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Analysis of Overpressure Mechanisms in a Field of Southwestern Malay Basin

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Abstract

This study demonstrates the utilization of wireline logs for pore pressure mechanism analysis in a field of southwestern Malay Basin. Development of overpressures means that fluid movement in the pores is retarded both vertically and laterally. In many Tertiary basins overpressure is mainly generated by compaction disequilibrium due to high deposition rate and low permeability in shales. In the Malay Basin, temperature and high heat flow also plays an important role in generating overpressure at shallow depth as geothermal gradient is very high 40-60 ^{o}C/km. Overburden pressure is calculated for all the wells using density log. Pore pressure profiles, cross plots of sonic velocity-vertical effective stress and sonic velocity-density are used to derive the overpressure generating mechanisms. The results obtained from the cross plots of 10 wells reveals that in the study area overpressure is generated by both primary and secondary mechanisms such as compaction disequilibrium and fluid expansion. Overpressure magnitude analysis suggests that overpressure generated by the secondary mechanism is very high as compare to primary mechanism. Eaton's method with exponent 3 gives good prediction where overpressure is the result of compaction disequilibrium mechanism but under-predicted the high pore pressures where fluid expansion mechanism is also present. However, the overpressures are predicted quite well by using higher Eaton exponent of 5 for fluid expansion mechanism. Bowers method is also used for pressure prediction and it gives reasonably good prediction in high overpressure zone by using the unloading parameter (U) of 6.

Introduction

Abnormal pressure is the pressure higher or lower than the normal/hydrostatic pressure, often referred as overpressure or under pressure respectively and has significant importance in geohazards analysis and prediction [1]. Accurate pore pressure prediction is very important for safe drilling, casing point selection and well planning in the high overpressured regions, has implication in migration modeling for prospect evaluation and seal prediction. Overpressure is commonly generated by two different mechanism, undercompaction or fluid expansion. Different pore pressure prediction schemes are required for both mechanisms as they have different effect on rock properties [2]. The phenomena are called undercompaction when overpressure is generated by the fast deposition and low permeability that prevents rapid escape of pore fluids. In cases of undercompaction, the effective stress remains constant. Fluid expansion mechanism such as hydrocarbon generation increases pore fluid volume within the confined pore space. Unlike undercompaction, overpressure generated by fluid expansion may lead to reduction in effective stress [1].

In most of the Tertiary sedimentary basins where sedimentation rate is high, undercompaction is the dominant mechanism for overpressures generation. In the deeper part of the sedimentary basins other mechanism such as fluid expansion can also cause overpressure generation. To describe the mechanism of overpressure Deming et al., (2002) introduced the 'static' and 'dynamic' terminologies. When overpressure is generated due to the pressure barriers this process is called static, while dynamic is the process when the imbalance between pressure generation and pressure dissipation generates overpressure and in this case pressure seal is not required [3]. In many basins faults are associated with traps for oil and gas. Some faults are sealing and some are non sealing. Sealing and non sealing properties of faults have significant effect on pore pressure. Hence, pore pressure data obtained from the well logs can be used for fault seal analysis.

For accurate pore pressure prediction it is important to understand the different mechanisms of overpressure generation and their effect on rock properties [4]. In this paper we analyzed the origin of overpressure in the southwestern Malay Basin, the effect of overpressure on well logs and evaluated various pore pressure prediction methods (i.e. Eaton's and Bowers). Overpressure mechanism analysis is very important for overpressure prediction and it will help in understanding the behavior of pore pressure and applying the appropriate pore pressure prediction method.

Geology of the Study Area

The Malay Basin is situated to the east of Peninsular Malaysia, in the South China Sea (Fig. 1). Malay Basin has northwest-southeast trend and geometrically asymmetric in form with the depositional axis begin closer to the southwestern flank of the basin [5]. Sedimentary sequence in Malay Basin is subdivided into different stratigraphic Groups starting from the youngest (A) to the oldest (M) and the exploration focuses primarily on Groups E–K. In a lower coastal-plain setting, coal is found from E through the deeper groups but most prominently in Group I [6]. In this study, Group H is subdivided to 3 Groups (Lower, Middle and Upper) from base to top.

The Malay Basin is one of the most prolific hydrocarbon-producing basins in Southeast Asia. In the deeper parts of the basin overpressure is developed due to the deposition of 12 km fine grained Tertiary sediments during the last 35 Ma [7].Malay Basin is characterized by high heat flow with average geothermal gradient of 40 to 60 °C/km that has influence on hydrocarbon generation and migration. Malay Basin is also a part of the rift and basin inversion occurred in Middle-Late Miocene [8].

The study area is located in the southwestern part of the Malay Basin and it comprises an elongated WNW-ESE trending anticline (Fig. 1). This anticlinal structure is dissected by a series of broadly north-south trending normal faults. On the basis of structural interpretation the study area can be divided into four clearly defined fault blocks (Fig.2). The fault block A (main fault block) is not significantly affected by normal faulting and is tested by seven wells (Well CN-1,2, JM-2,3 & LN-1,2,4), while fault block B and C (shear zone) is structurally more complex due to the presence of many extensional faults and is tested by two well (JM-1and JM-4). The fault block D is on the western side of the study area and tested by one well (LN-3), normal faults has en echelon arrangements which suggest the presence of shear component in the western flank of the study area.

Origin of Overpressure in the Malay Basin

The depth to the start of overpressure varies across the Malay basin and is shallowest in the basin centre 1.9-2.0 km. and on the basin flanks, overpressure starts deeper often at 3.0 km as shown in Figure 3[9] . There is a strong correlation between rate of sedimentation and overpressure development by disequilibrium compaction. However, when wells are drilled deeper into the basin, thermal processes in shales will result in secondary overpressure generation. It suggests that additional overpressure mechanisms such as clay mineral digenesis and hydrocarbon generation exist in the Malay Basin.

