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Utilization of Acoustic Wave Velocity for Permeability Estimation in Static Reservoir Modeling: A Field Case

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Abstract – Several researches have shown that P-wave velocity carries information on the complexity of the rock's pore geometry and pore structure. Their complexity can be characterized by critical porosity. Therefore, the P-wave velocity is used to estimate permeability. This research uses data taken from the Tomori formation from Banggai-Sula basin, Central Sulawesi, which is a carbonate rock reservoir. Also, this research aims to obtain a 3D permeability model by using acoustic wave velocity cube data. The results show that permeability can be modeled well using acoustic wave velocity data. Furthermore, compared to the raw data log of permeability, the modeling results using wave velocity based on critical porosity show good results. This method is another alternative to permeability modeling if acoustic wave velocity cube data is available.

Keywords: acoustic wave velocity, pore complexity, critical porosity, modeling 3D permeability.

Introduction

Many researches have been carried out to determine the permeability of reservoir rock. Generally, permeability determination is carried out by constructing porosity and permeability relationship from core data. Also, several other researches link permeability estimation with porosity and connate water saturation (Timur, 1968; Tixier, 1949). Using the linear relationship, permeability estimation results obtained are good for homogeneous rocks. Meanwhile, this method cannot be applied to heterogeneous rock. Scatter data on porosity and permeability relationship is influenced by grain size and uniformity, clay volume, and degree of compacting (Nelson, 1994). This means a linear equation cannot represent the porosity and permeability relationship.

Furthermore, several researchers show that permeability can be determined if the rock is classified based on rock quality (Abbaszadeh *et al.*, 1996; Amaefule *et al.*, 1993; Wibowo and Permadi, 2015). Rock quality can be defined by the hydraulic unit concept using the Kozeny equation (Amaefule *et al.*, 1993). In addition, Wibowo and Permadi (2015) develop a power-law model and define pore geometry and pore structure to identify rock quality.

Another challenge is the permeability estimation in lateral and vertical areas that do not have core data, and this is solved by some research using a statistical approach. Furthermore, Abbaszadeh uses the similarity response of well-log data with hydraulic flow units obtained from core data to predict permeability at uncore intervals (Abbaszadeh *et al.*, 1996). Furthermore, practically the industry using geostatistics to distribute permeability in the lateral direction.

Advances in technology make it possible to obtain seismic data in a 3-dimensional cube. Currently, advanced seismic data processing allows people to use seismic data for reservoir characterization. Furthermore, several researchers have linked pore complexity with P-wave velocity based on reservoir rock characteristics. In carbonate rocks, variation in P-wave velocity is strongly influenced by internal characteristics of the pore (Weger et al., 2009). Several researches prove that the internal characteristics of pores significantly affect rock quality and permeability (Amaefule et al., 1993; Wibowo and Permadi, 2015).

In addition, both internal characteristics and quality of pores greatly influence the variation of acoustic wave velocity of sandstones (Prakoso *et al.*, 2016), and critical porosity characterizes each rock group with different qualities (Prakoso *et al.*, 2018).

This research is designed to use velocity and inversion data obtain from advanced seismic processing to build permeability distribution in a 3D cube. This approach is another alternative to obtain permeability distribution required in dynamic reservoir modeling.

Materials and Methods
Data

Data used for this research were limestone Tomori formations from Banggai-Sula Basin, Central Sulawesi, in the Lower Miocene age. The lithology of Tomori formation consists of shallow marine bioclastic limestone, in part dolomite, with claystone and coal. Also, available data includes well log data, core routine analysis data, static reservoir model, Acoustic Impedance, P-wave velocity, S-wave velocity, and density. Permeability model from static reservoir modeling is built by considering the hydraulic flow unit concept. Permeability from the static model is used as a comparison to the permeability estimation results of this research. Acoustic wave velocity is measured at dry conditions, room pressure, and temperature (1 atm and 77° F). The rock samples were dried at 150 °F for 12 hours. The acoustic wave velocity is measured using SonicViewer-Sx. The P-wave velocity (Vp) is measured using a piezoelectric transducer with a frequency of 200 or 500 kHz and an S-wave velocity (Vs) using a piezoelectric transducer with a frequency of 100 kHz (Figure 1).
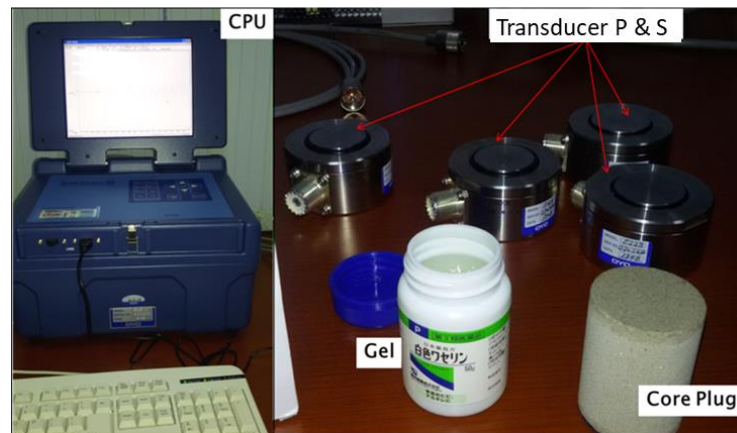

Figure 1. P-wave and S-wave velocity measuring instrument.

