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**Research Paper**

# Detection of Overpressure using 3D Seismic Response in the AL Field in the Niger Delta, Nigeria

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***ABSTRACT:****Three dimensional (3D) seismic and well-log data acquired in AL Field in the Niger Delta is analyzed to predict overpressured zones ahead of drilling using RocDok, VITAL and Excel softwares. The pressure increases to 0.67psi/ftah at a depth of about 12400ftah. At a depth of about 12600ftah, the pressure stabilizes and then gradually increases to 0.8psi/ft at a depth of about 15200ftah. From depth estimations, the three target reservoir levels are at depths of 11500ftss, 11700ftss and12400ftss. The implication is that the reservoirs experience hydrostatic to mild overpressures. The onset of mild overpressure has been interpreted at 11.5MFS corresponding to a depth of 11,500ft true vertical depth. The onset of hard overpressure has been interpreted at 12.1MFS corresponding to a depth of 12535ft. Using seismic method, overpressure is detected at 12400ft having pressure gradient of 0.67psi/ft.The results of this work can be used to predict overpressured depths and drilling rig capacity ahead of drilling in the area of study.*
***KEYWORDS:*** *Seismic, Well-Log Data, Overpressure Prediction, Pressure Gradient, Seismic Velocity*.

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## I. INTRODUCTION

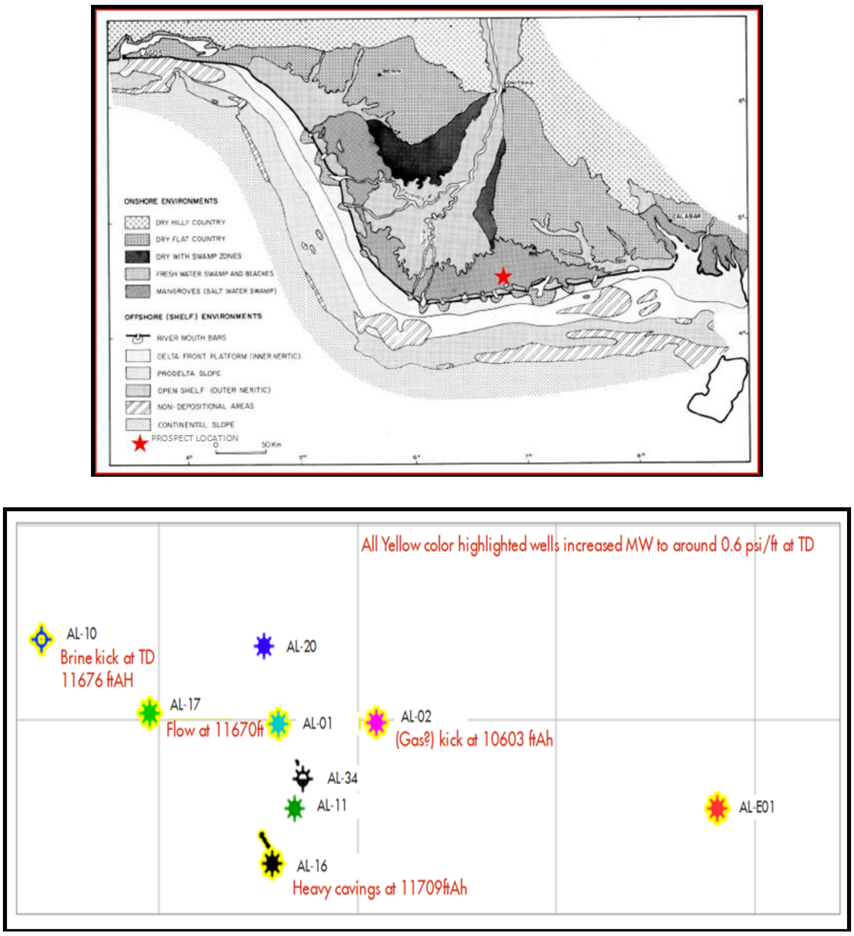
Pore pressure prediction helps in studying the hydrocarbon trap seals, mapping of hydrocarbon migration pathways, analyzing trap configurations and basin geometry and providing calibrations for basin modelling. Pre-drill pore pressure prediction allows for appropriate mud weight to be selected and drill casing program to be optimized[1, 2], thereby enabling safe and economic subsurface drilling. The importance of determination of this information has gradually been realized as some major well disasters have led to the loss of precious human life, material and adverse publicity. The only way to predict potential hazards like overpressured subsurface zones ahead of drill-bit is through the use of seismic surveys [3, 4, 5, 6]. Seismic methods detect changes of interval velocities with depth from velocity analysis of Common Dept Point (CMP) data [7]. Seismic interval velocities get influenced by changes in each of these properties and this is exhibited in terms of reflection amplitudes in seismic surveys.

This study attempts to demonstrate that seismic velocity can be used to successfully predict the depth level at which over pressure begins in the subsurface in AL prospect in the Niger Delta. The results of this project can assist in the safe and effective evaluation of the hydrocarbon potential of deep high-pressure reservoirs in AL prospect by providing a pore pressure model which will be used for the proposed high pressure well drilling design and well drilling programme. The proposed subsurface pore pressure model will also predict the capacity rig. The decision on which rig to use is critical for economic success of the drilling programme.

