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RESEARCH ARTICLE

The Influence of Pore Porosity on Overpressure Formation: A Case Study of Field X, Kutai Basin, Indonesia

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Abstract

Abnormal pore pressure (overpressure) poses a significant challenge in drilling operations, particularly in deltaic environments such as the Kutai Basin, East Kalimantan. This study aims to analyze the relationship between rock porosity and overpressure zones based on the interpretation of exploratory well log data. Sonic log (DT), resistivity (ILD), density (RHOB), and neutron porosity (NPHI) data were integratively analyzed using Interactive Petrophysics (IP) software. Pore pressure estimation was conducted using the Eaton method, based on both sonic and resistivity logs, approaching the normal compaction trend. Results show that overpressure zones were first detected at depths of 700–820 m in the Kampung Baru Formation, with anomalies continuing at depths of 1150–3100 m, especially within the Pulau Balang Formation. These zones are characterized by high and constant DT values, low ILD, and porosity (NPHI and total) that does not decrease with depth, indicating undercompaction as the main mechanism causing overpressure. Data points in the sonic-density crossplot confirm the dominance of smectite minerals, with no indication of transformation to illite, ruling out thermal mechanisms such as hydrocarbon generation. The study concludes that overpressure at this location is primarily driven by loading mechanisms resulting from rapid sedimentation in impermeable shale lithology. These findings have significant implications for drilling planning, enabling safer and more effective mud program design and blowout risk mitigation in high-pressure areas

Keywords: Overpressure Zone, Undercompaction, Porosity, Well Log Analysis, Kutai Basin

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1. Introduction

Pore pressure is one of the crucial parameters in hydrocarbon exploration and production, particularly in the context of drilling planning and subsurface risk evaluation (Irwan, 2017). Generally, pore pressure is classified into three categories: normal hydrostatic pressure, underpressure, and overpressure (Zulyan et al., 2024). Normal hydrostatic pressure refers to the pressure generated by the weight of a static fluid column, whereas underpressure occurs when pore pressure is lower than hydrostatic pressure, and overpressure describes a condition where pore pressure exceeds normal hydrostatic pressure (Swarbrick & Osborne in Tappi & Cherdasa, 2023).

The phenomenon of overpressure has significant technical implications, especially in sedimentary basins with complex geological histories such as the Kutai Basin in East Kalimantan (Zahran et al., 2024). This region is known for its extremely thick sedimentary sequences and diverse lithology, making it one of the areas with the highest geomechanical uncertainty in Southeast Asia. Stratigraphically, the Kutai Basin comprises major formations including the Kampung Baru, Balikpapan, Pulau Balang, and Pamaluan Formations, which were deposited in deltaic to shallow marine environments, with dominant lithologies of sandstone and shale (Satyana et al. in Jamaluddin et al., 2024).

According to Swarbrick & Osborne in Setyawan et al. (2020), the mechanisms behind overpressure formation are categorized into two groups: loading and non-loading. Overpressure mechanisms related to loading occur due to one or more principal stresses acting on the sediments, such as high sedimentation rates. Meanwhile, non-loading mechanisms are caused by increases in pore fluid volume under conditions where the fluid cannot escape the pore space. Examples of non-loading mechanisms include clay mineral diagenesis and hydrocarbon generation. The transformation of smectite to illite and kaolinite to illite increases fluid volume within the rock's pore space. The smectite-to-illite transformation also alters clay mineral size, contributing to a decrease in effective stress.

The primary geological process contributing to overpressure formation in this area is compaction, which is the densification of sediments due to increasing overburden load with depth (Putri et al., 2024). Imperfect compaction, especially in low-permeability shale lithology, can reduce porosity and trap fluids within the pore system, thereby increasing pore pressure abnormally or causing overpressure (Osborne & Swarbrick in Asih et al., 2024). Imperfectly compacted shale also acts as an effective cap rock, allowing the accumulation of high-pressure fluids beneath it.

The accumulation of high pore pressure creates overpressure zones, which pose serious challenges during drilling operations. A mismatch between actual formation pressure and the applied mud pressure may lead to well control failure (Huque et al., 2020). In extreme cases, this condition can trigger uncontrolled blowouts—unregulated flow of formation fluids to the surface—which not only endanger operational safety but also result in significant economic loss and environmental risk (Riadh et al., 2019).

