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# Investigating Differential Pressure Effect on Lithology and Fluid Discriminators

R. C. Nwankwo[1] and I. Aigbedion[2]
*Department of Physical Sciences, Faculty of Science, Edwin Clark University, Kiagbodo, P.M.B. 101, Ughelli, Delta State, Nigeria; Email: nwankwo_c_rufus@yahoo.com*
*[2]Department of Physics, Faculty of Science, Ambrose Ali University, Ekpoma, Edo State, Nigeria; Email: isaacaigbedion@yahoo.com*

***Abstract***
*We have analysed the crossplots of rock properties and attributes against differential pressure. Our core objective was to investigate the effect of the differential pressure on the ability of the rock properties and attributes (velocity, Vp/Vs, Poisson ratio, lambdarho, murho, lambdarho/murho, impedance, impedance ratio, and Poisson impedance) to discriminate lithology and hydrocarbon fluids in reservoir sands at depths. Observed vulnerability or otherwise to the masking effect of differential pressure/sediment compaction at depths has served as a criterion for classification of the rock properties/attributes into good and poor discriminators. From our results, we found that λρ, λρ/μρ, Vp/Vs, Poisson ratio, PI, and Zp/Zs are good fluid discriminators owing to their non-vulnerability to compaction and differential pressure effect, while μρ, Vp. Vs, Zp, and Zs tend to discriminate lithology and fluids poorly because of their observed susceptibility to the differential pressure effect. These observations are quite consistent with results documented in the literature on the assessment of rock properties and attributes for lithology and fluid discrimination. Therefore, in selecting a rock property or attribute for the purpose of lithology and fluid discrimination, the differential pressure/compaction effect criterion must be placed on the rock property or attribute. Overall, a rock attribute seems to owe its lithology/fluid discrimination effect to its derivation from the combination of Vp and Vs. Rock attributes whose derivations are linked to the combination of Vp and Vs discriminate fluids effectively, while the attributes linked only to Vp or Vs are most easily affected by increase in sediment compaction and differential pressure, and have been observed to be poor discriminators. Our results in this study therefore support the need for a more aggressive acquisition of Vs data in conjunction with the usual acquisition of Vp data in the hydrocarbon search.*

**Keyword:** *differential, pressure, compaction, depth, effect, lilthology, fluids, discriminator,*

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## I. Introduction

The importance of Vp/Vs, Poisson ratio, Poisson impedance and the λ-μ-ρ rock attributes in hydrocarbon exploration lies in their application for fluids characterization in reservoirs, lithology discrimination and separation of hydrocarbon sands from non-hydrocarbon background shales, among others. Many published works in the literature show that a relationship exists between the material matrix, fluid saturant and the rock properties for a given sedimentary formation. This assertion is strongly supported by the Biot-Gasmann two-phase system which is composed of the rock frame matrix and pore fluid saturant (Gasmann 1951; Biot 1956; Biot 1962a). The Biot-Gassmann theory shows the bulk modulus of a rock to be dependent on the skeleton modulus $K_{ma}$, pore fluid modulus $K_{fl}$ and Biot coefficient β. Krief et al (1990) used the pickette's (1963)'s model to further derive a relationship between the shear modulus of a formation and the matrix material. They found that in a gas-filled formation the ratio of the velocities of the p-and s-waves remains constant for a wide range of porosities and that the ratio is equal to the value of the ratio of the velocities of the p-and s-waves in the matrix. From the observations of Krief et al (1990), Lee et al. (1996) used the relationship between p– and s-wave velocities for water-saturated sediments to establish the dependence of rock shear modulus on the elastic moduli of the matrix, the frame porosity and Biot coefficient. It is therefore clear that compressional and shear wave velocities and their ratios are affected by two components of the rock (the lithology matrix and pore fluid saturant) that constitute the Biot's and Gassmann's two-phase system. Tatham (1982) highlights the relationship between seismic velocity and pore fluid properties. From the results of his work, he reports that the Vp/Vs ratio is especially sensitive to the pore fluid found in sedimentary rocks. In particular, the Vp/Vs value is much lower by 10-20% for gas saturation than for liquid saturation. This encouraging result is reported in the theoretical work of Gardner and Harris (1968). Gardner and Harris observed that Vp/Vs ratio for water-saturated unconsolidated sands is greater than 2.0, while the Vp/Vs ratio for a well consolidated rock has values less than 2.0. Hamilton (1976) made measurements on shallow marine sediments including both sands and shales, and found that shallow, unconsolidated marine sediments to a depth of 2000ft have Poisson ratio between 0.45 and 0.50. Furthermore, Domenico (1976) carried out measurements of Poisson ratio in shallow gas fields which have related seismic amplitude anomaly on both a synthetic high porosity glass bead and a high porosity Otawa sandstone mixture. Interestingly, Domenico found marked changes in Poisson's ratios between brine and gas saturations. In these unconsolidated 38 percent porosity specimens, the replacement of brine with gas remarkably reduced Poisson's ratio from 0.4 to 0.1. The results of Gardner and Harris (1968), Hamilton (1976), and Domenico (1976) imply that first, unconsolidated shallow brine-saturated sediments tend to have very high Poisson ratio of 0.40 or greater. Second, Poisson ratio tends to decrease as porosity decreases and sediment becomes more consolidated. Third, high porosity brine-saturated sandstones tend to have high Poisson's ratio of 0.30 to 0.40. And fourth, gas saturated high porosity sandstones tend to have abnormally low Poisson's ratio in the order of 0.10.

