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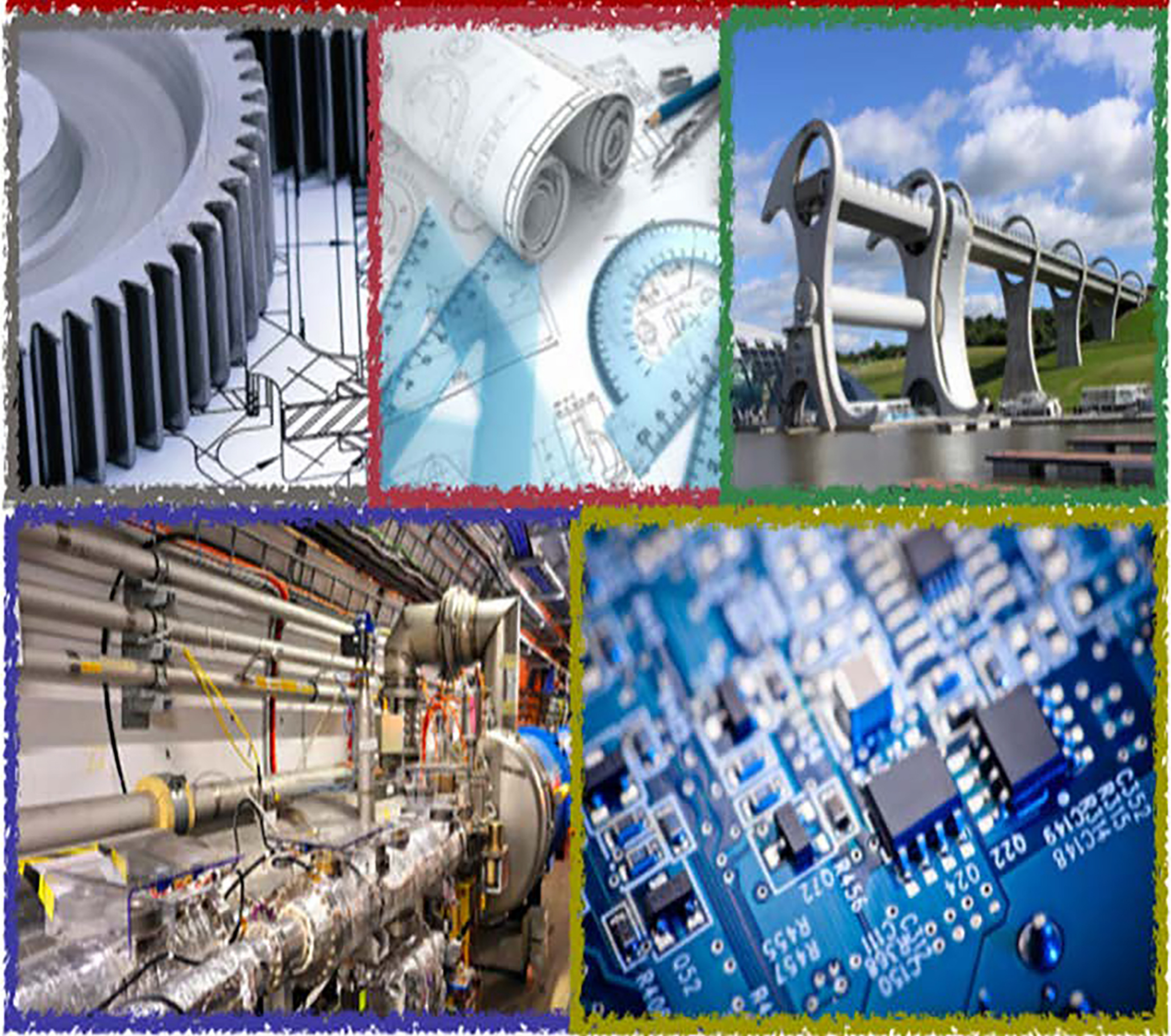

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Brittleness Prediction Using Sonic and Density Logs to Determine Sweet Spot of Brown Shale Reservoir

