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RESEARCH ARTICLE

FLUID PREDICTION THROUGH LITHOLOGICAL ANALYSIS IN 'M' OIL FIELD NIGER DELTA: USING ROCK PHYSICS APPROACH

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ABSTRACT

3D Lithology and reservoir fluid studies based on conventional interpretation approach, such as low Vp/Vs values indicating gas presence have been used to discriminate hydrocarbon fluids. This work was provoked by the emerging trends of noticeable uncertainties leading to drilling of dry wells in the study area. Confirming the physical indicators of hydrocarbon in the reservoirs through the employed method is worthwhile. Well log data of *M* oil field was investigated with the aim of identifying reservoir rocks through qualitative and quantitative interpretations of subsurface well log data of *M* oil field through rock properties cros-splots analysis in the select reservoir in the field (M-5000) and to derive elastic rock attributes such as Lame's parameter terms (λρ and μρ), Vp/Vs, P-Impedance and S-Impedance from available petrophysical data. Rock attributes derived from well logs were combined to produce three major forms of crossplots, which described and characterized the reservoir in terms of fluid and lithology present. The combinations were: V_P/V_S versus I_P, μρ against λρ and I_P versus I_S. These rock parameters were analyzed in cross-plots space and used to determine which of them constitutes better indicators of pore fluids and lithology. The M- oil field cross-plot analysis indicate the lowest values of V_P/V_S (2.05-2.40); I_P (5600-6300 (m/s*(g/cc)), λρ (16-20 (GPa*g/cc)), and μρ (4-9.5 (GPa*g/cc)). However, the low values of V_P/V_S, I_P, λρ, and μρ, perhaps I_S corresponds to hydrocarbon (Gas) saturation within the M- oil field.

KEYWORDS

reservoir, lithology, rock attributes, hydrocarbon, crossplots

1. Introduction

Characterising a reservoir entail knowing the complete reservoir architecture including the internal and external geometries, its mode of distribution of reservoir properties, and understanding the fluid flow within the reservoir or its carbon sequestration (Akpan et al., 2022; Eshimokhai and Akhirevbulu 2012; Ekanem et al., 2021). Such information helps to improve production rates, rejuvenate oil field, predict future reservoir performance and also helps oil companies in managing to draw up accurate financial models (Akpan et al., 2021 a, b). The success of reservoir characterisation effort depends on how well the integration of the above disciplines is carried out. Accurate description of a reservoir in terms of lithology and fluid content is an important factor in reducing the risk involved in hydrocarbon exploration (Ebong et al., 2020). Lithology and reservoir fluid studies based on conventional interpretation approach, such as low V_p/V_s values indicating gas presence that do not incorporate an understanding of rock Physics always lead to biased interpretations. The V_p and Vs values are given in equations 1 and 2:

$$V_P = \sqrt{\frac{K+\left(\frac{4}{3}\right)\mu}{\rho}} = \sqrt{\frac{\lambda+2\mu}{\rho}} \quad (1)$$

$$V_S = \sqrt{\frac{\mu}{\rho}} \quad (2)$$

where λ – Lame's coefficient, ρ – density, μ – shear modulus and K- bulk modulus. The aim of reservoir characterization is to identify reservoirs, delineate them, and subsequently determine the distribution of relevant physical properties opined by as lithology, porosity, permeability, water saturation and pore pressure, which will make for an easy determination of the reservoirs economic potential (George et al., 2016; Ebong et al., 2020). Reservoir characterization research is focused on techniques that would integrate all available geologic data and interpretation that would aid in unravelling the subsurface environment as an input to the reservoir simulation model. Cross plotting appropriate pairs of attributes so that common lithologies and fluid types of generally cluster together allows for simple interpretation. The off-trend aggregations can then be more elaborately evaluated as potential hydrocarbon indicators (Chopra et al., 2006). Crossplotting of rock properties from well logs is a convenient way of looking at two rock properties and their attributes (combination of rock properties) at the same time (Burianyk, 2000). It also shows decisively which rock properties, and their attributes will be helpful to discriminate gas in a particular reservoir.

