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Pore Pressure Prediction in Onshore West Niger Delta Using Inverted Seismic Velocity and Derived Velocity (Vp) - Vertical Effective Stress (VES) Coefficients

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Abstract
In this study, pore pressure has been predicted using seismic data and derived compressional wave velocity (V_p) - Vertical Effective Stress (VES) coefficients. Post Stack Time Migration (PSTM), angle stack gathers, seismic horizons, checkshot, wireline logs, drilling and pressure data from six wells in the Onshore West Niger Delta, Nigeria were analysed and interpreted. Using generated velocity and density crossplots, the active overpressure generating mechanisms for the studied area were deduced. The V_p-VES coefficients were modelled using the direct pressure data and the overburden profile computed from density log. Post stack seismic inversion was performed to improve the seismic resolution as well as derive acoustic impedance using well velocities and stacking velocities from velocity analysis of the 3-D seismic data. The derived V_p-VES coefficients were used to transform the seismic acoustic impedance velocity into seismic pore pressure volume. Pore pressure profiles were accordingly extracted along well paths so as to test the accuracy of the model. Interpreted density-velocity crossplots revealed a decrease in velocity at constant density of 2.4 g/cc, an indication that unloading mechanisms contribute to overpressure in the field. The Bowers' V_p-VES coefficients of 7.43 and 0.77 were determined for A and B parameters respectively. Based on the results obtained, the top of overpressure occurred at a depth of 3750 ft and 3800 ft in UMO-001 and UMO-002 wells respectively with a corresponding average pore pressure gradient of 0.47 psi/ft for both wells, indicating that the wells are mildly overpressured. Onsets of unloading were observed in UMO-001 and UMO-002 wells at depths of 6250 ft and 6800 ft with pore pressure gradients of 0.51 psi/ft and 0.60 psi/ft respectively. The Derived Seismic Pore Pressure (DSPP) matched the measured pressure value (kick) of 5300 psi at a depth of 7450 ft and this validated and further increased confidence on the values of the V_p-VES coefficients derived. These results show that the derived seismic acoustic impedance volume, vertical effective stress and overburden model produce high resolution seismic pore pressure cube in both time and space. The derived models when applied especially, with seismic acoustic impedance volume can be used to plan and drill future wells with great successes in the studied area.
Keywords: pore pressure, vertical effective stress, seismic velocity, acoustic impedance
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1. Introduction

Overpressures occur world wide and have been reported frequently by hydrocarbon exploration and production teams across various sedimentary basins. These high pore pressures are known to be responsible for drilling hazards such as stuck pipe, lost circulation, well kicks, borehole instability and blowouts (Narciso *et al.*, 2018). In the Niger Delta basin, these drilling problems have also been encountered and widely reported, hence a good quantitative understanding of formation pore pressure is required for successful exploration and production ventures. According to Udo (2015), Eaton's method has been widely applied for overpressure prediction in onshore Niger Delta and accurate results are only obtained at depths where undercompaction is the primary mechanism for overpressure generation. This often leads to errors in the predicted results because secondary mechanisms have been found to also contribute to overpressure generation in the Niger Delta basin (Udo, 2018). Uko *et al.,* (2013) predicted that porosity data can be used in the prediction of overpressure in the absence of seismic data. Composite log were used to obtain the required data by digitizing the logs and deduction using the appropriate relationships. It was observed that porosity decreases with depth.

More so, most of the legacy seismic surveys in the Niger Delta have limited azimuth and spread length, thus making detailed velocity analysis for deep overpressure prediction impracticable due to poor resolution at greater depths. This is even made more complicated by the use of methods based on Normal Compaction Trends (NCT) in transforming the seismic velocity to seismic pore pressure cube. Hence, the need to obtain high-resolution velocity through seismic inversion and convert the resulting acoustic impedance to seismic pore pressure directly using velocity- vertical effective stress model. In this way, uncertainty in seismically derived pore pressure is reduced.

Arising from the foregoing, we have proposed a new Velocity – Vertical Effective Stress (VES) model for transformation of seismically derived acoustic impedance cube into pore pressure cube for accurate pore pressure estimation in the Niger Delta basin. This work is based on the Bowers' method (Bowers, 1995) which is an effective stress approach that takes into account more than one mechanism of overpressure generation. In particular, we have derived the Velocity-Vertical Effective Stress(V_p-VES) coefficients in Bowers model for the Niger Delta. The fidelity of the model is tested by correlating the seismically derived pore pressure with measured pressure data at well locations. This approach holds the extra advantage of eliminating the additional steps of converting impedance into acoustic velocity and density which is known to introduce more potential uncertainties into pore pressure prediction.

