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PORE PRESSURE ESTIMATION IN HARD UNLOADING-OVERPRESSURE ZONE USING SINGLE COMPACTION EQUATION, CASE STUDY: LOWER KUTAI BASIN

ESTIMASI TEKANAN PORI DI ZONA *HARD-UNLOADING-OVERPRESSURE* MENGGUNAKAN SATU PERSAMAAN KOMPAKSI, STUDI KASUS: CEKUNGAN KUTAI BAGIAN-BAWAH

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ABSTRAK

Estimasi tekanan pori di zona hard-overpressure *sangat penting dalam kegiatan pengeboran. Estimasi yang benar dan presisi dapat mengurangi biaya pengeboran karena mengurangi non-productive time (NPT) dan mampu meningkatkan aspek keselamatan saat pengeboran. Estimasi tekanan pori dilakukan dengan analisa secara post-mortem pada sumur-sumur eksplorasi menggunakan titik validasi dari pengukuran tekanan seperti* Drill Stem Testing *(DST), Modular Dynamic Tester (MDT), dan* Repeat Formation Tester *(RFT). Data log tali kawat digunakan untuk mengidentifikasi tipe* overpressure *dan memprediksi besaran tekanan pori di lapisan shale. Melalui korelasi antara tegasan efektif dan kecepatan, satu persamaan kompaksi didapat untuk Cekungan Kutai Bagian-Bawah dengan persamaan :* $5.097 * \sigma^{0.854}$*. Dengan menggunakan satu persamaan ini, aktifitas prediksi tekanan pori sebelum pengeboran akan lebih mudah dan dapat mengestimasi tekanan pori di zona* hard-overpressure *dengan presisi.*

Keywords: satu persamaan kompaksi, tekanan pori, unloading, hard-overpressure, cekungan Kutai bagian bawah

ABSTRACT

Pore pressure estimation in hard-overpressure zone is very important in drilling activities. Correct and precise estimation are able to reduce the cost for drilling due to reduced non-productive time (NPT) and in increase in safety aspect while drilling. Pore pressure estimation is done by post-mortem analysis in exploration wells using validation points from pressure measurement data such as Drill Stem Testing (DST), Modular Dynamic Tester (MDT), and Repeat Formation Tester (RFT). A wireline logs data used for identification of the type of overpressure and predicts pore pressure magnitude in the shale section. Through the correlation between effective-stress and velocity, a single compaction equation was obtained for the Lower Kutai Basin with the value of : $5.097 * \sigma^{0.854}$. By using this single equation, pre-drill pore pressure prediction activity will be more easy and could estimate pore pressure in hard-overpressure zone precisely.

Keywords: *single equation compaction, pore pressure estimation, unloading, hard-overpressure, Lower Kutai Basin*

I. INTRODUCTION

Pore pressure prediction is one phase of the activities carried out prior to drilling. Errors in predicting the pore pressure will affect the stability of the borehole especially the overpressure zone. Dodson (2012) mentions that drill-hole stability problems accounted for the largest portion (31%) of non-productive time (NPT) in the drilling process (Figure 1). This big contribution to this NPT problem can lead to budget increases for drilling activity. For that reason, the phase of pore pressure prediction becomes very important in drilling.

A considerable number of methods were created to predict pore pressure in the zone of overpressure such as *Eaton Methods* (Eaton 1975), *Cheating with Eaton's methods* (op.chit in Bowers, 1995), *Effective stress-velocity (Bower's methods)* (Bowers 1995), *and Fluids Retention Depth methods (Swarbrick's methods)* (Swarbrick and Osborne 1998., Swarbrick et al. 2002). Out of the above list, Effective stress-velocity (Bower's methods) was prefered to be chosen to estimate the pore pressure in this study. Selection of the method is based on the following considerations:

1. The method is able to explain the phenomena of rock compaction in terms of stress and velocity.
2. By understanding the compaction trend, it is expected to be able to make a single compaction equation.
3. The method is able to describe the phenomena of overpressure and its relationship with the generating mechanism of loading and unloading overpressure.
4. By using only a single compaction equation, it will be easier and more precise to estimate the magnitude of hard overpressure.

II. METHODOLOGY

This research was conducted by means of post-mortem analysis using wireline logs and pore pressure measurements data such as Drill Stem Test (DST), Modular Dynamic Tester (MDT), and Repeat Formation Tester (RFT) of seven exploration wells in the onshore and offshore of Lower Kutai Basin. The wells are SEM-39, BKP, NB-1, SS- 1, PCK-19, HDL-121 and MTR-45. All seven are successful examples of deep drilling exploration wells that managed to penetrate the hard-overpressure zone and

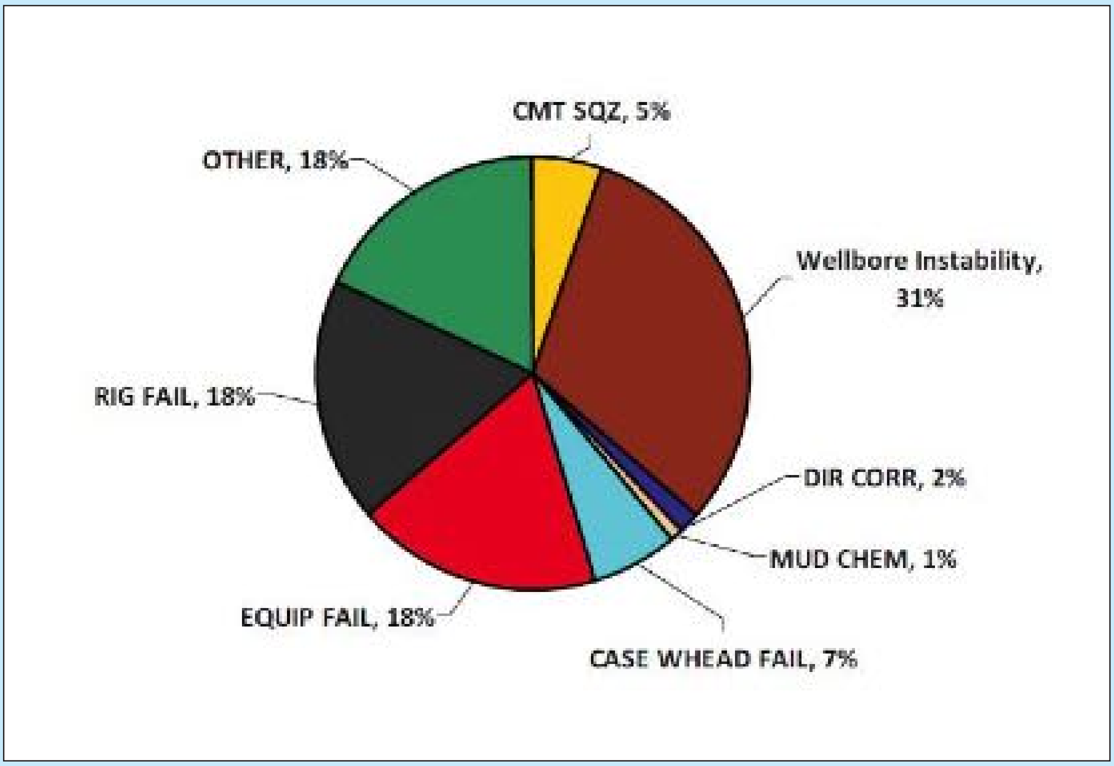

Figure 1
Non Productive Time (NPT) (Dodson, 2009).

Table 1
Data used in the study

No	Well Name	Wireline logs				DST/RFT/ MDT
		Temperature	Sonic	Density	Neutron	
1	SBR-39	v	v	v	v	v
2	BKP-11	v	v	v	v	v
3	HDL-B1	v	v	v	v	v
4	SS-1	-	v	v	v	v
5	NB-12	-	v	v	v	v
6	NLM-109X	-	v	v	v	v
7	NWPCK-9	-	v	v	v	v

represent the characteristics of the pressure profile in every field.

