DISCRIMINATION OF RESERVOIR FLUID CONTACTS USING COMPRESSIONAL AND SHEAR WAVE VELOCITY

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ABSTRACT

Improved fluid detection and lithology discrimination using rock properties and attributes cross plots have been attempted using well log data in an Onshore Niger Delta field. Rock properties and attributes were extracted using empirical rock physics models on well logs and used to validate their potentials as pore fluid discriminants. These rock properties and attributes were cross plotted for the primary purpose of investigating their sensitivity to fluid and lithology in cross plot space. V_p and V_s logs were derived from the inverse of interval transit times of sonic and dipole shear logs respectively. V_p/V_s ratio, acoustic impedance and porosity were derived from V_p, V_s and density logs using appropriate relations. The identified depth of reservoir of interest (A2) for Well A and B ranges from 5842 ft to 5964 ft and 5795 ft to 5936 ft respectively. The properties cross plotted comprise V_p *vs* V_s, V_p/V_s *vs* I_p, V_p/V_s *vs* Porosity, V_p/V_s *vs* Density and V_p *vs* Density. V_p *vs* Density cross plot revealed that the reservoir consists of sand lithology with intercalated shale. V_p *vs* V_s shows a linear relationship and does not discriminate fluid in the reservoir. V_p/V_s ratio *vs* I_p distinguish A2 into hydrocarbon, brine and shale zones. V_p/V_s ratio *vs* density and porosity crossplots distinguishes the A2 into gas, oil, brine and shale zones. The analysis validates the fact that V_p/V_s ratio and their combinations cross plots are more sensitive and robust for fluid discrimination. It also reveals that the ratio of V_p/V_s is more sensitive to change of fluid type than the use of V_p or V_s separately.

KEYWORDS: Crossplot, Reservoir, Porosity, Acoustic Impedance, Density

INTRODUCTION

In reservoir characterization, the prediction of elastic properties such as density, P- and S-wave velocities, as well as their relations to rock properties such as lithology, porosity or fluid content, is of critical importance. This analysis also constitutes a crucial step for different applications such as seismic modeling, amplitude versus offset (AVO) variations. These techniques are used to alter well curve to reflect a change of fluid type. It generates fluid scenarios of different pore fills, which might explain an observed amplitude variation with offset (AVO) anomaly (Veeken and Rauch, 2006).

In petrophysical evaluations, compressional wave velocity data are very useful in identifying lithology, porosity and pore fluids. Shear wave velocity data are also useful for mineral identification. Velocity is one of the most important petrophysical parameters used in oil-field optimization or other geophysical surveys to easily determine and predict horizons, faults, facies, unconformities, stratigraphic boundaries, geologic structures, fluid contents etc. (Tamunobereton-ari *et al.,* 2010).

Identification of lithology, porosity and pore fluids in a reservoir requires data on *P*-wave transit time. *S*-wave data are also useful for mineral identification and porosity determination. There is evidence that *S*-wave transit time may be useful for fluids identification.

Combining *S*-wave data and *P*-wave data will help in fluid type identification especially gas reservoirs (Hamada, 2004).

The use of *P*-wave and *S*-wave is very helpful in identifying fluids type in porous reservoir rocks. It is found that *P*-wave velocity decreases and *S*-wave velocity increases with the increase of light hydrocarbon in place of brine saturation. This is true within the range of free gas or free hydrocarbon saturation. In this work, the technique of *Vp/Vs* was used as fluid identification tool and how the *Vp/Vs* cross plot can distinguish between fluids.

Cross plotting appropriate pairs of attributes so that common lithologies and fluid types generally cluster together allows for straightforward interpretation. The off-trend aggregations can then be more elaborately evaluated as potential hydrocarbon indicators (Chopra *et al.*, 2006).

Cross plotting of rock properties from well logs is one very convenient and efficient way to look at two rock properties and their attributes (combination of rock properties) at the same time (Buriank, 2000). It also shows quit decisively which rock properties and their attributes will be helpful to discriminate gas in a particular reservoir. Rock properties are those physical properties of a rock such as P-wave and S-wave velocity, bulk density, porosity, rigidity, that will affect how seismic wave travel through the rock (Dewar, 2001).

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In this work, cross plotting techniques of rock properties (particularly Vp and Vs) has been extracted and used to validate their potential as pore fluid discriminant using logs in an Onshore field.

1.2   LOCATION/GEOLOGY OF THE STUDY AREA
The four well logs (Well A, B, C & D) used in this study are from 'X' field. It is located in the costal swamp depobelt of Niger Delta (Figure 1). It lies within the concession of Shell Petroleum Development Company of Nigeria. The field is located between located 3º - 6ºN and 5º- 8ºE and situated on the West African continental margin, at the apex of the gulf of Guinea, which formed the site of a triple junction during continental breaking up in the cretaceous age (Whiteman, 1982). The Niger Delta is one of the world's largest tertiary Delta systems and an extremely prolific hydrocarbon province (Reijers *et al.*, 1996). Its present morphology is that of wave - dominated delta with a smoothly seaward – convex coastline traversed by distributaries. From apex to coast, the aerial portion stretches more than 300 km (Reijers *et al.*, 1996), covering an area of 75,000 km^2 (Doust and Omatsola, 1990; Tuttle *et al.*, 1999). Below the Gulf of Guinea two enormous lobes protrude a further 250 km (Doust and Omatsola, 1990; Tuttle *et al.*, 1999) into deep water.
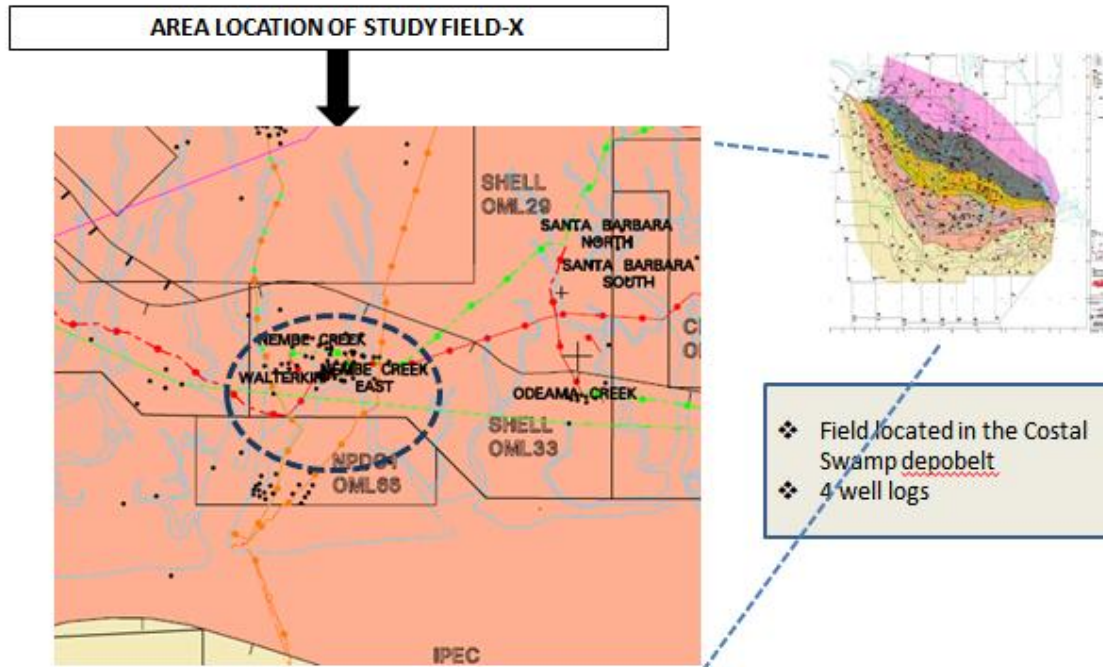

Figure 1: Map of Niger Delta showing the study Area X- FIELD.

