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# A Comparative Model Approach to Pore Pressure Prediction Applied to Central/Coastal Swamp Depobelt of the Niger Delta Basin

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## ABSTRACT

Overpressured zones and porosity values in shale beds have been estimated for selected fields of the central/coastal swamp depo-belts of the Niger Delta. Pore pressure prediction (PPP), when done accurately can be used to avert disaster and helps in safe drilling. Eaton's sonic model, Bowers' model and Zhang's porosity-based model have been applied to predict overpressures using petrophysical log data from six 6 wells, each representing a field of the studied area. Predicted zones of hard overpressures (HOVP > 0.70 psi/ft) are generally below the depth of 10000ft. Top of geopressures (TOG) for the case study wells; WELL_A, WELL_B, WELL_D, WELL_G, WELL_H and WELL_K are 7000ft, 10500ft, 10000ft, 12500ft, 9000ft and 10400ft respectively. Eaton exponent '5.5' and Bowers model plotted with robust matches to measured pore pressures (MPP) everywhere except in one well. The porosity model equally yielded better matches to MPPs with higher values of fluid-transit-times typical of hydrocarbon fluid type (oil). These suggest, in combination with Vp-density analyses, a strong evidence of secondary mechanism causing overpressure in the basin. Very hard overpressures characterizes the deeper section of the basin (lower part of Agbada formation) at most of the well locations suggesting a strong evidence of fluid expansion mechanism which is also related to sediments unloading. The robust concordance between PPP and MPP profiles validates the results here and is a better guide for future drilling.

**Keywords :** Eaton's Model, Pore Pressure Prediction, Disequilibrium Compaction, Niger Delta, Porosity Model, Overpressure Mechanism, Unloading Mechanism.

## I. INTRODUCTION

Pore pressure is one essential phenomenon that must be studied. Accurately predicting pore pressure is very important in exploration, de-risking of hydrocarbons, appraisal, reservoir integration studies, well design and the drilling of wells in a safe and cost-effective manner. Prediction difficulties are usually encountered in some geologic settings with complexities and inaccurate prediction would also be the outcome when"pressure-generating mechanisms" are not properly diagnosed. A few authors have reported on the overpressures distribution in "the Niger Delta basin" and its mechanism of generation (Anowai et al., 2003 and Nwozor et al., 2013).

The basic principle underlying overpressure prediction from log is that overpressured sedimentary rocks maintain anomalously higher porosity than they do in normally pressured zones. In formations with normal pressures, pore fluids communicate efficiently with surface during burial. Therefore, the fluids in the pore spaces are squeezed out following normal compaction rate and results to hydrostatic pressure regime. Meanwhile the lithostatic (overburden pressure), S, is the pressure resulting from weight of rock matrix and pore fluids combined that is overlying the formation of consideration. Mathematically, this is written as (equation 1):

$$S = g\int_0^z \rho_b z dz \tag{1}$$

Where $\rho_b$ is the bulk density dependent on depth and given by;

$$\rho_b = \phi\rho_f + (1-\phi)\,\rho_{ma} \tag{2}$$

where $\phi$, $\rho_f$, and $\rho_{ma}$ are respectively the porosity, density of pore fluid and grain density or rock matrix densiy.

The resultant different between overburden pressure, S, and pore pressure Pp gives us the differential pressure or effective pressure and its acts on the rock matrix. This effective pressure is given as:

$$\sigma = S - \alpha P_p \tag{3}$$

The poro-elastic coefficient, α , is introduced in Terzaghi's original equation when applied to consolidated rocks to take care decreasing effect in fluid pressure now applied on less of the grain surface. Generally, $\alpha \leq 1$ but the values between 0.7 and 1.0 are commonly used. For overpressured rocks, α is usually around 0.8 (Ugwu, 2015). The process of sediment compaction is actually controlled by the effective stress and as such if the effective stress is reduced in anyway, then compaction rate is slowed down.

Accurate prediction of geopressures would, however, depend on the suitability of prediction model chosen for the sedimentary basin under study, the prediction expert, data availability and not limited to these alone. This work is aimed at predicting zones that are overpressured within the sediments of some fields in the central/coastal swamp depo-belts of the Niger Delta basin by comparative models method. Several models of prediction exist but those of Eaton, Bowers and Zhang (Eaton, 1975; Bowers, 1995 and Zhang, 2011) were applied, taking into consideration the uniqueness of each of the methods and equally examine their suitabilities to the Niger Delta sedimentary formations.