2. Method

This research employs a quantitative approach based on well log data to analyze the relationship between porosity and overpressure within stratigraphic intervals in the Kutai Basin. The data used include sonic logs (DT), resistivity (ILD), neutron porosity (NPHI), and density (RHOB) from a single exploration well. These data were analyzed using Interactive Petrophysics (IP) software, which allows integrated log interpretation and accurate pore pressure calculation in this study.

The overall analytical procedure is systematically described in the flowchart shown in Figure 1. The analysis began with the calculation of overburden pressure using density data, followed by the estimation of pore pressure using the Eaton method to identify overpressure zones.

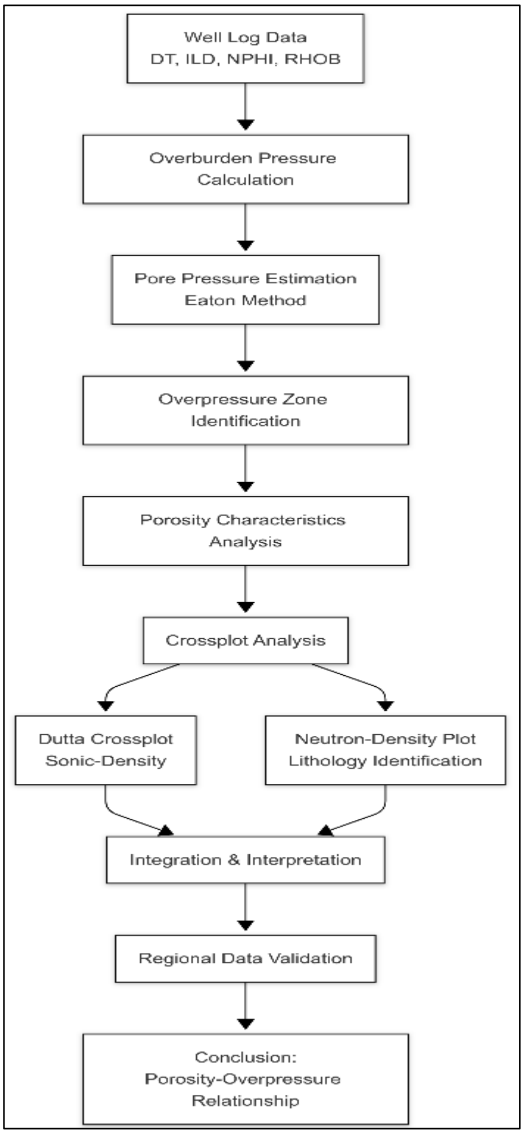

Fig. 1. Flowchart of this research

Eaton (1975) used transit time data to determine the Normal Compaction Trend (NCT) (Datu et al., 2020). The NCT illustrates the pattern of porosity reduction with increasing depth (Verma et al., 2021). If the compaction process occurs normally, data points will follow the NCT line, where porosity decreases, effective stress increases, and pore pressure remains in a normal state equivalent to standard hydrostatic pressure (Ramdhan, 2017; Haris et al., 2017). The Eaton equations are described as follows (Rinaldo & Haris, 2025):

$$P = \sigma_v - (\sigma_v - P_n) * \left(\frac{R}{R_n}\right)^n \qquad (1)$$

$$P = \sigma_v - (\sigma_v - P_n) * \left(\frac{\Delta t_n}{\Delta t}\right)^n \qquad (2)$$

Where:

P = Pore Pressure (psi)
σ_v = Overburden Pressure (psi)
P_n = Hydrostatic Pressure (psi)
R = Shale Resistivity (ohm.m)
R_n = Normal Shale Resistivity (ohm.m)
Δt_n = Normal Sonic Log (us/ft)
Δt = Observed Sonic Log (us/ft)
n = Eaton exponent

Equation (1) is used to calculate pore pressure (P) using resistivity data, while Equation (2) calculates pore pressure based on sonic log transit time. The choice of this method is based on the geological conditions and the overpressure formation mechanism at the study location. According to Budiman et al. (2017), the Eaton method is not recommended under unloading conditions, where overpressure results from pressure release or diagenetic processes, because, in such cases, the relationship between logs and pore pressure no longer follows the normal compaction trend.

However, in this study, based on data analysis by Fauzan et al. (2024), the overpressure formation mechanism is due to loading—i.e., sediment load accumulation causing increased overburden and mechanical pore pressure buildup. In this condition, the Eaton method is more appropriate because it assumes that overpressure results from deviations from the normal compaction trend caused by continuous sediment load. Thus, the use of the Eaton method in this study is considered geomechanically relevant and valid, supported by the available log data.