Prior to generating the pore pressure estimation equation, an analysis was conducted to determine the presence/interval and type of overpressure condition. An indication of overpressure can be detected from a variety of data, wireline logs (Rider 2002), drilling parameters (dc exponent, connection gas, background gas, temperature, etc), drilling problems (kick, gain, etc) (Fertl et al. 1994), pressure measurement such as Drill Stem Test (DST), Repeat Formation Tester (RFT), Modular Dynamic Tester (MDT), and mudweight (Mouchet and Mitchell 1981).

As for knowing the type of overpressure condition, this can be done through pressure profile analysis and observation pattern responded by wireline logs (sonic, density and neutron porosity). This particular study will only use wireline logs data, mudweight, and pressure measurements such as Drill Stem Test (DST), Repeat Formation Tester (RFT), and Modular Dynamic Tester (MDT) of the 7 wells (Table 1).

The type of overpressure is divided into two parts, namely loading and unloading. This division is based on the pattern of effective stress values that were observed and from the response of wireline logs (Ramdhan, 2013) to microscopic mineral diagenesis and dewatering processes during compaction (Figure 2). Loading-overpressure is characterized by constant value of effective stress and constant patterns of wireline logs with increasing depth. The constant value of effective stress represents *"dissequilibrium-compaction"* while loading process.

Unloading-overpressure is characterized by a decreasing value of effective stress and a reverse pattern of wireline logs data. The decrease in effective stress correlate with increased pore fluids in connecting or storage pore due to illitization process under temperature 55 - 192°C (Powers, 1967., Perry & Hower, 1970., Boles & Frank, 1979., Freed & Peacor, 1989., Swarbrick & Osborne, 1998) or kerogen to gas/oil transformation under temperature 120 - 150°C (Tissot 1987., Barker, 1990). Swarbrick et al. (2002) also said that kerogen to gas/oil phenomenon could increase the volume of pore fluids in 14 – 75%. Not only the increase in the pore fluids, but also the decrease in effective stress is also caused by shrinking of solid materials e.g kerogen maturation or smectite-illite transformation (Katahara 2006).

Furthermore, to estimate pore pressure, 3 methods were used namely Eaton Methods, Cheating with Eaton's methods, and Effective stress-velocity (Bower's methods). The estimated result is then calibrated with pore pressure measurements coming from Drill Stem Test (DST), Repeat Formation Tester (RFT), and Modular Dynamic Tester (MDT). These three methods are discussed below:

1. Eaton's Estimation Method

Eaton (1975) introduced the pore pressure estimation method in the overpressure zone using sonic or velocity data for a case study in the Gulf of Mexico. This method is a numerical method. To use this method, firstly you must generate a normal compaction curve (NCT). The curve is created from sonic / velocity data on shale lithology at the intervals of normal hydrostatic pressure. Below is the general form of the equation to get NCT value from sonic log data:

$$\Delta t_n = \Delta t_o \times e^{-bz} + \Delta t_m \quad (1)$$

Explanation:

Δt_n = Sonic log value in normal compaction conditions (NCT) (us/ft)

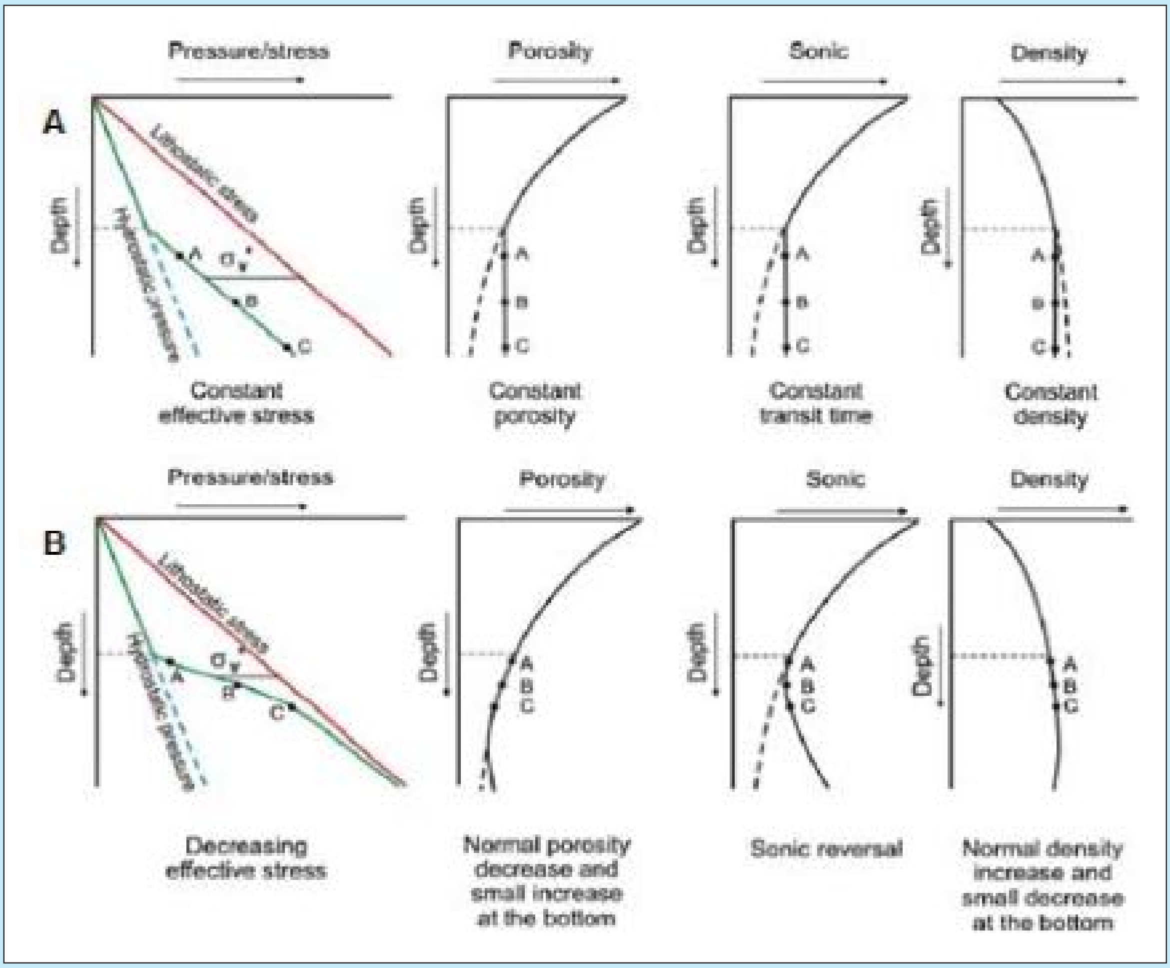

Figure 2
A) Loading-overpressure, B). Unloading-overpressure (Ramadan, 2013).

Δt_o = Sonic log value at the surface (us/ft)

z = Depth (m or ft)

b = Constant

Δt_m = sonic log values on rock matrix/grains (us/ft).

