associated with drilling and field development (Rose, 2001; Bentley et al., 2016; Ozowe et al., 2024). This outlook prompts the need to integrate and sync techniques and analyses in order to effectively de-risk, highlight, and give credibility to our models and prospect findings (Avseth et al., 2005). In this work, amplitude versus offset (AVO) attributes have been employed to enhance reservoir identification and delineation (Castagna & Swan, 1997). AVO analysis has become a veritable tool for prospect de-risking in the industry, having been found capable of lithology identification and pore fluid prediction, if properly executed (Downton et al., 2000; Onum et al., 2021). The deployment of AVO analyses at this stage in this study was motivated by the encountered challenges, such as low resistivity contrast, inverted lithologic elastic velocity, and the general complexity of the field (Mavko et al., 2009). The study was carried out in the coastal swamp depobelt of the Niger Delta (Figure 1), which is known for its lithofacies diversity, heterogeneous reservoirs, which resulted from multi-process influenced depositional environments and abnormal pressures (Doust & Omatsola, 1990; Okoli et al., 2018; Jonathan & Odigi, 2020; Johnson et al., 2023). The objective here was to effectively delineate and characterize reservoirs and highlight prospects with high fidelity. Some of the specific challenges of this field include the paucity of data and geologic complexity, which made lithofacies and hydrocarbon reservoir identification difficult (Ukpebor & Maju-Oyovwikowhe, 2023; Odiegwu et al., 2024). Particularly for one of the two (2) available wells, W-4, which

had no neutron porosity log and the available resistivity log did not show any reliable contrast to indicate hydrocarbon saturation at depth intervals that are considered charged in the other well.

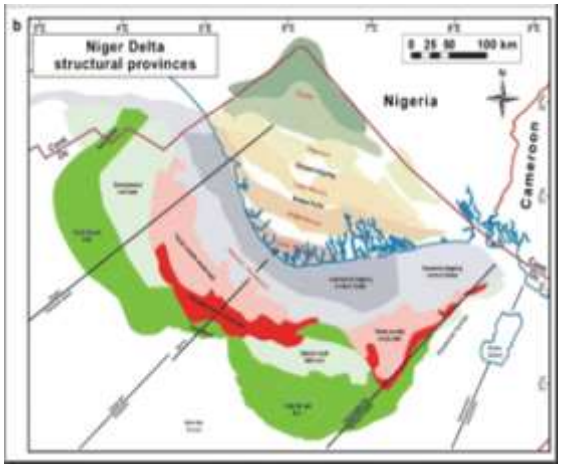

Figure 1: Geologic Map of the study location (Wiener et al., 2010; Nwaezeapu et al., 2017)

2. METHOD

The study carried out employed well data from two (2) wells, W1 and W4. The well log data contained a suite of wire line logs that are required for basic petrophysical reservoir evaluation, including gamma ray, density, resistivity, neutron porosity and sonic logs. One of the wells, W1 had the complete suite whereas W4, did not contain neutron porosity and shear sonic logs. The process involved synthesizing required logs, such as shear wave velocity (Vs) log, from the compressional wave velocity log, using the DES model (Dagogo, et al., 2019) and AVO attributes, plotting AVO curves, analyzing them and confirming reservoir zones, before petrophysical evaluation and characterization of identified reservoirs.

The workflow involved mapping probable reservoirs on the two wells. On W-1, reservoir mapping was straight forward, since the resistivity curve was usable in conjunction with the density – neutron porosity plot, despite the low resistivity contrast. However, in W-4, it was challenging to use the resistivity, especially in the absence of density – neutron porosity logs, Figure 2, shows the log sections of the wells, highlighting the challenge of hydrocarbon reservoir identification in W-4. The low gamma ray zones on W-4 were thus identified as probable reservoirs.

