Overpressure Study, Refining Wireling-based Prediction in Southern Pattani Basin, Gulf Of Thailand

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Abstract

The application of Eaton's sonic log-based pore pressure prediction method is typically the pore pressure analyst's preferred method for predicting overpressure in the Gulf of Thailand and other hydrocarbon basins in SE-Asia. However, the fracture gradient approach has not yet been used successfully for reliable fracture pressure prediction in this area. Testing the fracture gradient approach and its use in understanding overpressure generation is the focus of this study. Data from ten development wells and two exploration wells from Moragot and Funan fields were used and subjected to Eaton's sonic-based method for computing pore pressure and fracture gradient were calculated. The results were then compared with RFT log data and LOT measures, respectively. A further comparison using TOC and vitrinite reflection measurements plotted against overpressure across three wells with organic maturation data shows that the onset of overpressure corresponds to the onset of organic maturation. It is likely that the main drivers creating overpressure in the study area are a combination of hydrocarbon generation and variable levels of compaction disequilibrium. The computed overpressure via Eaton's sonic-based method with an exponential x factor equal to 2 gave the closest result to RFT values showing it can reliably predict overpressure in the Gulf of Thailand. Furthermore, the fracture gradient results show this approach can predict lost circulation zones in wells that had drilling issues. The sonic-based methods produce an estimated pore pressure and fracture trend, which can be useful in areas where pore pressure profiles are not well defined or sediments have experienced depletion pressures, and/or drilling problems (i.e. loss of fluid circulation or fluid influxes). When determining top of overpressure, which will affect porosity and subsurface stress, the application of these methods facilitates an approach of "filling in the gaps". In addition, in order to minimize drilling risks, this methodology can be reliably employed as the one of techniques utilized while drilling, or in realtime pore pressure estimation (in MWD) and in calculation of mud-weight safety windows.

Keywords: Overpressure Mechanism, Sonic log, Eaton Method, Pattani Basin

1. Introduction

The understanding of abnormal pressure or overpressure is important for drilling safety, because unexpected overpressure can cause severe drilling incidents such as gas kicks, fluid influxes or blowouts from zones when pore pressure profiles are not well defined. Therefore, pore pressure prediction is necessary before drilling starts, especially in the exploration phase where it is needed for determination of mud weight schedules and casing points, mitigation of drilling risks and avoiding non-productive time in the operation. Pore pressure prediction methods are done in many ways using well data and seismic data in order to determine pore pressure. The most commonly applied methods use wireline data centered on sonic transit time logs to predict hale pore pressure, which is at equilibrium level with pore pressure in adjacent sand intervals (Eaton, 1972). This study focuses in more detail on the evaluation of overpressure by using well log sonic-based data and better defining the overpressure mechanism in the southern part of the Gulf of Thailand. There, the mechanism generating overpressure is still not well understood. This study compiles and documents the nature of the overpressure and compiles additional evidence to test for fluid expansion, likely caused by hydrocarbon generation, as the main cause of overpressure. The results may also be useful for drilling safety.

2. Study Area

The area of interest is a gas field operated by Chevron Thailand Exploration and Production, located in the southern part of the Pattani Basin, Gulf of Thailand (Figure 1). Pattani Basin is underlain by a series of Tertiary age north-south trending rift basins. It is underlain by horst and graben structures, which formed as a result of strike-slip driven extensional tectonics (Jardine, 1997). The depositional environment during Tertiary time began with Oligocene fill into Pattani basin that consisted of non-marine and marginal marine silica-clastic sediments. According to Jardine, 1997, the stratigraphic character is divisible into five sequences, based on lithology and microfossils. There are two significant unconformities, which represent periods of non-deposition or erosion in the Gulf of Thailand around 25 Ma and 10 Ma and are represented by the Mid-Tertiary Unconformity (MTU) and Mid-Miocene Unconformity (MMU), respectively (Jadine, 1997).

In this study, the zone of interest is in sequence 3, which is the main overpressure interval. Sequence 3 was deposited during the Lower Middle Miocene as transgressive fluvial sediments that consist of thin fluvial-deltaic sand units and marginal marine units composed of widespread and thick flooding shales (Jadine, 1997).