Other important lithology/fluid discriminators whose values strongly follow the Biot-Gassmann (matrix-pore fluid) two-phase model include the Poisson Impedance (PI), λρ, μρ λρ/μρ, impedance (Zp, Zs) and impedance ratio (Zp/Zs) **(**Goodway et al 1997; Russell and Hedlin 2001, Quakenbush et al 2006). Goodway et al. (1997) introduced the concept of lamda–mu-rho technique and showed from the results of their work that λρ, μρ and λρ/μρ ratio attributes are robust hydrocarbon fluids discriminators. Lamda-mu-rho technique as a pore fluid discriminator has its origin in the hard exploration areas of Canada. Lamdarho (λρ) refers to incompressibility modulus that quantitatively detects fluid types while Murho **(**μρ) refers to rigidity modulus which is sensitive only to the lithology of the rock. Omudu (2007) carried out a study with strong foundation in the lamda–mu-rho concept in order to discriminate hydrocarbon fluids in some reservoirs in the Niger Delta fields. He extracted estimates of Vp/Vs, σ, λρ, μρ, λρ/μρ, etc from the simultaneous AVO inversion of pre-stack time migrated seismic data. He found that the seismic attributes cross-sections generated clearly indicated zones of hydrocarbon saturation, with the gas-saturated zones showing lowest values of the Vp/Vs, σ, λρ, and λρ/μρ attributes. Like Vp/Vs and σ, the values of the λ-μ-ρ attributes are determined by the dual effect of material matrix and fluid saturants of the reservoir sand.

Interestingly, apart from the rock matrix and its fluid saturant proposed by Biot and Gassmann, an additional parameter implicitly inherent in how a rock tends to determine the response of a rock property or attribute is the differential pressure and its associated compaction effect at a depth. It then requires that the relationship between rock properties/attributes and differential pressure should be more extensively investigated in order to fully determine to what extent increase in the differential pressure arising from sediment compaction with burial depth can affect their fluid discriminating potential. Domenico (1984) had analysed data obtained from water-saturated sandstone, calcareous sandstone, dolomite and limestone cores, and reported that a relationship exists between porosity, differential pressure (that is burial depth) and Vp/Vs. Omudu (2007) reported that some rock properties and attributes discriminate lithology and fluids poorly which could be due to differential pressure and compaction effect, while others particularly the λ-μ-ρ attributes are robust for fluid discrimination even within the deeper reservoirs where compaction is high. The results of the 3D post-stack seismic amplitude inversion study carried out by Nwankwo (2016) show that fluid discrimination using the extracted impedance is masked significantly at the deeper horizons probably due to compaction. Besides, Hutahaean et al (2018) emphasized that rather than acoustic impedance which discriminates fluids poorly probably due to compaction, the Poisson impedance should be used as it is a better discriminator.

Although values of Vp/Vs, Poisson ratio, Poisson impedance, acoustic impedance, shear impedance, acoustic-shear impedance ratio, and the λ-μ-ρ attributes have been published for the clastic sediments of the Niger Delta in lithology and fluid discrimination (e.g Ebeniro et al. 2003; Omudu and Ebeniro, 2005; and Omudu 2007), there is need to further investigate the effects differential pressure (or burial depth) has on these fluid discriminators. This can help in distinctly classifying the rock properties and attributes into good and poor fluid discriminators on the basis of susceptibility to the differential pressure effect. Such classification is capable of increasing our success ratio in the hydrocarbon search and is the focus of this paper.

## II. Materials And Method

Well data obtained from a field in the Western Niger Delta was used for the analysis. The well data consists of the GR, density, compressional wave velocity, and shear wave velocity data. The Well data has samples over a depth range of 6,292ft to 8,480ft. Clean sand and shale zones were delineated at different depth ranges – shallower depth range and the deeper zone/horizon- for the analysis. The variations of Vp, Vp/Vs, σ, Zp, Zs, Zp/Zs, PI and the λ-μ-ρ attributes with differential pressure or burial depth were investigated through crossplots to determine whether high differential pressure arising from increasing sediment compaction with burial depth has an effect on the ability of the rock properties and attributes to identify and discriminate fluids within the reservoirs.

The Poisson ratio, which depends only Vp and Vs and is independent of density, is obtained using the equation:

$$\sigma = 0.5\,\frac{\left(Vp/Vs\right)^2 - 1}{\left(Vp/Vs\right)^2 - 2} \qquad (1)$$

Equation (1) gives Vp/Vs ratio as

$$Vp/Vs = \left(\frac{2(1-\sigma)}{(1-2\sigma)}\right)^{1/2} \qquad (2)$$

The dependence of shear modulus μ on Vs and density ρ is given by

$$Vs = \sqrt{\frac{\mu}{\rho}} \qquad (3)$$

so that: $\mu = V_s^2\rho$ (4)

and $\mu\rho = V_s^2\rho^2$ (5)

The fluid incompressibility λ can be found by the relation:

$$Vp = \sqrt{\frac{\lambda + 2\mu/3}{\rho}} \qquad (6)$$

Equation (6) allows us to derive the fluid modulus (lamdarho) λρ which is very sensitive to the presence of fluid in a porous rock. This is given by

$$\lambda\rho = V_p^2\rho^2 - cV_s^2\rho^2 \qquad (7)$$

where c is a constant (the fluid discriminant) which has been assigned a characteristic value of 2.0 to account for the clastic sediments of the Niger Delta, as proposed by Hilterman (2001) and Russell and Hedlin (2001) for different geologic environments.

