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Development of an Appropriate Model for predicting Pore Pressure in Niger delta, Nigeria using Offset Well Data

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Abstract

The pore pressure in most sedimentary formations such as it is in the Niger Delta, Nigeria are rarely normal. They predominantly occur as over-pressured zones, when these abnormal pressures are not predicted accurately prior to drilling, disastrous occurrences, such as kicks, and blowouts may occur. The existing models used for pore pressure predictions were developed using data outside Niger Delta environment as such a number of them yield inaccurate results. This paper provides a new approach for predicting pore pressures particularly for Niger Delta using offset well logs acquired in the Niger Delta. A number of industries utilized pore pressure prediction models were appraised using offset well data from the Niger Delta. Density and sonic velocity logs were used in generating the overburden pressure and Normal Compaction Trend. Shale trend and overburden pressure were used as inputs in the models for predicting pore pressure using RokDoc.

In the development of an appropriate model for pore pressure prediction, Eaton model was modified for Niger Delta environment. Results of the model's sensitivity analysis revealed sonic velocity as the most sensitive parameter while findings from the Goal Seek analysis showed that increasing the exponent in the original Eaton's model from 3 to 3.9 yielded the most concordant result with the measured pressure data. The statistical error analysis conducted revealed that the modified Eaton's model had the least absolute mean percentage error value of 2%. Given the above results, the modified Eaton's model showed more accurate predictions when compared with existing models and will be effective in predicting pore pressure in the study area.

Keywords: Pore Pressure; Niger delta; Model

Introduction

The forecast of pore pressure plays a crucial role in the planning and actual drilling phase of a hydrocarbon well. Pore pressures determine where the casings are placed in the well and the magnitude of drilling mud to use in the course of drilling the well. In an over-pressured region such as the Niger Delta, accurate prediction of formation pore pressure can greatly curtail non-productive time and destructive problems associated with drilling through over-pressured areas such as wellbore balance complications, influx of pore fluids into the well, blowouts, and lost circulations. As such, accurately predicting the pore pressure of the area will help to ensure an improved well design, mud weights program, risk assessment and field development plan. Pore pressures prediction in shale is an intricate process as it can't be evaluated directly and requires inference from seismic velocities or acoustic travel time [1]. Baltensperger PZ [2] stated that erroneous estimation of hydrocarbon reserves can occur due to inaccurate forecast of formation pressures. Techniques employed in evaluating abnormal pore pressures are separated into three categories; prediction methods, direct methods and detection techniques [3]. The prediction methods normally employ data acquired from nearby well logs, seismic studies, and general well records. These techniques are primarily used in the course of searching for hydrocarbons. The direct methods basically employ the use of wire line formation testers such as Repeat Formation Testers, and Modular Dynamic Testers to measure pore pressure directly from permeable formations. Meanwhile the detection methods primarily make use of drilling data acquired in the course of the drilling operation of wells which can be observed for pressure anomalies [4]. The basic principle of predicting pore pressure is based on Terzaghi's effective stress theory [5] which states that pore pressure is dependent on the overburden pressure and the effective stress. It is predicted by deducting the effective stress from the overburden pressure.

$$\sigma_v = S_v - P_p \quad (1)$$

Where S_v is overburden pressure

σ Is effective stress

P_p Is the pore pressure

Niger delta geology

The Niger Delta basin is one of the seven sedimentary basins in Nigeria. It is considered as the most significant owing to its petroliferous nature and consequent active hydrocarbon exploration and production operations occurring both onshore and offshore. The Niger Delta basin has three major formations namely, the Agbada, Akata and Benin Formations. The Benin Formation is the uppermost consisting of considerable amounts of non-sea sand predominantly sandstone together with deposits of gravels [6]. The formation contains negligible amounts of hydrocarbon [7]. The Agbada Formation lies beneath the Benin formation and overlies the Akata Formation. The formation encompasses reservoir rocks and seals. The Akata Formation, which is at the base is about 7000 m thick and consists of basically clay and shale. The formation is rich in organic matter and is believed to be the major rock generating hydrocarbons in the study area.