According to an early study [10] there exist no relationship between the temperature distribution and the top of overpressure in the Malay Basin. Similarly top of overpressure does not conform to any particular stratigraphic group. Previous studies had shown that overpressure is not generated by undercompaction alone. Fluid expansion or unloading mechanisms may have also contributed to the high overpressure in the Malay Basin.

The pressure transition zone varies across the Malay Basin. In the north, pressure transition is relatively abrupt as compared to the south. It is reported that tectonic uplifting during basin inversion was responsible for overpressure generation in the southern part of the Malay Basin. In the northern part of the basin, overpressure is due to smectite/montmorillonite to illite transformation [11].

Temperature may also play important role in the development of over pressure. Geothermal gradient is high (i.e. 50 °C /km) in the central Malay Basin due to which the dewatering zone is thin and shallow. This may explain the reason that in center of the Malay Basin overpressure occurs in the stratigraphically younger units at shallow depth, while towards the basin flanks geothermal gradient is less and overpressure progressively deeper in the older stratigraphic units [12]. Based on the previous studies it appears there could be more than one factors involved in overpressure development in the Malay Basin.

Overpressure in the Study Area

Overpressure is observed in almost all of the wells drilled in the study area. In this study, data from 10 wells is used for pore pressure mechanism analysis. Pore pressure data obtained from Repeat Formation Tests (RFTs), Drill Stem Tests (DSTs) and Modular Formation Dynamics Tests (MDTs) is used to analyze the overpressure distribution in the study area.

Pressure depth plots for all the wells are shown in Figure 4. The wells are grouped into four fault blocks. Pressure profiles showed different behavior in the different fault blocks. In fault block A, C and D overpressure start at shallow depth and gradually increase with the depth, while in fault block B overpressure start at greater depth and ramp up quickly.

This complex behavior of overpressure in the study area suggests the presence of different overpressure mechanisms. In the study area, heat flow is high (75 mW/m^2) that caused source rock to mature at early stages and hydrocarbon generation start at shallow depth which can also contributes in overpressure generation[13]. Geochemical investigation suggests the presence of Type II and Type III kerogen that have potential to generate oil and gas [14].

Well Logs Response to Overpressure

Wireline logs such as sonic, density and resistivity are commonly used for pore pressure prediction. Sonic logs give more reliable pore pressure prediction and are also very effective in porosity determination and lithology discrimination. The sonic log measure the transit time of a sonic impulse through a given length of rock and the rate of propagation depends on the elastic properties of the rock matrix and its contained fluid. Sonic logs are useful in pore pressure prediction because they are only affected with compaction related effects (porosity and density). Borehole size, pore water salinity and formation temperature has no effect on sonic logs. The shale bulk density will increase with depth due to the increased compaction, results in reduced porosity and pore water expulsion. In an overpressured zone the compaction will be retarded resulting in high porosities and lower densities than a normally pressured shale at the equivalent depth [15].Shale resistivity is also affected by porosity, salinity and temperature. Resistivity will be low in the overpressured shale due to high porosity and fluid contents. Both resistivity and sonic log respond to the textural changes in the rocks induced by overpressure, give information about the pore pressure changes where density log does not. Sonic and resistivity logs are sensitive to pore pressure changes either generated by compaction disequilibrium or fluid expansion [16].

Overpressures generated by undercompaction are associated with high porosities that decrease the sonic velocity in overpressured sediments. However, when fluid expansion is the mechanism, overpressures are not associated with a significant porosity anomaly. Transport properties (observed in resistivity and sonic logs) are sensitive to pore size, shape and the connectivity of the pores. Therefore, transport properties responded directly to fluid overpressure in shales compared to the bulk properties[17].

Sonic and density logs give large response to overpressure where disequilibrium compaction is the generating mechanism. However, where fluid volume expansion is involved, the effective stress is likely to have been higher in the past. The volume increase lead to the reduction in the effective stress and therefore only a small response is observed in sonic log with less significant response in the density log.

Velocity-Vertical Effective Stress Response

Bowers (1995) has developed an approach to distinguish between disequilibrium compaction and other overpressure generating mechanisms using velocity - vertical effective stress relationship.

The sonic velocity and vertical effective stress data obtained from well logs is used for overpressure mechanism analysis in the study area. The vertical effective stress for the clean shales is calculated by using the RFT pressure measurements from the adjacent sandstone section, which is within 5 meters of the RFT pressure measurements. The sonic velocity-vertical effective stress data is separated into normally pressured and overpressured zones as shown in Figure 5. Normally pressured data is used for normal compaction trend (loading curve) development. Scattering in the normal compaction trend can be due to the difference in pore pressure measured in sand and adjacent shales.

The sonic velocity - effective stress cross plots of two selected wells as shown in Figure 5 suggest the presence of both undercompaction and unloading mechanisms in the overpressured shales. In the case of undercompaction the overpressure data points lie mainly on the loading curve. In the deep overpressured shale the data points lie off the loading curve indicating unloading.

Velocity-Density Response

Velocity vs. Density cross-plots can be used to identify the presence of overpressure generated by mechanisms other than undercompaction. More sophisticated method was adopted by Bowers (2001) and Lahann (2002) which involves the velocity-density cross plots to differentiate between overpressure generated by disequilibrium compaction and fluid expansion mechanisms.

In the case of gas generation, reduction of effective stress has a much greater impact on the velocity but the effect of decreasing density trend is very small. Hence, the steep downwards trend is associated with “unloading” [19] . The schematic relationship between velocity and density is shown in Figure 6.

Sonic velocity and density of two selected wells are cross plotted to investigate the relationship between pore pressure and stratigraphic groups (Fig.7). It is observed that in most of the wells overpressure start in Group H (Upper) and increase gradually with depth. Velocity – density cross- plots do not show any reversal in Group H (Middle and Upper) and follow the trend for undercompaction as shown in Figure 6. The change in trend (reversal) is observed in Group H (Lower) and Group I which indicates the presence of unloading mechanism.

