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Rock Physics Analysis of Abnormal Pore Pressure Regime Offshore Niger Delta Basin

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Abstract

An accurate pore pressure prediction across a reservoir basin is an antidote to potential drilling hazards and proper positioning of infill wells. A formation is declared to be in a state of abnormal pore pressure when the pore pressure is lower or higher than the hydrostatic pressure (normal pore pressure). If the pore pressure exceeds the hydrostatic pressure, overpressure comes, and it is attributed to under compaction, fluid expansion, fluid migration, and tectonics. At this point the confined fluid in the pores of the rock formation finds it difficult to escape leading to a high-pressure regime in that formation. This research work was conducted in the offshore field of Niger Delta, using seismic and the only drilled well log. Cross-plot of the rock physics parameters was employed to predict the abnormal pressure region, and seismic velocity inversion was also conducted in addition to rock physics template. It was observed that the density of the predicted interval and P-wave velocity experiences a drastic decrease at the predicted interval while the porosity of this interval increases as against porosity decrease with depth. The VpVs ratio, acoustic impedance, lambda, and passion ratio cross-plots reveal that the interval in question is in the abnormal pressure range, which is far above the hydrostatic pressure of the region. This predicted result complemented the formation pore pressure of the formation.

Keywords: Pressure, rock physics, hydrostatic, prediction, cross-plot

1. Introduction

The study of pore pressure in sedimentary formations is of great importance in hydrocarbon exploration. In sedimentary basins around the world, the knowledge of pore pressure regime is necessary before, during, and even after exploration. This is because a good knowledge of formation pressure helps in well planning, well development, and its recovery plan (secondary production. Pore pressure ranges from normal hydrostatic pressure to abnormal pressure regime which is referred to as pressure above hydrostatic. Also, pressure can be said to be below the hydrostatic pressure and it is referred to as under pressure or subnormal pressure. This can be a result of burial or decrease in the formation temperature. In the case of burial, if the encapsulated unit is buried deeper, its original pressure is carried to a higher pressure environment. Failure for the rock to compact, means that the trapped pressure is abnormally low for the new depth. The same thing happens if there is a decrease in the heat associated with the formation, which is the cooling of pore fluids as they are uplifted and the overburden erodes.

Considering the Pressure above hydrostatic, Swarbrick and Osborne, 1998 attributed it to the under compaction of sediments, fluid expansion, and fluid migration. Under compaction, which is regarded as compaction disequilibrium, arises when the rate of deposition and burial are sufficiently great relative to the vertical permeability of sediments (Huffman, 2002). At this point, the confined fluid in the pores of the rock finds it difficult to escape so as to maintain a hydrostatic fluid pressure gradient as experienced in shale and clay deposits having high porosity with low permeability (Terzaghi, 1923). This effect is also associated with rocks with a young geological age. Other mechanisms of abnormal pressure include clay diagenesis, aqua thermal expansion, source-rock maturation, and fluid migration that can be traced to increase in temperature in the formation (Huffman, 2002). From the theory of anomalous expansion, can be realized that some fluids expand at certain temperatures, and fluids in the pore throat are not an exception to that. The same goes with the release of water due to mineral transformation. This will invariably lead to the change in the pressure of the fluids in the pores' space of the formation.

In order to optimize the output with more infill wells and recovery plans, there is a need to have a critical insight of what the pressure of the formation looks like, this is because the formation pressure has an important part role in predicting hydrocarbon reserves of a reservoir and its

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recoverability. This is because the pressure differential is a major drive mechanism of hydrocarbon fluids during primary recovery and a good knowledge of the formation pressure helps the reservoir engineers during secondary recovery which is invariable in the pressurizing of the reservoir for optimal output. With the knowledge that the reservoir elastic properties might have an important role to play in pressure distribution across the formation, rock physics will definitely have a role to play in pore pressure determination.

The application of rock physics in abnormal pore pressure prediction will play a significant role in the delineation of formation areas with the likelihood of abnormal pressure regimes. Carcione and Helle (2002) reveal that Poisson's ratio is a good indicator of abnormal pressure regime; in gas-saturated rocks, Poisson's ratio decreases with a significant increase in formation pore pressure, while in formations saturated with liquids, Poisson's ratio increases with a decrease in formation pressure. Accordingly, this work intends to delineate abnormal/ overpressure regime within the formation of the study field that is penetrated by a well log, by looking at the relationship of rock physics parameters, porosity, and acoustic impedance in relation to pore pressure.

1.1. The Geology of the Study Area

The Niger Delta Province (Figure 1) is situated in the Gulf of Guinea as defined by Klett et al. (1997). The Delta contains only one identified petroleum system which is referred to as the Tertiary Niger Delta (Akata – Agbada) Petroleum System (Kulke, 1995; Ekweozor and Daukoru, 1994). Lehner and De Ruiter, (1977) stated that the delta is formed at the site of a rift triple junction which is related to the opening of the southern Atlantic starting in the Late Jurassic and continuing into the Cretaceous and stopped in the Late Cretaceous.

Gravity tectonism became the primary deformational process at the post rifting era. Shale mobility induced internal deformation, and occurred in response to two processes (Kulke, 1995). First, shale diapirs formed from the loading of poorly compacted, over-pressured, prodelta and delta-slope clays (Akata Formation) by the higher density delta-front sands (Agbada Formation). Second, slope instability occurred due to a lack of lateral, basinward support for the under-compacted delta-slope clays (Akata Formation).

The delta proper began developing in the Eocene, and has prograded southwestward, forming depobelts that represent the most active portion of the delta at each stage of its development (Doust and Omatsola, 1990). These depobelts form one of the largest regressive deltas in the world with an area of some 300,000 km^2 (Kulke, 1995), a sediment volume of 500,000 km^3 (Hospers, 1971), and a sediment thickness of over 10 km in the basin depocenter (Kaplan et al., 1994). For any given depobelt, gravity tectonics were completed before the deposition of the Benin Formation, and are expressed in complex structures, including shale diapirs, roll-over anticlines, collapsed growth fault crests, back-to-back features, and steeply dipping, closely- spaced flank faults (Evamy et al., 1978; Xiao and Suppe, 1992). These faults mostly offset different parts of the Agbada Formation and flatten into detachment planes near the top of the Akata Formation (Tuttle et al., 1999).

