SCIENTIFIC CONTRIBUTIONS OIL AND GAS
Vol. 42, Number 2, August 2019: 1 of 5
RESEARCH AND DEVELOPMENT CENTRE FOR OIL & GAS TECHNOLOGY LEMIGAS
Journal Homepage:http://www.journal.lemigas.esdm.go.id, E-mail: jurnal.lemigas@esdm.go.id
ISSN: 2089-3361, e-ISSN: 2541-0520

ROCK PHYSICS TEMPLATE TO ESTIMATE THE EFFECTS OF TOTAL ORGANIC CARBON (TOC) AND MINERALOGY ON THE SEISMIC ELASTIC PROPERTIES OF IMMATURE SHALE RESERVOIR

(*Pemodelan Fisika Batuan untuk Mengestimasi Pengaruh Variasi Nilai Total Organic Carbon (TOC) dan Mineral Terhadap Parameter Elastik Batuan Reservoar Shale pada Kondisi Belum Matang*)

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First Registered on June, 25th 2019; Received after Correction on July, 19th 2019
Publication Approval on: August 30th 2019

ABSTRAK

Batuan shale yang memiliki nilai porositas dan permeabilitas yang rendah mulai dikenal sebagai batuan induk sekaligus reservoar hidrokarbon. Batuan shale organik mengandung sejumlah material organik (TOC) yang memiliki pengaruh signifikan terhadap nilai properti elastik batuan. Kandungan TOC dapat menurunkan nilai densitas yang terbaca pada data log karena densitas TOC yang sangat rendah sehingga cenderung mengisi pori batuan shale. Interpretasi secara kuantitatif sangat penting dilakukan untuk meminimalisasi ketidakpastian akibat kandungan TOC dan variasi mineral pada batuan shale tersebut dan memperoleh deskripsi reservoar shale dengan lebih baik. Pemodelan fisika batuan dilakukan untuk mengestimasi bagaimana pengaruh variasi nilai TOC dan mineral pada batuan shale terhadap properti elastik untuk studi kasus Cekungan Sumatera Selatan, Indonesia. Model batuan dibuat dengan mengikutsertakan sejumlah material organik sebagai inklusi ke dalam pori batuan shale, dengan kondisi awal sudah tersaturasi oleh air. Geometri pori batuan shale dianalisis melalui tinjauan nilai aspek rasio. Batuan reservoar shale yang tersusun atas beberapa variasi mineral dimodelkan dengan pendekatan teori medium efektif. Selanjutnya, perubahan nilai modulus elastik batuan akibat inklusi TOC diprediksi dengan pendekatan persamaan Brown-Korringa yang merupakan generalisasi dari persamaan Biot-Gassmann. Hasil penelitian melalui model fisis batuan menunjukkan bahwa sejumlah kandungan TOC yang terkandung dalam pori shale secara umum akan menurunkan nilai kecepatan gelombang seismik, impedansi akustik, dan densitas batuan shale. Hal yang menarik adalah data penelitian yang digunakan ternyata belum sampai masuk ke dalam jendela kematangan hidrokarbon atau masuk dalam klasifikasi batuan dengan kematangan awal. Kondisi ini ditunjukkan melalui respon rasio v_p/v_s *yang relatif meningkat terhadap peningkatan TOC. Analisis model batuan menunjukkan bahwa TOC yang belum matang dan cenderung bersifat solid gel akan lebih berpengaruh terhadap rigiditas batuan dibandingkan dengan kompresibilitas batuan shale.*

Kata Kunci: *reservoar shale, model fisika batuan, Total Organic Carbon (TOC), mineralogi, properti elastik*