The impedance Z is simply a product of wave velocity and density. Seismic amplitudes observed on seismic sections which can indicate internal layering as well as lateral variations in reservoirs are usually due to impedance contrast at the interface between two geologic layers. Thus, the impedance attribute has been extracted from various seismic inversions for the purpose of lithology and fluid discrimination (e.g Fatti et al, 1994; Ma 2002). The acoustic (compressional) wave impedance and shear wave impedance are obtained by multiplying compressional wave velocity and shear wave velocity by density. So we have:

$Z_p = V_p\rho$ (8)

and $Z_s = V_s\rho$ (9)

The Poisson impedance PI is defined as a difference between acoustic impedance and scaled shear impedance and is useful because of its sensitivity to fluids in reservoirs. It has been observed to be more sensitive to gas effect than oil effect (Quakenbush 2006; Direzza and Permana, 2012), and is given mathematically by

$PI = Zp - 2.78Zs$ (10)

Further in this analysis, we have related differential pressure to burial depth. We have utilized the description and derivation of differential pressure in relation to burial depth as given by Domenico (1984). With increase in burial depth, sediment compaction and differential pressure also increase. Compaction tends to exert masking effect on the fluid discriminating potential of some rock properties and attributes. Domenico (1984) defines the differential pressure as the difference between geostatic (overburden) pressure and pore fluid pressure. He states that a generally accepted nominal rate for geostatic pressure is 1psi/ft (3.28psi/m) of depth. Normal pore fluid pressure is equivalent to that exerted by a column of the pore fluid extending to the surface (i.e hydrostatic pressure). In our case here, it is assumed that the pore fluid pressure is normal and that the fluid is brine-water containing approximately 300, 000 ppm of dissolved solids. The density of the brine then results in an increase of 0.47psi/ft (1.54psi/m) of depth. Thus the differential pressure increases at a rate of 0.53psi/ft (1.74psi/m).

## III. Results

Figure 1 is the suite of logs obtained from the well data. This includes the GR log, density log, acoustic velocity log and shear wave log. The sand zones of investigation and associated depths in the well are delineated using the GR log.

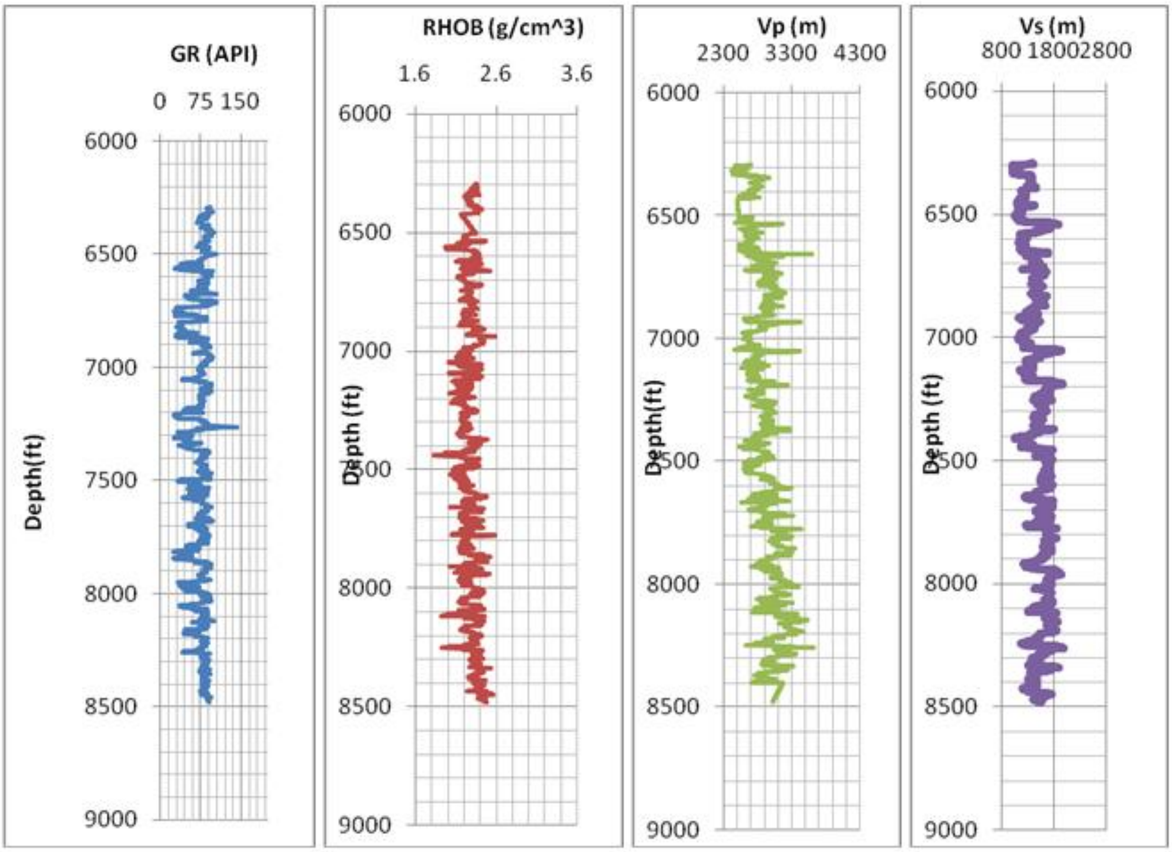



**Fig.1: The suite of logs- GR log, density log, compressional sonic log and shear sonic log - for the well.**

Figure 2 is the plot of differential pressure against burial depth. It indicates the variation (increase) in differential pressure with burial depth. As burial depth and bulk density increase, compaction of the lithology also increases, leading to associated increase in differential pressure.