2.0 Geology of Study Area

The Niger Delta is situated in the Gulf of Guinea and extends throughout the Niger Delta Province as defined by Klett*et al.,* (1997)with sedimentation patterns that reflect response to basement tectonism. From the Eocene to the present the delta has prograded southwestward forming depobelts (Figure 1) namely Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, Shallow Offshore and Deepwater (Knox and Omatsola, 1989) that represent the most active portion of the delta at each stage of its development. These depobelts form one of the largest regressive deltas in the world with an area of some 300,000km^2 (Kulke, 1995), a sediment volume of 500,000 km^3 (Hospers, 1965), and a sediment thickness of over 10 km in the basin depocenter (Kaplan, *et al.,* 1994)

The Tertiary section of the Niger Delta is divided into three formations, representing prograding depositional facies that are distinguished mostly on the basis of sand-shale ratios. The type sections of these formations are described in Short and Stauble (1967); Frankl and Cordy (1967) and Tuttle *et al*., (1999). These are from top to bottom, the Benin Formation made up of massive continental, fluviatile gravels and sands, up to 2000 m thick; the Agbada Formation that is characteriesed by interbedded fluviatile, coastal, fluviomarine sands and marine shales measuring up to 5000 m thick and the Akata Formation that comprise massive, marine shales or clays with stringers of sands and silt with thickness in excess of 5000 m. Together, they form a thick, overall progradational passive-margin wedge.

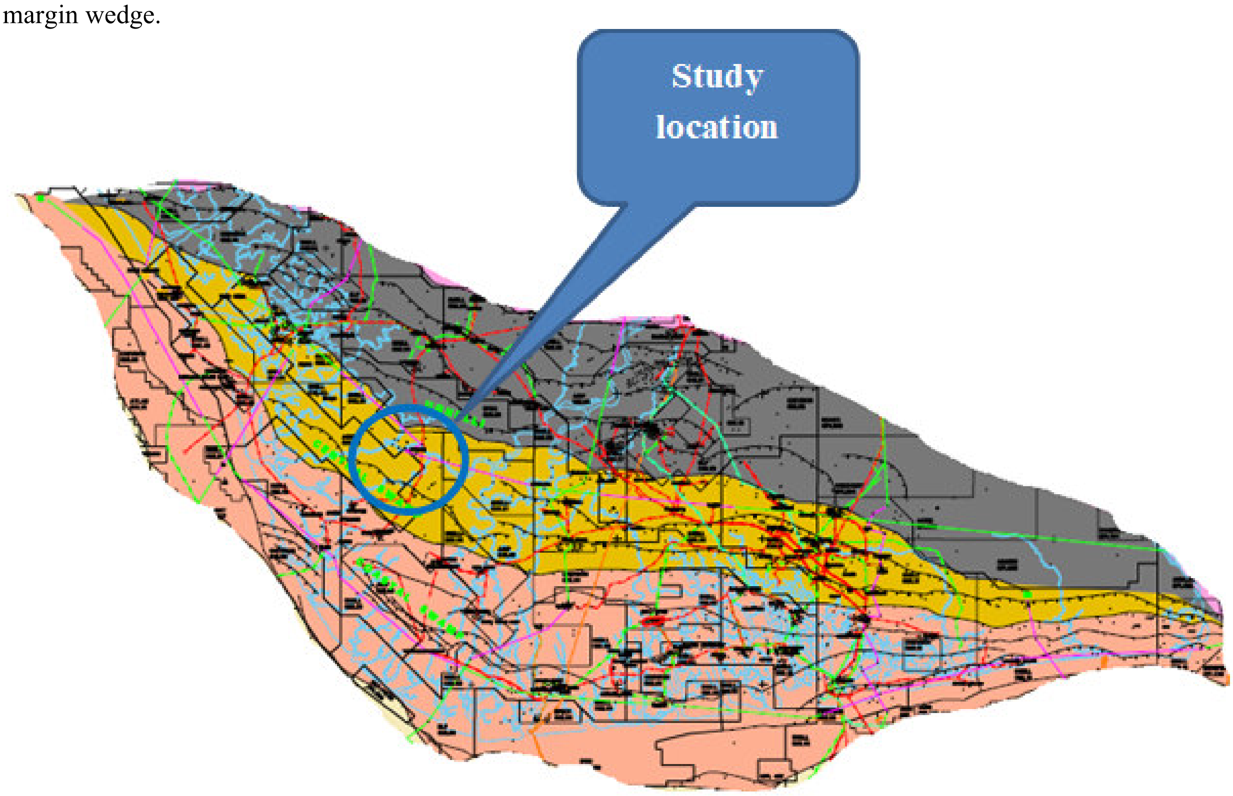

Figure 1 Niger Delta map showing the location of study area

3.0 METHOLOGY

3.1 Determination of Vp-VES coefficients

Bowers (2001) relationship between the effective stress and sonic velocity is used.

$$V_p = v_{ml} + A\sigma^B \tag{1}$$

where V_p is the velocity at a given depth; $\boldsymbol{V_{ml}}$ is the mudline(surface) velocity (normally 5000 ft/s); $\boldsymbol{\sigma}$is the vertical effective stress; and A and ***B*** are the Vp – VES coefficients to be determined from calibration with pressure data in a nearby well.

The coefficients, A and B are derived using equation 1 with sonic velocity (Vp from sonic log), VES (computed from measured pressure) and V_{ml} as inputs.

By rearranging Equation 1 and substituting in Terzaghi'sEquation ($S_v = \sigma + Pp$), pore pressure is obtained as follows:

$$P_p = S_v - \left(V_p - V_{ml} / A\right)^{1/B} \qquad \textbf{(2)}$$

To account for the unloading effect, Bowers (1995) empirical relation is used:

$$V_p = V_{ml} + A\left[\sigma_{\max}\left(\sigma / \sigma_{\max}\right)^{1/U}\right]^B \qquad (3)$$

where U is unloading parameter and is a measure of the plasticity of the sediments.