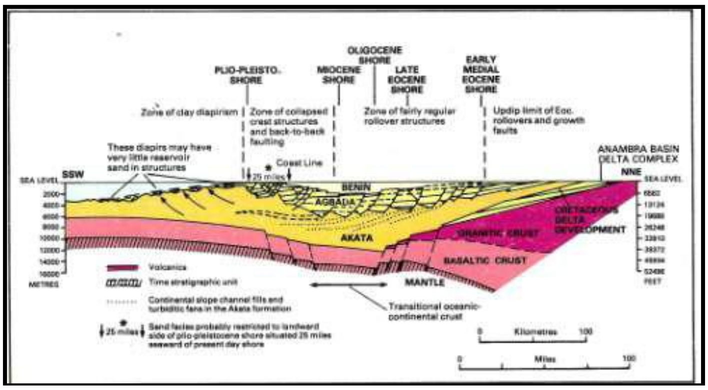
## II. THE STUDY AREA AND ITS GEOLOGY

The prospect is covered by PSI data and post stack depth migration (PSDM) data. The survey covers an area of 435 km2. A total of 34 wells (7 gas well, and 27 oil well) have been drilled in the entire AL field to date. Only one well has been drilled in the west (Y) block. Hydrocarbons have been encountered in 27 reservoirs between 6,692 and 11,500 ftss. AL Field is in the Niger Delta basin. The Niger delta is located in southern Nigeria, between latitudes 4° and 6°N and longitudes 3° and 9°E, Figure 1. It is bounded in the west by the Benin flank, and in the east by the Calabar, flank a subsurface expression of the Oban massif[8]. It is bounded in the south by the Gulf of Guinea and on the north by older (Cretaceous) tectonic elements, such as the Anambra basin, Abakaliki uplift, and Afikpo syncline[9].

The coastal sedimentary basin of Nigeria has been the scene of three depositional cycles. The first began with a marine incursion in the middle Cretaceous and was terminated by a mild folding phase in Santonian time. The second included the growth of a proto-Niger delta during the late Cretaceous and ended in a major Palaeocene marine transgression. The third cycle, from Eocene to Recent, marked the continuous growth of the main Niger delta [10].




.**Figure 1**Map of the Niger Delta showing the area of study




.**Figure2:**Structural section of the Niger Delta Complex showing Benin, Agbada and Akata Formations [10, 11, 12]

A new threefold lithostratigraphic subdivision is introduced for the Niger delta subsurface, comprising an upper sandy Benin formation, an intervening unit of alternating sandstone and shale named the Agbada formation, and a lower shaly Akata formation, Figure 2. These three units extend across the whole delta and each ranges in age from early Tertiary to Recent[10]. They are related to the present outcrops and environments of deposition. Subsurface structures are described as resulting from movement under the influence of gravity and their distribution is related to growth stages of the delta. Rollover anticlines in front of growth faults form the main objectives of oil exploration, the hydrocarbons being found in sandstone reservoirs of the Agbada formation [10].

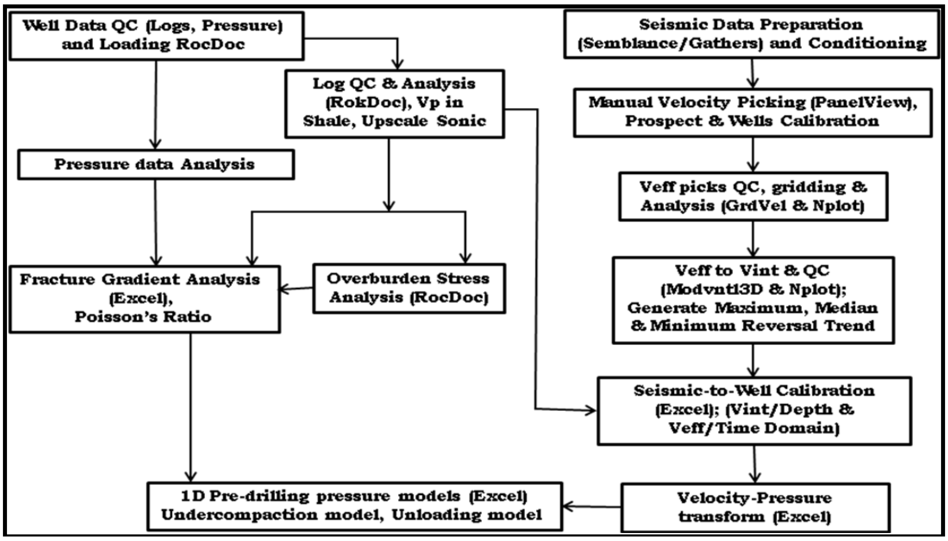
## III. METHODOLOGY

Data was considered good quality. A constrained sparse spike acoustic impedance data was also generated from the PSDM data, and the PSDM volume was the main volume used in carrying out the velocity analysis in the study.

The workflow for the prediction of pore pressure using an integration of well data and 3D seismic data (Figure 3) is in two major parts. A suit of logs and seismic data were supplied by SPDC. The first part is the rock property estimation using well data. It involves the loading and quality check (QC) of well logs and pressure data in RokDoc Petro-Geophysical software, the generation of the shale Vp trend and up scaling of sonic log, the analysis of pressure data from Mud weight and RFT data, the generation of overburden stress from density log and the estimation of fracture gradient.

