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Pore Pressure and Compartmentalization of Carbonate Reservoirs in Northern Madura Platform - East Java Basin, Indonesia

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Abstract - Understanding pore pressure characteristics in carbonate reservoirs is essential, because it concerns all aspects of subsurface, drilling, and occupational safety, as well as the environment in oil and gas exploration and exploitation. In this study, the pore pressure regime and connectivity of the carbonate reservoir (compartmentalization) of Kujung and Ngimbang Formations in the northern Madura Platform of East Java Basin are characterized by utilizing direct pressure data and wireline logs from five wells. The result shows that both hydrostatic and slight overpressure conditions are found in these formations, further indicating the presence of carbonate compartmentalization. The magnitudes of overpressure, however, are mostly very low, with an average of ~37 psi. Four compartmentalized carbonates are identified based on the presence of different pressure gradients in the water leg. The slight overpressure in the carbonates is likely owing to pressure transference from overpressured shale at depth. In addition, by using acoustic impedance from seismic, the depositional environments of the carbonates are interpreted as lagoon and tidal flat. These environments support the occurrence of patch reef carbonate buildups in the Kujung and Ngimbang Formations, which later become a good environment for overpressure generation and carbonate reservoir compartmentalization.

Keywords: carbonates, compartmentalization, depositional environment, slight overpressure

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Introduction

Background

Carbonates are commonly considered targeted reservoirs in hydrocarbon exploration and exploitation, including in Indonesia sedimentary basins. They can be categorized as unconventional reservoirs which are commonly heterogeneous in porosity and permeability. The heterogeneities are due to depositional environments, diagenetic processes, and dissolution (Jardine and Wilshart, 1982; Brasher and Vagle, 1996; Anselmetti and Elberli, 1999).

The pore pressure of carbonate reservoirs within the same formation can vary, *e.g.* from hydrostatic to overpressure (Green *et al.*, 2016). Since carbonate rocks are stiffer than shale, they may experience overpressure conditions without affecting their porosity (Atashbari and Tingay, 2012). This condition may cause challenges during drilling. Losses can take place if the mud weight designed for the drilling is too high, while kicks can be encountered if it is too low. These can lead to serious drilling problems as well as unexpected increases in drilling costs. Thus, understanding the pore pressure characteristic of carbonate reservoirs is of paramount importance.

Furthermore, reservoir compartmentalization is an essential uncertainty to be identified during the exploration as it affects the volume of oil and/or gas that can be produced (Smith, 2008). Unidentified compartmentalization can impact the profitability of any hydrocarbon field significantly. In an extreme case, it may lead to early field abandonment. Hence, this kind of uncertainty should be addressed; fortunately, pore pressure data can be used as one of the tools to assess the presence of reservoir compartmentalization.

This study was conducted in the northern Madura Platform of East Java Basin (Figure 1), where previous studies (*e.g.* Manik and Soedaljo, 1984; Kusumastuti *et al*., 2000; Davies *et al*., 2007) as well as more recent studies (*e.g*. Ramdhan *et al*., 2013; Sinulingga and Ramdhan, 2017; Ramdhan, 2021; Reksalegora *et al*., 2022) have not yet covered pore pressure and compartmentalization analyses in carbonates of this area. Carbonates of Kujung and Ngimbang Formations, which have been proven as hydrocarbon reservoirs, are the object of this study.

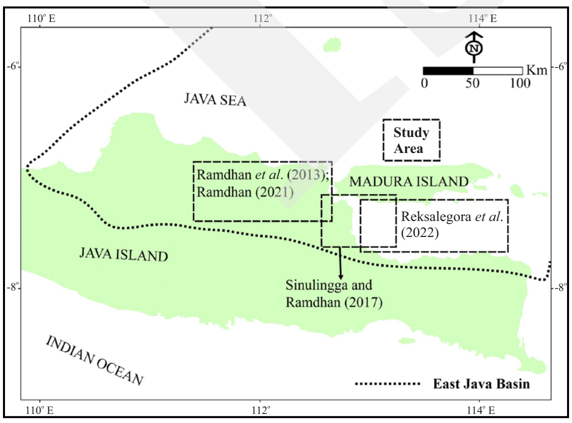

Figure 1. Location of this study compared with recent studies. East Java Basin boundary is from Koesoemadinata (2020).