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Abstract*—Brittleness be used as one of the important parameters to development of non-conventional hydrocarbon or shale reservoirs. Shale reservoir has very small permeability so that to produce oil and gas, hydraulic fracturing needs be done. For effectiveness in the fracturing process, it is necessary to do fractures in rock regions that have brittle properties. Therefore, brittleness be used as a parameter in determining the sweet spot. We use brittleness calculations based on the elastic properties of rocks, which is by calculating Young's modulus and Poisson's ratio based on logging data. The mechanical properties of rocks from the brown shale formation at a depth of 6979.8 ft - 8869.1 ft showed the Young's modulus value was high between 2.92 x 10^6 psi - 8.55 x 10^6 psi and the relatively low Poisson's ratio between 0.22 - 0.33. For brittleness values obtained by the brittleness average method, it is 0.46-1 which indicates that the brown shale formation be categorized as brittle rock.

***Keywords*—shale reservoir, brown shale formation, brittleness, young's modulus, poisson's ratio**

I. INTRODUCTION

Indonesia has a basin that has the potential to become a shale reservoir, one of them is the Central Sumatra Basin in the Brown Shale Formation [1]. The Brown Shale Formation acts as source rock, as shown by the wells that produce at that site. As the case study is the M-17 well, where the drilling be carried out to penetrate the brown shale formation. Further study is required to find out the sweet spot in the brown shale formation to developed into a non-conventional shale reservoir.

One parameter to find out the sweet spot of the shale reservoir is to know the brittle level of the rock, because to produce non-conventional oil, hydraulic fracturing needs to done, therefore the hydrocarbons could be flowed through the fractures [2]. The more brittle of the rock, the fracture that occurs will be more complex, while the more ductile rocks eat the fractures that occur will form a straight line as shown in Fig. 1. The brittleness value prediction of the brown shale formation will be based on the calculation of Young's modulus and Poisson's ratio using logging data [2, 3, 4, 5].

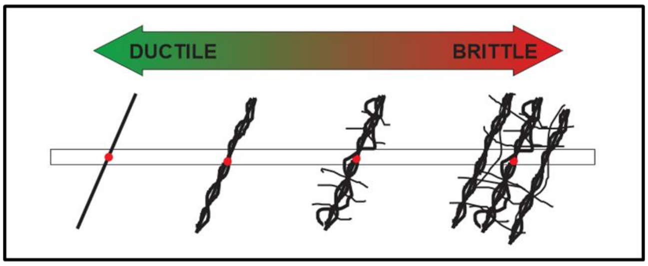

Fig. 1. Shape of fracture in shale [2]

II. LITERATURE REVIEW

A. Young's Modulus

Young's modulus or modulus of elasticity is an important factor in evaluating rock deformation in varying loading conditions. The modulus of elasticity of rock varies from one rock sample from one geological area to another due to differences in the formations of rocks and their genes or minerals [3, 4, 5]. Modulus of elasticity be influenced by rock type, porosity, particle size, and water content. Modulus of elasticity will be greater in value when measured perpendicular to the layer than measured parallel to the coating direction [5]. Modulus of elasticity be calculated from the ratio between axial stresses and axial strain [6]. The elasticity module could be determined based on the equation:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon_a} \quad (1)$$

There are three ways that could be used to determine the modulus of elasticity [6] as shown in Fig. 2, namely:

a. Tangent Young's modulus, which is the ratio between axial stress and axial strain calculated at a fixed percentage of compressive strength. Generally taken 50% of the uniaxial compressive strength value.
b. Average Young's modulus, which is the ratio between axial stress and axial strain calculated on the linear part of the stress-strain curve.

c. Secant Young's modulus, which is the ratio between axial stress and axial strain calculated by making a straight line from zero stress to a point on the stress-strain curve at a fixed percentage of the compressive strength. Generally taken 50% of the uniaxial compressive strength value.