Methodology

The data employed in this work was from a well situated in Niger Delta. Data used primarily consisted of wireline logs such as sonic compressional velocity, density, and gamma ray logs along with direct measured pressure data in the form of Repeat Formation Test (RFT) data. The tools employed for this study were RokDoc package and Microsoft Office Excel. The RokDoc package was used for the estimation of overburden pressure, normal compaction trend generation, selection of shale intervals, pore pressure forecasts, and carrying out an analysis of sensitivity using scatter-plots. Microsoft Office Excel (Goal Seek) was used in the calibration and optimization of the best pore pressure forecasting model and the statistical analysis to ascertain the models' precision and subsequently rank them. The basic workflow employed in the work is as follows;

- Generation of Overburden pressure profile (using density log), setting up the Normal Compaction Trend (using acoustic compressional velocity log) and building the shale velocity trend (using gamma ray and acoustic compressional velocity log) which were used as input parameters in the pore pressure forecasting models.
- Inputting the aforementioned generated parameters into pore pressure prediction models (Eaton, Bowers, and Equivalent Depth) and predicting the pore pressures of the area.
- Comparison of the predicted pore pressures with the measured pressure data (RFT) so as to ascertain their accuracies and conducting a statistical analysis of the results by way of computing the percentage errors of the results.
- Carrying out a sensitivity analysis on the most accurate model with a view to identifying the most sensitive variable to the measured pore pressure data.
- Optimizing the most accurate model by way of modifying the identified parameter so as to obtain more accurate predictions using Goal Seek.

Overburden stress

The overburden pressure is a pre-requisite for forecasting pore pressure in most models. Overburden pressure in the study was computed from density log by taking the accretive sum of weight of sediment at every depth. The overburden pressure was estimated using a model fit of the density log (Rho fit) by employing the RokDoc package using the equation.

$$R_{ho}(Z_{ml}) = R_{hoMatrix} - (R_{hoMatrix} - R_{hoTop}) * \exp(-b * Z_{ml}) \quad (2)$$

Where $R_{ho}(Z_{ml})$ density at depth z below ground surface (mudline).

R_{hoMatr}=density of matrix

R_{hoTop}=density at mudline (ground level)

b=Compaction coefficient (1.5 × 10^{-4} ft)

Shale trend

This is primarily used as a filter in selecting clean shale for the generation of Normal Compaction Trend line. Given that most compaction occurs in the shale formations, and a compaction trend is crucial to pore pressure prediction, only the cleanest shale lithology is used. To achieve this, a volume fraction of shale is generated using Gamma Ray log with the aid of the RokDoc package since the Gamma Ray log can discriminate between sand and shale lithology. Data points used for the analysis were further screened by virtue of choosing a shale fraction value of 50%. Data points with lesser values than the gamma ray from shale discrimination line are discarded, with the remaining points utilized. The volume fraction of shale, Vsh, is generated from the RokDoc package using the equation.

$$V_{sh} = \left(\frac{GR_{\log} - GR_{sand}}{GR_{shale} - GR_{sand}} \right) \quad (3)$$

where GR_{log} is the response of the gamma ray log

GR_{shale} is the measurement obtained in clean shale

GR_{sand} is the log measurement in clean sand.

Normal compaction trendline

This is a linear correlation between properties of shale such as sonic velocity with depth of burial. The generation of the normal compaction trend is crucial since prognosis of pore pressure in some models is determined by comparing the measured log data with the corresponding value of that measurement in a normally compacted formation. The normal compaction trendline in this study was established from the compressional velocity, V_p log. It was generated in the RokDoc package using the reciprocal input log transform of compressional velocity, V_p.

$$\frac{1}{V_p(Z_{ml})} = \frac{1}{V_{pMatrix}} - \left(\frac{1}{V_{pMatrix}} - \frac{1}{V_{pTop}}\right) * e^{-b*zml} \quad (4)$$

where V_{pTop} is the compressional sonic velocity at the surface (ft/s).