To characterize and describe the pore pressure regime of carbonate reservoirs in both formations based on five typical wells, direct pressure measurement data obtained from the repeat formation tester (RFT) and modular formation dynamics tester (MDT) were used. The deterministic method (Ramdhan and O'Connor, 2022) was partly utilized to identify the presence of overpressured shale, and to determine its generating mechanism. As the possible cause of overpressured carbonates in this study, the possibility of pressure transference from shale to the carbonate reservoirs was also discussed. Carbonate compartmentalization in each well was successfully identified based on the pore pressure characteristic. In addition, the influence of depositional settings on both the pore pressure regime and compartmentalization of carbonates in the studied area is also discussed in this paper.

Geologic Overview

The oldest Tertiary sedimentary rock in East Java Basin consists of a syn-rift deposit, Ngimbang Formation (Middle Eocene to Early Oligocene), as can be seen in Figure 2 (Pringgoprawiro, 1983; Pertamina BPPKA, 1996; Mudjiono and Pireno, 2001). This formation comprises both clastic sediments and carbonates. The Kujung Group, including the Prupuh Formation, which consists of mudrock, carbonate buildups and platforms, was deposited later (Late Oligocene to Early Miocene). It is overlain by Tuban Group, which is composed of marine mudrock of Tuban and Rancak limestone (Early Miocene). Then, Ngrayong Group (Middle Miocene) which consists of mudrock (Tawun Formation), sandstone (Ngrayong Formation), and limestone (Bulu Formation), was deposited and followed by the deep marine mudrock of Wonocolo Formation (Middle to Late Miocene), sandy marl of Ledok Formation (Late Miocene), sandy limestone and marl of Mundu Formation (Early Pliocene) and marl with sandstone intercalation of Kalibeng

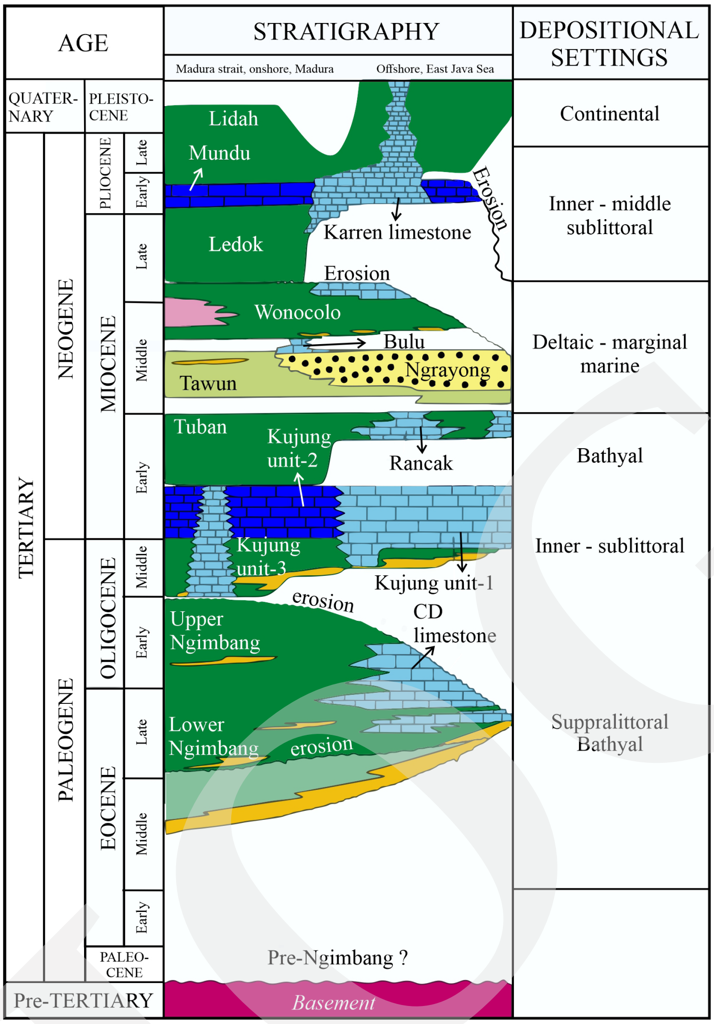

Figure 2. Stratigraphy of East Java Basin (compiled and modified from Pringgoprawiro, 1983; Pertamina BPPKA, 1996; Mudjiono and Pireno, 2001).

Formation (Pliocene). The youngest sedimentary rock deposited in this basin is Lidah Formation (Late Pliocene to Pleistocene) which is dominated by clay deposits.

The tectonic history of East Java Basin can be summarized into four stages (Koesoemadinata, 2020), *i.e.* pre-rift, extensional rifting, sagging, and compressional stages. The pre-rift occurred before Eocene and was followed by extensional rifting with syn-rift sediment deposition from Early Eocene to Early Oligocene. After that, the sagging process took place from Late Oligocene to Early Miocene, accompanied by post-rift stable shelf deposition. The compressional stage from Middle Miocene to the present day marks the latest tectonic stage in this basin. During this last stage, onshore Northeast Java and Madura zones were down-warped into East Java back-arc Basin.

