CHARACTERIZATION OF RESERVOIR FLUIDS USING BODY WAVE VELOCITIES

O.I. HORSFALL,
AND
O.A. DAVIES

ABSTRACT.

Improved fluid detection and lithology discrimination using rock properties and attributes cross plots have been attempted using 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. Compressional wave velocity ($V_p$) and Shear wave velocity ($V_s$) logs were derived from the inverse of interval transit times of sonic and dipole shear logs respectively, acoustic impedance and porosity were derived from $V_p$, $V_s$ and density logs using appropriate relations. The identified depth of reservoir of interest (A2000) for Well A and B ranges from 1781m to 1818m and 1766m to 1809m respectively. The ratio of compressional wave to shear wave velocity also known as Poisson's ratio ($V_p/V_s$) is a key parameter in characterizing reservoir fluids. The properties cross plotted comprise: $V_p$ against $V_s$, $V_p/V_s$ against Ip, $V_p/V_s$ against Porosity, $V_p/V_s$ against Density and $V_p/V_s$ against Density. $V_p$ against Density cross plot revealed that the reservoir consists of sand lithology with intercalated shale. $V_p/V_s$ against Vs shows a linear relationship and does not discriminate fluid in the reservoir. $V_p/V_s$ against Ip distinguishes A2000 into hydrocarbon, brine and shale zones. $V_p/V_s$ against porosity and density crossplots distinguishes the A2000 into gas, oil, brine and shale zones. The analysis validates the fact that $V_p/V_s$ 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.

KEY WORDS: Reservoir, Well log, Petrophysical properties, Lithology Discrimination, Body Waves.

INTRODUCTION.

The prediction of elastic properties such as density, body waves which consists of compressional wave (P) - and shear (S)-wave velocities, as well as their relations to rock properties such as lithology, porosity or fluid content, is critically important in reservoir characterization. This analysis also constitutes acrucial step for different applications such as seismic modelling, amplitude versus offset (AVO) variations.

Compressional wave velocity data are very useful in identifying lithology, porosity and pore fluids in petrophysical evaluations. 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. (Tamunobereron-ari et al 2010). P-wave transit time data are very useful in identifying lithology, porosity and pore fluids. 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. (Omudu and Ebeniro, 2007) in their work established 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 paper, the technique of Vp/Vs is presented as fluid identification tool and field examples are presented to show 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 (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 (Burianyk, 2000). It also show 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).

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 (Chopra et al., 2006). The knowledge of shear and compressional wave velocities and Poison ratios can provide valuable information about lithology differentiation and physical properties of rocks including how rocks will deform under a given stress (Horsfall et al., 2014).

**METHODOLOGY**

The data used in this study consists of well log data suites from two wells from a coastal swamp depobelt field in the Niger Delta. The suite of wireline log data comprises of sonic log, density log, resistivity log, caliper log, and gamma ray log. The inverse of the interval transit times of the sonic logs were used to generate the compressional velocities for each well. Shear log data are not available but were generated from Castagna’s relation. The Castagna's relations is dependent on velocities and elastic moduli which are expressed in the equations below

\[ V_p = \left( \frac{\lambda + \frac{4}{3} \mu}{\rho} \right) \]  \hspace{1cm} \text{eq.1}

\[ V_s = \left( \frac{\mu}{\rho} \right)^{\frac{1}{2}} \]  \hspace{1cm} \text{eq.2}

\[ V_p^2 = \frac{\lambda + 2\mu}{\rho} = \frac{k + \frac{4}{3} \mu}{\rho} \]  \hspace{1cm} \text{eq.3}

\[ V_s^2 = \frac{\mu}{\rho} \]  \hspace{1cm} \text{eq.4}
\[ k = \frac{E}{3(1-2\sigma)} \quad \text{eq.5} \]
\[ \mu = \frac{E}{2(1+\sigma)} \quad \text{eq.6} \]
\[ \lambda = \frac{E\sigma}{(1+\sigma)(1-2\sigma)} \quad \text{eq.7} \]
\[ \frac{V_p^2}{V_s^2} = \frac{1-\sigma}{2-\sigma} \quad \text{eq.8} \]
\[ \sigma = \frac{0.5\left(\frac{V_p}{V_s}\right)^2-1}{\left(\frac{V_p}{V_s}\right)^2-1} \quad \text{eq.9} \]

Where \( \lambda \) = Lame’s Constant, \( k \) = Bulk Modulus, \( \rho \) = Density, \( \mu \) = Shear Modulus, \( \sigma \) = Poisson’s Ratio.

