Rock Physics Template Application on Carbonate Reservoir

Judy Hilman1, Ignatius Sonny Winardhi2
1Master Program of Geophysical Engineering, Institut Teknologi Bandung
2Global Geophysics Group, Institut Teknologi Bandung
*Correspondence email: judyhilman@gmail.com

Abstract. A good characterization of a reservoir is required to understand its properties. One of the methods known is Rock Physics Template (RPT). This method attempts to characterize a reservoir in order to predict the behavior of the reservoir under different porosities and water saturation. However, most of RPT technique applications are limited to granular rocks and not for carbonates. Although carbonates generally suitable as reservoir rocks, it is proven to be more challenging. The complex system of carbonates porosities often gives scatter pattern on the correlation between porosity and P-wave. Therefore, this research attempt to use RPT to model carbonate reservoir. We use Kuster Toksoz as the basis for carbonate rock modeling with the help of the Biot-Gassmann equation. The target of this paper is the Baturaja formation that is located in South Sumatra Basin. This formation is known to be a carbonate reservoir that has produced gas hydrocarbon. This study offers an approach on how to better understand the application of RPT on carbonate formation. Based on the RPT modeling done in this research, specific parameters need to be obtained in order to develop a functional RPT model. These parameters are the aspect ratio of the porosities and the elastic modulus of the minerals.

Keywords: rock physics template; carbonate reservoir; aspect ratio

1. Introduction

A reservoir needs to have decent porosity and permeability in order to contain the hydrocarbon from a source rock. This is why it is important to gain a solid reservoir characterization to predict its behavior. One of the methods known is by utilizing Rock Physics Template (RPT). This method attempts to characterize a reservoir in order to predict the behavior of the reservoir, such as different porosities and water saturation. This technique is proven to give good results on sandstones. However, most of RPT technique applications are limited to granular rocks and not enough on carbonates. It is known that carbonate reservoir has accommodated more than 60% oil and 40% gas. Although carbonates generally have good properties as reservoir rocks, it is proven to be more difficult to ascertain. The complex system of carbonates porosities often gives scatter pattern on the porosity and P-wave relationship. Therefore, this research will attempt to use RPT to model carbonate reservoir, thus giving a suitable approach on the application of this method to carbonates. This will be achieved by using Kuster Toksoz as the basis for carbonate rock modeling and by the help from Biot-Gassmann equation (Mavko et al., 2009)[1]. The study object of this thesis is on Baturaja formation that is located in South Sumatra Basin. This formation is known to be a carbonate reservoir that has produced gas hydrocarbon. Through this thesis, hopefully it will gain more insights on the reservoir characteristic as well as a better understanding on carbonate rocks RPT application.
2. Materials and Methods

The availability of petrophysics data is crucial to get a good model that fits the original data. However, the lack of some desired data would affect the model. Thus, some assumption was made to substitute the absence. On this modeling process, well OAK was used as the main source of data, mainly due to the availability of the petrophysics data. The data which are available and used for this research are Vp log, Vs log, Depth log, Density log, Gamma Ray log, Water Saturation, Total Porosity.

The rock physics modeling is based in between 7143 to 8130 feet of well OAK, in which this zone belongs to Baturaja formation, a Carbonate Reservoir. Due to the absence of some reservoir parameter such as temperature, pressure, salinity, and GOR, thus the reservoir is assumed to be saturated by gas. Bulk and shear modulus is calculated following the input of Vp, Vs, and ρ from the well data. This output will be used further in several of the upcoming steps. Before the solid rock estimation begins, the data needs to be filtered based on the volume of the shale in each depth as this modeling is focused on carbonates.

Rock physics template is based on relationship between elastic properties (velocity, density, impedance, and Vp/Vs ratio) and reservoir properties (water saturation and porosity). This technique is proposed by Odegaard and Avseth (2003) based on the theory of Dvorkin and Nur (1996)[2,3], in which mineralogical content and fluid of a reservoir rock can be predicted based on the crossplot in domain Vp/Vs ratio and Acoustic Impedance. This method is mostly done in granular rock, which has more predictable results. The steps on constructing the rock physics template are: (1) Dry rock frame moduli computation for a given porosity or pressure. (2) Dry rock frame moduli computation over a range of porosities. (3) Fluid substitution with Biot-Gassmann equation. (4) Computing Vp, Vs, and ρ for each scenario in a crossplot of Vp/Vs ratio vs AI.