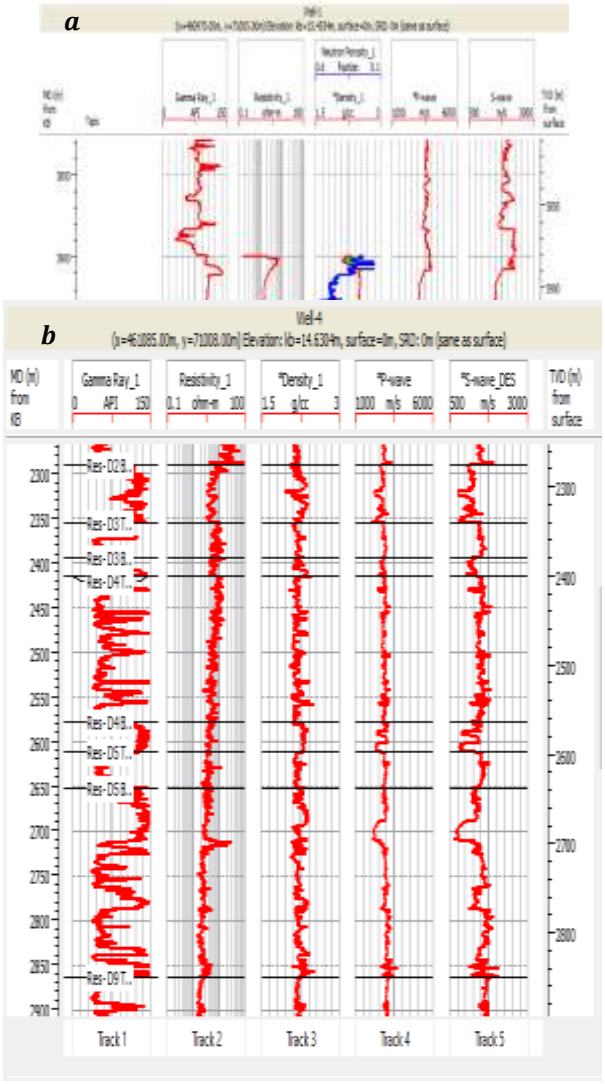

Figure 2: Well-1 (a) and Well-4 (b) log panels showing picked probable reservoir zones

The Vs was estimated and then employed in the computation of elastic moduli and AVO scenario modeling. From the models, AVO synthetics were generated and their amplitude-versus-angle plots produced. The plots of the probable reservoir zones in W-4 were then compared with those of W-1 to confirm their saturation status. Zones whose hydrocarbon charge was confirmed were then further evaluated petrophysically.

The estimation of petrophysical properties was done using already established models (Equations 1-4). For the volume of shale which is a vital reservoir parameter, impacting porosity and permeability was estimated using linear equation (~~Equation~~ 1).

$$V_{sh} = I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (1)$$

$$V_{sh} = 1.7 - [(3.38 - (I_{GR} + 0.7)^2]^{0.5} \quad (2)$$

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Where I_{GR} is gamma ray index, GR_{log} is gamma ray reading from log, GR_{max} is maximum gamma ray (shale), GR_{min} is minimum gamma ray (clean sand),

Density log measuring the bulk density of the formation, is related to the porosity of the formation, is used to compute porosity (Equation 3)

$$\rho_b = (1-\phi)\rho_{ma} + \phi\rho_f \quad \Rightarrow \quad \phi = \frac{\rho_{ma}-\rho_b}{\rho_{ma}-\rho_f}$$
$$\Rightarrow \quad \phi_D = \frac{\rho_{ma}-\rho_b}{\rho_{ma}-\rho_f} \qquad (3)$$

where ϕ is p*orosity*, ϕ_D is density derived porosity, ρ_{ma}, ρ_b and ρ_f are matrix density, bulk density and fluid density respectively.

The water saturation and hence hydrocarbon saturation of the reservoir zones were estimated using Archie's empirical equation (4).

$$S_w = \left(\frac{a\times R_w}{R_t\times\phi^m}\right)^{1/n} \qquad (4)$$

3. RESULTS AND DISCUSSION

The results of the preliminary AVO analyses conducted to identify probable hydrocarbon-charged sand zones, which aided the highlighting of charged zones despite the data and complex geological challenges, are shown for W-4 and Res D9, which is a representative typical sand zone within the hydrocarbon window that shows poor resistivity contrast (Kartika et al., 2025). The results of the AVO scenario modeling (Figure 3) show modeled Vp, Vs, density, and Poisson's ratio (PR) logs for in-situ (red), 100% brine (blue), oil (purple), and gas (orange) situations, and also for a randomly picked saturation distribution (33% brine, 5% gas, and 62% oil (green)) (Mavko et al., 2009). The results indicate that density and PR are most sensitive to saturation variations (Yan et al., 2023). It shows qualitatively more similarity between the in-situ and 100% oil saturation situations than the brine and gas saturations, suggests a possible hydrocarbon presence within the zone (Yudanur et al., 2025).