2. Geology of the Study Area

The Niger Delta Basin is situated along the southern end of Nigeria bordering the Atlantic Ocean between latitudes 4^0N and 8^0N and longitudes 4^0E and 6^0E (Eanem et al., 2022 a, b). The Niger Delta is perhaps the most important sedimentary basin in sub-Sahara African due to its petroleum production, and it is one of the most important deltas in terms of its geology, which is unique and classical. The onshore portion of the Niger Delta Province is delineated by the geology of southern Nigeria and south-western Cameroon (figure 1). The northern boundary is the Benin Flank--an east-northeast trending hinge line south of the West Africa Basement Massif. The north-eastern boundary is defined by outcrops of

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the Cretaceous on the Abakaliki High and further east-south-east by the Calabar Flank--a hinge line bordering the adjacent Precambrian (Doust and Omatsola 1990). The offshore boundary of the province is defined by the Cameroon Volcanic line to the east, the eastern boundary of the Dahomey Basin (the eastern-most West African transform-fault passive margin) to the west, and the two-kilometer sediment thickness contour or the 4000-meter bathymetric contour in areas where sediment thickness is greater than two kilometers to the south and southwest. The province covers 300,000 km^2 and includes the geologic extent of the Tertiary Niger Delta (Akata-Agbada) Petroleum System.

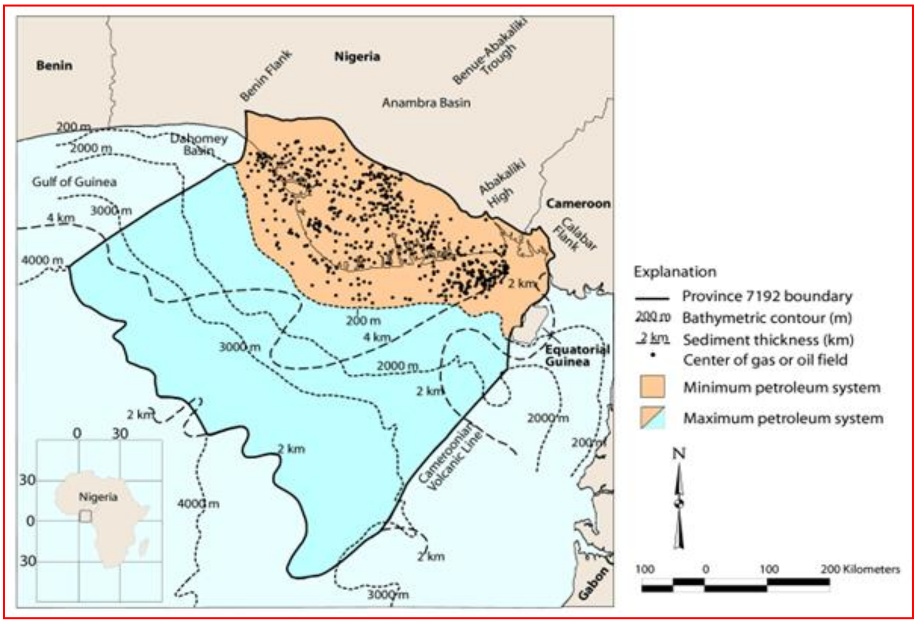

Figure 1: Regional geology outline map of the Niger Delta (Tuttle et al., 1999)

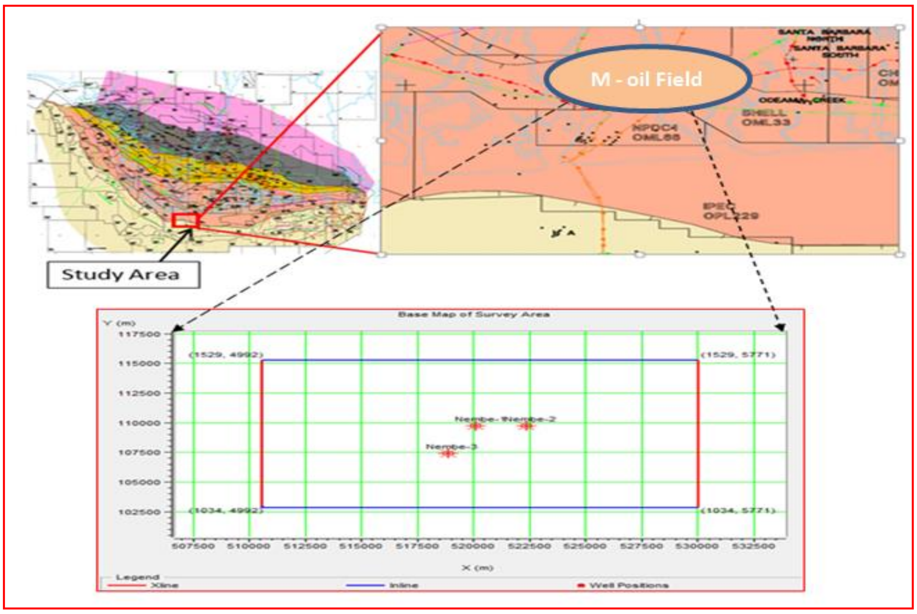

Figure 2: Location map showing the study area and Base Map

Niger Delta Basin is situated at the southern end of Nigeria boarding the Atlantic Ocean where the M oil field is located. M Oil field has several stacked reservoirs including the M-5000 reservoir analyzed in this study, which is 120.00 ft thick. The assumed wells are (M -1, 2 and 3) respectively as in figure 2.

