Petrophysics Evaluation for Determining Porosity of Shale Reservoirs

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Abstract. Indonesia is known for its large potential of shale resources, yet the character of their physical properties remains unclear. This study focuses on how to assess the petrophysical properties of shale using conventional wireline logs. Shale has been largely known as a host rock producing hydrocarbon in the conventional petroleum system due to the amount of kerogen trapped during the depositional process. The kerogen or continuously called Total Organic Carbon (TOC) behaves like a porosity to a density log and this will be misleading to the higher porosity than the actual shale rock. Prior investigation evaluates the physical properties in shale rock, including shale porosity, TOC, and matrix mineralogy, at a certain limited depth. A solid rock is presumed to consist of a shale matrix and TOC. Meanwhile, shale porosity is contained only in water. TOC responses to sonic wave, density, and porosity logs. We calculated the experimental data to estimate the volume of TOC at the limited depth to obtain the correlation of available logs. Shale porosity is then computed using a density log with the TOC-influence removed. The results show that the shale porosity is to be TOC-free with a value range of 3-14%.

Keywords: Shale, Porosity, TOC, Wireline logs, Petrophysics

1. Introduction

Shale is a fine-grained sedimentary rock which is formed by the consolidation of clay (less than 4 µm) and silt (in the range of 4-62.5 µm) sized particles into rock layers of ultralow permeability [1]. In the conventional petroleum system, shale is known as a host rock producing hydrocarbon due to the amount of organic material (kerogen) trapped during the depositional process. It also acts as a sealing rock that has very low porosity and permeability. Shale is now developing to be potential unconventional reservoir rocks. The 'unconventional' definition arises due to the analysis of the right combination of geological, petrophysical, geochemical, and geomechanical properties of shale rocks.

This study focuses on how to assess the petrophysical properties of shale rocks to get a better understanding of discriminating potential shale reservoirs. Prior investigation evaluates these properties, such as shale porosity with the influence-free of kerogen and matrix mineralogy, which are yielded both from core samples and conventional wireline logs readings at a certain...
limited depth of a data set from Indonesia. Determining the unique characteristic of shale rocks is challenging yet significantly important to obtain reliable and robust information of the potential shale reservoirs from logs. In this case, we attempt to delineate the unique characteristics of shale porosity which is presumed to be composed of matrix porosity and kerogen porosity by using the algebraic solution, thus the only shale porosity that appears is the one with no kerogen influence to estimate the possibility of the shale reservoir potentials. This study also may help to obtain the value of mineralogy and kerogen at the uncored zones of the targeted area.

2. Petrophysical Analysis

A constructed model of solid rock by incorporating kerogen as a part of shale matrix (Fig.1a). At a certain maturity temperature and pressure, solid kerogen will be converted into hydrocarbon and formed kerogen porosity as a pore space inclusion (Fig.1b). Therefore, the total porosity of shale is naturally composed both of matrix porosity and kerogen porosity.

![Figure 1. Constructed model of the shale rock composed of TOC and mineralogy](image)

2.1 Matrix mineralogy of shale rocks

There are numerous challenges in discriminating the mineralogy composition to get the best solid rock model to represent the actual condition of rock due to the limited data available. We have information on matrix mineral composites from the dataset extracted by the X-Ray Diffraction technique at a certain limited depth. Our first work was to distribute these available points toward the whole targeted depth to obtain the information related to matrix mineralogy in the well. It shows that the shale rock is composed of simplified clays (~50% volume fraction), quartz (~45% volume fraction), and the addition of pyrite, siderite, and organic material with the volume fraction less than 5% of the whole solid rock.
The correlation of quartz and the porosity is hard to be investigated [2], yet a tiny volume fraction of clay minerals can cover the entire surface area of rocks, thus reducing the total porosity of shale. Consequently, we found a negative correlation between clay minerals and the total porosity of shale (Fig. 2). This information acts as simple guidance to delineate the shale rocks from the other lithology by finding the area with a higher volume of clay as well as lower porosity from logs. The relationship of these parameters will be statistically utilized to estimate the correlation between the available porosity logs and the mineral clay where it is uncored at the whole depth of the well.