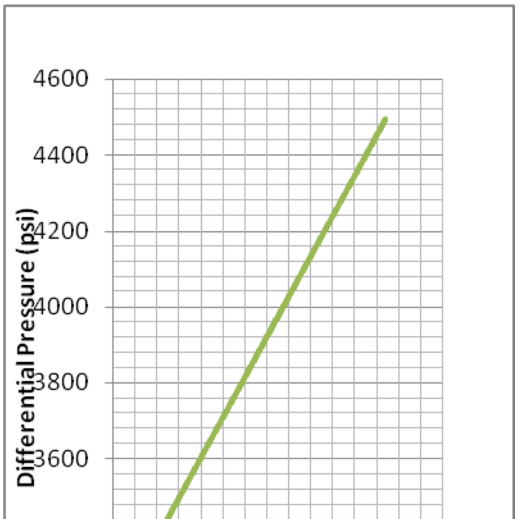
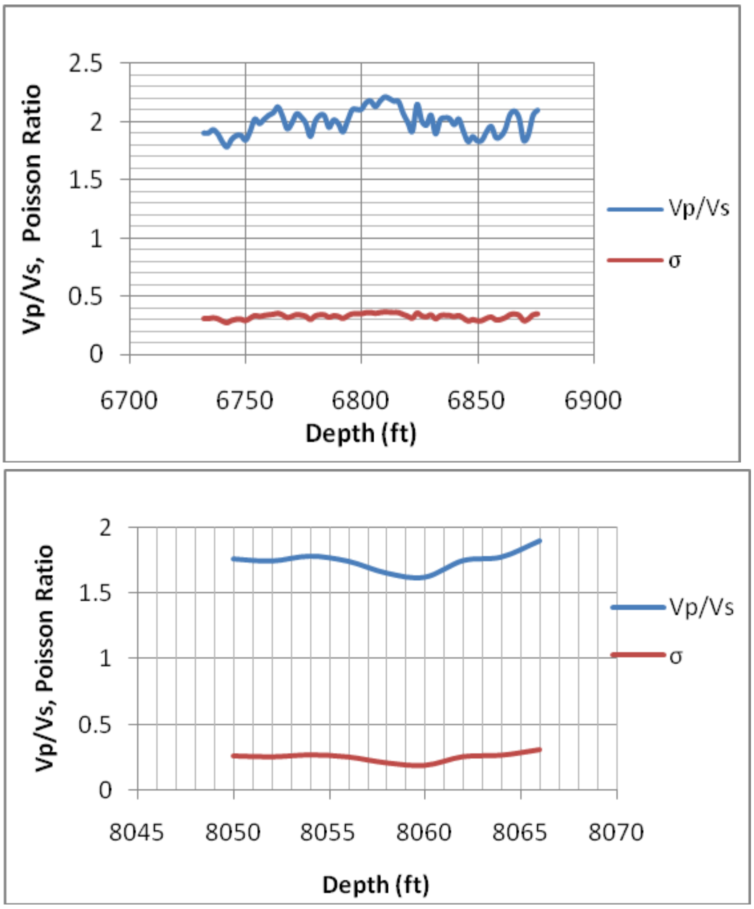



**Fig2:** Increase of Differential Pressure with burial depth

Figure 3(a) shows crossplot of Vp/Vs and Poisson ratio against burial depth, with the attributes unaffected (retaining typical values for hydrocarbon fluids saturation) in spite of increase in burial depth and differential pressure, as depicted by the horizontally undulating curves. The plot was derived from samples of Vp/Vs and σ obtained from the sand zone at the shallower depths. The values of Vp/Vs range from 1.8 to 2.2 and σ ranges from 0.30 to 0.37, depicting brine-water saturation in the reservoir. It is clear that compaction arising from increasing burial depth has no effect on the discriminators. The depth range for this reservoir (6732ft to 6866ft) corresponds to a differential pressure increase of 3568psi to 3639psi. Figure 3(b) shows the crossplot of Vp/Vs and Poisson ratio against burial depth and are observed to be non-susceptible to sediment compaction at the deeper horizon, as depicted by the curve lying nearly flat with increase in differential pressure. The Vp/Vs values lie within the 1.62 to 1.78 range, and Poisson ratio ranges from 0.19 to 0.27, lower than the values for the shallower sand, thus depicting oil/water-saturated reservoir sand. The deeper zone of investigation between 8050ft and 8066ft corresponds to a differential pressure increase from 4267psi to 4275psi. Interestingly, these variations in Vp/Vs and σ between the shallower and deeper zones show the non-susceptibility of the discriminators to compaction and differential pressure effect. Both attributes have retained their fluids discrimination effect at the shallower and deeper zones of investigation in spite of increase in compaction and differential pressure.




(a)

(b)

**Fig. 3 (a,b): Plots of Vp/Vs and Poisson ratio against depth (differential pressure). Both attributes are unaffected by increasing compaction with increase in burial depth or differential pressure**

Figure 4 (a,,b) shows plots of the lamdarho (λ-ρ) attribute against differential pressure, with samples of lamdarho taken from the shallower and deeper horizons. Values of the lamdarho attribute are observed to be non-susceptible to differential pressure effect as sediment compaction increases with burial depth. Thus at the shallower and deeper zones of investigation, the attribute's fluids discriminating effect is not masked by compaction but it retains its ability to identify fluid saturation in the reservoir sands. This non-susceptibility to differential pressure/compaction is clear from the λρ curves undulating horizontally with increase in differential pressure both at the shallower and deeper zones of investigation. The λρ values only depend on lithology matrix and fluid saturant effects, and are insensitive to the compaction effect. At the shallower zone, the λρ-values lie between 15 (GPa x g/cm$^3$) and 30 (GPa x g/cm$^3$) at a differential pressure range of 3568psi to 3639psi corresponding to a depth range of 6732ft to 6866ft, indicating brine-water saturated sand. Again interestingly, we find that the λρ-values are lower at the deeper sand zone than at the shallower zone, with the values ranging from 9.8 to 16 (GPa x g/cm$^3$) at a differential pressure range of 4267psi to 4275psi corresponding to a depth range of 8050ft to 8066ft, indicating oil/water saturation in the reservoir sand. This clearly shows that the λρ attribute is non-susceptible to increase in sediment compaction and differential pressure.