3. Theoretical Framework

Reservoir Characterization is a process of integrating various qualities and quantities of data in a consistent manner to describe reservoir properties of interest in inter well locations. The main purpose of reservoir characterization is to generate a more representative geologic model of the reservoir properties. More so, the goal of any reservoir characterization or reservoir modelling is to understand the reservoir connectivity in static and dynamic conditions by integrating data from different sources (Kelkar and Perez 2002; Uwa et al., 2019). Reservoir Characterization generally determines the gross volume within the trap that has the potential to hold hydrocarbons (Udoinyang et al., 2019). The accuracy of reservoir estimation such as thickness and other Petrophysical parameters of each reservoir is a critical element in interpretation, estimation of reservoir properties such as Porosity, Water Saturation and other parameters from well log data (Muslime and Moses 2011).

A group researchers investigated the integration of 3D Seismic and Well log Data in the optimal reservoir characterization of EMI field, offshore Niger Delta oil province, Nigeria (Oyedele, et al., 2013). The study was carried out in two phases - Seismic data interpretation and Petro-physical data analysis. Time-Structure and Depth-Structure maps were generated from the seismic sections while formation parameters such as porosity, water saturation, and net to gross were calculated from petro-physics. Abe and Olowokere investigated the reservoir characterisation and formation evaluation of some parts of Niger Delta using 3-D seismic and well log data (Abe and Olowokere, 2013). The analysis was focused on delineation of lithologies and identification of reservoirs from the log signatures of gamma ray and resistivity logs. Fault mapping was done on the vertical seismic display across the whole seismic volume. Seismic to well tie was done to match events on well logs to the specific seismic reflections.

Eshimokhai and Akhirevbulu discussed reservoir characterization using seismic and well logs data (a case study of Niger Delta) (Eshimokhai and

Akhirevbulu, 2012). The aim is to use an integrated technique in computing various petrophysical parameters, these techniques include using well log data and combining various mathematical equations, which ranges from the linear, non-linear Vsh Stieber and the Archie's equations (Adeoti et al., 2009). From the data used in computing the petrophysical results such as the log data, which consist of gamma ray, resistivity, density and neutron logs, the Stieber and Archie's equations were applied in carrying out petrophysical evaluation such as the water saturation, porosity and the hydrocarbon saturation (Akpan et al., 2022). They have revealed to be successful at almost all stages, from prospecting, characterization to exploitation monitoring. Based on elastic properties of rocks and fluids, they provide multitude of attributes that help to obtain a direct or indirect answer to many questions arising in hydrocarbon industry (Eshimokhai and Akhirevbulu, 2012).

4. Materials and Method

This research work focus on reservoir characterisation of Niger Delta hydrocarbon field (M- Oil field). The methodology employed here examines the response of reservoir properties to the presence of hydrocarbons when rock properties are crossplotted (Omudu and Ebeniro, 2007). Next, the crossplots are closely observed, to identify the rock properties that are more robust than others in terms of sensitivity to either fluid or lithology, or both. At the end, the results from these processes are analyzed in other to determine fluid presence and discriminate lithology in the reservoirs (Akpan et al., 2022; Ebong et al., 2023).

4.1 Data Sets Used

The data used in this work are well logs data from M Oil field all in the coastal swamp depobelt within the Niger Delta basin. These data were analysed using Hampson Russell Software (HRS). The well log data were evaluated, rock attribute cross-sections were created. M Oil field has several stacked reservoirs including the M-5000 reservoir analyzed in this study, which is 120.00 ft thick. The assumed wells are (M -1, 2 and 3) respectively as shown in figure 3a, b, c.

