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Well-Based Pore Pressure Validation: A Case Study of Akos Field, Coastal Depobelt, Niger Delta Basin

Emudianughe, J.E.[1] and Ogagarue. D.O.[1]
[1]Department of Earth Sciences, Federal University of Petroleum Resources, Effurun, Nigeria

Abstract
The importance of proper and accurate pore pressure prediction prior to drilling cannot be overemphasized. Such prediction is needed for accurate planning for safe drilling of a well. Inaccurate pre-drill pore pressure prediction may result in avoidable catastrophic incidents during drilling. Till date, the Eaton's empirical pore pressure prediction model is widely adopted and applied in the industry for pore pressure prediction. The prediction is predicated on the relationship between porosity and formation physical properties such as resistivity, interval transit time and density, with derived overpressure model and normal sediment compaction trend as input. Employing the Eaton's model, pore pressure was modeled in this study in AKOS field, Niger Delta coastal swamp depobelt, using overburden model and normal sediment compaction trend derived in ADA field, situated about 33 km offset from the AKOS field. The purpose was to determine if overburden model and compaction trend derived in an offset field could be deployed to adequately predict pore pressure in a given field in the Niger Delta. Comparison of the modeled pressures with pore pressures directly measured in the AKOS field shows good agreement in the pore pressure trends, with prediction success rate of only 19%. Since direct pressure measurements give accurate pressure information in the subsurface, the lack of correlation between the modeled and measured pressures indicates that precise pore pressures cannot be predicted for a field by the use of overburden and normal compaction trends derived in another field. In order to use offset data for well-based pore pressure predictions, wide error margins must thus be included in the model to give some level of confidence in the prediction.

Keywords: Pore Pressure, Eaton's model, Normal Compaction Trend, Overburden, Depobelt

1. Introduction
The weight of the drilling mud plays a substantial role in preventing influx of formation fluid into the wellbore that may result in kicks or blowouts in intense cases during drilling in over pressured sediments. Determination of optimum weight of the drilling mud is dependent on good understanding of the subsurface geology and pore pressure regime. Compared to a normally pressured sediment at the same depth, overpressured sediments may exhibit a reduction in interval velocity, higher porosity, lower effective stress, higher Poisson's ratio, lower resistivity, lower density and higher temperature (Dutta, 2002). In many cases, the porosity may,

rather than increasing with compaction, remain unchanged or preserved. Pore pressure prediction requires knowledge of the overburden pressure and vertical effective stress. Whereas overburden pressure is obtained by direct integration of the bulk density log measurement, the vertical effective stress cannot be measured directly; it can only be inverted from log measurements of porosity indicators such as velocity, density or resistivity. Except for resistivity, a change in seismic interval velocities results in changes in each of the mentioned properties, and the converse is true. Changes in seismic velocities are manifested in the magnitude of the amplitudes of seismic reflection from individual acoustic boundaries in a seismic reflection survey. Consequently, seismic interval velocity determination is key to pore-pressure prediction.

As sediments compact, their density is reduced leading to loss in porosity. This also results in increase in the bulk and shear moduli of the formation arising from increase in effective stress due to increase in grain-to-grain contact. During this process, the overburden pressure is mainly born by the pressure due to grain-to-grain contact, known as the vertical effective stress. At some point in the mechanical compaction process, pore fluid pressure may counteract the pressure due to grain-to-grain contact, and this slows down porosity decrease arising from compaction. In essence, porosity becomes preserved or remains unchanged with increasing depth of burial. This is known as undercompaction or compaction disequilibrium. When this happens, the pressure due to the overburden becomes mainly born by the fluids in the pore spaces of the rocks rather than the grain-to-grain contact. The grain-to-grain contact area may remain essentially unchanged, but the increase in pore pressure causes a reduction in the grain contact stress, which results in decrease in velocity with increasing burial depth. In this study, the property of velocity decrease with depth due to reduction in vertical effective stress is utilized in pre-drill pore pressure prediction in the Akos field, Coastal depobelt of the Niger Delta basin.