Dry Bulk, Critical Porosity, and Permeability Estimation

Nur modified Voigt bound using critical porosity (ϕ_c) (Nur et al., 1995), which is the maximum porosity of consolidated sediment. Meanwhile, if porosity is above critical porosity, it is categorized as suspension. Modification of Voigt equation is carried out by normalizing porosity with critical porosity (ϕ_c) and replacing bulk modulus of fluid (B_f) with the bulk modulus at critical porosity (B_c) as follows:

$$B = \left(1 - \frac{\phi}{\phi_c}\right)B_m + \left(\frac{\phi}{\phi_c}\right)B_c$$

As previously discussed, Reuss average curve describes effective modulus for suspension; therefore, the values of ϕ_c and B_c are determined from the intersection of the Voigt average curve with the Reuss average curve.

Prakoso derived an equation for permeability estimation based on rock quality and critical porosity (Prakoso *et al.*, 2018). Using this equation, the permeability is well determined. Permeability equation as a function of P-wave velocity and based on critical porosity, it can be written as follows:

$$k = 0.9869 \frac{c\left(\phi_c \frac{\left(Vp^2\rho - B_m - 4/3\mu_m\right)}{\left(B_c - B_m + 4/3\mu_c - 4/3\mu_m\right)}\right)^3}{\left(m'e^{n(Vpx1000)}\right)^2}$$

where k in Darcy, Vp in km/s, ϱ in gr/cc, B_m and μ_m in Gpa, B_c and μ_c are critical bulk modulus and critical shear modulus (Gpa) whereas $\left(m'e^{n(Vpx1000)} \right)^2$ is the empirical equation of S_b as a function of V_p.

Results

Acoustic wave velocity is obtained from seismic inversion in the form of a 3D cube of P-wave velocity (Figure 2a) and S-wave velocity (Figure 2b). Furthermore, variations in P-wave and S-wave velocities show a pore rigidity variation associated with the quality of the rock.
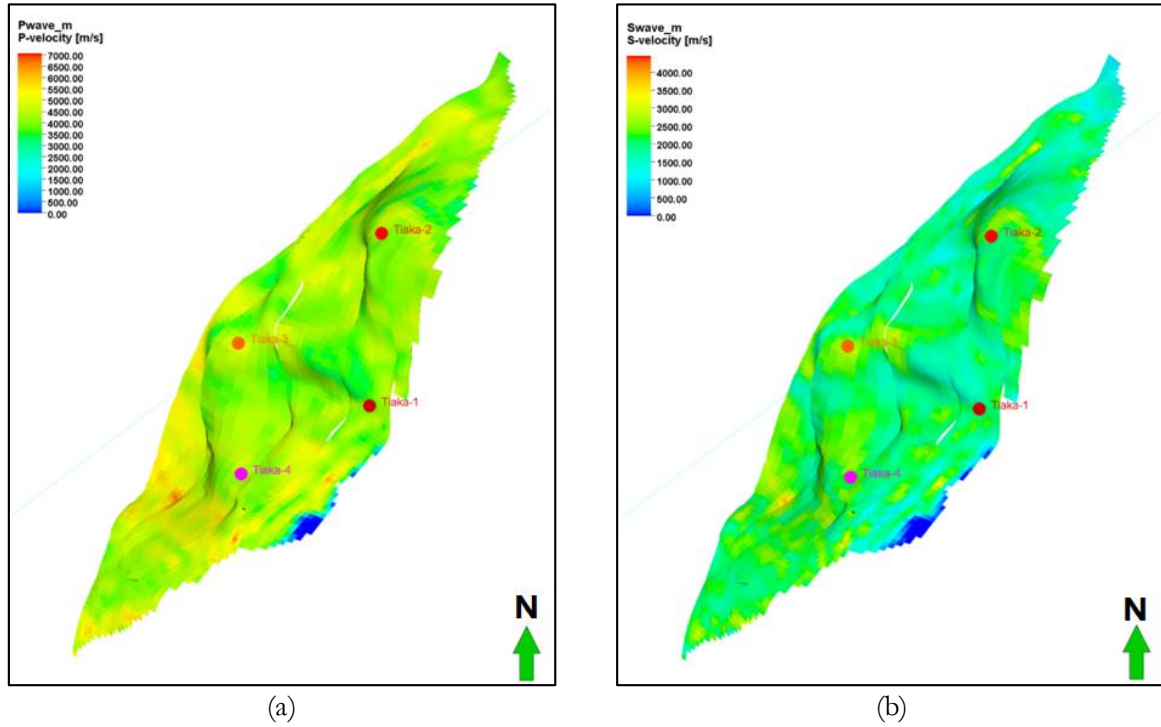

Figure 2. Velocity cube of (a) V_p (A) and (b) V_s

Critical porosity can be determined using its concept proposed by Nur *et al.* (1995) for both dry and wet P-wave velocities (Prakoso *et al.*, 2018; Prakoso and Burhannudinnur, 2020). It is necessary to estimate bulk modulus obtain from P-wave and S-wave velocities to apply Nur *et al.* (1995)'s critical porosity concept (Figure 3b). Rock density is obtained from the seismic inversion (Figure 3a). For practical purposes, it is easier to estimate critical porosity for dry conditions. Furthermore, Gassmann's equation has been used for fluid substitution from dry to saturated or vice versa (Gassmann, 1951). Also, assumptions used for fluid substitution in this research are:

- The predominant mineral is calcite
- Fluid-filled pore space is represented by a water saturation distribution model, which is estimated by the following equation:

$$\rho = S_w\rho_w + (1 - S_w)\rho_h$$

- The bulk modulus of minerals and the bulk modulus of fluid are assumed to be constant (*B* calcite and *B* air).