2.1 Pore Pressure Regime

Wireline repeat formation tests (RFT) collected for pore pressure evaluation across several wells in this study area demonstrate that the normal pressure gradient or hydrostatic gradient is typically 8.2 to 8.6 PPG EMW. The pressure gradient increasing above the normal pore pressure trend defines zones of overpressure development in most of the studied wells at depths from 6500 ft TVDSS to 9000 ft TVDSS. The main zone of over- pressure development generally commences in the top of sequence 3, where this succession is comprised of widespread and thick low-permeability shales, associated with thin fluvial-deltaic sands deposited in marginal marine environments. The reversal pressure, where abnormal pore pressures revert to the normal pressure trend, tends to occur at the top of sequence 2, where the succession is dominated by thick fluvial point bar and channelized sand units (Jardine, 1997).

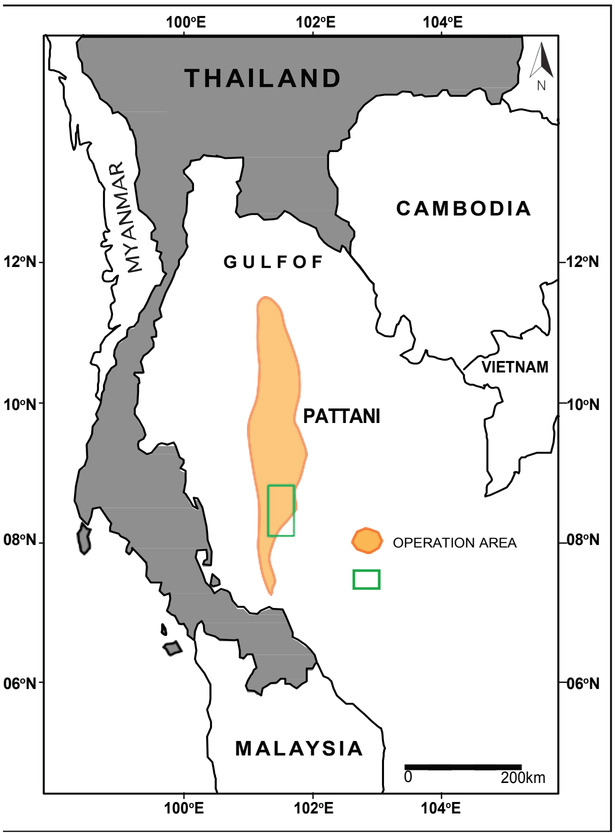


Figure 1. The area of interest is the Moragot and Funan fields operated by Chevron Thailand Exploration and Pro- duction, located in the southern part of Pattani Basin, Gulf of Thailand and identified by the shaded rectangular.

3. Database

Wireline data from 2 exploration and 10 development wells, all with repeat formation test (RFT) measurements, are used in this study. The pressure data from RFT measurements were examined for validity. The pressure samplings that were not valid such as depleted, tight or dry, and supercharged intervals were excluded from this study.

The set of geochemical data collected from 3 exploration wells were analyzed to make sure datasets were free of compilation and standardization errors.

4. Methodology

The most common methods for quantitative pressure estimation from wireline logs are those of Eaton (1972) and Bowers (1995). Justification for selecting the method of pore-pressure evaluation depends on the pore-pressure analysis experience in a particular basin or/and wireline data available. Sonic-based pore pressure prediction by Eaton's sonic transit time has beensuccessfully applied in several sedimentary basins of offshore Thailand. Therefore, Eaton's sonic method is considered an appropriate approach for this study and also has not yet been done in a study of fracture gradient prediction in this area.

4.1 Eaton's Sonic method

In this study, Eaton (1972) presented the following empirical equation to construct pore pressure gradient prediction from sonic compressional transit time:

$$P_p = OBG - [(OBG - P_n) \times (\Delta t_n / \Delta t)^x] \quad (1)$$

Where P_p is the pore pressure, OBG is the overburden pressure, Pn is the hydrostatic pressure, Δt_n is the sonic transit time or slowness in shales at the normal pressure, Δt is the sonic transit time in shales obtained from well logging and x is the Eaton's exponent, which typically varies from 2.0-4.0. The Eaton's exponent as used in this study is 2.0, because it has to be adjusted to provide the best fit between the estimated and measured pore pressure trends and to be more consistent when applied in every well.