## Study location, Geologic Setting and Clay Mineralogy

Representative wells of Gbaran, Santa Barbara, Kolo Creek, Elepa and Korokoro fields respectively; all from the Central/Coastal swamp depobelts of the Niger Delta basin are studied. (Figure 1). The Niger Delta is one of the largest sub-aerial basins in Africa having a sub-aerial section of about 75,000km2, area measuring about 300,000km2, and with sediment thickness of about 500,000km3. The thickness of the sediments varies between 9to12km. Large scale tectonics of the area must have resulted to different complexities in the geologic formation (Tuttle et al., 2015).

Three main lithostratigraphic formations have been identified and classifiedaccordingly as being "Continental", "Transitional" and "Marine" depositional environments which corresponds the Benin formation on the top, the Agbada formation in-between and the Akata formation at the bottom (Short and Stauble, 1967). The Akata formation composes mostly of the marine shales. These shales are undercompacted and most probably contain "abnormally high-pressured" siltstones or fine-grained sandstones. The Agbada formation is typically made of sediment with alternating sands and shale from the transitional environment and comprises the lower delta plain. Proportion varying from 30 to 70% is typical of the sands in Agbada formation and can be linked to the cycles of depositional off lap. The Benin formation has the characteristic sand percent of about 70-100% forming the top of depositional sequence.

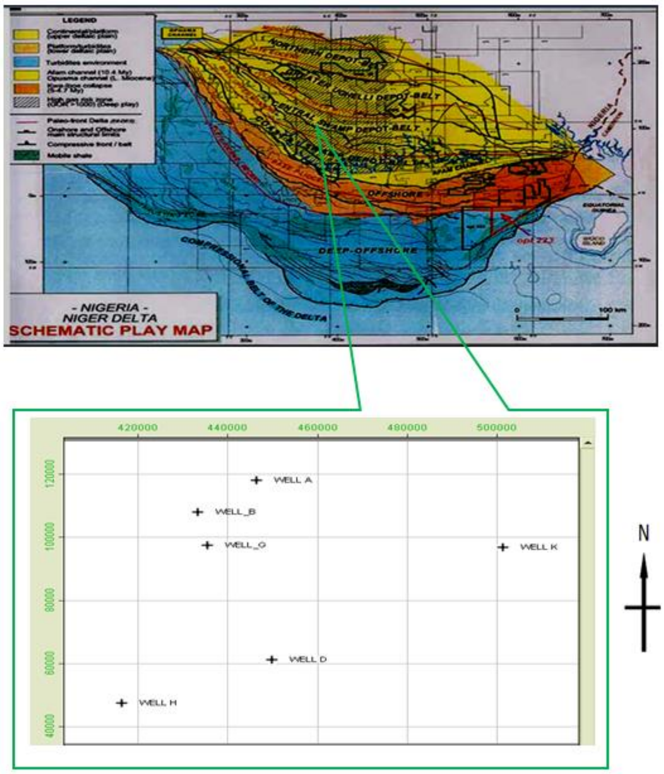


**Figure 1:** Map of the Niger Delta cmplex showing depositional belts (Doust and Omatsola, 1990) Studied wells located within the Central/Coastal Swamp Depo-belts

Shales in both the Agbada and Akata formations are made up of predominantly clay minerals measuring up to (55-90%) with pyrite, feldspar, carbonates and quartz making up the lesser amount. The assemblage of clay mineral comprises of 35-60% kaoline, 20-50% smectite and 10-30% illnite. Burial diagenesis has such effect on clay mineralogy in shales within these formations which appear to its minimal. Temperature of burial principally controls the diagenetic process even though other factor also may contribute their influence to smectite transformation, mixed-layer phase, overburden pressure, reaction rates and pore water chemistry (Lambert-Aikhionbare and Shaw, 1982).

**Overpressure-Generating Mechanisms and Identification Methods**

Known causes of overpressures include (Bower, 1995; Osborne and Swarbrick, 1997; Swarbrick and Osborne , 1998 and Traugott 1997):

1. Mechanically induced Mechanisms which are mechanical compaction disequilibrium in low permeability sediments, and lateral stresses or compressive tectonics.
2. Thermally/Chemically Induced Mechanisms relating to normal loading of sediments and are referred to as "secondary mechanisms". They are processes involving volume-alteration (fluid expansion) including such like hydrocarbon generation and maturation, diagenesis of clay minerals, and sea water expansion; they dominate in this group.
3. Dynamic Transfers and Other Minor Mechanisms including such processes like hydraulic head, osmosis, lateral drainage and buoyancy effect arising from contrast in density. Piezometric fluid level and thermodynamic processes are other two potential causal mechanisms.

