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Velocity-Induced Pitfalls in Pore Pressure Prediction: Example from Niger Delta Basin, Nigeria.

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Abstract: *In the past two decades, the application of seismic velocities to pore pressure estimation has received a great deal of attention within the oil and gas industry. This increasing dependence on seismic velocities forpore pressure prediction is well understood given the shift in hydrocarbon exploration focus to frontier areas, especially the deepwater where well data is rarely available for measured pressure information for well planning.*

In this study, we present pitfalls in pore pressure prediction results in onshore Niger Delta due to the application of seismic interval velocity to the velocity-pressure transform using the Bowers' model. Results obtained show that stacking velocities and its corresponding seismic interval velocity derived through Dix conversion produce low resolution velocity field and pore pressure prediction. These resultsdemonstratethat low resolution seismic interval velocity produce pitfalls in pore pressure prediction. Finally, the seismic pore pressure cube obtained are unsuitable for mud weight design, planning and safe drilling of new wells in the study area.

Keywords:*Pore Pressure, stacking velocities, seismic interval velocities, overburden model, Niger Delta.*

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I. Introduction

Understanding the pressure regime of a sedimentary basin is essential for any successful exploration and drilling venture. This is necessary to evade common drilling hazards such as borehole collapse, lost circulation, stuck pipe, kicks, blowouts and consequent loss of investment and human lives (Uko*et al*., 2013).Somenotable examples of these drilling hazardsinclude: the 1980 well kick at around 1,400ft offshore Warri, Nigeria in a Sea Quest semi-sub rig operated by Texaco (subsidiary of Chevron) which resulted in explosion, the GSF Adriatic Jack up – offshore Egypt in 2004, the notorious Mary Sudik 1 Well, drilled in 1930 by the Indian Territory Illuminating Oil Company (ITIO) in Oklahoma, the 2010 explosion which recorded 11 fatality and loss of crude oil (in excess of 5MMbbl) in the Gulf of Mexico Deepwater Horizon rig during drilling a well in about1.5 km water depth (Soleymani and Riahi, 2012).

Geoscientists require a good knowledge of formation pore pressure for the study of hydrocarbon migration pathways and trapping (Yan *et al*., 2012). Pore pressure in a basin changes on a larger scale than characteristics of the solid phase such as lithology and porosity, because it is modified by diffusive process of percolation (Scott and Thomsen, 1993). These formation pore pressures can be estimated from elastic wave velocities using appropriate velocity-pressure transform and velocity-based estimation approaches such as those of Eaton and Bowers (Bowers, 2001; Sayers *et al*., 2002). Since 1968, when Pennebaker (1968) pioneered the first work on pore pressure prediction using seismic interval velocities derived from stacking velocities, many workers have conducted several studies on pore pressure prediction using seismic velocities.Gregory (1977) found that pore fluids having different pressures produce substantial effects on rock velocities, hence used rock velocities to estimate pore fluid pressure. Dutta (2002), Bowers (2002), Sayers (2006), Cranganu (2007) in their separate work established that geophysical methods of geopressure prediction rely on the effects of pressure on the velocity of seismic waves and applied seismic velocities to estimate formation pore pressure. Other examples include the work of Uko*et al*. (2013) and Udo *et al*. (2015) using sonic velocities, Osinowo*et al*. (2007) applying interval transit time, Jones (1978) employing temperature logs and the use of shale density and velocity analysis by Satinder and Huffman (2006).In this work, seismic interval velocities obtained through Dix conversion (Dix, 1955) is applied to Bowers model and Bowers calibration factors derived for the study area to estimate pore pressure.