4.2 Eaton Fracture Gradient

Eaton (1969) successfully accounts for the subsurface stress regime in a fracture gradient calculation by using the Poisson's Ratio, which is the elastic constant reflecting the horizontal to vertical stress ratio.

$$F_p = (OBG - P_p) x (v/(1-v)) + P_p \quad (2)$$

Where F_p is the fracture pressure gradient, OBG is the overburden pressure, P_p is the pore pressure and v is the Poisson's ratio. This approach by Eaton applies a LOT that tests, before drilling, a calculation of Poisson's ratios. Furthermore, the applicability was determined as successful using Gulf Coast (Gulf of Mexico) measurements to compare with the result of LOT.

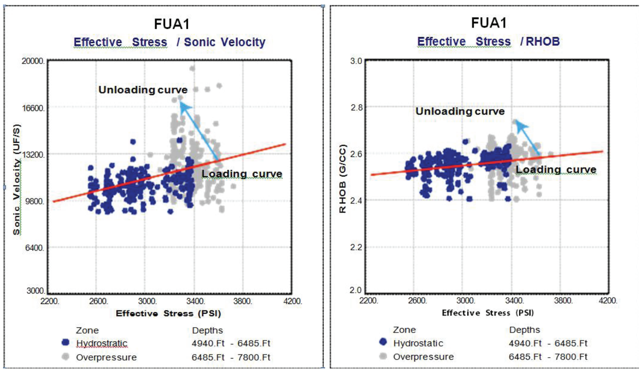
5. Results

5.1 Sonic Velocity/Density versus Vertical Effective Stress Analysis in the Study Area

A sonic velocity/density versus vertical effective stress analysis highlights the presence of over-pressures generated by a fluid expansion mechanism in the Pattani Basin, as constructed for eight of twelve selected wells. The overpressure interval plots predominantly off the loading trend. This indicates overpressures are more likely caused by fluid volume expansion, rather than compaction disequilibrium. The other four wells lie predominantly on the loading trend for velocity-vertical effective stress analyses and density-vertical effective stress analyses (Figure 2). However, the primary conditions necessary for overpressure generation by fluid expansion, especially the required existence of an extremely effective seal, are also ideal for the generation of overpressures via disequilibrium compaction (Neuzil, 1995; Osborne and Swarbrick, 1997). Indeed, once a seal of sufficient quality has been developed to allow the formation of overpressures by fluid expansion, any increase in stress applied to the sealed sequences (e.g., burial or tectonic loading) will also generate overpressure by disequilib-rium compaction. Work by Neuzil (1995) and Osborne and Swarbrick (1997) found that over-pressures generated by fluid expansion are un-likely to occur in isolation and will also include some component of overpressure generated through disequilib- rium compaction. Osborne and Swarbrick (1997) suggested that overpressures commonly associated with gas generation may be enhanced by disequilibrium compaction.

This is because the increase in porosity and destruction of kerogen in the framework, which is associated with kerogen turning into gas, means that the matrix becomes

a) Fluid expansion



b) Disequilibrium compaction

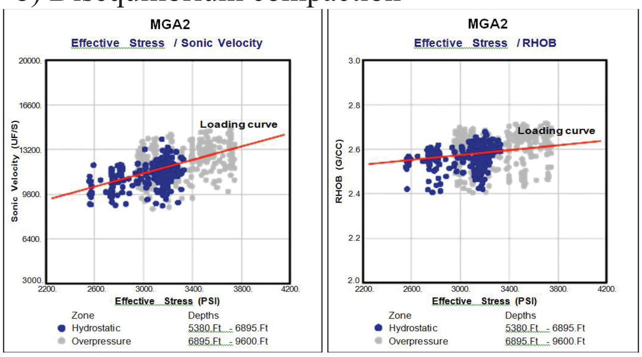


Figure 2. a) The relationship between sonic velocity/densing and effective stress, showing the unloading mechanism in the reversal or overpressure interval (grey points) indicating fluid expansion. b) The relationship between sonic velocity/density and effective stress, showing the unloading mechanism in the reversal pressure or overpressure interval (grey points) indicating disequilibrium compaction.