High temperature has effect on the rock properties and wireline logs. In Malay Basin high geothermal gradient has significant effect on porosity reduction through chemical compaction [19]. Estimated downhole temperatures are also included on velocity-density cross plots of two selected wells to investigate the effect of chemical compaction in the study area (Fig. 8). The increase in density and velocity with increasing depth indicates continued porosity reduction with depth. The departure in velocity-density trend in most of the wells occurs at temperature range between 100°C and 110°C. This indicates there exists a relationship between temperature and departure of the velocity- density trend. It is observed that in deep over pressured shales (Group H Lower and Group I) velocity drops faster than density which suggests the contribution from unloading mechanism.

Pore Pressure Prediction

Eaton (1972) method and Bowers (1995) method are commonly used for pore pressure prediction, are discussed below

(i) Eaton Ratio Method

Eaton Ratio method is based on the detection of changes in porosity with depth and is derived from Terzaghi (1953) equation based on soil mechanics (Equation 1) [20]. The observed discrepancy between the RFT pressure and the predicted pore pressure from the Eaton method has been used as an indication of additional pressuring mechanisms besides disequilibrium compaction.

$$S_v = \sigma_v + Pf \qquad (1)$$

Here, S_v is the total vertical stress, Pf is the pore fluid pressure; σ_v is the vertical effective stress.

The Eaton method estimates pore pressure from the ratio of acoustic travel time in normally compacted sediment to the observed acoustic travel time (Equation 2)[21]. In this study data from 10 wells are used for pore pressure prediction from sonic velocity by using Eaton method. Hydrostatic and overburden pressures are calculated for all the wells in different fault blocks.

$$P_p = S_v - (S_v - P_h)\,(V_{obs} / V_{norm})^{(x)} \qquad (2)$$

Here, P_p is the pore pressure, P_h is hydrostatic pore pressure, S_v is the total vertical stress, V_{norm} is the normal velocity, V_{obs} is the observed velocity and X is the Eaton Exponent (resistivity = 1.2, velocity = 3).

The Eaton method is empirical, uses a regionally defined exponent (Eaton Exponent) that can be easily varied to calibrate the trend to predict the pore pressure generated by different mechanisms. An Eaton exponent of 3.0 is typically used in sediments where undercompaction is the mechanism of overpressure generation. In the presence of fluid expansion mechanism, sonic log will show a small response to the overpressure, can be compensated by using higher Eaton exponent [4].

Pore pressure was successfully predicted by using an Eaton exponent of 3.0 (for sonic velocity) in the wells, where the overpressures are believed to be generated by disequilibrium compaction only. In the deeper part of the wells where overpressure is generated by fluid expansion, Eaton method underpredicted the pore pressure. However, a reasonable pore pressure prediction was obtained using the Eaton exponent of 5, determined from calibration with RFT pressure data (Fig.9).

(ii) Bowers Method

In 1995, Bowers introduced a new method for pore pressure prediction using effective stress approach. This method is used to predict overpressure generated by either undercompaction or fluid expansion mechanism [22]. Bowers method uses the concept of virgin and unloading curves, empirical relation for both the curves are given below

Virgin Curve:

$$V = 5000 + A\,\sigma^{B} \qquad (3)$$

Here, V= velocity (ft/s), σ is effective stress (psi) and A, B are Virgin curve parameters.

Unloading Curve:

$$v = 5000 + A\,[\sigma_{max}\,(\sigma/\sigma_{max})^{(1/U)}]^{B} \qquad (4)$$

Here, $\sigma_{\mathbf{max}}$ is the estimate of effective stress at the onset of unloading, U is the unloading parameter.

$$\sigma_{max} = ((V_{max} - 5000)/A)^{1/B} \qquad (5)$$

Here, V_{max} is the velocity at the onset of unloading.

U = 1 implies no permanent deformation. Because the unloading curve reduces to the virgin curve, U = ∞ corresponds to completely irreversible deformation.

The value of the two empirically parameters (A & B) can be determined by using sonic velocity - effective stress cross plots from the offset well data. Bowers (1995) method also underpredicted the high pore pressures in the deeper zone that are believed to be generated by fluid expansion. However a good fit between the predicted and RFT pressure data is obtained by using an unloading parameter (U) of 6 (Fig.10).

Conclusions

The results of this study provide critical insights into the nature and origin of overpressure in a part of Southwestern Malay Basin. In conclusion, current study shows there is a strong relation between the overpressure development by disequilibrium compaction in the Group H (Middle and Upper) in the study area. However, when wells are drilled deeper into Group H (Lower) and Group I, thermal processes in shales will result in secondary overpressure generation.

Two different methods were used for pore pressure prediction and gave mixed result for all the wells used in this study. The mismatch observed between the formation pressure and predicted pressure is attributed to the presence of different mechanisms and normal compaction trend selection. Where overpressure is resulted from disequilibrium compaction, the two tested methods provide a reasonable good fit with the formation pressure. Otherwise, the methods resulted in under prediction of pore pressure.

In the study area, overpressure is believed to be the result of disequilibrium compaction (shallow) and fluid expansion (deep). Results obtained from this study provide valuable information about the origin of overpressure in the study area and would be useful for pore pressure prediction strategy in the southwestern Malay Basin. The key results obtained from this study are:

- Overpressures in Group E and H (Middle and Upper) are caused by disequilibrium compaction, and overpressure can be accurately predicted from sonic log data using Eaton (1972) method with an exponent of 3.0.

- Overpressures in Group H (Lower) and Group I are caused by fluid expansion mechanism. Overpressure in Group H (Lower) and Group I can be accurately predicted from sonic log data using the Eaton (1972) method with an exponent of 5.0 and Bowers (1995) method with an unloading parameter of 6. However, the Bowers method does not give good prediction in the wells that are strongly affected by non mechanical compaction.