In the Niger Delta basin, undercompaction is seen as the number one cause of overpressures. Most recent researches, however, support other causes.

Various authors (Bowers, 1995; Zhang, 2011; Kumar et al., 2012) have been able to show that plotting certain petrophysical parameters together can provide useful information on overpressure mechanisms at play. The cross-plots of vertical effective stress and velocity (VES-Vp), vertical effective stress and density (VES-density), and velocity against density are effective analyzing tools for this purpose. On the plots, disequilibrium compaction goes alone the normal/virgin curve. Various secondary mechanisms such as an unloading episode can be identified when there is a significant deviation from the normal trend; the deviation can equally be a reflection of a change in shale composition. Figure 2 shows a standard model for identifying overpressure generation mechanisms.

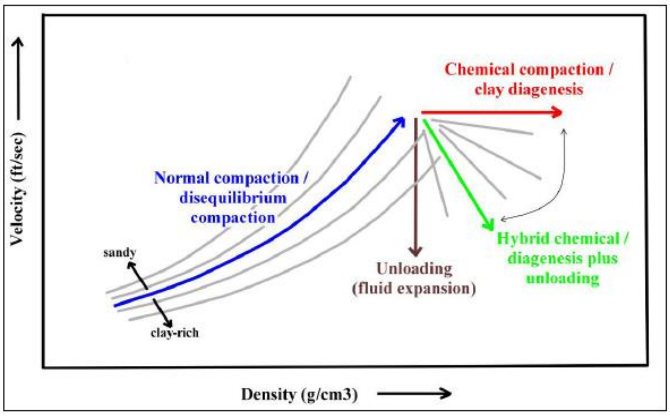


**Figure 2:** Standard Hoesni-type curves from velocity-density cross-plots with associated "overpressure generating mechanisms" (O'Connor et al., 2011)

## II. METHODS AND MATERIAL

Pore pressure prognosis studies yield results depending on the data quality used and the techniques applied. In this study, overpressured zones are predicted using petrophysical log data obtained from six 6 exploration wells in the Central/Coastal swamp depositional belts of the Niger Delta. The data were made available by Shell Petroleum Development Company (SPDC), Port Harcourt. The Eaton's, Bowers' and Porosity based prediction methods were applied on the RokDoc software. The first two models are inbuilt on the software while the porosity based model (Zhang, 2011) was inputted to the software by means of log calculator function. Figure 3 is the adopted workflow pattern.

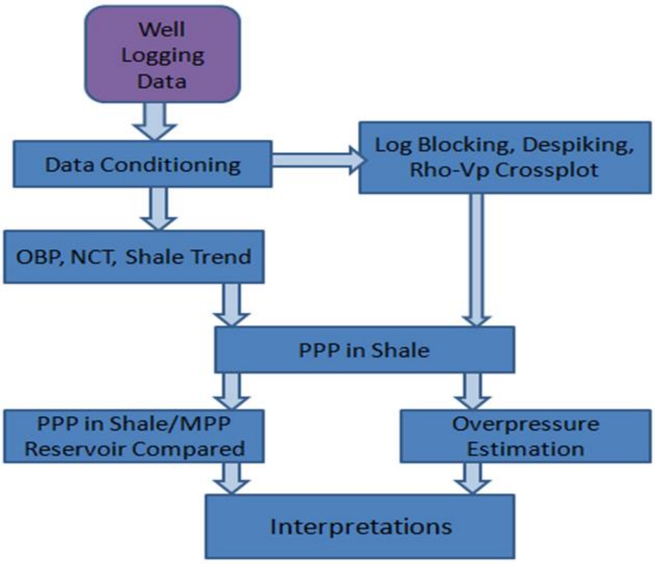


**Figure 3 :** Diagrammatic workflow for overpressure prediction studies.

**Prediction Models Applied.**

**1. Eaton's Sonic Velocity Model**

Eaton (1975) presented an empirical relation for the pressure from compression transit time:

$$P_{pg} = S_g - (S_g - P_{hg})\left[\frac{\Delta t_n}{\Delta t}\right]^3 \quad (4)$$

Where $\Delta t$ is the sonic transit time in shales obtainable from seismic interval velocity or well log data and $\Delta t_n$ is the transit time in shales at normal compaction pressure.

Eaton's sonic method applies predominantly to thick shale-rich lithology where overpressure is primarily due to disequilibrium compaction. This model, however, has some limitations because it does not take into account unloading effects. This implies that the method is valid only when the construction of normal compaction trend is possible for all depths of interest.