The second part involves the preparation and application of the available seismic data for the interpretation of velocity trends and the estimation of pore pressure. This entails manual velocity picking and QC using VITAL software, manual seismic horizon interpretation in 123DI, the conversion of effective velocity (Veff) from seismic to Interval velocity (Vint), the calibration of the interval velocity from seismic using well interval velocity and the pore pressure estimation. These two stages are merged to generate the integrated 1-D pre-drill pressure model.

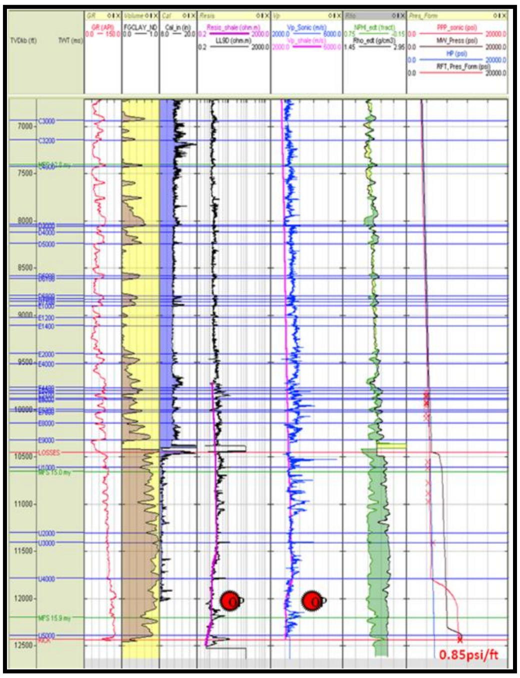
Two sets of wells were used for the pressure calibration and analysis in the AL project. One set consisted of two wells located within the same regional macro structure as the AL Field but not within the same field. These are referred to as ‘Regional reference wells. These wells are the KO-10 well in KO Field and AK-10 well in AK field. These two wells encountered hard over pressure and velocity reversal was observed at the depth onset of the hard overpressure. The second set consisted of 13 wells within the AL Field. Five of these wells had pressure data from mud weight while seven wells had measured pressure data.




.**Figure 3:**Workflow diagram for the prediction of pore pressure study

AL-017, located in the fault block north of the prospect has penetrated the mild over pressured zone. Therefore, horizon interpretation corresponding to the depth of onset of mild over pressure in the well was interpreted across from the AL-17 well to the prospective fault block. None of the wells in the AL Field has penetrated the hard overpressure zone. The available data was loaded in RokDoc and Excel spreadsheets for QC and analysis.

Figures 4 and 5 show the available logs of the two regional correlation wells loaded into RokDoc. From left to right, the logs are Gamma Ray, Volume of Shale, Resistivity, Sonic and Density logs and formation pressure measurement points all displayed on an increasing depth scale. For KO-10, Hydrostatic pressure was encountered from the surface up to 11600ft along hole. A gradual increase in pressure, mild overpressure, was observed. The pressure increase became significantly higher at a depth of 12200ft along hole, corresponding to the interval of 'thick' regional marine shale. The depth of this high increase in pore pressure corresponds to the depth of the observed deviation (decrease) in velocity as indicated by the red dot. A similar trend is noticed in AK-10 well where a reversal in velocity at 12100ftah can be correlated to the observed onset of overpressure as indicated by the red dot.



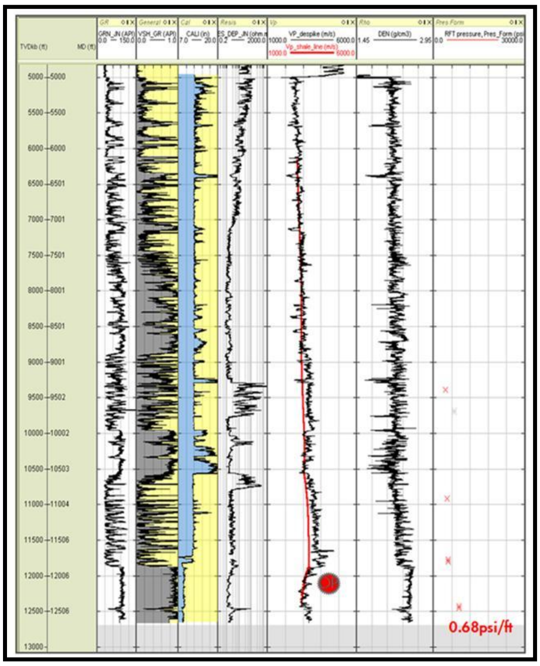




**Figure 4:** Composite log of well KO-10**.** **Figure 5:** Composite log of well AK-10
**(Red dot indicates the onset of Overpressure).**

Although none of the well in AL field encountered 'hard' overpressure, the data was collated and used for Pore pressure calibration of hydrostatic to mild over pressure section of the field. Figure6 shows a pressure depth plot of wells in AL field. The pink-colored outlier is AL-02 which took a mild kick and flowed at 10603ft ah. It finally encountered over pressure and was stopped at 10753ftah. AL-17 also took a brine kick at 11670ftah.