The estimated overpressure value is a representation of the comparison between sonic/velocity NCT against the measured sonic/velocity value multiplied by the value of effective stress. The following is a standard equation for pore pressure estimation using this method from sonic log data:

$$pp = \sigma - \sigma' \left(\frac{\Delta t_n}{\Delta t}\right)^3 \quad (2)$$

Explanation :

pp = Pore pressure (psi)

σ = Overburden stress (psi)

σ^1 = Effective stress (psi)

Δt = Sonic Log Value (us/ft)

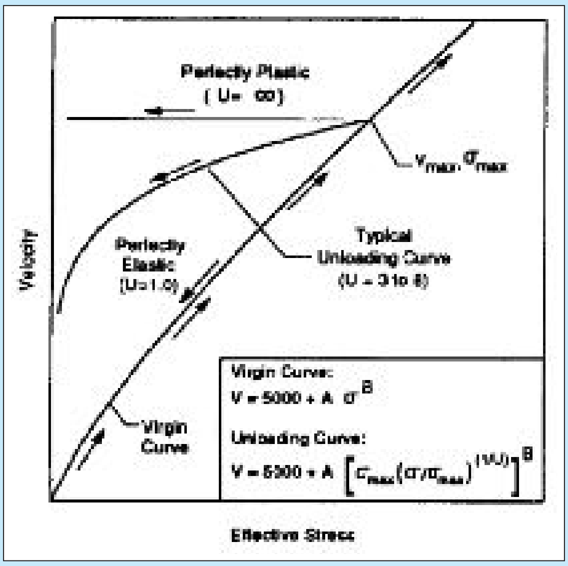

Figure 3
Crossplot of effective stress against velocity (Bowers, 1995).

2. Cheating with Eaton's Methods

This method is the development of the previous Eaton's methods and was discussed also in Bowers (1995), and is distinguished by changing the order of the equation so that the values match with the measured pressure Drill Stem Test (DST), Repeat Formation Tester (RFT), and Modular Dynamic Tester (MDT). The numbers used to change the order may vary or differ for each well.

3. Effective Stress-velocity Method (Bower's Methods)

Bowers (1995) introduced this estimation method by crossplotting the values between effective stress to the velocity. The results indicate the emergence of 2 cross plot trends, the virgin curve and the unloading curve (Figure 3).

Virgin curve represents normal compaction which also explains normal hydrostatic conditions, where the compaction strengthens along with increasing depth. The increasing influence of compaction is due to the increasing value of effective stress and also the value of velocity in response to the increasingly compact rock.

If this phenomena is associated with loading-overpressure, the data will only be gathered at one point with the same velocity and effective stress value (Figure 3A). In other words, the pore pressure estimation on loading-overpressure can be solved just by using the equation from this virgin curve. As for the case of unloading-overpressure, it can be estimated using the unloading curve where the curve represents a reduced value of effective stress and velocity.

III. RESULTS

A. Detecting Overpressure and its Mechanism *"Pore Pressure Profile and Wireline Logs Response"*

1. Well SBR-39

SBR-39 Well was drilled to a depth of 4400 meters. Based on the above picture, it can be seen that the Drill Stem Test (DST) measurement results indicate the overpressured condition begins at a depth of 2900 meters (Figure 4). The overpressure pattern based on the pressure measurements showed the

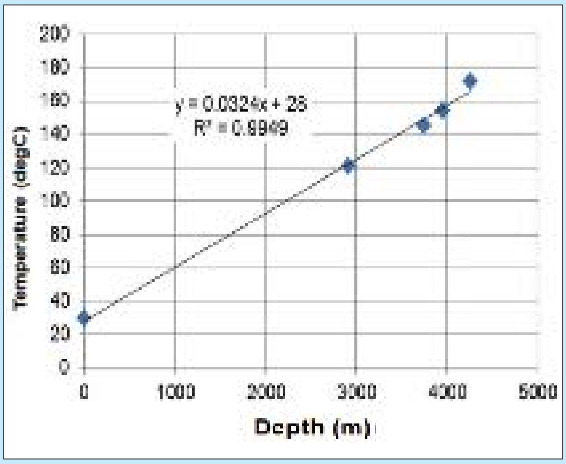

Figure 5
Temperature gradient of SBR-39 Well from DST measurement.

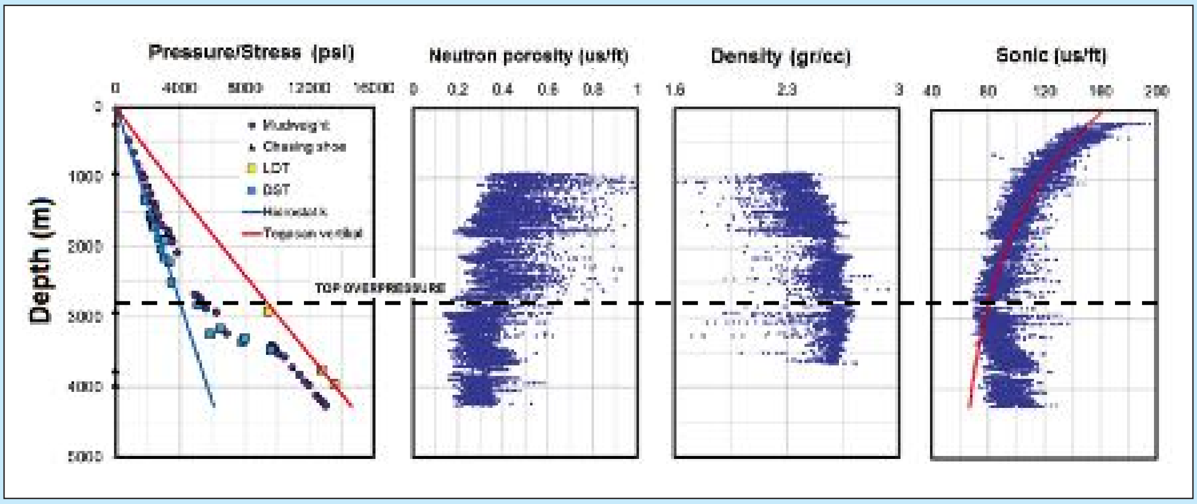

Figure 4
Pressure/stress profile and wireline logs responses of SBR-39 Well.

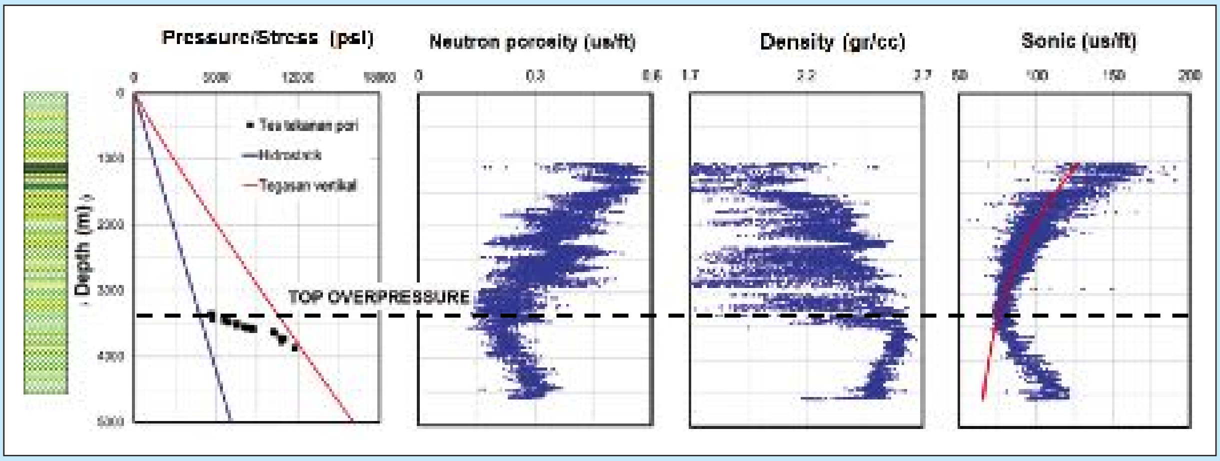

Figure 6
Pressure profile and wireline logs responses of BKP-11 Well.

characteristics of the unloading overpressure, such as the reduction in the value of effective stress along with increasing depth (Refer to Figure 2B).