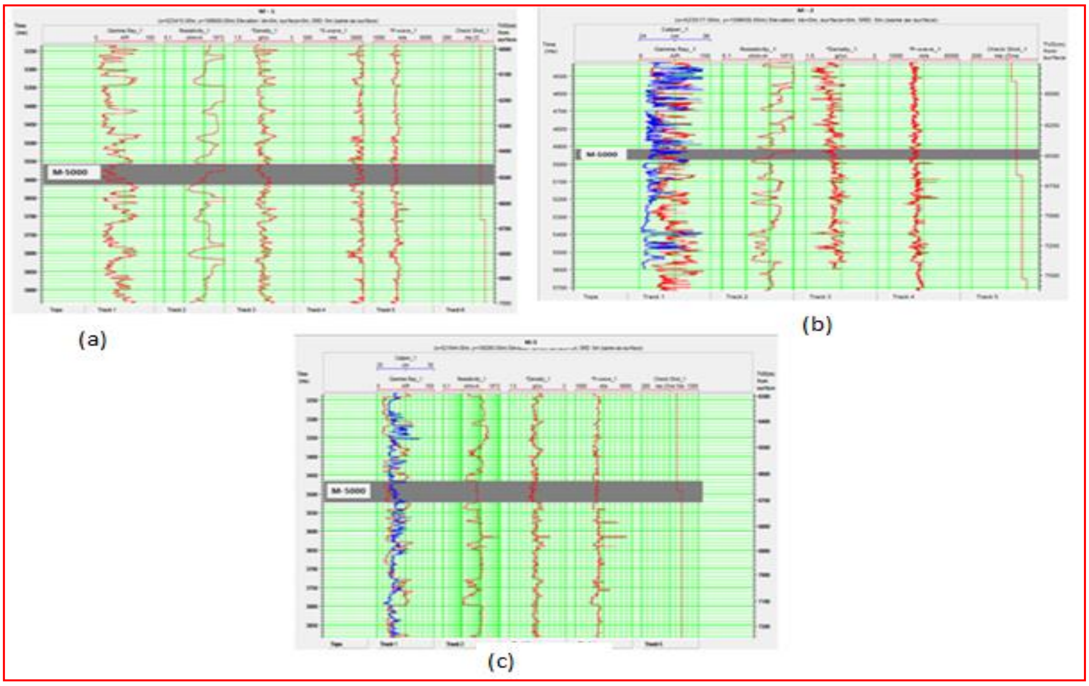

Figure 3: (a) Suite of imported logs for M-1; (b) Suite of imported logs for M-2 and (c) Suite of imported logs for M-3 showing log signatures of Gamma ray, Resistivity, Density, S-wave, P-wave, Check-shot and imported M-5000 reservoir of interest.

4.2 Well Log Importation

Well log is a record of one or more physical measurement as a function of depth (occasionally versus time) that represents continuous parameters measured in a well or derived from them. Three wells from the M- oil field were imported for the well log analysis and model based inversion process. This provides the much needed low-frequency component. The wells give insight into the various formation properties measured. The importation of the well data was done through the use of eLog application of the HRS in addition to their tops (M-5000) and check-shot corrections. Care was taken to append the various log properties to the appropriate well as shown in figure 3a, b, c.

The suite of wireline log data imported comprises caliper log, gamma ray log, resistivity log, density log and sonic log. The inverse of the interval transit times of the sonic logs were used to generate the compressional velocities for each well. We generated S-wave data from Castagna´s relation using P-wave for well that did not have S-wave log. This recorded suite of logs can be grouped into two categories: properties that affect seismic wave propagation (example; compressional- and shear- velocity log and density log) and properties of interest for reservoir description which indirectly affect seismic-wave propagation (example; porosity, water saturation, V_p/V_s, P-impedance, S-impedance, Mu-rho and Lambda-rho).

4.3 Well Attributes Crossplots

Crossplots are visual representations of the relationship between two or more variables, and they are used to visually identify or detect anomalies which could be interpreted as the presence of hydrocarbon or other fluids and lithologies. This is carried out to determine the rock properties / attributes that better discriminate the reservoir (Omudu and Ebeniro, 2007). The goal is to determine the feasibility of discriminating between reservoir fluids. To illustrate this point, the cross plot of V_P/V_S against acoustic impedance (AI) shows fluid as well as lithology discrimination along the acoustic impedance axis. It describes the conditions in terms of lithology and fluid content than V_P/V_S. P-impedance and V_P/V_S relationship discriminate both fluid and lithology. The V_P/V_S is a fluid indicator because compressional waves are sensitive to fluid changes, whereas shear waves are not except in the special case of very viscous oil (Han et al., 2007). P-impedance shows a better discrimination which can better describe the reservoir conditions in terms of lithology and fluid content than the V_P/V_S. Acoustic impedance versus V_P/V_S contrast can show the position of gas-sand, water-sand and shale in V_P/V_S versus impedance crossplot as shown in figure 4 below.