ABSTRACT

The low porosity and permeability shale are nowadays known as self-resourcing reservoirs. In the unique organic shales, TOC has a significant contribution to the elastic properties of rocks. TOC behaves like porosity to a density log and effects in decreasing density. To reduce the uncertainty due to TOC and mineral variability effect, a quantitative interpretation of shale reservoirs should be done properly to obtain the best image of shale systems. In this study, we built rock-physics templates (RPT) to estimate seismic response by defining the relationship between total organic carbon (TOC) and effective elastic properties of shale reservoirs of a data set from South Sumatera Basin, Indonesia. RPT is carried out by incorporating the amount of organic matter into shale pore space as a solid-filling inclusion. Moreover, shale porosity is assumed to be fully water-saturated determined by the in-situ conditions. We have estimated the general distribution of pore geometry by investigating aspect ratio from the dataset. A solid background of shale from several different minerals is estimated by using effective medium theory. Properties of porous rocks for solid pore infill are estimated from a generalization of Brown-Korringa Equation. Effective elastic properties of bulk rock frame filled with a fluid are obtained from Gassmann equations. Results show that increasing the TOC volumes generally reduces both P-wave and S-wave velocities, acoustic impedance, and density. On the contrary, the v_p/v_s ratio increased as the impact of immature organic matter which will be more affecting shale rigidity than its compressibility.

Keywords: shale reservoir, rock physics, organic content, clay mineral, elastic properties.

How to cite this article:

Hutami, H., et al., 1, 2019, ROCK PHYSICS TEMPLATE TO ESTTIMATE THE EFFECTS OF TOTAL ORGANIC CARBON (TOC) AND MINERALOGY ON THE SEISMIC ELASTIC PROPERTIES OF IMMATURE SHALE RESERVOIR , *Scientific contributions Oil and Gas*, 42 (2) pp, 43-49 DOI: 10.29017/ SCOG. 42.2.43-49

I. INTRODUCTION

Shale is a fine-grained and organic-rich sediment that acts as source rocks in the conventional reservoirs. The low porosity and permeability shale are nowadays known as self-resourcing reservoirs (SRR). A major challenge in shale reservoir characterization is to identify the TOC effect on the geophysical response as well as mineralogy. Kerogen is the most important factor to indicate the potential target zones of the shale reservoir because of its unique resistivity, velocity, and density characteristics. This rock-physics templates (RPT) aim to link the relationship between elastic properties of rocks (e.g., velocities, density, and wet-rock stiffness moduli) by incorporating organic matter and mineralogy effect, especially.

Zhu et al (2012) use the Gassmann-type model developed by Carcione et al. (2011) to incorporate TOC effects, mineralogy, porosity, and fluid content. Their model indicates that an increase in TOC generally reduces the P-wave impedances and v_p/v_s ratio (Carcione and Avseth, 2016). Ciz and Shapiro (2007) quantify the effective elastic properties of porous rock using Gassmann equation for bulk rock frame filled by fluid and Brown-Korringa equation to the situation with solid kerogen filling the pore space. The classical Gassmann is inapplicable if the pore filling material is solid.

Moreover, it is important to evaluate the number of clay minerals forming the shale matrix as well as porosity. Minerals can affect the stiffness moduli and wave velocities of rock (Carcione and Avseth, 2016). Zargari and Prasad (2013) stated that the total porosity of shale is mostly controlled by the change of clay mineral volumes and the amount of kerogen within pores. Moreover, volume changes of these minerals also cause significant variations in the elastic properties of the rocks.

In this research, we consider the Gumai shale of the South Sumatera Basin at a limited certain depth to estimate the differences of seismic properties of shale systems due to mineralogy and kerogen content variabilities on the case of immature organic matter (which the TOC has not transformed yet to hydrocarbon).

II. DATA AND METHOD

The research data are taken from side-wall cores of a gas conventional well from Gumai Formation, South Sumatera Basin which consists of the volume of dominant clay and non-clay minerals and weight percentage of TOC at certain depth only. We use the data (Table 1) to build a model later using rock physics approached to estimate the effective elastic properties of rocks due to the presence of immature TOC and clay mineral volume.

Table 1
The available data set used to build a rock physics model

Data	Information
Measured log	Bulk density, DTC, DTS, PHIT at depth of 4000-6000 ft
Mineral fraction	Clay (~50%), Quartz (~45%), Calcite (~5%)
TOC (weight%)	0 - 3

Our general data processing divided into two stages, which are investigating petrophysics data conditions and building a rock physics template.

