OPEN ACCESS

International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-4, November 2019

Pore Pressure Prediction using Well-Logging Data in the West Baram Delta, Offshore Sarawak Basin, Malaysia

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***Abstract**: Well-predicted pore pressure is vital throughout the lifetime of an oil and gas field starting from exploration to the production stage. Here, we studied a mature field where enhanced oil recovery is of high interest and pore pressure data is crucial. Moreover, the top of the overpressure zone in west Baram Delta starts at different depths. Hence, valid pore pressure prediction prior to drilling is a prerequisite for reducing drilling risks, increasing efficient reservoir modeling and optimizing costs. Petrophysical logs such as gamma-ray,* **density logs, and** *sonic transit time were used for pore pressure prediction in the studied field. Density logs were used to predict the overburden pressure, whereas sonic transit time, and gamma-ray logs were utilized to develop observed shale compaction trend line (OSCTL) and to establish a normal compaction trend line (NCTL). Pore pressure was predicted from a locally observed shale compaction trend line of 6 wells using Eaton's and Miller's methods. The predicted pore pressure using Eaton's DT method with Eaton's exponent 3 showed a better matching with the measured pressure acquired from the repeat formation test (RFT). Hence, Eaton's DT method with Eaton exponent 3 could be applied to predict pore pressure for drilling sites in the study area and vicinity fields with similar geological settings.*

***Keywords**: Eaton method, Miller method, pore pressure prediction.*

I. INTRODUCTION

The pressure of fluids within a porous rock is known as pore pressure or formation pressure [1]. If the change in pressure per unit depth is equivalent to the hydrostatic pressure of the formation pore pressure of the rocks it is called a normal pore pressure. Pore pressures which are found to lie above or below the normal pore pressure gradient line are called abnormal pore pressures [2]. Abnormal pore pressures could be classified into overpressure or under pressure depending on their magnitude. If the pore pressure of the formation is greater than the hydrostatic pressure at a given depth, it is called overpressure, whereas if the formation pore pressure is lower than the hydrostatic pressure of a given depth it is known under pressure [3]. Overpressure has been one of the major global geological challenges in the drilling operations in the oil and gas industry, while predrill pore pressure remained as the basic input data for proper selection of casing optimization and specifying a reliable of a drilling fluid density [4]. Thus, implied that validated pore pressure (over or under pressure) prediction is crucial for the oil and gas industry due to its decisive impact on the safety and cost of drilling for petroleum exploration and production [5]. Hence, precise pore pressure prediction is required to minimize the risks of drilling incidents such as blowouts, kicks, instability of wellbore, whole washouts, loss of drilling fluid circulation and protect the pay formation [3]. Accurate pore pressure prediction prerequisites a better understanding of the overpressure generation mechanisms in a particular field. Tectonic setting, rate of sedimentation and lithology have a major influence on overpressure distribution mechanisms [6]. This signifies the importance of geological and tectonic understanding of the basin evolution for the analysis of overpressure mechanisms and pore pressure prediction in a given study area.

Manuscript published on November 30, 2019.
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II. GEOLOGICAL SETTING

The Baram Delta Province is a Tertiary basin located in the northern part of Sarawak and extending north-eastward though Brunei into the southern part of Sabah (Fig.1). It was formed in the late Eocene following a major orogenic event that folded and uplifted the late Eocene deposits [7]. The study area is located 40 km offshore Sarawak in the south-western part of the Baram Delta Province (Fig. 1).

A. Overpressure generation mechanisms

Overpressure is the result of geological, physical, chemical, and mechanical processes [8]. According to Swarbrick and Osborne [9], the mechanisms of overpressure generation are classified into three broad categories: (1) stress-related mechanisms, (2) fluid volume increase mechanisms, (3) the fluid movement and buoyancy mechanisms. The stress-related overpressure generation mechanisms are disequilibrium compaction which is also known as under compaction and overpressure caused by tectonic structures such as faults and folds. Depending on whether the structures act as a conduit or as a seal.

The increment of temperature with depth, the release of water due to the transformation of minerals (clay diagenesis), hydrocarbon maturation, and oil to gas cracking are under the category of fluid volume increase mechanisms. Buoyancy and lateral transfer are under the third category.

B. Distribution of overpressure in the study area

The distribution of overpressure in the Baram Delta is believed to be influenced by the rate of sedimentation [10]. It is known that overpressure is mainly generated by under compaction due to the fast rate of deposition of less permeable shales in many tertiary basins [6]. However, two types of overpressure mechanisms were suggested in the study area; the disequilibrium compaction in the pro-delta shales, and fluid expansion in the outer shelf of the region [11].