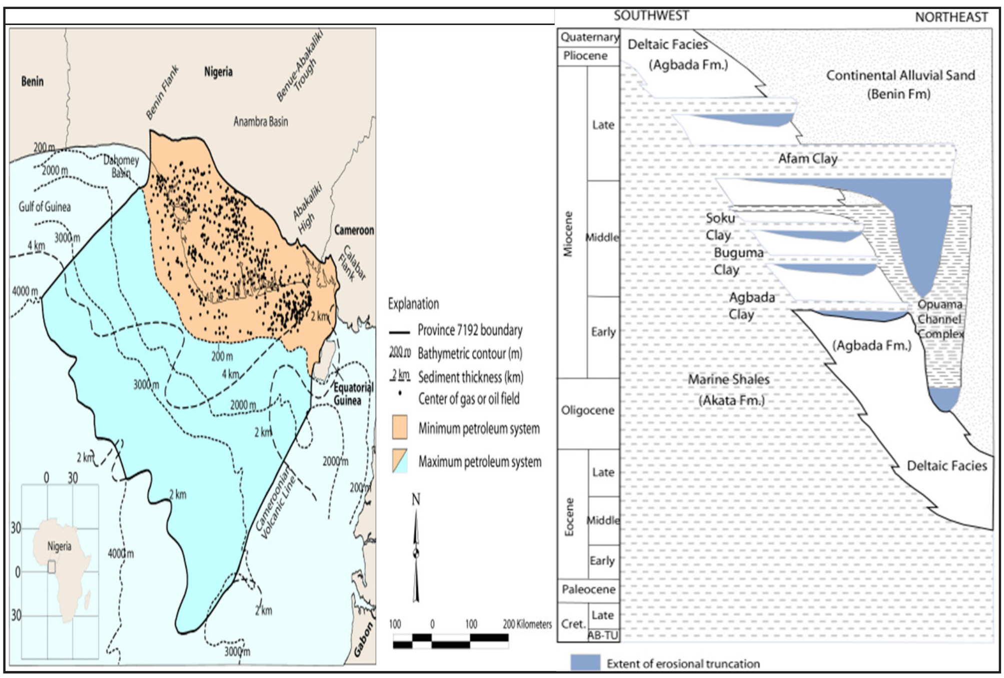

Figure 1. The Niger Delta Province Outline and Stratigraphic Column showing Formations of the Niger Delta modified after Tuttle et al., 1999 and Doust and Omatsola, 1990.

1.2. Stratigraphy and Structural Styles of the Area

The three main stratigraphic units, as shown in the stratigraphic column in Figure 1, are the Akata, Agbada and Benin Formations. It has been noted that the age of the formations becomes progressively younger in a down dip direction and ranges from Paleocene to Recent. The Akata Formation is a marine sedimentary sequence composed of shales, clay, and silts at the base of the known Delta sequence. Doust and Omatsola (1990) stated that the thickness of the sequence is not known for certain, but may reach 7,000 m in the central part of the Delta. The Akata shales are mobile, undercompacted and typically overpressured. They are considered to be the main source rock of the Niger Delta with the upper part considered a matured source rock (Weber and Daukoru, 1975; Ekweozor and Daukoru, 1984). According to Avbovbo (1978), the hydrocarbon, generated in the Akata Formation, probably migrated up dip through growth faults to accumulate in the shallow reservoirs of the Agbada Formation. The Agbada Formation occurs within a depth interval of about 1,700 m to about 2,900 m). It is characterized by the alternation of sandstone and sand bodies with shale layers. The thickest known section of the Agbada Formation is about 10,000 feet, but the maximum thickness may well be much greater. The Benin Formation consists of predominantly massive highly porous fresh water bearing sandstones with thin shale interbeds. Short and Stauble (1967) noted that genetically, the Benin sands and sandstones are mainly deposits of the continental upper deltaic plain environment. This formation is characterized by a high sand percentage (70-100%) and variable thickness, which may be more than 6,000 feet. The age spans from Oligocene in the north and becomes progressively younger southwards.

The structural architecture is characterized by the interplay of subsidence and supply rates which resulted in the deposition of discrete depobelts. When further crustal subsidence of the basin could no longer be accommodated, the focus of sediment deposition shifted seaward, forming a new depobelt (Doust and Omatsola, 1990). Each depobelt is a separate unit that corresponds to a break in regional dip of the delta and is bounded landward by growth faults and seaward by large counter-regional faults or the growth fault of the next seaward belt as shown in figure 2 (Evamy et al., 1978; Doust and Omatsola, 1990). The northern delta province, which overlies a relatively shallow basement, has the oldest growth faults that are generally rotational, evenly-spaced, with their steepness increasing seaward. The central delta province has depobelts with well-defined structures such as the successively deeper rollover crests that shift seaward for any given growth fault. Last, the distal delta province is the most structurally complex due to the internal gravity tectonics on the modern continental slope.