**Bowers' Model**

Bowers (1995) published a proposition in which he stated that in loading stage, the compressional velocity,$V_p$, and the effective stress, $\sigma_e$, are related by the power relationship of the form:

$$V_p = V_{ml} + A\sigma_e{}^B \quad (5)$$

Where $V_{ml}$ is the compressional (p-wave) velocity measured in the mudline (i.e., the sea floor or the ground surface, normally $V_{ml}$ ≃1520 m/s or 5000 ft/s,); A and B are the model parameters which have been calibrated with offset velocity. To account for the unloading curve, Bowers model takes this form ( in equation 6)

$$P_{ul} = S - \left[\frac{1}{A}(V_{max} - V_{ml})\right]^{\frac{U}{B}}(\sigma_{max})^{1-U} \quad (6)$$

Bowers' method can be applied in many sedimentary basins (e.g., the Gulf of Mexico, Niger Delta, etc), but may overestimate pore pressure in shallow un-consolidated or poorly compacted formations due to very slow velocity in such formations.

**Zhang's Model**

(Zhang, 2011) derived a theoretical equation for pore pressure prediction (PPP) from porosity according to normal compaction trend of porosity. The expression for the pore pressure gradient given as:

$$P_{pg} = S_g - (S_g - P_{hg})\frac{\ln\phi_0 - \ln\phi}{cZ} \quad (7)$$

Several other predictions based on porosity exist (Holbrook et al. 2005; Flemings et al. 2002), however, the good thing about Zhang's calculated pressures from porosity model is depth as a function is also considered. Overpressure sets in where porosity ($\phi$ ) at an interested depth is greater than the normal porosity ($\phi_n$) at the same depth. To determine the normal compaction trendline, equation (10) is applied:

$$\phi_n = \phi_0 e^{-cZ} \quad (8)$$

## III. RESULTS AND DISCUSSION

**Preliminary Results**

We begin with preliminary well logs analysis, which include loading logs, Measured Depth (MD) to True Vertical Depth subsea (TVDss) conversion and log QC/conditioning. Next, volume of shale, overburden gradient, normal-compaction-trend, shale trend and porosity are generated from various logs which are the required variables for the various models to be used in this work. The models applied include the Eaton's Model, Bower's Model and PPP from Porosity. Finally, the results of predictions are presented, compared and discussed. Preliminary analysis were done for all the wells but are only a few are demonstrated here for well A (Figure 5and 6)

**One Dimensional (1-D) Predicted Pore Pressure (PPP) in Shale**

Thick shale beds were considered for the predictions and prediction points picked were at depths within the shale beds where washouts are minimal or even without washouts at all. The responses of logs to overpressure are easily noticeable in thick shale beds, hence, the choice of them for prediction. Sand formations allow for easy dewatering during “sediment compaction” and are more porous. This would usually not support overpressure build-ups giving reverse log responses. Also, washout zones are interpretations from the caliper log data which describes how deviated the diameter of the wellbore is from normal; this also may affect the results of predictions. This is because the widening of the wellbore, in the first place, would reduce the accuracy of logging data.

Key logs requirement for the 1-D prediction were conditioned and checked for quality. Measured pore pressures (MPPs) in the form of repeat formation tester (RFT) data and predicted pore pressures (PPPs) from the three models; Results from the analysis reveal the presence of mild overpressures at all depths in well A location. The calculation is done using the depth-dependent porosity compaction model and Wyllie transit-time equation (Zhang, 2011) with $\Delta t_{ma}$= 73µs/ft, $\Delta t_{ma}$ =200µs/ft, C = 0.00016 /ft and mudline porosity ($\boldsymbol{\phi_0}$ = 0.8 ) for well A, the result is presented in figure 4 and shows fair