Thus pore pressure in unloading case is obtained using Equation 4

$$P_p = S_v - \left(V_p - V_{ml} / A\right)^{U/B} \left(\sigma_{\max}\right)^{1-U} \qquad (4)$$

3.2 Seismic Velocity Analysis

Also, 3-D seismic stacking velocitiesare converted to interval velocities (V_{int}) using Dix Equation:

$$V_{\text{int}} = \left[\frac{t_2 v_{rms2}^2 - t_1 v_{rms1}^2}{\left(t_2 - t_1\right)}\right]^{\frac{1}{2}} \qquad (5)$$

Wheret$_2$ and Vrms$_2$ are the two-way travel time and rms velocity, respectively, in the lower layer and t_1 and Vrms$_1$ are the properties in the upper layer

The stacking angle at any given zero-offset two-way travel time (t) and offset (x) is given by:

$$\text{Sin}^2\theta = x^2 V_{\text{int}^2} / \left[V_{rms^2} t^2 + x^2\right] \qquad (6)$$

WhereV$_{rms}$ is the Root Mean Square (RMS)P-wave velocity at time t and Vint is the interval velocity at time, t, (Connolly, 1999).

Seismic velocity data may be provided in the form of stacking velocities (V_{RMS}) as the case here, which need converting to interval velocities (V_{int}) for use in seismic pore pressure prediction. Stacking velocities are picked by seismic interpreters on strong seismic reflections, and can be as far as 500 metres to 1 km apart horizontally. Each V_{RMS} value is an average velocity between the seismic reflection pick and the surface. V_{int} is the velocity between the picked seismic reflections, analogous to a sonic log (V_p) but a much coarser resolution. The V_{int} profile maps lateral velocity variation between reflection events. Where V_{INT} reduces or stays constant with depth it can indicate higher than expected preserved porosity, and perhaps an indication of overpressure.

After the seismic velocity analysis, the derived Vp-VES coefficients are used to transform the derived seismic acoustic impedance velocities into seismic pore pressure.

4.0 RESULTS AND DISCUSSION

4.1.V_p -VES Coefficients

With V_{ml} taken as 5000ft/s, VES computed as the difference of overburden and measured pressure values, and Vp from sonic log, the values of A and B are determined to be 7.43 and 0.77 respectively for the field. The Bowers loading and unloading curves and the determined parameters are shown in Figure 2.