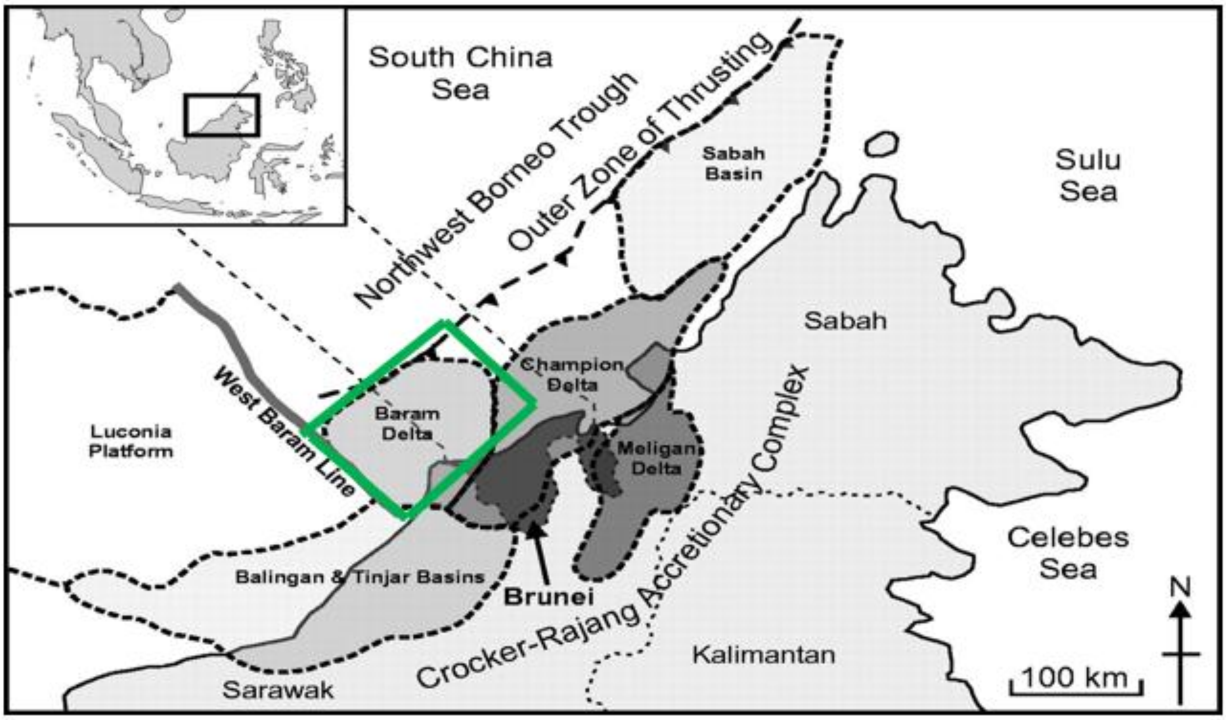

Fig. 1. Location map of the Baram Delta Province(the green box), Sarawak, Malaysia [12]**.**

III. METHODOLOGY

In this study, we have used different types of petrophysical logs such as gamma-ray (GR), density logs (RHOB), and sonic transient time (DT) to predict the pore pressure. The density logs have been used to predict the overburden pressure. Gamma-ray and sonic transit time were used to calculate the observed Shale Compaction Trend Line (OSCTL) and Normal Compaction Trend Lines (NCTL). The sonic log (DT) was used to develop the regional normal compaction trendline. Pore pressure was predicted from the locally observed shale compaction trendline, which was taken from the smoothed log response.

A. *Pore pressure prediction methods*

The effective stress method is the most popular pore pressure prediction method in the industry. According to Terzaghi [13], the total vertical stress is equal to the sum of rock grain pressure and the pore pressure of the formation. This is the basic theory in pore pressure prediction.

The vertical effective stress can be calculated by:

$$V_{es} = P_{OB} - \alpha PP \quad (1)$$

Where. V_{es} is the vertical effective stress, P_{OB} is the overburden stress, PP is the pore pressure, and α is the vertical effective stress coefficient which is less than 1.

The factor α is the Biot consolidation coefficient and defined as:

$$\alpha = \frac{Kf}{Ks} \quad (2)$$

Where, Kf is the bulk modulus of the dry rock frame (drained) and Ks is the bulk modulus of the solid material. For soft rocks α = 1 and for hard rocks α = 0. The value of α can be estimated either through laboratory measurements or field data [14]. For this purpose, two methods are briefly described in the following.

The Eaton method is based on the change in the porosity of rocks with depth. It is derived from equation (1) above. Eaton [15], developed a method by comparing the normal and observed values from sonic travel time. Therefore, the pore pressure of the formation can be estimated from the ratio of the observed and the expected values.