2.0   Literature Review
Numerous studies have shown that the ratio of compressional wave velocity (Vp) to shear wave velocity (Vs) is indicative of lithology. Pickett (1963) was one of the first to suggest using Vp/Vs as a lithologic indicator, by determining Vp/Vs values from core measurements from different types of rocks, such as dolomite, limestone and sandstone. The knowledge of velocity at any depth is very important in the recognition of reflectors and refractors with dip or plane horizontal beds (Tamunobereton-ari *et al.,* 2011).

Banik *et al.,* (2010) alleviate the requirement for density by using the correlation of I_s or I_p and Young's modulus from log data, and using that relationship for computation of Young's modulus. They also demonstrated the determination of Young's modulus from seismic data by way of inversion.

Eastwood and Castagna (1983) studied full waveform sonic logs in Appalachian limestone and observed that shear wave amplitude was attenuated in shale zones, and thus it could be used for lithology discrimination.

Rafavich *et al.,* (1984) in a detailed laboratory study of velocity relationships with petrographic character in carbonates concluded that the (Vp/Vs) ratio successfully differentiated limestone and dolomite.

Rock physics approaches have also been used for predicting elastic properties. Greenberg and Castagna (1992) predict Vs using Biot-Gassmann theory under the assumption that P- and S-wave velocities are related robustly and that nearly linear mixing laws for solid rock constituents are valid.

Xu and White (1996) predict S-wave velocity using a combination of Kuster and Töksoz (1974) theory and the differential effective medium theory, incorporating pore aspect ratios to characterize the compliance of the sand and clay components.

Wang (2000) developed another empirical equation that predicts S-wave velocity using the bulk density of the saturated rock, the pore fluid modulus and the P-wave velocity, allowing for other fluids besides water to fill in the pore space.

Shear waves are slower than compressional waves, polarized and cannot propagate through fluids.

making converted-wave exploration useful for fluid and lithology discrimination, imaging structure through gas clouds and fracture detection by analysis of shear wave splitting, among other applications (Garotta *et al.,* 2002). The rock properties obtained from sonic and density logs can also be used to construct the reflection coefficients of the various reflectors or geologic boundaries (Henry, 2006). Dabagh *et al.,* (2011) have shown a comparison of   and   , and that   comes out as a superior attribute for fluid detection.

3.0   METHODOLOGY

The proposed methodology comprised of the following stages: well-log conditioning, attribute generation from log data and crossploting. However, there are other processes that shall be involved.

The proposed workflow for this work is shown in figure 2.
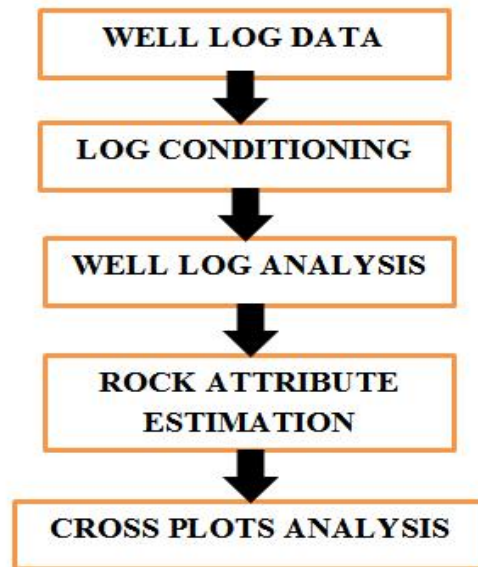
Figure 2: Summarized Workflow showing the proposed methodology

In the end, the results from the four stages shall be analyzed in other to delineate fluids in the reservoir A2000.

The methodologies that shall be employed are described as in the following sections.

3.1   Well Log Loading and Quality Control

The well logs, each with a basic petrophysically QC'ed (Quality Checked) log suite, was loaded and compiled in a new project. Also, other data imported included directional survey and well markers. The logs shall be de-spiked, filtered, edited to remove spurious events reduce the scatter in the lithology, fluid and cross plot analyses. The median filter shall be applied iteratively to the logs in order to remove high frequency noise from the sonic log using one or more input logs acquire from the well without increasing the high frequency geologic component of the surface.

3.2   Well Log Analysis

The next step will be to evaluate the well logs for petrophysical properties to determine reservoir zones with considerable hydrocarbon saturation. The wells shall be analysed in terms of fluid type, fluid contact and lithology. Hydrocarbon-water-contact (HCWC) analysis and hydrocarbon saturation estimation based on well logging data shall be done too.

3.2.1   Lithology Discrimination

The wells shall be analysed for lithology. Gamma ray logs will be used to delineate shale/sand lithologies. High gamma ray value indicates shale lithology.

3.2.2   Hydrocarbon-Water-Contact (HCWC) Analysis

Resistivity logs are used to determine OWC and GWC depth in a well bore. Resistivity logs are used to calculate Water saturation (Sw), and if there is a significant decrease in the Sw values, that depth is defined as the fluid contact depth.

3.3   Well Log Attribute - Cross Plot Analysis

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 interpreted as the presence of hydrocarbon or other fluids and lithologies. Cross plot analysis are carried out to determine the rock properties / attributes that better discriminate the reservoir (Omudu and Ebeniro, 2007).

The V_P/V_S ratio 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).

Acoustic impedance versus V_P/V_S ratio contrast can show the position of gas-sand, water-sand and shale in a V_P/V_S versus impedance crossplot as shown
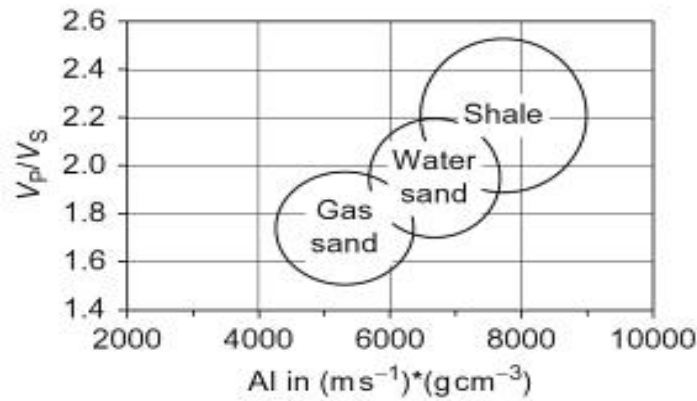
Figure 3: Position of gas sand, water and shale in Vp/Vs versus acoustic impedance AI plot

Figure 4 below shows a cross plot based on a figure from Odegaard and Avseth, 2004.