Since there is no Vshale data from well’s petrophysics data, thus IGR method is used to estimate the vshale percentage. The filtered data are the depths that have more than 20% of Vshale. Based on the information from the well, Baturaja reservoir is filled with Gas type Hydrocarbon, hence the fluid bulk modulus calculation is made regarding to gas. However, there are no information on bulk modulus and density of both water and gas. Therefore the assumption for those variables are used, which are 1 g/cm3 and 0.000717 g/cm3 for water and gas density respectively, and 2.2 GPa water bulk modulus with 0.0001 GPa gas bulk modulus. Then the fluid bulk modulus is calculated with the information of water saturation from the well. Certain primary steps of the research are presented in Figure 1.

![Figure 1. The Research Workflow: (a) Data processing, (b) Kmin, μmin, and aspect ratio simulation, (c) Rock Physics Template construction](image-url)

The solid rock estimation, which are the K and μ mineral, is calculated by using RHG due to the absence of mineral percentage data provided by XRD. The RHG calculation only works as an approach, due to the formula application is basically for sandstone not carbonates. Hence, only a single value is taken to represents the whole depths as initial K mineral. For this research, the value taken is 64 GPa for K mineral.
Unlike sandstone, carbonate rocks have more variety of pore shapes, which is why aspect ratio determination is conducted in carbonate rocks modeling. Before the aspect ratio determination, the bulk and shear modulus at state of ‘dry’ need to be calculated with Biot Gassmann. Then Based on Zimmerman pore space stiffness[4], the data can be plotted as observed in Figure 1. Three aspect ratios are taken from this plot as the reference, stiff, and soft bound, which are 0.09, 0.7, and 0.001 respectively. These 3 aspect ratios are assumed to be the representative pore shapes for this rock. However, Zimmerman equation is addressed for sandstone rather than carbonate rocks, thus values used in this plot only act as a guide for further process in Kuster Tokzos equation. To proceed on the modeling, Kuster Toksoz theory for inclusion is used to calculate the bulk and shear modulus on the ‘dry’ state affected by the aspect ratios. This theory could be used to determine the K sat and μ sat as well, however the value tends to overestimate.

The method to predict the pore shapes fraction starts with creating 2 separate tables for each reference pore fraction + soft pore fraction and reference pore fraction + stiff pore fraction. Then, a number of pore shape fraction combinations, which has the total of 201 data for each table is collected, which ranging from 0 to 1 with 0.01 increment (ie. 0.99 for reference and 0.01 for soft/stiff, 0.98 for reference and 0.02 for soft/stiff, and so forth) as seen in Figure 2.

![Figure 2. Pore Space Stiffness Plot with Kmin: 64 GPa. The green lines represent pore shapes or aspect ratios, while the black lines represent the value taken for the aspect ratios used in this research.](image)

These combinations of fractions are simulated through Kuster Toksoz model, which calculates K and μ dry. This process is followed by Biot-Gassmann to calculate K and μ in saturated condition in order to gain the Vp and Vs of the model. A combination of fractions that results the least error between the calculated Vp and Vs with the well data Vp and Vs are selected for each depth. Up until this stage this model runs on a single K mineral, thus more realistic K mineral needs to be calculated to gain more accuracy of this model. It can be achieved by running same simulation (using the fractions selected from the previous step) with different combinations of K and μ mineral. The range of K mineral used is from 64 GPa to 70 GPa with 1 GPa as increment, and 15 GPa to 26 GPa with 1 GPa increment for μ mineral. After the simulation, combination of K and μ with the least error between calculated Vp and Vs with the well data VP and Vs are selected.

In order to create a rock physic template, the behaviour of the rock when there are changes in porosity and fluid content is evaluated. Hence, ranges of porosity and water saturation variation are applied to the model. The range for porosity is from 0.02 to 0.3 with 0.02 increments, and the range for water saturation is 0 to 1 with 0.1 increments. The first step to construct Rock Physics Template is to calculate the ‘dry’ state of the rock bulk and shear modulus as this state has the most immediate effect due to the change in porosity. The change in can be observed in the equation 1 below.
Next step is to calculate new K and μ saturated with the new porosities and water saturations, in order to find the new Vp, Vs, and ρ in saturated condition. These properties then are converted into Vp/Vs ratio vs Acoustic Impedance domain, where Rock Physic Template operates. The changes can be seen in equation 2 below.