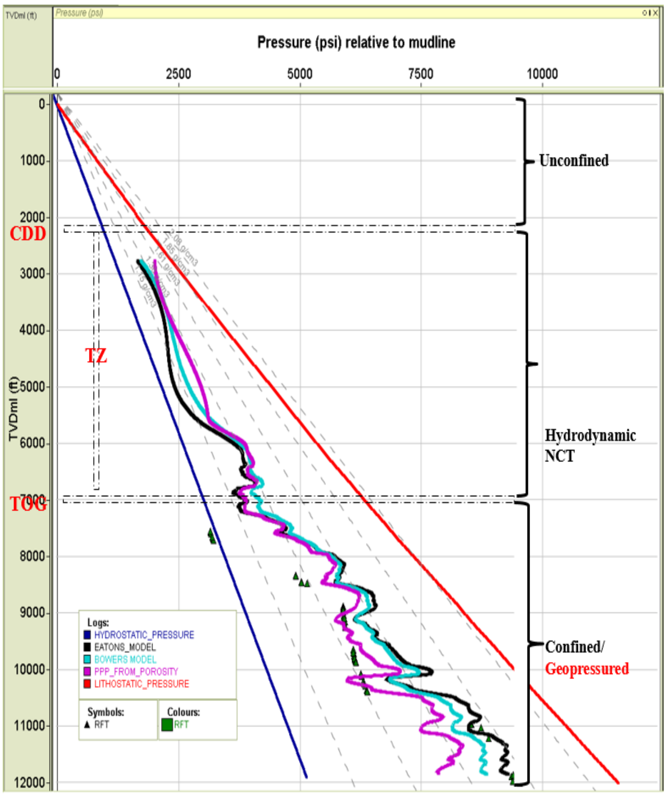


**Figure 4 :** Pressure-Depth plot showing top of overpressure for well A.

Figure 4 presents an interpreted section of pressure-depth plot for well A. In the Niger Delta area generally, hydrostatic pressure gradient averages to a value of about 0.44psi/fit for the fresh water formations and 0.46psi/ft for the saline water formations.

The result shows that well A maintains hydrostatic pressure mudline to a depth of about 7000ft where an onset of overpressure measuring between 0.55 and 0.60 psi/ft are predicted.The responses from “key logs” compared with standard models also confirm the presence of overpressures in the well. Robust matches also exist between the Measure Pressure (MPP) and Predicted Pressures at the well location, a result which approves the suitability of prediction models used. Formation pressure gradient averaging about 0.65 psi/ft is observed; falling to the class called **mild overpressure**. The “mild overpressures” are seen continuing steadily down to about 11000ft beyond which “hard overpressures” measuring up to about 0.80psi/ft are observed.

### Other Case-Study Wells

All case study wells were chosen because of the history of overpressures of their associated fields. Predictions from all three models applied to the wells confirm that overpressures are present at the well locations.

All Eaton's plots were calculated using exponent of '5.5' except in well H where exponents higher than '3' yielded over predictions. Generally, in applying the Bowers model to the wells, the parameters A and B were set to the range of values 2.0000 to 2.26206 and 0.89 to 1.00 respectively. For the porosity model, suitable transit times were inputted in the calculation of the porosities and compaction constant were computed from the constructed normal compaction porosity trends. The values for each well set are; WELL B ($\Delta t_{ma}$= 72µs/ft, $\Delta t_{ma}$ =224µs/ft, C = 0.00020); WELL D ( $\Delta t_{ma}$ = 70µs/ft, $\Delta t_{ma}$ =219µs/ft, C = 0.00023); WELL G ($\Delta t_{ma}$= 73µs/ft, $\Delta t_{ma}$ =237µs/ft, C = 0.00012); WELL K ($\Delta t_{ma}$= 79µs/ft, $\Delta t_{ma}$ =239µs/ft, C = 0.00053) and WELL H ($\Delta t_{ma}$= 73µs/ft, $\Delta t_{ma}$ =209µs/ft, C = 0.00042). Mudline porosity value used for all studied wells is$\boldsymbol{\phi_0} = 0.8$.

### Discussion of Results from Other Case study Wells

Results from all the case studies indicate the presence of overpressured zones, hydrostatic formations and even zones characterized with certain degrees of underpressures. Top of overpressures are generally within depth of 6000ft to about 12500ft across all studied wells; mild overpressures are observed at shallow depths while hard overpressures occur at depths generally below 10000ft (TVDss) for all studied wells.

Well B (Figure 8) is characterized with hydrostatic pressure from the beginning to about 10500ft where very mild overpressure (<0.6psi/ft) sets in. Hard overpressures zone predicted at about a depth of 15500ft to about 16000ft where the well is terminated probably suggesting why the well is terminated at that depth (MPP values approaching lithostatic pressure). All PPPs from the "prediction models" each compares favorably with MPPs except at the terminating depths; an observation which cannot be resolved.

At well D (Figure 9) location, similar result has been obtained at shallow depths as that in well B but slightly different at deeper zones. Hydrostatic pressure is observed until about 10000ft where an onset of mild overpressure begins. The zone between 13000ft and 15000ft can be referred to as a "wavy" pore pressure zone, since there are switches between overpressures and hydrostatic pressures at short intervals. This zone is a transition zone within which there are quick alternations between shale and sand beds before penetrating the thick shale bed just below the zone (below 15000ft) where the well is overpressured until last drilled depth. The wavy nature of the pore pressure gradient may be due to a varying volume of quartz within the shale beds which would help in dewatering process. In well G (Figure 10), the reading of RFT starts at about 11000ft with hydrostatic status to around a depth of 12000ft where it reads sub-normal (under) pressures and mild overpressures (0.6 to 0.7psi/ft) from 12500ft to the last drilled depth. Predicted pressures compare favourably with the measured pressures; Eaton's model provided a better match at the hydrostatic zone while Bowers model however does at the deeper depth with overpressures. Well G is a much deviated well and mud losses were also reported during the course of well drilling. The sub-normal pressure conditions must have been responsible for these drilling challenges. The fact that the predicted plots are also matching these rather discordant MPP; the data should be validated and accounted for as it can possibly give clue on mechanisms causing the pressuring and bleed-off occurrence.