Pore pressure prediction was recently carried out in ADA field, Niger Delta (Emudianughe et al., 2018). The study entailed the derivation of overburden model and normal compaction trend in the ADA field. In the present study, the overburden model and compaction trend derived for the ADA field were applied for pore pressure prediction in the AKOS field, situated some 37 km from the ADA field in the Niger Delta coastal swamp depobelt. The purpose was to determine if overburden model and compaction trend derived in a given field could be deployed to adequately predict pore pressure in another field.

1.1 Geologic Setting

The Niger Delta basin is an extensional rift basin located in the Niger Delta and the Gulf of Guinea near the western coast of Nigeria. It is a major geological feature of significant petroleum exploration and production in Nigeria, extending from longitude 3˚E - 9˚E and latitude 4˚30'N - 5˚20'N, and ranks amongst the world’s most prolific petroleum producing Tertiary deltas,(Michele et al 1999) (Stacher, 1995). The geology of the Niger Delta has been extensively studied by several authors and is now well documented. It is bounded in the north by the Benin flank, in the northeast by the outcrops of the cretaceous Abakaliki anticlines, and extends to the southeast as the Afikpo syncline and Calabar flank. Stratigraphically, the Niger Delta basin is made up of three formations with unique characteristics: the topmost massive continental fluviatile gravels and sands of the Benin Formation, the deltaic facies of the Agbada Formation and the marine shales of the Akata Formation. The Akata shale is significantly overpressured, and is believed to be the main source rock of the hydrocarbons, usually trapped in faulted rollover anticlines associated with growth faults in the Niger Delta basin. In the last 55 Ma, the Niger Delta is predominantly composed of regressive clastic sequence has prograded southwards, forming some depobelts (Figure1) (https://pubs.usgs.gov/of/1999/ofr-99-0050/OF99-50H/ChapterA.html)

Till date, majority of hydrocarbon reservoirs in the Niger Delta are located in the structurally complex Agbada Formation which also has multivariate pore pressure system. Drilling in the complex Niger delta basin is very challenging due to the overpressure concerns, especially at deep depths and in offshore areas of the basin. The potential impact of overpressure on the overall outcome of drilling campaigns in the overpressured zones underscores the importance of this study.