By using these assumptions, the dry bulk modulus can be appropriately estimated (Figure 4a).
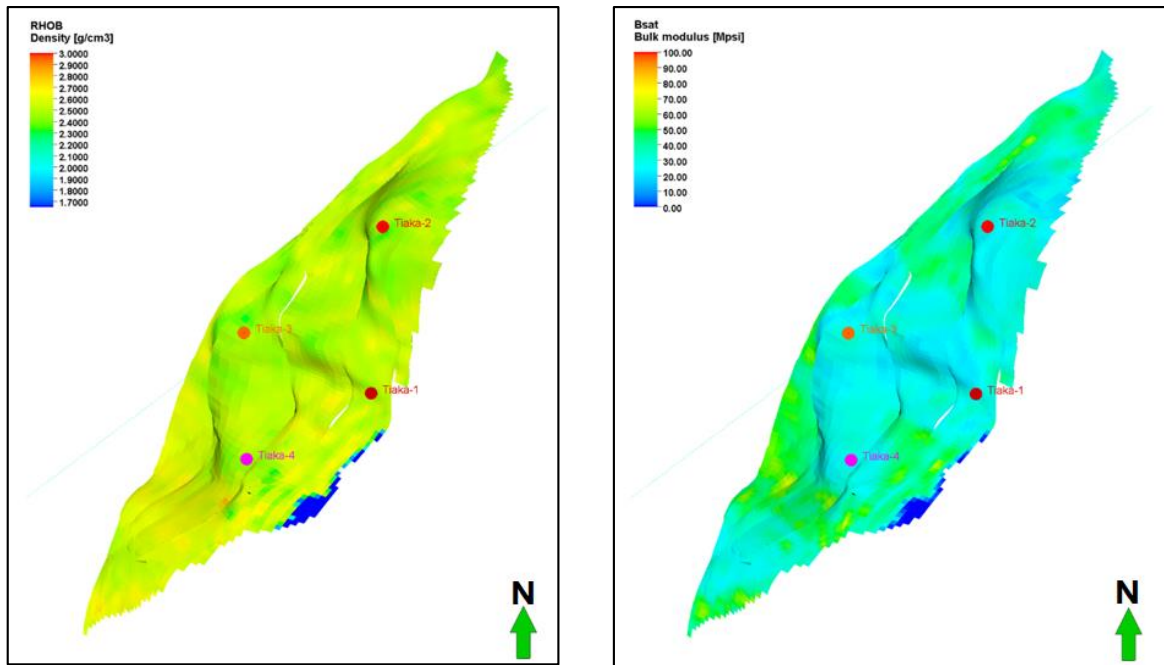
(a)   (b)

Figure 3. (a) RHOB and (b) Bulk modulus for saturated rock.

Assuming each rock sample has different pore geometry and structure, critical porosity can be estimated using dry bulk modulus and porosity models (Figure 4b).

The critical bulk modulus (B_c) and critical shear modulus (μ_c) are needed to calculate permeability using the equation, as follow:

$$k = 0.9869 \frac{c\left(\phi_c \frac{\left(Vp^2\rho - B_m - 4/3\,\mu_m\right)}{\left(B_c - B_m + 4/3\,\mu_c - 4/3\,\mu_m\right)}\right)^3}{\left(m'e^{n(Vpx1000)}\right)^2}$$
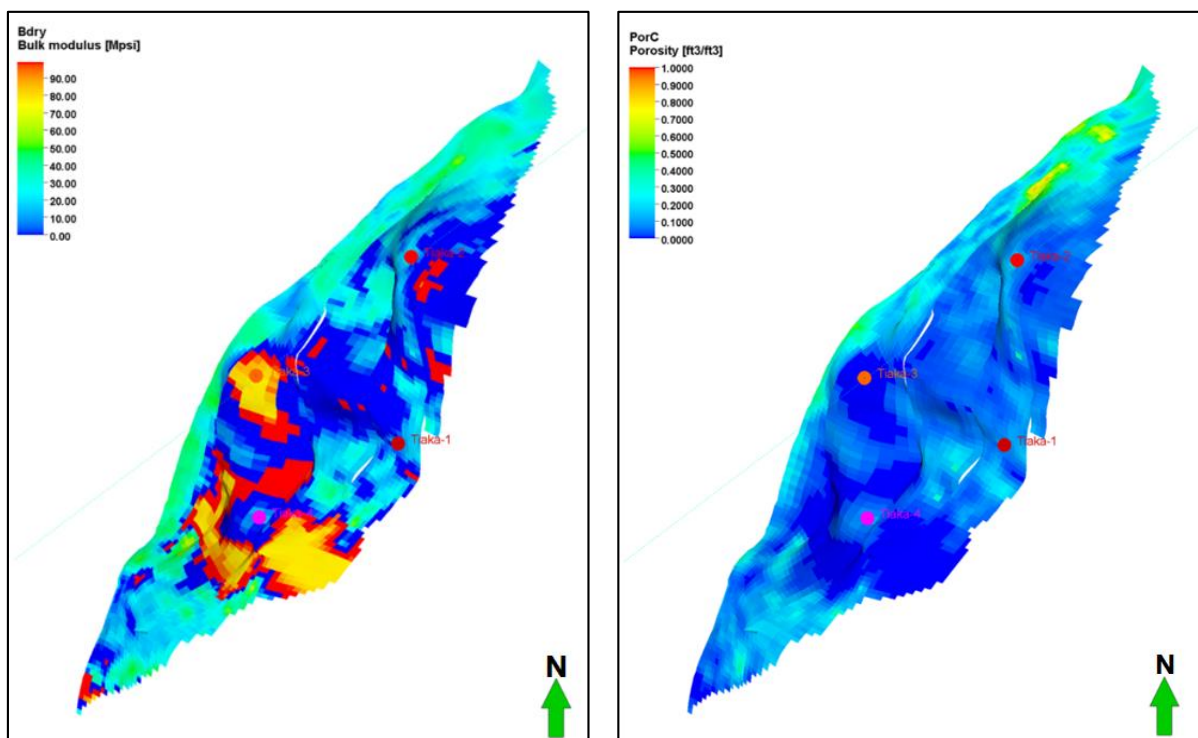
(a)   (b)
Figure 4. (a) Bulk modulus for dry rock and. (b) Distribution of critical porosity modeled by the Nur *et al.*
(1995) equation.