The log measurement results for Well SBR-39 indicate deviation (reverse) of the normal condition / trend. Likewise, the results of sonic log measurements also show deviation (reverse) from normal condition starting at a depth of 2900 meters.

Figure 5 shows the value of geothermal gradient in the SBR-39 well. Based on Figure 4, the top of overpressured zone was obtained at a depth of 2900 m and at a temperature of 122°C. The temperature value is sufficient enough to support the overpressure unloading mechanism either due to kerogen maturation or smectite to illite transformation.

2. Well BKP-11

BKP-11 wells was drilled to a depth of 4600 meters. Based on the above picture it can be seen that the DST measurement results indicate the condition of overpressure begins at a depth of 3400 meters (Figure 6). Overpressure pattern based on the pressure measurements showed the characteristics of unloading overpressure which is the reduction in the effective stress values along with increasing depth (Refer to Figure 2B).

The results of Neutron-Porosity and Denstiy log measurements of BKP-11 well showed deviation (reverse) condition of the normal trend. Likewise, the results of sonic log measurements also show deviation (reverse) from normal condition starting at a depth of 3400 meters.

Figure 7 shows the value of geothermal gradient in BKP-11 well. Based on Figure 6, the top overpressure zone is at a depth of 3400 m at a temperature of 129°C. The temperature value is sufficient enough to support the overpressure unloading mechanism either due to kerogen maturation or smectite to illite transformation.

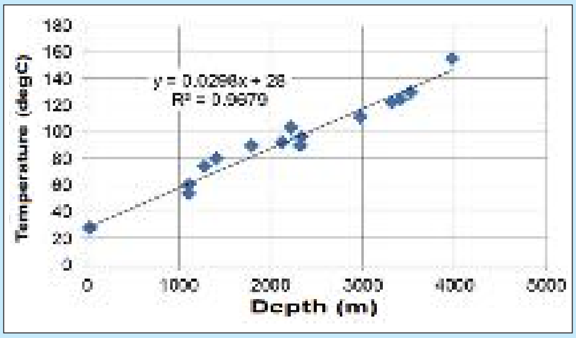

Figure 7
Temperature gradient of BKP-11 Well from DST measurement.

3. Sumur HDL-B1

HDL-B1 well was drilled to a depth of 4000 meters. Based on the above picture it can be seen that the DST measurement indicates the condition of overpressure begins at a depth of 2900 meters (Figure 8). The overpressure pattern based on the pressure measurements showed the characteristics of unloading overpressure which is the reduction in the value of effective stress along with increasing depth (Reffered to Figure 2B).

The results of measurements of Neutron-porosity and Denstiy log for HDL-B1 well can not be analyzed due to limited data availability. However, the sonic

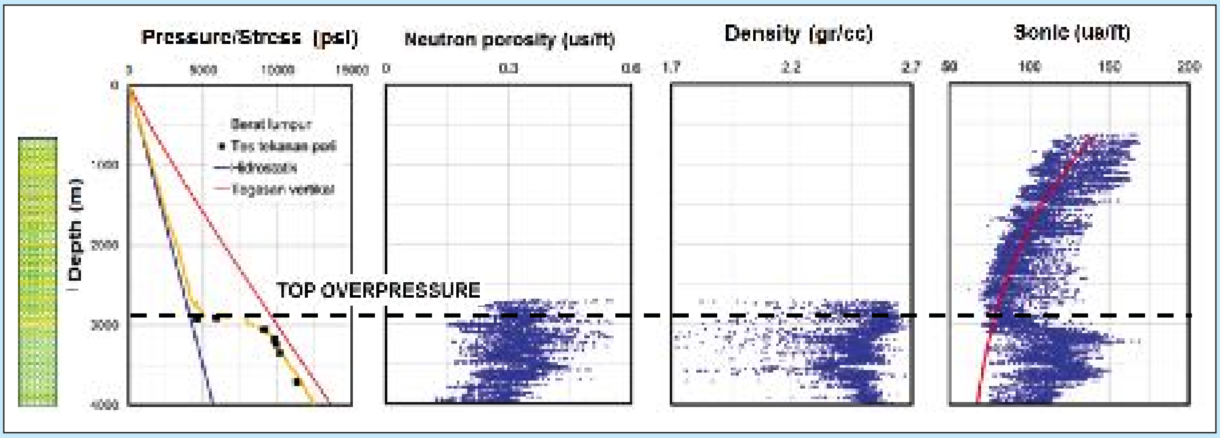

Figure 8
Pressure profile and wireline logs responses of HDL-B1 Well.

log measurement result gives a good response for the analysis. Sonic log data shows deviation (reverse) of normal condition starting at a depth of 2900 meters.

Figure 9 shows the value of geothermal gradient in HDL-B1 well. Based on Figure 8 the top of overpressure zone is at a depth of 2900 meter at a temperature of 125°C. The temperature value is sufficient enough to support the overpressure unloading mechanism either due to kerogen maturation or smectite to illite transformation.

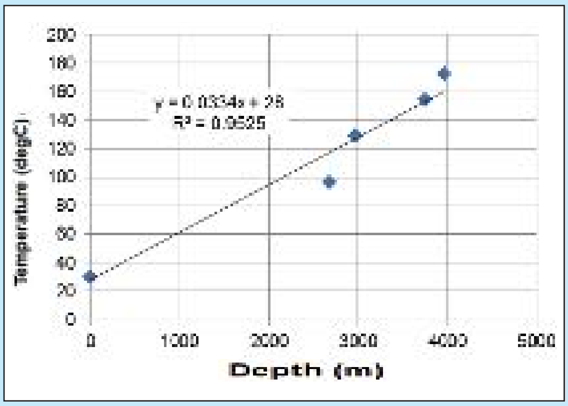

Figure 9
Temperature gradient of HDL-B1 Well from DST measurement.

4. Sumur SS-1

The SS-1 Well was drilled to a depth of 3900 meters. Based on the above picture it can be seen that the DST measurement has not shown any overpressure condition. Mudweight data also do not show clearly the location of top overpressure.

In this Figure 10, the measurement results for Neutron-porosity, Density logs, and Sonic logs for the SS-1 show a little deviation (reverse) from normal trend at a depth of 3600 m. It could be assignment of location of top overpressure.

5. Well NB-12

NB-12 Well was drilled to a depth of 3500 meters. Based on the above picture it can be seen that the DST measurement has not shown overpressure condition in contrast to the mud weight data which indicates the characteristics of unloading overpressure at a depth of 3300 meters.

The measurement results of Density log did not show deviation (reverse) from normal condition/ trend. But in Neutron-porosity and Sonic logs show a little reversal from normal trend condition in 3300 meters. It can be interpret that top of overpressure in this well is located at a depth of 3300 meters.

6. Sumur NLM-109X

NLM-109X Well was drilled to a depth of 5500 meters. Based on the above picture it can be seen that the RFT measurement shows the condition of overpressure begins at a depth of 4100 meters. The overpressure pattern based on the pressure measurements showed the characteristics of unloading overpressure which is the reduction in the value of effective stress with increasing depth (Refer to Figure 2B).

The results of measurements of Neutron-porosity and Density logs for Well-109X NLM shows deviation (reverse) from normal condition/trend. Likewise, the result of sonic log measurement also indicate deviation (reverse) from normal condition starting at a depth of 4100 meters.