Retrieval Number: D9050118419/2019©BEIESP
DOI:10.35940/ijrte.D9050.118419
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The equation is given as:

$$PP = P_{ob} - (P_{ob} - P_{hyd})(\frac{\Delta Tn}{\Delta To})^{n} \quad (3)$$

Where PP is the pore pressure of the formation, P_{ob} is the overburden stress, P_{hyd} is hydrostatic (normal) pressure, ΔTn is the normal transit time (sonic), ΔTn is observed sonic transit time, and n is an exponent.

Provided the normal compaction trendline is well determined, the Eaton method is applicable for pore pressure prediction of young sedimentary basins [16].

Miller's method is the second approach which bases on the relationship between the velocity in the formation and vertical effective stress, which in turn can be used to relate sonic transit time to pore pressure of the formation. Sonic is the main input data to determine the maximum velocity depth that can be associated with the existing unloading mechanism [17]. Miller's sonic velocity can also be applied for pore pressure prediction [18].

Miller's sonic velocity(loading) method is given as:

$$PP = V_{es} - \frac{1}{\lambda} ln \left\{\frac{vm - vml}{vm - vp}\right\} \quad (4)$$

Where, Where, PP is the pore pressure of the formation, V_{es} is the vertical effective pressure, vm is the interval velocity from sonic measurement in the matrix of the shale, vp is the velocity (compressional), vml is the interval velocity of the sediments in the mudline, λ is the empirical parameter which defines the increment rate of velocity as the function of effective stress (normally is λ = 0.00025).

Miller's sonic velocity (unloading) method is given as:

$$PP = V_{es} - \frac{1}{\lambda} ln \left\{am(1 - \frac{vm - vulo}{vm - vp}\right\} \quad (5)$$

Where, PP is the pore pressure of the formation, V_{es} is the vertical effective pressure, vm is the interval velocity from sonic measurement in the matrix of the shale, , vp is the velocity (compressional), vml is the interval velocity of the sediments in the mudline, λ is the an empirical parameter which is defines the increment rate of velocity as the function of effective stress (normally is λ = 0.00025), am is the ratio of the loading and unloading velocities for the effective stress curve $vulo$ (normally am =1.8) and am = vp / $vulo$, $vulo$ is the effective stress from unloading of the sediment

Repeat formation test (RFT) was used to validate the pore pressure prediction at well locations. Out of the six wells, only two wells have RFT data. Hence, the RFT data of those wells was used to validate the pore pressure prediction.

IV. RESULT AND DISCUSSION

Based on Eaton DT equation (3) and Miller methods equation (5), pore pressure for the study was successfully predicted for 6 wells. As a result, the Eaton DT method with Eaton exponent 3 and Miller method with velocity exponent 3 have able to predict reasonably consistent pore pressure that matches the measured RFT data at well locations.