It demonstrates the difference between sand and shale, the change of properties from pore fluid gas to water and the influence of porosity.
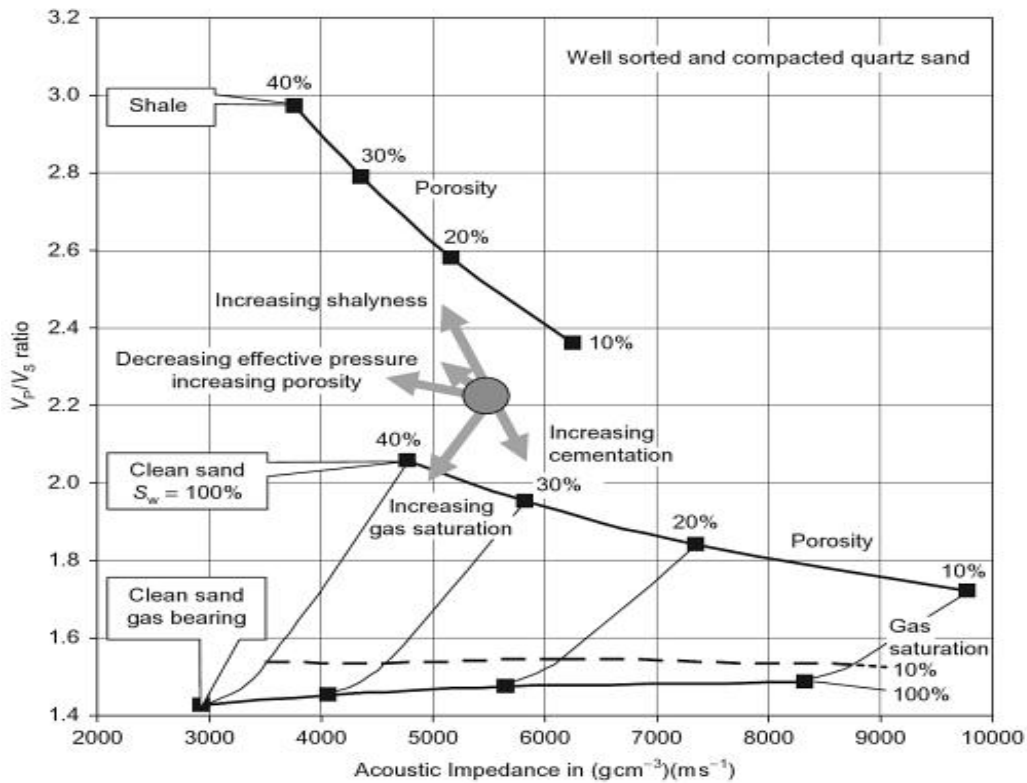

Figure 4: Crossplot V_P/V_S versus acoustic impedance AI, drawn after a figure 'RPT' from Odegaar and Avseth 2004. The effects of changing reservoir parameters on a point of the crossplot are here shown by arrows.

4.0 RESULTS AND DISCUSSIONS

In this section, the results of well log analysis, attribute generation and crossplots analyses are presented. The analysis of the various logs is vital to determine the lithology of the reservoirs and to study the reservoirs of interest. The attributes (P-impedance and VpVs ratio) are then generated from Vp, Vs and density logs. Several crossplots are carried out to see which best

well. Our analysis was performed on real field data from onshore Niger Delta.

4.1 Well Log Analysis

The logs used for the analysis (Figure 5 and Figure 6) include caliper, gamma ray, porosity, resistivity (LLD), density and P-wave for well A and well B, respectively. The depth of the reservoir of interest (A2000) ranges

for well B. The wells exhibit a dominantly shale/sand/shale sequence typical of the Niger delta formation. The hydrocarbon-water-contact (HCWC) occurs at a depth of 5866 ft in well A and at 5795 ft (TVD) in well B. The wells were analysed in terms of fluid type and lithology. Shale lithologies were delineated by the high gamma ray value. Regions showing low gamma ray, high resistivity, and low acoustic impedance are mapped as sand lithologies. Sand lithologies showing very low acoustic impedance and high resistivity are regions of high hydrocarbon saturation. However, the unavailability of neutron log and SP log has restrained further discrimination of the wells in terms of their fluid contacts and fluid type.
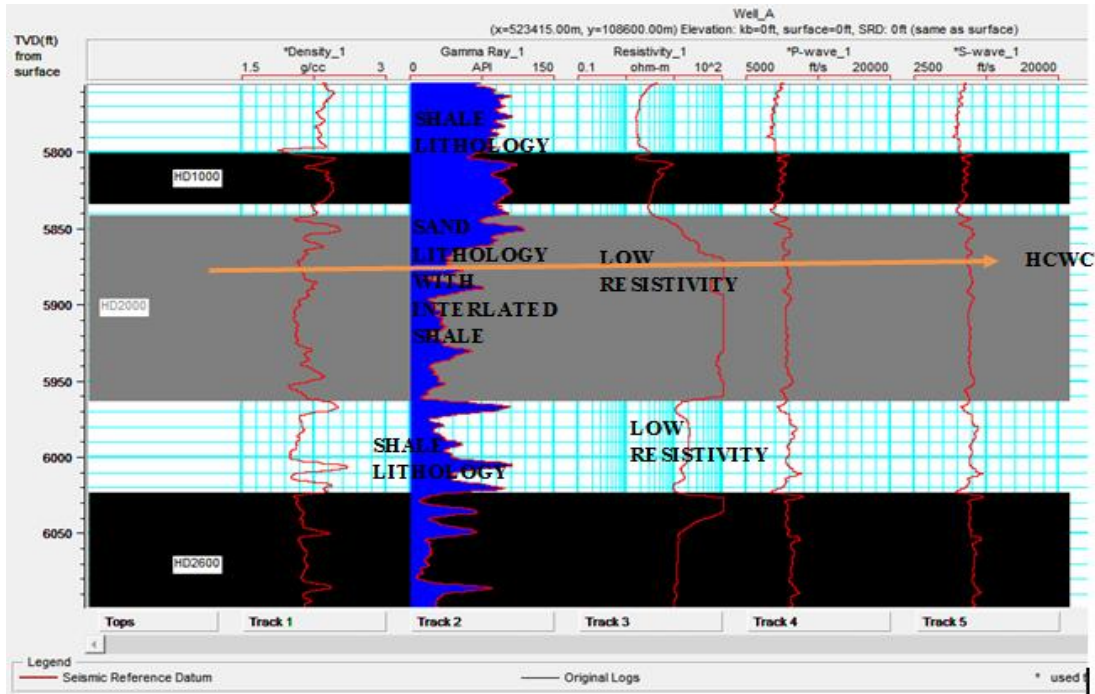
Figure 5: Well A and suite of Logs used in the analysis; Gamma ray, Porosity, Resistivity, Density, P-wave.
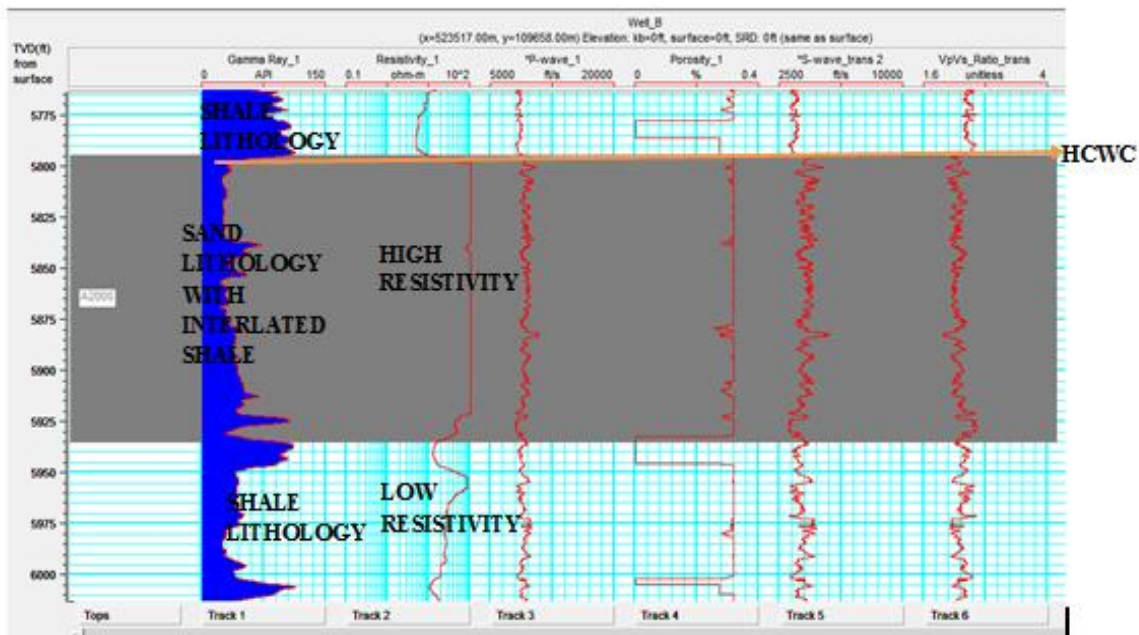