$V_{pMatrix}$ is the compressional sonic velocity at maximum extrapolated (ft/s),

b is the compaction coefficient (1.5 × 10^{-4} ft^{-1})

Hydrostatic pressure

The hydrostatic pressure was computed by multiplying the normal pressure gradient of the study area by the depth of interest. A pressure gradient of 0.433 psi/ft was used in the project.

$$P_{hyd} = 0.433 * TVD \quad (5)$$

where P_{hyd} is the hydrostatic pressure.

TVD is the true vertical depth (ft).

Prediction of pore pressure

A number of models were employed in the study for the prediction of pore pressure using primarily the sonic velocity, V_p logs. The models used are Eaton's, Bowers, and Equivalent Depth. These models were chosen based on their compatibility with the sonic compressional velocity log data. Parameters such as the estimated overburden pressure, hydrostatic pressure, and normal compaction trend were utilized as inputs in the models. The RokDoc package was used for the prediction of the pore pressures.

Eaton's method (1975): The model was developed according to the effective stress concept of Terzaghi K [5], which correlates pore pressure to the difference between effective stress and overburden pressure. The model is one of the most widely utilized methods for predicting formation pressure using well logs in the industry [4]. Basically the model correlates pore pressure to well log data such as sonic velocity, interval travel time or resistivity. The model generally compares an observed petrophysical property say velocity to its equivalent in a normally compacted formation at the same depth. This is done by finding the log data ratios and multiplying them to the effective stress. Subsequently formation pressure can be determined using the Terzaghi correlation. The model requires both a line of best fit along normal pressured data (NCT) and an Overburden pressure for its computation. The model is most effective in formations where under compaction is the primary reason for high pressures. The model was developed as a means of upgrading the [8] method which is devoid of overburden influence in its formulation.

$$P_p = P_{obs} - (P_{obs} - P_{hyd}) * \left(\frac{V_p}{V_n}\right)^3 \quad (6)$$

where P_p=predicted pore pressure in psi.

P_{obs}=overburden pressure

P_{hyd}=hydrostatic pressure

Bowers model: The model represents a correlation of effective stress with velocity that could be utilized to associate sonic velocity to formation pore pressure [9]. Bowers stated that a power relationship exists between velocity V_p and effective stress $\sigma_{e'}$:

$$P_p = S - \left(\frac{V_p - V_o}{A}\right)^{\frac{1}{B}} \quad (7)$$

where V_o=velocity of unconsolidated fluid saturated sediments (about 5000 ft./s=1524 m/s) in Niger Delta.

V_p=compressional sonic velocity A and B are constants which describe the variation in velocity with increasing effective stress. Where A and B are assumed to be 0.69 and 1.0 respectively.

Equivalent depth method (1966): The model was formulated on the premise that formations with equal physical properties at different depths will have an equal effective stress, hence the pore pressure can be inferred at each depth of investigation since the value of the petrophysical property depends on the effective stress [10].

$$P_{ovb} = \sigma + P_p \quad (8)$$

$$\sigma_B = P_{ovb,B} - P_{p,B} \quad (9)$$

$$\sigma_B = \sigma_A \quad (10)$$

If the overburden pressure for point A ($P_{ovb,A}$) is known, the pore pressure at A ($P_{p,A}$) can be calculated.

$$P_{p,A} = P_{ovb,A} - \sigma_B \quad (11)$$

$$P_{p,A} = P_{p,B} + (P_{ovb,A} - P_{ovb,B}) \quad (12)$$

where P_p is Pore pressure.

P_{ovb} is the overburden pressure

σ_A Effective Stress at A.

σ_B Effective Stress at B.

A and B=depth of interest and depth on the best fit normal compaction line where the measured data corresponds to that the depth of investigation.