Subsequently, overpressure zones were identified based on deviations between actual pore pressure and normal hydrostatic pressure. To evaluate porosity characteristics, porosity log analysis (NPHI and total porosity) was conducted along with sonic response interpretation. The correlation between porosity parameters and overpressure zones was analyzed by observing log value consistency patterns with depth and confirmed using a sonic-density crossplot (Dutta crossplot) to identify the diagenetic state of clay minerals as indicators of the type of compaction mechanism. All results were integratively analyzed to obtain a comprehensive understanding of the relationship between rock porosity and pore pressure development in the geological system of the Kutai Basin.

3. Result and Discussion

The data point distribution on the sonic-density crossplot by Dutta (2002) in Figure 2 shows that the log response from the Kampung Baru Formation (Figure 2a) follows the smectite mineral trend, which generally exhibits low density values (<2.5 g/cc) and high transit time (>100 µs/ft). According to Dutta (2002), this pattern is characteristic of formations still in the early stages of diagenesis, where the dominance of smectite indicates that no significant mineral transformation to illite has occurred, typically taking place at temperatures >80–100°C and depths >2000 m.

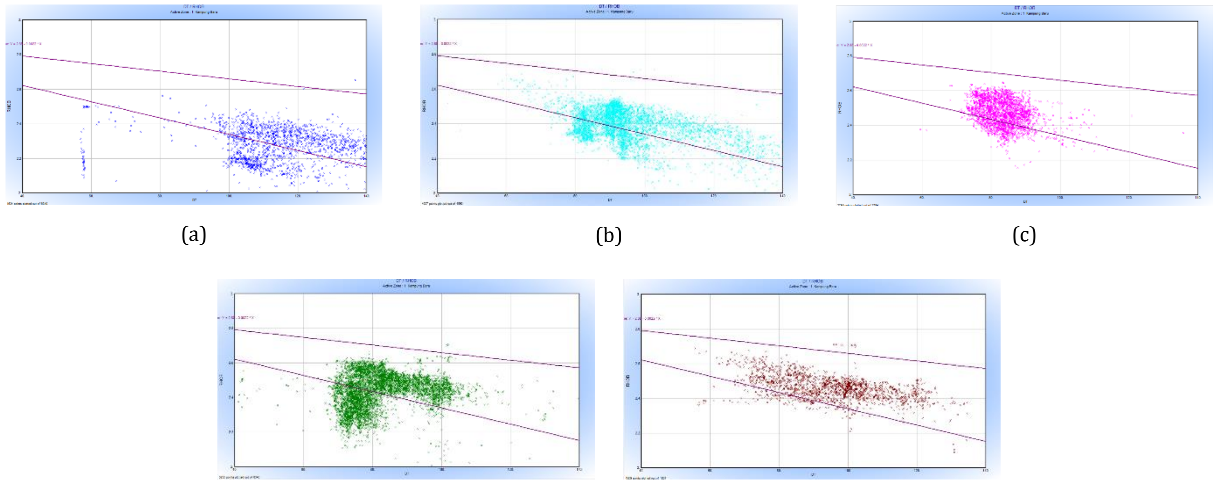
(a) (b) (c)
(d) (e)

Fig. 2. Sonic–density crossplot for formations: a) Kampung Baru, b) Balikpapan, c) Pulau Balang, d) Pulau Balang, and e) Pamaluan

The transformation from smectite to illite usually occurs as a response to increased temperature and pressure, reflecting thermal maturation and advanced compaction. Therefore, the continued dominance of smectite in the Kampung Baru Formation indicates that the rocks in this zone have not undergone significant chemical compaction or reached intermediate to advanced diagenesis conditions required for mineral transformation.

A similar phenomenon was also observed in the Balikpapan Formation (Figure 2b), Pulau Balang Formation (Figures 2c and 2d), and Pamaluan Formation (Figure 2e), where the crossplot points continue to follow the smectite trend line without shifting toward the illite trend. This reinforces the notion that these four formations—especially in the well intervals observed—are still predominantly influenced by mechanical or physical compaction (mechanical compaction), also known as loading or undercompaction.

Imperfect compaction occurs when sediments are buried too rapidly, preventing pore water from being expelled efficiently. As a result, pore pressure increases and causes disequilibrium compaction. This process commonly leads to overpressure, especially in fast-depositing environments such as deltas and fluvio-deltaic systems, which are key characteristics of the Kutai Basin (Jamaluddin et al., 2023).