Methods

In this paper, available direct pressure measurement data from RFT and MDT were mainly used to indicate the pore pressure regime in the carbonate reservoirs, *i.e.* Kujung and Ngimbang Formations. As discussed by O'Connor (2022), predicting pore pressure in carbonates is still challenging since existing techniques like Eaton's method (Eaton, 1975) often give inconsistent results. In addition, the deterministic method proposed by Ramdhan and O'Connor (2022) was also partly used to investigate the presence of overpressured shale as well as its generating mechanism, which is later used in analyzing pressure transference from shale to carbonate reservoirs.

According to Ramdhan and O'Connor (2022), overpressure generated by loading and unloading mechanisms should be quantified separately. Density and sonic logs were utilized for this purpose. First, sonic and density cross-plots (Dutta, 2002; Katahara, 2006) were used to interpret the overpressure generating mechanism, as illustrated in Figure 3. If the overpressure is solely caused by loading, the data will follow the trend of smectitic or illitic lines and will halt at a certain point on these lines. However, if unloading also contributes to the overpressure, the data will diverge from the lines (Sargent *et al*., 2015), following the curves indicated in Figure 3. In addition, the composition of clay minerals in the carbonate interval was also analyzed using available XRD data to assess whether clay diagenesis, *i.e*. smectite to illite transformation, occurred and caused the overpressure.

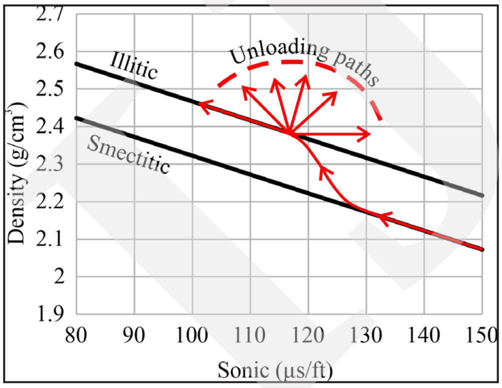

Figure 3. Density and sonic cross-plot were used to identify the causes of overpressure (Dutta, 2002; Katahara, 2006).

To generate pressure/stress-depth plot in this study, overburden stress (σ) was calculated using available density data. The equation used is as follows:

$$\sigma = \int_0^z \rho_b . g . dz \quad \text{..................................(1)}$$

where

ρ_b is bulk density from the density log,

g is gravitational acceleration,

z is depth.

Fortunately, in this study, there is one water density data obtained from water analysis of the MDT water sample to determine the hydrostatic pressure gradient $(\frac{dP}{dz})$ of formation water using Equation 2.

$$\frac{dP}{dz} = \rho_w . g \quad \text{..(2)}$$

where:

ρ_w refers to the density of water.

When the pore pressure has been characterized well enough, then the reservoir connectivity is analyzed. According to Dahlberg (1995), a composite plot of pressure gradients of wells can be utilized to identify the presence of reservoir compartmentalization, as illustrated in Figure 4. As can be seen, there are two reservoirs on the left-hand side, while the right-hand side shows offset pressure gradients, indicating separate pressure compartments. This practical approach is applied and tested in this study to identify the carbonate compartmentalization of Kujung and Ngimbang Formations.

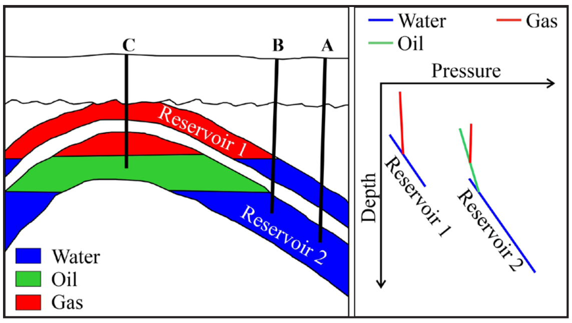

Figure 4. An example of schematic reservoir connectivity analysis carried out in this study based on pore pressure gradient in three wells (modified from Dahlberg, 1995).