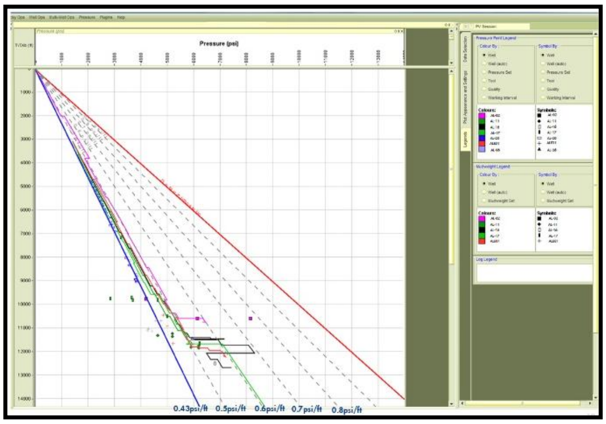



**Figure 6:** Pressure depth plot of wells in AL Field

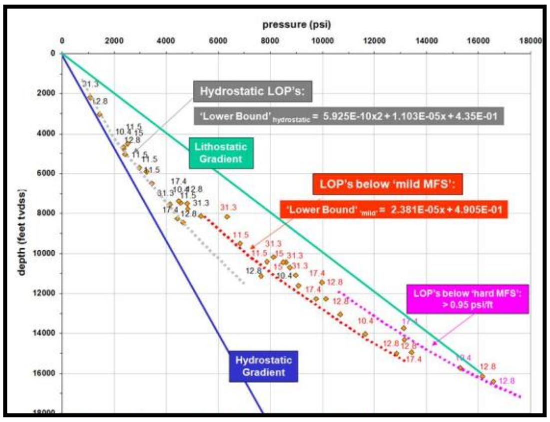



**Figure 7:**Fracture gradient estimation from regional wells for overburden stress computation.

The fracture gradient was estimated using the regional Leak off Test (LOT) data. Multiple LOP data from several wells in the region was plotted and the regional trends for hydrostatic, Mild over pressure and hard over pressure zones were established (Figure 7). The trend equations were used to estimate the fracture gradients at the Al prospect.

The expected effect of over pressure on seismic velocity data is to cause a 'velocity reversal'[7, 13, 14], which refers to a gradual (or sharp) decrease in seismic velocity trend at depth instead of the gradual increase in seismic velocity with depth. In order to properly analyse the seismic velocity for a possible velocity reversal, velocity semblances were generated. The generated velocity semblance data, also called Vacks, are effective velocity profile representing the best normal move-out velocity that produces the best stack at each discrete time or depth. Picking the best points on the Vacks volume will give the best flattening of the gathers and therefore the best stacks.

The velocity semblance volume was loaded onto VITAL software for manual velocity picking used for seismic velocity analysis and evaluation tool used in estimating the Effective seismic velocity, Veff, and the interval seismic velocity, Vint, for pore pressure prediction. The trend reversal effect was consistent across the entire fault block for AL West deep. The white arrow is inferred to be the onset of mild over pressure (0.6 – 0.69 psi/ft) while the purple arrow is inferred to be the onset of hard over pressure. At this stage, this is just an interpretation which will be confirmed by further analysis and ultimately during drilling.

From the velocity interpretation it was observed that the point of velocity reversal can be interpreted across the Field using the available seismic volume. The two points coincide with the 11.5MFS and 12.8MFS and where interpreted as surfaces across the volume and depth converted. This was used as the seismically derived onset of mild over pressure and hard over pressure (Figure 8). The point indicated by the white arrow coincides with the onset of over pressure tested in AL-17.

The result of the manual velocity picking is a set of effective velocity points in time. These points where plotted on a velocity versus two-way time plot to identify the time of velocity reversal (Figure 9). Also plotted was the hydrostatic trend (in blue). Using the plot the minimum, median and maximum reversal trends where derived. Analysis of the plotted data shows that a velocity slowdown is noticed from about 2000ms and a velocity reversal is clearly noticed at about 2800ms.

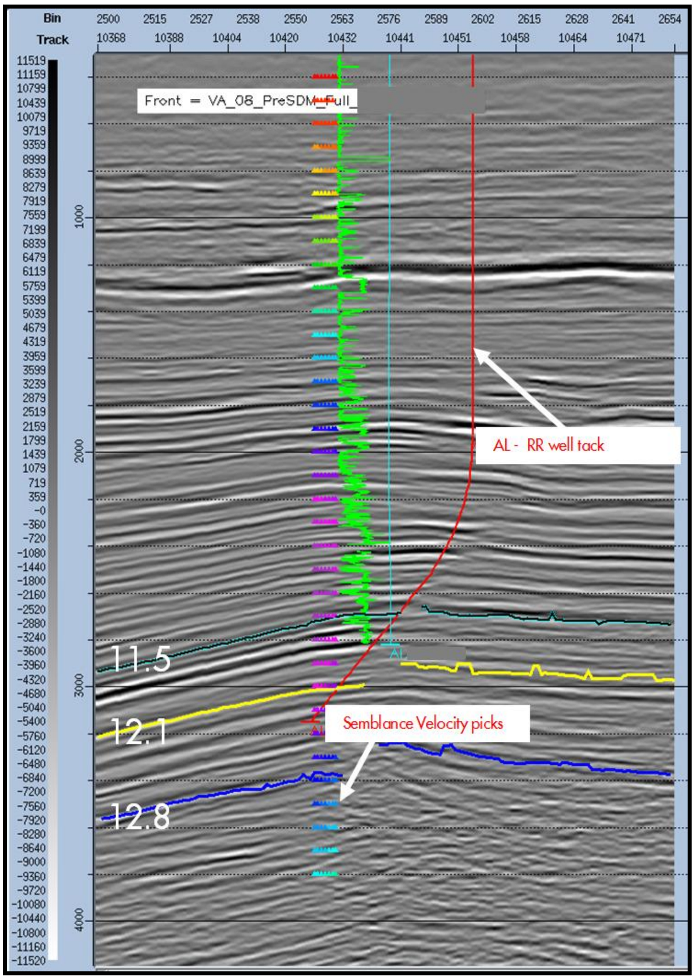



**Figure 8:** Interpreted levels 11.5 and 12.1 corresponding to velocity reversals seen on semblance sections. Seismic trace section through AL-17 well location. White arrow indicates measured onset of mild over pressure**.**