Figure 6: Well B and suite of Logs used in the analysis: Gamma ray, Porosity, Resistivity, density, P-wave

4.2   Well-Log Rock Attribute Estimation

In this stage, rock attributes were estimated from the input log data using rock-physics algorithms created in HAMPSON RUSSELL eLOG tool. Figure 7 shows the tool used in extracting rock attributes from input rock properties. These attributes include shear wave velocity from Castagna's equation, Vp/Vs ratio, porosity and acoustic impedance. Figures 8 and 9 show the computed attributes.
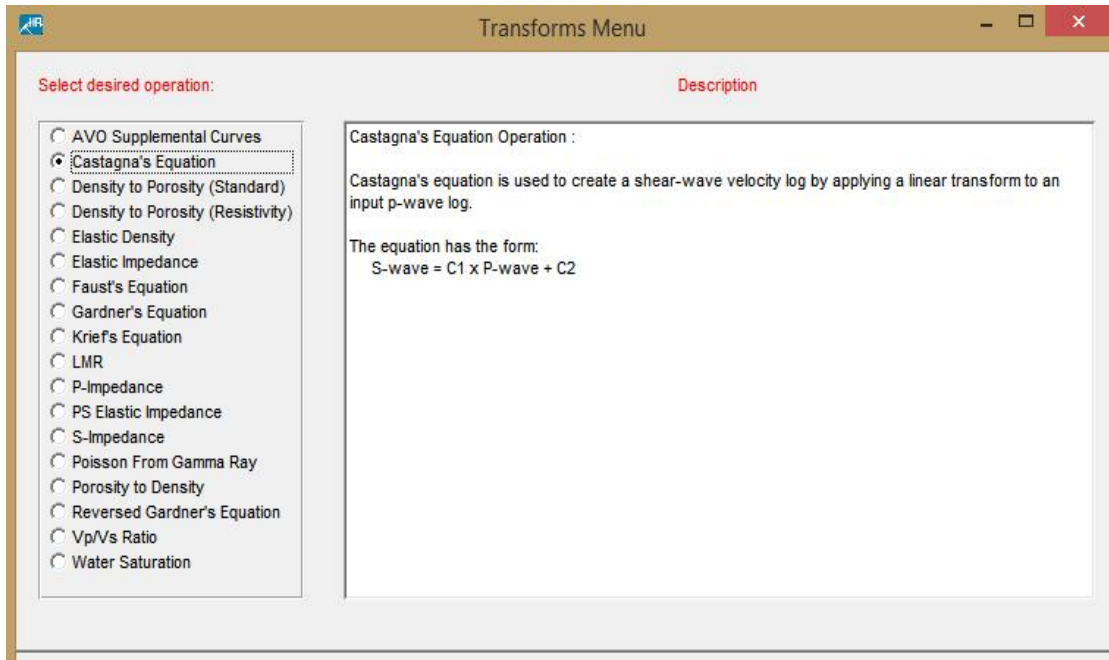
Figure 7: eLog tool used in generating rock attributes from input log data.
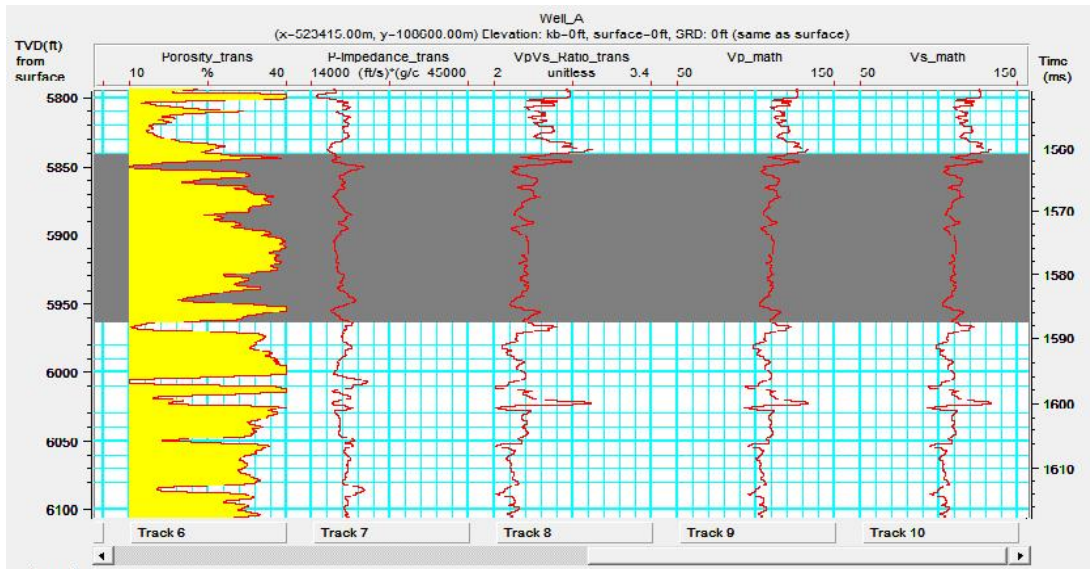
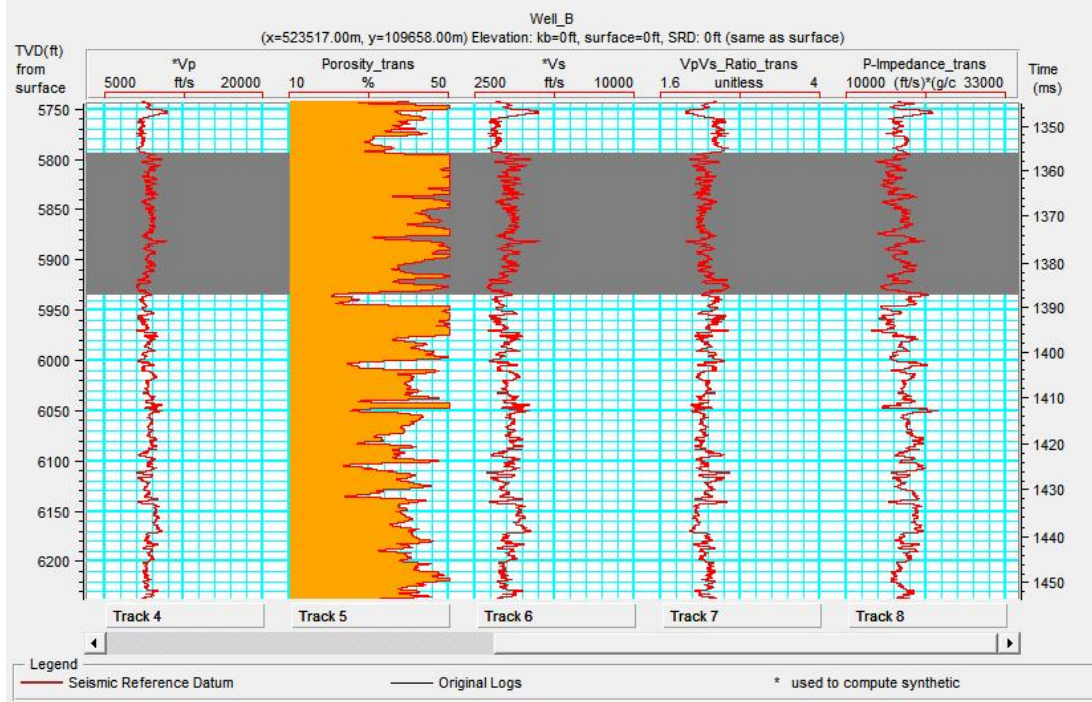**Figure 8:** Suite of logs for WELL A showing computed porosity, V_P/V_S ratio, P-Impedance and Vp and Vs logs