Result

Hydrostatic Gradient

Freshwater with a density of 1 g/cm^3 will give a hydrostatic pressure gradient of 0.433 psi/ft (calculated using Equation 2). However, for saline and brine waters, which are commonly found in formations at depth, the water density can be higher than 1 g/cm^3. It is very important to determine the hydrostatic pressure gradient, especially in the case of very low to low magnitude overpressure, using available water density data, which is usually pretty rare. Fortunately, in this study, one water density data was obtained from sampling using MDT in the carbonate interval. The formation water density at the formation temperature (~217 °F) is 1.009 g/cm^3, which gives a pressure gradient of 0.437 psi/ft. This pressure gradient was next used for analyzing pore pressure as well as compartmentalization in the carbonates reservoir of Kujung and Ngimbang Formations in this study.

Pore Pressure Regime

Composite pressure data from RFT dan MDT in each well (Figure 5) indicates there are two pore pressure regimes of carbonates (Kujung and Ngimbang Formations), *i.e.* hydrostatic and slight overpressure. AA-1 has the highest overpressure magnitude at a depth of 6142 ft. below the subsea (TVDSS), ~264 psi, while the average overpressure magnitude is only ~37 psi. Mathematically, this small average magnitude of overpressure equals an excess of water column only up to ~26 m.

Figures 6 and 7 show the typical density and sonic logs in the studied area, represented by AA-4 and AA-5. It can be seen that both Kujung and Ngimbang Formations are shaly carbonates, represented by lithology in green colour. Even though the pressure data clearly indicates the presence of slight overpressure (Figure 5), the density and sonic logs do not give a clear response to it.

Any reversal from the normal trend (*i.e.* increasing density with depth and decreasing sonic logs with depth) can not be observed in both density and sonic logs, that usually become a hint in identifying the presence of overpressure, and it has been discussed in depth by Ramdhan and O'Connor (2022). This may be due to the very low magnitude of the overpressure, which will be discussed later.

Figure 8 shows the sonic-density cross-plots for AA-4 (Figure 8a) and AA-5 (Figure 8b). The sonic-density data from ~5,000 to 7,000 ft have moved from the smectitic line to the illitic line. This, however, does not correspond to a high overpressure magnitude, as commonly expected and identified by some studies in several of Indonesia sedimentary basins (*e.g.* Ramdhan and Goulty, 2011; Hutasoit *et al.*, 2013; Ramdhan and O'Connor, 2022).

Compartmentalization

The presence of carbonate reservoir compartmentalization is illustrated in Figure 9. This figure is a composite plot of pressure data from

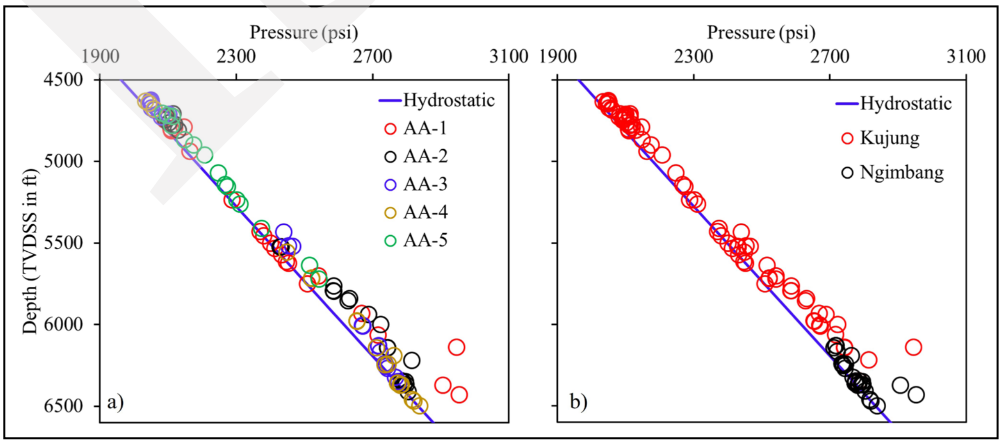

Figure 5. Composite pressure data from RTF and MDT: a) Plot of pore pressure data in each well. b) Plot of pore pressure data grouped by the formation. The depth is the true vertical depth subsea (TVDSS). AA-1 to AA-5 are the names of the wells.