(a)
(b)

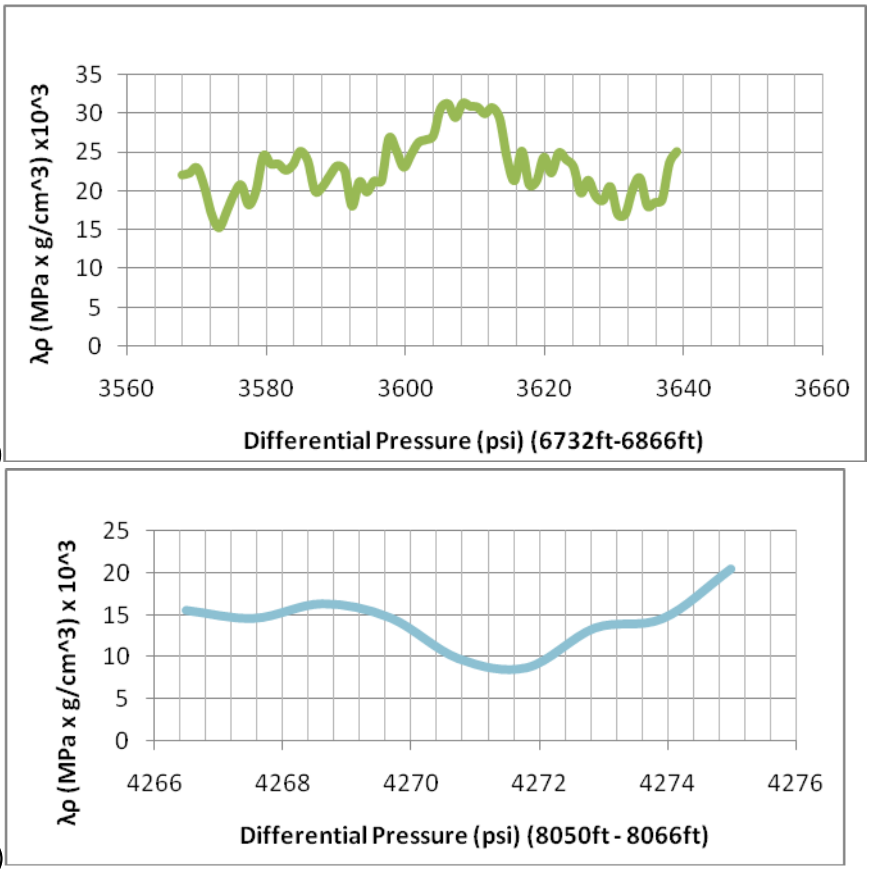



**Fig4(a,b): Plots of lambdarho attribute against differential pressure (depth of burial). The attribute remains unaffected by increasing compaction, with the curves undulating horizontally with increasing differential pressure at both the shallower and deeper sand zones of investigation.**

Figure 5(a,b) shows plots of λρ/μρ and Zp/Zs attributes against differential pressure, with samples taken from the shallower and deeper horizons. Values of the attributes are not affected by differential pressure effect with increase in burial depth. This is evident from the undulating curves of both attributes, depicting the ability of the attributes to identify the fluids in the reservoirs both at the shallower and deeper zones of investigation in spite of high compaction and differential pressure. The fluids in the sand reservoirs are well delineated with the λρ/μρ and Zp/Zs values depending only on lithology matrix and fluid saturant effects and are insensitive to any contribution from differential pressure. At the shallower zone, the λρ/μρ-attribute's values lie between 1.2 and 2.8 at a differential pressure range of 3568psi to 3639psi corresponding to a depth range of 6732ft to 6866ft, while the Zp/Zs values range from 1.8 to 2.1, indicating brine-water-saturated sand. At the deeper zone of investigation, the lambdarho/murho values range between 0.6 and 1.58 while the Zp/Zs values range from about 1.6 to 1.8 at a differential pressure range of 4267psi to 4275 psi corresponding to a depth range of 8050ft to 8066ft, thus depicting oil/water-charged sand. The lambdarho/murho and Zp/Zs attributes therefore show ability to identify and discriminate fluids within the hydrocarbon-charged sand in spite of increase in compaction and differential pressure.

