Pore type characterization of kais carbonate reservoir using differential effective medium

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Abstract. The Kais Formation is a hydrocarbon reservoir that produces in the Salawati Basin. However, the success in drilling has diminished so a new concept of exploration is needed to characterizing the pore type. Carbonate reservoirs are classified into three pore types based on pore geometry, namely interparticle pore, stiff pore, and crack pore. The pore geometry of carbonate reservoir is very complicated which is compared to siliciclastic rock. The process has greatly affects heterogeneity and pore geometry complexity are cementation, dissolution, and fracturing. These processes modify the pore geometry which correlates with rock porosity. The modification of pore geometry will change the rock elastic properties. It can be identified from the P-wave velocity (Vp). The change in P-wave velocity (Vp) has an effect of 40 %, as a result of modification of the pore geometry. Therefore, studies of rock physical properties that take into account the complexity of pore geometry are very important in characterizing carbonate rocks. Differential Effective Medium (DEM) is one of the elastic rock modeling methods which calculates the geometry aspect of the pore by including porosity into the parent material. The aim of this study is to characterize pore type using DEM in the three different wells; MEI-1 well, MEI-2 well, and APR-1 well. The result of this study shows that MEI-1 and APR-1 well is dominated by interparticle and crack pore, while MEI-2 well is dominated by interparticle and stiff pore.

Keywords: Pore type, kais carbonate, differential effective medium

1. Introduction

In Indonesia, the Tertiary Basin is a productive resource for oil and gas exploration, such as Salawati Basin. Kais Formation is one of all productive resource in the Salawati Basin. More than 200 billion cubic feet gas and 400 million barrels of oil have been produced since 1936–2014 by the Salawati Basin [1]. The characteristics of carbonate reservoirs have a diversity of physical properties. The diversity of physical properties is influenced by the processes that occur in carbonate reservoirs. The process that influences the diversity of physical properties such as sedimentation processes, diagenetic processes, and tectonic settings.

Pore geometry is one of the various physical properties of carbonate reservoirs. Crack, stiff, and interparticle is a pore type carbonate classified according to aspect ratio [2]. In 1999, a study showed porosity was controlled by heterogeneity and complexity of pore type carbonates based on acoustic velocity deviations [3]. Identification of pore types is important, considering that reservoir permeability correlates with pore type carbonate rocks to increase reservoir productivity [2]. There are several rock
physic methods to identify pore types of carbonate reservoirs, such as Kuster-Toksoz, Self-Consistent, and Differential Effective Medium.

Differential Effective Medium (DEM) is the best method after a comparative study with Kuster-Toksoz (KT) in 2017 [2] and Self Consistent (SC) in 2014 [4]. The fundamental of DEM method is input the mineral content, fluid content, and porosity fraction fluid which generates elastic modulus of rock to build compressional velocity \( V_p \) and shear velocity \( V_s \) model [5]. \( V_s \) is a physical parameter that is sensitive to rigidity (solid medium), while \( V_p \) is a parameter that can measure solid and fluid mediums. The data used in this study are consisted of 3 well log data and thin section on one well for validation. The study is focused on the Kais Formation as a hydrocarbon producing reservoir in the Salawati Basin. All data are used to characterize the pore type of Kais carbonate reservoir.

2. Methodology

Xu-White success applied of ellipsoidal pores model in shaly sandstones [6]. Xu-Payne expand the ellipsoidal pores model in shaly sandstones for carbonate rock, which pore type carbonates are classified into four types such as: stiff pores, interparticle pores, micro-crack pores, and clay-related pores [7].

2.1. Voigt-Reuss-Hill method and Wood’s relation

Rock physics modelling aims to obtain a rock elasticity model that approaches to the actual conditions. This elastic modelling is done by including the elastic modulus of rock, fluid, volume fraction, and geometry aspect. The best way to do this is to estimate upper and lower bounds on the elastic modulus. Voigt-Reuss-Hill is an empirical way of estimating elastic modulus, when rock conditions are solid, as shown in equation 1.

\[
M_v = \sum_{i=1}^{n} M_i f_i \quad \frac{1}{M_r} = \sum_{i=1}^{n} f_i M_i \quad M_{vhr} = \frac{M_v + M_r}{2}
\]  

(1)

where:

- \( M_{vhr} \): Hill elastic modulus
- \( M_v \): Voigt elastic modulus
- \( M_r \): Reuss elastic modulus
- \( M_i \): \( i^{th} \) elastic modulus mineral
- \( f_i \): \( i^{th} \) volume mineral fraction

Voigt and Reuss act as upper bound and lower bound, respectively. Hill is average of the two methods. The bound is used to give a limit in estimation. If the measurement falls outside the boundary, then there is an mistake in the estimation. Wood’s Relation is carried out in the next step to get the elastic fluid modulus, as shown in equation 2.