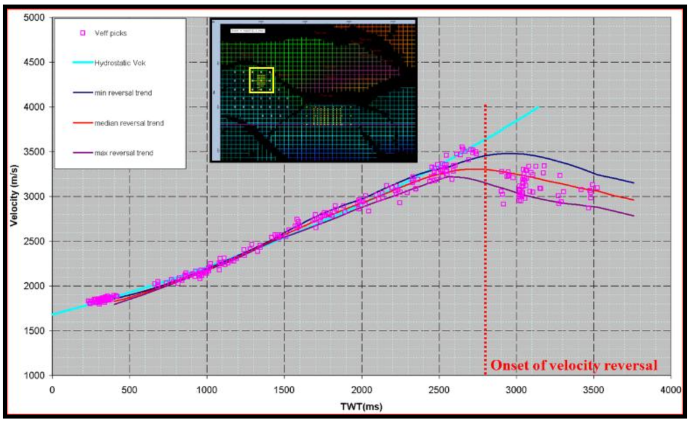



**Figure 9:** Velocity pick for AL Field. Velocity here is interval Velocity derived from manually picked Effective (rms) velocity (stacking velocity).

The Picked effective seismic velocity also recorded as $V_{rms}$ was gridded with 'Gridvel' and merged with the original picks using 'Velmerge'. It was then converted to interval velocity using the Modvntl3d package in VITAL while the data quality checking was carried out in Nplot. The Equation used for the conversion is

$$V_{int} = \frac{V_{rms.N}^2 t_N - V_{rms.N-1}^2 t_{N-1}}{t_N - t_{N-1}} \quad (1)$$

Where $V_{int}$ is the interval velocity of the Nth layer, $V_{rms.N}$ is theroot mean squared velocity of the $N^{th}$ layer and $t_N$ is the two-way travel time to the $N^{th}$layer.

In order to calibrate the seismic velocity to well velocity at prospect location, the average velocity from wells AL-001, AL-002, AL-027, AL-029, AL-034 and ALE001 was plotted on a two-way time versus average velocity. Also plotted was the effective velocity picks from the seismic velocity data (Figure 10). The plot was used to compare, in time, the correlation between the well velocity data (hard data) and the seismic effective velocity data. The plot showed that down to the end of well control (indicated on the diagram) there is a good correlation of the two sets of data. Care was, however, applied in using the points deeper than well control.

## IV. RESULTS AND DISCUSSION

Although no well in the AL field has penetrated the top of hard over pressure (pressure > 0.7 psi/ft), AL-017, located in the fault block north of the prospect has penetrated the mild over pressured zone. Velocity picking was carried out around the AL-17 well location and two velocity reversals were observed on the velocity semblance profile. Figures11 and 12 shows the seismic section through the AL-17 well and the observed velocity reversal. Figure13 shows the observed velocity reversal at the AL well location. The observed velocity reversal, indicated by the white arrow corresponds to the level where the mild overpressure was recorded in the AL field. This is a direct indication that the seismic velocity is sensitive to overpressure[15]. This level was interpreted across the seismic volume as the seismically derived onset of overpressure.

To calibrate the seismic velocity to the well velocity, the effective velocity from the well picks were plotted on an interval velocity versus depth cross plot with sonic velocities and shale velocities from well logs (Figure14). The maximum possible reversal trend and the minimum possible reversal trend from the effective velocity picks were also plotted. It was observed that the effective velocity aligns properly with the sonic velocity over the hydrostatic section of the model. The seismic data and well data on this plot follow the same trend up to 11,500ft which is the end of the well. Beyond this limit, the seismically derived effective velocity shows a trend reversal indicating the onset of over pressure. As shown in Figure15 the velocities had a one to one fit so no up-scaling was required for the seismic velocity. The seismic velocity was therefore used for the estimation of the interval velocity without any additional scaling applied.In addition to this, the level where the second reversal was observed was also interpreted as the seismically derived onset of hard overpressure (Figure16).