- High geothermal gradient plays a significant role in high overpressure generation

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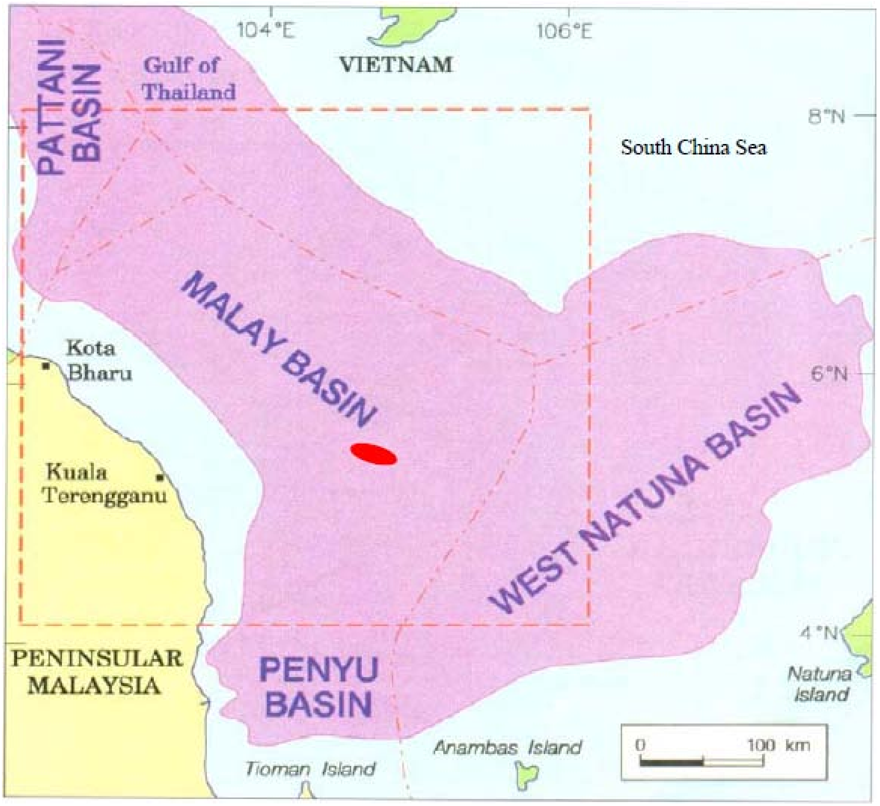

Fig.1. Location Map of the Malay Basin modified from [23]. The red oval shape shows the location of the study area.

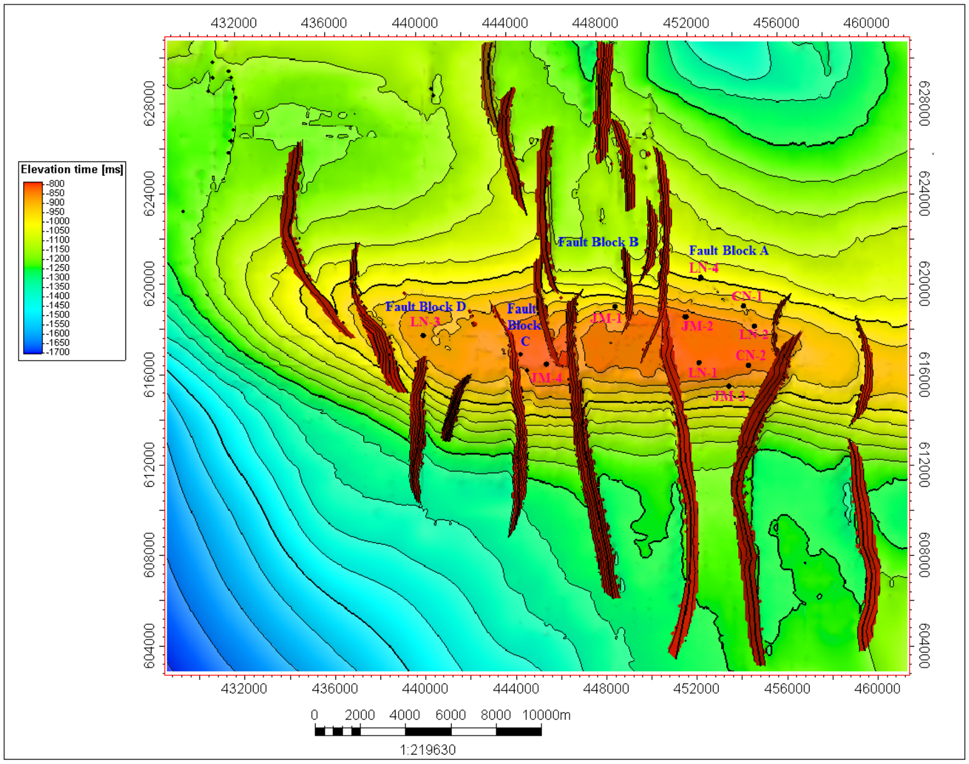

Fig.2. Time Surface of Group E shows the presence of extensive normal faulting which indicates that the study area is in extensional regeime so the effect of lateral stress on overpressure will be less. The locations of different fault blocks and wells are also shown. Fault block B and C are also called shear zone due to complex faulting .