Sensitivity analysis

The methodology adopted for the analysis of sensitivity in the work was the use of scatter plots. This entailed plotting the output variable (pore pressure) against the individual input variables of the pore pressure forecasting models such as Vertical effective stress (VES), and the sonic compressional velocity (Vp). The analysis was done using RokDoc's data calibration function.

Development of model

This involves selecting the model with the best pore pressure prediction and modifying the previously identified sensitive variable (Vn) against the measured pressure data (Repeat formation Tester) to enable the model yield better predictions using Excel's Goal Seek function.

Prediction performance of Models

In order to ascertain the accuracy of the pore pressure predictive models, the percentage error of the results obtained from the models was computed using the equation below.

$$\%\,\text{error} = \frac{|predicted - RFT|}{RFT} * 100 \qquad (13)$$

Results and Discussion

The evaluated overburden pressure and computed normal compaction trend are showcased in table 1 below.

Prediction of pore pressures using various models

The outcome of the pore pressure forecast in the study area using the three (3) models are presented below in figure 1. By using the generated Normal Compaction trend (NCT) and Overburden pressure profile as inputs in the models, the pore pressure pressures were predicted using Rokdoc. The predicted pore pressures were analyzed with the measured pore pressures (RFT) at various depths to ascertain the accuracy of the models (Table 1).

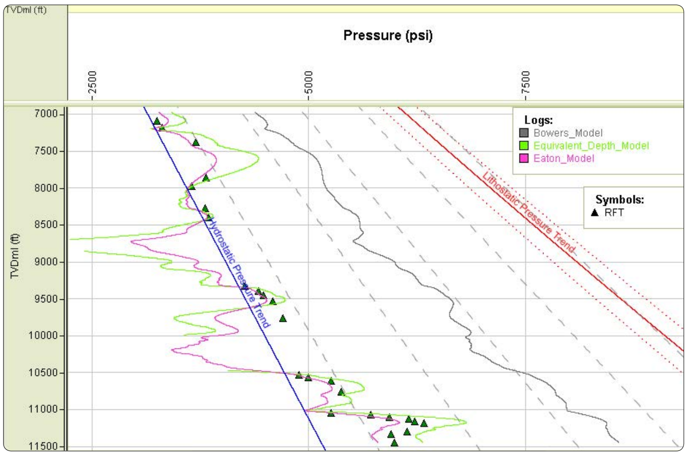

Figure 1. Pressure-depth plot depicting results of predicted pore pressures using the three models.

The multicolored curves between the hydrostatic pressures and overburden pressures are the prediction results. As depicted in the plot above, the Eaton's model [11,12], represented by a purple wavy curve coincides with the measured pressure at depths of 7176 ft to 9443 ft but did not accurately match the measured pressure at deeper depths between 9528 ft and 9756 ft where there were reversals in the predicted pore pressures [13]. However, at depths of 10524 ft to 11093 ft there were close matches between the predicted results and the measured pressure data, with the only reversal at 10751 ft. At deeper depths, the model under-predicted the pore pressure [14]. The Equivalent-Depth model's predictions (green curve) closely matched the measured pressure data from 7176 ft to 11063 ft but over-predicted the pore pressure at depths of 11093 ft to the final depth (11434 ft). Bowers models represented by grey curves respectively over-predicted the pore pressures from the initial depth up to the final depth of interest in the well.

Table 1. Table presenting results of the Predicted pore pressures from the models.