Well H (Figure 11) maintains hydrostatic condition from the beginning to about 9000ft where mild overpressures begin to set in and returns to hydrostatic at 11000ft. Another overpressure regime is observed at about 11600ft and to hard overpressure at terminating depth about 16200ft. The last value of MPP shows a further increase in overpressures down depth; since predictions were done for thick shale beds rather than reservoir sands where the last MPP value was read, this could not be ascertain. However, prediction models for this well are in perfect match with "Measured Pore Pressures (MPPs)".

And finally in the case study well K (Figure 12), the result demonstrates hydrostatic pressure down to a depth of about 10,400ft where an "onset of overpressure" is observed. Hard overpressures in the well location exist within the range of 12000ft to 12400ft. Before the overpressure zone, a subnormal pressure zone is also observed. A slight mismatch is however seen between the predicted and measured pressures within these depths range of subnormal pressures. This could probably be owed to information mix-up in the data provided. Since the mismatch is just not too out of place, the depth range can be put between 8000ft and 11000ft where the subnormal pressures are observed, although this result cannot be validated for future exploration need otherwise drilling information is incorporated to these interpretations (these were not provide for this well). Logs reversals just below the hard overpressure zone suggest a return to hydrostatic pressure regime.

**Evident Overpressure Mechanisms and Suitability of Models**

The results of this work have produced perfect matches between Predicted Pore Pressures (PPP) and Measured Pore Pressure (MPP) for each of the applied models and in all the wells, making the models suitable for the study area. However, certain parameters were adjusted to achieve their suitabilities. Eaton exponent 5.5 and Bowers' model which produced concordant results with MPP in a good number of the studied wells suggest a strong evidence of unloading mechanism. Also, porosity model predicted with better match to MPP in most of the wells when values for pore fluid transit times approached or were above 230µs/ft; a value known for hydrocarbon (oil) fluid type (Carmichael, 1982 ). With this we can infer fluid expansion mechanism ensued from expansion of formation fluids (hydrocarbon cracking) since most overpressures occur within the deep Agbada shales.

Cross-plots of velocity against density for all of the wells show a twin exponential increase in both parameters as it is expected for a disequilibrium compaction mechanism. In some wells, however, there are notable downward trending which depicts unloading paths when compared with the typical Hoesni cuve-types from velocity-density cross plots.

Finally, zones predicted in this work as having hard overpressures (>0.75psi/ft) are generally within the depth of 10,000ft to 16,000ft corresponding to the hydrocarbon generative window described by (Akpononu *et al.*, 2012). At these depths, it is believed that thermal cracking of hydrocarbon takes place at high temperatures with volume increment. This further confirms the views in (Opara, 2011 and Nwozor *et al.*, 2013) that fluid expansion mechanism is also a major source of overpressures in the Niger Delta basin as against the earlier believe where all emphasis were laid on compaction disequilibrium alone as the major cause of overpressuring in the sedimentary basin.

## IV. CONCLUSION

Zones of overpressures have been predicted from the three models applied; Eaton's, Bowers' and Porosity models, each of which yielded results with good match to MPPs and with various degrees of accuracy. Geopressures are correspondingly higher in thick shale zones with sharp increase in porosity values and hard overpressures are generally at depths below 10,000ft. The predictability and suitability of each of the models are however, majorly dependent on overpressure mechanisms at play. Analysis of Vp and density logs revealed an interplay of mechanisms causing overpressures other than compaction disequilibrium. Bowers give better matches at much deeper zones with the hard overpressures indicating sediments unloading probably due to fluid expansion mechanism resulting from hydrocarbon cracking/generation Therefore, these results have successfully met the objectives of this work and are also in agreement with results from similar works.

## V. RECOMMENDATIONS

The results of this work are valid for whatever purpose as the reference could be made namely; future exploration works, academic research, economic evaluation and otherwise. An integrated approach is recommended and with pre-drilled predictions more confidence can be built for the drillers. With the knowledge that temperature affects the density of rocks and permeability of formations/fault-sittings in an area will give an idea of pore fluid mobility, I also recommend that temperatures and hydrodynamics be integrated to future research in this area for better interpretations.