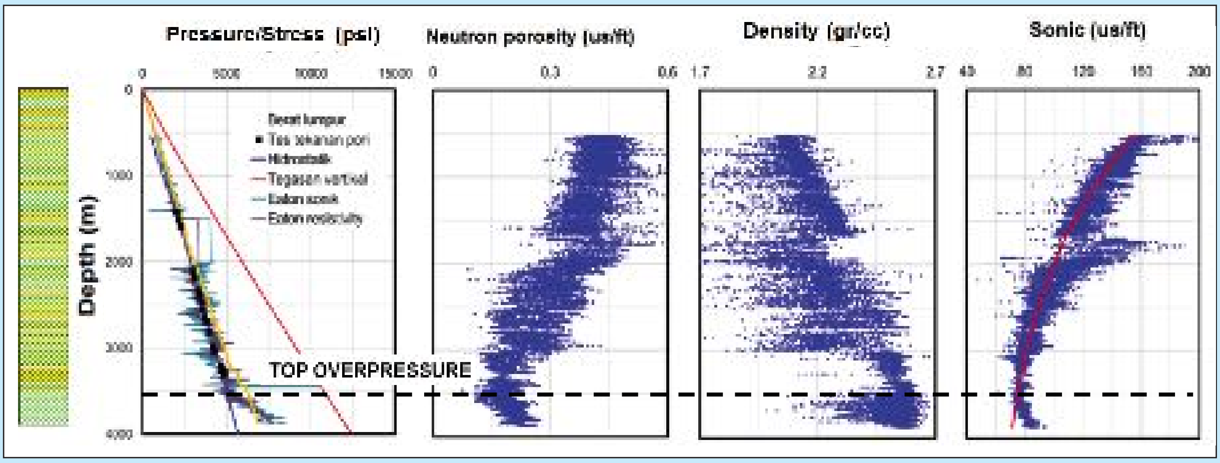

Figure 10
Pressure profile and wireline logs responses of SS-1 Well

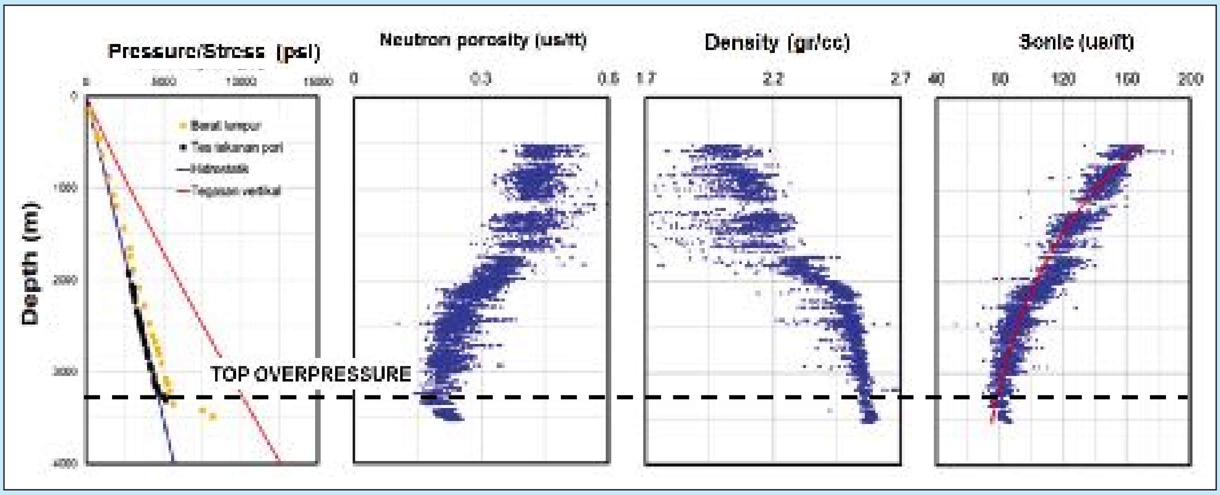

Figure 11
Pressure profile and wireline logs responses of NB-12 Well

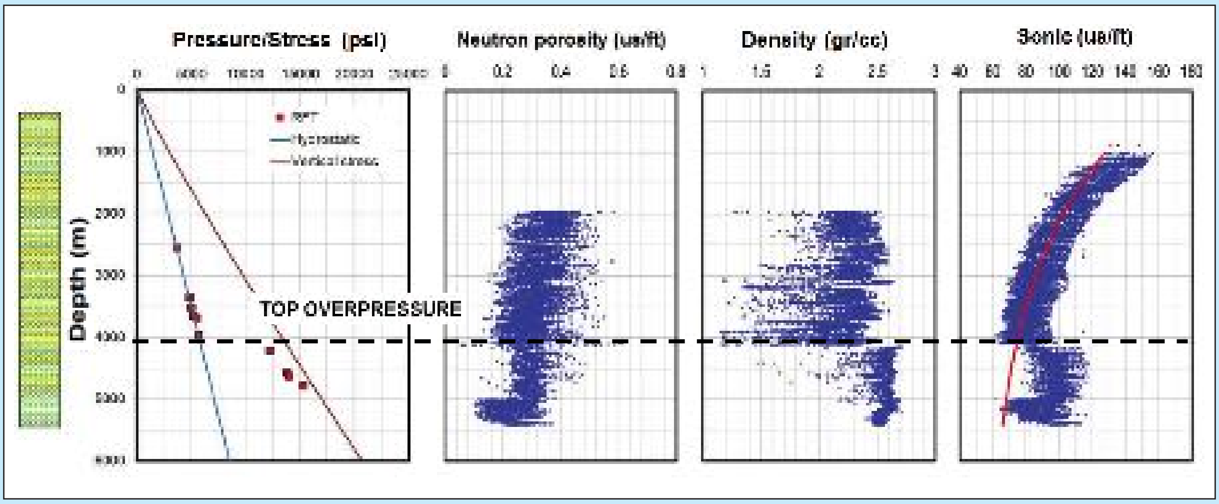

Figure 12
Pressure profile and wireline logs responses of NLM-109X Well.

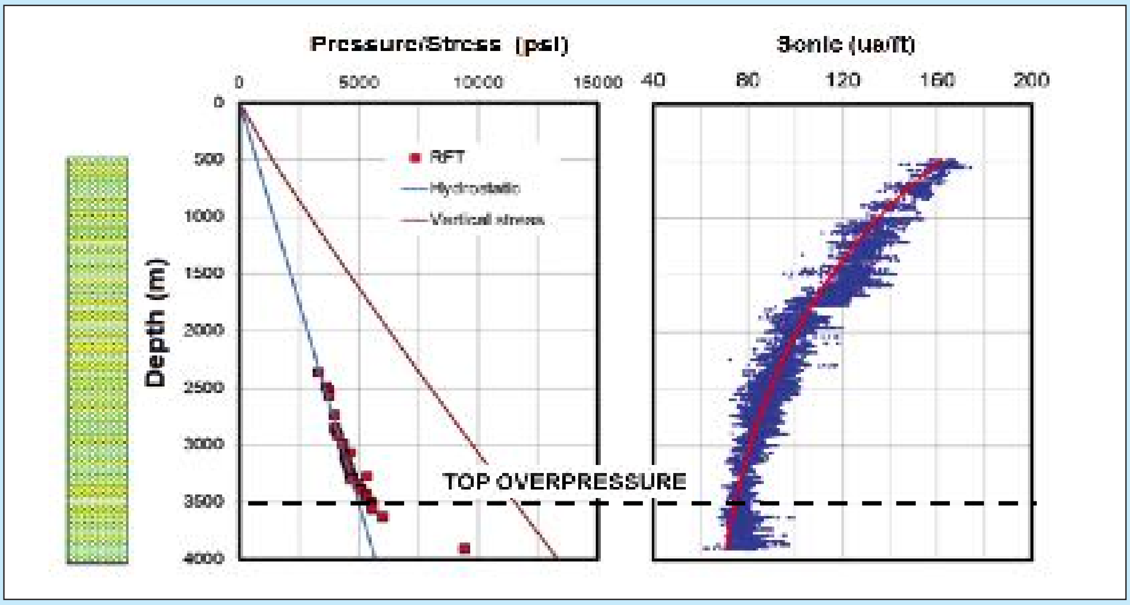

Figure 13
Pressure profile and wireline logs responses of NWPCK-9 Well.