Equations (1) and (2) provide the link between seismic velocities and rock properties. The rock bulk modulus is strongly dependent on the pore fluid bulk modulus while the rock shear modulus may be unaffected by the fluids. The ratio of compressional-to-shear-wave velocity \( \left(\frac{V_p}{V_s}\right) \) is expected to be an excellent indicator of free gas in pore space. Poisson’s ratio is directly related to \( \left(\frac{V_p}{V_s}\right) \) by eq. 9.

Petrophysical analysis through conventional crossplot was done to relate two rock attributes. The zone of interest is typically a sand/shale/sand sequence. The method used in delineating the reservoir fluids comprise of the following stages: well-log conditioning, attribute generation from log data and crossplotting, which is presented in fig. 1.
Fig. 1 Workflow showing the methodology

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

**WELL LOG LOADING & QUALITY CONTROL**

The well logs, each with a basic petrophysically Quality Checked (QC'ed) log suite, was loaded and compiled in a new project. Also, other data imported include directional survey and well markers. The well markers are used in identifying the probable reservoir within the well logs. In practice, well logs contain several inherent problems especially problems of inversion. Efforts are thus made to check the data for quality control. 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.

**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.

**LITHOLOGY DISCRIMINATION**

The wells shall be analysed for lithology. This is based on the fact that logs respond to different lithologies. Gamma ray logs was used to delineate shale/sand lithologies. High gamma ray value indicates shale lithology. Shale lithologies cause the deflection of acoustic impedance curve to the right and resistivity to the far left due to its high conductive nature. Low gamma ray, high resistivity, and low acoustic impedance shall be mapped as sand lithologies. Shale volume logs represent the volume fraction as measured or inferred from formation properties. It can be calculated from gamma–ray logs. The lithologies (sandstone and shale) were identified using the gamma ray log with reference to sand/shale baseline. The percentage sand/shale is computed from the gamma ray log using the equation below:

The % (shale/sand) is computed from the gamma ray log as:

\[
\%\text{Shale} = \left( \frac{GR_{\text{log}} - GR_{\text{min}}}{GR_{\text{max}} - GR_{\text{min}}} \right) \times 100
\]

\[\text{eq.}\]

Where,

- \(\%\text{shale}\) = Percentage volume of shale in the formation
- \(GR_{\text{log}}\) = Gamma Ray Log Reading
- \(GR_{\text{max}}\) = Gamma Ray Log Reading in Shale Zone
- \(GR_{\text{min}}\) = Gamma Ray Log Reading in clean Sand Zone.
From the above equation,
\[ \%\text{sand} = 100\% - \%\text{shale} \quad \text{eq.2} \]

Lithological presumptions are made based on which percentage is greater than or equal to 50%

**HYDROCARBON-WATER-CONTACT (HCWC) ANALYSIS**
Resistivity logs are used to determine oil-water-contact (OWC) and gas-water-contact (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.

**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 goal of this rock physics analysis is to determine the feasibility of discriminating between reservoir fluids. To illustrate this point, the cross plot of \( V_p/V_s \) ratio 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 \( V_p/V_s \) ratio. P-impedance and \( V_p/V_s \) ratio relationship discriminate both fluid and lithology. 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 (Mallick, 1993). P-impedance shows a better discrimination which can better describe the reservoir conditions in terms of lithology and fluid content than the \( V_p/V_s \) ratio.