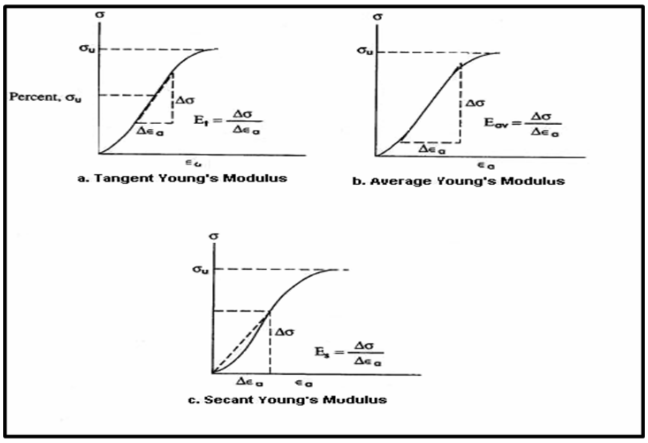

Fig. 2. Method of calculating Young's modulus at the laboratory [6]

Young's modulus dynamic rock could be determined using empirical equations obtained from P-wave velocity and S-wave velocity data. With limited data from Sonic Log that only has the P-waves velocity value, it is assumed that the S-waves value with the Castagna's equation [7]. Castagna's plots between Vp and Vs in the dominant shale formation, resulting in the equation:

$$V_s = 0.862\,V_p - 1.172 \qquad (2)$$

with the Young's dynamic modulus equation:

$$E = \rho V_s^2 \frac{(3V_p^2 - 4\,V_s^2)}{(V_p^2 - V_s^2)} \qquad (3)$$

B. Poisson's Ratio

The value of Poisson's ratio be defined as the value of the comparison between lateral strain and axial strain at a stress condition of σi. The voltage value is σi which be measured at the tangent point between the volumetric voltage graph and the parallel line of the axial voltage axis when the volumetric strain starts to change direction [6, 7].

The tangent point projected perpendicular to the axial stress axis be obtained by the value of σi. Through the point σi make a line perpendicular to the axial stress axis, thus cutting the axial and lateral strain curves. Then each cut point be projected perpendicular to the axial and lateral strain axes so that the values of εai and εli could be obtained [6], as shown in Fig. 3. Hence, from these values can be determined the amount of Poisson's ratio with the equation:

$$\upsilon = -\frac{\varepsilon_l}{\varepsilon_a} \qquad (4)$$

Poisson's ratio dynamic rock can be determined using empirical equations obtained from P-wave velocity data and S-wave velocity with the equation:

$$\upsilon = \frac{1-2\left[\frac{v_s}{v_p}\right]^2}{2\left[1-\left[\frac{v_s}{v_p}\right]^2\right]} \quad \text{or} \quad \upsilon = \frac{V_p^2 - 2\,V_s^2}{2\,(V_p^2 - V_s^2)} \qquad (5)$$

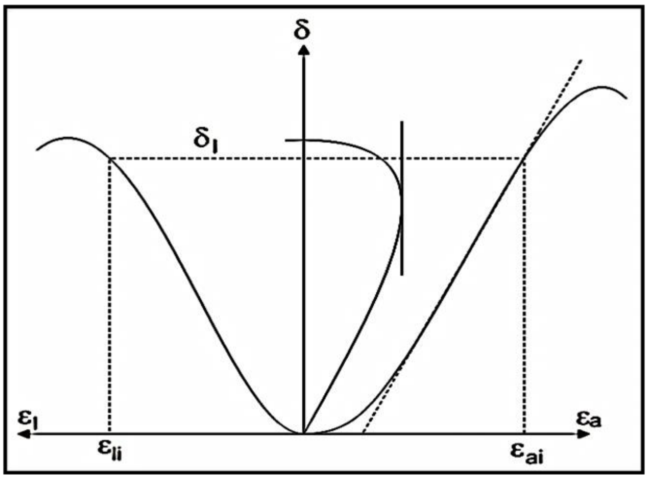

Fig. 3. Extraction of εai and εli values [6]

C. Brittleness

Brittleness is defined as a mechanical property of rocks varies from author to other authors. Hucka, V, and Das, B [4] defines brittleness as a lack of ductility or vice versa, the level of brittleness is usually reflected in the low value of extensive elongation or reduction. This is a relative term because there are no universally accepted values of brittle and ductile values. Horsud's [8] states that when internal cohesion of rocks be damaged, the rock is brittle. While, Holt, R. M et.al. [9] define brittleness as a characteristic of broken or broken material with little or no plastic flow. Because of the lack of the right definition or concept, measurement of brittleness has not been standardized.