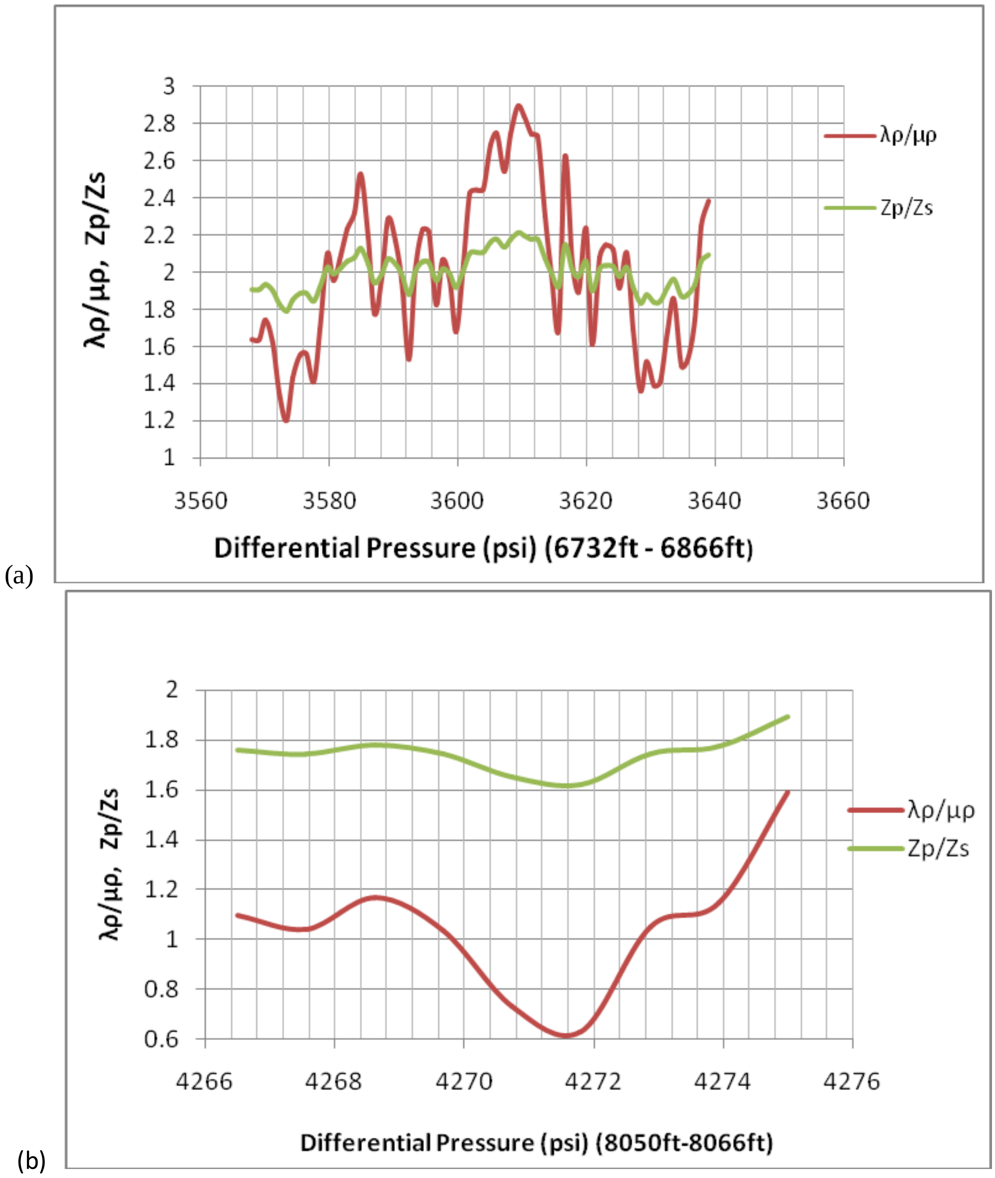
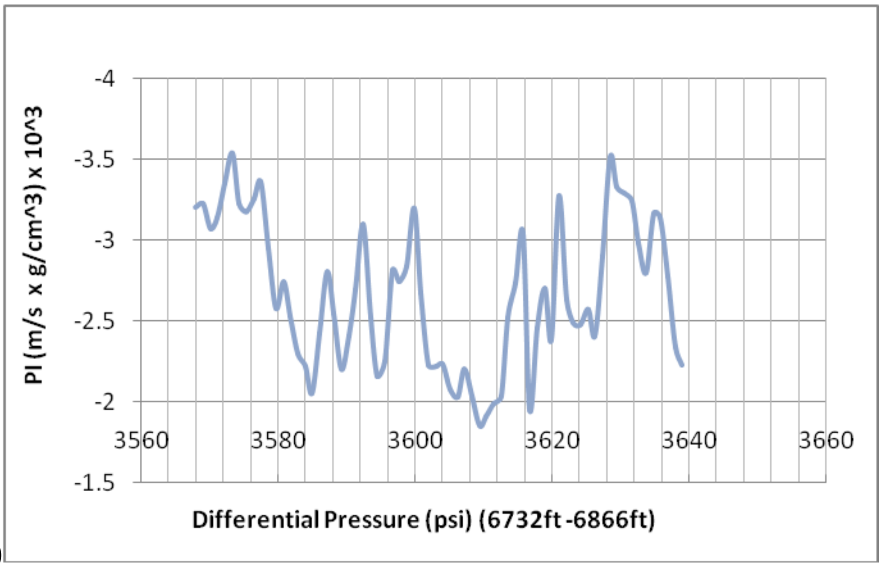
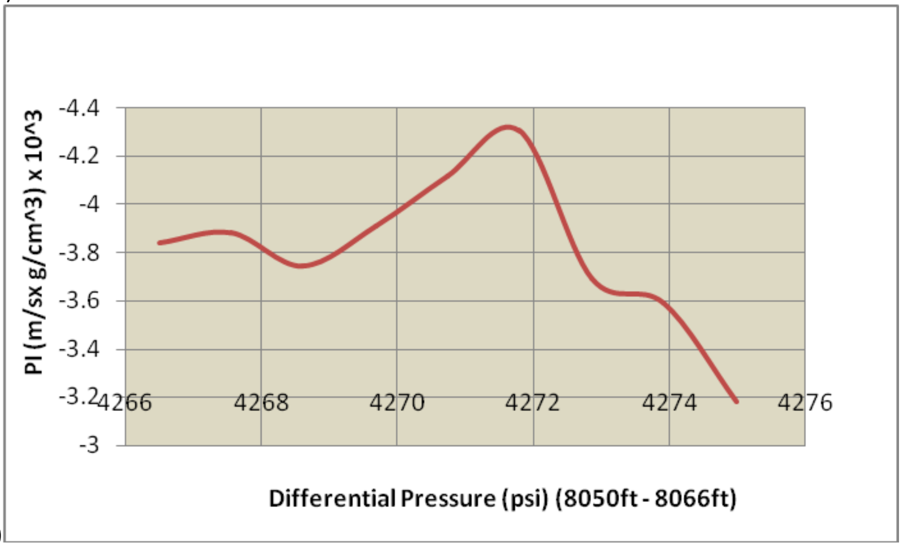



**Fig.5 (a,b): Plots of lambdarho and Zp/Zs attributes against differential pressure (depth of burial). The attributes are observed to be non-susceptible to increasing compaction and differential pressure.**

Figure 6(a,,b) shows plots of the Poisson impedance (PI) against differential pressure for the shallower and deeper zones of the depths of investigation. The PI attribute is observed to be non-vulnerable to increasing differential pressure, and shows good discriminating effect in the reservoirs under investigation (Quakenbush et al, 2006; Hutahaean et al, 2018). This is again clearly indicated by the curve of the Poisson impedance attribute undulating horizontally as differential pressure increases both at the shallower and deeper horizons. At the shallower sand zone, the PI values lie between -1.9 x $10^3$ and -3.5 x $10^3$ (m/s x g/$cm^3$) at a differential pressure range of 3568psi to 3639psi corresponding to a depth range of 6732ft to 6866ft (Fig 6a), justifying the indication of water-saturation as previously obtained. At the deeper sand zone of investigation, the values range from -3.2 x $10^3$ to -4.3 x $10^3$ (m/s x g/$cm^3$) at a differential pressure range of 4267psi to 4275psi corresponding to a depth range of 8050ft to 8066ft, justifying the presence of oil/water saturation in the hydrocarbon-charged sand (Fig.6b).