Figure 9: Suite of logs for WELL B showing computed, Vs, V$_P$/V$_S$ ratio, P-Impedance, and porosity logs.

Acoustic impedance is the product of p-wave velocity and density.

V$_p$ and V$_s$ are computed using the following formula:

V$_p$ = 1/ t$_c$ * 304800 (m/s)   (1)
V$_s$ = 1/ t$_s$* 304800 (m/s)

Where Compressional sonic t$_c$=1/V$_p$ (μs/ft) and Shear sonic t$_s$ = 1/V$_s$ (μs/ft)

The Shear wave velocity (V$_s$) was computed from the compressional wave velocity using the Castagna and Greenberg's (1993) relations for sand and shale beds as shown in equation 2.

Vs = (0.80416Vp) – 0.85588 (For Shale Beds)   (2)
Vs = (0.76969 Vp) – 0.86735 (For Sand beds)

Porosity was calculated as shown in equation 4.3 below

Fluid Density ρ_f [1.09000]   grams/cc   [Default Brine ▼]

Matrix Density ρ_{ma} [2.65000]   grams/cc   [Default Sandstone ▼]

Porosity Calculation:

$$\phi = \frac{\rho_{ma} - \rho_{obs}}{\rho_{ma} - \rho_f}$$

ρ_{obs} is the log density

4.3   Crossplot Analysis

Crossplots of the elastic properties based on the log measurements for each well were evaluated to better define the relationship between elastic parameters and rock properties, such as lithology and fluid.

The crossplots carried out include the following:

4.3.1   Vp versus Vs

The cross plot of shear wave velocity against compressional wave velocity showed a linear trends. Transit time decreases with increasing depths. Compressional wave velocity is greater than shear wave velocity in the study area (figures 10 and 11). This plot does not show fluid contacts but however shows the linear relationship between Vp and Vs.
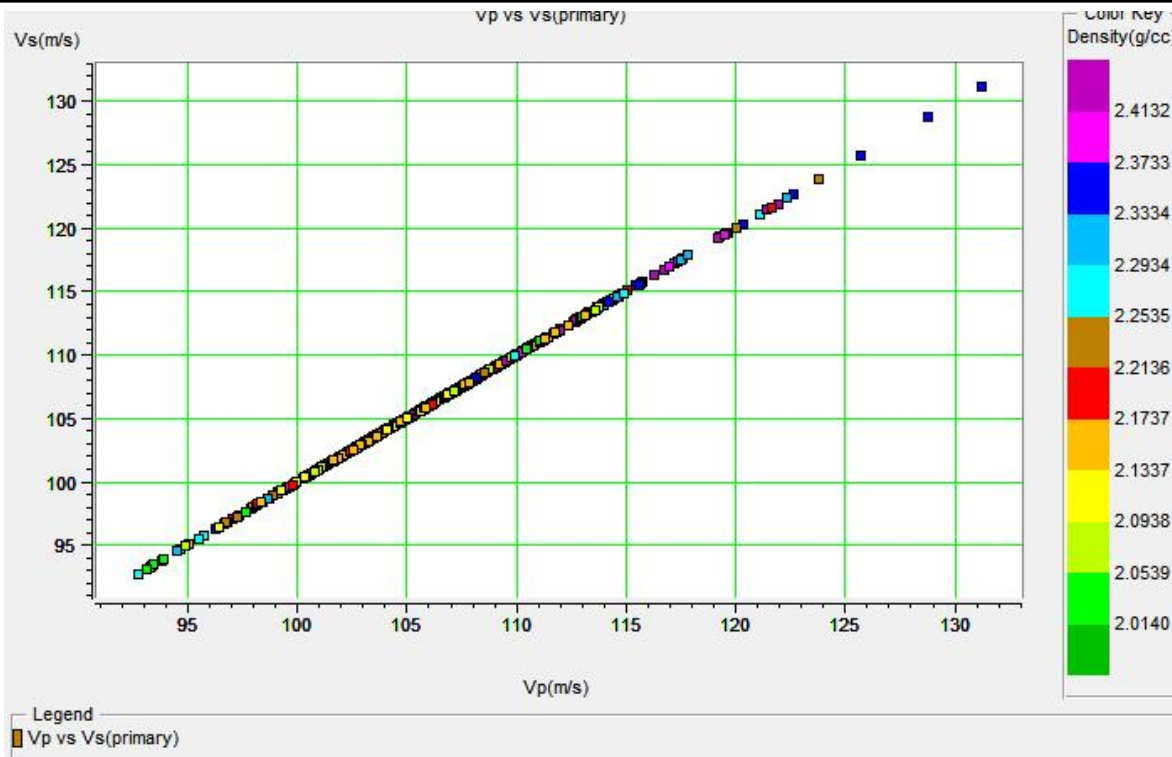
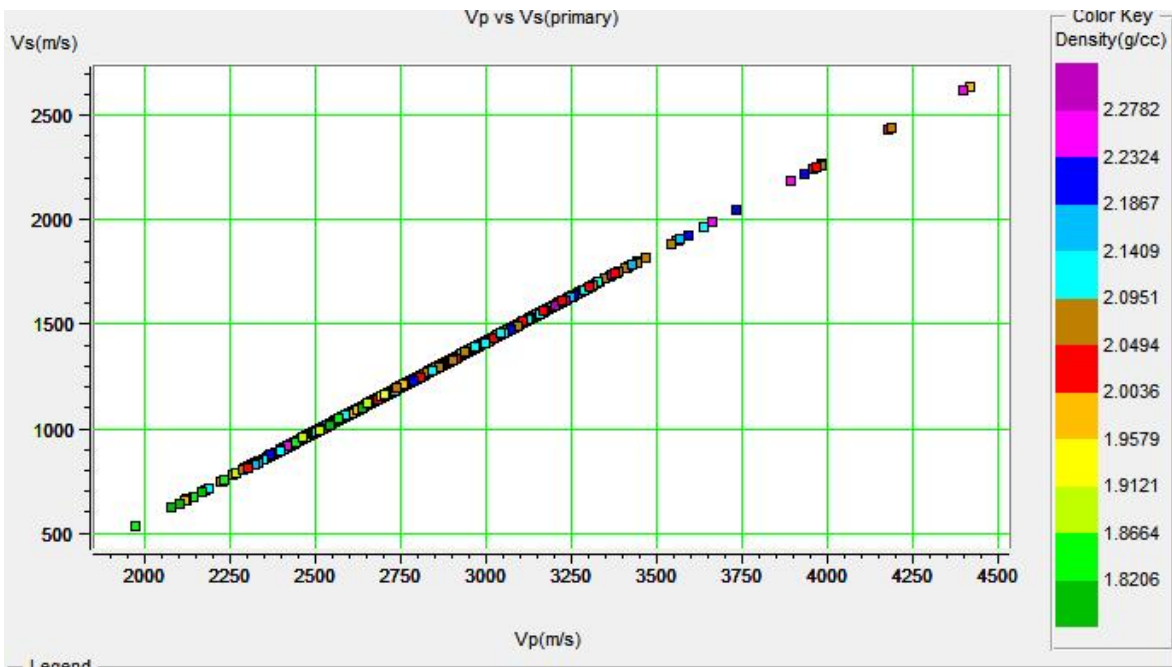**Figure 10:** Shear Wave Velocity (Vs) Vs Compressional Wave Velocity (Vp) for Well A