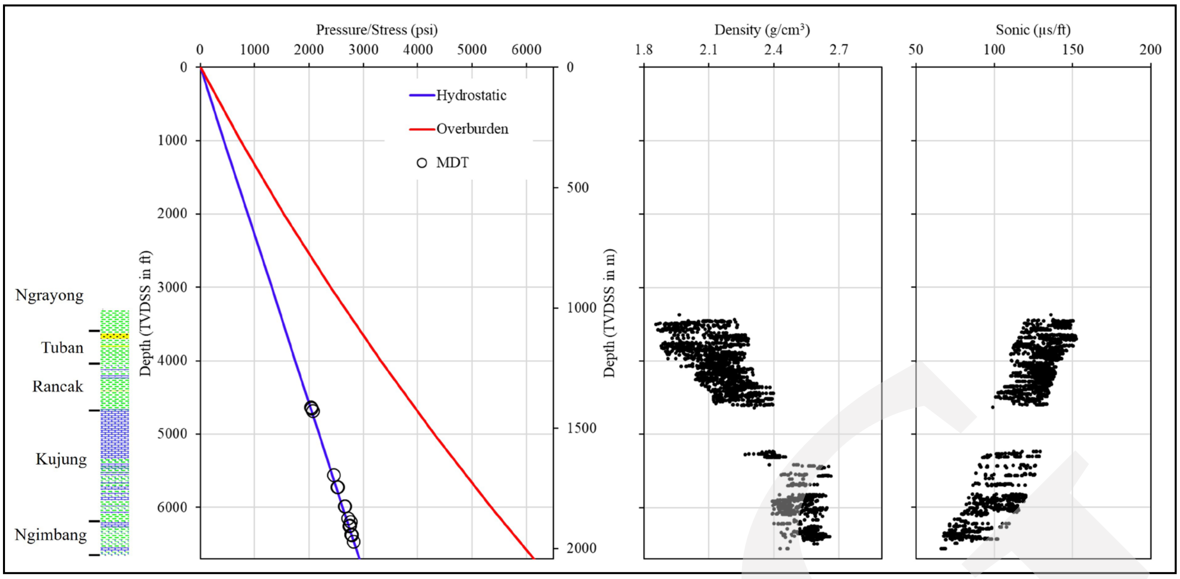

Figure 6. Generalized lithologic column, pressure/stress-depth plot, and wireline log in the shale section of AA-4. As for the lithology: sandstone (yellow), shale (green), and limestone (blue).

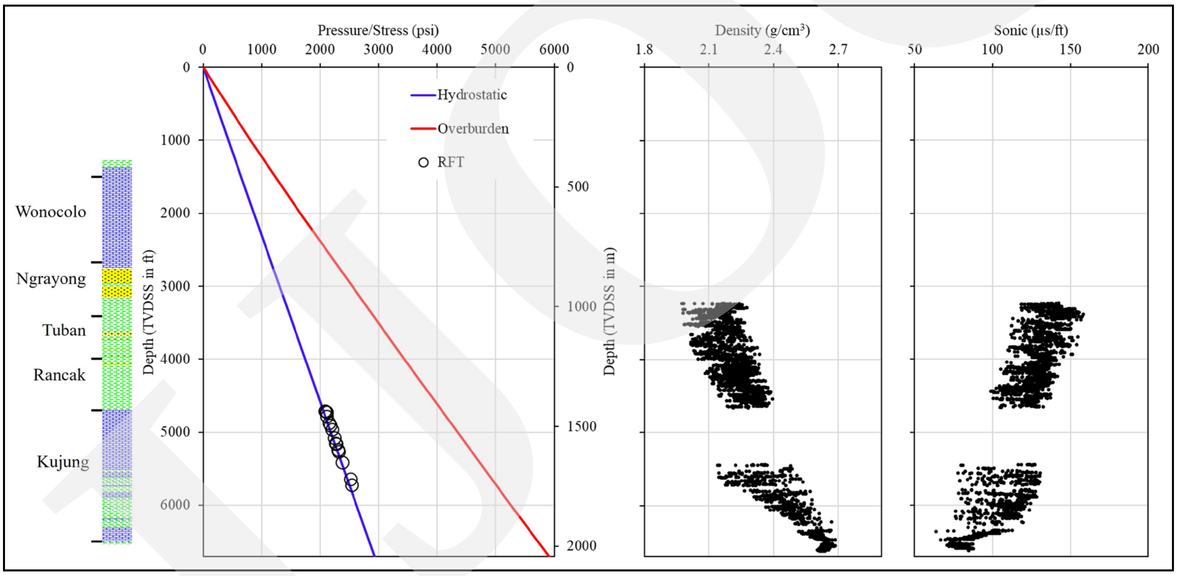

Figure 7. Generalized lithologic column, pressure/stress-depth plot, and wireline log in the shale section of AA-5. As for the lithology: sandstone (yellow), shale (green), and limestone (blue).

all wells. Although data on fluid type is not available, Figures 9a to 9d show very clear trends of pore pressure data, following as well as parallel to the hydrostatic pressure gradient of the water. Therefore, the data can be interpreted and represent pressures in the water leg. There is a possibility of errors in the pressure data. The RFT with quartz gauge (QG) has an error of ~15 psi, while the MDT with combinable quartz gauge (CQG) has a smaller error of ~2.5 psi (Ireland *et al.*, 1992). The red dashed lines in Figure 9 indicate the error interval of ~15 psi for each carbonate compartment.