A. Investigating Petrophysics Data

The first step for evaluating shale reservoirs is to define its petrophysical model. Shales are commonly assumed to consist of the solid matrix and pore spaces. In this research, we put organic matter in a part of pore spaces as solid inclusions (Fig.1)

This model has been properly done by Zhu et al. (2012) which also treated the organic matter as a part of inclusion. He shows this approaching has given the best match to velocity measurements. Furthermore, it is expected to help us identify the influences of TOC and mineralogy variability at the immature temperature to the potential shale reservoir compared theoretically to the mature shale reservoir

1. Determining Total Porosity of Shale

As we work in a gas conventional well, we need to evaluate typical shale reservoir porosities. Importantly, considering the additional effects of the TOC component within pore spaces. Shale reservoir porosities may have a very low range of porosities (about 3-10%). Porosity calculations using only conventional log measurements may have significant uncertainties due to the variable mineralogies, amounts of low-density organic material, and fluids present in these reservoirs (Franquet et al. 2012).

Generally, the total porosity of shale is obtained from the matrix (shale) porosity and kerogen (TOC) porosity (when it is fluid-contained). Thus, we need to evaluate both of them separately to analyze the effects on the shale reservoir. In this study, we use density log measurements to determine the total porosity of shale which is free of TOC content. Due to the high heterogeneity of the shale layers, it is not possible to determine a specific value for $\rho_{ma.}$ Therefore, we simplify our model of the matrix minerals to consists only of clay and non-clay (e.g., quartz and calcite) as these minerals play a significant role in controlling shale properties, such as pore structure of the rock.

Equation (1) is the bulk density of a rock where the TOC component is added to it (Sondergeld et al., 2010).

$$\rho_b = \rho_{ma}(1 - \phi - V_{TOC}) + \rho_{fl}\phi + \rho_{TOC}V_{TOC} \quad (1)$$

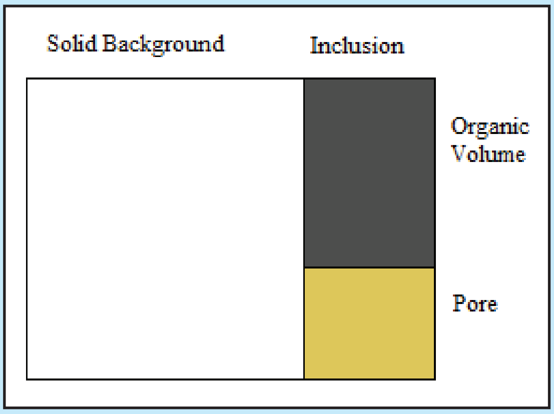

Figure 1
Petrophysical model showing when all organic matters are considered as a part of the inclusion spaces.

Since TOC has been expressed as a weight percentage, this value has to be converted to TOC volume fraction (V_{TOC}).

$$V_{TOC} = \frac{w_{TOC}}{\rho_{TOC}}\rho_b \quad (2)$$

Then we calculate the total porosity by using Equation (3) (Labani and Rezaee, 2015).

$$\phi_T = \frac{(\rho_{ma} - \rho_b) + \rho_b\left(w_{TOC} - \rho_{ma}\frac{w_{TOC}}{\rho_{TOC}}\right)}{\rho_{ma} - \rho_{fl}} \quad (3)$$

where ρ_b is the bulk density from density logs, ϕ_T is the total density-porosity, ρ_{ma} is the solid matrix density, w_{TOC} is a weight fraction of TOC, ρ_{TOC} is kerogen density, and ρ_{fl} is a fluid density. We assume ρ_{TOC} = 1.3 g/cc. Also, assuming the porosity of shale is fully water-saturated ($\rho_{fl} = \rho_{water}$ = 1.1 g/cc).

2. Determining Porosity-Clay Mineral Volume-TOC content Correlation

A limitation of the data set is becoming our challenge in doing this research. We have overcome this problem by obtaining the correlations between the volume of clay minerals and organic matter with the total porosity of shale (Fig.2a and 2b). Among all the factors influencing the effective properties of shale reservoirs, organic matter and the volume of clay minerals are the most important variables.

Hence, these cross-plots may help us to not only indicate the potential target of the shale reservoir but also to estimate TOC content in a well where the availability of core data minerals is limited. A relatively small adjustment of the organic content and clay mineral volumes are done to see how much these factors will influence the total porosity of shale in the case of our data set.

A. Rock Physics Modelling

Our data set covers a relatively fair to a good range of TOC fractions (from 0 to 3%) (Peter and Cassa, 2007). The model suggests that increasing organic content generally decreases the elastic parameters (v_p, v_s, and bulk density) (Fig. 3). On the contrary, these show us that our organic matter is in a zero level of maturity, as v_p/v_s ratio increases strongly with the increasing of TOC content. Therefore, putting them as a solid inclusion into shale pore space will do a good fit.