Critical porosity is obtained from the intersection of the Voigt curve and the Reuss curve. Therefore, at the intersection of these two curves, a critical Bulk modulus (B_c) is also obtained. Critical Bulk modulus (B_c) is calculated using the Reuss equation, as follows:

$$B = \left(\frac{(1-\phi)}{B_m} + \frac{\phi}{B_f} \right)^{-1}$$

If the porosity is equal to the critical porosity using the equation above, the bulk modulus value is the critical bulk modulus. The Kozeny constant (c) is approximated using the Mortensen equation (Mortensen *et al.*, 2007). Kozeny constant is written as a function of porosity as follows:

$$c = \left(4\cos\left(\frac{1}{3}\arccos\left(\phi \frac{8^2}{\pi^3} - 1 \right) + \frac{4}{3}\pi \right) + 4 \right)^{-1}$$

By using these two approaches above, critical bulk modulus and Kozeny constant are modeled, shown in Figure 5.

Specific surface area is determined empirically using core data. Kozeny equation (Kozeny, 1927) for permeability is modified to estimate specific surface area to bulk volume as follows:

$$S_b = \left(\frac{c\phi^3}{k/0.9869} \right)^{0.5}$$

Plot between porosity and specific surface area from core data obtain an empirical equation which is further used to model specific surface area in a 3D model. The relation of specific area per unit bulk volume with porosity is shown in Figure 7, and the model-specific surface area is presented in Figure 8.
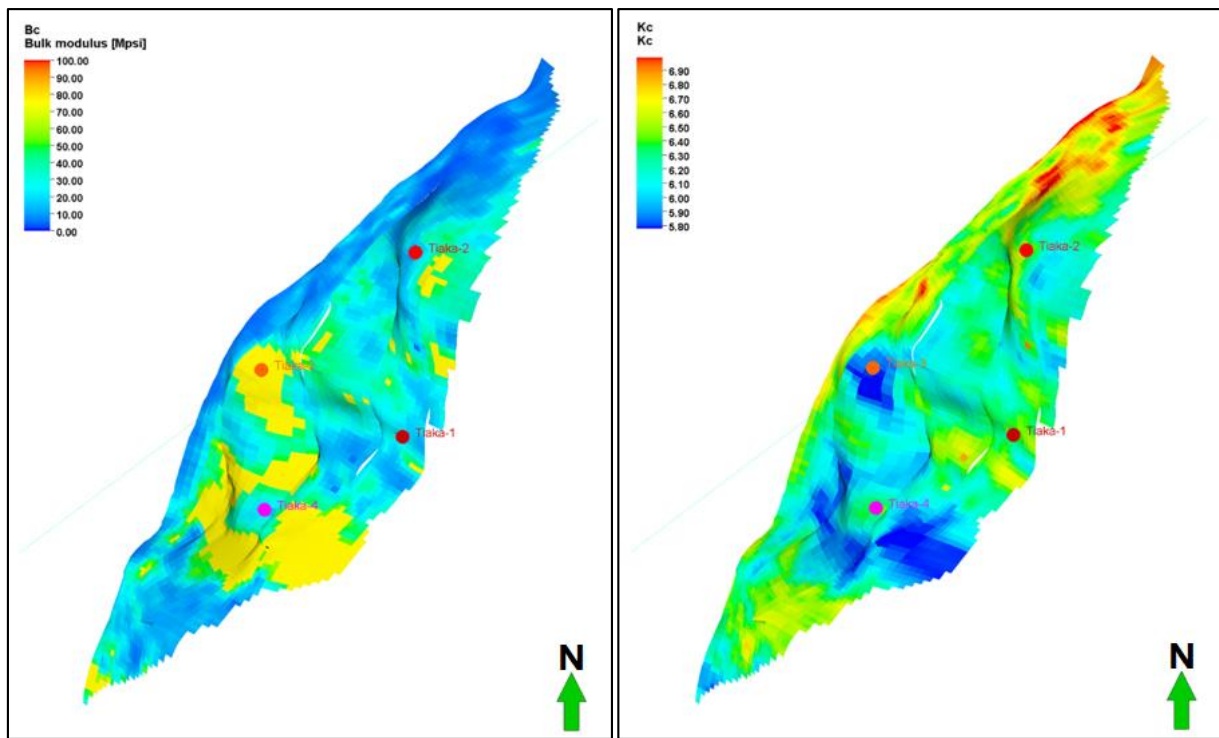
(a)   (b)
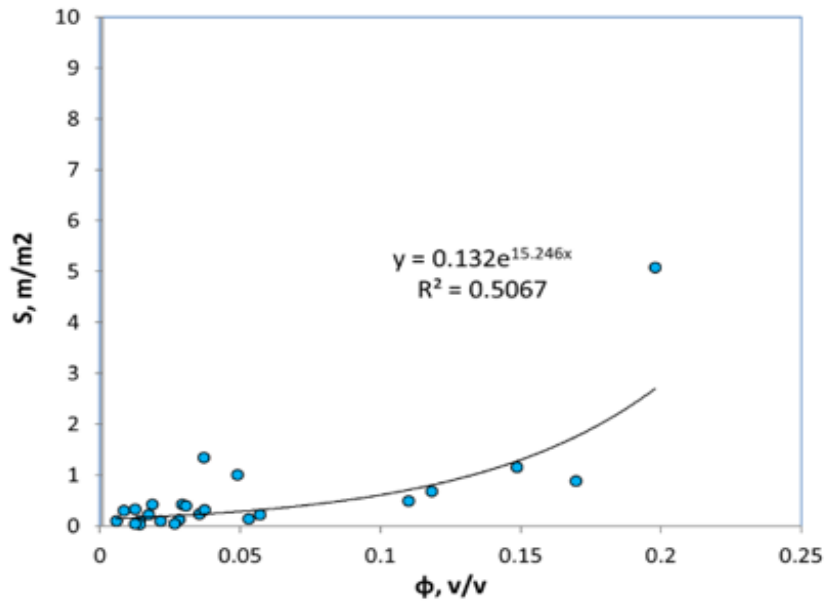Figure 5. Distribution of critical bulk modulus and Kozeny constant.