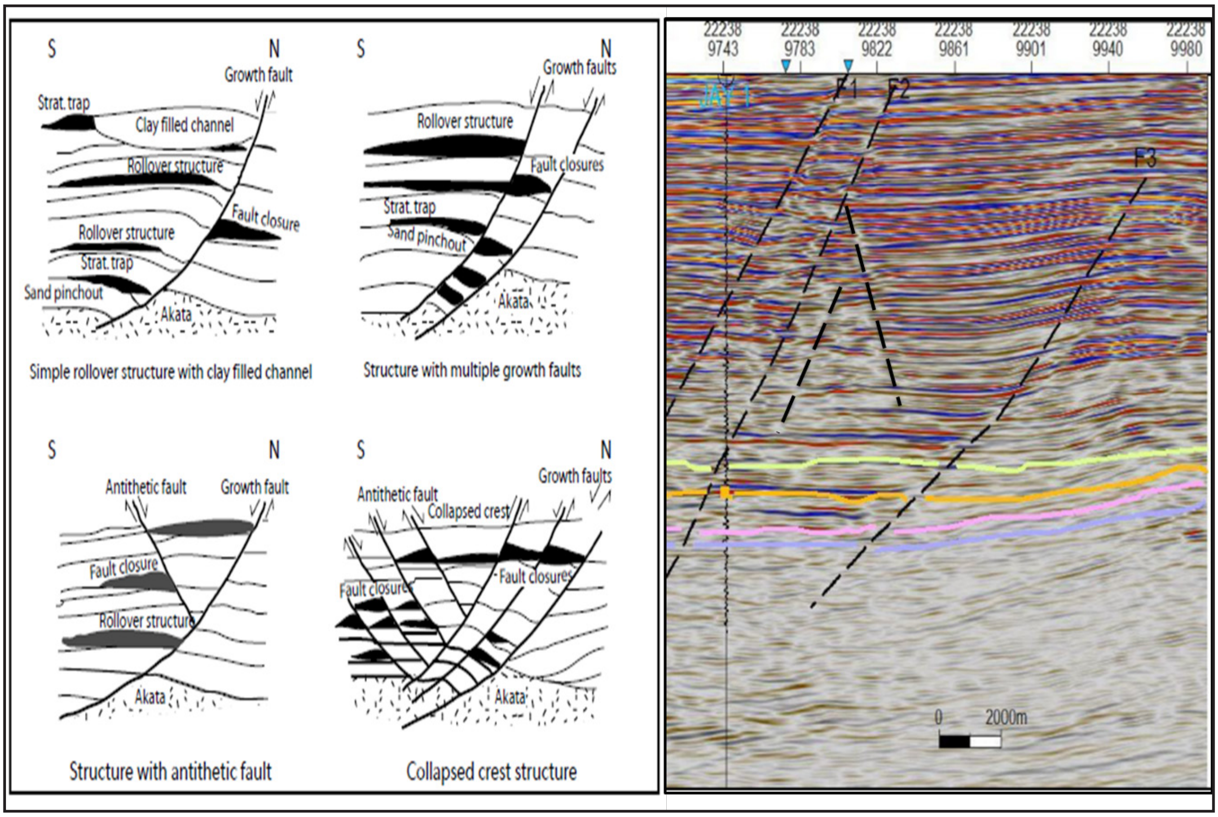

Figure 2. Structural styles of Niger Delta, Modified from Doust and Omatsola (1990) and Okpogo et al. (2018)

2. Materials and Method

Jay Field is situated in the Niger Delta Hydrocarbon Province. The field comprises 3D seismic data and a Well log, with suits of logs, density, resistivity, gamma, neutron, and sonic logs. The data were analyzed for quality control check, and were processed using Rok Doc and HRS software. The base map of the study area is displayed in Figure 3, while the seismic section with the inserted drilled well is presented in Figure 4. The quality of the section as transversed from the Benin down to Agbada formation is appreciably good, but becomes chaotic when moving down the Akata formation (marine shales) that is described in the literature to be diapiric in nature.

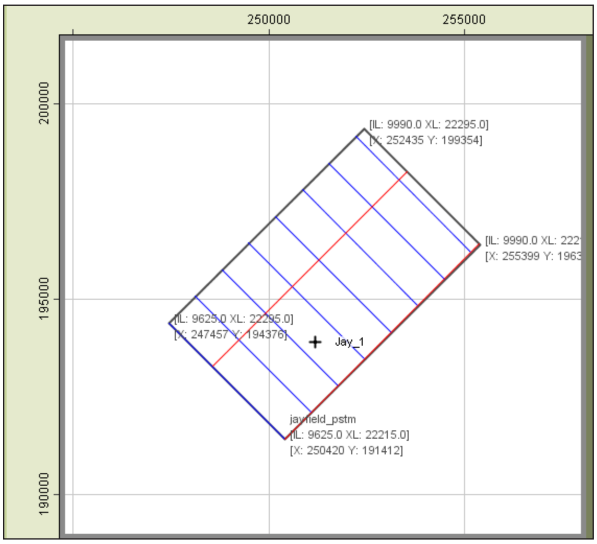

Figure 3. The base map of the study field.

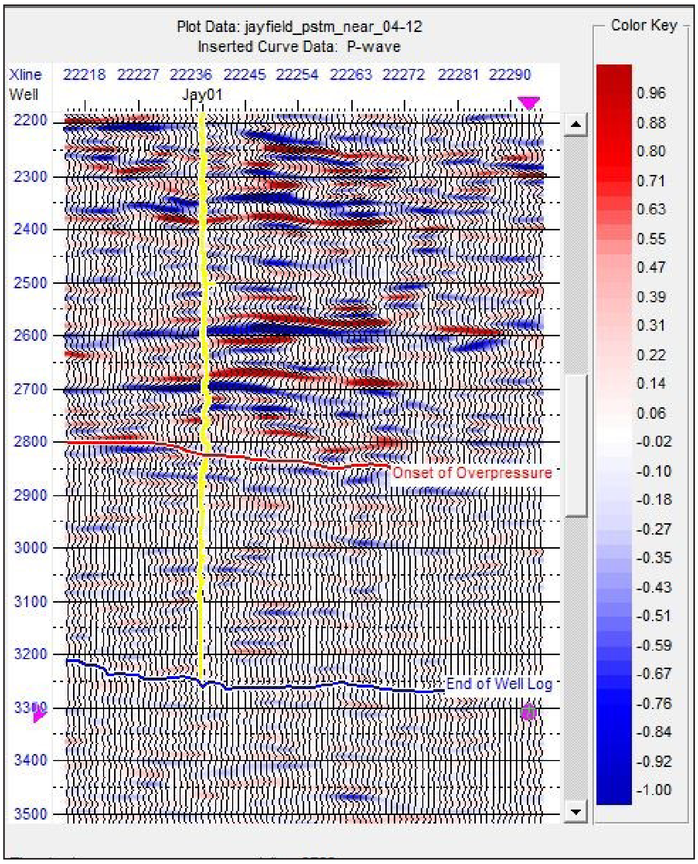

Figure 4. Display of seismic section with the Well, showing the quality of seismic section and the investigated region.

Goodway et al. (1997) calculated rock physics parameters such as velocity ratio, Lamé parameters and Poisson's ratio using P-wave and S-wave logs.

Velocity ratio, which is given as $v = \frac{Vp}{Vs}$ 2.4

Where Vp and Vs are the P-wave and S-wave velocities respectively

Incompressibility (lamba Rho) $\lambda = \rho(Vp^2) - 2(\rho Vs^2)$ 2.5

Rigidity modulus (mho Rho) $\mu = \rho(Vs^2)$ 2.6

Poisson's ratio $\varphi = \frac{\lambda}{2(\lambda+\mu)}$ 2.7

The cross-plot of P-wave (Vp) and density log is expected to reveal compaction/ disequilibrium trend, since the density and compressional wave velocity increase with depth. In a situation where the reverse becomes the case, disequilibrium compaction sets in. This implies that instead of decreasing with depth, the porosity of sediments appreciated significantly at some depth, causing the abnormal pressure regime in the formation.