The rock physics approached in this study is done following several steps:

(Step 1) - Building a solid matrix background consists of available volume mineral fractions using the combination of Voigt-Reuss-Hill Bound and The Critical Porosity Theory from Nur et al., 1992. To account for the specific characteristics of the available dataset, we computed matrix modulus (K_m) derived from log saturated bulk modulus (K_{sat}) and plotted with the volume of clay and non-clay minerals to estimate the specific value of moduli for each clay (K_{cl}) and non-clay (K_{ncl}) minerals

(Step 2) - Estimating the pore geometry and dry rock moduli using the Pore Space Stiffness Analysis and Kuster-Toksoz (1974). We performed two approaches to modeling the dry rock frame (K_{dry}) as a function of porosity, which is the pore space stiffness (K_ϕ) method and critical porosity (ϕ_C) method. We discuss pore space stiffness (Rusell and Smith, 2007), which tells us that the dry rock over matrix bulk modulus ratio is an inverse function of porosity and the pore space stiffness over matrix bulk ratio *k*.

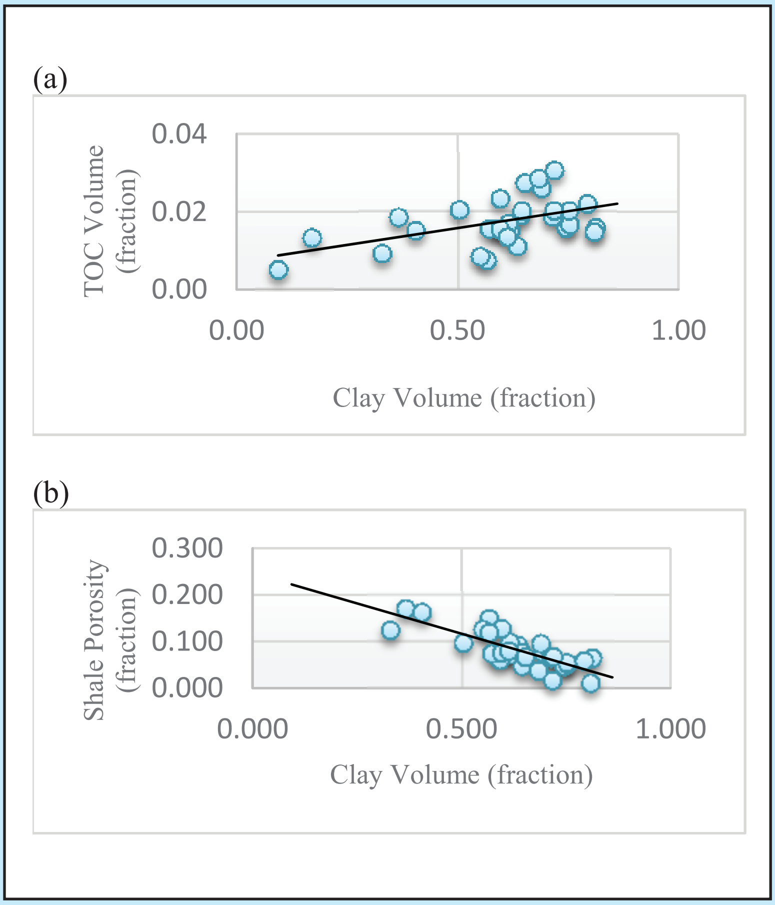

Figure 2
Relationship between (a) clay volume and TOC, and (b) clay volume and porosity are used as a guide to identifying shale reservoirs area at a certain depth. That is the area with clay-rich source rocks and lowy porosity. Clay minerals and TOC have linear correlation so that this relation is applied to calculate TOC volume using the rock physics method.

Table 2
Obtained Parameters used to the RPT

Properties	Value
K_{cl}	11 (Gpa)
K_{ncl}	22 (Gpa)
K_{TOC}	7.98 (Gpa)
Aspect Ratio (α)	0.01 (*softest*)-0.15 (*stiffest*)
Critical Porosity (ϕ_c)	0.23

(Step 3) - Gassmann Equations predict effective elastic properties of an isotropic homogeneous bulk rock frame filled with fluid. This theory has been generalized for an anisotropic porous frame by Brown and Korringa's equations (Ciz & Saphiro, 2007). In this study, we estimate the effective elastic properties of kerogen-filled and water-filled pores using Brown-Korringa and Gassmann substitution, respectively. Finally, we calculated the seismic velocity and impedance models from these stages.