TVD (ft)	RFT (psi)	P-Hyd (psi)	P-Litho (psi)	Vp (m/s)	Vn (m/s)	Eaton (psi)	% Error	EDM (psi)	% Error	Bowers (psi)	% Error
7081.4	3267	3186	6213	2702	2764	3400	4%	3605	10%	4520	38%
7176.5	3327	3229	6305	2759	2771	3282	1%	3322	0%	4528	36%
7366.1	3716	3315	6492	2693	2785	3634	2%	3936	6%	4810	29%
7851	3832	3533	6958	2759	2821	3770	2%	3980	4%	5182	35%
7970.5	3669	3587	7070	2817	2830	3646	1%	3978	8%	5209	42%
8260.5	3822	3717	7358	2875	2851	3639	5%	3683	4%	5415	42%
8391.1	3867	3776	7490	2844	2860	3851	0%	3553	8%	5589	45%
9323.5	4285	4195	8427	2960	2925	4059	5%	3911	9%	6361	48%
9386.5	4434	4224	8491	2895	2929	4386	1%	3910	12%	6518	47%
9443.6	4500	4249	8550	2889	2933	4454	1%	3923	13%	6586	46%
9528.9	4608	4288	8637	2885	2939	4536	2%	4519	2%	6678	45%
9756.6	4725	4390	8862	3053	2954	3939	17%	4627	2%	6659	41%
10525	4901	4736	9658	2980	3003	4866	1%	4747	3%	7562	54%
10552	5011	4748	9685	2966	3005	4952	1%	3471	31%	7609	52%
10602	5277	4771	9736	2936	3008	5138	3%	4962	6%	7705	46%
10751	5388	4838	9893	2933	3017	5264	2%	5118	5%	7864	46%
11036	5275	4966	10194	2991	3035	5208	1%	5429	3%	8082	53%
11064	5733	4978	10222	2941	3037	5478	4%	5601	2%	8184	43%
11093	5950	4992	10254	2891	3039	5737	4%	5402	9%	8286	39%
11122	6171	5005	10284	2854	3040	5934	4%	5875	5%	8371	36%
11150	6243	5018	10314	2836	3042	6038	3%	6316	1%	8426	35%
11175	6349	5028	10338	2834	3043	6067	4%	6635	5%	8454	33%
11293	6157	5081	10463	2909	3051	5811	6%	6800	10%	8469	38%
11321	5963	5094	10493	2920	3052	5779	3%	6802	14%	8483	42%
11434	6002	5145	10615	2933	3059	5809	3%	6840	14%	8586	43%
							3%		**7%**		**42%**

Sensitivity analysis results

Below are the results of the sensitivity analysis conducted on the best model (Eaton's) using scatter plots to illustrate the correlation between the model's input variables (vertical effective stress, and sonic compressional velocities) and the desired output, figure 2 being the measured formation pore pressure (RFT) data [15].

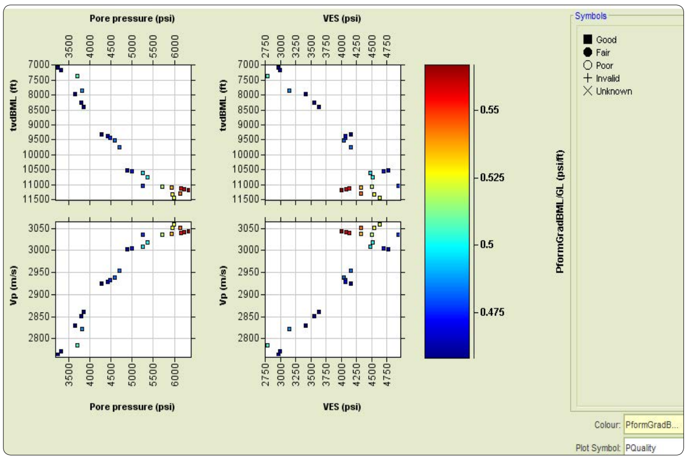

Figure 2. Composite Cross-plot containing measured pore pressure, sonic compressional velocity (Vp), Vertical Effective Stress (VES) and True vertical depth (TVD).