Velocity ratio is independent of the rock density and acoustic impedance (Abbey et al. 2018) and can be employed to determine the over-pressured region in the formation. In a normally compacted formation, Vp/Vs ratio decreases with depth, while the acoustic impedance increases with respect to burial depth. Thus, the abnormal/ overpressure regime within the formation can be easily mapped out from the cross-plot template. Again from Hamada (2014), the Vp/Vs ratios for most consolidated rocks vary from 1.5 to 2 and Poisson's ratio for the same is between 0.1 to 0.3 3, so with the cross-plot template of Velocity ratio against Poisson's ratio, unconsolidated/un-compacted rocks' materials within a greater depth of burial will be identified.

3. Results and Discussion

Figure 5 displays the well view showing the logs of gamma-ray, resistivity, neutron porosity, density and P-wave. The gamma-ray log appears in yellow and grey colorations which represents the sand and shale stone formations respectively. The reservoirs in this well fall within 2350 ms - 2775 ms and 2900 -3700 in meters. The mapped interval with the inscription of overpressure region to the end of well is the area of interest. This is because density and p-wave velocity increases with depth in a normal compaction setting, but the area in consideration comes with a decrease in density and velocity when moving down the formation. Also, porosity decreases with depth due to compaction as a result of overburden, the reverse applies in this mapped out region due to experiencing an increase in porosity in the probed region against the former.

P-wave and density increase with depth due to the compaction of sediments in formations. According to the cross-plot in Figure 6, the en-circled clusters ought to appear at the arrow point, since from the color key it represents sediments with a greater depth of burial. This was not so because of the under-compaction of sediments which is also regarded as a disequilibrium compaction becoming a major source of overpressure regime in sedimentary formations around world. By the virtue of overburden on the overlying formation, the porosity of sediment decreases as the fluids escape the pores' space bringing about a reduction in pore space and compaction. Based on this principle, clusters which represent deposited sediments about 3700 to well end are predicted to be overpressure and are in the abnormal pressure regime.