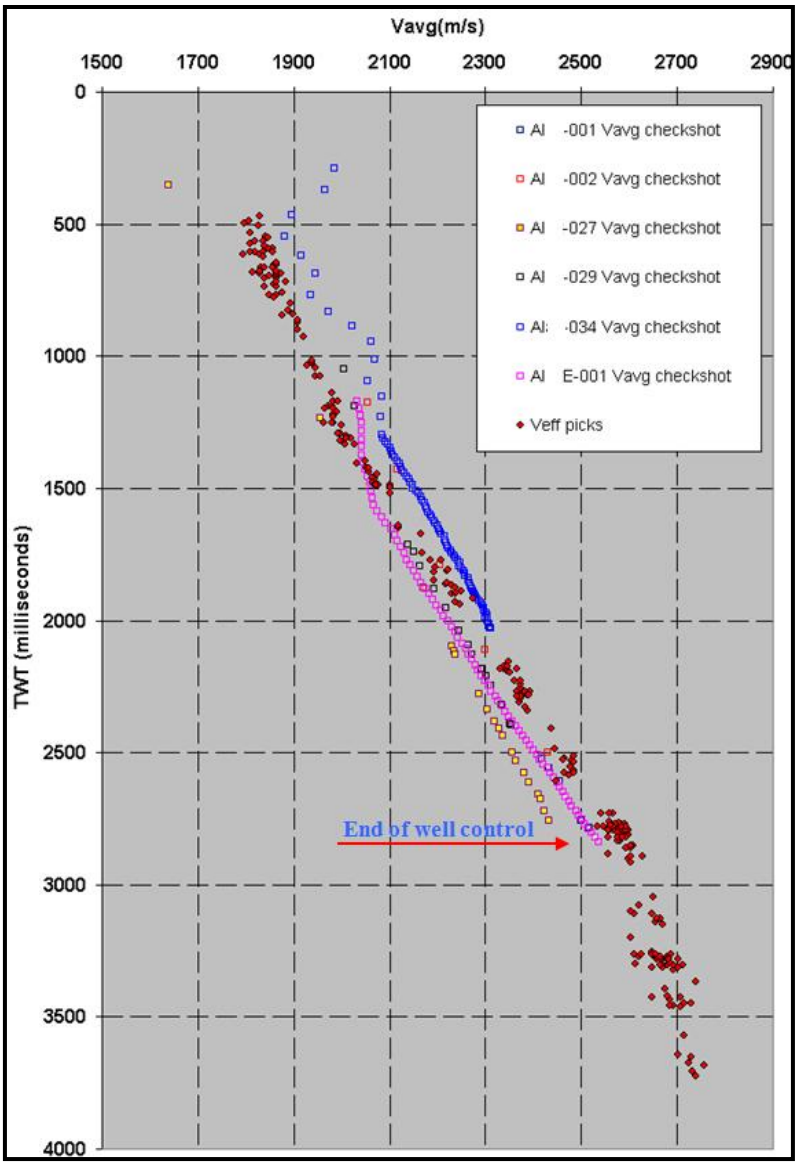



**Figure 10:** Velocity-depth cross-plots

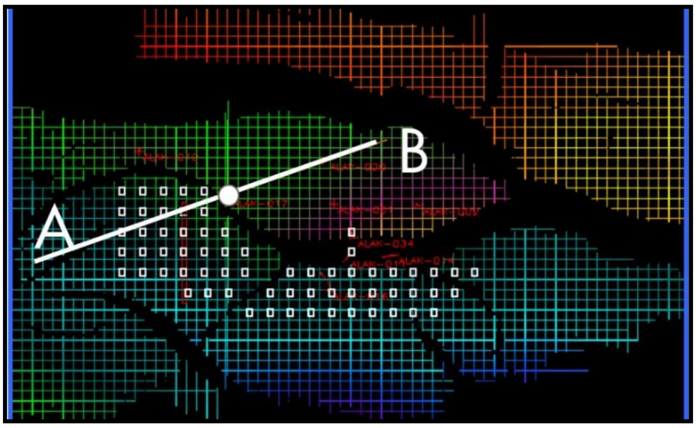



**Figure 11:** Seismically-derived onset of mild over pressure (11.5) Line A to B is a line through AL-17

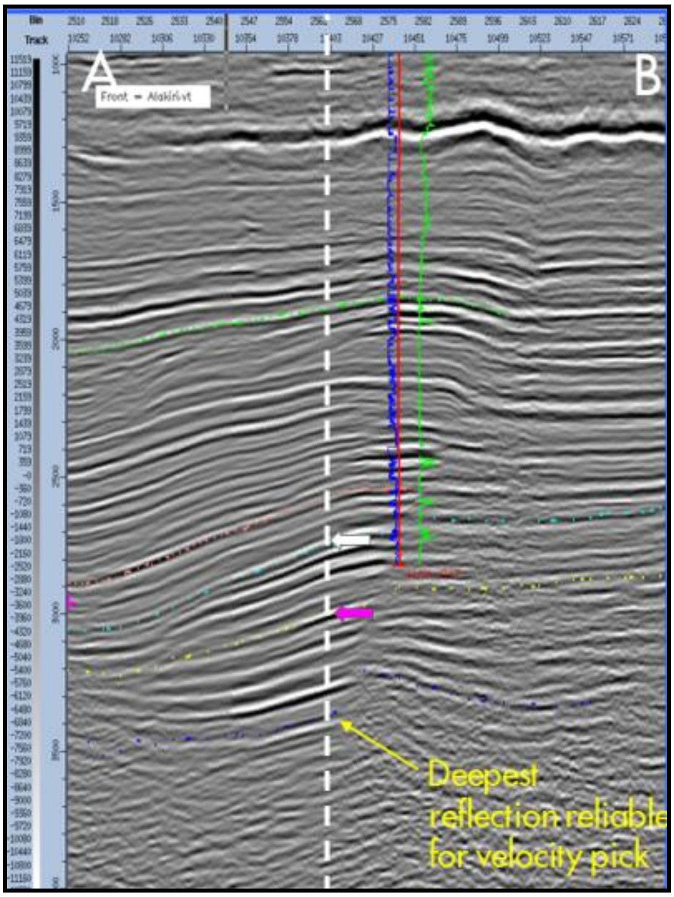



**Figure 12:** Seismic trace section through Well AL-17 location. [White arrow indicates measured onset of mild over pressure].