II. Study Location

The Niger Delta (Figure 1) is a sedimentary basin of Tertiary age, situated on the passive margin of West Africa between latitudes 3^0N and 6^0N and longitudes 5^0E and 8^0E (Doust and Omatsola, 1990).Modern studies of the Niger Delta morphology reveal that the three delta-forming processes (tide, wave and fluvial effect) interact in near-equal magnitudes, thereby making the Niger Delta essentially tide-dominated, wave-influenced and fluvial-based delta. The Niger Delta is the most prolific hydrocarbon-producing basin in Africa. This delta covers an estimated area of 300, 000 km^2 (Kulke, 1995), approximately 500, 000 km^3sediment volume (Hospers, 1965) and a substantial sediment thickness above 10 km in the depocentre (Kaplan *et al.*, 1994). Three major lithostratigraphic units have been identified in the delta viz: Akata, Agbada and Benin Formations. These formations constitute the key elements of the Niger Delta petroleum system and have been drilled in wells across the five depositional cycles of the Niger Delta province.

The origin of the delta is linked to the breaking of the South American and African plates, development of trough along the Benue-Abakiliki axis and the downward deformation of the Anambra section to create Afikpo Syncline, Ikang Trough and the Anambra basin throughout the Early Createaceous (Opara, 2010). Beginning from the Eocene to the Mid-Miocene, the delta is believed to have prograded towards three major axes: the Afikpo syncline known to be fed by the Cross River and the Anambra and subsidiary basins which are fed by rivers Benue and Niger. For a brief period, deposition by the Cross River occurred along the Ikang Trough from Eocene to Late Oligocene. At this time, it is generally believed that sedimentation was rapid as clastic debris was transported to these relatively small areas, prompting suggestions that the shape of the early delta could have been lobate as against the present day arcuate shape (Reijers*et al.*, 1997).

Based on recent studies, it is believed that the Cross River and Niger-Benue delta system fused after Mid-Miocene and the impact of tectonic elements of the Upper Cretaceous was no longer pronounced (Reijers, 2011). Consequently, the present day delta is considered to encompass areas beyond the modern delta geographical limits, integrating sub-deltas which hitherto were not parts of the Niger Delta structure, particularly the Cross River Delta as well as portions of adjoining Equatorial Guinea and Cameroun.

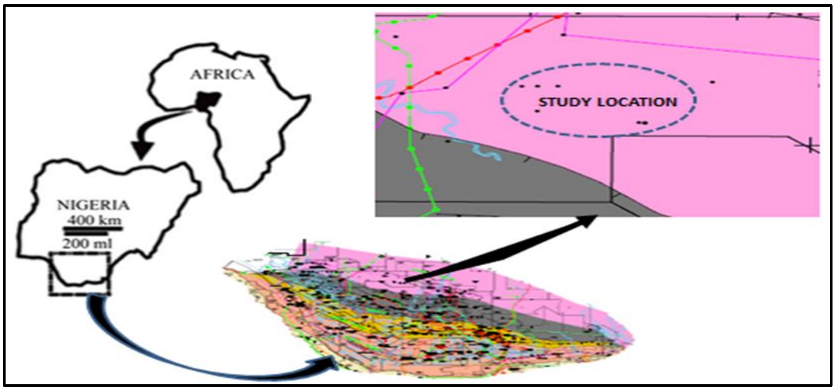

Figure 1: Map of study area.

III. Materials And Method

The primary inputs for this study are the seismic stacking velocity and well data.

3.1 Diagnosis for Overpressure Mechanisms

Velocity-Density crossplots were generated and used to identify the mechanisms responsible for overpressure generation in the study area following Hoesni's plot (Hoesni, 2004) of Figure 2. This technique has been widely employed in documented literature to discriminate between disequilibrium compaction and other (secondary) mechanisms of overpressure generation.

