A systematic effect of clay volume on porosity – p-wave velocity relationship

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Abstract. It has been believed that P-wave velocity is strongly influenced by complexity of pore arrangement. In Sandstones, the pore complexity is influenced by the constituent material of rock including clay volume. Rocks with a certain clay volume will have a certain pore geometry and pore structure and also, they have certain qualities. This research is intended to study the effect of clay volume on rock quality and its effect on the relationship of porosity with P-wave velocity. This research used 3 sandstone data sets from the North West Java basin, Kutai basin and Southern Sumatra basin. The mineralogy of each rock sample is dominated by quartz and kaolinite. The three data sets show the relationship of porosity and P-wave velocity can be clearly separated by clay volume. Each of these rock groups indicates different qualities called rock types. It can be concluded that the variation of P-wave velocity is influenced by rock type. The lower rock quality is denoted by the larger rock type number and is indicated by the increase in clay volume.

1. Introduction
Several studies show that the variation of P-wave velocity is strongly influenced by pore complexity. The complexity of pore is strongly influenced by material constituent formed during the deposition and diagenesis process. In sandstones, the complexity of pores is controlled by the presence of clay in pore space. The presence of clay causes the establishment of rock groups with certain pore geometries and pore structures that are different from one another. Thus, the P-wave velocity corresponds to the complexity of the pore space arrangement. Information about the complexity of the pore space is needed to understand the variations of P-wave velocity.

Some researchers have attempted to quantify the effect of clay on P-wave velocity even though the study has not specifically linked to pore geometry and pore structure. Picket states that P-wave velocity carry out information about rock mineralogy \cite{1}. Furthermore, Minear showed that pore lining clay would cause the pore space to be rounded and increase rock elasticity and P-wave velocity \cite{2}. In shaly sandstones, the increase in clay volume causes porosity to decrease and the acoustic wave velocity increases \cite{3,4}. Although not specifically linking to rock quality, Han show that for rocks with the same clay content, the relationship between Porosity and P-wave velocity can be represented by a linear straight line \cite{5}. Regarding the clay volume, Yin and Nur show that if the clay volume is smaller than porosity, the clay particles will fill the pore space so that the porosity decrease and increase the P-wave
velocity [6]. However, the influence of clay on the P-wave velocity also depends on the type of mineral clay [7]. In addition to clay volume, the distribution of clays in pores space also greatly influences the rock elasticity and wave velocity [8]. Poor grain sorting causes the efficient grain arrangement and increases the rigidity of the rock framework which results in increased acoustic wave velocity [9].

Related to grain size and pore space distribution, Prasad used the hydraulic unit concept to describe the relationship between acoustic wave velocity and permeability [10]. As for Weger show that simple and large pore structure (moldic and vugy) have a large velocity compared to small pore sizes and complex pore structure [11]. Thus pore architecture not only affects rock permeability but also P-wave velocity variations [12]. In relation to the physical properties of rocks, grouping of rock sample based on the pore complexity can be expressed by the relationship of pore geometry and pore structure [13,14]. Pore geometry and pore structure are expressed simply by a combination of porosity and permeability [13,14]. Furthermore, Wibowo and Permadi arrange a reference curve or type curve for rocks grouping based on pore geometry and pore structure [14]. The type curve is not only valid for carbonate but also sandstones [14]. Prakoso showed a systematic effect of pore geometry and pore structure on P-wave velocity [15]. Rock samples with similar pore geometry and pore structure will have their own group and have different relationships between velocity and porosity. Specific relations of dry bulk modulus and dry P-wave velocity \( V_{pdry} \) to porosity are obvious when the rock samples are grouped on the basis of similar por attributes, pore geometry and pore structure. This led to the results of a critical porosity is a specific property [16].

Prakoso proved that rock quality expressed by HFU is strongly influenced by pore attributes [17]. This research is intended to study the effect of clay volume on rock quality and its effect on the relationship of porosity with P-wave velocity.

2. Data and method

2.1. Data used
This study uses 3 data sets from the North West Java Basin, Kutai Basin and Southern Sumatra Basin. Available data include physical properties of rocks such as porosity, permeability and P-wave velocity. P-wave velocity data measured in dry conditions and atmospheric pressure. Sedimentology analysis was carried out to obtain an overview of the geological characteristics of reservoir rocks. The Sedimentology data included the types of lithology and depositional environment, mineral composition, texture, rock classification, and diagenetic processes and their effects on reservoir quality. Petrographic analysis includes identification of composition and type of grain/mineral, texture, porosity and diagenesis process and also clay content.