Grieser and Bray [10], convey the term average brittleness as an empirical relationship between Poisson's ratio and Young's modulus to distinguish ductile from the brittle area. They hypothesize that rock ductile has low Young's modulus and high Poisson's ratio, while brittle rocks have high Young modulus and low Poisson's ratio. Grieser and Bray [10] normalize Young's modulus and Poisson's ratio with its range, which be called Young's modulus brittleness ($E_{brittleness}$) and Poisson's ratio brittleness ($\upsilon_{brittleness}$). Young's modulus brittleness ($E_{brittleness}$) will be between 0-1. Where the higher the Young's modulus value or close to the maximum value of the Young's modulus rock calculation in a well with Equation 3 then the rock will be brittle and otherwise. Otherwise, the Emax value be obtained from the Young's modulus calculation highest from the well log calculation, on the contrary Emin be obtained from the lowest Young's modulus calculation from the well log calculation as in Fig. 4, so the determination of

Young's modulus brittleness could be determined by the equation:

$$E_{brittleness} = \frac{E - E_{min}}{E_{max} - E_{min}} \quad (6)$$

Furthermore, Poisson's ratio brittleness ($\upsilon_{brittleness}$) will be also between 0-1, where the lower Poisson's ratio value or close to the minimum value of the rock Poisson's ratio calculation in a well with Equation 5, then the rock will be brittle and vice versa, where the max value be obtained from the Poisson's ratio calculation highest from well log calculation. However, it be obtained from the lowest Poisson's ratio calculation from well log calculation as in Fig. 4. Therefore, determination of Poisson's ratio brittleness could be determined by the equation:

$$\upsilon_{brittleness} = \frac{\upsilon - \upsilon_{max}}{\upsilon_{min} - \upsilon_{max}} \quad (7)$$

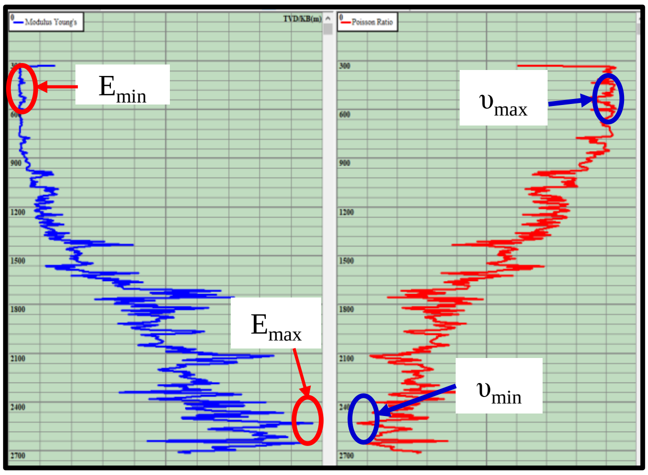

Fig. 4. Determination of minimum maximum Young's modulus and minimum maximum Poisson's ratio [10]

So, the brittleness average can be determined by averaging between Ebrittleness and ubrittleness using the equation:

$$B_{avg} = \frac{E_{brittleness} + v_{brittleness}}{2} \quad (8)$$

For the value of the brittleness index is considered brittle rock which has a brittleness index value > 0.48. If the value of the brittleness index is between 0 - 0.16, the rock is ductile, then if the brittleness index is 0.16 - 0.32, the rock is less ductile and if the brittleness index is 0.32 - 0.48 then the rock is less brittle [11, 12].

III. METHODOLOGY

The methodology used to be based on the property of elasticity of rock, which has been widely used in several case studies of shale reservoirs in the world [10 - 15], and the steps, there are:

1. Collecting the data needed includes data logging such as sonic log and density log; well data such as well depth, penetrated rock, core data and total depth of logging.
2. Determining rock mechanic with sonic log and density log data by calculating Poisson's ratio and calculating Young's modulus.
3. Determining the average brittleness calculation between Poisson's ratio and Young's modulus.
4. Validation and analysis the results between brittleness from logging with brittleness from core.