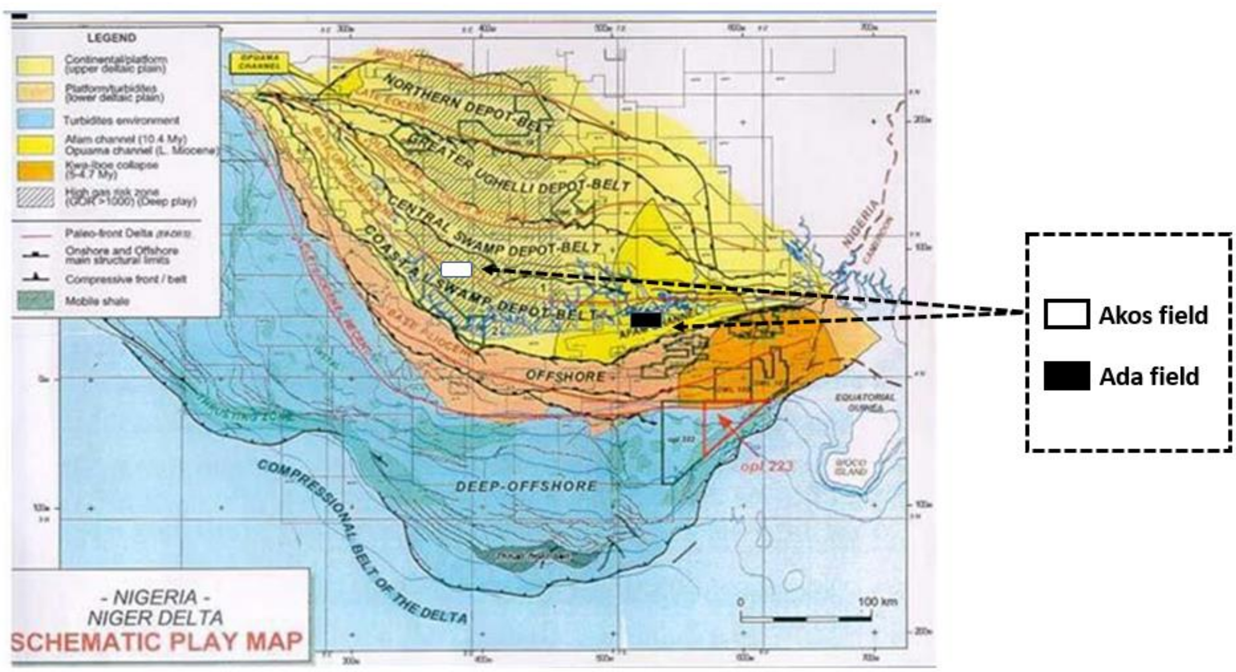

Figure 1: ***Section map of Niger Delta showing the depobelts***

2. Materials and Methods

The study data comprise GR, sonic and density logs, as well as deviation data obtained from ADA field. The measured data were first converted to true vertical depth measurements, using the deviation data from well. Thereafter, volume of shale was computed using the GR. The shale volume was used as input in the derivation of the compressional velocity in shales and normal sediment compaction trend. Since the study area is in the Niger Delta coastal swamp, the overburden pressure was obtained by integration of the bulk density log from below the mudline to deeper depths after which the pressure due to the water column and atmospheric pressure of 14.7 psi were added to obtain a complete model of the overburden. The overburden model and normal compaction trend derived from the shale picks in ADA-1 (Emudianughe et al., 2018) are shown Figure 2.

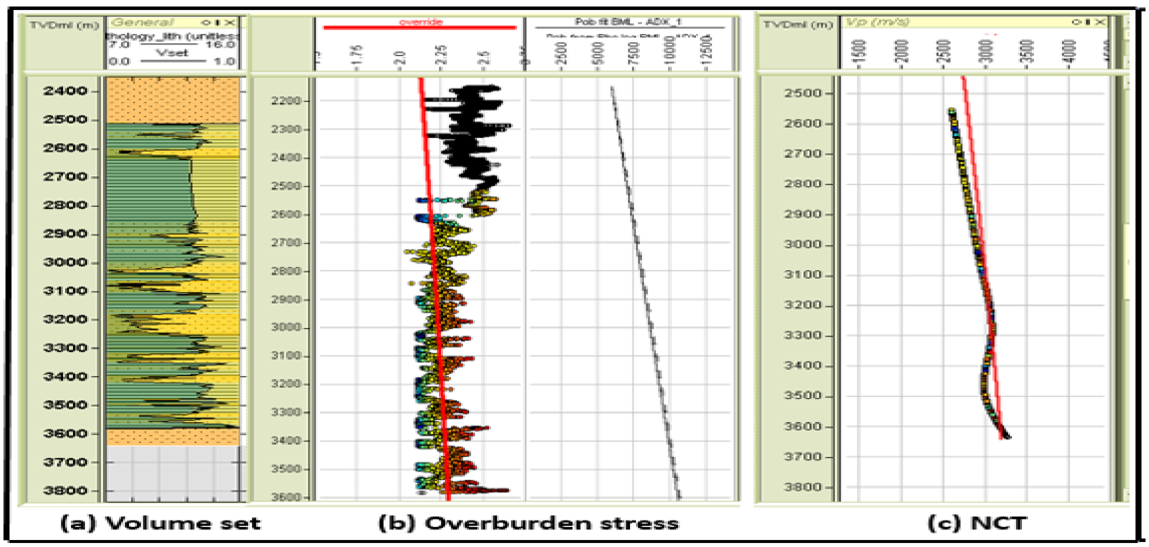

Figure 2: Showing volume set, overburden stress and NCT

The overburden model and normal compaction trend derived from the ADA field, were then applied for pore pressure prediction in the AKOS field, using the Eaton's model (Eaton, 1975), given in Equation 1.

$$Pp = Sv - (Sv - Phyd)\left[\frac{V_x}{V_y}\right]^3 \qquad (1)$$

where,

V_x = interval seismic velocity in shale

V_y = interval velocity trend in normally compacted shale

Pp = geopressure, otherwise known as pore pressure

Sv = vertical component of the overburden stress.