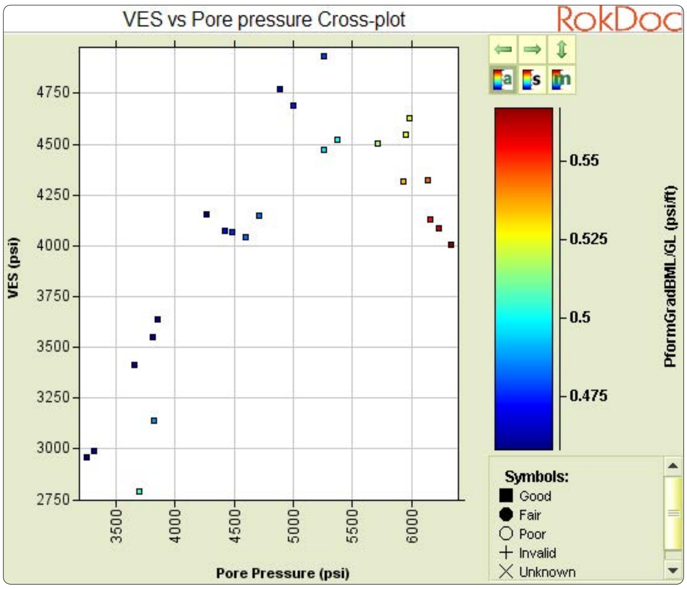

Figure 3. Cross-plot of vertical effective stress against pore pressure.

In all the scatter plots, the points are colored using another parameter being the formation pressure gradient and the plot symbols represent the measured pressure quality [16]. The scatter plot of compressional velocity (Vp) against pore pressure (bottom left) showed that sonic compressional velocity has a strong influence on the pore pressure as both parameters increased together thereby implying a positive correlation (Figure 3). The scatter plot of vertical effective stress (VES) and pore pressure also showed a positive correlation for the most part but later exhibited a negative correlation (reduction of Vertical Effective Stress with a rise in pore pressure). The cross-plot of sonic velocity (Vp) against VES equally yielded a positive correlation with points slightly spread out across plot. However the data appears more scattered on the plot implying the correlation is not very powerful. Lastly both the measured pore pressure and vertical effective stress have a positive correlation with depth as they both increase with it. Overall it can be surmised that all model input parameters are crucial to the pore pressure predictions of the models but the parameter with the most effect on the pore pressure forecast appears to be the sonic velocity (Vp) owing to its positive correlation with the pore pressure. Furthermore, the sensitivity analysis has also shown that the sonic velocity has a significant effect on the vertical effective stress (VES) which in turn has a good influence on pore pressure since $P_p = P_{ob} - VES$. As such the subsequent model optimization would zero in on this parameter for improved model performance.

Optimization of formation pressure prediction model

Eaton's model was chosen for the optimization as its pore pressure predictions had the closest match with the measured pressure data and consequently the least percentage error of the ten models used in the work. The optimization basically involved modifying the most sensitive variable in the model (Table 2). The sonic compressional velocity (Vp) was observed as the most impactful variable, hence it was focused on for the optimization. Given that an exponent (3) was attached to the sonic velocity data, the optimization was done by modifying this exponent using Goal Seek to calibrate the model's prediction with the RFT data. The result showed that the best exponent for most data points fell between 3.9 to 4.0. and the mean of the exponent was 3.2. By iteratively trying different exponents ranging from 3.2 to 4.0 in place of the exponent 3 used in the original Eaton's equation, an exponent of 3.9 yielded the best fitting match.

$$P_p = P_{obs} - (P_{obs} - P_{hyd}) * \left(\frac{V_p}{V_n} \right)^{3.9} \quad (14)$$