Figure 11: Shear Wave Velocity (Vs) Vs Compressional Wave Velocity (Vp) for Well B

4.3.2 V_P/V_S ratio vs Acoustic Impedance (P-Impedance)

The cross plot of V_p/V_s ratio against Acoustic impedance (Z_p) (Figures 12 and 13 for Well A and B respectively), distinguishes the A2 reservoir sands into three zones namely; hydrocarbon zone (Green ellipse), brine zone (red ellipse) and shale zone (purple ellipse). This crossplot show better fluid as well as lithology discrimination, indicating that Vp/Vs versus acoustic impedance attribute will better describe the reservoir conditions in terms of lithology and fluid content than Vp versus Vs.
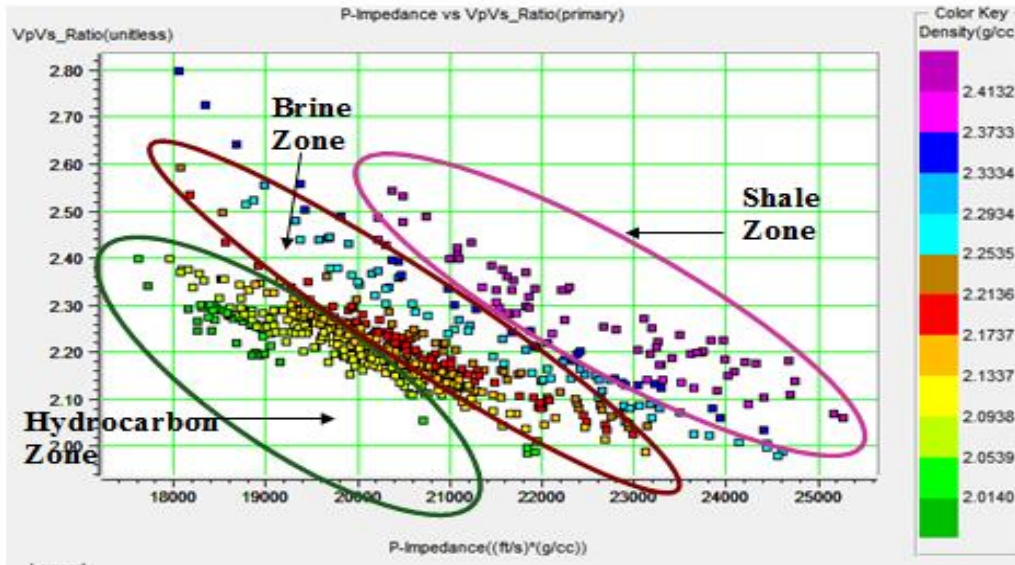
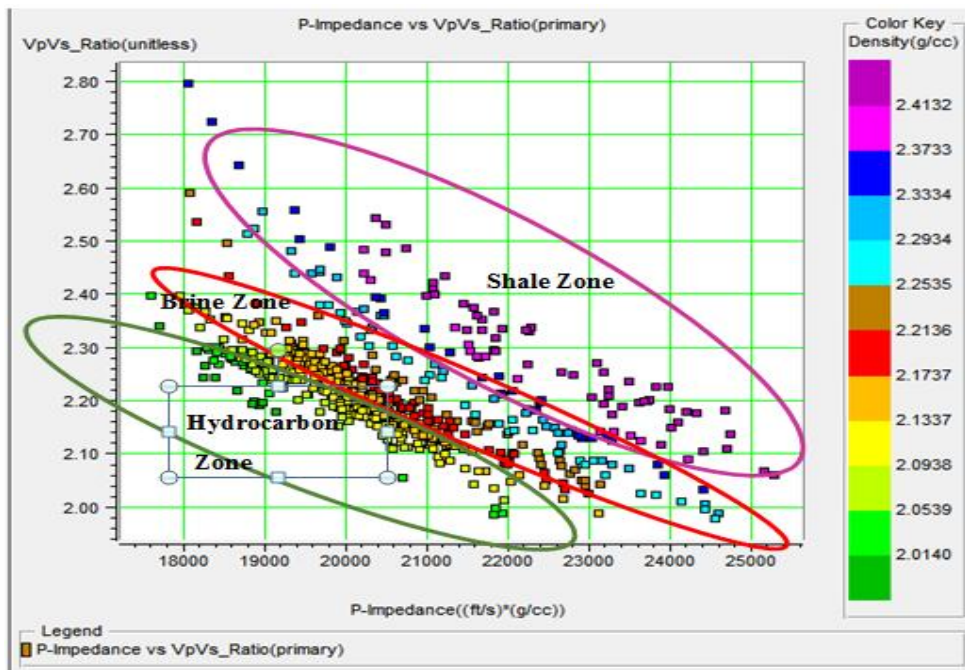**Figure 12:** Crossplot of Vp/Vs ratio vs. Acoustic impedance