$Phyd$ = hydrostatic pressure.

The hydrostatic pressure and shale velocity in the above model are obtained from the respective AKOS wells where this test was carried out. Hydrostatic pressure, in psi/ft, is given by:

$$P_{hyd} = 0.433 * (Z_{bml}) \qquad (2)$$

where 0.433 psi/ft is the hydrostatic gradient and is Z_{bml} sediment depth below the mudline. To ground-truth the predictions in the AKOS field, Repeat Formation Tester (RFT) data, measured in the AKOS fields were plotted to compare pore pressure predictions for the various wells in the AKOS field. Several sonic versus density crossplots were also carried out to study any likely overpressure generation mechanisms in the wells or different un-loading mechanisms.

3. Results and Discussion

Figures 3 and 4 show well logs and predicted versus RFT pore pressure models at AKOS wells 1 and 2 respectively, with pore pressure profiles from RFT measurements

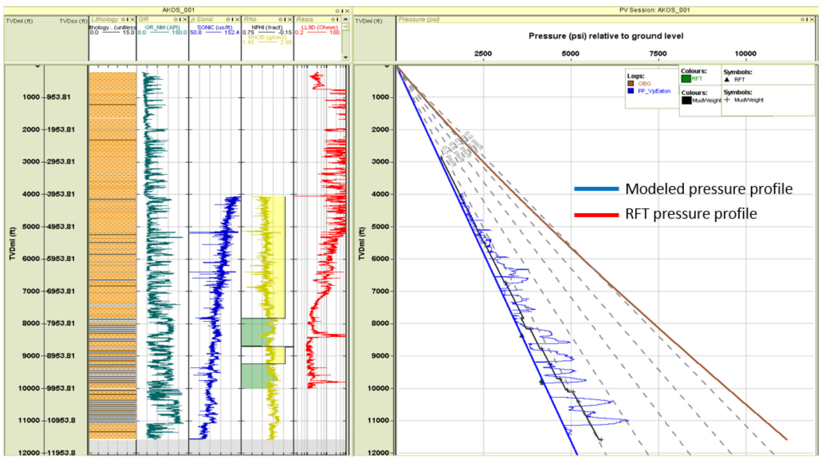

Figure 3: Well logs and pressure profiles at AKOS-1 well.

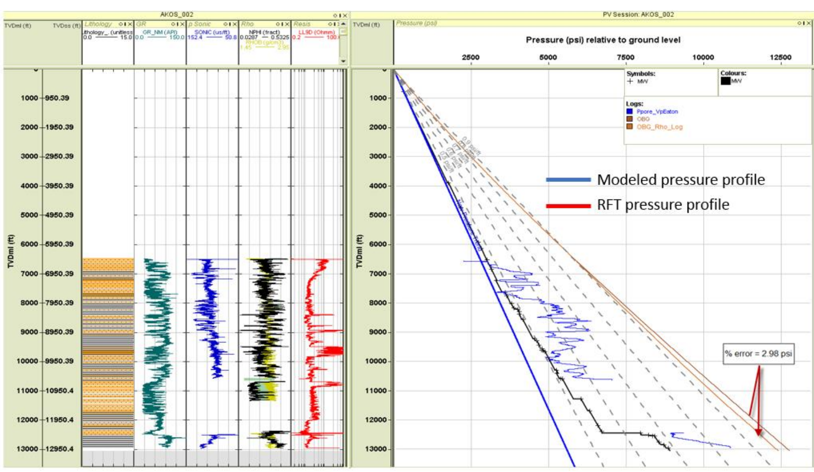

Figure 4: Well logs and pressure profiles at AKOS-4 well.