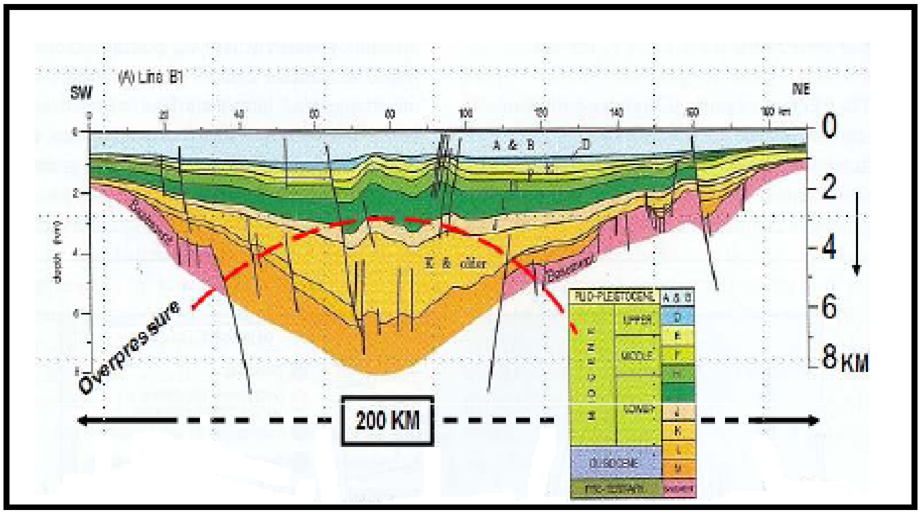

Fig.3. The onset of overpressure in Malay Basin. The depth to the start of overpressure is shallowest in the basin center and increase gradually towards the the basin flanks [23].

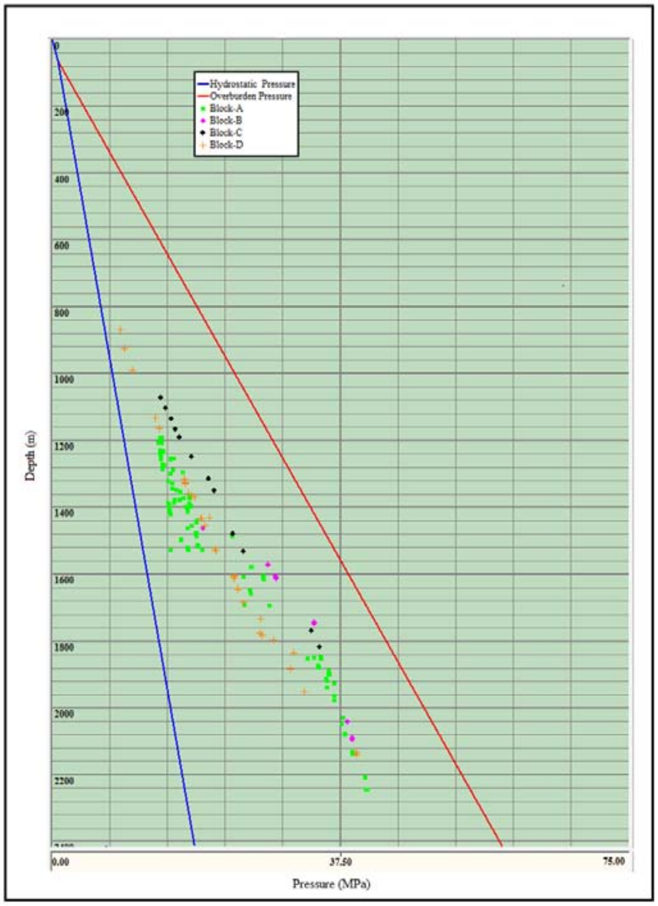

Fig.4. Pore Pressure (RFT, DST, MDT) profile of the study area according to fault blocks shows the complex behavior . Onset of overpressure is shallow in fault block A,C and D but is much deeper in fault block B. This complex nature of pore pressur shows the presence of diiferent mechanisms that generate overpressure in the study area. Hyrdostatic and overburden pressure is for the reference and calculated from density log, taken as lowest and highest in all fault blocks respectively.