\[
\begin{align*}
\frac{K_{sat} - K_{min}}{K_{max} - K_{sat}} &= \frac{K_{dry} - K_{sat}}{K_{max} - K_{dry}} + \frac{\phi(K_{max} - K_{dry})}{\phi(K_{max} - K_{dry})} \\
\frac{K_{max} - K_{min}}{K_{sat}(\phi_{min}, S_{min} - s_{min})} - K_{min} &= \frac{K_{dry} - K_{sat}}{K_{max} - K_{dry}} + \frac{\phi(K_{max} - K_{dry})}{\phi(K_{max} - K_{dry})} \\
\rho_{sat}(\phi_{min}, S_{min} - s_{min}) &= \rho_{sat}(1 - \phi_{min}) + \rho_{min}(S_{min} - s_{min} + \rho_{min}(1 - S_{min} - s_{min})) \\
V_{p,sat}(\phi_{min}, S_{min} - s_{min}) &= \frac{K_{sat}(\phi_{min}, S_{min} - s_{min}) + \frac{4}{3} \mu_{sat}(\phi_{min})}{\rho_{sat}(\phi_{min}, S_{min} - s_{min})} \\
V_{s,sat}(\phi_{min}, S_{min} - s_{min}) &= \frac{\mu_{sat}(\phi_{min})}{\rho_{sat}(\phi_{min}, S_{min} - s_{min})} \\
AI(\phi_{min}, S_{min} - s_{min}) &= V_{p,sat}(\phi_{min}, S_{min} - s_{min}) \rho_{sat}(\phi_{min}, S_{min} - s_{min})
\end{align*}
\]

Before creating the template, how the data would behave according to the aspect ratio needs to be regarded. It is due to the template line that is sensitive to aspect ratio change, as illustrated figure 3. Therefore the construction of the fitting rock physics template for well OAK needs further analysis, which will be discussed in the next chapter.

**Figure 3.** Illustration of template line behaviour. The bolded colour line is the porosity line and the dotted line representing the water saturation, the nearer the dotted line to the bolded colour line the lower the water saturation. The aspect ratio of red: 0.7, green: 0.3, blue: 0.1. This illustration is using Kmin=70, μmin=26, and ρmin 2.7

3. Results

In order to analyze the well data optimally using the Rock Physics Template that has been made in the previous chapter, the well data needs to be distributed into some division. The classification is made in regards to the data behavior, especially in this case is based on the aspect ratio and the matrix
modulus properties. This is due to the fact that carbonate rocks have more variety in pore shapes factor as well as mineral diagenesis.

Based on Figure 4 (a), the data can be divided into 3 classes, which are high, intermediate, and low. Then the rocks physic template will be made for each class by using their matrix dominant value of density, bulk and shear modulus, and aspect ratio. The compatibility of the rock physics template and the well data will be evaluated for each class. In addition to dividing the data into 3 classes of aspect ratios, it is distributed into more sub-class based on the mineral properties. As can be observed in Figure 4(b), the template behaves more sensitive with the change of $\mu_{\text{min}}$ compare to $K_{\text{min}}$. The $\mu_{\text{min}}$ parameter exists in both $V_p$ and $V_s$ formula, while $K_{\text{min}}$ presents only in $V_p$. Thus, $\mu_{\text{min}}$ parameter will be used to categorize the subclass of the well data as can be seen in Figure 4(c), which shows the distribution of $\mu_{\text{min}}$ throughout the well data.

3.1. Low Aspect Ratio Class

As explained in previous chapter, the value of aspect ratio affects the template behavior (porosity and water saturation) drastically. Thus, as can be observed in Figure 5(a), both porosity and water saturation line are very sensitive in softer pore shapes. Therefore most of the data in the low aspect ratio class fit with this rock physic template.

However in the domain of water saturation colour key (Figure 5(b)), not all the data match with the corresponding template due to the nature of water saturation template that is less responsive than porosity template. Thus, the slight decrease in mineral properties such as $K_{\text{min}}$...
and ρmin could shift the rock physics template to top-left direction and match with some well data water saturation. Nevertheless, for most points this rock physics template is representative for low class aspect ratio.

3.2. Intermediate Aspect Ratio Class

For the intermediate aspect ratio class, the approach is slightly different compare to the low class. As the aspect ratio increase, the template sensitivity will decrease, thus mineral properties subdivision need to be applied in the intermediate aspect ratio class. The subdivision is categorized into 3 μmin intervals, which are 15-19 GPa, 19-23 GPa, and 23-26 GPa. These rock physics template is illustrated in figure 6(a), (b), and (c) respectively. From these figures, it can be observed that most of the points fit to the rock physics template created for each subdivision.