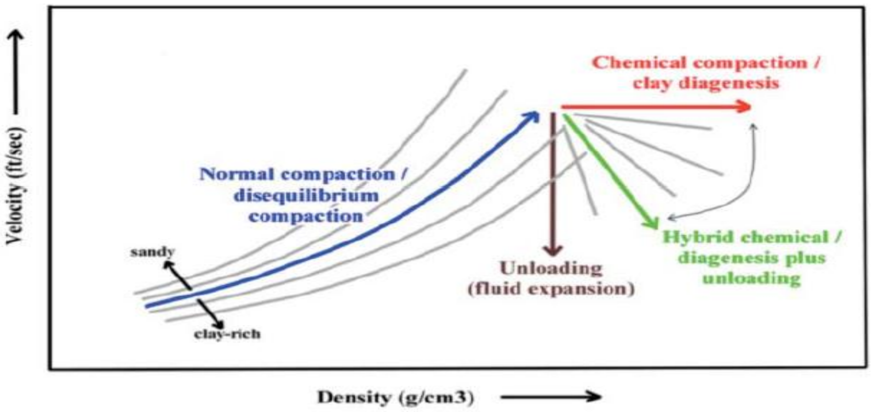

Figure 2: Hoesni's curve showing different signatures and associated overpressure generating mechanisms from Velocity-Density crossplots (Hoesni, 2004).

3.2 Determination of Overburden Model

Overburden profile was estimated from density logs in offset wells in the study area using Equation 1. Before the estimation, the density logs were first subjected to conditioning and validation procedures such as depth shifting, normalising, reconstruction of complete and reliable set of well logs. Blocking for high frequency removal and noise reduction were performed through frequency filtering to eliminate observed spikes in the logs. The "soft rock-physics model" such as Gardner *et al*. (1974) and Greenberge and Castagna (1992) were used to solve for missing density logs.

$$\rho_{z_{ml}} = \rho_{matrix} - (\rho_{matrix} - \rho_{top})e^{bz_{ml}} \quad (1)$$

where, ρ is density in g/cc as it applies to top and matrix, Z_{ml} is mudline depth in ft, and b is a constant (Dutta, 2002).

3.3 Estimation of Bowers Calibration Factors

The constants A and B in Bowers Model (Equation 2), commonly referred to as compressional velocity (Vp)-to-Vertical Effective Stress (VES) calibration factors or simply virgin curve parameters were derived through iteration process and calibration with direct pressure data. The pressure data were subsequently used with sonic data for the calibration of **A** and **B** values based on Bower's relationship (Equation 2). The values derived for the study area were applied with confidence where VES lies within the range applied in arriving at the calibration factors.

$$V_p = V_{ml} + A\sigma^B \quad (2)$$

3.4 Determination of Interval Velocity

Stacking velocity data was the only velocity data available for this work. The velocity data was analysed using Hampson-Russel software. A tedious and rigorous semblance analysis was carried out to refine the provided seismic data despite the presence of the background noise. The data was subsequently converted to interval velocity, which is a close approximation to rock velocity, using the Dix-velocity conversion (Dix, 1955):

$$v_{int} = \left[\frac{t_2 v_{rms2}^2 - t_1 v_{rms1}^2}{t_2 - t_1}\right]^{\frac{1}{2}} \quad (3)$$

where t_2 and V_{rms2} 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.

3.5 Estimation of Seismic Pore Pressure

The VES model obtained in 1D were combined with the optimised seismic interval velocity and the Bowers' virgin curve parameters in Bowers' model (Equation 5) to estimate a pore pressure volume for the study area based on Terzaghi (1943) relation (Equation 6).

$$Pp = S_v - \left(\frac{V_p - 5000}{A}\right)^{\frac{U}{B}} (\sigma_{max})^{1-U} \quad (4)$$

whereA and B are Bowers virgin curve parameters, u is the unloading parameter,σ_{max} is the maximum effective stress

$$\sigma_{\max} = \left(\frac{V_{\max} - 5000}{A} \right)^{\frac{1}{B}} \tag{5}$$

where V_{max} is the velocity at the onset of unloading (Ugwu, 2015).

$$S_v = \sigma + P \tag{6}$$

where S_v is the vertical component of the overburden pressure.