In this study, five well attributes were combined to produce three crossplots using each well in both fields within the chosen interval. These three crossplots (V_p/V_s versus P-Impedance, Mu-Rho versus Lambda-Rho and P-Impedance versus S-Impedance) were used to discriminate how potential is one well to the other probably, what lithology/fluid saturated in a given well through numbers of scatters each cross plot produced as shown figures 5a, b, c; 6a.b, c and 7a, b, c. The crossplot analysis was carried out to determine the rock properties / attributes that better discriminate the reservoir and to ascertain those attributes that are sensitive to 3D effects caused by changes in the reservoir fluid saturation and pressure as shown in the figure 5, 6 and 7 for M- 5000 reservoir sand respectively. The crossplots analyses delineate hydrocarbon/wet sand/shales clusters in wells in M oil field within the selected reservoirs (M-5000). The summaries of the crossplot analyses are given in tables 1, 2 and 3 respectively.

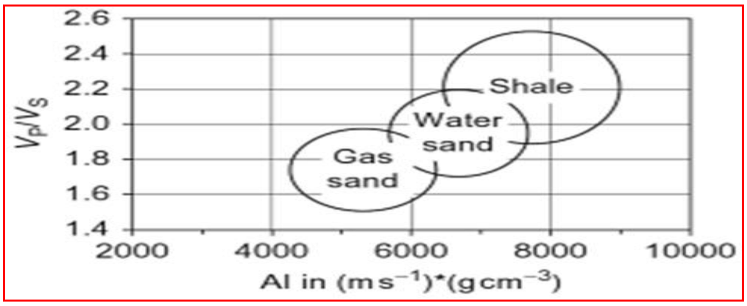

Figure 4: Position of gas sand, water and shale in Vp/Vs versus acoustic impedance AI plot. (Source: Odegaard and Avseth, 2004; Ebong et al., 2020)

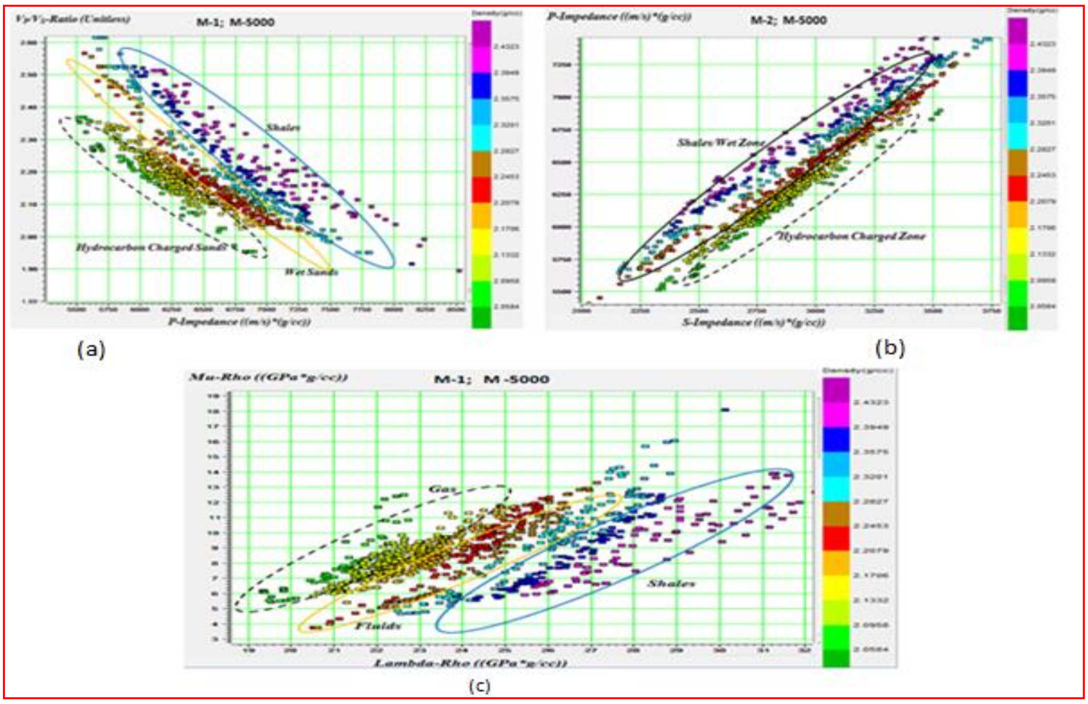

Figure 5: (a) V_p/V_s versus P-Impedance Cross Plot for M-1indicative of three anomalous sands mapped using density as a color code within the interval of M-5000. **(b)** P-Impedance versus S-Impedance Cross Plot for M-1indicative of two anomalous zones mapped using density as a color code within the interval of M-5000. (**c**) Mu-Rho versus Lambda-Rho Cross Plot for M-1indicative of three anomalous fluid zones mapped using density as a color code within the interval of M-5000.