Four main carbonate compartments were found based on the pore pressure data of all wells. In Figure 9a, the pressure data fall on the hydrostatic line, thus, indicating that this carbonate reservoir compartment is in a hydro-

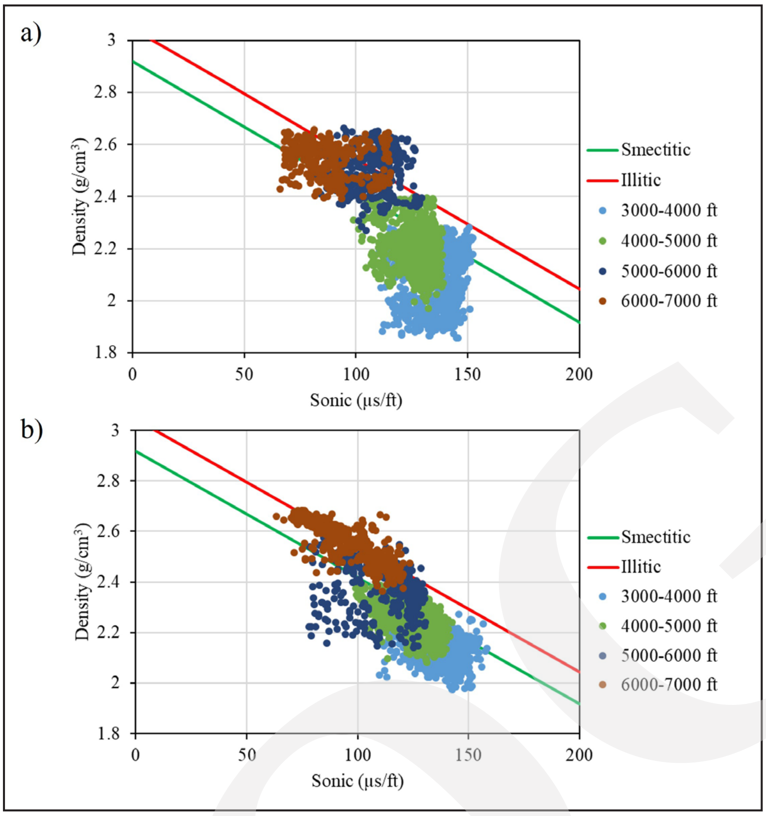

Figure 8. Sonic-density cross-plots in shale section at a) AA-4 and b) AA-5.