IV. Results And Discussion

Results of the velocity-density crossplots, estimated overburden profile, derived seismic interval velocity, layer cake model and pore pressure prediction for the study area, following the methods described in sections 3.1, 3.2, 3.3, 3.4 and 3.5 are presented in Figures 3, 4, 5, 6, 7 and 8. Velocity-density crossplots (Figures 3 and 4) of wells 1 and 2 were used to discriminate between the excess pressure generating mechanisms in the study area. Based on Hoesni's curve (Figure 2), it is observed that disequilibrium compaction and unloading mechanisms are responsible for overpressure in the study area. Overpressure due to disequilibrium compaction cause sediment properties to plot on the normal compaction or virgin (loading) curve while that due to unloading mechanisms plot above and away from the normal compaction curve. Also, at depth intervals where unloading is suspected to have started, velocities drop (reverse) at nearly constant densities. These observations are consistent with several literatures that velocity reversals and undercompaction in low permeability sedimentsare diagnostic features of overpressure in Tertiary sedimentary basins such as the Niger Delta (Ugwu, 2015).

The generated overburden profile (Figure 5) and the seismic interval velocity cube (Figure 6) realised from stacking velocities through Dix conversion (Equation 3) were combined with effective pressure and Bowers calibration constants of 7.43 for A and 0.77 for B to transform the derived seismic interval velocity (Figure 6) into pore pressure cube (Figure 8)using the Bowers unloading model (Equation 4), which accounts for the unloading effects. It can be observed that the seismic interval velocity (Figure 6) used for the velocity-pressure transform has a very low spatial resolution and in turn produced a pore pressure volume (Figure 8) which cannot yield any useful estimation of pore pressure in the study area. Though overpressure is evident in the study area as confirmed through the velocity-density crossplots analyses, the pore pressure volume (Figure 8) obtained for the study area using the seismic interval velocity (Figure 6) fails to give any prediction and therefore cannot be applied to obtain safe and economic mud weight program. This is a pore pressure prediction pitfall caused by low resolution of the seismic interval velocity.This low velocity field is further corroborated by the poor resolution of the layer cake model (Figure 7)which does not produce any reflection of geobodies and subsurface geology of the study area.