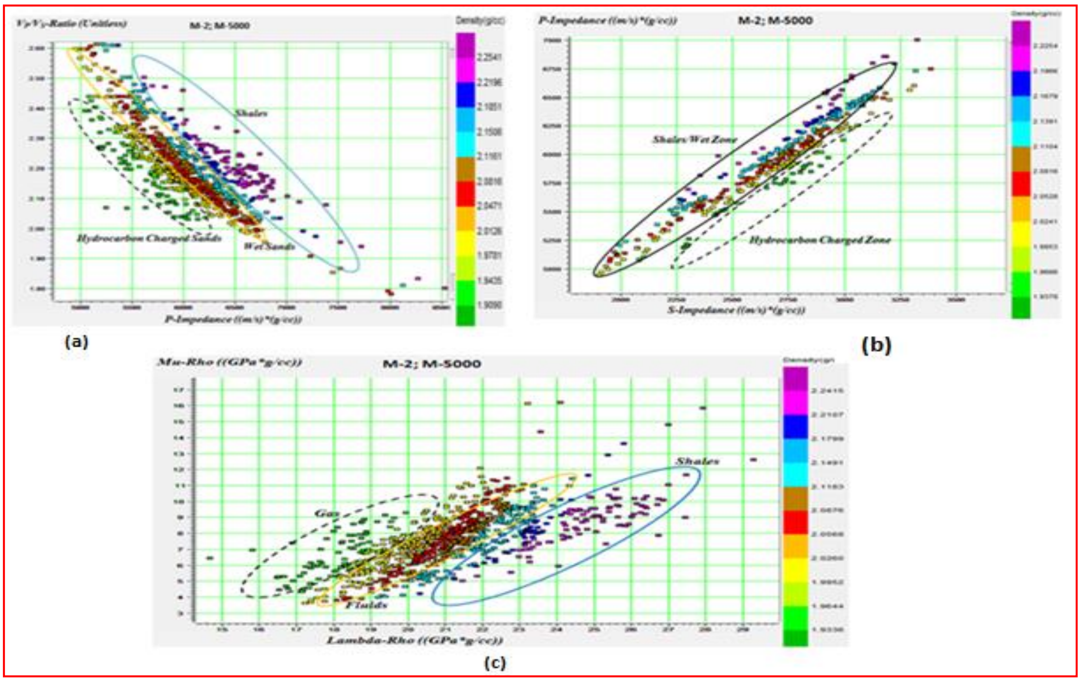

Figure 6: (a) V_p/V_s versus P-Impedance Cross Plot for M-2 indicative of three anomalous sands mapped using density as a color code within the interval of M-5000. **(b)** P-Impedance versus S-Impedance Cross Plot for M-2 indicative of two anomalous zones mapped using density as a color code within the interval of M-5000.**(c)** Mu-Rho versus Lambda-Rho Cross Plot for M--2 indicative of three anomalous fluid zones mapped using density as a color code within the interval of M-5000.