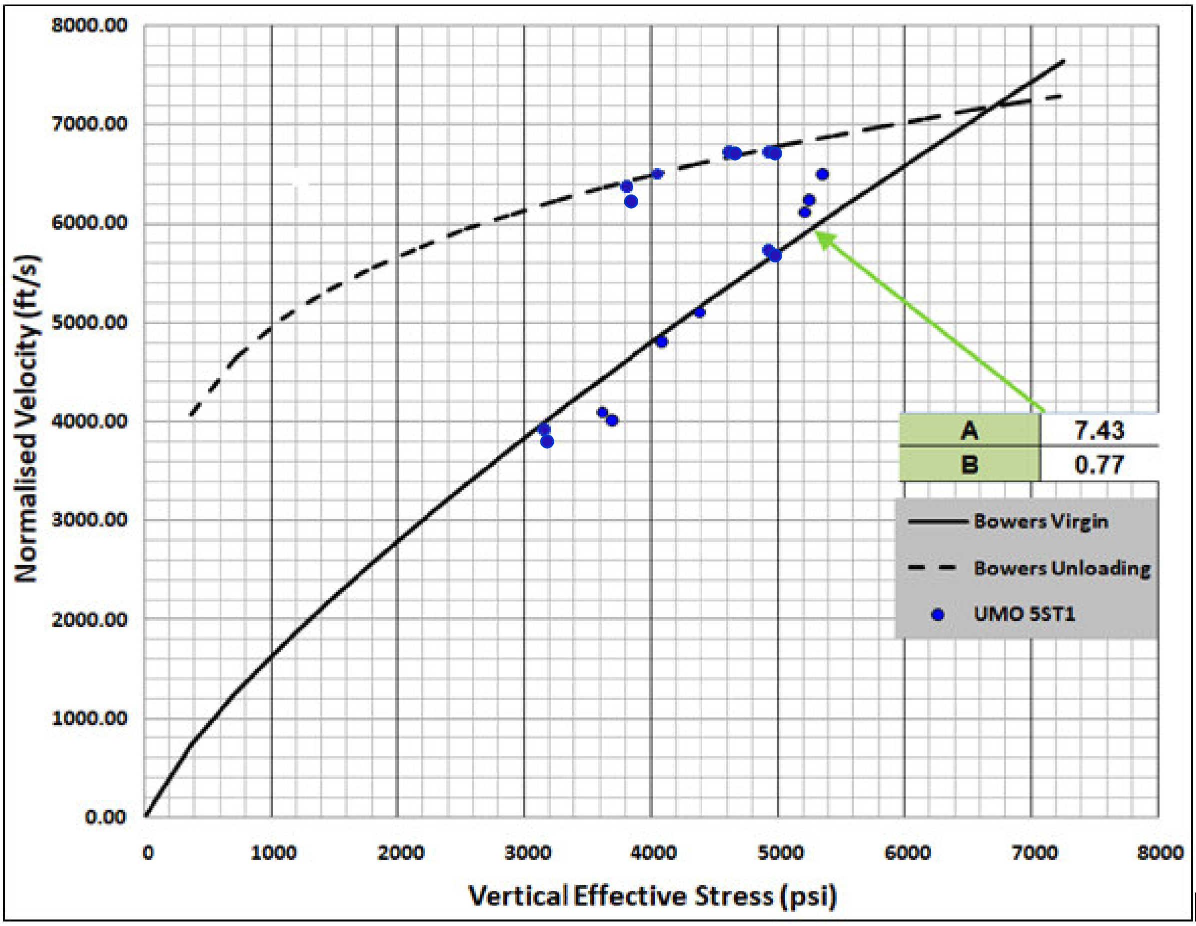

Figure 2: Velocity-Effective Stress Data from UMO_5ST1 wells.
The dashed and thick lines represent loading and unloading curve respectively. The blue data points are > 8,000 ft TVD subsea and aligned with both loading and unloading curves

4.2 Velocity Analysis

There are different types of seismic velocities, but only those velocities that are accurate and are close to the propagation velocity of the formation under consideration are suitable for pore pressure prediction. Processing of seismic velocity is to account for the moveout in reflection time with offset. Common processing procedure is to sort the data into common midpoint gathers and determines the best-fit normal moveout velocity (V_{nmo}) as a function of vertical two way time for each major reflector i.e. velocity that flattens the reflector at zero-offset time. Generally, stacking velocities are inadequate for detailed pressure prediction work because of migration velocity that is applied to seismic volumes during processing to improve image quality. Migration velocity is usually a smoothed version of the stacking velocity field that has been adjusted a few percent. This usually results in a highly smoothed velocity field that is designed to operate with migration algorithms that are not designed to handle abrupt changes in the velocity across features like faults, salt bodies and other geological features. Velocity analysis for geopressure prediction is designed to detect such abrupt velocity changes and record them for use in the prediction process. This is the reason why this tedious process of picking the best velocity that flattens the reflector at zero offset must be embarked upon, to ensure the accuracy of the prediction.

Seismic interval velocity realised from Dix equation before post stack inversion appear to be poor in terms of structural and reservoir properties imaging. Clearly, V_{rms} input in which velocity picks have been interpolated by repeating each higher value invalidates the Dix formula. If this is addressed by smoothing, long operators may be required. This could smooth over any low velocities thereby hiding fine detail associated with overpressure. It is therefore important that V_{rms} input velocities should be appropriately interpolated to avoid erroneous or false seismic interval velocity that is capable of misrepresenting the subsurface.

For instance, the geobodies are conspicuously not visible in Figures 2a as a result of poor data quality. This was greatly improved both in time and space through the post stack inversion as can be seen in seismic acoustic impedance volume (Figure 2b). The seismic velocity profile extracted along each well that has sonic-velocity shows a reasonable match; evidence that the calibration process was optimal as shown by the seismic-to-well tie in Figure 3.

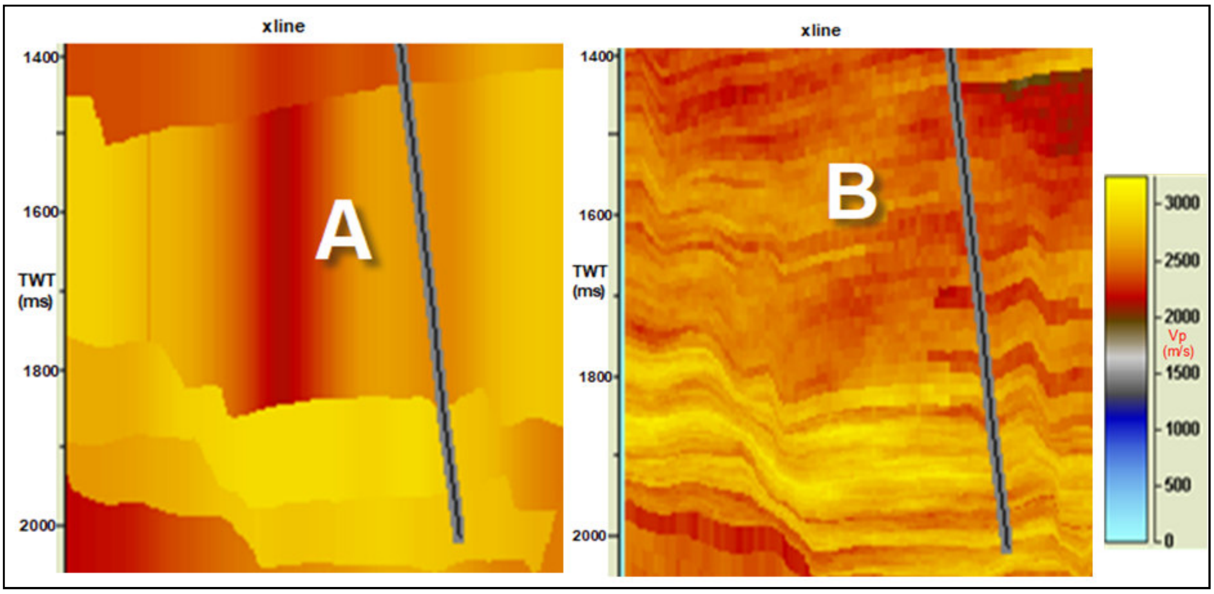

Figure 2: (A) Seismic Interval Velocity before post stack inversion and; (B) Seismic Interval (Acoustic Impedance)velocity (after post stack inversion) with obvious reflection of the geobodies derived from seismic-inversion analysis.