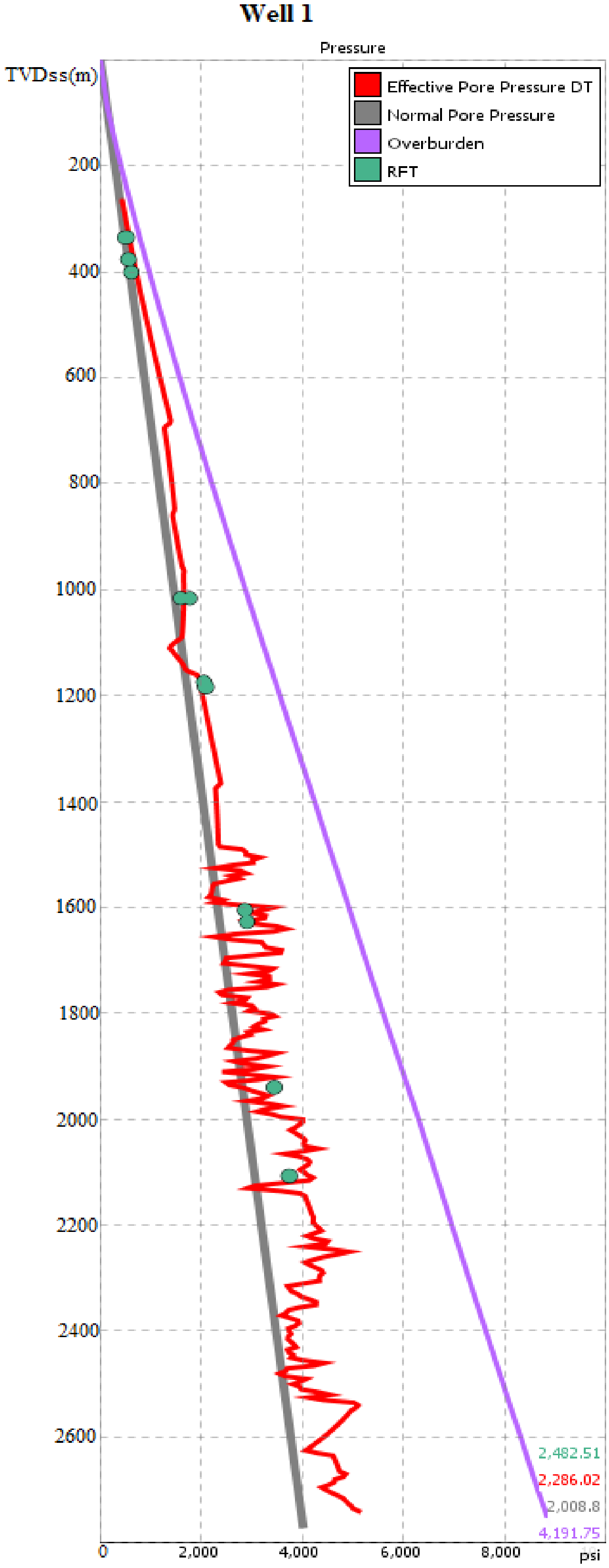

Fig. 2. Pore pressure prediction for well 1 using the Eaton DT method. Grey black color is the hydrostatic pressure, purple color is the overburden stress (pressure), the red curve is the predicted pore pressure of the formation (psi) using Eaton DT method with Eaton exponent 3, and the green dots are measured RFT pressure data.

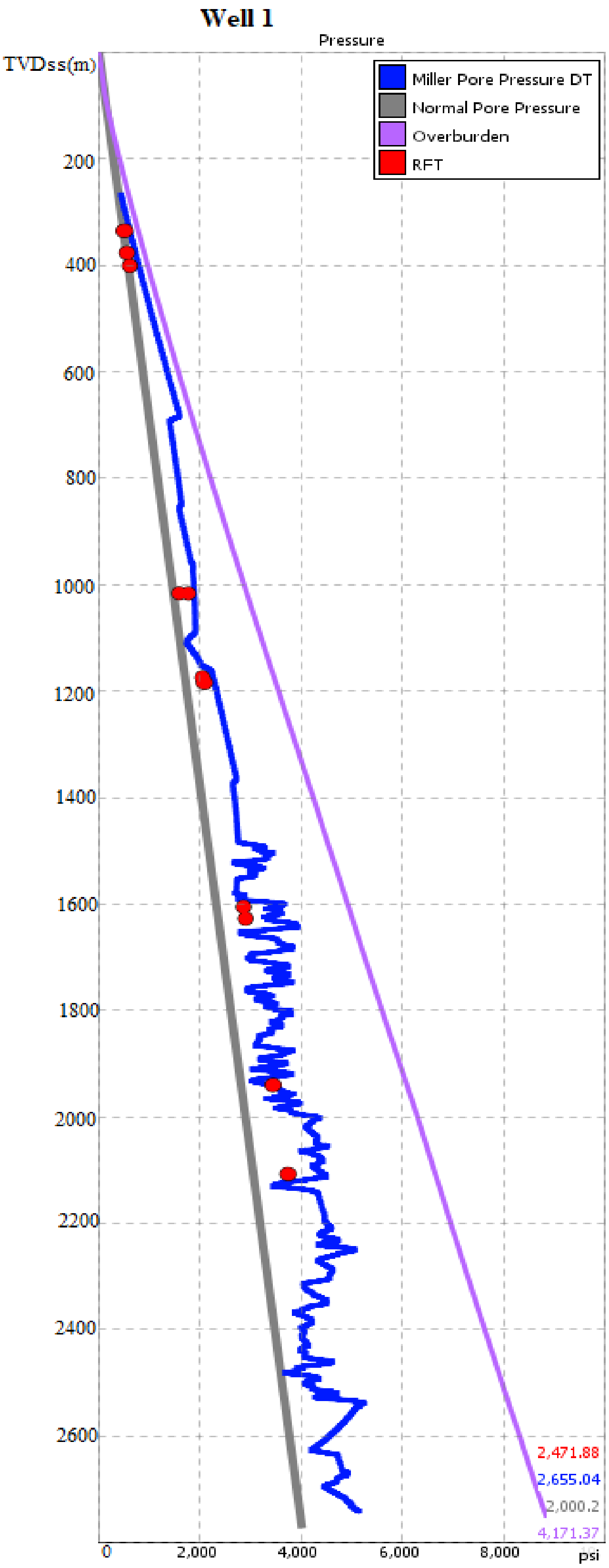

Fig. 3. Pore pressure prediction for well 1 using the Miller method. Grey black) color is the hydrostatic pressure, (purple color) is the overburden stress (pressure), the blue curve is the predicted pore pressure of the formation (psi) using Miller method with velocity exponent 3, and the red dots are measured RFT pressure data.