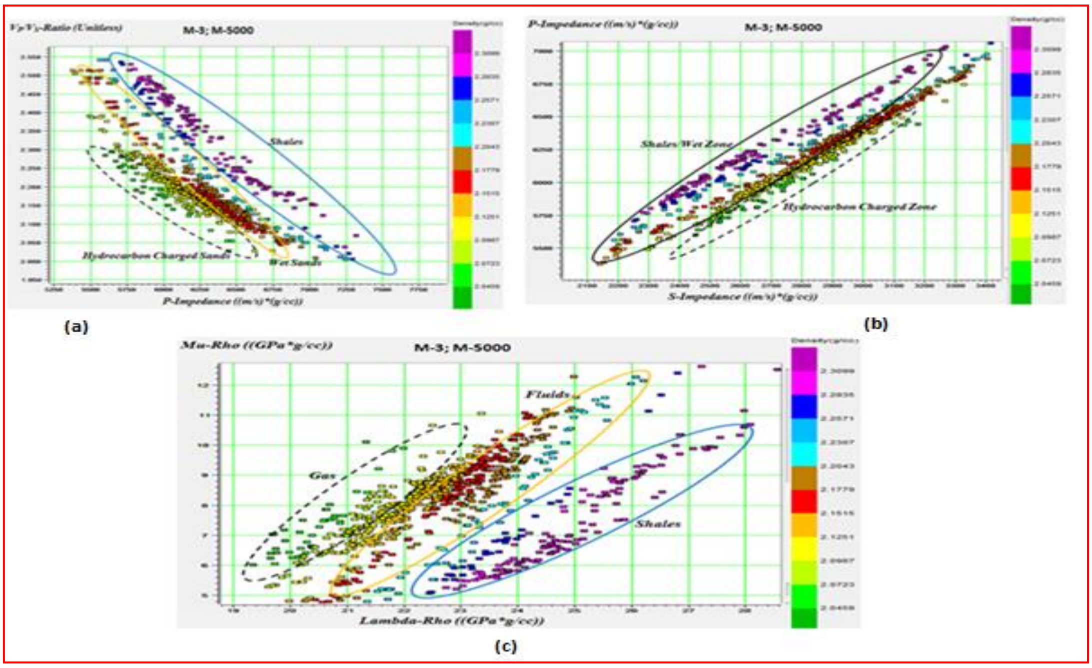

Figure 7: (a) V_p/V_s versus P-Impedance crossplot for M-3 indicative of three anomalous sands mapped using density as a color code within the interval of M-5000. **(b)** P-Impedance versus S-Impedance crossplot for M-3 indicative of two anomalous zones mapped using density as a color code within the interval of M-5000. **(c)** Mu-Rho versus Lambda-Rho crossplot for M-3 indicative of three anomalous fluid zones mapped using density as a color code within the interval of M-5000.

5. Data Analysis, Results and Discussion

5.1 Well Attributes Crossplot Analysis

Crossplot analysis was carried out to determine the rock properties/attributes that better discriminate the reservoir and to ascertain those attributes that are sensitive to 3D effects caused by changes in the reservoir fluid saturation and pressure (Tables 1 – 3). However, crossplots are visual representation of the relationship between any two variables, which are used to detect significant departures from a background trend. Or in other words, to detect anomalies which are related to lithology/fluid contrasts (Akpa et al., 2020a, b). Elastic parameters mostly combined to delineate lithology/fluid clusters are V_P/V_S and Acoustic Impedance because combination of these two is a good lithology fluid indicator (Avseth et al., 2005). Other elastic properties exist the combination of Shear Impedance (SI) versus Acoustic Impedance (AI) and Lambda-Rho versus Mu-Rho cross plot proposed by used to improve petrophysical discrimination of rock properties (Goodway et al., 1997). Three forms of crossplots are considered using five well derived attributes to delineate hydrocarbon/wet sand/shales clusters in each well using both fields within the selected reservoirs (M-5000).

5.2 V_P/V_S versus P-Impedance Crossplot

The crossplot of Vp/Vs against P-Impedance (Figure 5a,b,c), distinguishes reservoir sand (M-5000) into three lithologies using density as a colour code; Hydrocarbon charged sands (dotted black eclipse) in which the low values of density (green to yellow - 2.058-2.1332 g/cc) correspond to low values of V_p/Vs (1.900-2.40) and P-Impedance (5500-6750 m/s*g/cc). Wet sands (yellow eclipse) in which the moderately high values of density (brown to cyan -2.1706-2.2827 g/cc) correspond to Vp/Vs (2.19-2.50) and P-Impedance (6000-7250 m/s*g/cc). Shales (blue eclipse) in which the high values of density (light blue-Purple -2.3201-2.4323 g/cc) correspond to high values of Vp/Vs (2.0-2.60) and high values of P-Impedance (6500-8250 m/s*g/cc). This crossplot shows better fluid as well as lithology discrimination, indicating that of V_P/V_S versus acoustic impedance attribute will better describe the reservoir conditions in terms of lithology and fluid content (Ebong et al., 2023). However, a better discrimination/separation of clusters is observed along the P-Impedance axis, which discriminates between lithologies in the reservoir compared to Vp/Vs.

5.3 P-Impedance versus S-Impedance Crossplot

The crossplot of P-Impedance against S-Impedance (Figure 6a,b,c), distinguishes both reservoir sands (M-5000) into two anomalous zones using density as a color code; Hydrocarbon charged sands (dotted black eclipse) in which the low values of density (green to yellow -2.058-2.1332 g/cc) correspond to low values of P-Impedance (5600-6500 m/s*g/cc) and low values of S-Impedance (2500-3250 m/s*g/cc). Shales/wet zones (black eclipse) in which the high values of density (Red to Purple – 2.4-2.4323 g/cc) correspond to high values of P-Impedance (5750-7250 m/s*g/cc) and high values of S-Impedance (2000-3750 m/s*g/cc). The crossplot shows that P-Impedance is a robust discriminator compared to S-Impedance.