unable to fully support the overlying load. Hence, additional evidence in this current study, collected from three exploration wells, using a combination of wireline logs and geochemical analyses has significant implications for observed overpressures and will be discussed further after considering the importance of sonic velocity-density data with respect to overpressure.

5.2 Sonic Velocity–Density Crossplot

A number of sonic velocity–density crossplot analyses have been conducted on shales in overpressured wells in the Pattani basin. Based on this work and broader studies, sonic velocity–density approach has been suggested as a reliable method for distinguishing between different overpressure mechanisms and particularly, between different fluid expansion or transfer mechanisms (Hoesni, 2004). Hoesni (2004) suggested that shales overpressured by disequilibrium compaction have essentially the same porosity and density and sonic velocity as normally pressured sequences and will plot on the loading curve. Overpressures generated by kerogen-to-gas maturation are suggested to show decreasing sonic velocity with increasing overpressure but to have essentially little or no density change.

The sonic-density cross-plot analysis highlights that sonic velocity exhibits a significant change with both increasing and decreasing overpressure magnitude. Hence, the sonic-density response to overpressure sug gests that gas generation is a key influence on overpressure generation in the Pattani Basin. Furthermore, the observation that sonic and density values return to the loading curve as pore pressures return to hydrostatic provides very strong evidence against clay diagenesis or load transfer having any significant function in overpressure generation in the Pattani Basin (Figure 3).

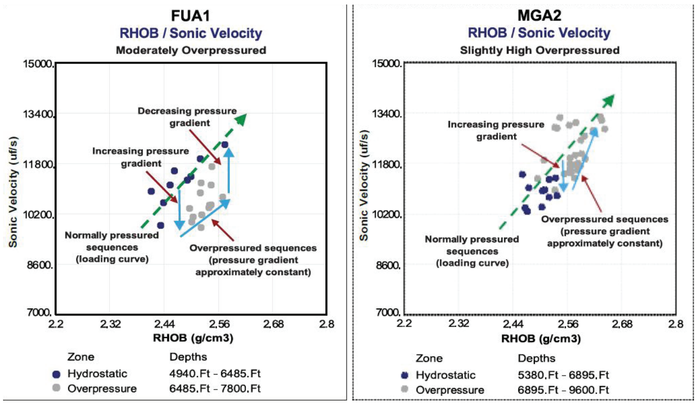


Figure 3. Sonic and density cross-plots showing the character of the level is of overpressure in the Pattani Basin.

5.3 Additional Evidence on the Overpressure Mechanism

Strong evidence exists that disequilibrium compaction is also a significant factor in generating overpressure in the Pattani Basin, in addition to the previously discussed theoretical constraints and the hypothesis suggesting that kerogen-to-gas overpressures are unlikely to occur in isolation. Overpressure sequences in many moderately to highly overpressure wells in the study area are associated with abnormally high sonic transit times (Figure 4). The higher transit times (lower sonic velocities) observed in overpressure sequences suggest that these formations are undercompacted and this is a classic indicator of overpressures generated by disequilibrium com paction (Mouchet and Mitchell, 1989).