Clay mineralogical analysis within the overpressure intervals showed no indication of smectite-to-illite transformation. This transformation generally occurs at higher temperature and depth conditions and is often associated with the release of bound water, contributing to pore pressure buildup (Kazainullah et al., 2021; Johan et al., 2024). The absence of this transformation suggests that overpressure formation in this interval is more likely due to undercompaction rather than generative mechanisms like hydrocarbon expansion or mineral transformation that produce additional fluids.

Furthermore, thermal immaturity is supported by the continued presence of dominant smectite, which is typically unstable at elevated temperatures. The preservation of smectite indicates that the formation has not yet reached sufficient thermal maturity to trigger significant hydrocarbon generation (Barberes et al., 2025).

Thus, the excessive pore pressure identified in this interval can be effectively linked to fluid accumulation caused by hindered compaction (undercompaction), while contributions from thermal mechanisms such as hydrocarbon generation can be ruled out as primary causes.

Figure 3 below presents the vertical stress (overburden pressure) calculated using formation density (RHOB) log data along with estimated density for validation. The graph on the right shows that vertical stress increases with depth, consistent with the principle that vertical stress depends on the weight of the overlying rock column. These vertical stress values are essential inputs for pore pressure calculations, which are useful for predicting overpressure zones and designing safe drilling parameters.

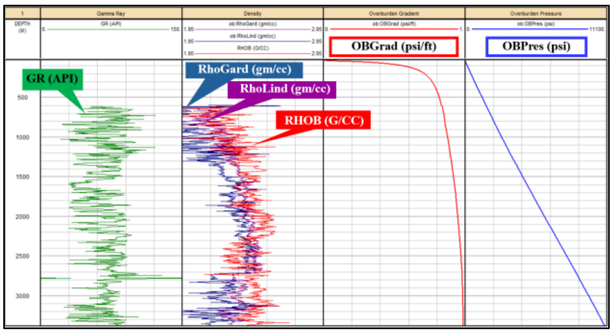

Fig. 3. Gamma ray log, density, gradient, and overburden pressure for lithology analysis and formation pressure evaluation.

Interpretation of Figure 4 above reveals that the onset of overpressure begins at a depth of approximately 700–820 meters within the Kampung Baru Formation.

The zone continues progressively at other depths, namely around 1150–1200 m, 1300–1330 m, 1700–1900 m, 2200 m, 2500 m, 2700–2800 m, and 3000–3100 m. The presence of these zones indicates that pore pressure significantly increases at various depth intervals, suggesting a multi-level overpressure distribution along the stratigraphic column.

This is further supported by mud weight data from the well, which shows a consistent increase with depth. The rise in mud weight values reflects the need to balance increasing pore pressure and also serves as an indirect indicator of significant overpressure in the area.

The most dominant overpressure zone is within the Pulau Balang Formation, lithologically composed of gray to black shale and clay with very low permeability (Rizky et al., 2023). The disconnected nature of pore spaces in these claystones prevents formation water from escaping as sediments are buried deeper. This leads to overpressure generation via the loading or undercompaction mechanism, where sedimentation rate exceeds the rate of pore fluid expulsion. As a result, fluid becomes trapped in the pores, creating pressure that exceeds normal hydrostatic levels.

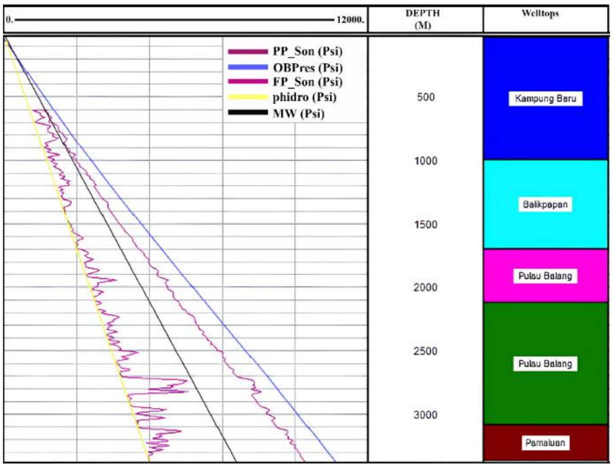

Fig. 4. Pore pressure calculation results using the Eaton method

Interpretation of Figure 5 shows that the Delta-T (DT) or sonic log value in the Pulau Balang Formation's overpressured intervals remains relatively constant and high compared to the normal zones above or below. These high DT values indicate that acoustic wave velocity is reduced due to the medium being relatively porous and fluid-saturated (Irmaya et al., 2022). In normally compacted rock, wave velocity increases and DT values drop. Conversely, consistently high DT values in overpressure zones suggest incomplete compaction, meaning porosity remains relatively high and formation fluids are not fully expelled.