Comparison of the predicted and measured pore fluid pressures at these wells show a clear lack of correlation. Repeat Formation Tester measurements are in situ pressures; they give accurate information on pore fluid pressures in the subsurface. Although RFT measurements are recorded only in sands and not shales or silty layers, it is often assumed that in normal conditions, pore pressures equilibrate between sands and shales, hence the continued use of RFT measurements in pore pressure studies. There is lack of correlation of up to 81% between the predicted and measured pressures, although there is a general agreement in the overpressure trends. Since knowledge of accurate pre-drill pore pressure is important for developmental and exploratory drilling activities, it would therefore not be safe to make use of the major components of pore pressure prediction data from different fields in pore pressure prediction. One would argue that globally, data from offset wells have conventionally be used in pore pressure prediction. The results of this study have not negated this practice, however, it has shown that the use of important data such as overburden model and normal compaction trend from a completely different geological setting, as in this case, would result in inaccurate pore pressure prediction. Even though it is generally assumed that overburden pressure does not vary much laterally, reasonable prediction of the pore fluid pressure is not likely to be obtained without the use of overburden model and the normal compaction data from the prospective field. Since the modeled pressures are not reliable for these two wells, a reasonable explanation of overpressure and its generation mechanism cannot be given based on the modeled pressures. The measured pressures from both wells show that whereas AKOS-1 is mildly overpressured at depths, AKOS-2 is heavily overpressured at depths. Pore pressure ranges from hydrostatic value of about 0.433 psi/ft at 3000 ft below mudline to about 0.54 psi/ft at 11,000 ft below the mudline in AKOS-1, and about 0.45 psi/ft at 4,000 ft to approximately 0.62 psi/ft at 12,600 ft below the mudline in AKOS-2. There is a pressure ramp in AKOS-2 at 12,600 ft, jumping to as much as about 0.70 psi/ft at the TD. The pore high pressures measured in these wells which could not be detected reliably in the modeling justifies the use of a robust pre-drill pore pressure model to derisk drilling activities.

Figure 5 shows velocity-density crossplots for AKOS-1, colour-coded by shale volume fraction (a) and depth below mudline (b), respectively.

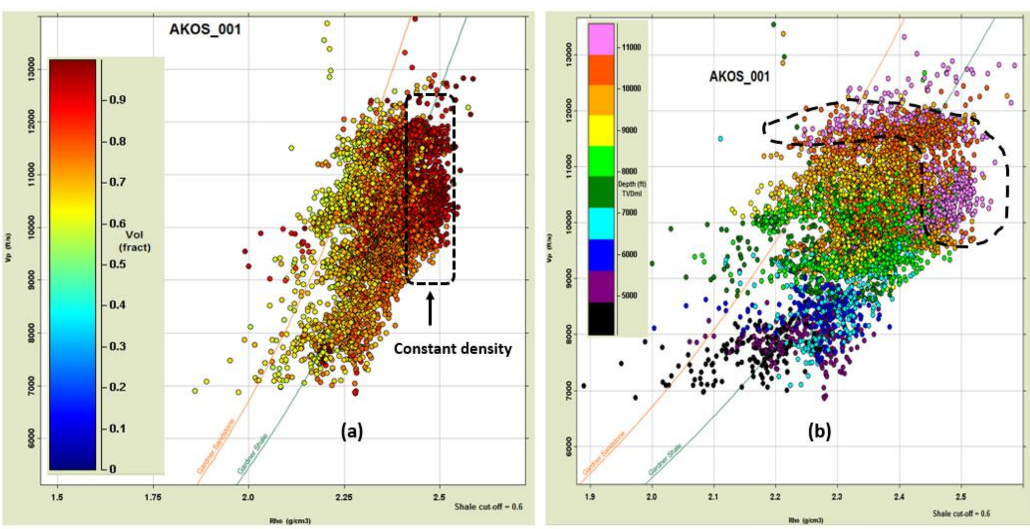

Figure 5: Velocity-density crossplot for AKOS-1. The crossplots are colour-coded by shale volume (a) and depth below mudline (b). Gardner density models in shale and sandstone are also plotted.