IV. RESULT AND DISCUSSION

A. Young's Modulus

Young's modulus dynamic could be done using sonic log and density log data. Due to the limitations of the sonic log data which only has the P-waves velocity value, therefore it be assumed that the S-waves velocity value with the Castagna's [7] equation follows an example of Young's modulus calculation at a depth of 2280 m:

- ρ = 2.51 gr/cc
- DT = 70.1805 µs/ft

1. Calculates P-wave velocity (Vp) by converting DT units obtained from log results from µs/ft to km/s

$$Vp = \frac{\frac{1}{DT} \times 10^3}{3.28} = \frac{\frac{1}{70.1805} \times 10^3}{3.28} = 4.3428 \text{ km/s}$$

2. Calculates S-Wave Velocity (Vs) with Equation 2

$$Vs = 0.826\,Vp - 1.172 = 0.826\,(4.3428) - 1.172 = 2.4152$$

3. Calculate the Young's modulus (E) with Equation 3

$$E = \frac{\rho Vs^2 (3Vp^2 - 4Vs^2)}{Vp^2 - Vs^2}$$

$$E = \frac{2.51\,(2.4152)^2 \times (3(4.3428)^2 - 4(2.4152)^2)}{4.3428^2 - 2.4152^2}$$

$$E = 37.369 \text{ Gpa}$$

The results of the modulus Young's calculation could be seen in Fig. 5. It could be seen that the modulus of Young is getting deeper and higher, this is consistent that the deeper the Young's modulus of rock gets more higher as the rock becomes more compact. The brown shale formation has a large Young's modulus compared to other formations as shown in Fig. 6, hence it could be said that the rock in brown shale is brittle.