Figure 6. Relation of specific area per unit bulk volume with porosity.

Figures 9 and 10 show the result of permeability modeling. Figures 9 and 10 Column A is permeability modeled by a hydraulic flow unit concept, while Figures 9 and 10 Column B is a permeability model estimated using the P-wave velocity based on critical porosity.
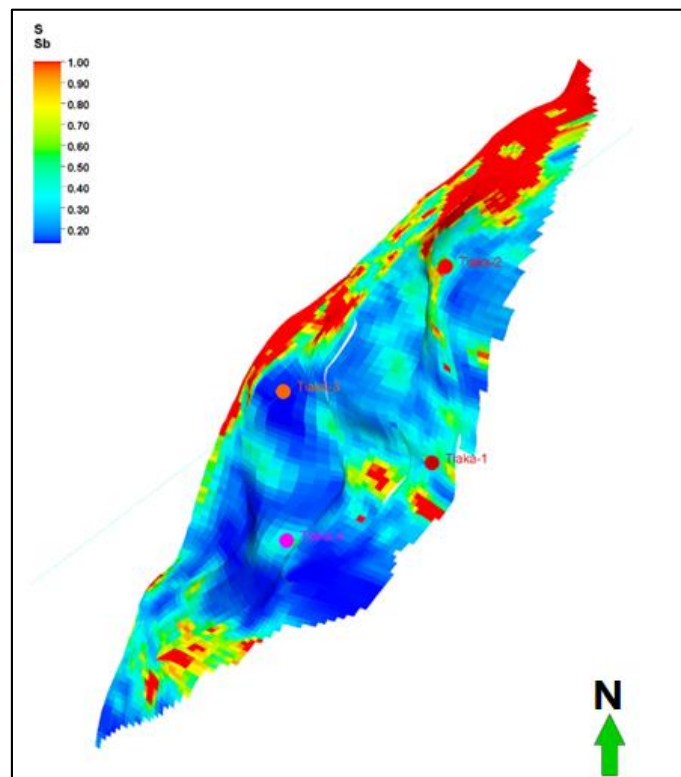

Figure 7. Model-specific surface area.