\[
\frac{1}{K_f} = \frac{S_{water}}{K_{water}} + \frac{S_{oil}}{K_{oil}} + \frac{S_{gas}}{K_{gas}}
\]

(2)

where:

- \( K_f \): Mixed fluid elastic modulus
- \( K_{water} \): Water elastic modulus
- \( K_{oil} \): Oil elastic modulus
- \( K_{gas} \): Gas elastic modulus
- \( S_{water} \): Water saturated
- \( S_{oil} \): Oil saturated
- \( S_{gas} \): Gas saturated
2.2. Differential Effective Medium (DEM) Method

The last step in elastic modulus modeling is the Differential Effective Medium (DEM) method. This method models two-phase composites by including the matrix phase. The matrix acts as the initial phase of the matrix inclusion with zero value. Porosity, mixed fluid elastic modulus, and aspect ratio are added gradually until they reach the ideal model. As a result, shear and bulk modulus are extracted to make \( V_{p_{\text{reference}}} \) (interparticle pore condition). The rock condition is dominated by the stiff and interparticle pore types, when the \( V_{p_{\text{measurement}}} \) value is higher than the \( V_{p_{\text{reference}}} \) after comparison. The interparticle and crack pore types are classified when the \( V_{p_{\text{reference}}} \) value is higher than the \( V_{p_{\text{measurement}}} \). The DEM method will be applied to see the characteristic of pore type in the three different wells such as MEI-1 well, MEI-2 well and APR-1.

\[
K(y + dy) = K(y) + \frac{1}{3} \left[ K_2 - K(y) \right] \sum_{i \in e} \frac{dy_i}{(1 - y_i)}
\]

\( (3) \)

\[
\mu(y + dy) = \mu(y) + \frac{1}{5} \left[ \mu_2 - \mu(y) \right] \sum_{i \in e} \frac{dy_i}{(1 - y_i)}
\]

\( (4) \)

\( K \): Bulk modulus in the initial conditions

\( \mu \): Shear modulus in the initial conditions

\( K_2 \): Bulk modulus of inclusion phase

\( \mu_2 \): Shear modulus of inclusion phase

\( y \): Porosity

\( dy \): Gradually inclusion porosity

\( P^{*2} \) and \( Q^{*2} \): Geometrical aspect

3. Results and discussion

The parameters used in rock physics modelling are based on field data and literature assumptions. These parameters consist of the value of bulk and shear modulus minerals and fluid contents (table 1).

3.1. Cross-plot Analysis

Cross-plot \( V_{p_{\text{DEM}}} \) on \( V_{p_{\text{measurement}}} \) shows best result. It is proven from linear regression, low error and high correlation on three wells. APR-1 well has \( R^2 = 0.9939 \) and RMSE = 0.05366 (figure 1), MEI-1 well \( R^2 = 0.9994 \), RMSE = 0.0204 (figure 2), MEI-2 well \( R^2 = 0.9725 \) RMSE, 0.07837 (figure 3), respectively. MEI-2 well have only \( V_s \) data. The cross-plot shows good results, \( R^2 = 0.95316 \) RMSE = 0.035508 as shown in figure 4.

According to cross-plot the figure 4 shows the high quality of coefficient correlation. DEM method is significantly accurate to generate \( V_s \) in other well data that do not have \( V_s \) data. DEM method is stated to be better than general empirical method because it can estimate \( V_s \) for multi-mineral. This method calculates clay factors, fluid contents, and aspects of geometry. Cross-plot correlation between \( V_{s_{\text{DEM}}} \) and \( V_{p_{\text{DEM}}} \) shows low RMS Error and good correlation coefficient. However, the relationship between \( V_p \) and \( V_s \) tends to quadratic polynomial rather than linear as shown figure 5, figure 6 and figure 7.

| Table 1. The elastic modulus values |
|-----------------------------------|
| Fluid and Mineral | Bulk Modulus/K (Gpa) | Shear Modulus/\( \mu \) (Gpa) |
|-------------------|----------------------|-----------------------------|
| Gas               | 0.093                | 0                           |
| Oil               | 0.889                | 0                           |
| Water             | 2.314                | 0                           |
| Limestone (Calcite)| 76.8                 | 32                          |
| Clay              | 21                   | 7                           |
Figure 1. Cross-plot correlation of $V_{pDEM} - V_{pmeasurement}$ at APR-1 well.

Figure 2. Cross-plot correlation of $V_{pDEM} - V_{pmeasurement}$ at MEI-1 well.

Figure 3. Cross-plot correlation of $V_{pDEM} - V_{pmeasurement}$ at MEI-2 well.