Synthetic seismograms were generated for the two wells to assess their amplitude variations with offset/angle (Avseth et al., 2005). Well W-1, where reservoir identification was straightforward, was used as a control to calibrate responses observed in W-4 (Kartika et al., 2025). The synthetics were generated using the 2-term Aki and Richards equation, using an incident angle range of 0–30° (Aki & Richards, 2002).

The result shows a general brightening of amplitudes with angle, from near to far, and in some cases, some polarity reversals (Rutherford & Williams, 1989). The brightening effects observed on the confidently mapped hydrocarbon-charged zones of W-1 are similar to what is observed in W-4 (particularly for zones D4 and D9), for zones that would ordinarily have been written off as brine-saturated (Figure 4) (Kartika et al., 2025). The AVO plots are shown in Figure 5, where for W-1 (left side), the displayed sand tops show typical class 1 and 2p responses, the first zone having a low positive intercept, with amplitudes decreasing as offset increases, undergoing a polarity reversal and then followed by brightening (Castagna & Swan, 1997; Zhang et al., 2024). For zone two, there is a low negative intercept, with amplitude brightening as offset increases (Castagna & Swan, 1997). For W-4, the representative sand tops (D4 and D9) show class 1 or 2p anomalies, without a polarity change within the angle range considered (Yudanur et al., 2025). Figure 6 shows the result of the intercept versus gradient plot for the zones D4 and D9. From the plots, the tops plot in the fourth quadrant of the space, such that the D4 top, which plots slightly below the intersection, may be considered a class 2p anomaly, while D9, which plots farther away into the quadrant, may be considered a class 1 anomaly (Yudanur et al., 2025). These AVO signatures indicate that these sand packs are very likely hydrocarbon-charged and should be further considered as prospects (Kartika et al., 2025). Petrophysical analysis was then conducted to determine the quality of the reservoirs quantitatively (Table 1). The results of the petrophysical analysis show that the sands within the hydrocarbon window in the field have good reservoir properties (Aduwa et al., 2025). The representative zones, D4 and D9, have good thicknesses, excellent net-to-gross and porosity values, and hydrocarbon saturations of 62% and 52% respectively, for which they are classed as viable prospects in the field (Table 1).