(a)



(b)

**Fig6 (a,b): Plots of Poisson impedance (PI) against differential pressure (depth of burial). The attribute remains unaffected by increasing compaction both at the shallower and deeper sand zones of investigation.**

Figures 7, 8 and 9 are respectively plots of Vp, Zp and murho attributes against burial depth (differential pressure). Velocity, acoustic impedance and murho follow the same trend, indicated by their observed susceptibility to compaction effect, with the Vp, Zp and μρ curves sloping upwards from left to right as differential pressure or burial depth increases. The sloping curves represent a deviation from the Gassmann's two phase (matrix-fluid) model and show that differential pressure or burial depth is an important parameter in determining the discriminating potential of velocity, acoustic impedance and the murho attribute. It is clear that as differential pressure increases, the lithology and fluids in the sand reservoir may not be effectively detected by the murho, velocity, and impedance attribute because of compaction effect.

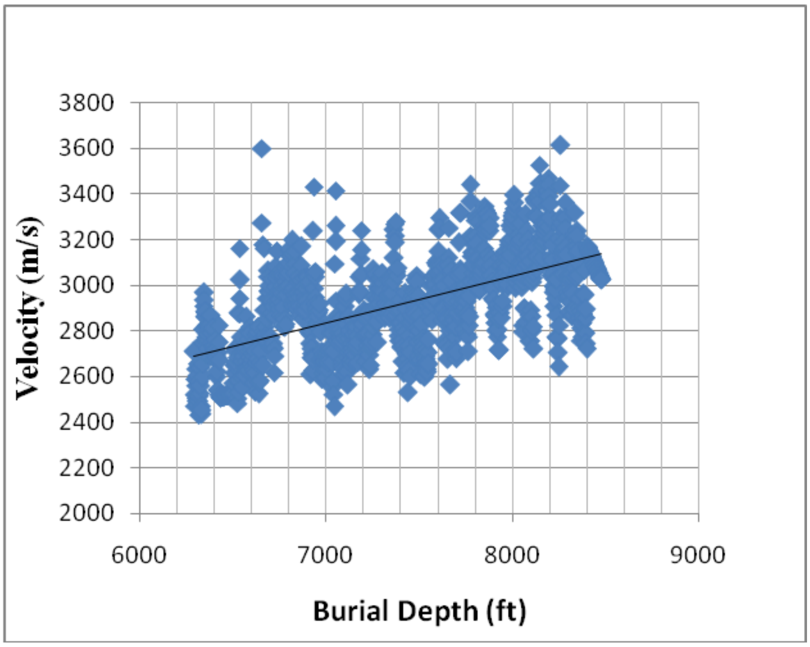



**Fig7: Plot of velocity against differential pressure (depth of burial). The velocity curve slopes upwards from left to right, indicating the effect of differential pressure on velocity with increasing sediment compaction or burial depth**

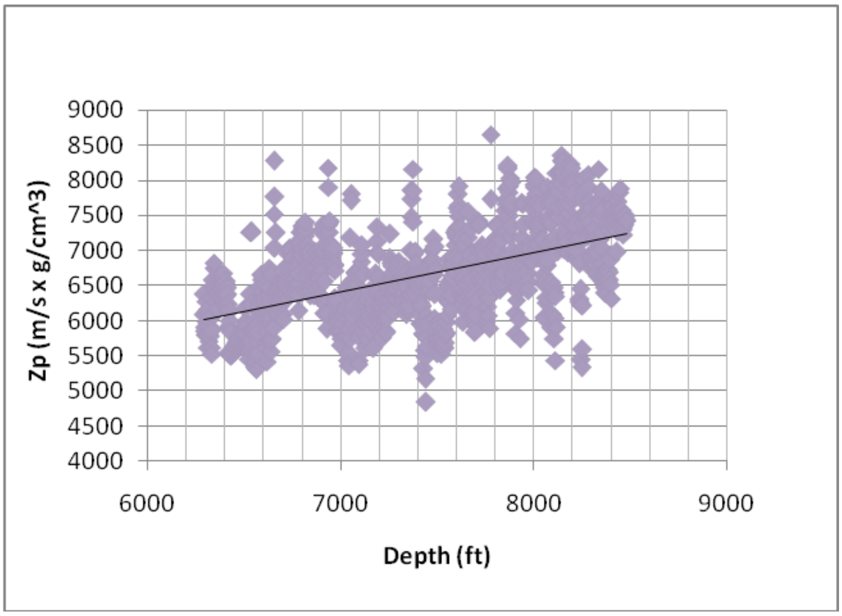



**Fig8: Plot of acoustic impedance Zp against differential pressure (depth of burial). The impedance curve slopes upwards from left to right, indicating the effect of differential pressure on Zp with increasing sediment compaction**

