Prediction of Lithology using the Ratios of Compressional and Shear Wave Velocities and their Travel Times

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ABSTRACT

The ratio of compressional wave (V_p) to shear wave (V_s) velocities, and the ratio of their travel times are important parameters for interpretation of geophysical field data. Recent studies have emphasized the role played by pore geometry in controlling V_p/V_s. To infer lithologies, the ratios of V_p/V_s and $\frac{T_s}{T_p}$ were cross-plotted. V_p/V_s ranges from 0.0706 to 2.568 m/s and $\frac{T_s}{T_p}$ varies from 0.483 to 1.655 m/s. These variations were due soil composition, total porosity and pore geometry. The various lithologies inferred through this study conformed to those obtained from the field.

(Keywords: lithology, porosity, shear, compressional, velocity, travel time)

INTRODUCTION

Knowledge of P-wave velocity is useful; it is a function of three separate properties of the rock and is only a very ambiguous indicator of rock lithology. The V_p/V_s ratio, however, is independent of density and can be used to derive Poisson's ratio, which is a much more diagnostic lithological indicator (Kearey et al., 2002). According to Hyndman (1979), the ratio for velocity of compressional waves V_p to the velocity of shear V_s is an important parameter for interpreting geophysical field data in terms of both structures and lithology. The plots by Tosaya (1982) of empirical relation for V_p in shaly rocks to 100 % clay and zero porosity. The classic paper by Pickett (1963) popularized the use of the ratio of compressional to shear wave velocities as a lithology indicator.

The V_p/V_s ratio is a key parameter for lithology and fluid prediction. In an oil layer, compressional wave velocity decreases as shear wave velocity increases (Bahremandi et al., 2012). Compressional wave velocity data are very useful in identifying lithology, porosity and pore fluids in petrophysical evaluations.

The seismic velocity ratio (compressional and shear wave velocity ratio, $\frac{V_p}{V_s}$ is especially sensitive to the fluid in the pores existing in the sedimentary rocks. Particularly, the $\frac{V_p}{V_s}$ ratio in the gas saturated environments is much lower than liquid saturated environments (Tatham, 1982). In this paper, the technique of V_p/V_s and $\frac{T_s}{T_p}$ ratios are presented as lithological identification tool and field examples are presented.

GEOLOGY OF THE STUDY AREA

The study area named "Benin River Field" is located in the Niger Delta of Nigeria. It belongs to an active oil company in Nigeria. The Niger Delta is situated on the Gulf of Guinea on the west coast of Central Africa within latitude 4^o and $8^o\ N$ and longitude 5^o and $8^o\ E$. During the tertiary, it built out into the Atlantic Ocean at the mouth of the Niger-Benue system and covers an area of catchment that encompasses more than a million square kilometers of predominantly savannah covered with low land.

The Delta is one of the world's largest, with the sub-aerial portion covering about 75,000 Km^2 and extending more than 300 km from the apex to mouth. It is composed of regressive edge of clastic sediments which compacted to reach maximum thickness of about 12 km. The geological history of the Delta shows that its structure and stratigraphy have been controlled by interplay between rates of sediments supply and subsidence. The sequence is extensively affected by syn-sedimentary and post sedimentary faults; the most of which can be traced over considerable distances along strikes. The Niger Delta forms one of the world's hydrocarbon provinces, with proven estimated recoverable reserves of approximately 26 bbl of oil.

MATERIALS AND METHODS

Basic Theory of Seismic Method

If at a point on the earth or near the surface, there is a disturbance or shaking of the earth, the disturbance will be propagated to the earth's interior like wave and decreases in amplitude with depth. The travel time of the seismic waves are measured from the response of the wave that return to the surface after reflection or refraction from geological boundaries within the layered earth (Figure 1). The time necessary for the seismic energy to reach the detector (geophone) is the fundamental parameter that is studied in seismic exploration.

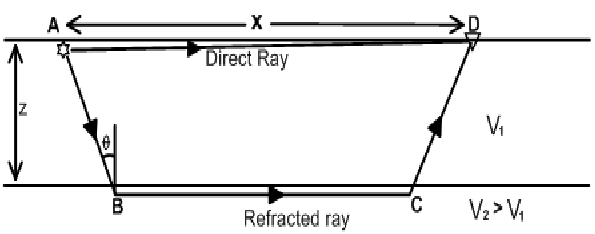

Figure 1: Direct, Reflected and Refracted Ray Paths from a Near-surface Source to a Surface Detector in the case of a Simple Two-layer Model.