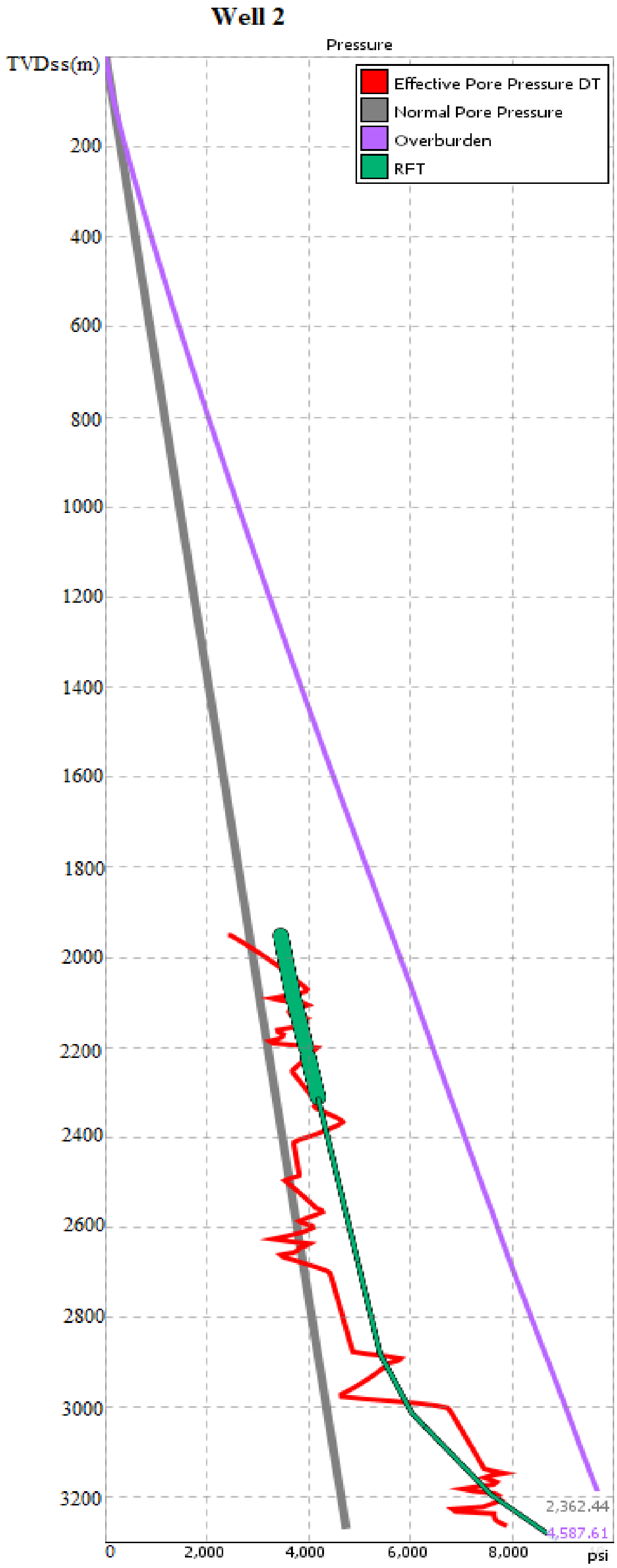

Fig. 4. Pore pressure prediction for well 2 using the Eaton DT method. Grey black color is the hydrostatic pressure, purple color is the overburden stress (pressure), the red curve is the predicted pore pressure(psi) using Eaton DT method with Eaton exponent 3, and the green dots are measured RFT pressure data.