**Figure 6.** (a) RPT in Well data in intermediate aspect ratio class with porosity colour key. The data are points with μmin from 15 GPa to 19 GPa. ρmin = 2.72 g/cc, Kmin = 69 GPa, μmin = 16.5 GPa, aspect ratio = 0.38. (b) μmin from 19 GPa to 23 GPa. ρmin=2.71 g/cc, Kmin= 64 GPa, μmin= 20 GPa, aspect ratio= 0.39. (c) μmin from 23 GPa to 26 GPa. ρmin=2.71 g/cc, Kmin= 64 GPa, μmin= 24.5 GPa, aspect ratio= 0.32.

3.3. High Aspect Ratio Class

As the pore shapes get stiffer, both the porosity and water saturation template become less responsive, thus this class needs more subdivision than the intermediate class. This requires more rock physics templates to be created in order to accommodate the variety of the data. The templates constructed in μmin intervals of 13-15 GPa, 15-19 GPa, 19-23 GPa, 23-25 GPa, and 26-27 GPa. The templates and the data are plotted into figure 7(a), (b), (c), (d), and (e) respectively.
Figure 7. (a) RPT in Well data in high aspect ratio class with porosity colour key. The data are points with $\mu_{\text{min}}$ from 13 GPa to 15 GPa, $\rho_{\text{min}}=2.72$ g/cc, $K_{\text{min}}=65$ GPa, $\mu_{\text{min}}=13$ GPa, aspect ratio= 0.44. (b) $\mu_{\text{min}}$ from 15 GPa to 19 GPa, $\rho_{\text{min}}=2.72$ g/cc, $K_{\text{min}}=65$ GPa, $\mu_{\text{min}}=16$ GPa, aspect ratio= 0.44. (c) $\mu_{\text{min}}$ from 19 GPa to 23 GPa, $\rho_{\text{min}}=2.72$ g/cc, $K_{\text{min}}=64$ GPa, $\mu_{\text{min}}=19.5$ GPa, aspect ratio= 0.42. (d) $\mu_{\text{min}}$ from 23 GPa to 26 GPa, $\rho_{\text{min}}=2.71$ g/cc, $K_{\text{min}}=64$ GPa, $\mu_{\text{min}}=24$ GPa, aspect ratio= 0.42. (e) $\mu_{\text{min}}$ from 26 GPa to 27 GPa, $\rho_{\text{min}}=2.72$ g/cc, $K_{\text{min}}=64$ GPa, $\mu_{\text{min}}=26$ GPa, aspect ratio= 0.42.

4. Discussion

The total of rock physics templates constructed in this research reaches 9 templates, in which are categorized into classes and subclasses. Almost all of the data points fit with the templates, although some points are still missed. This is due to the minor variation in $K_{\text{min}}$ or $\mu_{\text{min}}$, while the $\rho_{\text{min}}$ of the data appear to be constant around 2.7 to 2.75 g/cc, thus do not affect the shifting of template as far. Rock physics template is originally created for clastic rock to obtain porosity and water saturation estimation in a reservoir with limited data such as only with $V_p$, $V_s$, and $\rho$. However this is proven to be difficult for carbonate rocks to follow as it needs a proper aspect ratio and mineral properties information. By having these specific information, then the data can be plotted according to its division.

5. Conclusion

1. Due to the variety of porosity types in carbonate rocks, aspect ratio needs to be determined in the dry state modeling, in which the fractions are calculated by running through simulation to get the least error in $V_p$ and $V_s$.
2. Rock physics template application on carbonate rocks cannot be treated similar to its application on clastic rocks.
3. In carbonate rock, the rock physics template needs to be divided into several classes due to the template inability to contain the variety of aspect ratio and mineral properties, in which is the result of diagenetic nature of carbonates.
4. The classes mainly based on aspect ratio and are divided into more subclasses based on shear modulus of the mineral as $\mu_{\text{min}}$ has more impact on both $V_p/V_s$ and AI.
5. In clastic rock, rock physics template is originally used to estimate water saturation and porosity based on only $V_p$, $V_s$, $\rho$. However, it is concluded to be difficult to conduct as aspect ratio and mineral properties parameters are essential.

References

[1] Dvorkin J and Nur A 1996 *Elasticity of High-porosity Sandstones: Theory for Two North Sea Data Sets* vol 61 (Geophysics) pp 1363-70
[2] Mavko G, Mukerji T, and Dvorkin J 2009 *The Rock Physics Handbook* 2nd ed.(New York: Cambridge University Press)
[3] Odegaard E and Avseth P 2003 *Interpretation of elastic Inversion Results Using Rock Physics Templates* (EAGE)
[4] Zimmerman R W 1991 *Elastic Moduli of A Solid Containing Spherical Inclusions* vol 12 (Mech. Materials) pp 17-24