7. Sumur NWPCK-9

NWPCK-9 Well was drilled to a depth of 3900 meters. Based on the above picture it can be seen that the RFT measurement shows the condition of overpressure begins at a depth of 3500 meters. The overpressure pattern based on the pressure measurements showed the characteristics of unloading overpressure which is the reduction in the value of effective stress with increasing depth (Refer to Figure 2B). Additionally, the measurement result from sonic log shows deviation (reverse) from normal condition starting at a depth of 3500 meters.

B. Pore Pressure Estimation

1. Pore pressure estimation using Standard Eaton's method

In order to perform pore pressure estimation using standard Eaton's method and Cheating with Eaton's method, known values of normal compaction trend (NCT) is needed. These values are obtained from the equation on the sonic log data under normal hydrostatic condition. Table 2 shows the normal equation compaction trend (NCT) of the wells within the studied area. The table shows variation of NCT equations in each well.

Based on the equations in Table 2, a compiled graph of normal compaction trend (NCT) of the seven wells in the study area is displayed in Figure 14. According to the chart, NCT variation

Table 2
Normal Compaction Trend (NCT)
Equations for each well

No	Wells name	Normal Compaction Trend (NCT) Equation
1	HDL-B1	131.127566159*EXP((-0.000554426*DEPTH)+55
2	BKP-11	131.127566159*EXP((-0.000554426*DEPTH)+55
3	SS-1	145.433258007*EXP(-0.000559231*DEPTH)+55
4	SBR-39	103.725573103*EXP(-0.000468902 *DEPTH)+55
5	NB-12	150.865126669*EXP(-0.000572138 * DEPTH)+55
6	NLM-109X	112.052907089*(EXP(-0.000427815*DEPTH)+55
7	NWPCK-9	141.305264968*(EXP(-0.000564214*DEPTH)+55

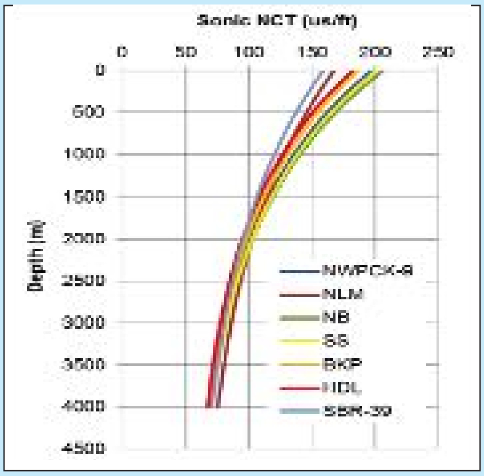

Figure 14
Variation of normal compaction trend of all the seven wells.

is potentially found in depth intervals close to the surface. This variation is thought to link with the process of sedimentation and erosion within the studied area.

Wells that are located in the offshore area have a sonic value of about 200 us/ft, which indicates an absence of erosion. The following is compatible with the tectonic history and sedimentation of the basin where only the sedimentation process occurred in the offshore region.

As with the wells that are located onshore, the relative value of the sonic surface ranges from 160-180 us/ft. This suggests an erosion process taking place which coincides with the last uplift in this basin.

After the normal compaction trend (NCT) values are obtained from all the studied well above, standard Eaton's equation is applied to calculate the pore pressure value on each of the seven wells (Figure 15, A-G).

The results of pore pressure estimation using standard Eaton's method on Well HDL-B1, BKP-11, SBR-39, NB-12, NLM-109X, and NWPCK-9 display unsatisfactory results in hard-overpressure interval. This is indicated by the discrepancy of the estimated values where they are less than the pore pressure calibration (DST/RFT/MDT).

2. Pore Pressure estimation Using Cheating with Eaton's Method

In response to the latter problem, Cheating with Eaton's method was tried to be applied to estimate the pore pressure in hard-overpressure zone. The results of pore pressure prediction using Cheating with Eaton's method is shown in Figure 16 A-F.

By setting the Eaton's order in Cheating with Eaton's method between 4-7, the results produced a much better outcome. Adjustment of Eaton's order was based on synchronization between estimated values against the calibrated pore pressure values for each well.