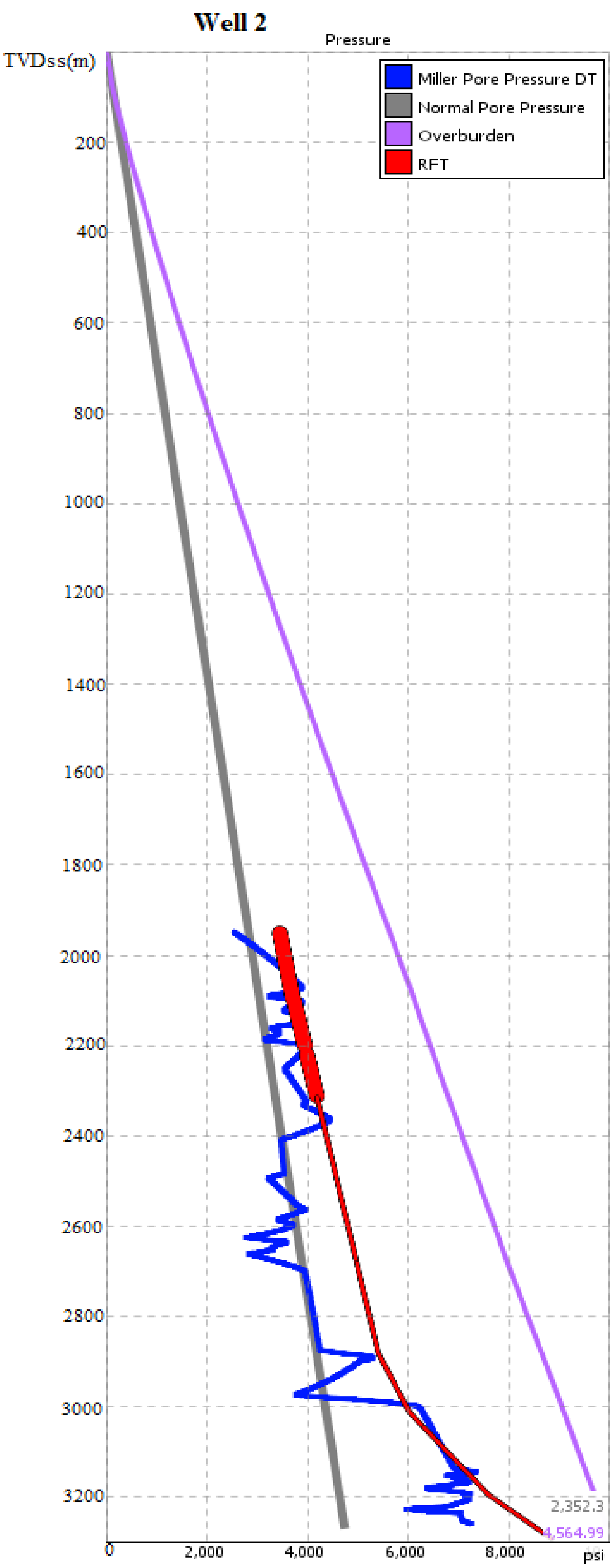

Fig. 5. Pore pressure prediction for well 2 using the Miller method. Grey black color is the hydrostatic pressure, (purple color) is the overburden pressure, the blue curve is the predicted pore pressure (psi) using the Miller method with velocity exponent 3, and the red dots are measured RFT pressure data.

The predicted pore pressure using the Eaton DT method with Eaton DT exponent 3 and Miller method with velocity exponent 3 showed a very good correlation with the measured pressure data from RFT for both wells; well 1 and well 2. The predicted pore pressure using the Eaton DT method with Eaton DT exponent 3 also showed an excellent correlation with the measured pressure (RFT) data in the shallow depths of the wells. This could be related to the fact that the overpressure generation mechanism at the shallower depth of the study area is mainly caused by disequilibrium compaction (under compaction) which is consistent with previous works of Yusoff [10]. However, the predicted pore pressure using the Miller method with velocity exponent 3 showed excellent matching with the measured RFT pressure data in the deeper depths of the studied field, where fluid expansion could be the main mechanism of over pressure in the study area.

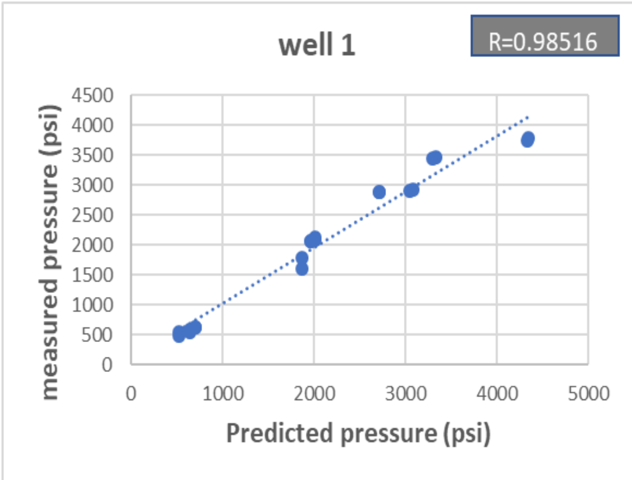

Fig. 6. The predicted pore pressure for well 1 using the Eaton DT method with Eaton DT exponent 3 is compared with measured RFT pressure data.