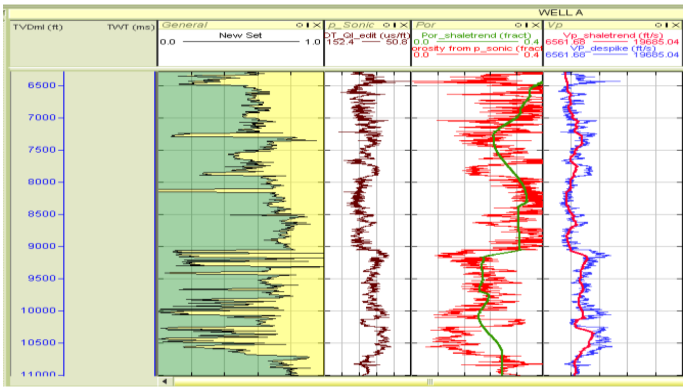


**Figure 5:** Preliminary results for well A (Volume of shale, p-sonic log, Porosity shale trend, Vp shale trend)

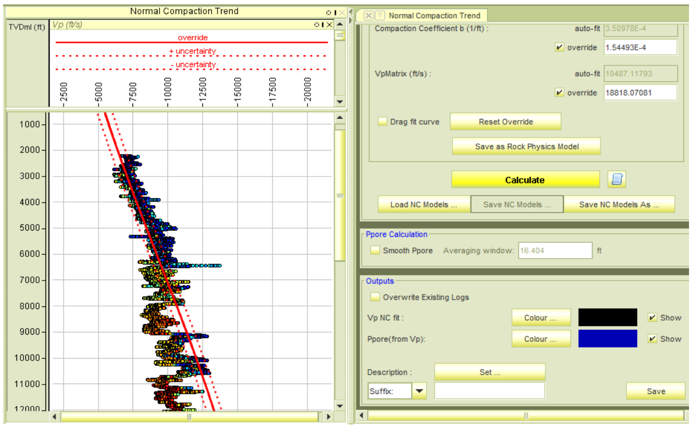


**Figure 6:** Normal compaction trend and line of fit for Well A

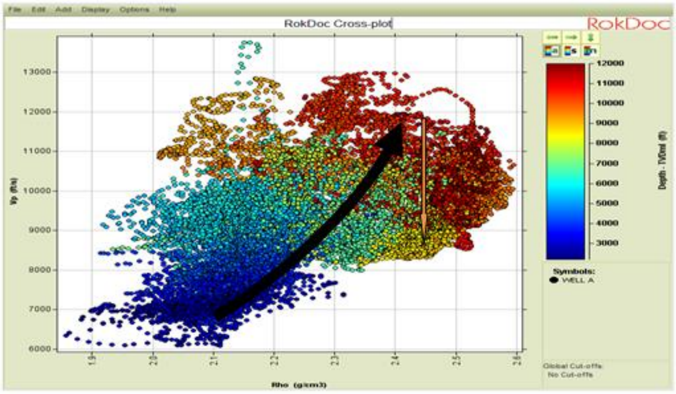


**Figure 7:** Velocity vs. Density cross-plot for WELL A demonstrating the presence of secondary mechanism due to unloading.