Table 1: Summary of the petrophysical properties of delineated sands inW-4

Sand zones	Thickness (m)	Porosity %	Vshale %	Sw %
D4	164	27	34	38
D9	82	26	27	48

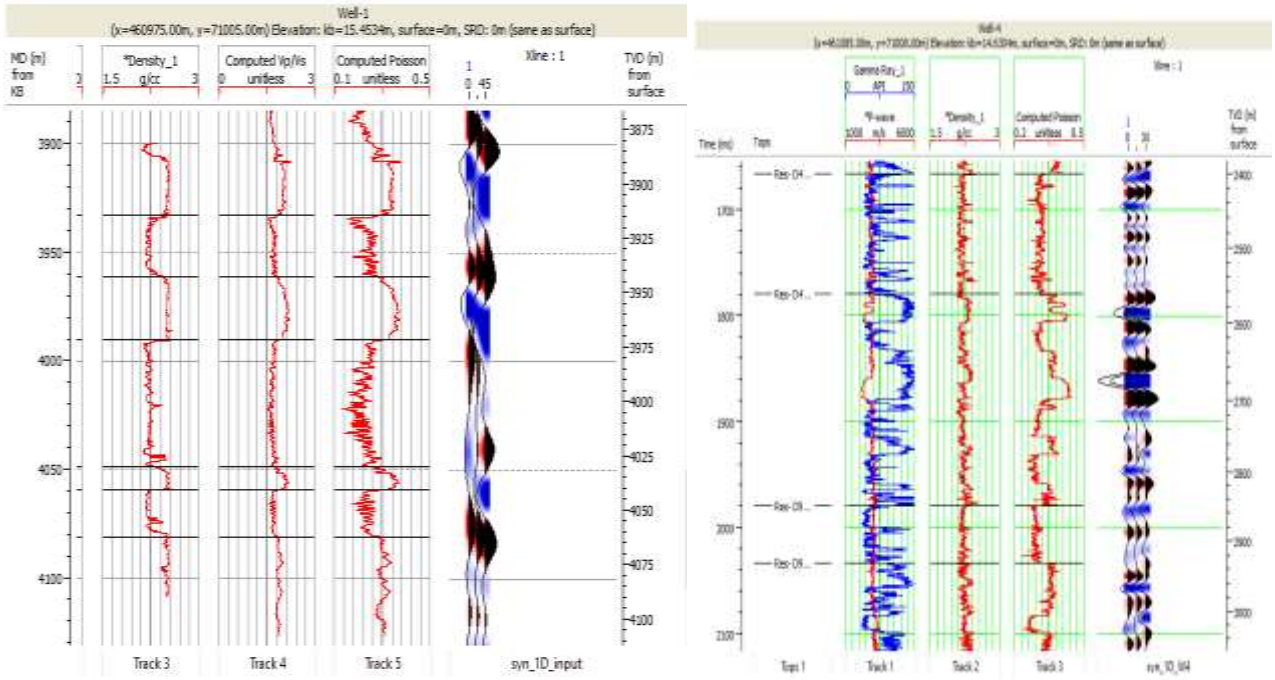

Figure 4: Synthetic seismograms amplitude variation with offset for (a) W-1 and (b) W-4

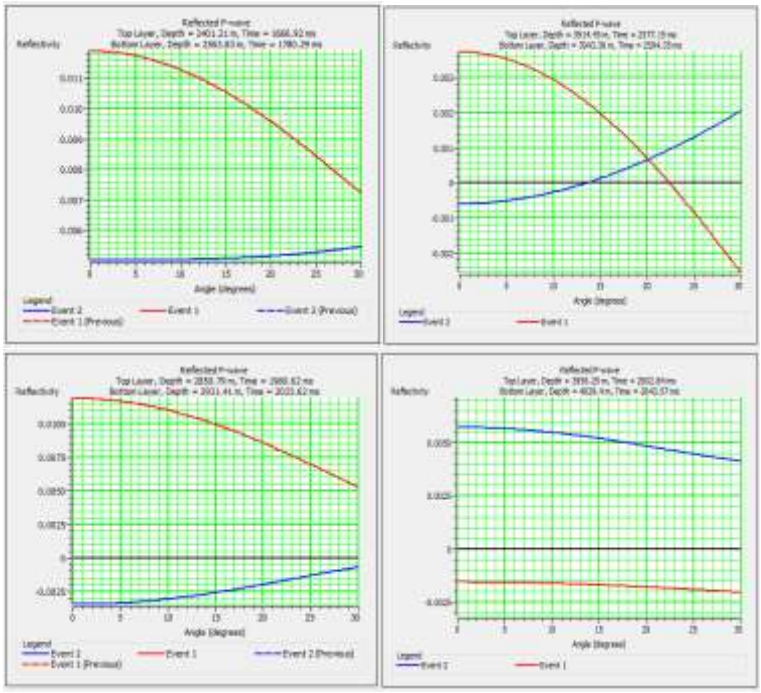

Figure 5: Amplitude vs offset plots for sands from modeled synthetics for W-1 (leftside) W-4 (rightside