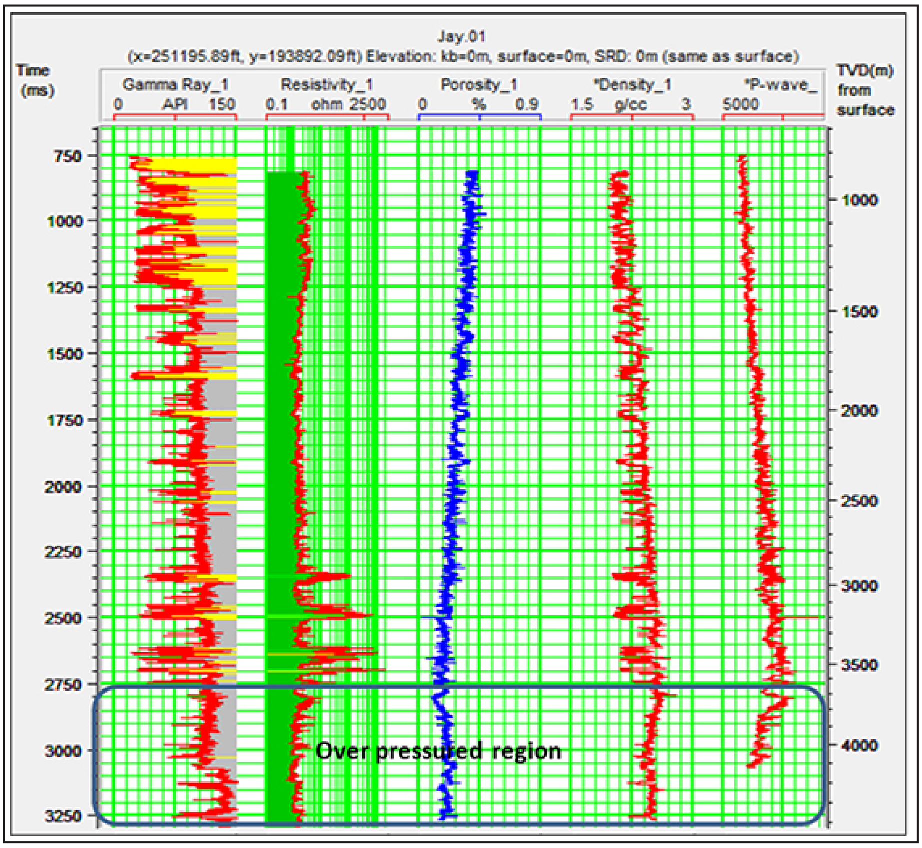

Figure 5. Well log display of in Jay field

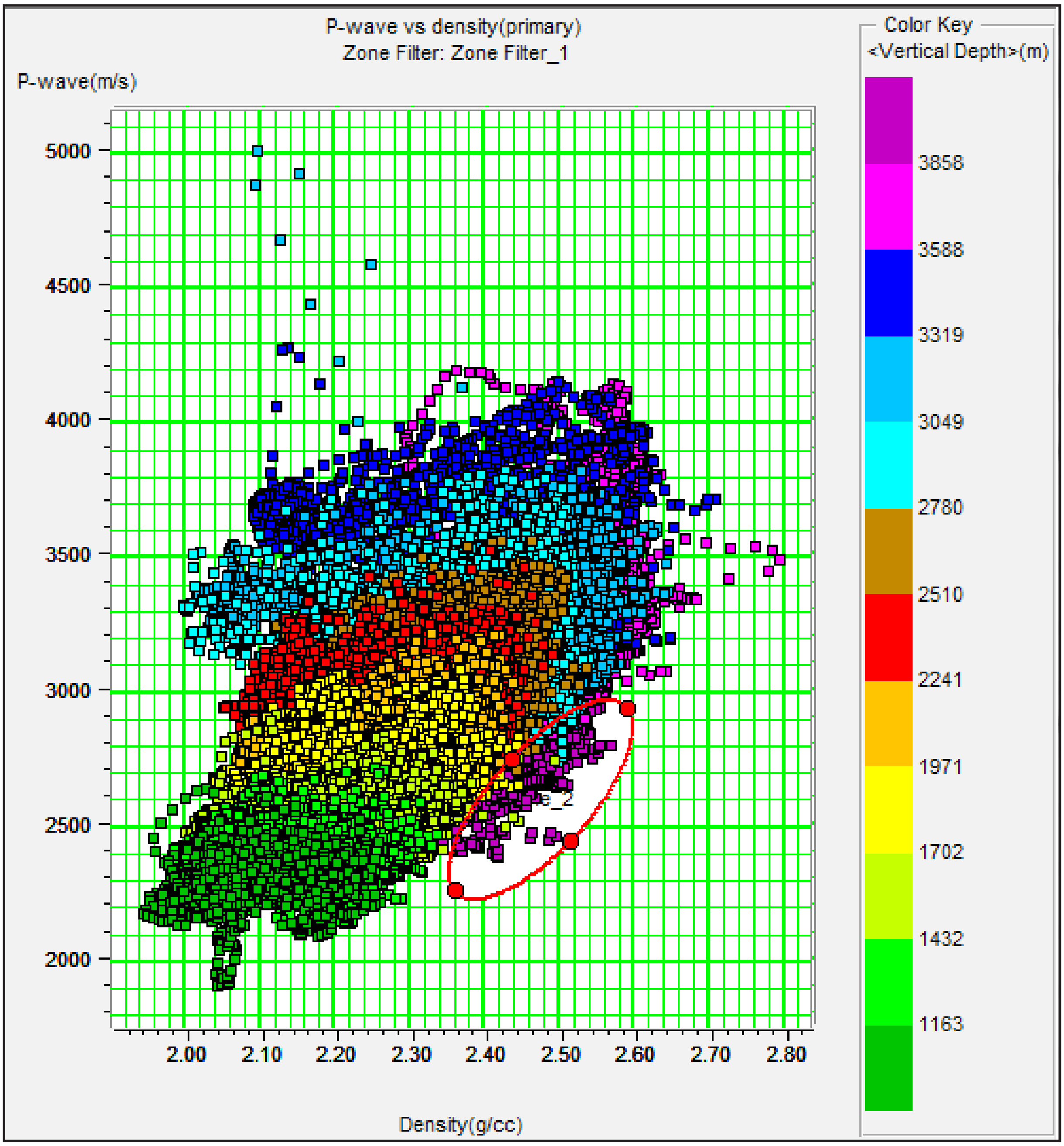

Figure 6. plot of P-wave against formation density, showing under-compacted sediment's

Consider the cross-plot of velocity ratio versus P-impedance in Figure 7a, this under compaction of sediments is made visible in the circled portions of the plots. In Figure 7a, the velocity ratio experienced an increase against what is expected when there is an increase in burial depth. The acoustic impedance, on the other hand, reveals a reduction which is against the principle when acoustic impedance increases as the depth of burial increases. The same is also applicable in Figure 7b, which is colored by porosity. Porosity decreases with the depth of burial, the porosity of the sediments in the investigated formation is observed to be greater than those above it, as observed in the circled part in Figure 7b. In Figures 7c and 7d, the same anomaly is also pictured out in the VpVs plot against porosity and the Plot of VpVs against Lambda-Rho.

The plot of p-impedance against Poisson's ratio in Figure 8 depicts the un-consolidation of sediments at the burial depth of about 3600m to the end of the log. P-impedance increases with he increase in the depth, while Poisson's ratio decreases with the increase in depth of burial. At about the abovementioned depth mention, there is an indication of an increase in Poisson's ratio with a decrease in impedance of the formation. This abnormal relationship with depth reveals an abnormal pressure regime within the probe formation. Also, in Figure 9c, the velocity ratio and Poisson's ratio increased with increases in the depth in the investigated area. This is against a decrease due to compaction and cementation of sediments, as depth increases. In Figure 10, the inverted seismic velocity displays a decrease in seismic velocity at the overpressured zone region. Sound energy increases in consolidated material and decreases in unconsolidated material. So it is expected that as burial depth increases, the velocity will also increase. From Figure 10, an increase in seismic velocity can be observed until the marked horizon of the onset of overpressure as shown from the colour indicator. The inverted seismic velocity is far better off in determining the true velocity of the formation compared to the interval transit velocity.

Furthermore, the Lame's Constant Lambda, was considered, which is a measure of rocks brittleness, and also a function of both Young's Modulus and Poisson's Ratio in this rock physics analysis of overpressure. Lambda relates stresses and strains in perpendicular directions which is closely related to the incompressibility and it is capable of revealing the resistance to a change in volume that is caused by a change in pressure. So the cross-plot of pressure and Lambda as in Figure 11 shows that the shale/clay is ductile based on the porosity and its properties. With the increased formation pressure, which has been identified as over pressured zones, comes an exponential decrease in lambda. This is anticipated since Young Modulus, similar to Lambda, is a measure of the stiffness of a material, at this point of lambda, the reduction or decrease signifies that the formation is unconsolidated with the increased porosity, thereby making the sediments accumulation at this interval not stiff otherwise ductile in nature. Considering the relationship that exists between the cross-plot of pressure against the acoustic impedance, Figure 12 reveals a direct linear relationship between pore pressure and acoustic impedance at the region where the pore pressure is normal, and an inverse relationship where there is an abnormal or overpressure regime. At this point a drastic reduction occurs in the acoustic impedance since this is a function of density and velocity when burial depth increases.