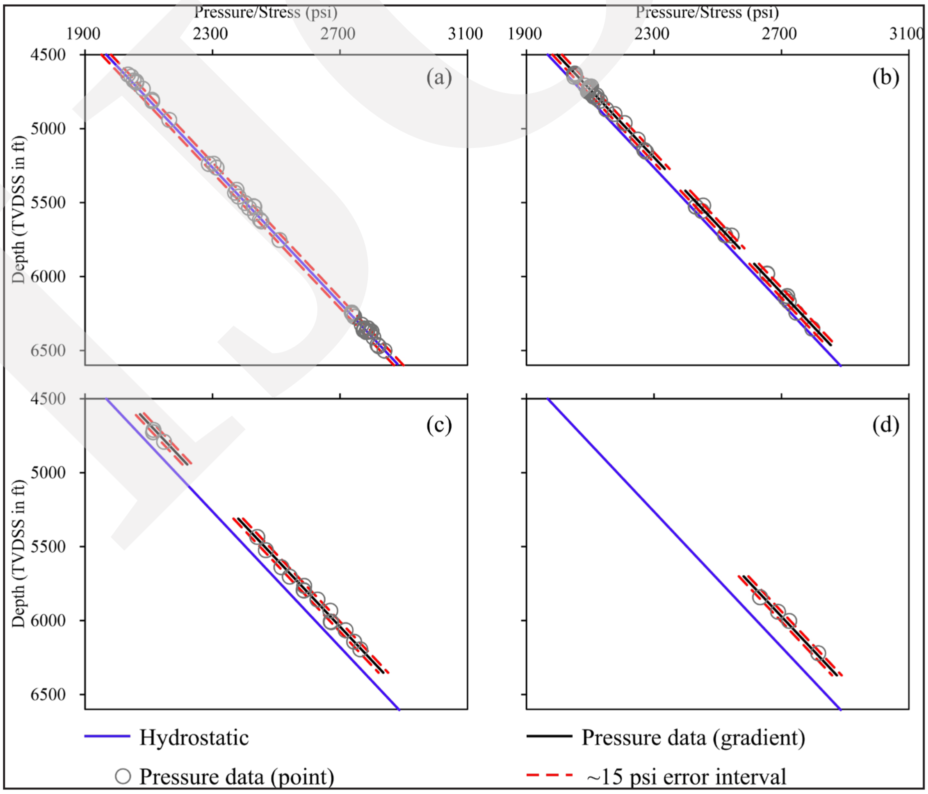

Figure 9. Composite pore pressure data from all wells. (a) to (d) indicates each carbonate reservoir compartment, interpreted based on the offset or shifting of the pore pressure gradient (black line).

static condition. Meanwhile, the other compartments, shown in Figures 9b to 9d, are in a slight overpressure condition, though the overpressure magnitude is considerably low, ranging from ~15 to 101 psi. Therefore, on a bigger scale, as illustrated in Figures 6 and 7, it is difficult to observe the presence of the slight overpressure visually from the pressure data plotted on the pressure-depth plot.

Discussion

The shaly carbonate lithology of Kujung and Ngimbang Formations (illustrated by the lithologic column in Figures 6 and 7) was suspected to contribute to the slight overpressure in the studied area. The shale may not be as thick as the common high overpressured shale in other Indonesia sedimentary basins, *e.g.* Baong Formation in North Sumatra Basin (Syaiful *et al*., 2020). However, its presence contributes to the overpressure. As generally known, overpressure will occur, either by loading or unloading mechanism, only if the water in rock pores can not escape at a considerably high rate compared to the increase of overburden stress in the loading mechanism or the rate of fluid expansion in the unloading mechanism. This is the typical characteristic of shale, which is low in permeability. Therefore, shales at depth are usually suspected to be overpressure over the geologic-time scale of burial.

In this study, like the carbonates of Kujung and Ngimbang Formations, the shales at the carbonate interval are interpreted to be in a slight overpressure, with a very low magnitude of overpressure. It may be the reason for the absence of any sign of overpressure from the wireline log, both density and sonic logs in the shale section. In addition, Goulty and Ramdhan (2012), suggested that overpressure in shales might be undetectable from wireline logs when it built up during burial in chemical compaction regime, without actually unloading the shales. As for the carbonate reservoir, the slight overpressure was interpreted to be due to pressure transference from the overpressured shale to the carbonates. Since the carbonates are compartmentalized, as can be seen in Figure 9, they become a perfect condition for overpressure generation. The limited connectivity among the carbonate reservoirs enhances the likelihood of overpressure, as the likely case in this study.

Regarding the generating mechanism, both loading and unloading mechanisms are interpreted to contribute to overpressure. Loading or disequilibrium compaction can be considered the almost certain generating mechanism of overpressure due to the fact of natural compaction processes experienced by sediments. Unloading mechanism also contributes to the total overpressure, and was evaluated based on the sonic-density cross-plots (Figure 8). The shifting of sonic-density data from smectitic to illitic line indicates the occurrence of clay diagenesis, *i.e.* smectite to illite transformation. The reasons why it does not produce a high magnitude of overpressure, as observed in other Indonesia sedimentary basins, *e.g.* Kutai Basin (Ramdhan and Goulty, 2011), are probably because of the small amount of illitization, as indicated by the XRD data from AA-3 (Figure 10).

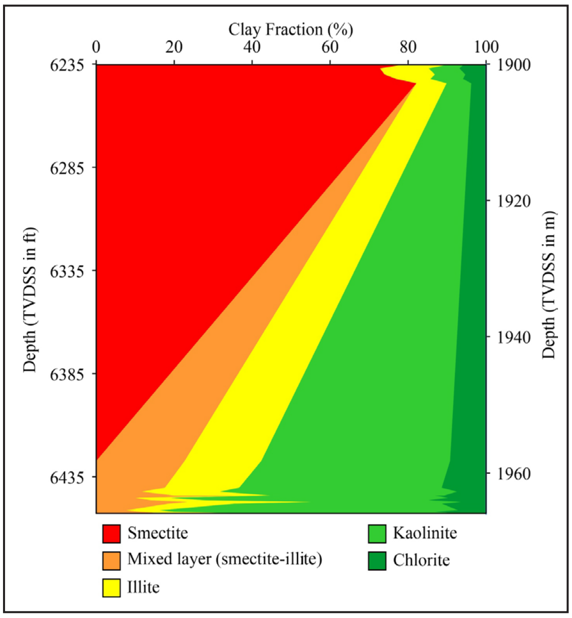

Figure 10. A plot showing the fraction of clay minerals from XRD data in AA-3, indicating a small amount of illite at depth.