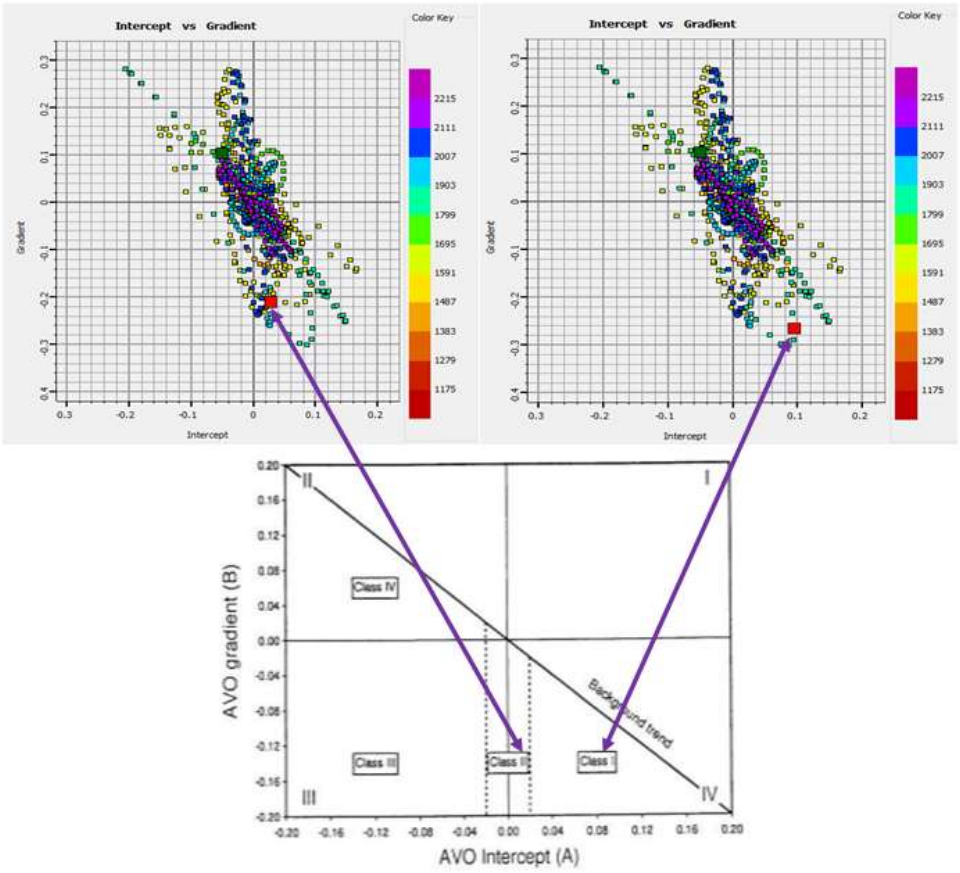

Figure 6: Intercept versus gradient plots for sand zones D4 and D9 of W-4 and a standard AVO anomaly distribution (after Castagna & Swan 1997)