There are two groups of seismic waves: body waves and surface waves. The surface waves are the Love and the Rayleigh waves. These are horizontally polarized waves which travel along boundaries of two dissimilar media. Body waves can propagate through the internal volume of an elastic solid and is of two types. *Compressional waves* (the longitudinal, primary or *P-waves*) propagate by compressional and dilational uniaxial strains in the direction of wave travel. Particle motion associated with the passage of a compressional wave involves oscillation, about a fixed point, in the direction of wave propagation. *Shear waves* (the transverse, secondary or *S-waves* of earthquake seismology) propagate by a pure shear strain in a direction perpendicular to the direction of wave travel (Figure 2 a & b).

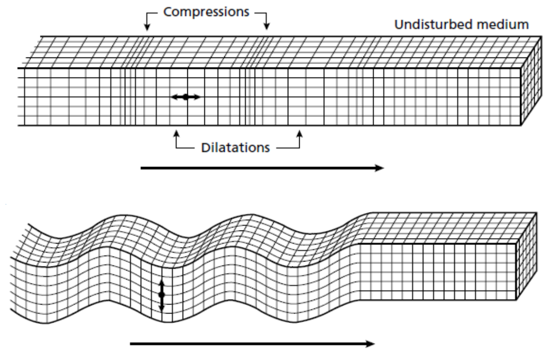

Figure 2: Propagation of Compressional Wave in the Direction of Wave Travel.

Method of Analysis

Lithology can be predicted using shear and compressional waves, interval velocity and their corresponding travel times, from their stacked records with seismic lines from the same field.

In a compressional wave reflection record, the output of the seismic wave are presented with the horizontal axis corresponding to the depth Z (m) and the vertical axis corresponding to the time t (sec.).

Using the relation $V_p = \frac{2Z}{T_p}$, the compressional wave velocity V_p and the corresponding travel time T_p can be determined (i.e., at a particular depth Z, the values of V_p and T_p are estimated). This process is also repeated on a shear wave reflection section using the relation $V_s = \frac{2Z}{T_s}$ from which V_s and T_s are determined. After computing the values of V_p, T_p, V_s and T_s from the stacked records, the ratios of ${V_p}/{V_s}$ and $\frac{T_s}{T_p}$ are also estimated.

Cross-plots of ${V_p}/{V_s}$ against $\frac{T_s}{T_p}$, $\frac{T_s}{T_p}$ against V_s, $\frac{T_s}{T_p}$ against V_p and time t against interval velocity are carried out in series of graphs.

RESULTS AND DISCUSSION

Castagna et al., 1985 gives the value of ${V_p}/{V_s}$ for different rocks/lithology as shown below.

Table 1: $^{V_p}/_{V_s}$ Ratio for Different Rock Types (Castagna et al. 1985).

Range of $\frac{V_p}{V_s}$	Rock type
0.0 – 1.2	Fine grained sand
1.2 – 1.45	Medium-grained sand
1.46 – 1.6	Coarse-grained sand
1.6 – 1.8	Sandstone
Above 2.0	Shale or Clay

While knowledge of the P-wave velocity is useful, it is a function of three separate properties of the rock and is only a very ambiguous indicator of rock lithology. The $^{V_p}/_{V_s}$ ratio, however, independent of density and can be used to derive Poisson's ratio, which is a much more diagnostic lithological indicator (Kearey et al. 2002).

TABLE AND CHARTS

The effect of lithology is best determined from the velocity data. Cross-plots of the ratio $^{V_p}/_{V_s}$ against $^{T_s}/_{T_p}$ which established a linear relationship (in a scattered chart with a corresponding regression line and equation) between velocity and travel time ratio are shown in Figures 3 – 6 below. Values of V_p increase monotonically with time, while V_s are invariant with time.

Results from Table 2 and the graph of shot point 101.5 taken on line GP 87-405, show that $T_p$varies from 0 – 2942 ms, $T_s$varies from 0 – 4201 ms, V_p varies from 1963 – 4022 m/s, V_s varies 1700 – 2850 m/s, the $^{V_p}/_{V_s}$ ratio varies from 1.122 to 1.504 m/s and $\frac{T_s}{T_p}$ ratio varies from 0 – 1.428 ms. The inferred lithology based on the values of $^{V_p}/_{V_s}$ suggests a sandy formation of medium grain size. The cross-plot of velocity-time ratios also reveals concentration of data points between 1.0 and 1.6 characteristic of medium grained sand according to Castagna et al. 1985. The slope of the graph indicates that velocity increases with depth (Figure 3).