(a)   (b)
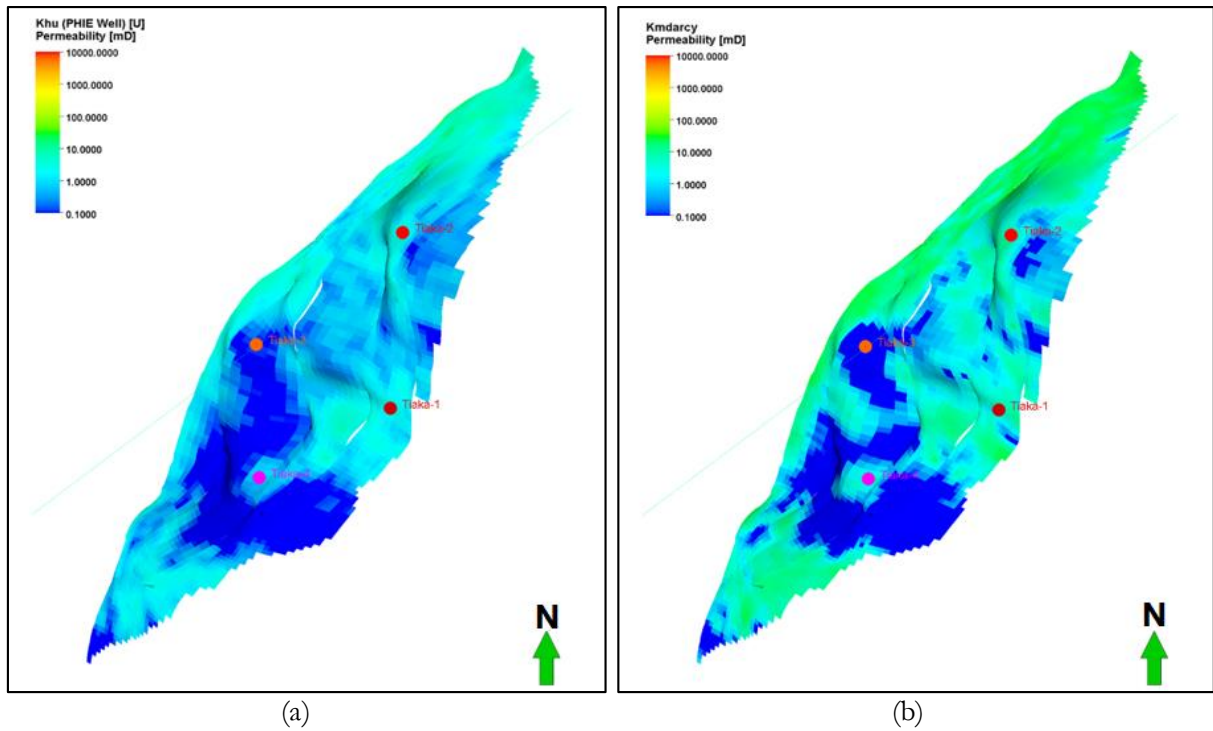
Figure 8. Comparison of (a) permeability model using the HFU concept and (b) permeability model using the concept of critical porosity.

The result of permeability modeled using the critical porosity concept is accurate compared to permeability modeled using the HFU concept, and it has a relatively similar pattern. Compared with Permeability from HFU, the results of permeability modeling using critical porosity concepts show a good correlation, but the value tends to be higher (Figures 9, 10, and 11).
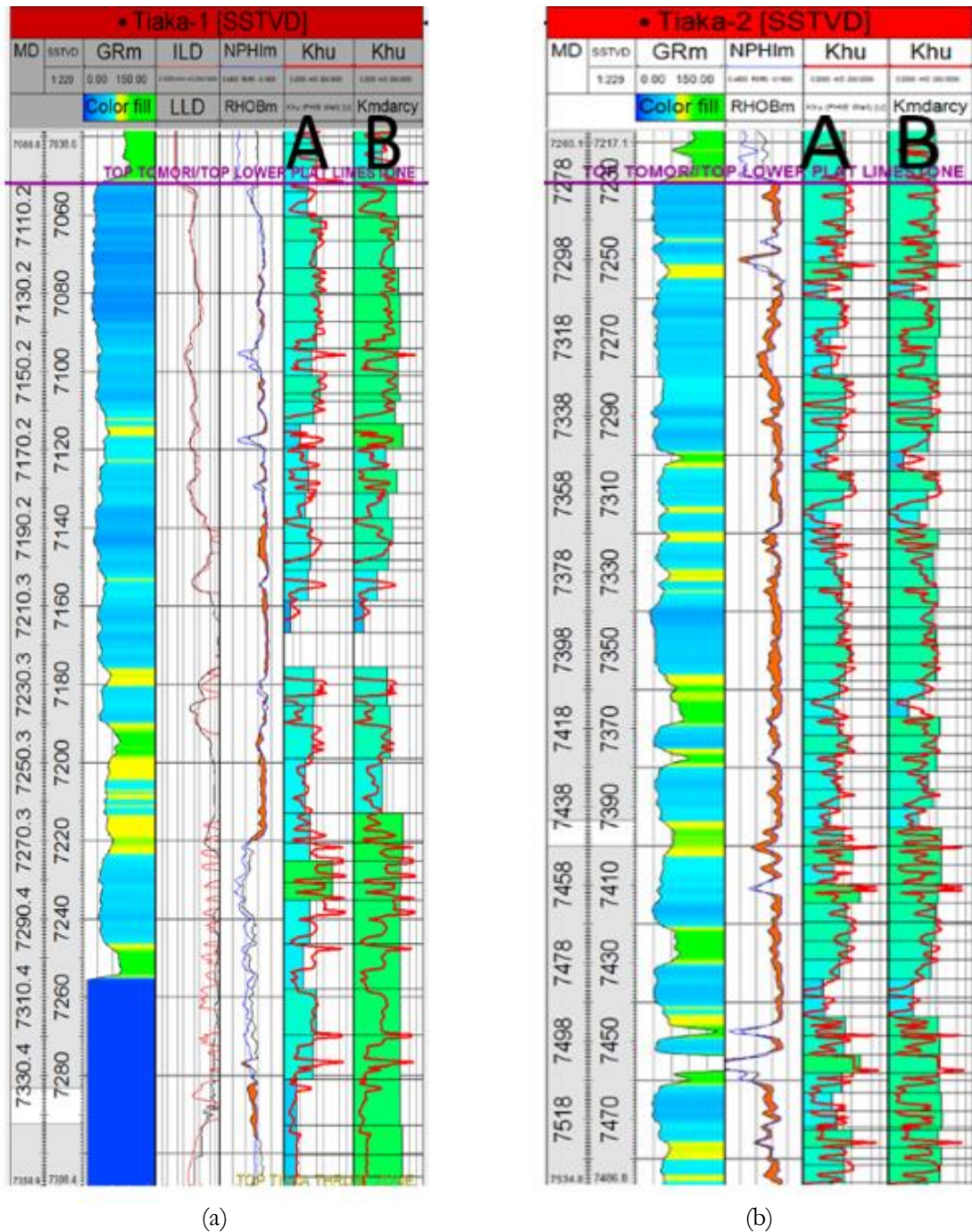
(a)   (b)