**RESULTS AND DISCUSSIONS**
The results of well log analysis, attribute generation and cross plots 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 \( V_p/V_s \) ratio) are then generated from \( V_p, V_s \) and density logs. Crossplot analyses are useful in differentiating stuck between fluid and lithologies in reservoirs (Omudu and Ebeniro, 2007). Several crossplots are carried out to see which best discriminates the fluid in the reservoir of interest in the well. Our analysis was performed on real field data from onshore Niger Delta.

The logs used for the analysis (Figure 2 and Figure 3) 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 from 1781m to 1818m for well A and 1766m to 1809m 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 depth of 1788m in well A and at 1766m (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. Shale lithologies cause the deflection of acoustic impedance curve to the right and resistivity to the far left due to its high conductive...
nature. 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.

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 4. 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 5. and 6 show the computed attributes.
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:

$V_s$ versus $V_p$

The cross plot of shear wave velocity against compressional wave velocity showed a linear (Figures 7 and 8). Transit time decreases with increasing depths. Compressional velocity is greater than shear wave velocity in the study area. This plot does not show fluid contacts but however shows the linear relationship between $V_p$ and $V_s$. 

Figure 5. Suite of logs for WELL A showing computed porosity, $V_p/V_s$ ratio, P-Impedance and $V_p$ and $V_s$ logs for well A

Figure 6. Suite of logs for WELL B showing computed, $V_s$, $V_p/V_s$ ratio, P-Impedance, and porosity logs, for well B

Figure 7. Shear Wave Velocity ($V_s$) Vs Compressional Wave Velocity ($V_p$) for Well A

Figure 8. Shear Wave Velocity ($V_s$) Vs Compressional Wave Velocity ($V_p$) for Well B $V_p/V_s$ ratio vs Acoustic Impedance (P-Impedance)
The cross plot of $V_p/V_s$ ratio against Acoustic impedance ($Z_p$) (Figure 9. and 10. for Well A and B respectively), distinguishes the A2000 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 $V_p/V_s$ versus acoustic impedance attribute will better describe the reservoir conditions in terms of lithology and fluid content than $V_p$ versus $V_s$.

Cross plots of $V_p/V_s$ ratio Versus Porosity

Crossplot of $V_p/V_s$ against Porosity distinguishes the A2000 sand into four zones (Figure 11. and 12. for Well A and B respectively), inferred to be shale (purple), brine (blue), oil (red) and gas (green). The lowest values of $V_p/V_s$ and Porosity associated with hydrocarbons are validated by low bulk density as observed from the color code. The plot also indicates that both $V_p/V_p$ and porosity, show good discrimination in terms of fluid content.
Crossplot of Vp/Vs ratio Versus Density
Crossplot of Vp/Vs ratio against density distinguishes the A2000 sand into four zones (Figure 12. and 13 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.

Crossplot of Vp ratio Versus Density Color-coded to Gamma Ray
The Crossplot of Vp ratio Versus Density Color-coded to Gamma Ray differentiates the reservoir based on lithology to sand, shale and shaly sand. Within the target zone (A2000), 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 14 and 15 respectively for Well A & B). Note how P-wave velocity values overlap for sands and shales within the target interval.
Figure 14. Cross plot of P-wave velocity versus density for Well A for reservoir A2000. 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 15. Cross plot of P-wave velocity versus density for Well B for reservoir A2000. 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 several field examples with different fluid types (oil, gas and water).

The 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 (A2000) for Well A and B ranges from 1781m to 1818m and 1766m to 1809m 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 linear relationship and does not discriminate fluid in the reservoir. $V_p/V_s$ ratio vs $I_p$ distinguish A2000 into hydrocarbon, brine and shale zones. $V_p/V_s$ ratio vs density and porosity crossplots distinguishes the A2000 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 artefacts. It can also be used as a quality control (QC) tool on the reliability of well log data.

ACKNOWLEDGEMENT

The authors would like to express our appreciation to Shell Petroleum Development Company (SPDC) Rumubiakani, Port Harcourt Nigeria, for providing the suits of well logs and other relevant materials for the purpose of this study.

REFERENCES