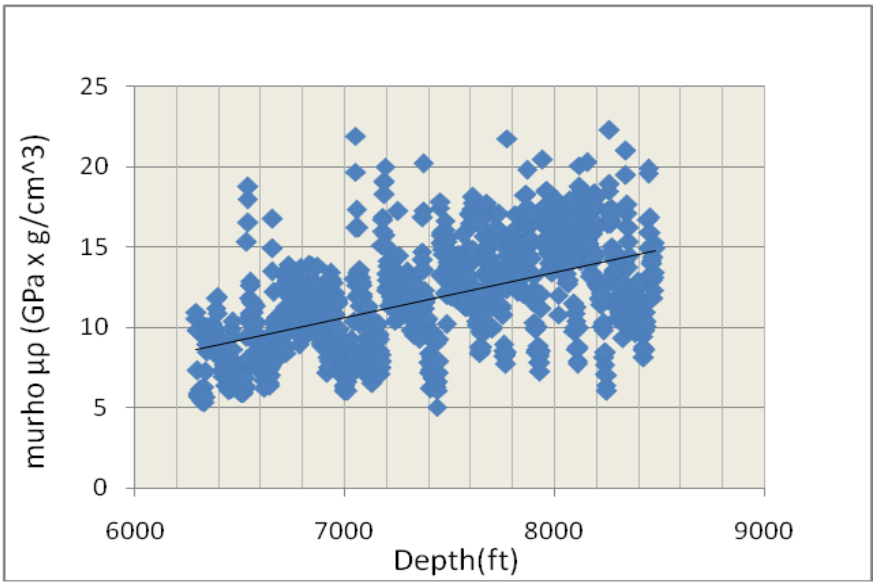



**Fig9: Plot of murho attribute against differential pressure (depth of burial). The μρ-curve slopes upwards from left to right, indicating the differential pressure effect on the discriminating potential of the murho attribute with increasing sediment compaction.**

## IV. Discussion Of Results

We have analysed the crossplots of the rock properties and attributes against differential pressure. Our core objective was to investigate the effect of the differential pressure on the ability of the rock properties and attributes (velocity, Vp/Vs, Poisson ratio, lambdarho, murho, lambdarho/murho, impedance, impedance ratio, and Poisson impedance) to discriminate hydrocarbon fluids in reservoir sands at depths. Vulnerability or otherwise to the masking effect of differential pressure/sediment compaction at depths has served as a criterion for classification of the rock properties/attributes into good and poor discriminators. From our results, we found that λρ, λρ/μρ, Vp/Vs, Poisson ratio, PI, Zp/Zs are good fluid discriminators owing to their non-vulnerability to increasing compaction and differential pressure effect, while μρ, Vp. Vs, Zp, and Zs tend to discriminate lithology and fluids poorly because of their observed susceptibility to the increasing differential pressure effect. These observations are quite consistent with the results of the crossplots of rock properties for fluid discrimination in the Niger Delta by Omudu and Ebeniro (2005). They observed from their crossplots that certain rock properties such as acoustic velocity and impedance discriminate fluids poorly while the λ-μ-ρ attributes are better discriminators. Nwankwo (2016) carried out a 3D-poststack seismic amplitude inversion with data obtained from fields in the Niger Delta and found that the inverted (extracted) impedance attribute is a poor fluid discriminator. Also, Hutahaean et al (2018) conducted a study and reported that the acoustic or shear impedance used alone discriminates hydrocarbon fluids poorly in reservoirs. Therefore, in selecting a rock property or attribute for the purpose of fluid discrimination, the compaction/differential pressure effect criterion must be placed on the rock property or attribute. Our results show that rock properties and attributes which are susceptible to differential pressure (or sediment compaction) tend to discriminate lithology and fluids poorly while rock properties and attributes that are unaffected by differential pressure or sediment compaction at deeper zones are robust discriminators. High fluid discrimination occurs from response of a rock property or attribute only to the dual effect of lithology matrix and associated fluid saturant, in line with the Biot's and Gassmann's two-phase model for a sedimentary rock (Gassmann 1951; Biot 1956; Biot 1962a). Conversely, when a rock property or attribute is sensitive to the effect of differential pressure with increasing sediment compaction or burial depth, its discriminating potential is masked such that it cannot effectively discriminate lithology or fluids within a reservoir. This explains the poor fluid discrimination by some rock properties and attributes as observed by Omudu (2007), Nwankwo (2016), and Hutahaean et al (2018). In this analysis, the values obtained for the fluids-sensitive λρ, λρ/μρ, Vp/Vs, Poisson ratio, Zp/Zs and PI attributes all fall within the values published in the literature for the clastic sediments of the Niger Delta and across the globe (eg Hamilton 1971; Goodway et al 1997; Hilterman et al 1998; Omudu and Ebeniro, 2005; Quakenbush et al 2006; and Omudu 2007). Overall, a rock property or attribute seems to owe its lithology/fluid discriminating effect to its derivation from the combination of Vp and Vs. We found that rock attributes whose derivations are linked to the combination of Vp and Vs discriminate fluids effectively within the sand reservoirs, while the attributes linked only to Vp or Vs are most easily affected by sediment compaction and differential pressure, and have been observed to be poor discriminators. Our results in this study therefore support the need for a more aggressive acquisition of Vs data in conjunction with the usual acquisition of Vp data. Acoustic velocity or amplitude alone cannot be used to characterize reservoirs on seismic sections or the crossplot domain in the hydrocarbon search.

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## V. Conclusion

We have carried out analysis of the effect of differential pressure on rock properties and attributes in terms of their ability to discriminate lithology and fluids in reservoirs. We found that those rock properties and attributes that are vulnerable to differential pressure with increase in sediment compaction or burial depth poorly discriminate fluids within reservoirs, while attributes that are robust against the differential pressure effect of increasing sediment compaction with burial depth discriminate fluids well. Selection of rock properties and attributes for lithology and fluid discrimination should therefore be based on the differential pressure/compaction effect criterion.

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