III. RESULT AND DISCUSSION

A. Quantifying the Physical Properties of Rocks

To obtain the best parameters for our rock physics model at a given depth, we have to perform trial and error analysis during the time to get the best fit model parameters. These are controlled mostly by evaluating error analysis between model and the in-situ elastic properties (e.g., v_p and v_s). Figure 5 shows good correlations of our vp and v_s models compared to v_p and v_s from log measurements with the obtained parameters are provided in Table 2.

The most challenging part is we need to be very detail and specific when performing the fitting parameters. A single parameter is relatively difficult to represent the whole given depth. The result shows that the properties obtained from our cross plots are following the theory as well as match the unique condition of our dataset.

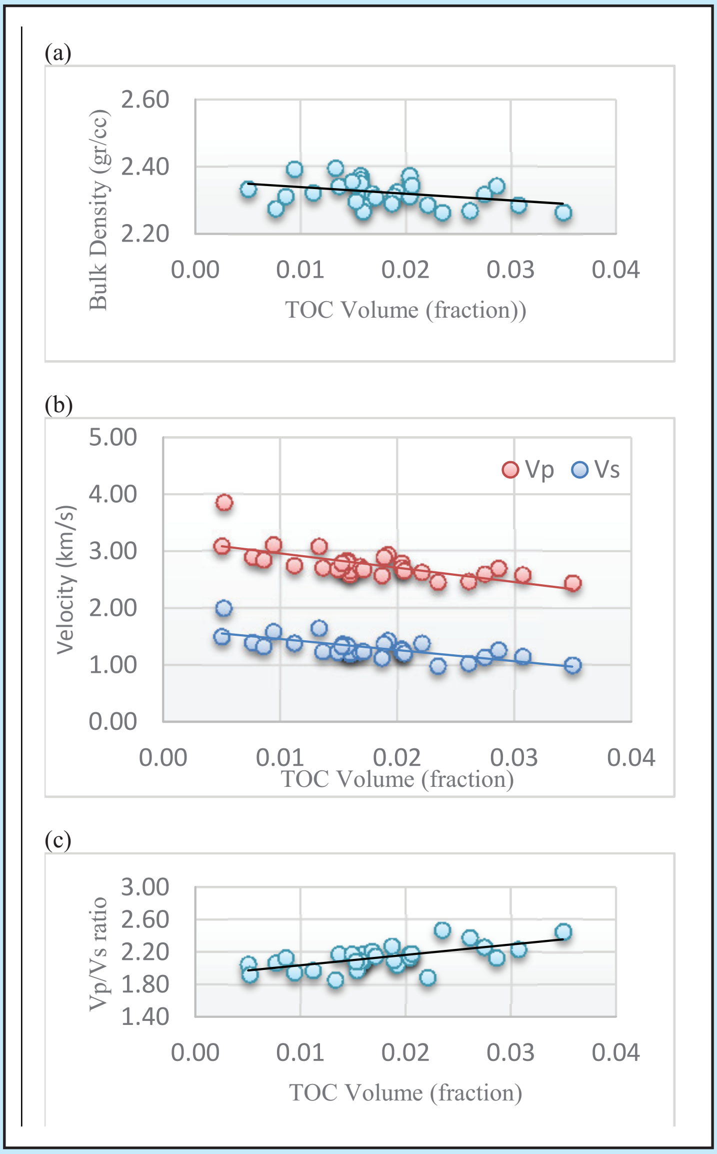

Figure 3
(a) cross plot of bulk density with TOC content volumetric fraction showing negative gradients with increasing of TOC content, (b) cross plot of Vp and Vs with TOC fraction showing negative gradients with increasing of TOC content, and (c) cross plot of Vp/Vs ratio with TOC fraction showing positive gradient with increasing of TOC content.