Figure 9. Comparison of the results at (a) Tiaka-1 and (b) Tiaka-2. Column A is the permeability model using the concept of HFU, and Column B is the permeability model using the concept of critical porosity.

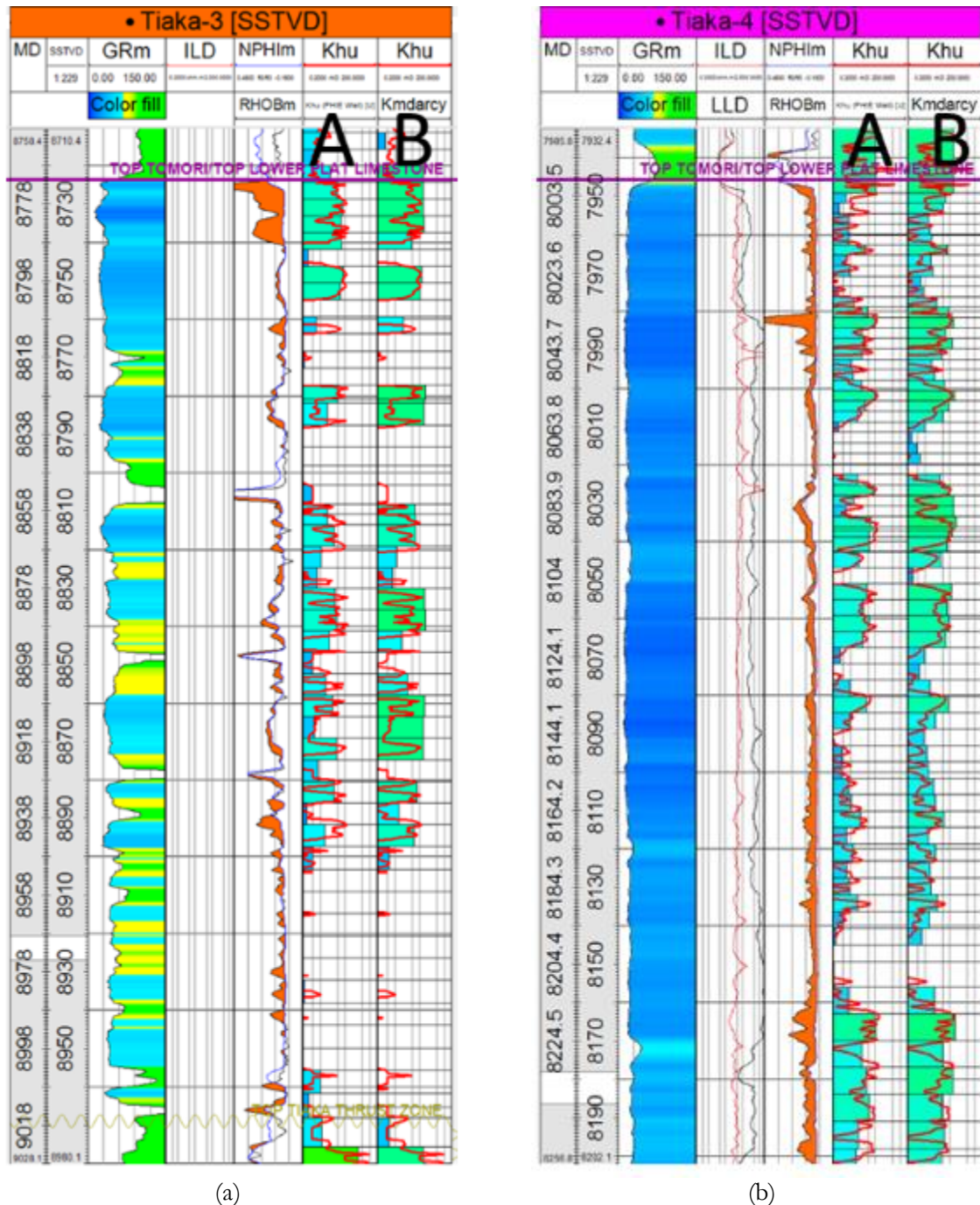(a)   (b)

Figure 10. Comparison of the results at (a) Tiaka-3 and (b) Tiaka-4. Column A is the permeability model using the concept of HFU, and Column B is the permeability model using the concept of critical porosity.