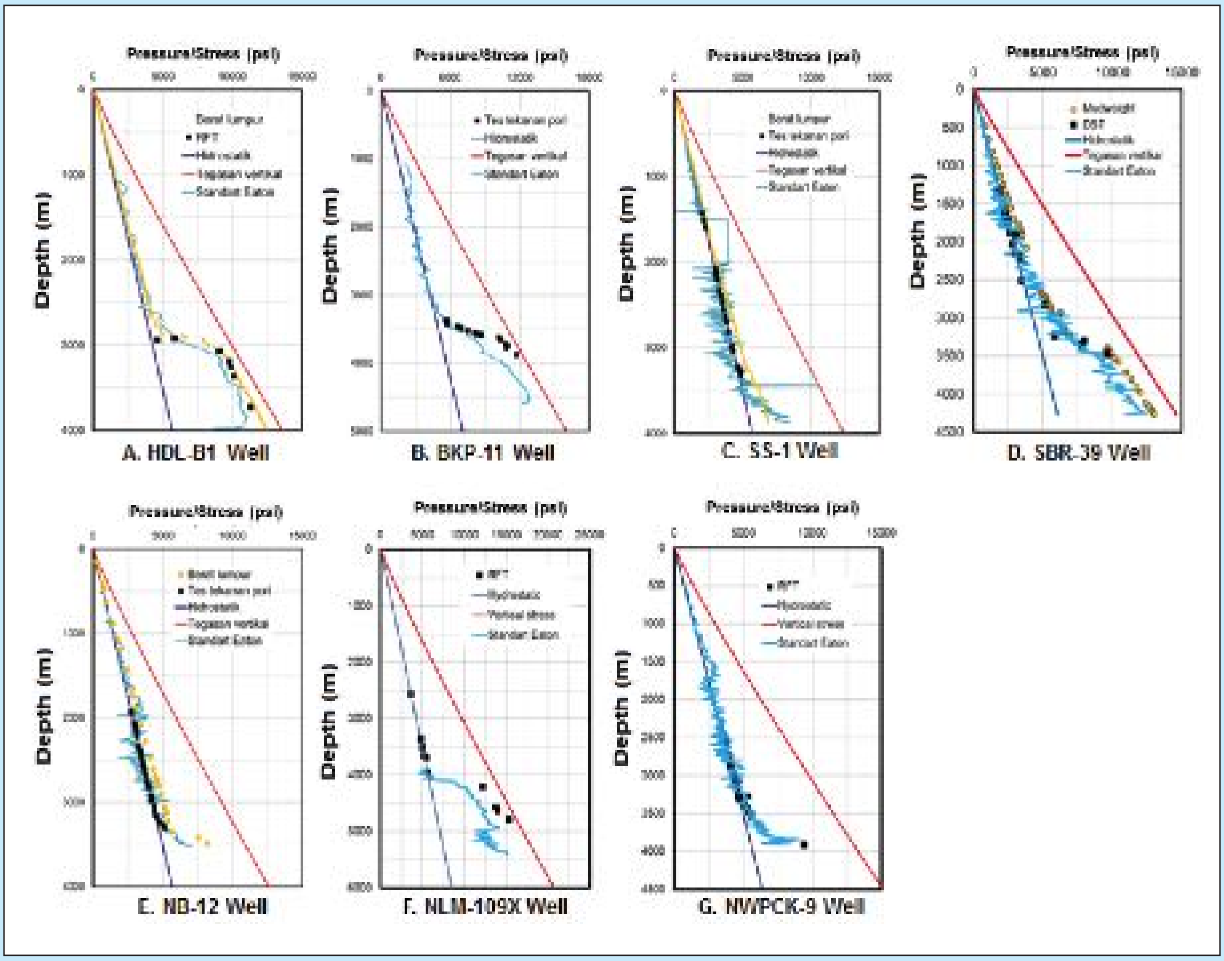

Figure 15
Pore pressure estimation results using standard Eaton's methods

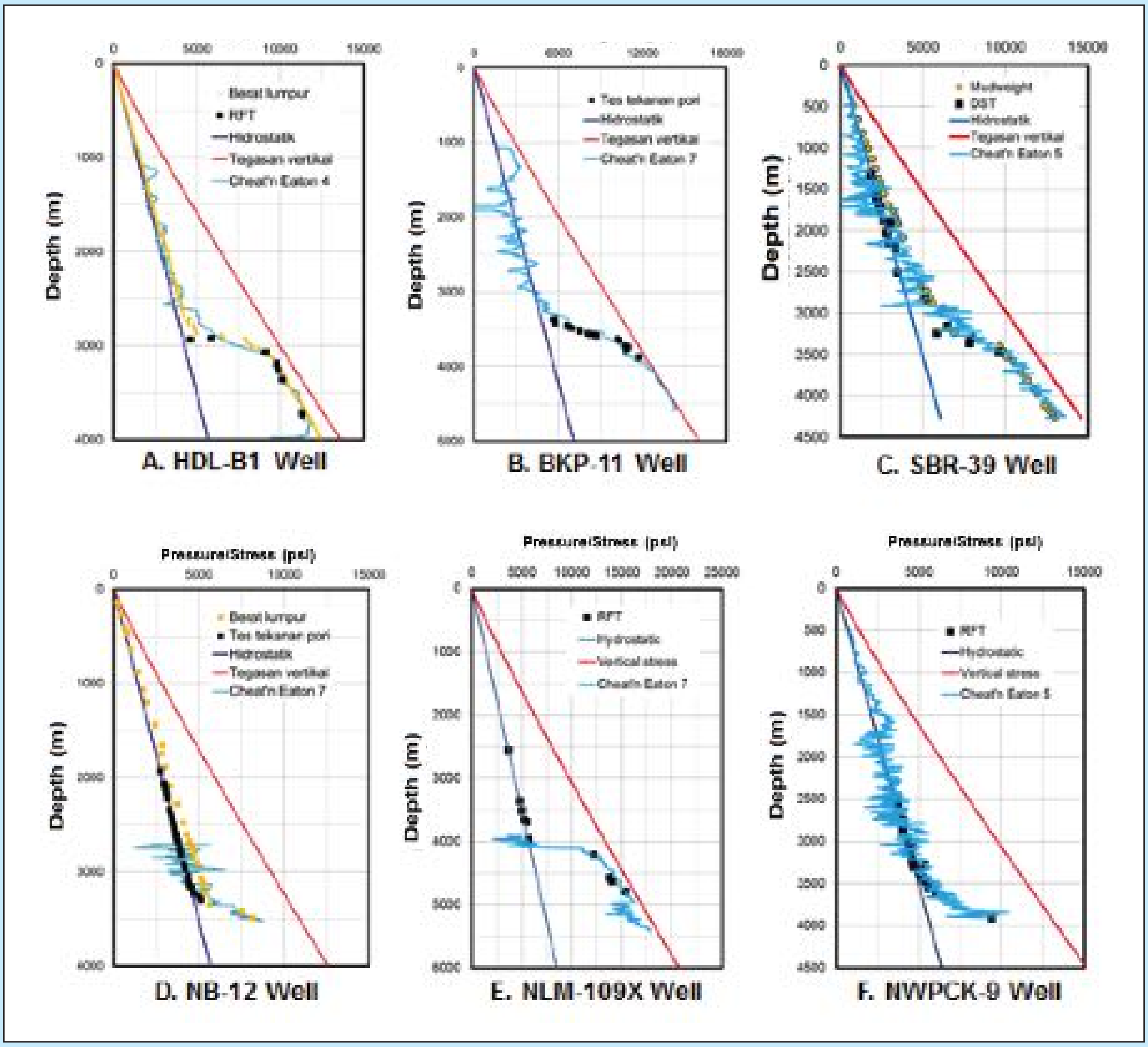

Figure 16
Results of pore pressure estimation by Cheating with Eaton's method with Eaton's order ranging from 4-7.

3. Pore Pressure Estimation Using Effective Stress-Velocity Method *(Bower's Methods)*

As described earlier in the chapter, prior to pore pressure estimation using Effective stress-velocity method**,** the first step is to generate a crossplot between velocity and effective stress to investigate the relationship between the two parameters. Two types of curves will be produced from the crossplot: Virgin/Loading/Compaction curve and Unloading curve. The Virgin/Loading/Compaction curve reflects normal hydrostatic under normal compaction condition while the Unloading curve explains overpressure condition due to unloading mechanism. Besides reflecting the normal hydrostatic condition, the Virgin/Loading/Compaction curve may also indicate the condition of overpressure due to disequilibrium compaction.

By using DST/RFT/MDT data and velocity of the seven wells within the studied area, a Virgin/Loading/Compaction curve equation was obtained (Figure 17):

$$V - 5000 = (5.097 * EFFSTRESS)\text{^}0.854$$

Two Unloading curve equations represent this particular basin for both offshore and onshore territory. The Unloading curve equation for this research area is (Figure 17):

$$V - 5000 = 5.097 * (Vmax * (EFFSTRESS / Vmax) \text{ ^ } (1 / U)) \text{ ^ } 0.854$$

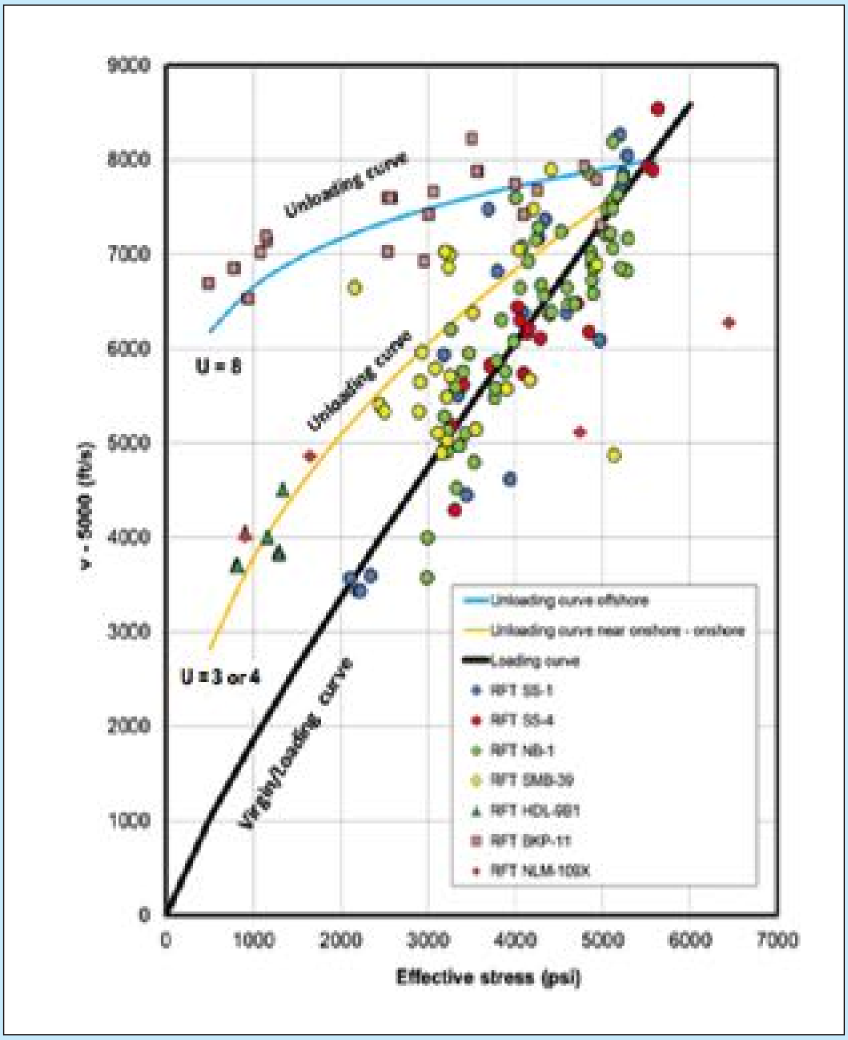

Figure 17
Crossplot velocity versus Effective stress.