B. Elastic properties of shale based on TOC and clay minerals

The key controls on the elastic properties of the organic shale are the TOC content, clay mineral, density, and porosity. We investigated the variations of velocities as a function of TOC content and clay minerals for our data set. The generated rock-physics templates in figure 6(a) and 6(b) show the graphs of measured velocities compared to velocities from the log as a function of TOC content and clay mineral. High TOC content of shale is generally characterized by low, both of P- and S- wave, velocities. Besides, the result of this study shows that as the clay mineral volume increased within pores, the velocities decreased linearly. Besides, figure 6(c) shows cross plot v_p/v_s ratio with TOC content that indicates an immature level of organic matter both in our data set and our model as the shear wave velocity is rapidly decreasing more than compressional wave velocity.

We also plotted Acoustic Impedance (AI) variations based on TOC volumes as further investigations to estimate the effects of these parameters of the

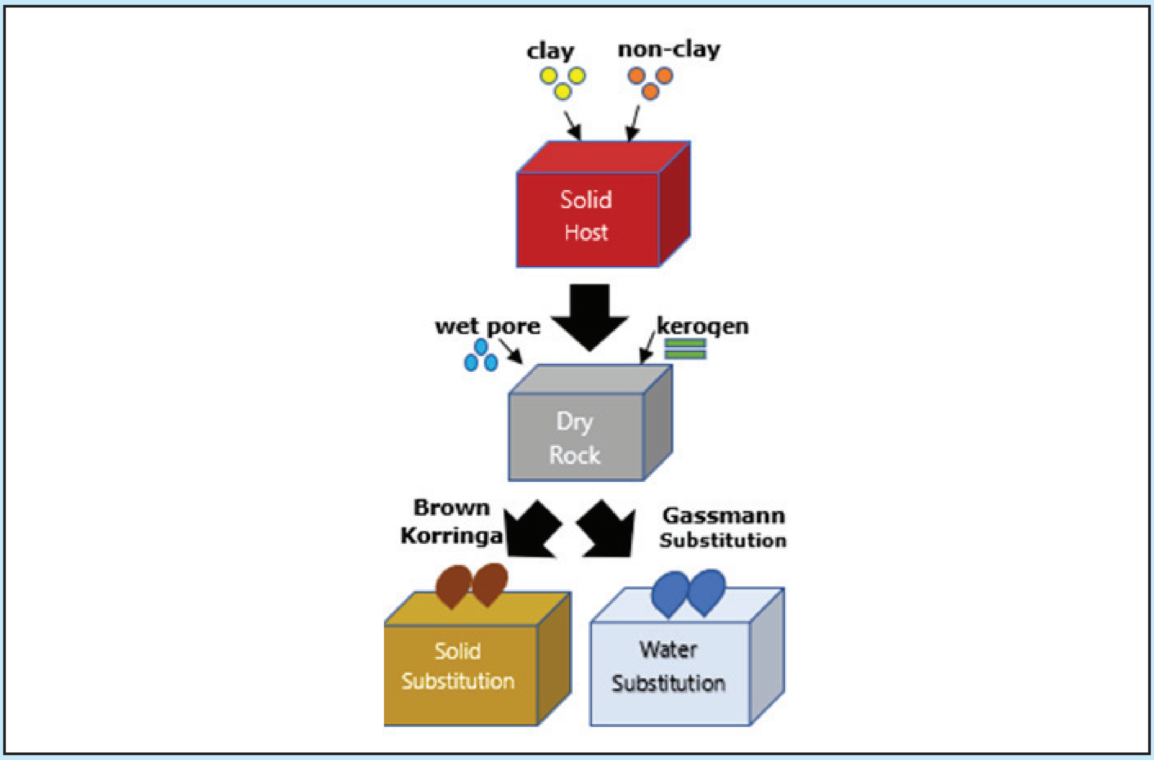

Figure 4
The workflow diagram to obtain the best model for Vp, Vs, and mass density compared to the original data from log measurement