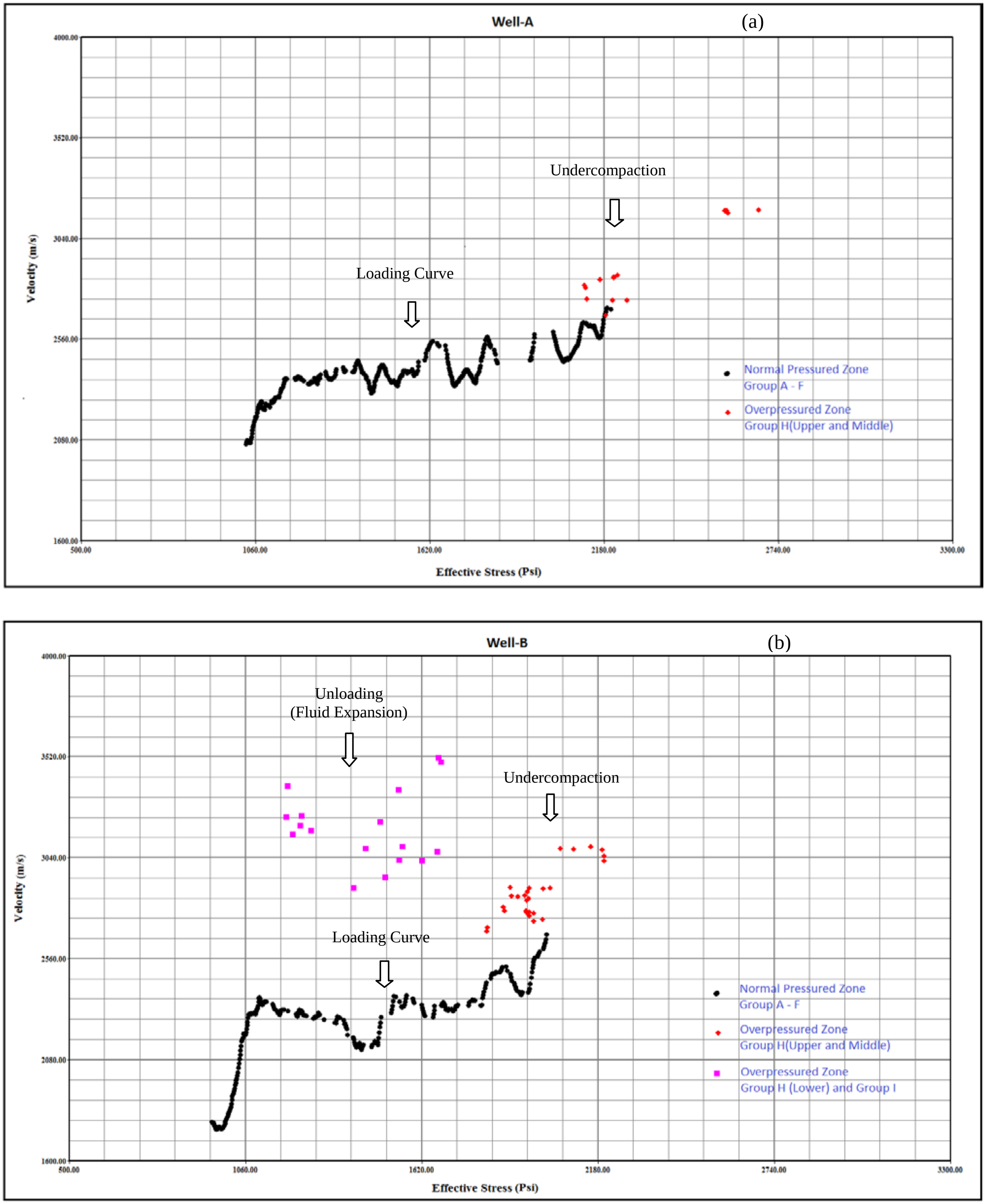

Fig.5. Examples of sonic velocity- vertical effective stress cross plots for overpressure mechanism analysis in the study area. In well-A (a) velocity - effective stress follows the loading curve and does not show any reversal in the overpressured zone which indicates the presence of undercompaction mechanism. In well-B (b) velocity - vertical effective stress cross plot show two different trends in overpressured zone. In the shallow overpressured zone (i.e Group H Upper and Middle) no velocity reversal has been seen and overpressured points follow the loading curve whereas in the deeper zone (Group H Lower and Group I) the overpressured points show reversal and lie off the loading curve. Hence, in both the wells, shallow overpressure is generated by undercompaction while in Well-B (b) deeper overpresusre (Group H Lower and Group I) is generated by secondary mechanism (fluid expansion). Well-A (a) did not penetrate the full Lower H Group interval and both RFT and MDT pressure data are not available.

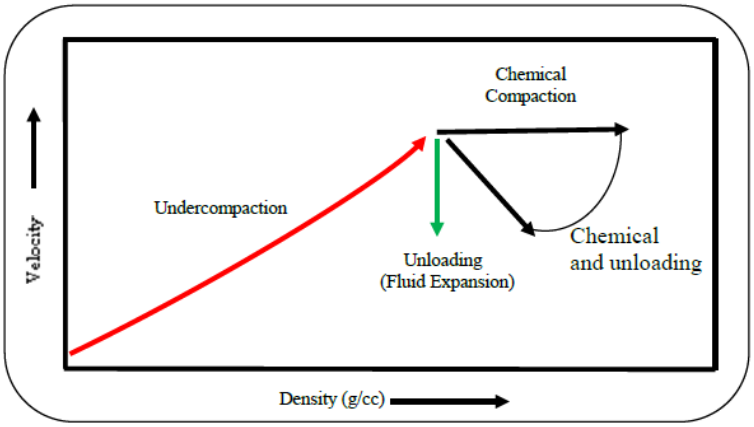

Fig.6. Schematic velocity - density cross plot for pore pressure mechanism analysis , modified from [19].

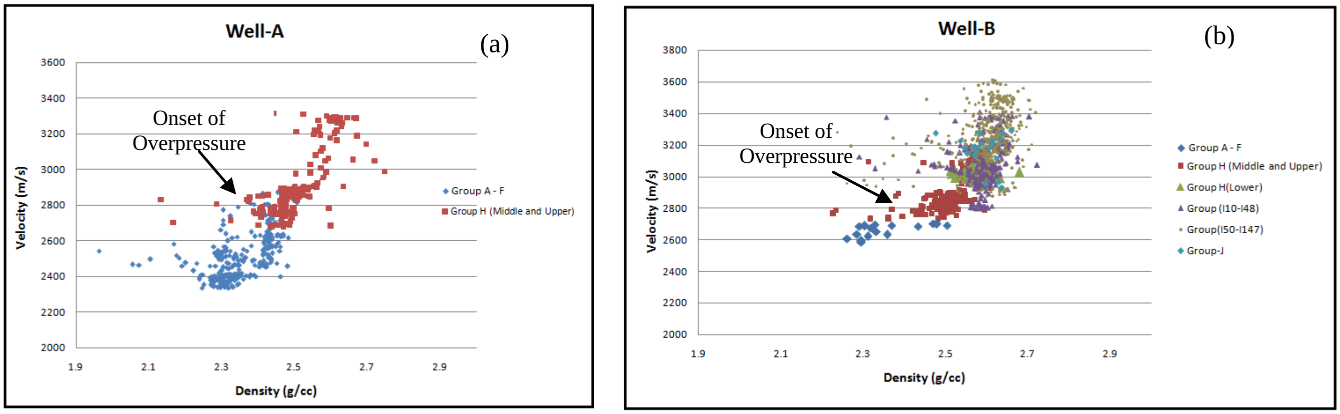

Fig.7. Example of sonic velocity- density cross plots used for overpressure mechanism analysis in the study area. Sonic velocity and density for clean shale points is cross plotted according to stratigraphic groups in the overpressure zone for the well-A (a) and well-B (b). It is noted that in most of the wells ovepresure start in Group H (Upper) , sonic velocity - density does not show any reversal in sahallow overpressured zone(i.e. Group H Upper and Middle), Hence, undercompaction mechanism is generating overpressure. In the deep overpressured zone (i.e Group H Lower and Group I) sonic velocity - density cross plot show reversal (i.e velocity is reduced faster then density) which indicates the presence of fluid expansion mechanism.