Table 2. Optimization of the Eaton's model using Goal Seek

P-Hyd (psi)	P-Litho (psi)	V_p (m/s)	V_n (m/s)	RFT (psi)	Expo-nent	Eaton (psi)	New Ex-ponent	modified Eaton (psi)	% Error
3186	6213	2702	2764	3267	1.0	3267	3.9	3457	6%
3229	6305	2759	2771	3327	6.3	3327	3.9	3296	1%
3315	6492	2693	2785	3716	3.9	3716	3.9	3720	0%
3533	6958	2759	2821	3832	3.9	3832	3.9	3832	0%
3587	7070	2817	2830	3669	4.2	3669	3.9	3664	0%
3717	7358	2875	2851	3822	-3.0	3822	3.9	3611	6%
3776	7490	2844	2860	3867	3.7	3867	3.9	3871	0%
4195	8427	2960	2925	4285	-1.5	4285	3.9	4009	6%
4224	8491	2895	2929	4434	4.0	4434	3.9	4429	0%
4249	8550	2889	2933	4500	3.7	4500	3.9	4510	0%
4288	8637	2885	2939	4608	3.9	4608	3.9	4606	0%
4390	8862	3053	2954	4725	-2.3	4725	3.9	3791	20%
4736	9658	2980	3003	4901	4.0	4901	3.9	4896	0%
4748	9685	2966	3005	5011	3.9	5011	3.9	5008	0%
4771	9736	2936	3008	5277	4.3	5277	3.9	5234	1%
4838	9893	2933	3017	5388	4.0	5388	3.9	5380	0%
4966	10194	2991	3035	5275	4.0	5275	3.9	5270	0%
4978	10222	2941	3037	5733	4.7	5733	3.9	5610	2%
4992	10254	2891	3039	5950	4.0	5950	3.9	5938	0%
5005	10284	2854	3040	6171	3.9	6171	3.9	6172	0%
5018	10314	2836	3042	6243	3.7	6243	3.9	6300	1%
5028	10338	2834	3043	6349	3.0	6064	3.9	6330	0%
5081	10463	2909	3051	6157	4.6	6157	3.9	6009	2%
5094	10493	2920	3052	5963	3.9	5963	3.9	5964	0%
5145	10615	2933	3059	6002	4.0	6002	3.9	5988	0%
					3.2				2%

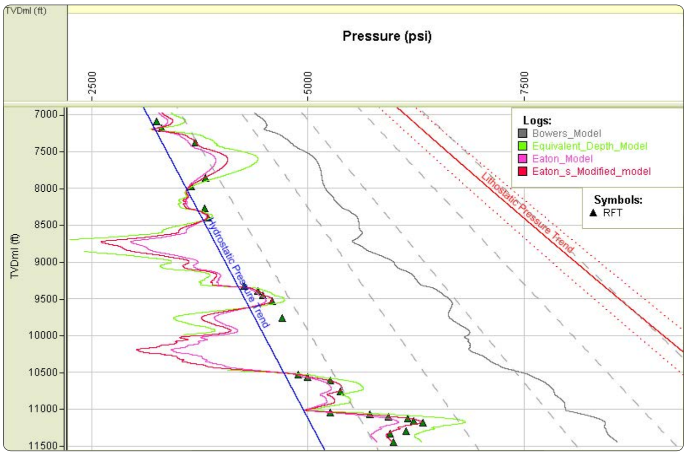

Figure 4. Pressure depth plot depicting developed model (red).

From the plot it is seen that based on the comparison of each pore pressure prediction model against the measured pressure data and the statistical analysis described above, the most accurate and suitable pore pressure prediction strategy for future use in Niger Delta environment is the developed Eaton's model (Figure 4).

Conclusion

The study involved the development of a new model for prognosis of pore pressures using well logs from an exploratory well in Niger Delta. The approach slightly varies from existing pore pressure forecasting techniques given that the model was developed for usage in Niger Delta environment. Three models were appraised with various degrees of accuracy. The predictive accuracy of the models was validated by comparison with measured pressure data (RFT) and computation of percentage errors. The modified Eaton's model gave the best correlations with the RFT data in comparison to the other models used. The sensitivity analysis done on the Eaton's model revealed the sonic compressional velocities have the most effect on the pore pressures, as such the model's optimization centered on the sonic velocity by virtue of modifying the exponent. By utilizing Goal Seek to calibrate the predicted pore pressures with the RFT data, an exponent of 3.9 was found to be the most apt for optimum formation pressure prediction which resulted in the least percentage error of 2%. This further validates the suitability of the developed model for usage in the study area. This study will aid in the selection of an accurate model suited for forecasting pore pressure in Niger Delta environment.

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