Table 1: M-1 Cross plot Analysis

Elastics parameters	*Hydrocarbon charged sand*	*Wet sands/fluids*	*Shales*
V_p/V_s (unitless)	1.90 – 2.40	2.19 – 2.50	2.00 – 2.60
P – Impedance ((m/s*(g/cc))	5500 – 6750	6000 – 7250	6500-8250
S – Impedance ((m/s*(g/cc))	2500 – 3250	2000 – 3750	2000 – 3750
Lambda- Rho (GPa*g/cc)	19.0 – 24.0	20.9 – 29.0	22.9 – 32.0
Mu- Rho (GPa*g/cc)	5.0 – 10.0	4.0 - 14.0	5.5-18.0
Density code (g/cc)	2.058 - 2.1332	2.1706 - 2.827	2.320-2.4323

Table 2: M-2 Crossplot Analysis

Elastics parameters	*Hydrocarbon charged sand*	*Wet sands/fluids*	*Shales*
V_p/V_s (unitless)	2.05 - 2.40	1.97 – 2.60	1.80 – 2.61
P – Impedance ((m/s*(g/cc))	5600 - 6300	5700 - 6800	5500 – 8500
S – Impedance ((m/s*(g/cc))	2250 – 300	1900 - 3250	1900 – 3250
Lambda- Rho (GPa*g/cc)	16 – 20	17 - 23	19 – 27.5
Mu- Rho (GPa*g/cc)	4 – 9.5	3.3 - 12	3.9 – 16
Density code (g/cc)	1.9090 -1.9781	2.0126 – 2.1161	2.1506 – 2.2541

Table 3: M-3 Crossplot Analysis

Elastics parameters	*Hydrocarbon charged sand*	*Wet sands/fluids*	*Shales*
V_p/V_s	2.050 – 2.30	2.000 – 2.500	2.000 – 2.550
P – Impedance ((m/s*(g/cc))	5500 – 6500	5300 – 7000	5400 -7300
S – Impedance ((m/s*(g/cc))	2450 – 3000	2170 - 3400	2170 – 3400
Lambda- Rho (GPa*g/cc)	19.3 – 22.5	20.5 – 26.7	21.5 – 28.5
Mu- Rho (GPa*g/cc)	5.3 – 10.0	4.3 – 11.5	5.0 – 12.5
Density code (g/cc)	2.0459 –.0987	2.1251 – 2.2043	2.2307 – 2.3099

Tables 1, 2 and 3 represent M-1, M-2 and M-3 oil well locations showing the ranges of various lithologies/fluids clusters; Hydrocarbon charged sands, wet sands/fluids and shales by cross plotting derived elastic parameters using density as a colour code in discriminating the separation of clusters within M-5000. Using the crossplot space of figure 5, 6 and 7, it is observed that clusters related to hydrocarbon charged sands have the lowest values of all elastic parameters combined.

6. Conclusion

Well log crossplots of a 3D data set from the M oil field were carried out. The objective of the study was to image the M- field subsurface to detect the hydrocarbon accumulation using M-5000 with integration of three wells (M-1, M-2 and M-3). Analysis of well log crossplots suggest that, in M-Oil field, figure 6 (a and c) have had the lowest values of V_P/V_S (2.05-2.40), I_P (5600-6300 (m/s*(g/cc)), λρ (16-20 (GPa*g/cc)), and μρ (4-9.5 (GPa*g/cc)). However, the low value of V_P/V_S, I_P, λρ, and μρ perhaps I_S corresponds to hydrocarbon (gas) saturation within the fields of study. Also the high value of all these parameters might be due to shales/wet sands intercalations. From the cross plots analysis, V_p/V_s, P-impedance, Lamda-rho and Mu-rho attributes were found to be most robust in lithology and fluid discrimination within the reservoir. The V_p/V_s-Ip technique was able to identify gas sands in the field because of the separation in responses of both Vp/Vs and Ip sections to gas sands versus shale. The Lambda-Mu-Rho (λ-μ-ρ) technique confirmed the gas sands delineation, because of the separation in responses of both λρ and μρ sections to gas sands versus shale. Low values of Lambda-Rho (λρ), Vp/Vs, Ip, associated with moderate to high values of Mu-Rho (μρ), indicate the presence of hydrocarbons within the sand reservoirs (HD5000). According to Akpan *et al.* (2022), these results now confirm that this approach can be applied with confidence in delineating hydrocarbons sands in mature fields within the Niger Delta Basin and thereby increasing production from such fields.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Human and Animal Rights

This article does not contain studies with human or animal subjects.

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