Figure 4. Cross-plot correlation of $V_{smeasurement} - V_{sDEM}$ at APR-1 well.

In figure 5, APR-1 well has a correlation coefficient of 0.9199, RMS Error 0.09754. The MEI-1 has correlation coefficient of 0.9942, RMSE 0.03418 as shown in figure 6. The Z-value describes the amount of clay content in Kais Formation. The APR-1 well has a little amount of clay content as shown in figure 5, which tends to be parabolic pattern. The MEI-1 well has a large amount of clay content, showing linear pattern, as shown in figure 6. MEI-2 well has a correlation coefficient of 0.9755, RMSE 0.06404 for $V_{pDEM} - V_{sDEM}$ in figure 7. On the other hand, $V_{pmeasurement} - V_{smeasurement}$ cross-plot shows $R^2 = 0.99598$ and RMSE $= 0.0869$ (figure 8). It proves that the cross-plot has a similar value. Limestone with dominated calcite mineral contents shows that it has a little clay content, while limestone with less dominated calcite has a lot of clay content. According to figure 5 and figure 7 shows that the reservoir with less dominated clay performs quadratic curve, while dominated clay (siliciclastic) mostly indicates linear (figure 6).
3.2. Characterize pore type
The Salawati Basin was identified as having several fault periods, but the most extensive faults occur during the Pliocene to the Pleistocene. Sorong Fault is a fault that created the Salawati Basin [8]. Sorong Fault caused the Kais Formation as a fractured reservoir which connects among the pores so that it enhances reservoir quality. Beside sedimentation and diagenetic processes, tectonic process has an important part, creating migration pathways and fractures in reservoir that increase effective of porosity. Therefore, characterization of carbonate reservoirs is carried out by quantifying pore types in percentages as shown in figure 9 to figure 11, respectively.

The well section explains the relationship of clay content, pore type, and porosity. Interparticle and crack (white and red) pore type are dominated by layers of carbonate in MEI-1 well. Significant increase is shown at depths 4171–4186 ft of porosity values on the porosity log (figure 9).
Figure 9. Clay content, pore type log, porosity log data at MEI-1 well.

Figure 10. Clay content, pore type log, porosity log data at MEI-2 well.

Figure 11. Clay content, pore type, porosity log data in APR-1 well.
In general, the interparticle and crack pore type show an increasing value of effective porosity, but with a lot of clay content, effective porosity has a low value. That is caused by any clay minerals which act as impurity minerals in the reservoir, closing to the pore space. In figure 10, the layers are dominated by interparticle and stiff (white and yellow) pore type. Interparticle and crack pore type is marked by the high total porosity and effective porosity. The APR-1 well shows the dominated calcite minerals, cracks and interparticle pore types. The values of total and effective porosity also have similar value. This also shows that APR-1 well is interparticle and crack pore types equal to high value effective porosity. However, interparticle and stiff pore types tend to have low value effective porosity as shown in figure 11. The type of lithology is not significantly influencing for classification of crack pore, but the condition and process of regional geology completely influences the crack pore in carbonate reservoir. In this case, the tectonic activity, Sorong fault, causes any fracturing in the Kais carbonate reservoir.

In figure 12, it is MEI-2 well petrographic data. The data is used to validate the analysis of the DEM method in characterizing the pore type. Open fracture in thin section is related to interparticle and crack pore type. Moldic or vuggy is correlated with interparticle and stiff pore type. This is appropriate with Zhao's classification. The Differential Effective Medium (DEM) method is very good on determining pore types with real geological conditions because it uses P-wave velocity in the calculation. The parameters measured by P-wave velocity are solid and fluid mediums. However, P-wave that passes through the fluid medium will be slower because the fluid in the pore absorbs it, particularly for the interparticle and crack pore type that connect the pores to each other. It is diminished from the velocity deviation.

![Figure 12. Pore type log and thin section validation well MEI-2 crack (open fractured) (left) and stiff (moldic/vuggy) (right).](image-url)
4. Conclusion
The condition of regional geology is an aspect that absolutely influences the characteristic of geometry for carbonates reservoir pore type. This study uses DEM in characterizing pore type by modelling with interparticle pore and comparing with for three different wells. Determination of rock elastic modulus with the DEM method has high certainty, seen from the $V_p^{measurement}$ with $V_p^{DEM}$ has a correlation coefficient MEI-1 = 0.9994, MEI-2 = 0.9725, APR-1 = 0.9939. The result rock physic modeling show that MEI-1 and APR-1 have dominant interparticle and crack pore type characteristics, while MEI-2 has dominant interparticle and stiff characteristics. The characteristics of interparticle and crack pore type correlates with an increase in the value of total porosity and effective porosity.

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