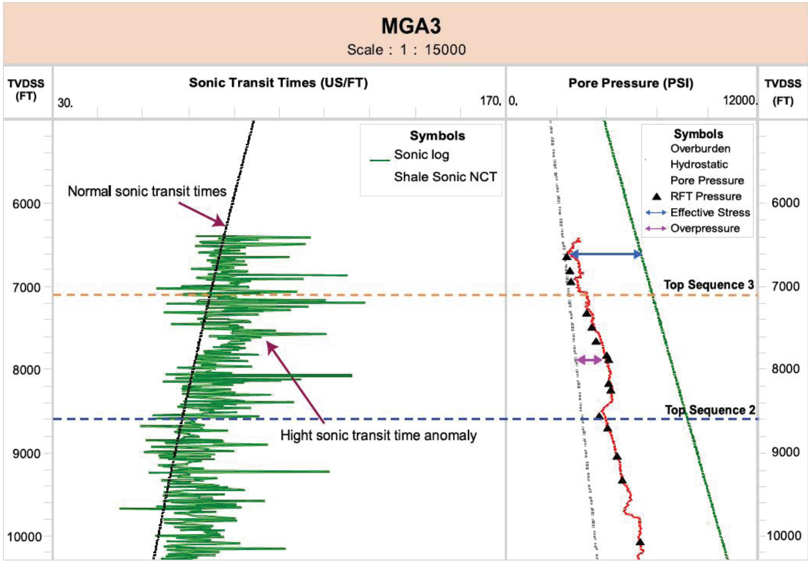


Figure 4. a) Observed sonic transit times versus predicted normal (hydrostatic as black line) sonic transit time val- ues for well MGA3. The highly overpressured sequence 3 is associated with a moderate sonic transit time anomaly, further indicating that a component of overpressure in these formations is generated by disequilibrium compaction. b) Pore pressure plot for well MGA3. Note that overpressures commence near the base of sequence 4 (above top of sequence 3), reach approximately 0.8 psi/ft near the middle of sequence 3, and maintain this gradient until the top of sequence 2.

Additional evidence for fluid expulsion being the cause of overpressure in this area comes from organic geochemical data, which was collected in three of the studied exploration wells. For the purposes of the current study this information is crosstied to organic rich units, and measures of total organic carbon (TOC) and vitrinite reflectance (R0) values are plotted against depth. The consistent relationship between the presence of organic rich units, changes in TOC and R0 trends (Figure 5).

6. Discussion

6.1 Pore Pressure and Stress Relationship

There is increasing evidence in basins worldwide that anomalous pore pressure is usually associated with anomalous horizontal stresses (Yassir and Bell, 1996). In this study, the onset of overpressure with depth is associated with a change in stress regime from extensional to compressional. The same relationship is observed over much of the Gulf of Thailand, where overpressures are associated with anomalously high horizontal stresses, and subnormal pressures are associated with anomalously low horizontal stresses. There is considerable interest in obtaining relationships between the two in order to predict one from the other. Such correlations can be misleading, because no single relationship holds true for different areas (or sometimes even within a single basin). The influence of the overpressure mechanism on pore pressureand stress relationships is discussed below.

From Eaton's fracture equation (2), when fluid is generated at depth, it can result in an increase in horizontal stress, while the total vertical stress, generated by the weight of the overburden, does not change. Within the same process set, a pore pressure reduction leads to a corresponding reduction in horizontal stress. Figure 6 shows that overpressure from fluid generation results in a pore pressure shift to the right, from 2630 psi shift to 4280 psi in the pore pressure gradient. Overburden gradient is 7500 psi, Fracture gradient is 6090 psi, so that the Pp/Fp ratio is 0.70. This ratio has its highest value at the onset of overpressuring (Figure 6).

6.2 Implications with respect to Overpressure Generation in the Study Area

The primary mechanism generating overpressure in many sedimentary basins worldwide is considered to be disequilibrium compaction (Osborne and Swarbrick, 1997). The relationship of velocity and density versus vertical effective stress plots and sonic versus density plots, fall somewhat or slightly off-the-loading-curve values in such areas, and so this observation is widely used to indicate that the cause of overpressure generation was fluid expulsion.