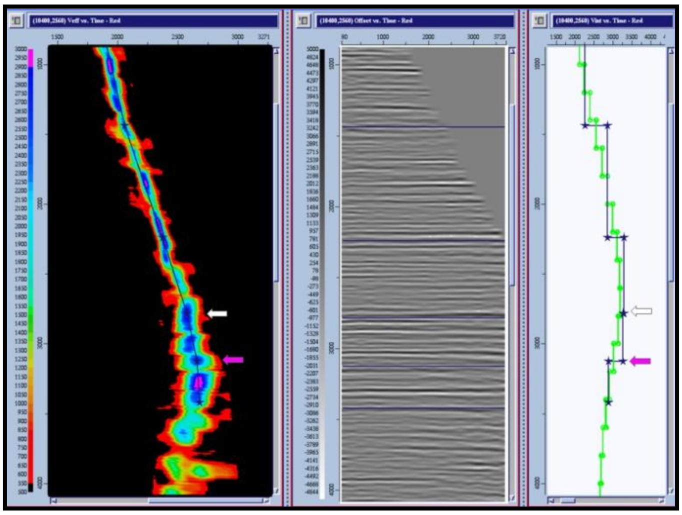


**Figure 13:** Semblance velocity extraction at Well AL-17 location. [The white arrow corresponds to the onset of mild over pressure measured in the well. The purple arrow corresponds to the interpreted onset of second velocity reversal which may indicate the onset of hard overpressure]**.**

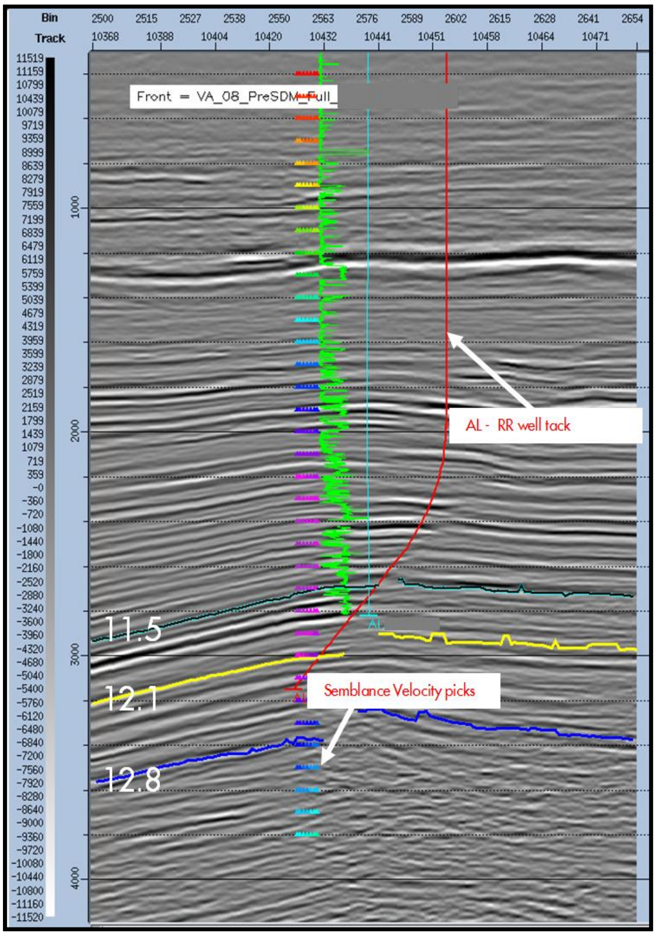



**Figure 14:** Interpreted levels 11.5 and 12.1 corresponding to velocity reversals seen on semblance sections.

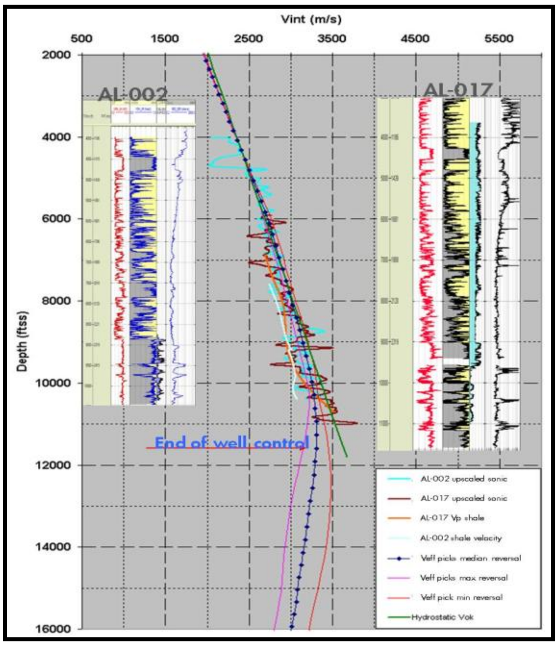



**Figure 15:** Velocity-depth cross-plots

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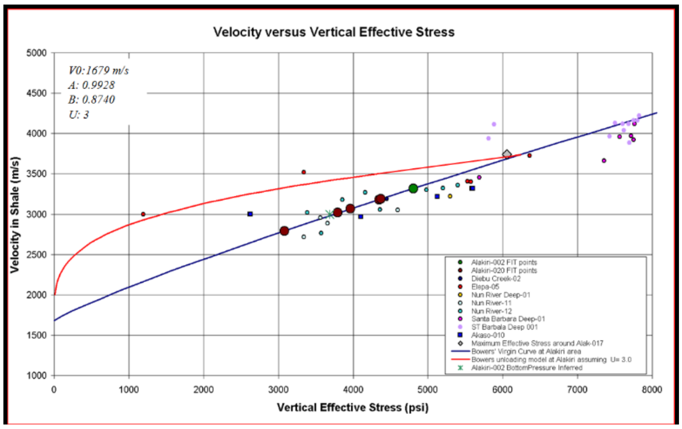