Based on the crossplot result, "U" value obtained for the unloading curve in the onshore region is either 3 or 4 and 8 for the offshore region. Vmax is the maximum velocity value, which is velocity at the top of the overpressure zone.

Furthermore, after deriving the equation above, pore pressure is then ready to be estimated. All of the wells in the studied area are in the carries zone of hard-overpressure especially for the unloading mechanism case. Hence, the unloading curve equation is used to estimate pore pressure (Figure 18 A-F). In the Figure 18 shows precisely the results of pore pressure prediction.

By knowing the wells position (onshore / offshore), such as for Well HDL-B1, SBR-39, and NLM-109X, which are relatively onshore it is advisable to use the parameter "U" equals to 3, specifically for Well NLM-109X where the "U" parameter is 4. Meanwhile Well BKP-11, NB-12, and NWPCK-9 used the parameter "U" equals to 8.

IV. DISCUSSION

A type of overpressure in the study area is unloading overpressure which is caused by either kerogen maturation or smectite-illite transformation. Both generating processes were supported by the value of temperature data in top overpressure around 122 - 129°C. The unloading overpressure due to kerogen maturation or smectite-illite transformation is indicated from decreasing value of effective stress. This phenomenon illustrates that grains contact decrease due to increase in pore fluids and overburden/vertical stress or solid shrinked. This type of overpressure has generated hard-overpressure magnitude in this study area.

In order to estimate the magnitude of pore pressure in the hard-overpressure zone, three methods (standard Eaton's, Cheating with Eaton's and Effective stress-velocity method), have been choosen to be used. The use of standard Eaton's method cannot be applied for hard-unloading-overpressure for this basin. In contrast the Cheating with Eaton's method shows rather satisfying results. The drawback of these two methods is the generation of NCT equation that varies for each well. Since Eaton's method is a numerical method, the order that is used is only for estimation that approaches the calibration value, without regard to geological conditions.

Another method that produces better pore pressure estimation is the Effective stress-velocity method (Bower's Method). The method only refers to one compacting equation called Virgin / Loading Curve. For the case of hard unloading overpressure, two "U" parameter values are used. For onshore wells, the "U" parameter used is 3-4, whereas for offshore wells is 8. According to Bower, the "U" Value reflects the nature of the rock that is perfectly elastic and perfectly plastic.

V. CONCLUSION

Based upon the results discussed above, a number of important points can be made. Crossplot

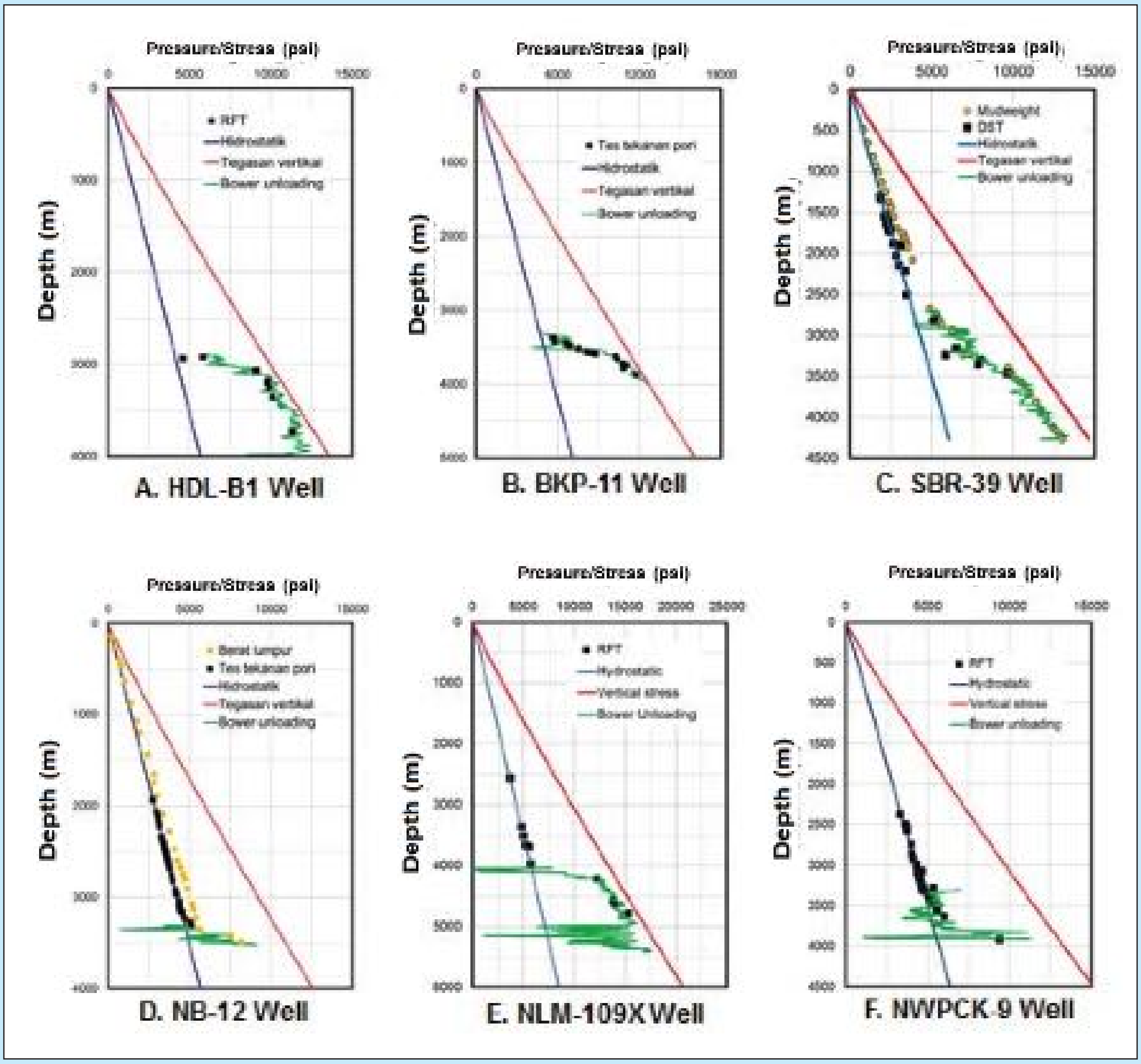

Figure 18
Results of the pore pressure estimation using Effective stress-velocity method (Bower's methods) in hard-overpressure zone.

between effective stress against velocity is able to generate a single equation to estimate the pore pressure in the zone of hard-overpressure. The use of the equation in unloading hard-overpressure condition showed better results compared to Eaton's method. In addition to generating acceptable estimation of pore pressure value, this method is also capable of explaining the phenomena of loading *"dissequilibrium compaction"*/unloading-overpressure. The derivation of this single equation would simplify the pore pressure estimation, as it only requires one compaction equation with a controllable order. The "U" value on Effective stress-velocity (Bower's Method) produces the value from 3-8, which shows the results of Typical Unloading Curve values and unloading phenomenon. By using this single equation, pre-drill pore pressure in hard-overpressure at Lower Kutai Basin will be easier and more precise if using only seismic data (interval velocity).

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