Based on seismic attribute data, *i.e.* acoustic impedance, the depositional environments of Kujung and Ngimbang Formations are interpreted by adapting the conceptual depositional model proposed by Paumard *et al.* (2017), who used seismic data to interpret carbonate buildups in Yadana Field, offshore Myanmar. Acoustic impedance is the product of seismic velocity and density, which is useful for differentiating lithologies. Generally, shales will give the lower acoustic impedance than limestone. As shown in Figures 11 and 12, four wells (AA-2 to AA-5) are located in a lagoon environment, while the other one (AA-1) is in a tidal flat environment.

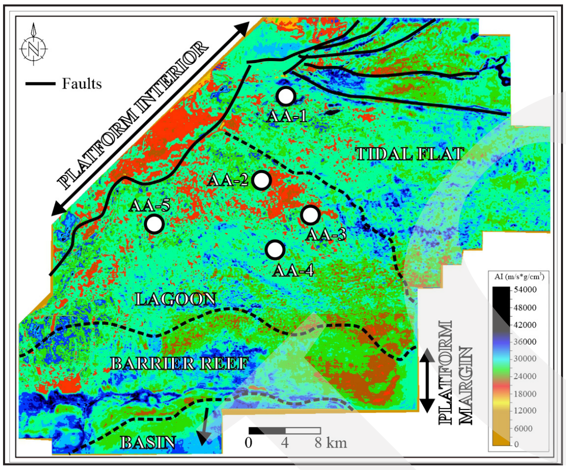

Figure 11. An interpretation of depositional environment boundaries of carbonates in the lower part of Kujung Formation using acoustic impedance.

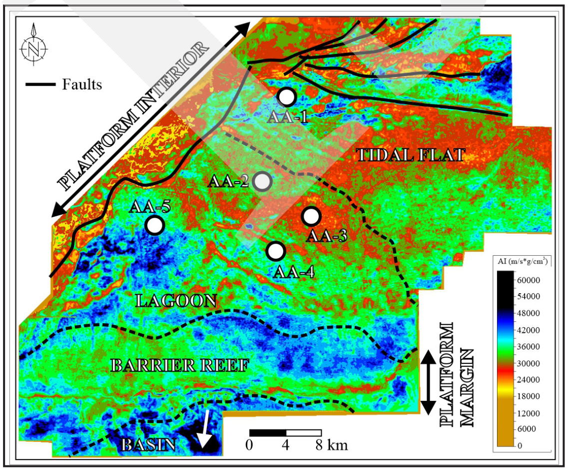

Figure 12. An interpretation of depositional environment boundaries of carbonates in the upper part of Ngimbang Formation using acoustic impedance.

Both slight overpressure conditions and carbonate reservoir compartmentalization are suggested to relate to the depositional environment. These can be the result of patch reef carbonate buildups, which limit the connectivity among the carbonate reservoir in Kujung and Ngimbang Formations. Shales deposited between the carbonates are expected to be in a slightly overpressure condition as discussed above. As the result, a pressure transference from the shales to the relatively isolated carbonated occurred.

Conclusions

Pore pressure data from direct pressure measurement are successfully applied to determine both the pore pressure regime and compartmentalization in the carbonate reservoir of Kujung and Ngimbang Formations. The availability of formation water density enables the determination of hydrostatic gradient for water, which is essential for finding the same pore pressure trend in the water leg to later interpret the carbonate compartmentalization. The results of this study show that the pore pressure regimes of the shaly carbonate reservoir are in hydrostatic and slight overpressure conditions. The shales at depth are interpreted in slight overpressure conditions with a very low magnitude of overpressure. It is suggested that this is the plausible explanation of undetected overpressure in the shale section from the sonic and density logs. As for the generating mechanism, both loading and unloading are interpreted as contributors to overpressure.

There are four main carbonate compartments within this study. This compartmentalized carbonate reservoir is very likely the condition that causes the slightly overpressured carbonates, as it reduced the connectivity between them. Moreover, it is also interpreted that overpressure transference, from slightly overpressured shales to carbonates, took place and resulted in the slight overpressure in the carbonate reservoir of the Kujung and Ngimbang Formations. In addition, using the acoustic impedance of seismic data, it is interpreted that the carbonate reservoirs in the studied area are patch reef carbonate buildups deposited in the lagoon and tidal flat environments.

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