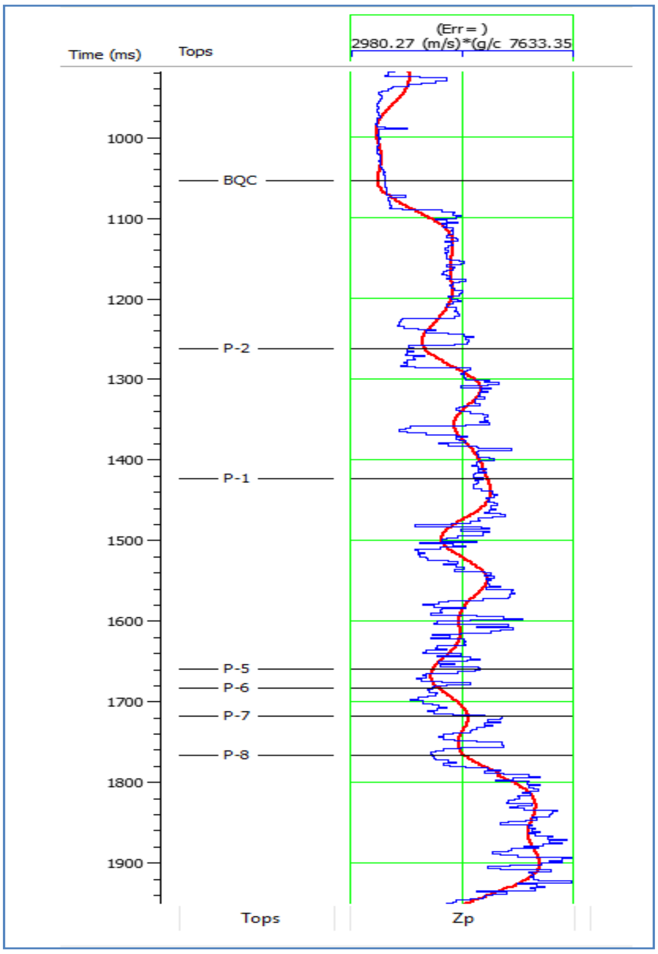

Figure 3: Seismic-to-well tie. The blue is the acoustic Impedance or wavelet (Zp) from well logs while the red is the Zp from the seismic. There seems to be a match (or correlation). In other words, the seismic –to-well tie is reasonable.

4.3 Seismically Derived Pore Pressure Prediction

By combining the VES model obtained in 1D with the calibrated or optimised seismic interval velocity and the

Acoustic Impedance Vint from seismic inversion obtained from the 3D seismic cube, it was possible to estimate a pore pressure volume for the area of interest. The derived seismic pore pressure and overpressure cubes as shown in Figures 4B and 5B were gotten from the seismic Acoustic Impedance interval velocity and the advantage the post stack inversion workflow is crystal clear when compared to seismic pore pressure and overpressure cubes (Figures 4A and B) gotten without inversion.The pore pressure and the corresponding overpressure values can be easily inferred in time and space in the two seismic pressure cubes in Figures 4B and 5B. The dark red data points are intervals with abnormal pore pressures with formation reaching 4000 psi while overpressure could extend 1000 psi in the field as revealed by the colour code on the legends. This information or interpretation is vital to drillers, exploration and asset team for future well planning and appraisal.