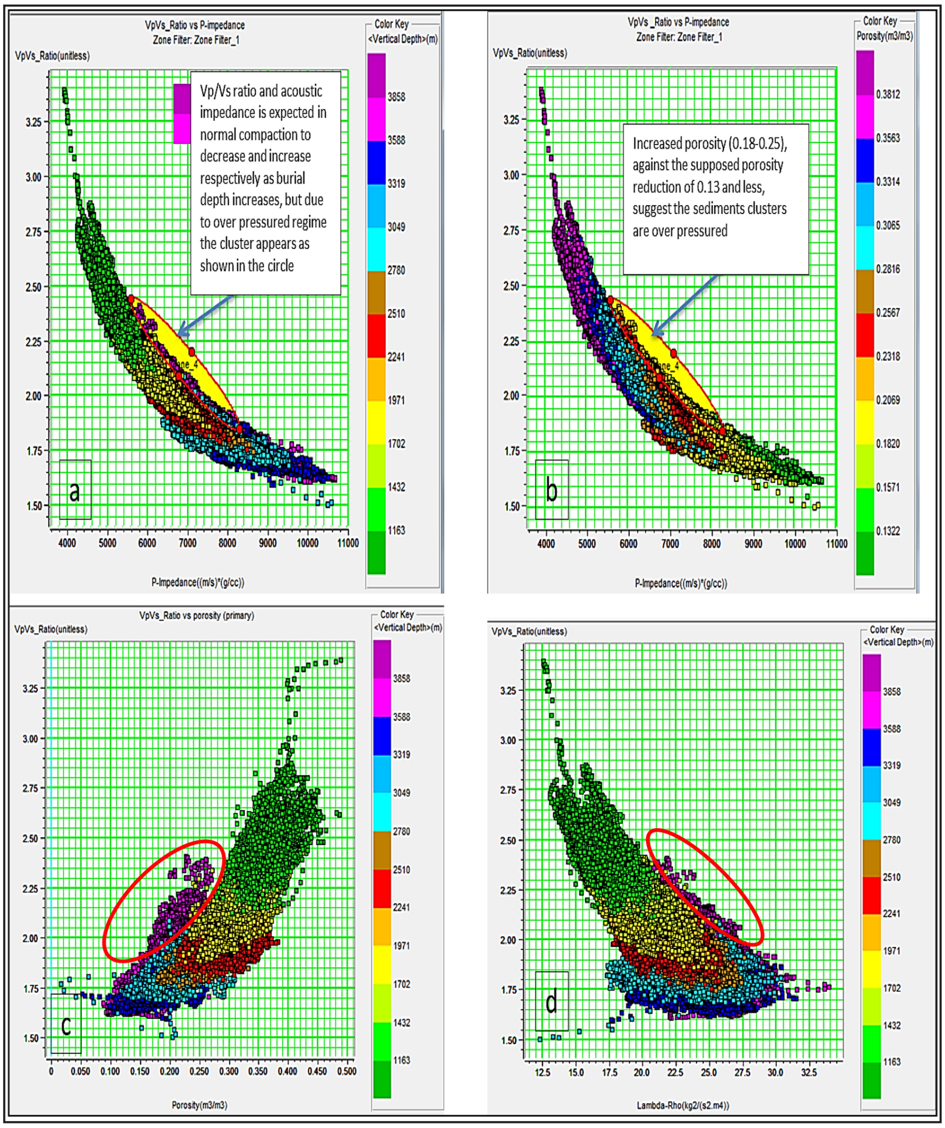

Figure 7. a and b: Plot of Velocity ratio against P-impedance revealing under-compaction, c: Plot of VpVs against porosity, d: Plot of VpVs against Lambda-Rho.

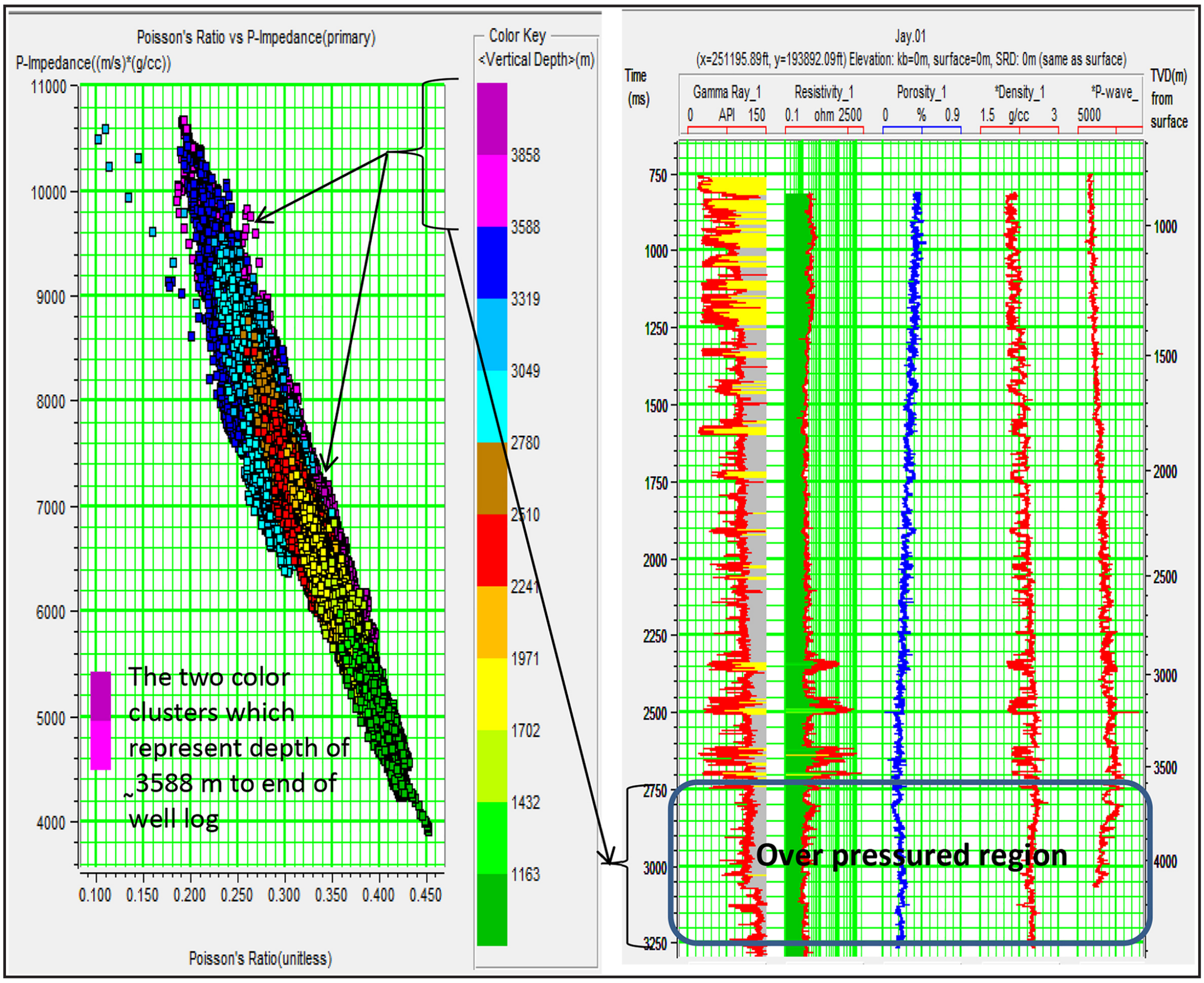

Figure 8. Plot of P-impedance vs Poisson's ratio showing the two clusters with abnormal pressure