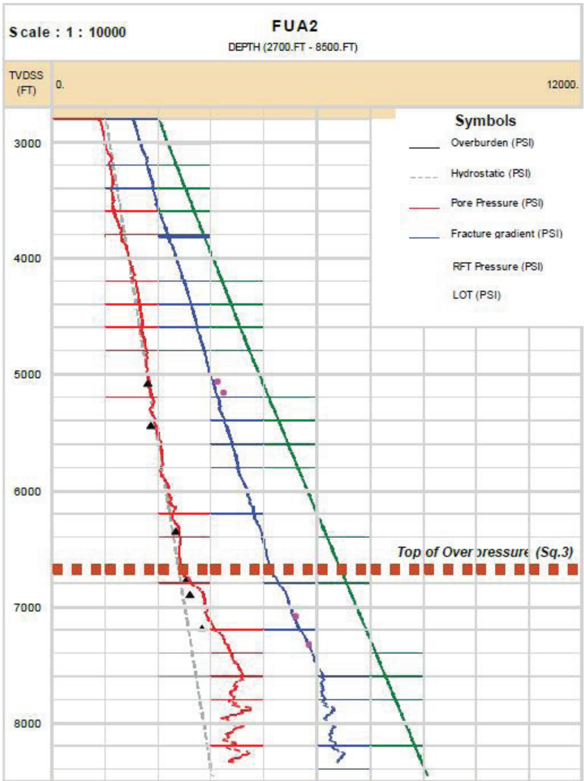
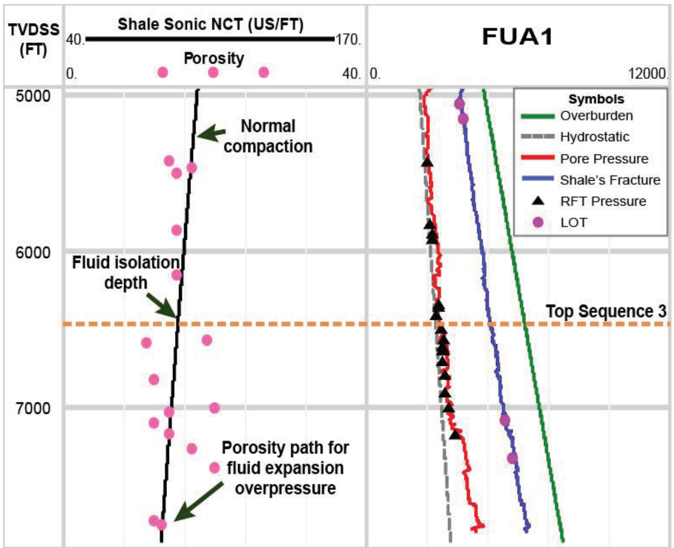


Figure 6. Pore pressure and fracture gradient prediction profile of FUA2.

According to Neuzil (1995) and Osborne and Swarbrick (1997) the overpressure generated by fluid expansion is unlikely to occur in isolation and will also include some component of overpressure generated through disequilibrium compaction. A sonic-density cross-plot analysis highlights the observation that sonic velocity exhibits a significant change with both increasing and decreasing overpressure magnitude. Hence, the sonic-density response to overpressure suggests that gas generation is a key influence on overpressure generation in the Pattani Basin. Furthermore, the observation that sonic and density values return to the loading curve as pore pressures return to hydrostatic provides very strong evidence against clay diagenesis or load transfer having any significant function in overpressure generation in the Pattani Basin.

Also, the porosity trend in this area shows the abnormal pressure as overpressure, the porosity show very low values and decrease with depth (Figure 7a) in the sequence; this is typical of regions controlled by the fluid expansion mechanism and increasing of porosity given a depth is controlled by disequilibruim compaction mechanism (Figure 7b).

a) Porosity vs. Pore Pressure (Fluid Expansion)



b) Porosity vs. Pore Pressure (Disequilibrium Compaction)