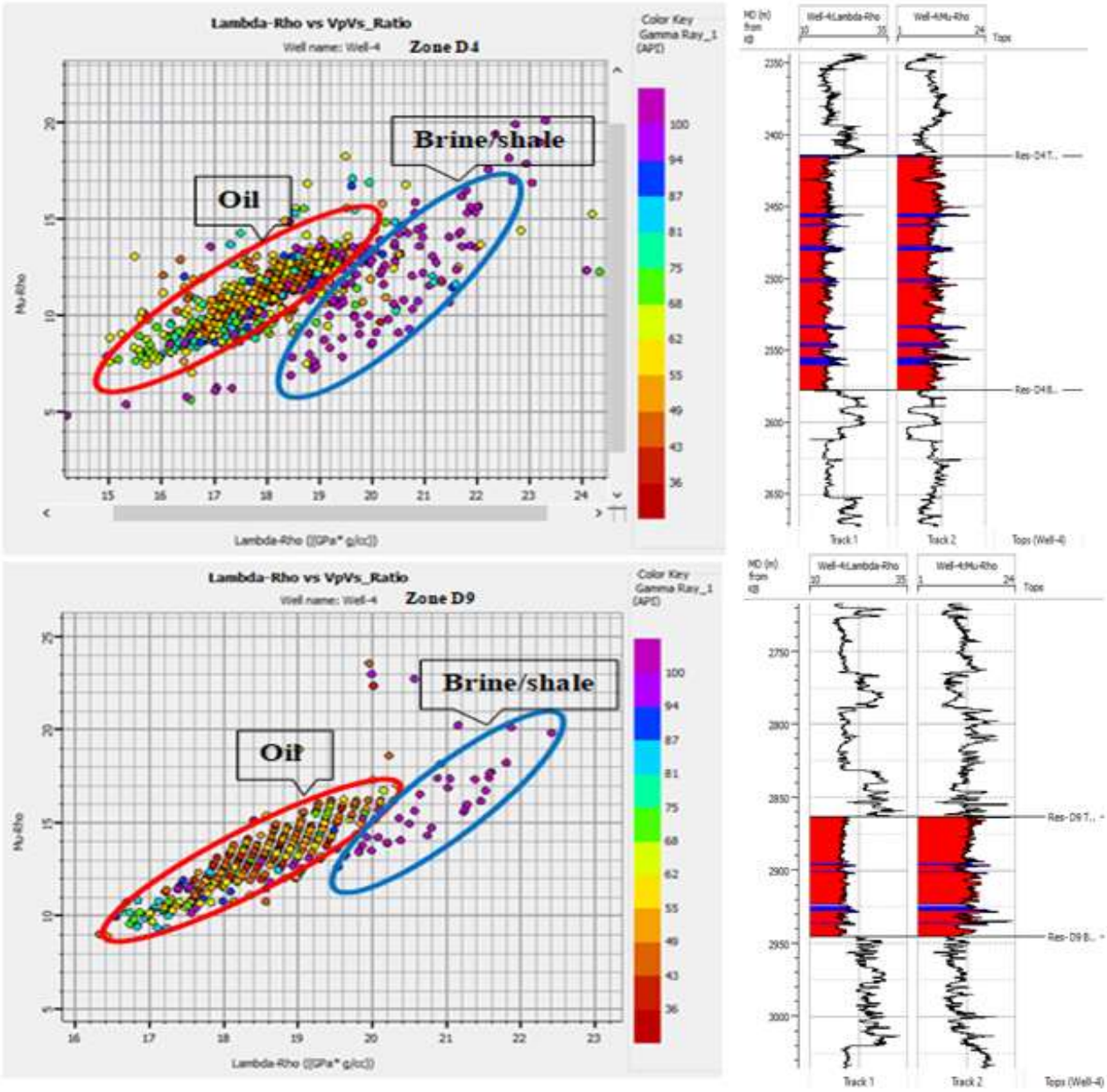

Figure 7: LR vs MR cross plots and cross sections highlighting oil, brine/shale distributions in zones D4 and D9 of W-4.

Cross plots of robust fluid and lithology discrimination elastic attributes such as Lambda-rho and Mu-rho (Figure 7) show that the sand zones are hydrocarbon-charged as highlighted from the AVO analysis (Fatti et al., 1994; Goodway et al., 1997). They show in each case two (2) clusters of points, which have been identified as hydrocarbon (oil)-saturated zones and areas of possible shale intercalation and/or brine saturation within the sands (Yudanur et al., 2025). Whereas in D4, the clusters are not discriminated along the Mu-rho axis, the distinction is clearer in D9. This may be related to the properties or fineness of the contact or transitions between sands and shales in both intervals (Kartika et al., 2025). It may be considered that whereas the shales are more dispersed into the sands in D4, they are somewhat more isolated in D9, such that their properties appear more distinct.

4. CONCLUSION

In the light of the heightened difficulty in identifying new prospects, it is imperative to evaluate and re-evaluate our prospect screening processes to ensure that no viable opportunity is missed. This reconnaissance application of AVO analysis proved very beneficial, as it aided the delineation of prospects that would otherwise have been missed on the basis of geological complexity or data limitations. Despite the low resistivity contrast in the field and the inadequacy of data to conventionally map viable

reservoirs in the wells of the field, considering the setting of the sands within a depth window which has been proven viable in the region, it was necessary to improvise a scheme for dealing with the uncertainty presented. This endeavor underscores the robustness of the AVO scheme for prospect delineation and characterization at the several stages of exploration and field development.

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