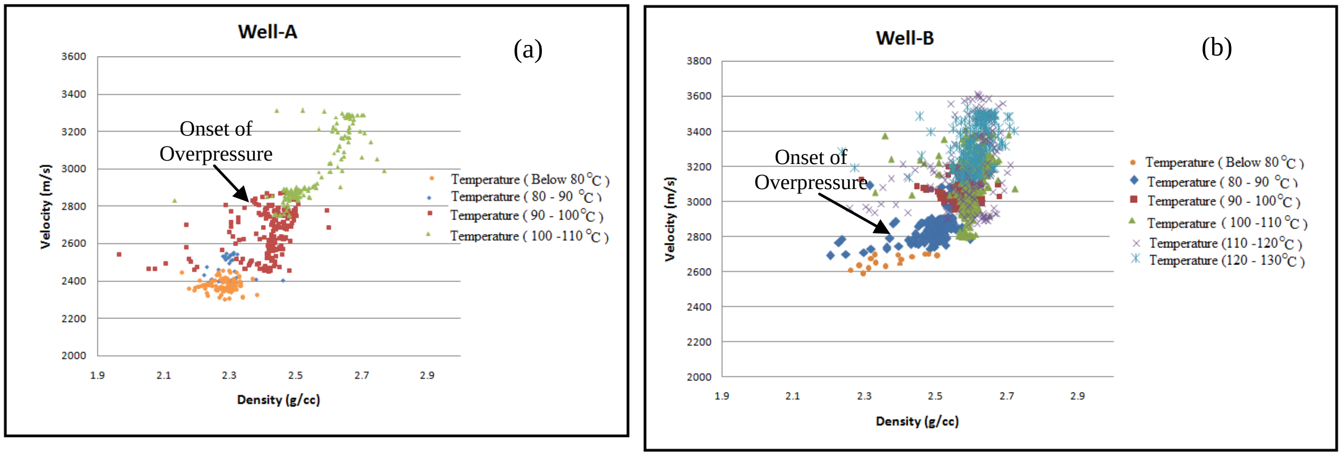

Fig.8. To investigate the role of chemical compaction in overpressure generation, sonic velocity and density cross plotted according to temperature interval. In both the well-A (a) and well-B (b) sonic velocity - density cross plots did not give any evidence for the presence of chemical compaction. Cross plot for the Well-B (b) shows the change in velocity-density trend start at temperature interval of 100-110 °C which indicates the presence of unloading (fluid expansion). Well-A (a) is not penetrated in full Group H (Lower) therefore, not showing any reversal at the same temperature interval (i.e. 100-110 °C). This suggests the velocity reversal is associated with both temperature and lithology group.