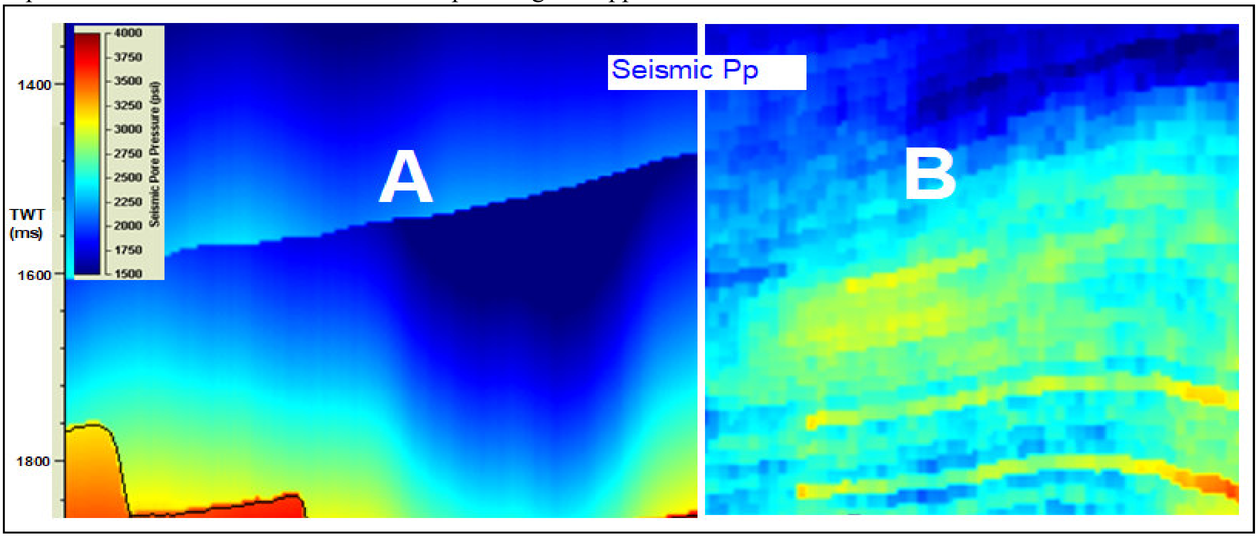

Figure 4: (A) Seismically-derived pore pressure using the optimised seismic Vint. (B) Seismically derived pore pressure using the Acoustic Impedance interval velocity.

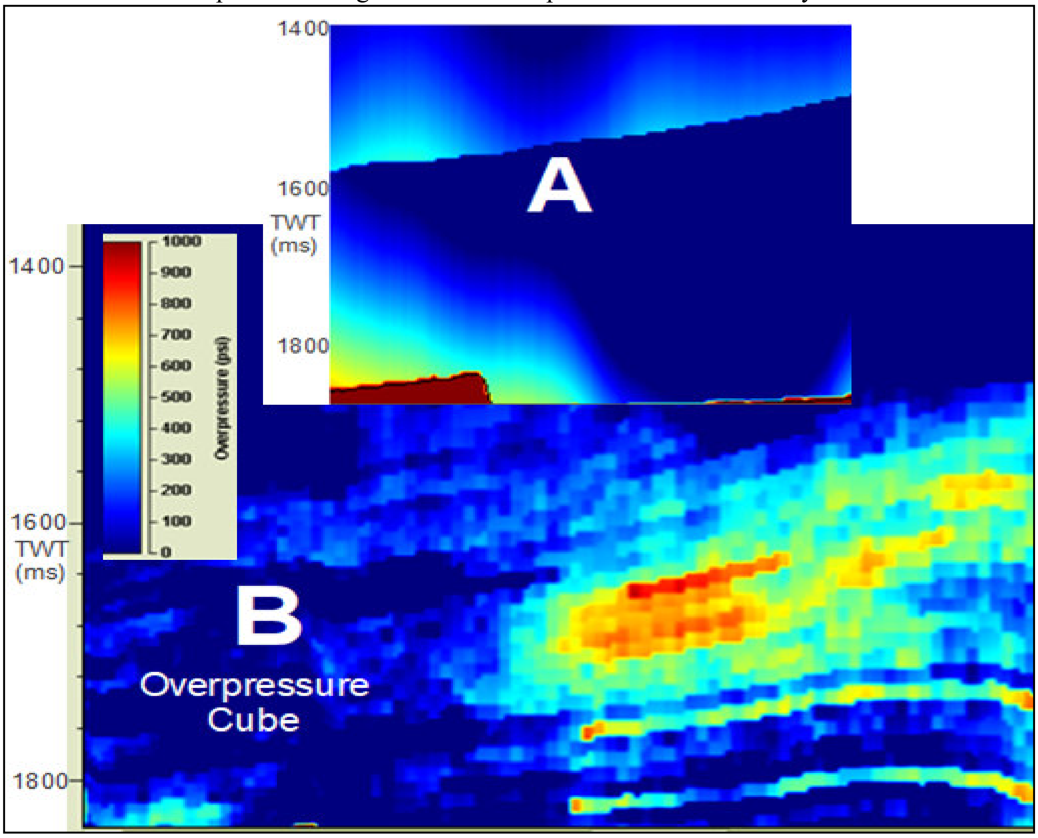

Figure 5: (A)Seismic overpressure volume from the optimised but oversmoothed seismic interval velocityand (B)overpressure volume from the acoustic impedance internal velocity.

As shown in Figure 5A, variation of overpressure could not be imaged as expected, hence the need for seismic inversion resulting from poor resolution. Figure 5B above shows the overpressure volume derived from the acoustic impedance. The values of the overpressure could range from 600 to 1000 psi.

Applying the velocity – pore pressure transform generated from offset sonic velocity; we got a pressure profile which calibrated well with the measured data. This increased our level of confidence in the transform and as such, it could be reliably applied to the proposed deep exploratory well that has no log data. The velocity was also scale on a factor of +/- 5% of the raw seismic velocity to account for local variation effect in seismic data. Furthermore, the extracted seismic pore pressure profiles along well path approximated the 1D shale pressure predicted using Bowers VES input parameters as shown in Figures 6 and 7. The kick recorded in UMO-001 well (Figure 6) was an evidence of underbalanced drilling resulting from inaccurate pore pressure prediction but the seismic pore pressure profile (pink trend) can be seen to match the kick. The response or reflection of the derived seismic pore pressure profile (cyan) from the optimised over-smoothed cube seems to ignore subsurface overpressure details in UMO-002 well in Figure 7. The error of over-smoothing in the seismic field mentioned above has been introduced to the seismic pore pressure. In otherwords, error in velocity profile can lead to error in estimated seismic pore pressure.