**Figure 16:** AL Bowers-models for undercompaction and unloading

Although it is believed that the velocity reversal seen in the prospect is caused by over pressure[7, 16, 17], it is not clear if this reversal is caused by over pressure due to undercompaction (weight of the overburden) alone or a combination of under-compaction and unloading effect. Unloading effect here refers to effects which causes increase in pore pressure other than under-compaction. Such effect could be due to thermal expansion, shale digenesis, pressure transmission, hydrocarbon generation etc[18, 19].

The VES was estimated using two variations of the Bowers model[13] to capture these two scenarios, (Figure16). These were the undercompacted Bower's model and the Unloading Bowers model. For the under-compaction model:

$$VES_{loading} = \frac{V_p - V_o}{A^{\frac{1}{B}}} \tag{2}$$

Where $VES_{loading}$ is the vertical effective stress caused by normal compaction (undercompaction); $V_p$ is the interval velocity from seismic semblance velocity picks, $V_o$ = 1679 m/s; $A$ = 0.9928; $B$ = 0.8740; A and B are parameters calibrated with offset velocity versuseffective stress data.

Using (Equation 1), the pore pressure for AL west deep was predicted. Figure17 shows the final pressure plots for AL prospect. Evaluation of the undercompaction and unloading models shows that the unloading model predicts a relatively higher pore pressure trend than the undercompaction model, as expected. The expected case is an average of the two models as shown in the Figure16 (red line).

For the unloading model:

$$VES_{unloading} = VES_{max} \times \left[\frac{\left(\frac{V_p - V_o}{A^{\frac{1}{B}}}\right)}{VES_{max}}\right]^U \tag{3}$$

Where $VES_{unloading}$ is the vertical effective stress as a result of unloading effect; $VES_{max}$ is the maximum vertical effective stress and $U$ unloading parameter: a measure of how plastic the sediment is. When $U$ = 1, it implies no permanent deformation because the unloading curve reduces to the origin (loading) curve. $U$ = ∞ (infinity) corresponds to completely irreversible deformation. Typically, $U$ is between 3 and 8[20]. In this evaluation $U$ was 3 as derived from the trend fit in the red curve (Figure17).

From the pressure-depth prognosis, the pore pressures remain hydrostatic up to a depth of about 12300ftah. The pressure suddenly increases to 0.67psi/ftah at a depth of about 12400ftah. The increase in pressure may be as a result of both under-compaction and unloading. At a depth of about 12600ftah, the pressure stabilizes and then gradually increases to 0.8psi/ft at a depth of about 15200ftah. From depth estimations, the three target reservoir levels are at a depth of 11500ftss, 11700ftss and12400ftss respectively. The implication is that the reservoirs will be hydrostatic to mild overpressured (Figure 17).

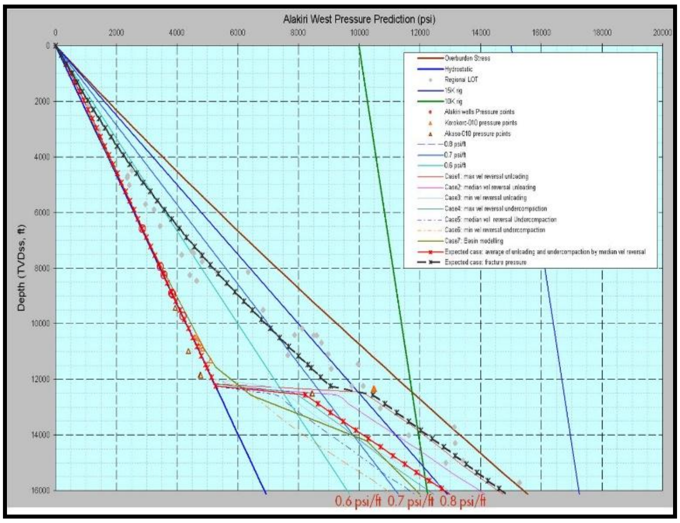


**Figure 17:** Pore pressure prediction of AL Field

## V. CONCLUSION

The study has attempted to predict the onset of overpressure in a deep hydrocarbon reservoir in the Niger Delta using and integration of 3D seismic data and well data. These reservoirs have not been penetrated by any wells in the prospect area. The onset of over pressure has been successfully interpreted using effective seismic velocities calibrated with velocity data from analogous wells in the same mega structure and with focal wells in the same field. The following conclusions have been drawn from the study:

- The seismic velocity data is sensitive to overpressure. An increase in pore pressure corresponds to a relative decrease in seismic velocity.
- The onset of mild over pressure has been interpreted as 11.5 surface, corresponding to a depth of 11,500ft true vertical depth.
- The onset of hard over pressure has been interpreted as 12.1 surface corresponding to a depth of 12535ft true vertical depth.
- Using seismic method, overpressure is detected at 12400ft having pressure gradient of 0.67psi/ft.

## ACKNOWLEDGEMENT

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