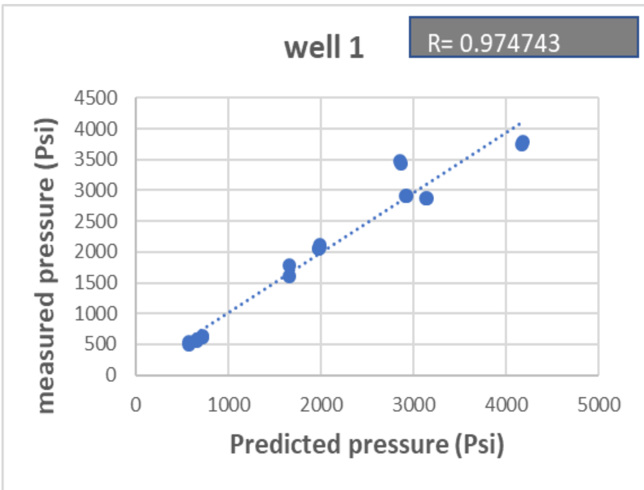

Fig. 7. The predicted pore pressure for well 1 using the Miller method with velocity exponent 3 is compared with measured RFT pressure data.

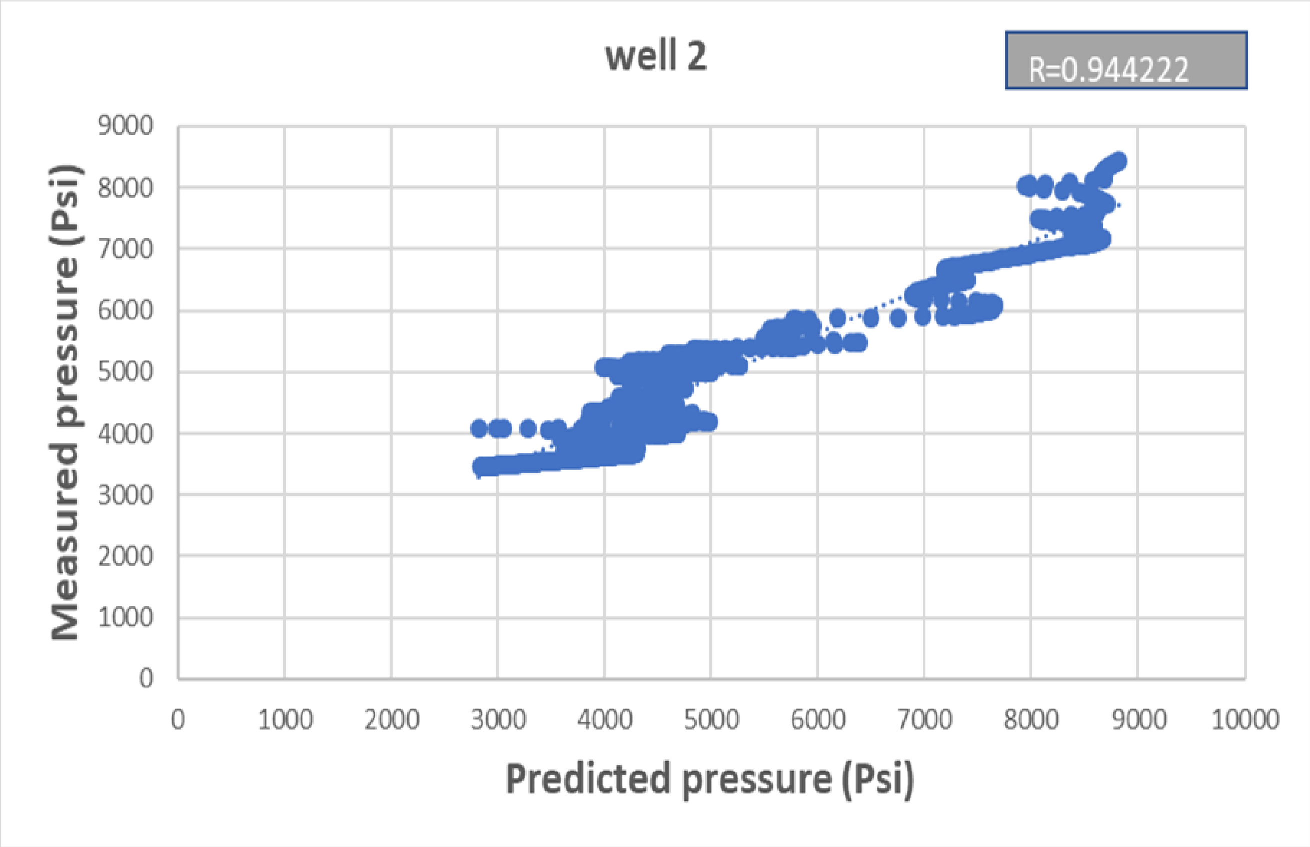

Fig. 8. The predicted pressure for well 2 using the Eaton DT method with Eaton DT exponent 3 is compared with the measured RFT pressure.