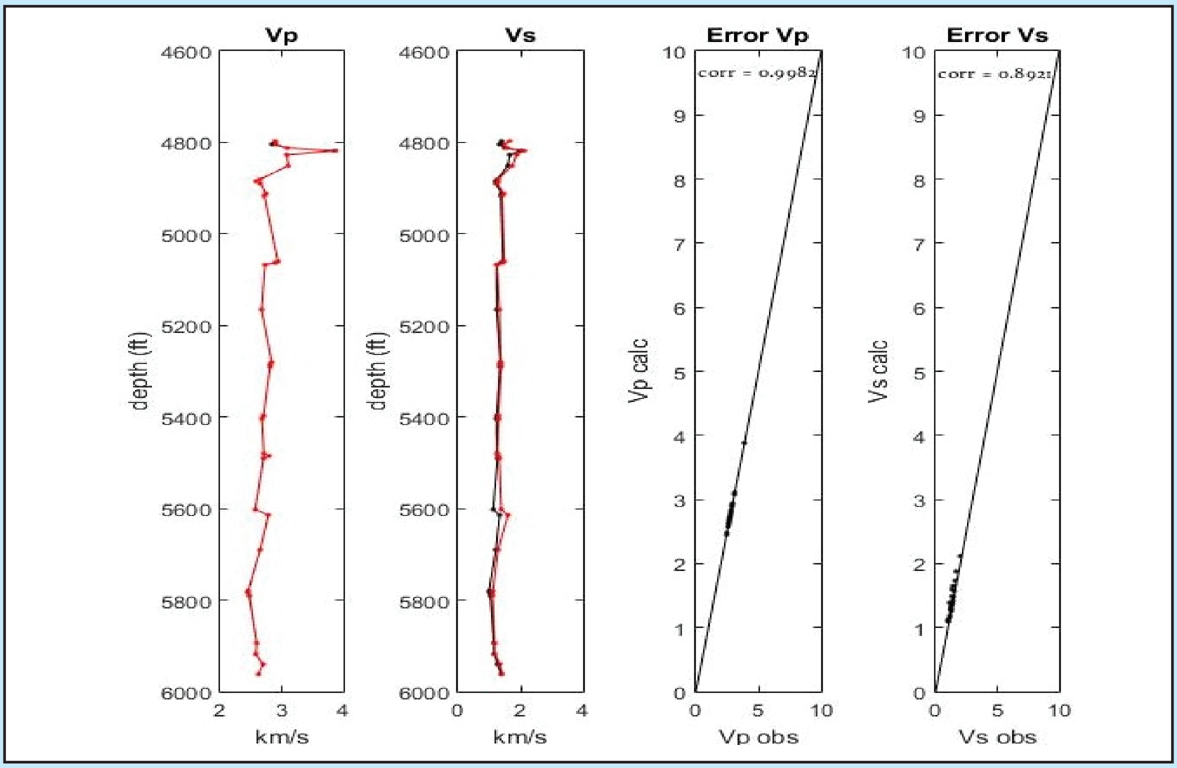

Figure 5
Vp and Vs models are calibrated to log measurement with good correlation of 0.9982 and 0.8921, respectively.

shale reservoir. Figure 7(a) shows the relationship between TOC content and AI. This study shows that AI relatively decreases with increasing TOC content. Moreover, modeling results also suggest decreasing v_p/v_s ratio versus AI in figure 7(b) compared to log data. That confirms our organic matter is at an immature level.

IV. CONCLUSIONS

We have proposed a rock-physics template for evaluating shale reservoirs potential from a conventional well log measurement. Some key petrophysical investigation and rock physics modeling results are summarized below:

- Determining the total porosity of shale becomes important to delineate the shale reservoirs from conventional log measurements. We have estimated the porosity within the proposed range (3-14%) by using a density log (Labani and Rezaee, 2015).

- Adjusting TOC content and clay minerals play a crucial part in determining shale porosity. The result shows porosity is an inverse function of clay minerals and TOC content.

- Increasing TOC content and clay mineral volumes are also relatively reducing density and porosity (e.g., Vernik and Nur, 1992).

- Increasing TOC content and clay mineral volumes generally decrease P- and S- wave velocities, as well as Acoustic Impedance of our shale reservoir model.

- This study show v_p/v_s ratio indicated immature kerogen as it increases along with the increase of TOC in an unpressured condition.

This model allows the prediction of elastic properties by including organic matter and mineralogy as a constituent of rocks. Introducing TOC as an inclusion medium shows a good fit with the measured rock physics model of our data set from the South Sumatera Basin, Indonesia.

ACKNOWLEDGE

Authors would like to thank Institut Teknologi Sumatera for providing the research grant (B/337/IT9.C1/PT.01.03/2019) through “Hibah Penelitian ITERA SMART 2019”.

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