Figure 13: Crossplot of Vp/Vs ratio vs. Acoustic impedance

4.3.3 Cross plots of Vp/Vs ratio Versus Porosity

Crossplot of Vp/Vs against Porosity distinguishes the A2 sand into four zones (Figure 14 and 15 for Well A and B respectively), inferred to be shale (purple), brine (blue), oil (red) and gas (green). The lowest values of Vp/Vs and Porosity associated with hydrocarbons are validated by low bulk density as observed from the color code. The plot also indicates that both Vp/Vs and porosity, show good discrimination in terms of fluid content.
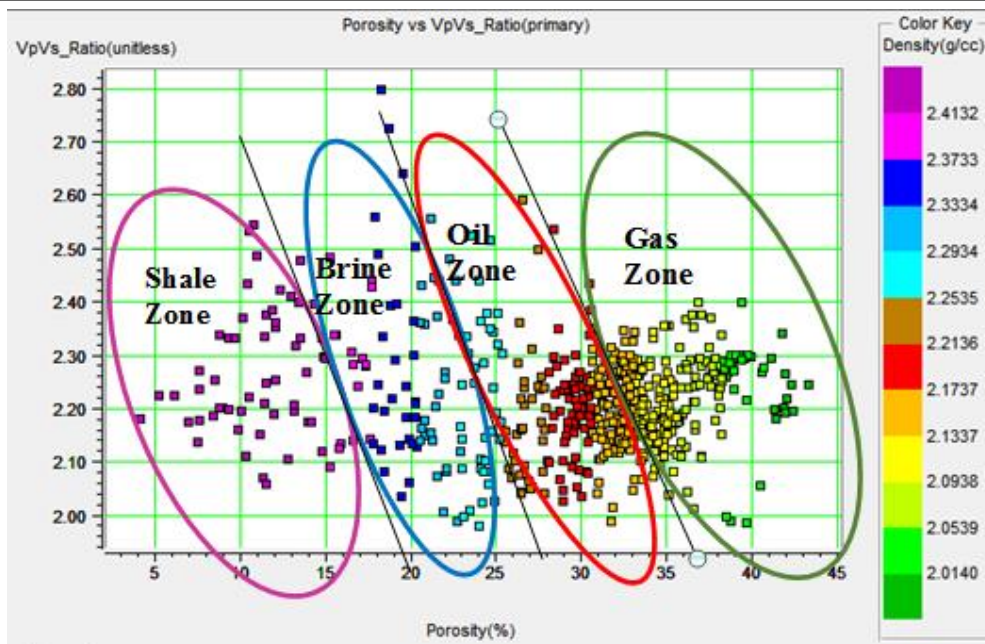
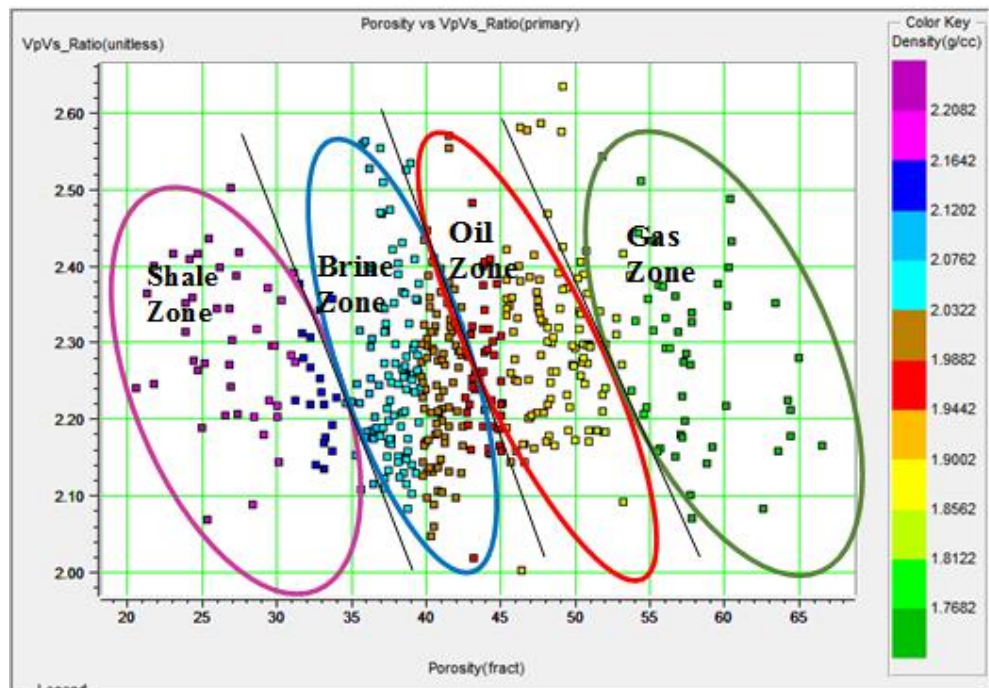**Figure 14:** Crossplot of Vp/Vs versus Porosity for Well A

Figure 15: Crossplot of Vp/Vs versus Porosity for Well B

4.3.4   Crossplot of VpVs ratio Versus Density

Crossplot of VpVs ratio against density distinguishes the A2 sand into four zones (Figure 16 and 17 for Well A and B respectively), inferred to be gas (green), oil (red), brine (blue) and shale (purple). The lowest values of Vp/Vs and density associated with hydrocarbons are validated by low bulk density as observed from the color codes. The plot also indicates that both Vp/Vs and density, show good discrimination in terms of fluid content.
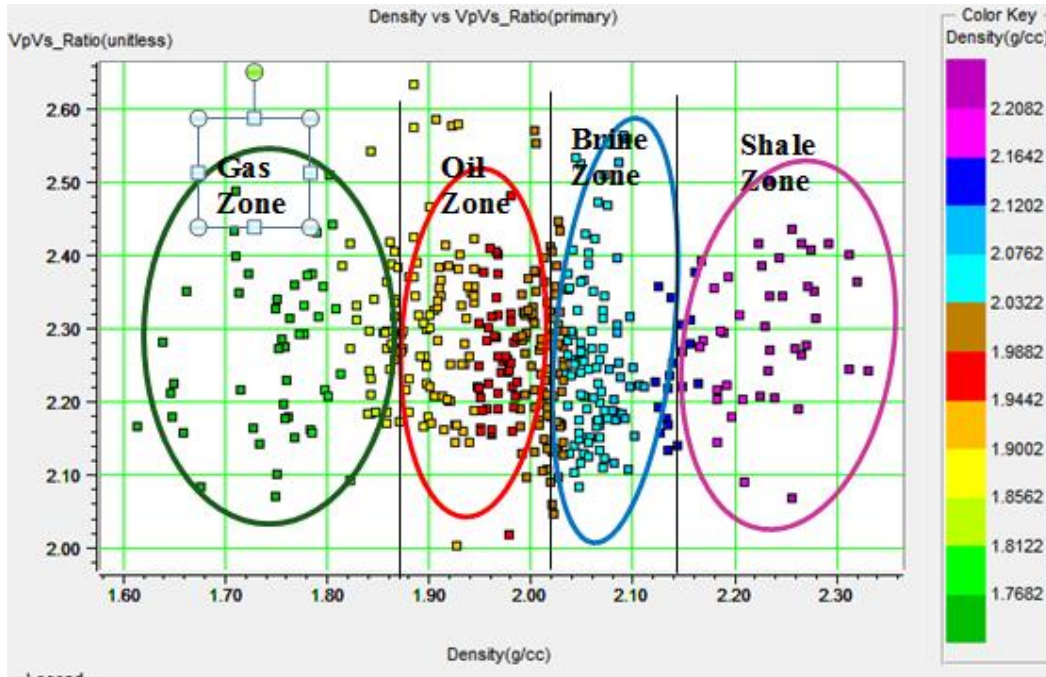
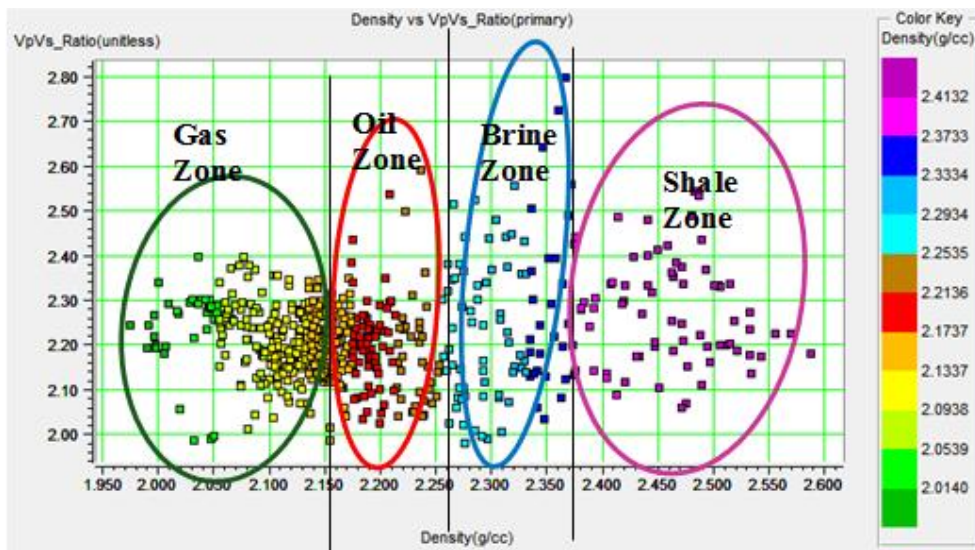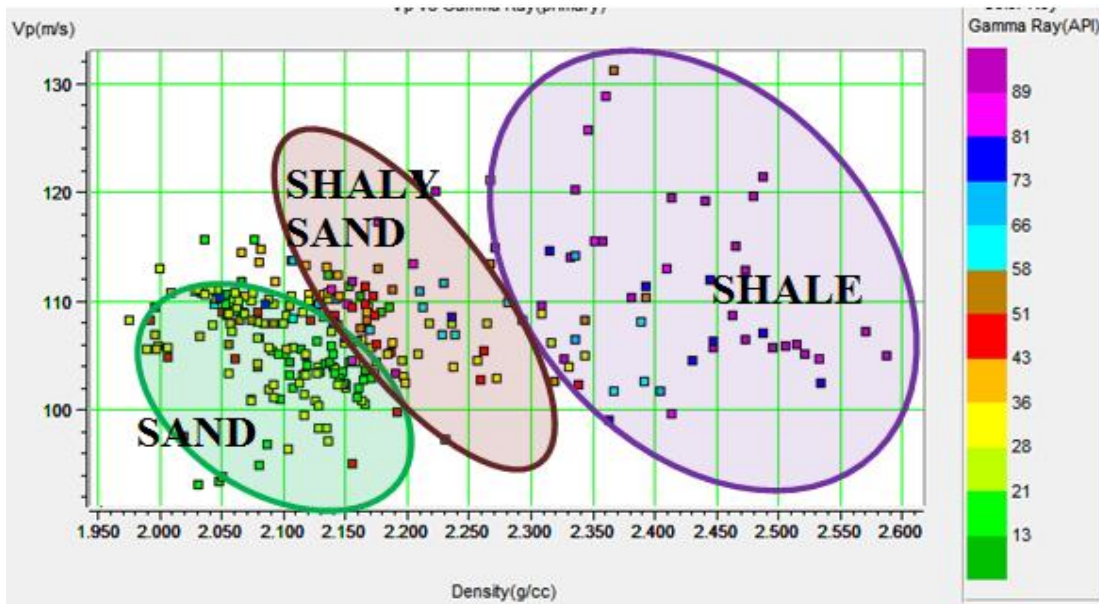**Figure 16:** Crossplot of Vp/Vs versus density for Well A