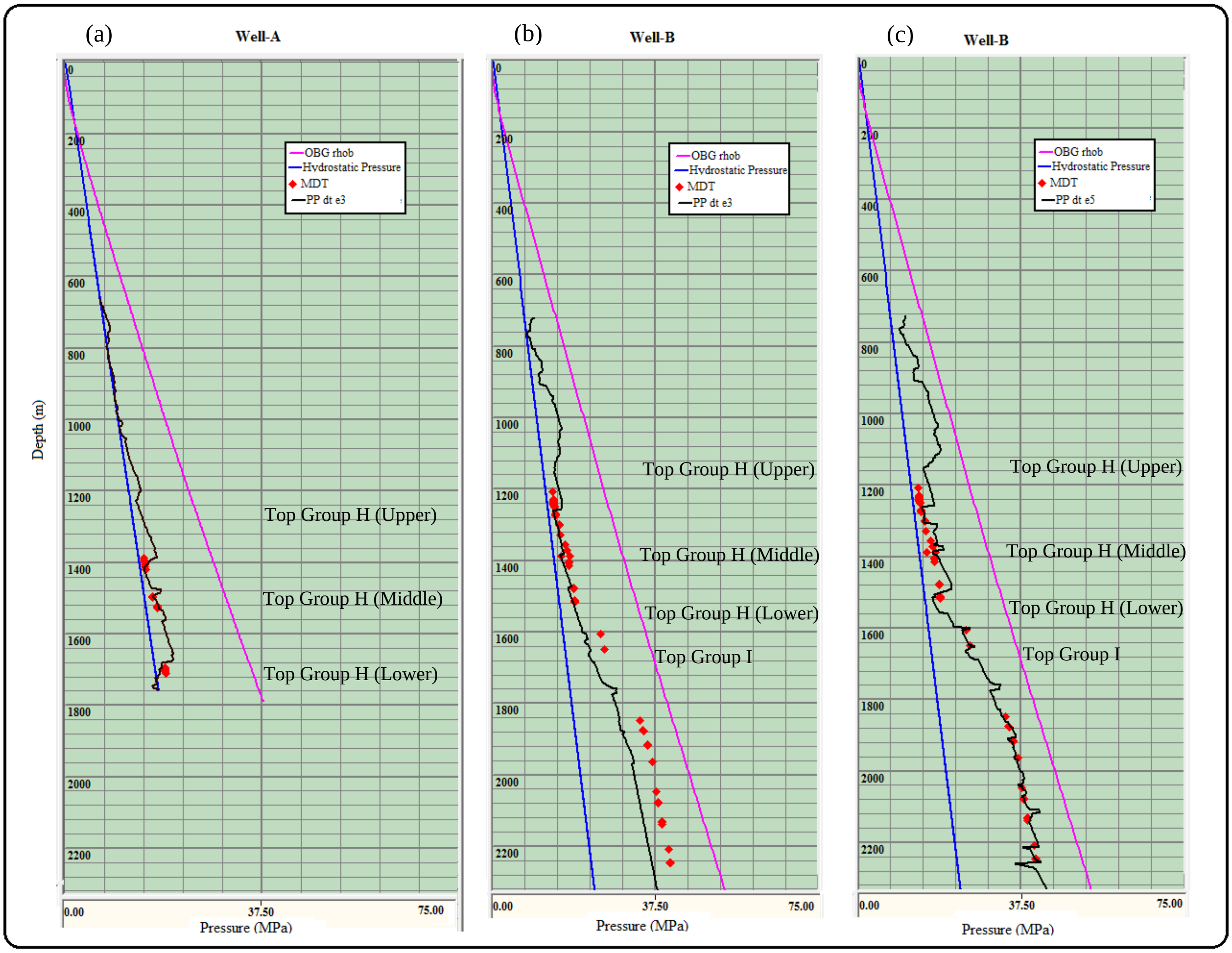

Fig.9. Example of pore pressure prediction by using Eaton (1972) method in a field of southwestern Malay Basin. Overpressure start in Group H (Upper) in all the wells. In well-A (a) overpressure is well predicted by using Eaton Exponent of 3 which shows the presence of undercompaction mechanism, While, in well- B (b) overpressure is predicted by using Eaton exponnet 3 in the Group H (Upper and Middle) but underpredicted in deeper zone . However, in well-B (c) overpressure is successfuly predicted in deeper zone by using Eaton exponent 5 which shows the presence of fluid expansion mechanism in the Group H (Lower) and Group I. Hence, undercompaction and fluid expansion both mechanisms are present in the Well-B.

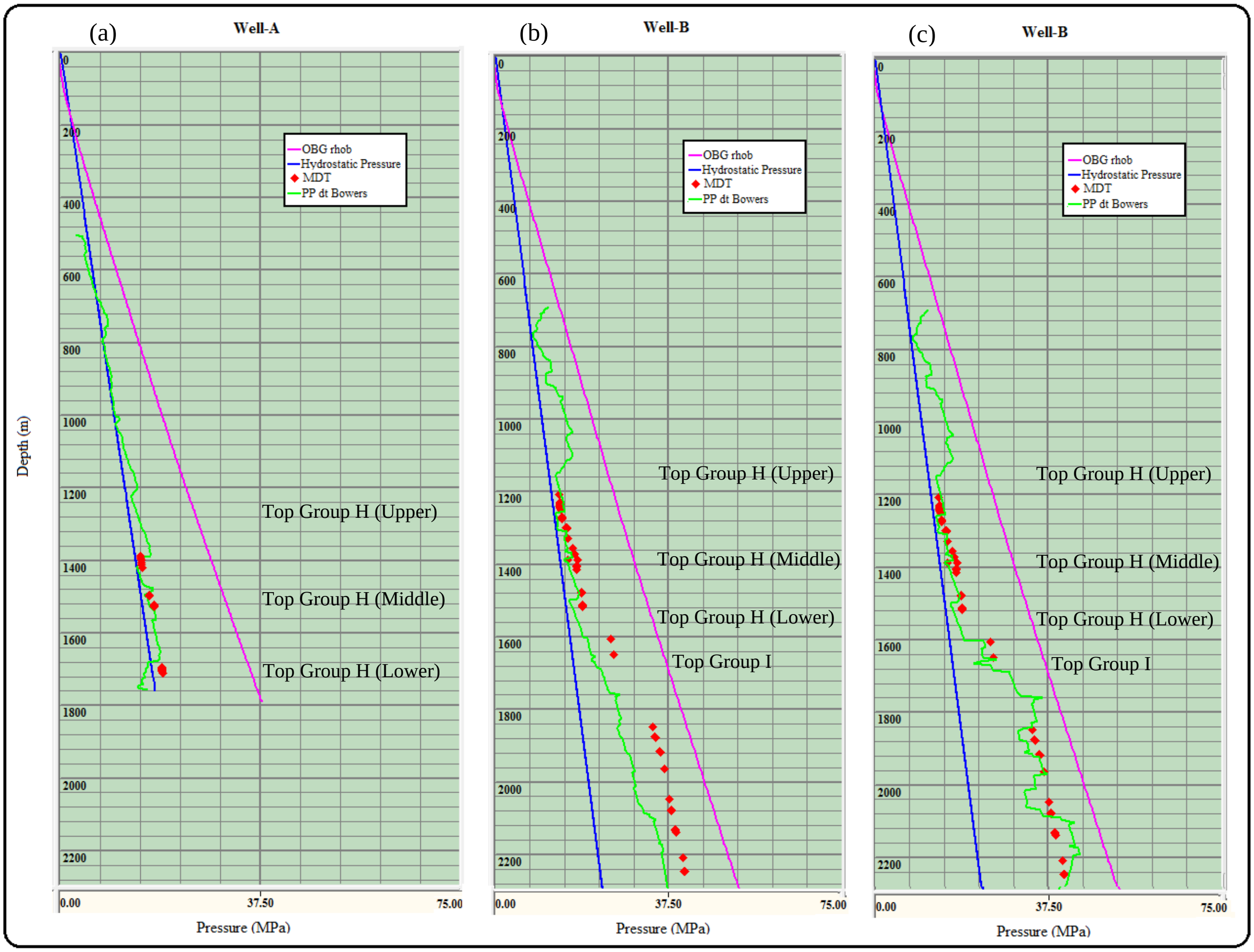

Fig.10. Example of pore pressure prediction by using Bowers (1995) method. In well-A (a) and Well-B (b) overpressure in the Group H (Upper and Middle) is reasonably predicted by using Bowers method for loading curve, while, in well- B (b) overpressure is underpredicted in Group H (Lower) and Group I (deeper zone) . However, in well-B (c) Bowers method with an unloading parameter (U) of 6 gives good prediction which shows the presence of fluid expansion mechanism in the deeper zone, small variation in the predicted pressure can be due to lithology variations.