2.2. Concept of pore geometry and pore structure
Pore Geometry and pore structure can be arranged simply by using a combination of porosity and permeability [14]. Pore geometry is expressed as \( (k/\phi)^{0.5} \) while the pore structure is in the form \( (k/\phi) \). The pore geometry \( (k/\phi)^{0.5} \) and the pore structure \( (k/\phi) \) are derived from the same equation so the factors that affect pore geometry and pore structure are basically the same. The pore structure \( (k/\phi) \) is referred to as the independent variable while the pore geometry \( (k/\phi)^{0.5} \) is the dependent variable whose influenced by the pore structure. The relationship between pore geometry and pore structure can be written as follows:

\[
\left( \frac{k}{\phi} \right)^{0.5} = a \left( \frac{1}{F_3 \tau S_b^2} \right)^b
\]

Equation 1 can be written in the form of the power law equation as follows:

\[
\left( \frac{k}{\phi} \right) = a \left( \frac{k}{\phi^3} \right)^b
\]
Constants $a$ in equations 1 and 2 is pore efficiency while $b$ is the exponent of the pore structure. One rock type has similarities in pore architecture as indicated by the similarity of microscopic geological features. The similarity of the pore architecture is expressed by the combination of porosity and permeability. Plot of $(k/\phi)^{0.5}$ on the Y axis and $(k/\phi)$ on the X axis on the log-log graph produces a straight line with maximum slope $b = 0.5$. Based on equation 2 Wibowo and Permadi arranged a rock type chart that can be used for rocks grouping.

Nur modified Voigt bound using critical porosity ($\phi_c$) [18]. Critical porosity is boundary of consolidated sediment and suspension. Modification of the Voigt bound is done by normalizing porosity with critical porosity ($\phi_c$). For dry conditions the pore space contains air so that the value of bulk modulus from the Reuss average is close to zero. Thus, dry bulk modulus ($B$) can be written as follows:

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

Equation 3 can be arranged into a linear equation as follows:

$$\frac{B}{B_m} - 1 = -\frac{\phi}{\phi_c}$$

Plot $B/B_m$ (Y axis) against $\phi$ (X axis) it will form a straight line, gradient $-1/\phi_c$ and the line will intersect the Y axis at the value $B/B_m = 1$

3. Results and discussion

3.1. Rock quality identification

Rock quality identification is done by classifying rock samples based on microscopic geology features. The grouping of rock sample was carried out using rock type charts published by Wibowo and Permadi [14]. Based on this method, all data sets can be grouped into several rock types. Starting from rock type 3 the best quality with the highest $b$ value up to rock type no 11 which is low quality rock (Figure 1).

![Figure 1](image.png)

**Figure 1.** Identification of rock quality for data set 1 (a), data set 2 (b) and data set 3 (c).

Figure 1 shows that in a rock type, the pore size or effective hydraulic radius enlarges in the direction of A. This phenomenon is expressed by increasing $(k/\phi)^{0.5}$. In one rock type the pore shape is similar but different in size[14]. So, for the same rock type, the tortuosity $\tau$ and shape factor $F_s$ is similar but different in specific surface area $S_b$ (Eq. 1). El-Khatib proved mathematically that Leverett's J-function ($J(Sw)$) describes rock tortuosity [19]. So that in one rock type will have similar in tortuosity and pore
shape complexity. The arrow B on the same value \((k/\phi)\) shows a simpler pore shape, close to a perfectly round shape or capillary pipe so that the pore quality getting better.

3.2. Effect of clay volume on the rock quality and dry p-wave velocity

The clay volume was obtained from the total fraction of clay minerals against the total bulk weight obtained from XRD analysis. Figure 2 is the average histogram of the total clay volume for each rock type. Starting from a good rock type (small rock type number) shows a tendency to have a low clay volume. The lower quality of rock type is indicated by the increase in clay volume.