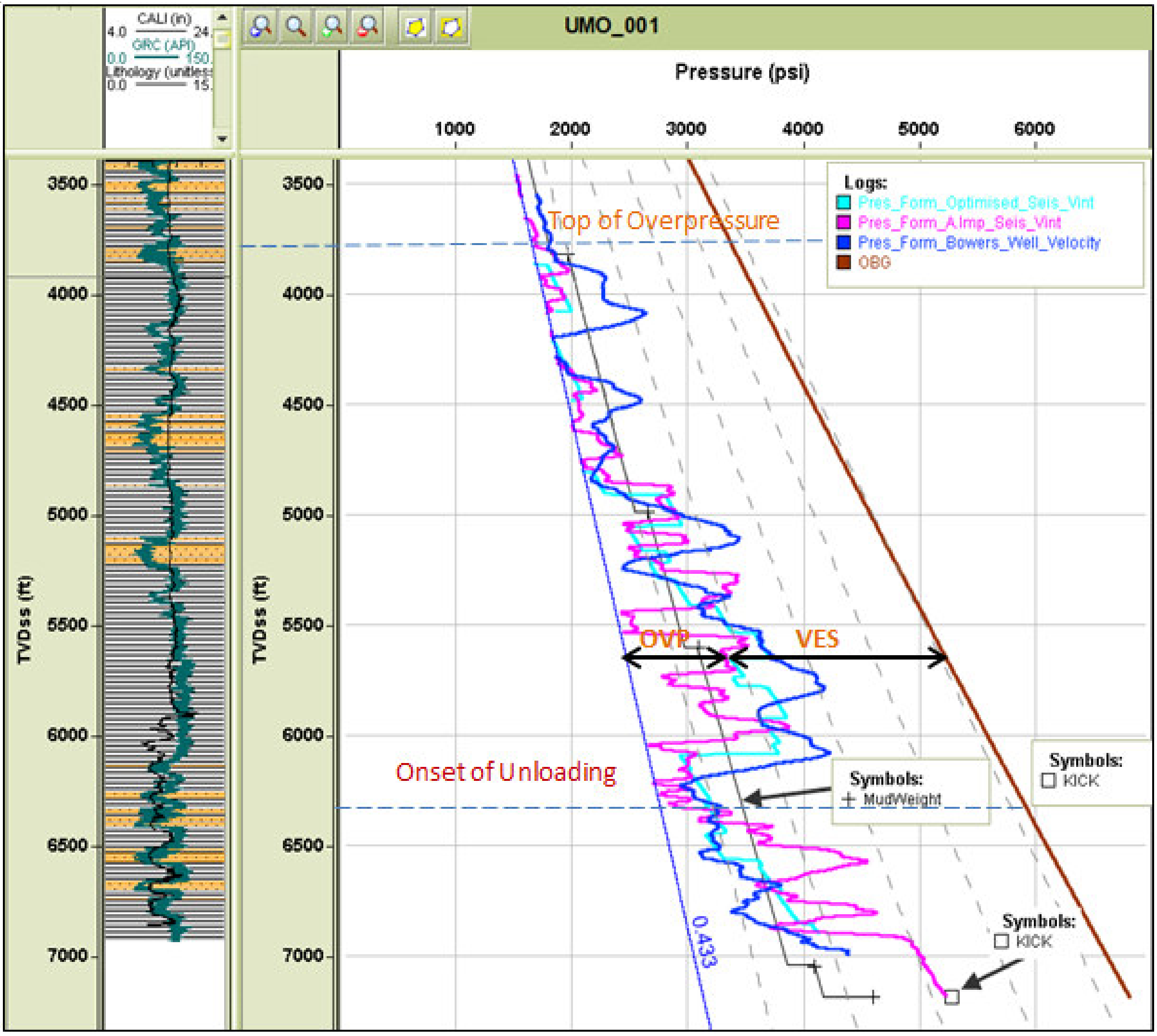

Figure 6: Seismically-derived pore pressure extracted along well path (UMO_1) and compared with the 1D shale pressure predicted using Bowers and well velocity.

The pressure profiles obtained from Bowers model, direct seismic and acoustic impedance are juxtaposed in Figure 8. The seismically derived pore pressure from acoustic impedance (pink) approximated the kick and this gives credence to the model used.