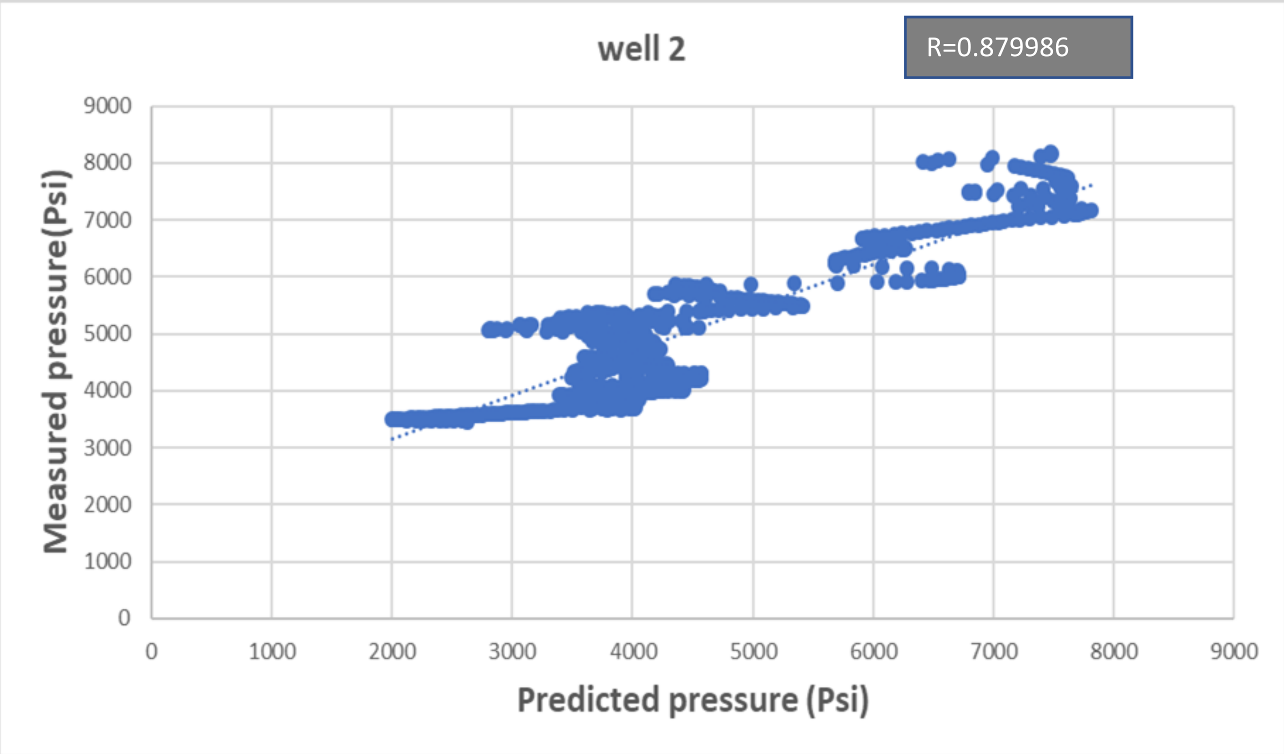

Fig. 9. The predicted pore pressure for well 2 using the Miller method with velocity exponent 3 is compared with measured RFT pressure data.

Retrieval Number: D9050118419/2019©BEIESP
DOI:10.35940/ijrte.D9050.118419
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V. CONCLUSION

Conventional pore pressure prediction methods such as Eaton DT and Miller methods with their standard exponents (Eaton DT exponent 3 and velocity exponent 3) have provided accurate pore pressure prediction results for a producing field in the Baram Delta of the Sarawak Basin. Eaton DT method with Eaton exponent 3 provided an excellent correlation with measured RFT pressure data. Hence, the Eaton DT method with Eaton exponent 3 could be applied to predict pore pressure for the planning and optimization of drilling operations in the study area.

ACKNOWLEDGMENT

Special gratitude to PETRONAS for providing us data for this research. We are also grateful to the Center of Excellence in Subsurface seismic Imaging and hydrocarbon prediction (CSI) for allowing us to use research facilities required to complete this research. Finally, the authors would like to Thank DUG downunder geosolutions company for free license to use Insight software.

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