![Figure 2](image)

**Figure 2.** Histogram average volume of clay for each rock type for data set 1 (a), data set 2 (b) and data set 3 (c).

The effect of clay volume on P-wave velocity is shown in Figure 3. Although the data points of the relationship of clay volume and \(V_{\text{dry}}\) are scattered, Figure 3 shows a clear trend that the increase in clay volume tends to increase \(V_{\text{dry}}\). This can be observed from the linear trend line obtained from the relationship of clay volume with \(V_{\text{dry}}\) even though it has a low correlation coefficient. The scattered data points are probably caused by variations in clay minerals which include illite and kaolinite. As is known, illite and kaolinite have different effects on P-wave velocity. Shape of Pore space of smectite/illite is more rounded (pore aspect ratio 0.55) and more stiff pore while kaolinite is dominated by elongate pore (pore aspect ratio 0.44) [20]. The more rounded pore shape tends to increase the P-wave velocity compared to the elongate pore shape. Based on Figure 3, it can be seen that low quality rocks (large rock type numbers) will tend to have high \(V_{\text{dry}}\). Thus the increase in clay volume causes a decrease in rock quality and is one of the factors that affect the increase of \(V_{\text{dry}}\).

Reuss bound assumes that stress for all components in the medium is equal so that Reuss bound better to describes a suspension [21]. Suspension is a condition where there is no inter-grain contact of material. Whereas Voigt bound describes solid material that has perfect inter-grain contact [22]. Reuss and Voigt bound are the lower and upper limits of elastic moduli of a material in ideal conditions. It is different for actual rock where there is no ideal grain arrangement and tends to have different heterogeneity. The effective modulus of a porous media will be between the upper and lower bound depending on the geometry detail so that bounding theory is not very useful for the purposes of predicting P-wave velocity.
Figure 3. Relationship of clay volume with P-wave velocity ($V_{pdry}$) for data set 1 (a), data set 2 (b) and data set 3 (c).

The equation of Nur's critical porosity models can be arranged into linear equations. If plotted $B_{dry}/B_m$ against $\phi$, a straight line with slope $-1/\phi_{c}$ will be formed and the line will intersect the Y axis at the value of $B_{dry}/B_m = 1$ (Eq. 4). $B_{dry}$ is a bulk modulus in dry conditions and $B_m$ is a mineral bulk modulus. This approach will be used to analysis the relationship of bulk modulus with porosity based on rock type. Figure 4 shows the relationship of $B_{dry}/B_m$ and the porosity of each rock type can be represented by 1 theoretical curve Nur's.

Figure 4. Relationship of $B_{dry}/B_m$ with porosity for data set 1 (a), data set 2 (b) and data set 3 (c).

Maximum theoretical Nur’s curve obtained by assuming the maximum porosity of sandstone 0.476. The maximum porosity occurs when the grain arrangement is simple cubic packing. In general, the $B_{dry}/B_m$
plot against $\phi$ for each rock type has a linear trend. The linear trend will intersect X axis at a certain porosity value at the $B_{dry} = 0$. Reuss bound describes the suspension so that for dry conditions the bulk modulus is equal to 0. Thus, the intersection of the theoretical Nur’s curve with the X axis at $B_{dry} = 0$ is proportional to the value of critical porosity. The critical porosity should be lower than the simple cubic packing porosity because the natural reservoir rock has a packing quality lower than the ideal simple cubic packing. Based on Figure 4, it can be seen that there will be a linear trend of $B_{dry}/B_m$ and $\phi$ relationship for each rock type. As discussed in the previous section, the increase in clay volume will reduce rock porosity and quality. The decrease in porosity tends to increase rock rigidity so that the bulk modulus will increase. The increase in rock rigidity will further increase the P-wave velocity (Figure 5). Based on Figure 5, it can be seen that the decrease in porosity due to increased volume of clay is followed by decreasing rock quality and increasing P-wave velocity.

![Figure 5. Relationship of porosity with P-wave velocity ($V_{pdry}$) for data set 1 (a), data set 2 (b) and data set 3 (c).]

4. Conclusion
The study of the clay impact on rock quality and P-wave velocity on 3 sandstone data sets from 3 different basins showed similar results. The presence of clay, systematically degrades rock quality and increases pore rigidity and P-wave velocity. The relationship of porosity to the P-wave velocity for each rock type can be represented specifically by a Nur’s curve. Each rock type is characterized by a certain value of maximum porosity.

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