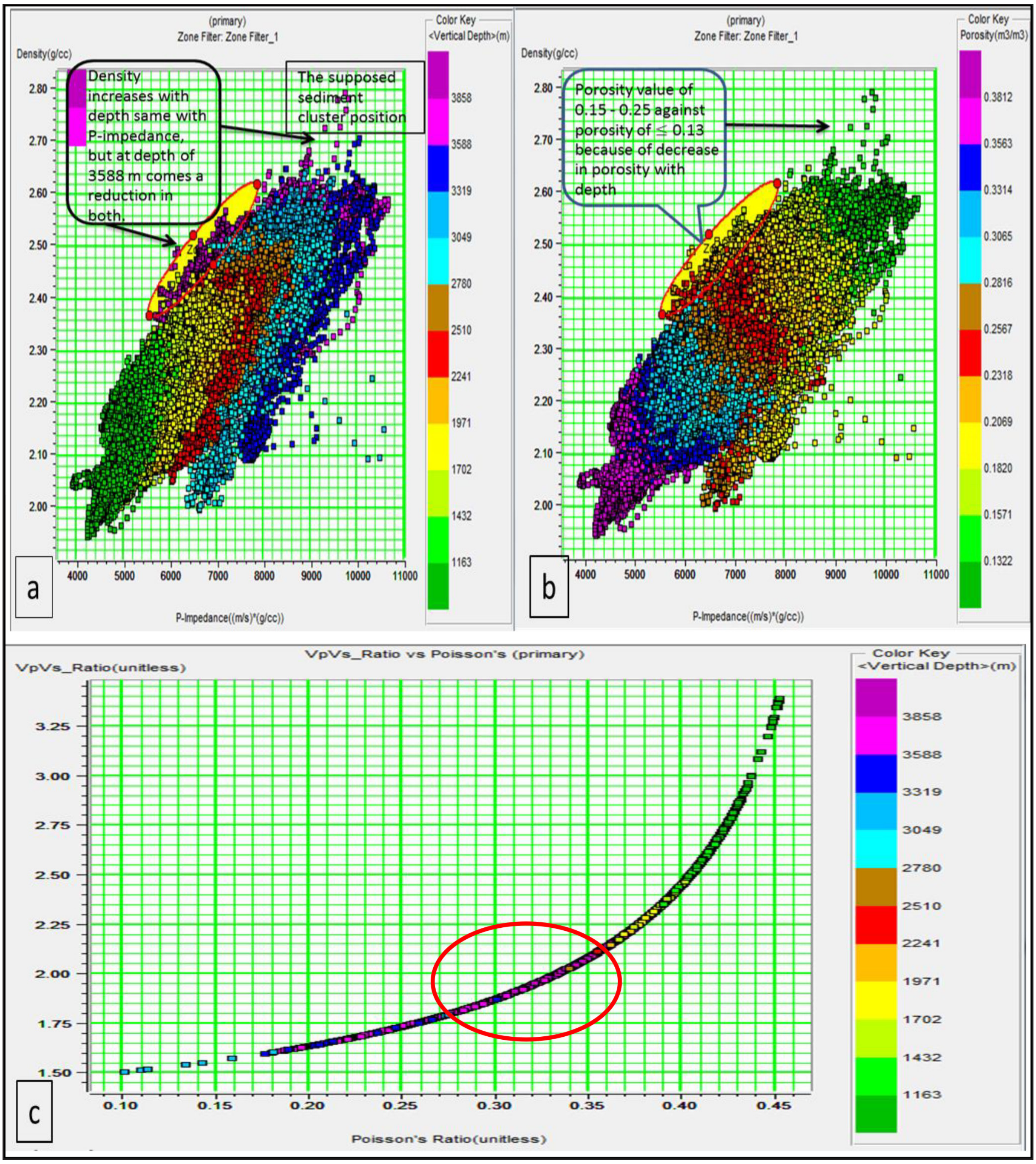

Figure 9. a and 9b: Plot of Density against P-impedance, 9c: Plot of VpVs against Poisson's ratio