![Figure 2](image.png)

**Figure 2.** The relationship between clay minerals concentration and the porosity of shale.

### 2.2 TOC

Shale rocks have been defined as an unconventional resource due to the presence of amount weight percentage of TOC. Therefore, TOC is a crucial part to predict the economically potential shale rock reservoirs. We had a set of weight percentage TOC at a certain limited depth from the sidewall core measurements. In addition to the correlation of matrix mineralogy, TOC shows a positive correlation with the clay minerals (Fig. 3). Hence, a negative correlation with the porosity of shale. A geochemical analysis using the information of Hydrogen Index (HI) and T_{max} has been conducted and shows that the TOC is in the fair to the good interval with gas-prone kerogen type. The vitrinite reflectance analysis found that the area is immature with less than 0.6% Ro as plotted in Figure 4.
Figure 3. A positive correlation between clay mineral and TOC (wt.%) fraction

This information confirms the relation of rock properties plotted to the weight percentage of TOC which all shows that TOC tends to reduce the value of density, p-wave velocity, and porosity. On the other hand, the higher TOC linearly correlating to the higher Vp/Vs ratio (Fig. 5). As the TOC is still at the immature level, it has not transformed yet into fluid hydrocarbon, thus Vp/Vs ratio increases.

Figure 4. Hydrogen Index (HI) and T\textsubscript{max} diagram to show the kerogen types and thermal maturity (after [3])
2.3 Shale porosity calculation

Kerogen behaves like a porosity in density logs. In this case, shale reservoirs usually contain abundant kerogen exhibiting similar logging responses with conventional reservoirs log, e.g. lower density, higher neutron porosity as well as sonic transit time. Moreover, organic-rich shale shows increasing gamma radiation response, as in higher TOC is correlating with higher Gamma-ray log (higher API) [4]. Furthermore, this will be affecting the calculation of shale porosity from conventional logs due to the variability of matrix mineralogy, lower density kerogen, and also fluid content in the shale rocks.

We calculated the shale porosity of the targeted well using the simple algebraic solution (Eq.1) [1], [5] by assuming that kerogen-free shale porosity is fully-water saturated. This equation accommodates the relation between the density of shale solid matrix ($\rho_{ma}$), kerogen ($\rho_{TOC}$), water content ($\rho_{fl}$), and their volume fraction of each component in the rock.

$$
\phi_T = \frac{(\rho_{ma} - \rho_b) + \rho_b \left( w_{TOC} - \rho_{ma} \frac{w_{TOC}}{\rho_{TOC}} \right)}{\rho_{ma} - \rho_{fl}}
$$  

(1)

In the case where the kerogen is immature, kerogen porosity is not yet created and the shale porosity will only be consisting of mineral matrix porosity. It simplifies the mathematical operations to predict the shale porosity which the kerogen effects have been purged.
3. Discussion

We attempted to calculate the actual shale porosity and removed the kerogen effect within the porosity using conventional wireline logs. Several factors are generally the value of the overestimated porosity logs for shale rocks. For instance, the heterogeneity of mineral matrix compositions in the shale rocks which hardly able to be well discriminated. The unique characteristics of kerogen as a solid-gel is also challenging when we are delineating the economical shale reservoirs from logs. This should be combined with the integration of geological and geochemical analysis to get the best model of targeted shale reservoirs. Moreover, a small amount of clay mineral in the shale rocks plays a significant role in reducing the porosity as it lowering the potential of fluid hydrocarbon to be stored. However, our study to a detailed investigation of all influencing factors of shale porosity should be able to give the first stage for identifying shale rocks as unconventional reservoirs. Figure 6 shows that the shale porosity which is only composed of mineral matrix/grain density has been detected to be TOC-free as they have no correlation plot. Besides, the porosity logs are generally overestimated than the actual shale porosity due to the kerogen presence which shows the value of shale porosity of 3-14% on average.

![Figure 6](image_url)

**Figure 6.** Correlation of grain density and TOC after taking out the TOC (**left**) and corrected porosity after removing TOC comparing to the porosity log (**right**)
4. Conclusion

Crucial findings that can be pointed out in this study are:

- Petrophysical parameters obtained from the log data show that the targeted model of shale rocks shows a negative correlation to the weight percent TOC, except for the Vp/Vs ratio which shows that kerogen is in immature thermal condition.
- Incorporating the kerogen as a solid rock along with the mineralogy variable shows a good model of rocks so that the immature kerogen porosity is neglected and the shale porosity is well-obtained from logs.
- We attempted to estimate the actual porosity of shale rocks which theoretically lie between 3-14% and the result shows a good fit using the constructed model of shale rock.
- The solution using simplified mineral composition is limited due to the different geological settings of the study area, but it might be utilized as a quick look to delineate the prospective area in the uncored well.

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