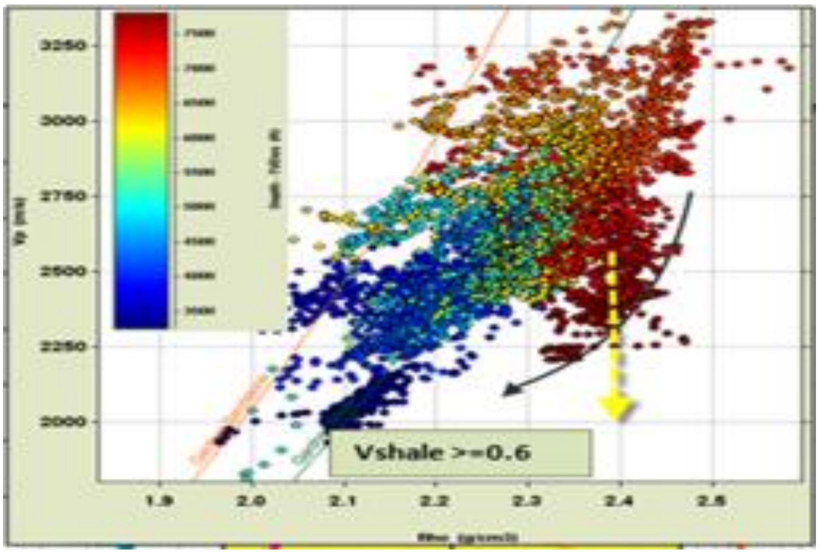

Figure 3: Velocity-Density crossplot for Well 001

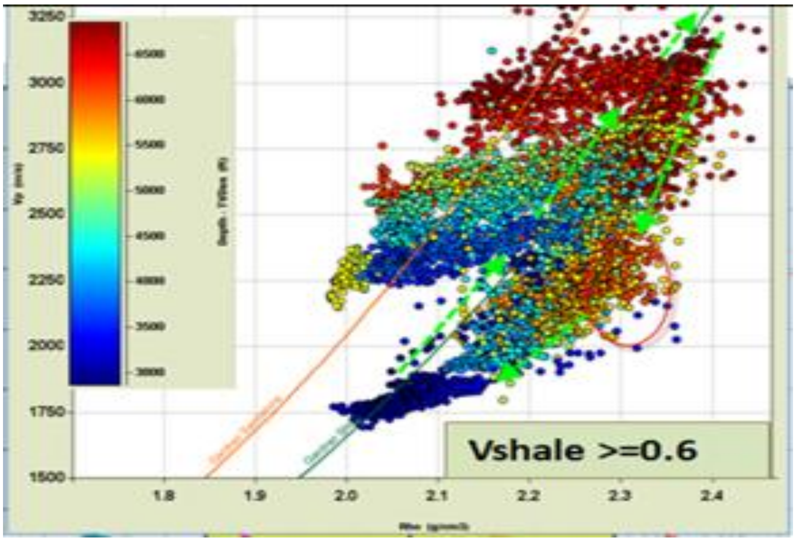

Figure 4: Velocity-Density crossplot for Well 002

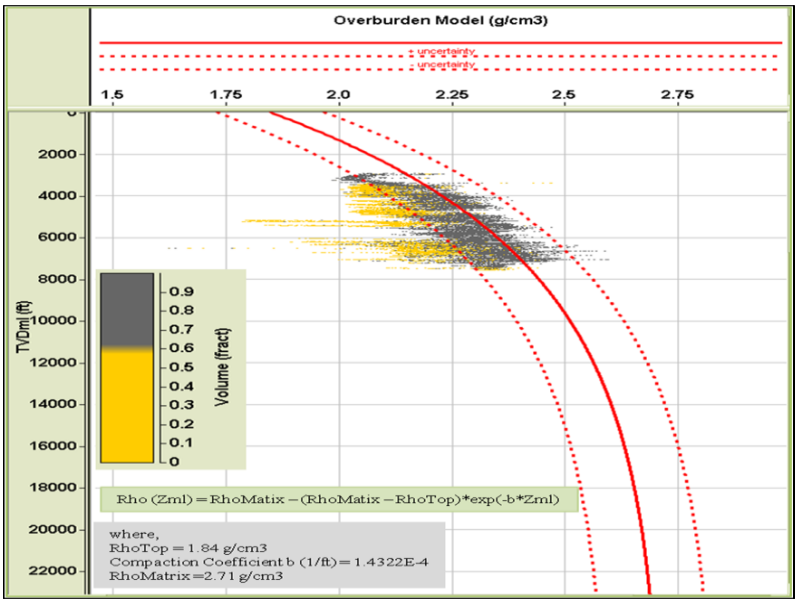

Figure 5: Overburden profile generated from combined density logs from offset wells