WELL B

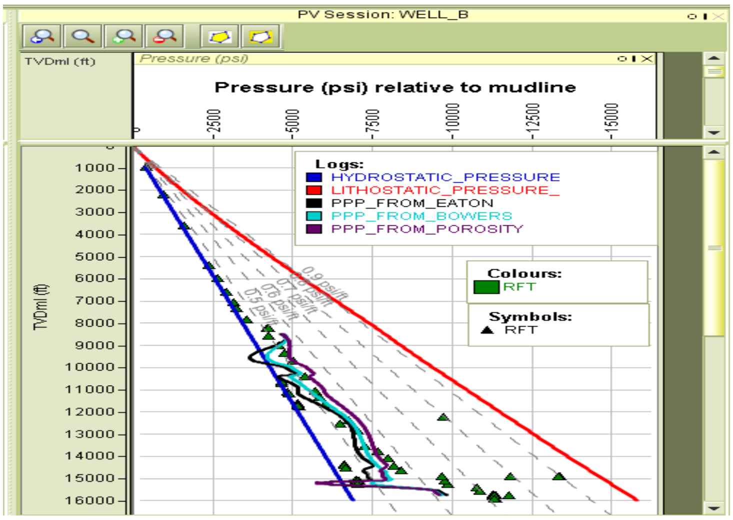


**Figure 8:** Comparison of models at well B location

WELL D

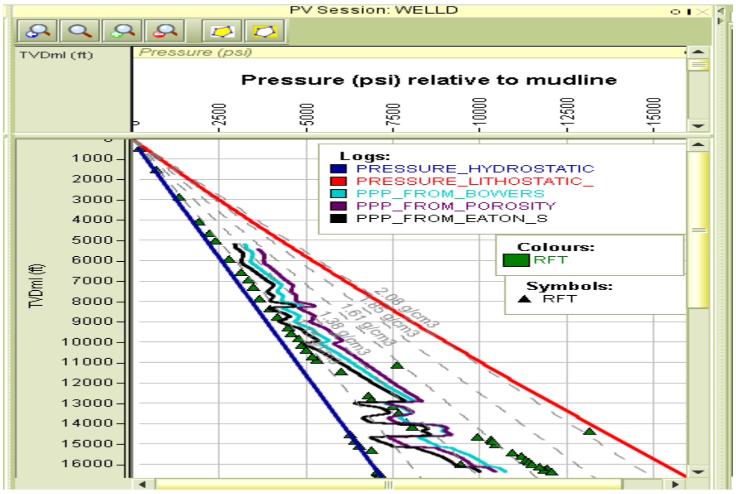


**Figure 9 :** Comparison of models at well D location

WELL G

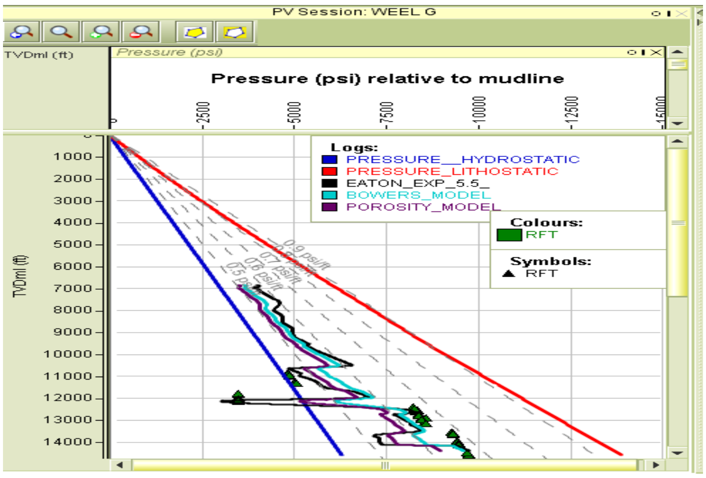


**Figure 10:** Comparison of models at well G location

WELL H

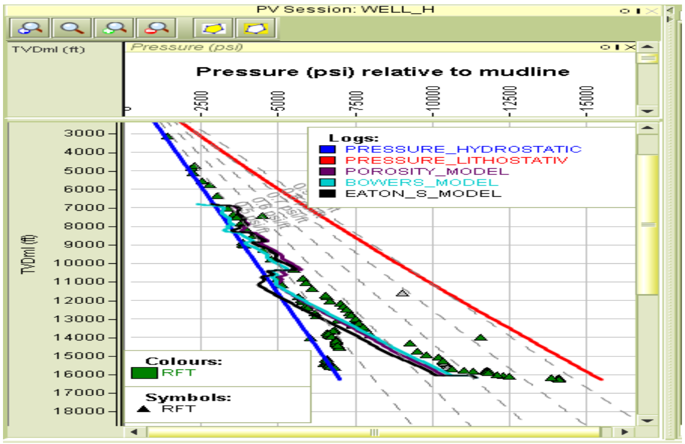


**Figure 11 :** Comparison of models at well H location

WELL K

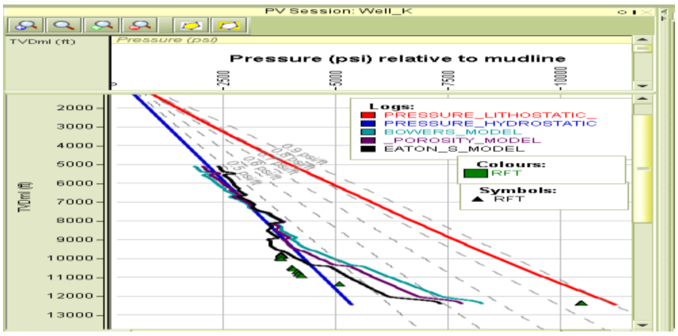


**Figure 12 :** Comparison of models at well K location

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