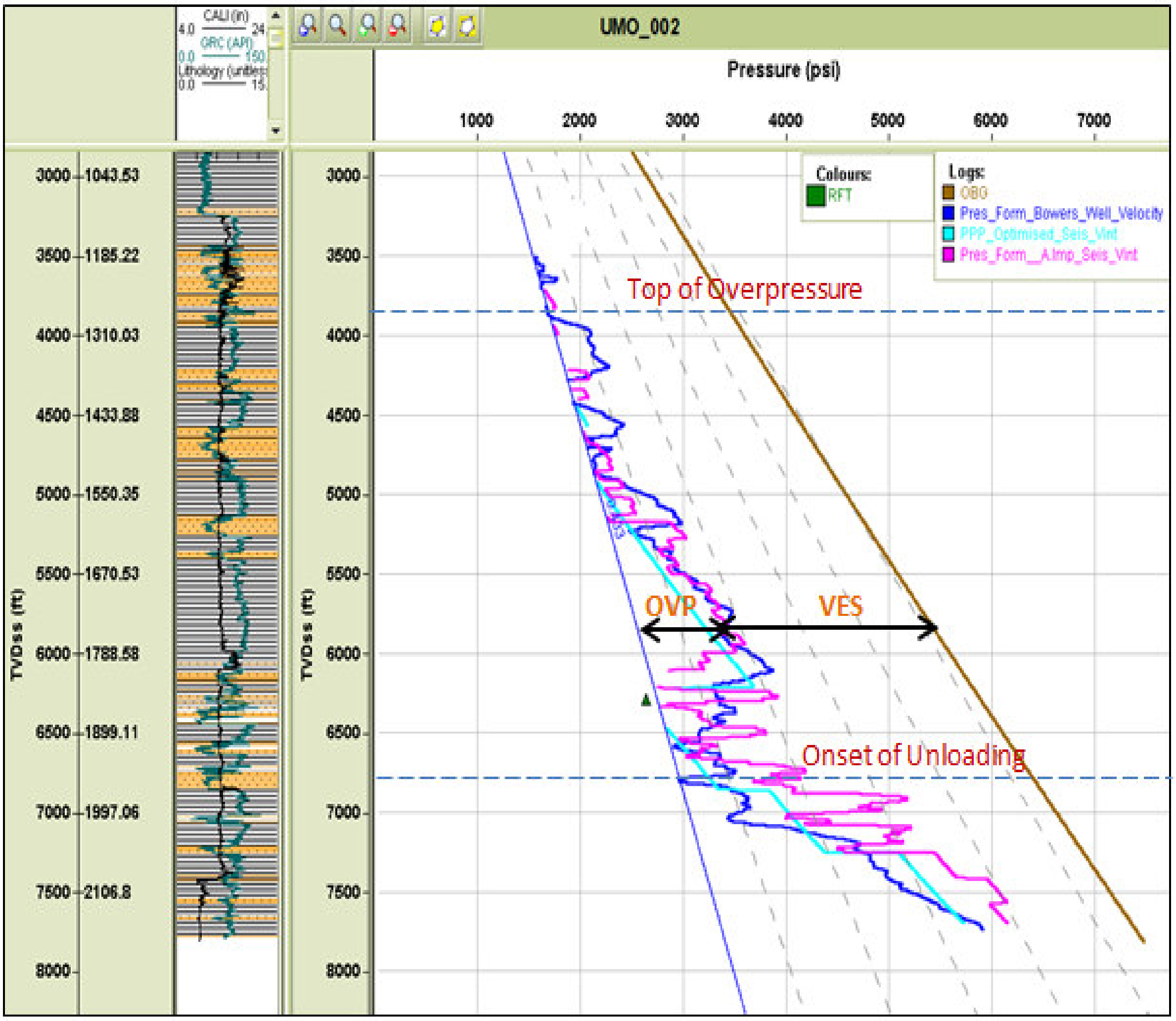

Figure 7: Seismically-derived pore pressure extracted along well path (UMO_2) and compared with the 1D shale pressure predicted using Bowers and well velocity.

Seismic velocity analysis for pore pressure prediction and calibration with well data makes it possible for the predicted pressure from seismic data to compare favourably with the measured pressure for the offset wells. This strengthens the assurance that seismic can be relied upon to give an accurate prediction of pore pressure. As observed in Figure 6 and 7, the seismic pore pressure from acoustic impedance (pink) approximated the Bowers 1D Shale pressure (blue) while the seismically derived pore pressure from optimized interval velocity (cyan) appears incoherent

CONCLUSION

This study has validated the direct use or plug-in of effective stress coefficients deduced from direct pressure measurements and overburden model derived from density logs in seismic pore pressure transform. It further demonstrated that seismic inversion cube would better reveal geobodies clearly and improved subsurface pore pressure prediction in the deeper overpressure shales intervals. The Niger Delta basin is known for itsmassive shales, with evidence of abnormal pressure at greater depth especially, when approaching the Akata Shale. In such scenarios, 3D seismic images poorly acquired or processed will be insufficient to discriminate individual reservoir horizons and estimate overpressure accurately irrespective of the efforts one would put into the velocity calibration process.Therefore, dedication to well and seismic data conditioning will help optimise signal-to-noise ratio and enhanced accuracy and stability of results.

Further, the use of velocity-vertical effective stress relationship for pore pressure prediction has been made readily available by this research by providing the effective stress coefficients for loading and unloading for this field.The uniqueness of the derived effective stress coefficients has been proven both in 1D and 3D pore pressure prediction in the studied field with a remarkable reduction in uncertainty. These coefficients are however, dependent on lithology, cementation, and even pore geometry and vary with the stress or geopressure regime and depth. Consequently, to account for lithology variation, it is recommended to measure Sonic-V_p by looking at the different stratigraphyand effective pressure in the study area. Secondly, seismic inversion should always be incorporated into the pore pressure workflow for improved seismic pore pressure interpretation both in lateral and depth positioning.In velocity picking, picked intervals should not be too small so that obtained resolution will not be too low for accurate pore pressure calculation as seismic sample resolution is 10m to 50m contrary to ~60 cm from sonic logging tool.

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