The crossplots give a qualitative interpretation of the overpressure-generating mechanisms in the respective wells. A region of nearly constant density is seen for the velocity range of about 9,500 ft/s and 12,000 ft/s. The velocity essentially increased with depth, but remained the same or reversed, decreasing with depth at some subsurface depths. This indicates that the overpressure seen in AKOS-1 is likely the result of compaction disequilibrium.

Velocity-density crossplot for AKOS-2 is shown in Figure 6. Unlike the AKOS-1 crossplot which shows undercompaction as the only likely cause of the overpressure, this plot shows evidence of a secondary overpressure generating mechanism in addition to compaction disequilibrium in this well. Determination of the causative secondary overpressure mechanism is outside the scope of this study, however, thermal expansion, hydrocarbon generation or mineral phase change during compaction.

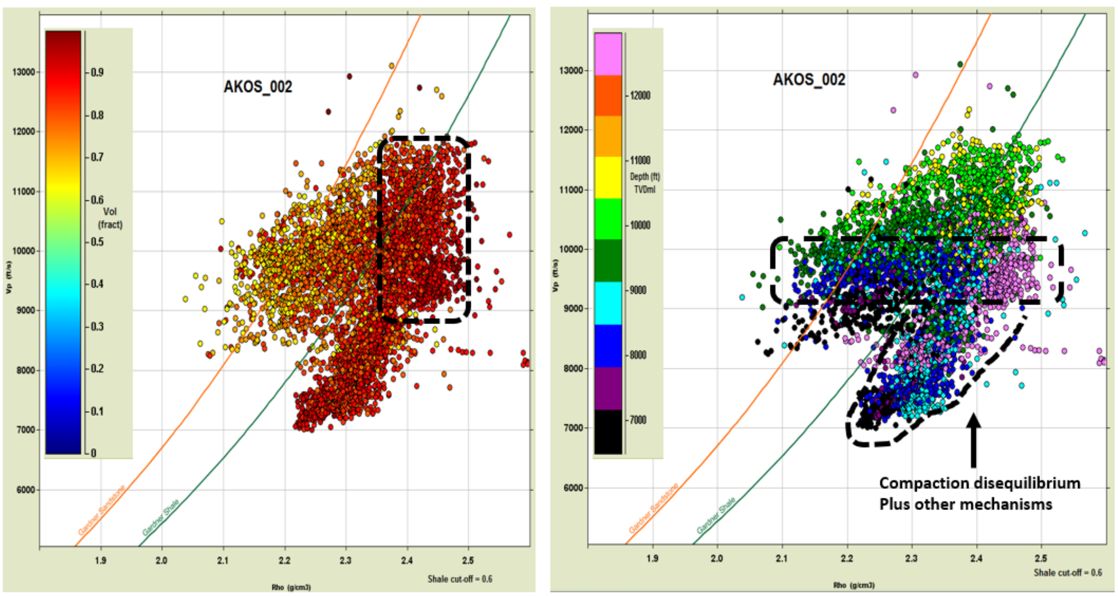

Figure 6: Velocity-density crossplot for AKOS-2

Conclusion

In the foregoing, pre-pore pressure was modeled at AKOS field using overburden and normal compaction trends derived in an offset field, the ADA field, to determine the success rate of pore pressure prediction in a given field with data obtained in another field in the Niger Delta coastal swamp depobelt. The study has shown only 19% success rate in pore pressures predicted in the AKOS field, Majority of the pore pressures predicted are not reliable when compared to pore pressures directly measured in the wells (RFT data). The learning from this study is that while it is generally believed that lateral variation in overburden pressures could be mild over a given area, field specific overburden model and sediment normal trend should be used in the prediction of reasonably accurate pore pressure models in the Niger Delta coastal areas. Apart from operation cost and efficiency, accurate knowledge of pore fluid pressure is important to derisk petroleum exploration and exploitation.

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