Figure 17: Crossplot of Vp/Vs versus Density for Well B

4.3.5   Crossplot of Vp ratio Versus Density Colour-coded to Gamma Ray

The Crossplot of Vp ratio Versus Density Colour-coded to Gamma Ray differentiates the reservoir based on lithology to sand, shale and shaly sand.

Within the target zone (A2), density is also a good lithological indicator, with densities lower than 2.2 cc/g and 1.9 cc/g (for well A and B respectively) indicating sands, and higher values corresponding to shaly sands and shales (Figure 18 and 19 respectively for Well A& B). Note how P-wave velocity values overlap for sands and shales within the target interval.

Figure 18: Cross plot of P-wave velocity versus density for Well A for reservoir A2. Note that there appears to be a separation between sand and shaly sand at 2.2 cc/g. Note how P-wave velocity values overlap for sands and shales within the target interval.
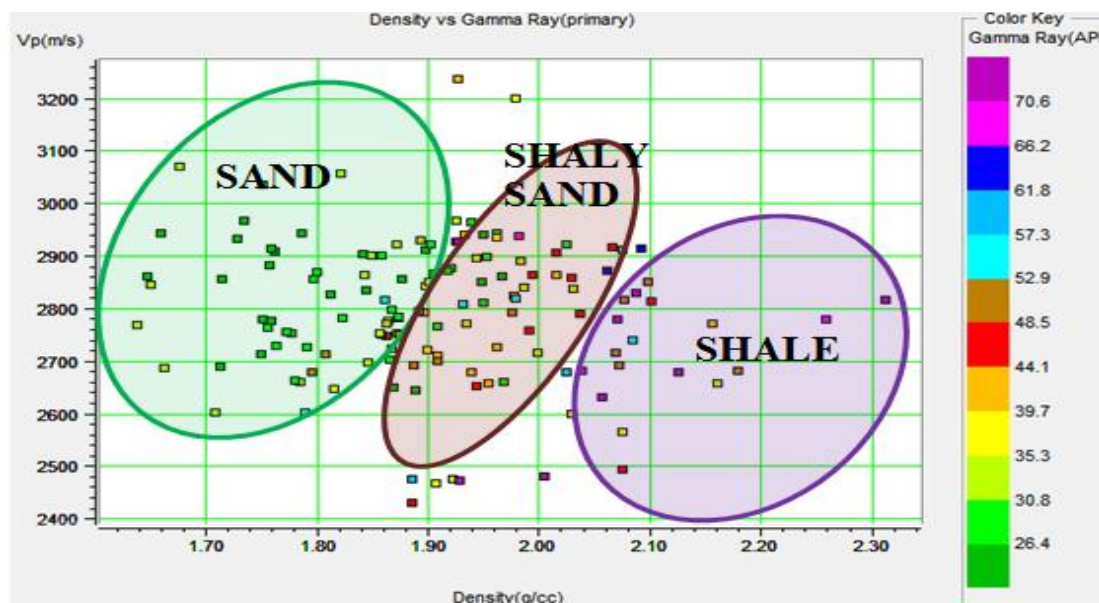
Figure 19: Cross plot of P-wave velocity versus density for Well b for reservoir A2. Note that there appears to be a separation between sand and shaly sand at 1.9 cc/g. Note how P-wave velocity values overlap for sands and shales within the target interval.

CONCLUSION

Rock attributes derived from well logs were analyzed in the cross plot domain to describe and characterize the reservoir in terms of fluid type present and lithology. V_p/V_s cross plot with other attributes is a good tool to identify fluid nature of a reservoir. It has been tested in this work in an Onshore Niger Delta field with different fluid types (oil, gas and water).

The rock properties and attributes were cross plotted for the primary purpose of investigating their

and V_s logs were derived from the inverse of interval transit times of sonic and dipole shear logs respectively. V_p/V_s ratio, acoustic impedance and porosity were derived from V_p, V_s and density logs using appropriate relations. The identified depth of reservoir of interest (A2) for Well A and B ranges from 5842 ft to 5964 ft and 5795 ft to 5936 ft respectively. The properties cross plotted comprise V_p vs V_s, V_p/V_s ratio vs I_p, V_p/V_s vs. Porosity, V_p/V_s vs Density and V_p vs Density. V_p vs Density cross plot revealed that the reservoir consists of sand lithology with intercalated shale. V_p vs V_s shows a

reservoir. V_p/V_s ratio *vs* I_p distinguish A2 into hydrocarbon, brine and shale zones. V_p/V_s ratio *vs* density and porosity crossplots distinguishes the A2 into gas, oil, brine and shale zones. The Acoustic impedance and V_p/V_s attributes were found to be most robust in lithology and fluid discrimination within the reservoir in the cross plot analysis.

This technique can also be effectively used as a reservoir anomaly tool to check the behavior of the reservoir in the presence of fluids and artifacts. It can also be used as a QC tool on the reliability of well log data.

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