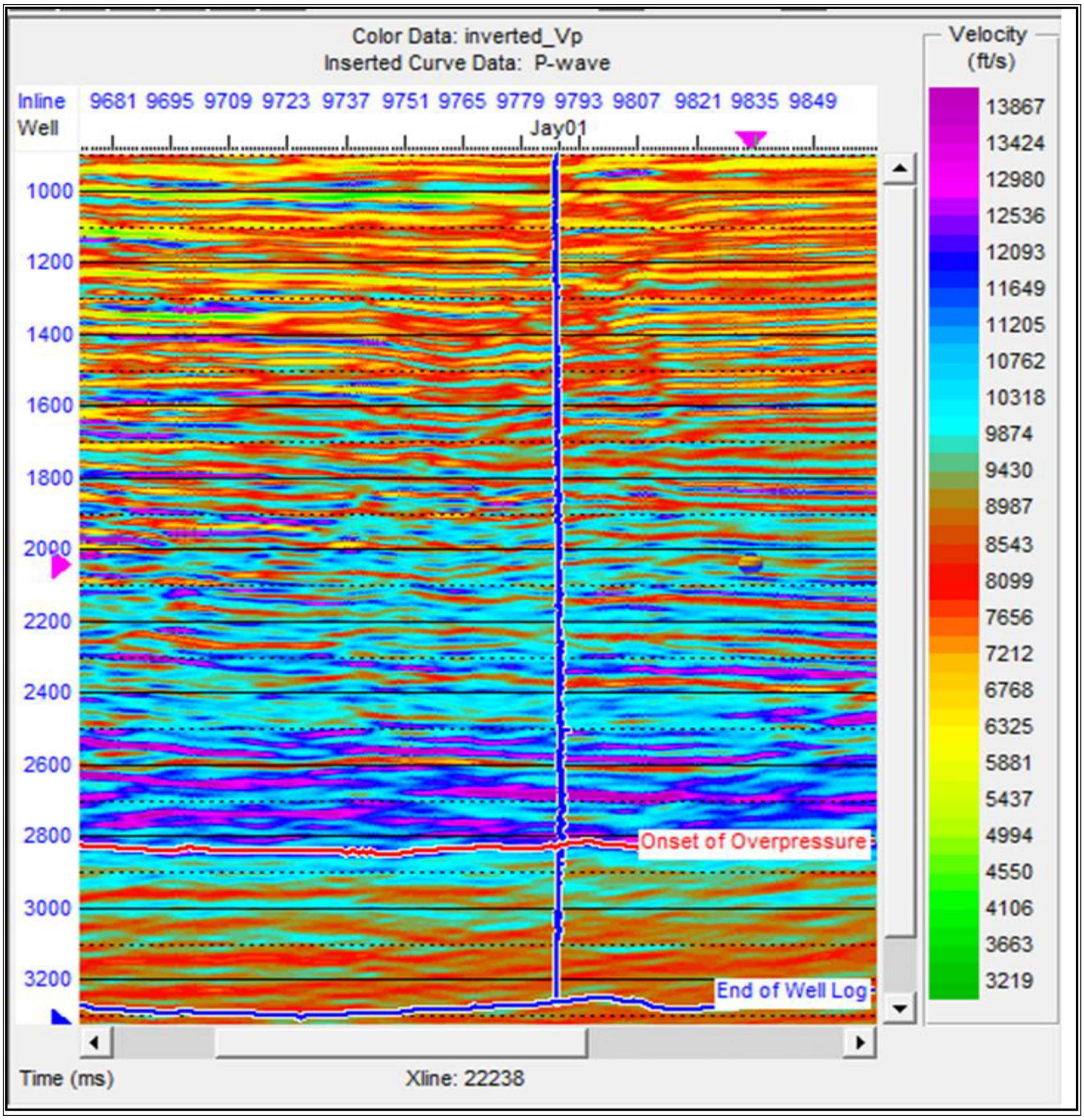

Figure 10. The seismic inverted velocity from Xline 2238

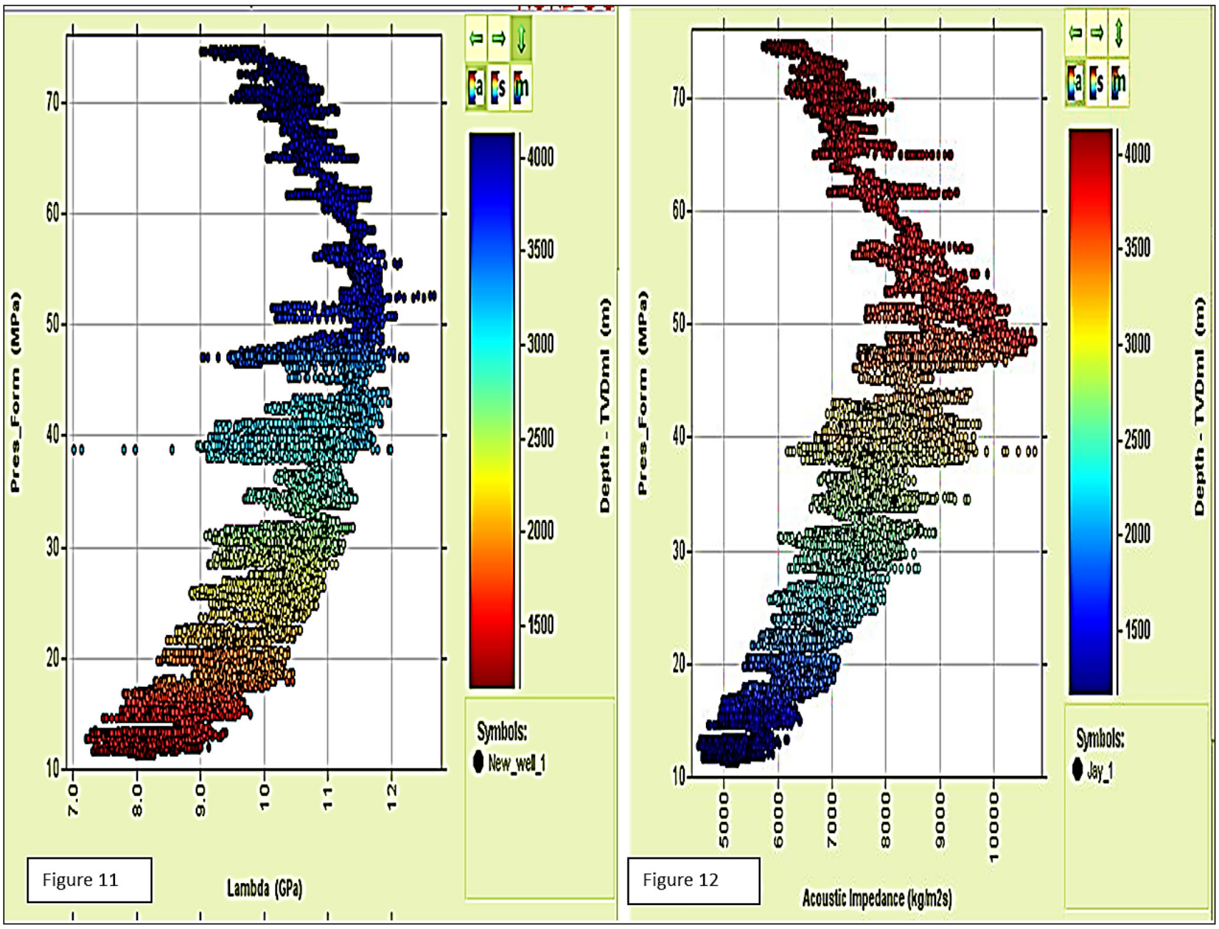

Figure 11. The Cros- plot of Pressure against Lambda and **Figure 12.** Cross-plot of pressure versus Acoustic impedance

4. Conclusions

This research was carried out with the purpose of predicting abnormal pore pressure regime in the basin through rock physics parameters and cross-plots. The field has one drilled well and a 3-D seismic volume. From the well plot, it was observed that P-wave and density logs were decreasing with depth due to the compaction of sediments. Nearly at the mapped interval, there was a reversal from the trend, with both the P-wave and density logs increasing down the hole. Porosity was also observed to be decreasing with depth till the point of the mapped interval where it began to increase, which shows that the interval is unconsolidated having a higher porosity against the depth interval. The relationship between lambda and acoustic impedance with formation pressure reveals an exponential decrease in lambda at the point of overpressured region and an inverse relationship at the over-pressured region. The acoustic impedance decreases with the increase of formation pressure which validates the un-consolidation or disequilibrium compaction within the predicted abnormal pressure interval.

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