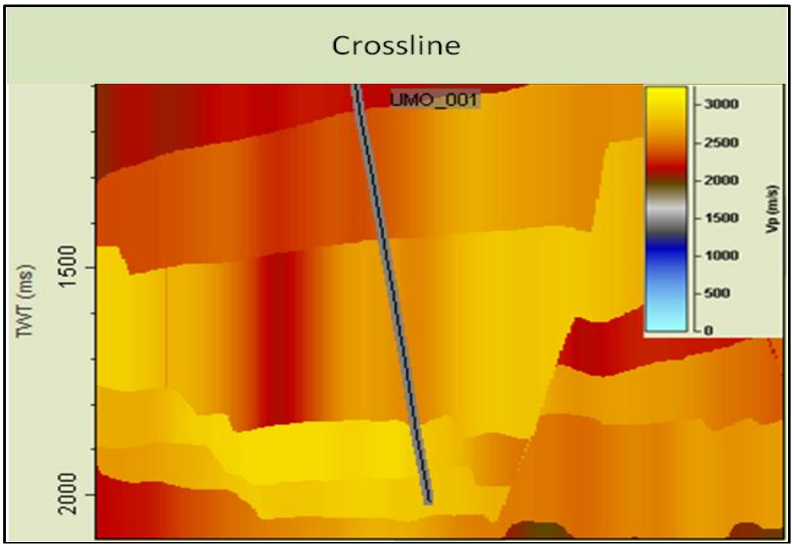

Figure 6: Seismic interval velocity derived by Dix-velocity conversion

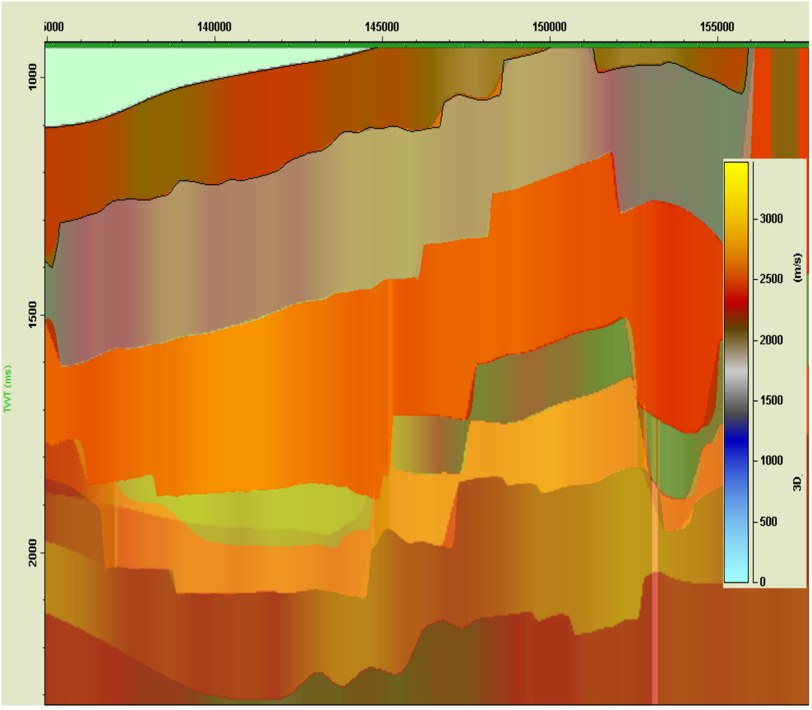

Figure 7: Layer cake model built from the seismic interval velocity

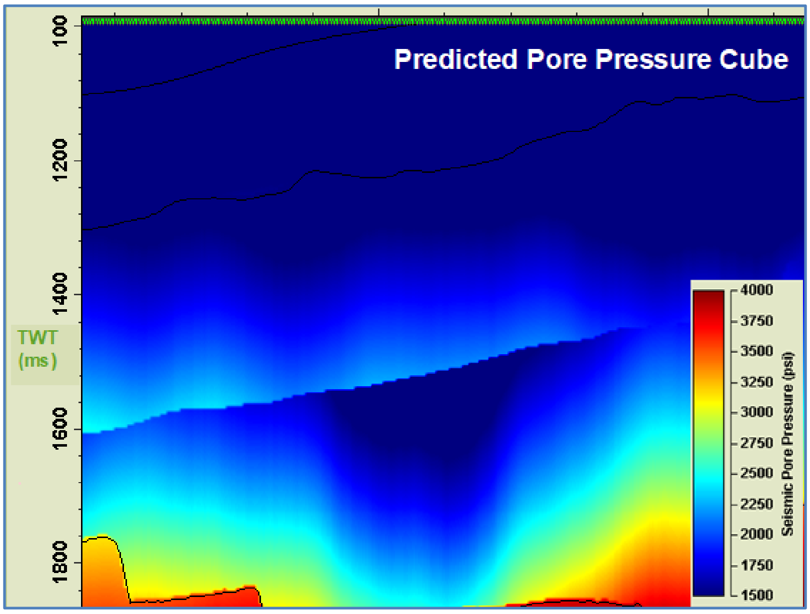

Figure 8: Pore pressure prediction (psi) using the seismic interval velocity from Dix-velocity conversion.

V. Conclusion

There is strong evidence from velocity-density crossplots analyses that mechanical disequilibrium compaction and secondary mechanisms (unloading effects) generate excess pore pressure in the study area. However, this is not supported by the pore pressure prediction result for the study area. The result rather demonstrates that low resolution seismic interval velocity produce pitfalls in pore pressure prediction. In conclusion, the pore pressure prediction result obtained in this work cannot be applied to safe and economic mud weight program and for planning of new wells in the study area.

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