Discussion

The variation of P-wave velocity has been proven by Prakoso to be influenced by rock quality or know as rock type (Prakoso *et al.*, 2016). The relationship of porosity with V_p can be adequately separated based on rock quality. This means P-wave velocity can be determined based on the relationship of V_p with pore geometry and structure. Low P-wave velocities characterize a group of rocks with low pore complexity compared to high pore complexity of rock groups. Pore complexity in this research is related to rock quality. Furthermore, good rock quality has low pore complexity characterized by a low P-wave velocity (Figure 2a). This is supported by the distribution of the rock density model, which shows low P-wave velocities areas characterized by low rock density (Figure 3a). These low-quality rocks usually have high pore complexity; therefore, bulk modulus tends to be high (Figure 3b and Figure 4a).
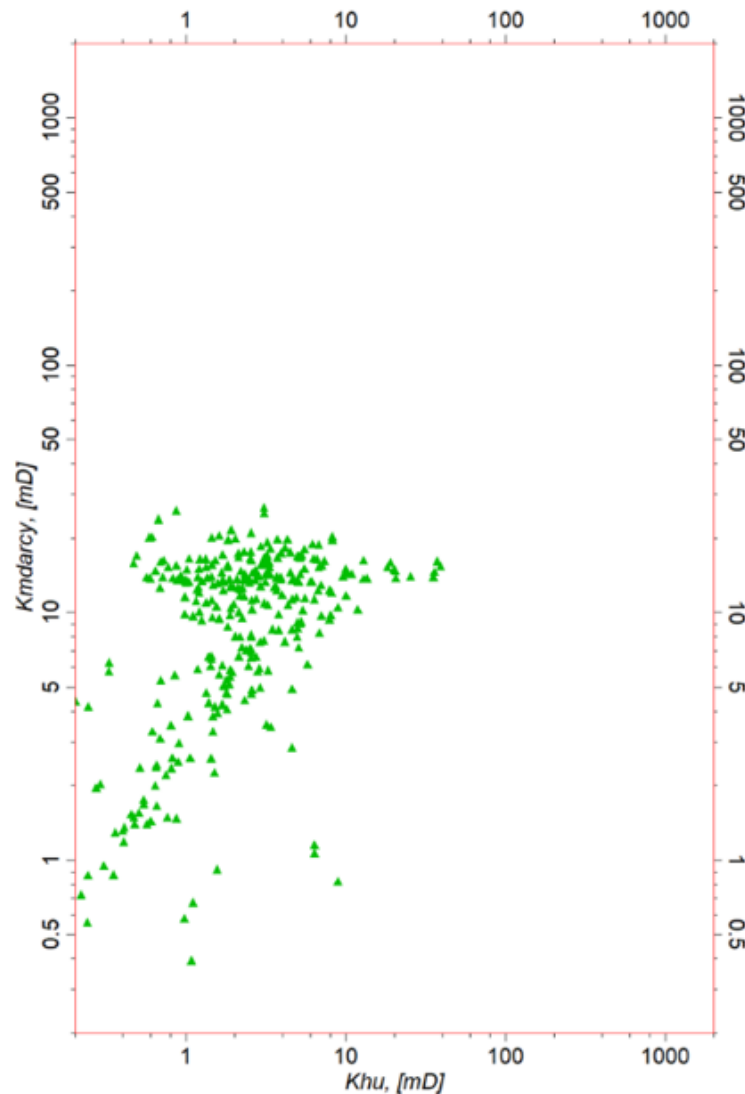
Figure 11. Raw data log permeability and cross-plot permeability estimation results using the concept of HFU and critical porosity.

Nur shows that each lithology has a different critical porosity (Nur *et al.*, 1995). Each group of dry rock is characterized by a certain critical porosity value that differs from one group to another (Prakoso *et al.*, 2018). Figure 4b is a critical porosity model estimated using the concept of Nur for dry rock. The critical porosity model in this research is built by assuming that each rock sample has a different pore geometry and structure. Furthermore, it shows that critical porosity has a similar pattern with bulk modulus. Meanwhile, high bulk modulus areas tend to have low critical porosity. This is in line with the concept of Prakoso for dry rock (Prakoso *et al.*, 2018) and saturated rock (Prakoso and Burhannudinnur, 2020).

The hydraulic flow unit concept identifies rock quality by classifying it according to flow zone indicators. Pore complexity is identified based on the similarity of the FZI value. In this research, rock complexity is modeled by looking at the similarity of critical porosity values as stated by Prakoso (Prakoso *et al.*, 2018; Prakoso and Burhannudinnur, 2020). Furthermore, in this research, Modeling permeability using the critical porosity concept gives good results. This is shown by permeability estimation results close to raw log data (Figures 9 and 10 Column B). The results of this modeling provide a more optimistic permeability value than using the KFU concept compared with permeability obtained using the HFU concept (Figure 11).

Conclusion

Permeability can be modeled well by using the concept of critical porosity. This proves that critical porosity carries information on the pore complexity of rock. Rocks with high critical porosity tend to have good quality due to good permeability. This research is another alternative to modeling permeability by using acoustic wave velocity data.

Acknowledgments

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