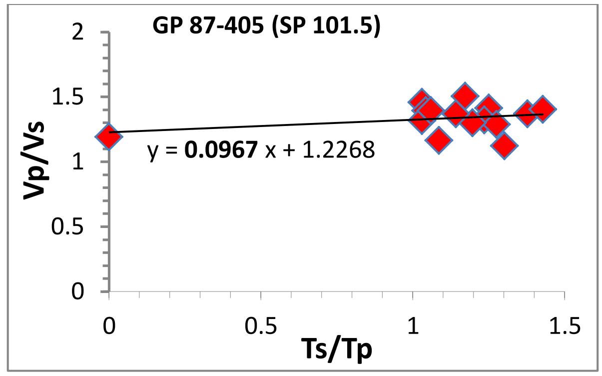

Figure 3: Plot of $^{V_p}/_{V_s}$ against $\frac{T_s}{T_p}$ for SP 101.5 on line GP 87-405.

Result in Table 2 also reveals that in shot point 161.5 on line GP 87-405, T_s varies 0 to 3894 ms, T_p varies from 0 to 3562 ms, V_p varies from 1300 to 1400 ms, V_s varies from 1250 to 2948 ms, the ratios $^{V_p}/_{V_s}$ and $\frac{T_s}{T_p}$ vary from 1.040 to 1.548 m/s and 0 to 1.378 ms, respectively. The inferred lithology suggests a sandy soil of medium to coarse grained size as observed from the clusters of data points on the graph. Lithification increases with depth (Figure 4).

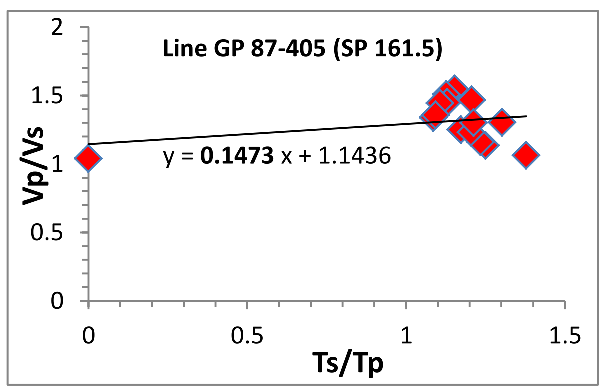

Figure 4: Plot of $^{V_p}/_{V_s}$ against $\frac{T_s}{T_p}$ for SP 161.5 on line GP 87-405.

The computed data on table 2 indicate that T_p varies 0 to 3268 ms, T_s varies from 0 to 4000 ms, V_p varies from 1490 – 4220 m/s, V_s varies from 1432 to 3000 m/s, the $^{V_p}/_{V_s}$ and $\frac{T_s}{T_p}$ ratios vary from 1.04 to 1.655 m/s and 0 to 2.568 ms, respectively.

The graph in Figure 5 shows a highly scattered data points with a negative slope which indicate high degree of inhomogeneity within the sedimentary strata due to the presence of either a blind zone or hidden layer occasioned by a progressively lower seismic velocity of the overburden which overlain a basement. It is suspected that the anomaly is either caused by a perched water table or a weathered layer which overlain a basement.

The values of T_p, T_s, V_p, V_s, ${}^{V_p}/_{V_s}$ and ${}^{T_s}/_{T_p}$ were also computed. The ranges are given as 0 to 3250 ms, 0 to 3560 ms, 1490 to 4220 m/s, 1432 to 3000 m/s, 1.040 to 1.655 m/s and 0 to 1.376 ms respectively. The lithology varies from fine to medium to coarse grained sand with increasing velocity with depth as indicated by the region of concentration of data point and slope of the graph.

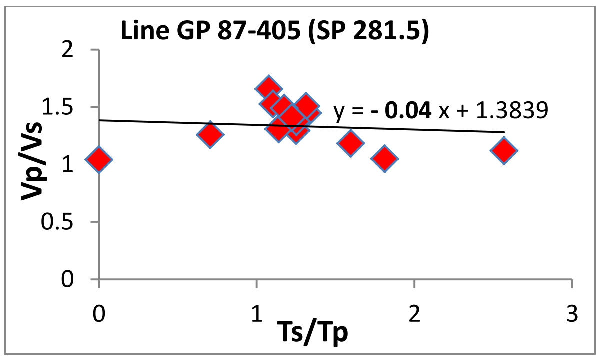

Figure 5: Plot of ${}^{V_p}/_{V_s}$ against $\frac{T_s}{T_p}$ for SP 281.5 on line GP 87-405.