This phenomenon aligns with the ILD (Induction Log/Resistivity) response, which shows low values in the Pulau Balang interval. Low resistivity values—opposite to the DT trend—indicate the rock contains conductive fluids, most likely formation water not yet replaced by hydrocarbons. The combination of high DT and low ILD is a classic indicator of overpressure due to loading or undercompaction, where fluids are trapped in impermeable formations like shale and clay.

Furthermore, the Neutron Porosity (NPHI) log in the Pulau Balang Formation also exhibits a consistent response, not decreasing significantly with depth. This shows that porosity is being retained, which should normally decrease with proper compaction. The consistent NPHI values reinforce the interpretation of overpressure, where high pore pressure inhibits grain compaction.

Lastly, the Total Porosity analysis (from both crossplot logs and model estimation) shows an increasing deflection in the Pulau Balang interval. Theoretically, as shown in Sari et al. (2023), porosity should decrease with increasing depth due to growing lithostatic load. This anomaly strongly indicates that fluid is still trapped within the rock pores, keeping pore space open, and further supports the presence of active overpressure zones in this interval.

In summary, the combined behavior of these four logs—DT, ILD, NPHI, and total porosity—consistently indicates that overpressure in the Pulau Balang Formation is caused by loading mechanisms, i.e., rapid sedimentation that prevents formation water from escaping due to the predominance of impermeable shale and clay lithology.

The presence of overpressure is also supported by a study by Morang et al. (2024) in the Sanga-Sanga Field, which found overpressure in Interval-I, correlating with delta plain to delta front depositional environments. The overpressure mechanism was due to loading and hydrocarbon generation, with pore pressure reaching 4000–4700 psi.

Additionally, a study by Arifin et al. (2024) demonstrated that overpressure in the Kutai Basin results from both loading and unloading mechanisms, including hydrocarbon generation and clay diagenesis. Sonic and density log data indicate that overpressure correlates with gas generation zones. Understanding these mechanisms is critical for safe and efficient drilling planning.

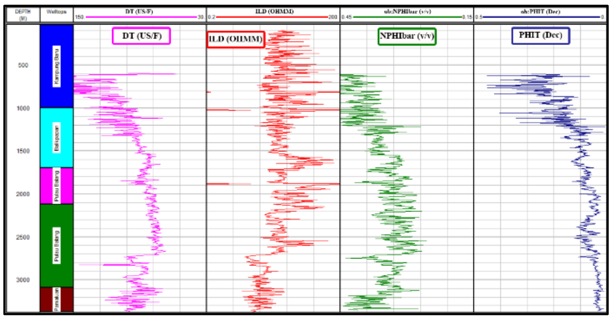

Fig. 5. Well log data including sonic, resistivity, neutron porosity, and total porosity

Based on the full interpretation of logs and crossplots, it can be concluded that the dominant overpressure mechanism at the study location is loading. This conclusion is supported by:

(1) The dominance of smectite minerals, with no indication of transformation to illite (i.e., no evidence of bound water release);
(2) The absence of high resistivity anomalies indicating hydrocarbon migration as a pressure source;
(3) No identified thermal fluid expansion zones from available log data.

Therefore, mechanisms such as hydrocarbon generation and fluid expansion cannot be considered the primary causes of overpressure at the study location.

4. Conclusion

Based on the analysis of well log data in the Kutai Basin, a strong correlation was found between porosity and overpressure, particularly in the Kampung Baru, Balikpapan, Pamaluan, and Pulau Balang Formations. Overpressure zones are characterized by high and consistent sonic log (DT) values, low resistivity (ILD), and porosity values (NPHI and total) that do not decrease with depth. These conditions indicate that porosity is being preserved due to loading or undercompaction mechanisms—that is, when sediments are buried rapidly, preventing pore fluids from escaping in impermeable rocks.

These findings have significant operational implications, especially in the context of drilling planning in deltaic basin environments like the Kutai Basin. Early identification of overpressure zones can enhance drilling safety, guide more accurate mud weight design, and optimize reservoir management strategies in similar geological systems. However, this study has limitations, as it relies on data from a single well without additional validation from seismic or core data. Therefore, further research is recommended, incorporating multi-well data and other geophysical approaches to improve the spatial validity and depth understanding of overpressure distribution in this area.

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