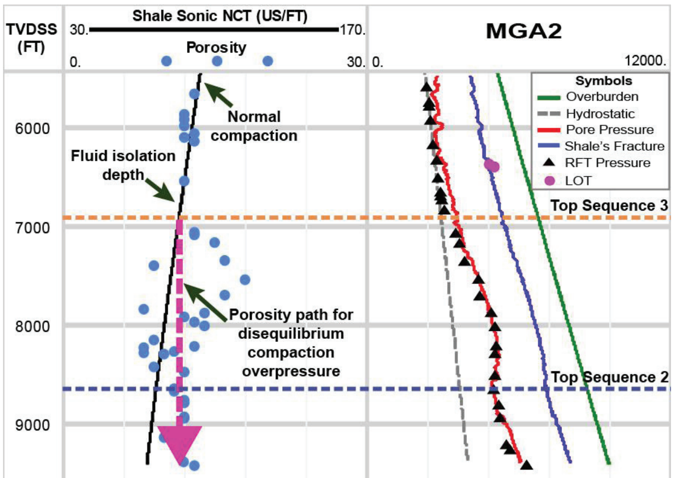


Figure 7. a) Porosity vs. Overpressure in case of fluid expansion show loss porosity with depth when pressure increase. b) Porosity vs. Overpressure in case of disequilibrium compaction show loss porosity with depth when pressure increase.

6.3 Implication of Kerogen to Gas Generation Maturation and Primary Migration

Overpressure is a temporary hydrodynamic phenomenon that can only exist in a sealed volume and, because no natural seal is perfect, will normalize over time. The generation of overpressure by kerogen-to-gas mat uration is also linked to primary migration of hydrocarbons away from the source rock. Hence, the occurrence and distribution of present day overpressure provides a snapshot of how overpressures, and thus fluids, migrate through the petroleum system (Tingay et al., 2009).

In this study area, a consistent observation across most studied wells is that the overpressure develops at the top of sequence 3, and is constrained within this sequence. This likely indicates that the mechanism generating abnormal pressure occurs in situ. Sequence 3 is mainly dominated by transgressive fluvial and marginal marine sediments, which conmprise a widespread and thick low permeability shale succession, associated with thin fluvial-deltaic sands (Jardine, 1997). From the Total Organic Carbon (TOC) and vitrinite reflectance trend (R0) measures available in three of exploration wells studied, there is a significant increase in TOC and R0 values that starts at the top of the overpressured interval and increases with depth (Figure 5). It is obvious that there is a significant amount of potential source rock present and that there is an observable increase in maturation rate within the overpressured sequence. This likely indicates hydrocarbon generation or primary migration from a maturing organic-rich shaley source rock. Thus, it is likely that this organic maturation association has led to the development of overpressure within sequence 3.

In combination, these observations suggest that the overpressured interval, intersected by the studied wells, contains a significant excess volume of hydrocar bon. Typically, these excess fluids are generated in situ within this low-permeability sequence and drive overpressuring of adjacent shale-sealed to higher permeability gas sand reservoirs, either through stratigraphic isolation of the pressured reservoir within maturing low-permeability shale sections or by lateral permeability reduction such as can occur in an unconnected sand body or fault-driven shale juxtaposition.

7. Conclusions

The results of this study show that the pore pressure magnitude and fracture gradient can be predicted reliably in the study area by applying the Eaton method. Combining these results to organic maturation measurements can identify the overpressure mechanisms operating an area and so better assess the potential difficulties in exploration and development drilling.

The relationship between pore pressure and fracture pressure is different for each of the pressure mechanisms so that correlations between the two for prediction purposes can be misleading. The assessment of the safety window between pore pressure and fracture pressure has to be performed with accurate measurements of both. The combination of an extensive and high-quality pore pressure database combined with sonic velocity/density–vertical effective stress and velocity-density crossplot analysis indicates that a significant component of overpressuring in the sequence 3 of the Pattani Basin is the result of fluid expansion, most likely gas generation through kerogen catagenesis or oil cracking. However, the highly effective seal required for gas generation overpressuring (or any fluid expansion or transfer mechanism) results in conditions also being favorable for overpressure generation by disequilibrium compaction. Based on the study of 12 wells the estimation of gas generation in this area, in excess of the hydrostatic pressure, contributes 1-4 ppg (0.052–0.208 psi/ft) of pore pressure. Thus, the gas generation, acting in isolation, will likely generate moderate overpressure. Furthermore, the combination of gas generation and disequilibrium overpressure can generate high-magnitude overpressures that represent a significant hazard to drilling operations. Clearly, the gas generation overpressures in the study area do not exist in isolation, and occur coincidently with overpressure generated by disequilibrium compaction.

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