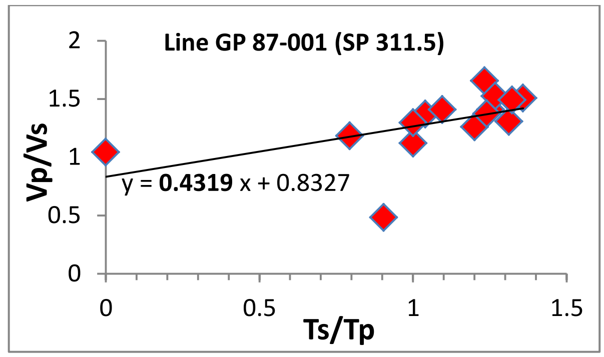

Figure 6: Plot of ${}^{V_p}/_{V_s}$ against $\frac{T_s}{T_p}$ for SP 311.5 on line GP 87-001.

Table 2: Result Summary for Some Selected Shot Points along two GP 87-405 and GP 87-001.

S/N	V_p/V_s (m/s)	T_s/T_p (ms)	Inferred Lithology (87-405/101.5)	V_p/V_s (m/s)	T_s/T_p (ms)	Inferred Lithology (87-405/161.5)	V_p/V_s (m/s)	T_s/T_p (ms)	Inferred Lithology (87-405/281.5)	V_p/V_s (m/s)	T_s/T_p (ms)	Inferred Lithology (87-001/311.5)
1	1.1912	0	F.G.S.	1.040	0	F.G.S.	1.04	0	F.G.S.	1.041	0	F.G.S.
2	1.1217	1.302	F.G.S.	1.305	1.302	M.G.S.	1.258	0.706	M.G.S.	1.258	1.200	M.G.S.
3	1.3694	1.378	M.G.S.	1.064	1.378	F.G.S.	1.119	2.568	F.G.S.	1.119	1.000	F.G.S.
4	1.4132	1.250	M.G.S.	1.137	1.250	F.G.S.	1.048	1.811	F.G.S.	0.483	0.904	F.G.S.
5	1.3219	1.235	M.G.S.	1.161	1.235	F.G.S.	1.182	1.597	F.G.S.	1.182	0.794	F.G.S.
6	1.1634	1.086	M.G.S.	1.339	1.086	M.G.S.	1.368	1.184	M.G.S.	1.368	1.040	M.G.S.
7	1.5042	1.172	F.G.S.	1.250	1.172	M.G.S.	1.294	1.250	M.G.S.	1.294	1.000	M.G.S.
8	1.2883	1.275	C.G.S.	1.232	1.204	M.G.S.	1.445	1.323	C.G.S.	1.408	1.253	M.G.S.
9	1.3000	1.196	M.G.S.	1.469	1.207	C.G.S.	1.655	1.077	C.G.S.	1.655	1.233	C.G.S.
10	1.3682	1.142	M.G.S.	1.548	1.153	C.G.S.	1.523	1.104	C.G.S.	1.523	1.267	C.G.S.
11	1.4588	1.030	M.G.S.	1.508	1.127	C.G.S.	1.306	1.140	M.G.S.	1.306	1.312	M.G.S
12	1.3942	1.043	M.G.S.	1.303	1.213	M.G.S.	1.505	1.313	C.G.S.	1.505	1.358	C.G.S.
13	1.3163	1.030	M.G.S.	1.449	1.129	M.G.S.	1.489	1.174	C.G.S.	1.489	1.322	M.G.S.
14	1.3943	1.060	M.G.S.	1.445	1.107	M.G.S.	1.371	1.252	M.G.S.	1.371	1.240	M.G.S.
15	1.4035	1.428	C.G.S.	1.357	1.093	M.G.S.	1.407	1.224	M.G.S.	1.407	1.095	M.G.S.

Note: F.G.S. – Fine grained sand, M.G.S. – Medium grained sand, C.G.S. – Coarse grained sand.

CONCLUSION

Variations in the ratio of the velocities of compressional and shear waves in sandstone depends upon the grain size, the shale or clay content and the pore geometry. Lithologies predicted from this analysis were also confirmed by the driller's logs. Anomalous zones can be observed on the chart scattered data points across the plot area and also give wide range of velocity ratio values. A normally stratified zone will exhibit agreement between velocity and travel time ratios and this will produce data points in a cluster; concentrating within a particular range of value characteristic of that rock. The regression line will dip gently with a positive slope. A negative slope in the regression is indicative of an anomalous zone due to a low velocity layer or presence of an anomalous fluid within the rock unit.

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SUGGESTED CITATION

Ogungbemi, O.S. 2014. "Prediction of Lithology Using the Ratios of Compressional and Shear Wave Velocities and their Travel Times". *Pacific Journal of Science and Technology*. 15(1):355-359.

Pacific Journal of Science and Technology