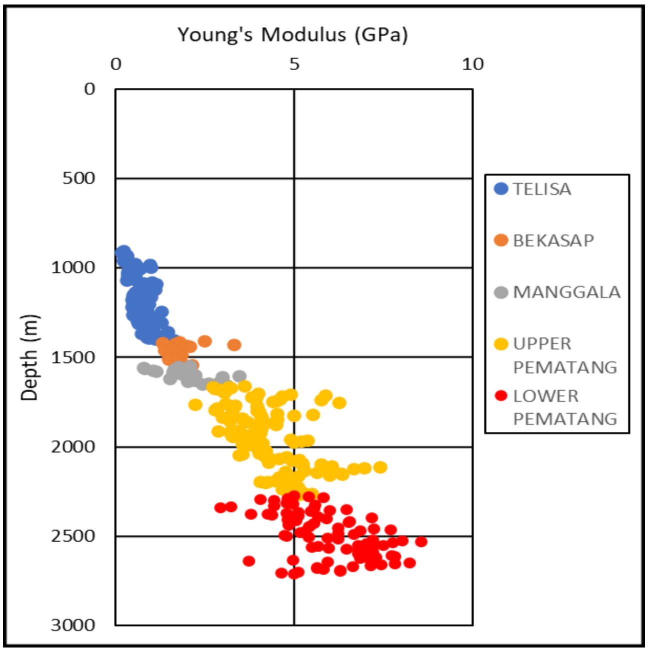

Fig. 5. Result of Young's modulus versus depth

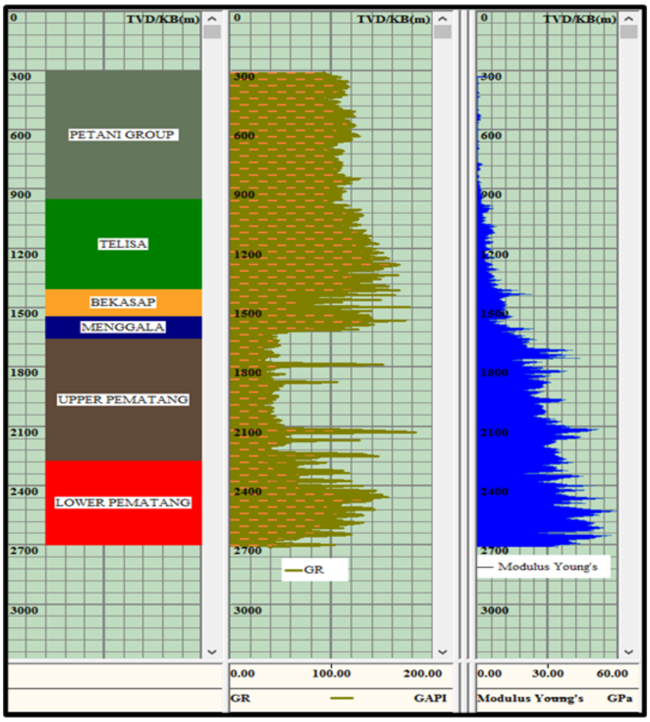

Fig. 6. Chart of Young's modulus, GR log and lithology

B. Poisson's Ratio

Estimating the Poisson's ratio in rocks could be estimated by the equation that be tested for ultrasonic wave velocity in rocks in the laboratory [4]. For the field could be done with the same equation using data from sonic log, here is an example of calculation of Poisson's ratio at a depth of 2280 m:

DT = 70.1805 µs/ft

1. Calculates P-wave velocity (Vp) by converting DT units obtained from log results from µs/ft to km/s

$$Vp = \frac{\frac{1}{DT} \, x \, 10^3}{3.28}$$

$$= \frac{\frac{1}{70.1805} \, x \, 10^3}{3.28}$$

= 4.3428 km/s

2. Calculates S-Wave Velocity (Vs) with Equation 2

Vs = 0.826 Vp – 1.172
= 0.826 (4.3428) – 1.172
= 2.4152

3. Calculate Poisson's ratio with Equation 5

$$\upsilon = 1/2 \frac{(Vp^2 - 2Vs^2)}{(Vp^2 - Vs^2)}$$

$$= 1/2 \frac{(4.3428^2 - 2(2.4152)^2)}{(4.3428^2 - 2.4152^2)}$$

= 0.27611 fraction

The results of the Poisson's ratio calculation could be seen in Fig. 7. It could be seen that the Poisson's ratio will get smaller in-depth, this is consistent with the deeper rock the Poisson's ratio will decrease due to rock compaction. Brown shale formation has a small Poisson's ratio compared to other formations as shown in Fig. 8, thus it could be said that the rock in brown shale is brittle.

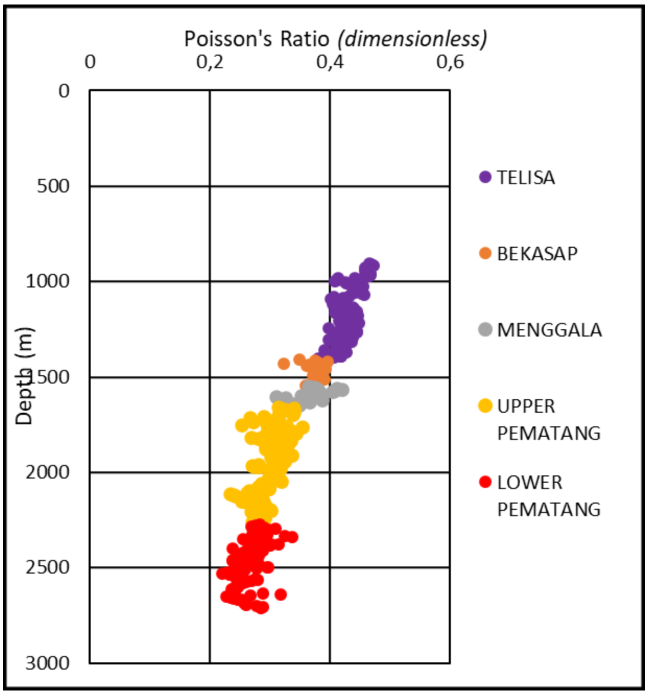

Fig. 7. Poisson's ratio versus depth

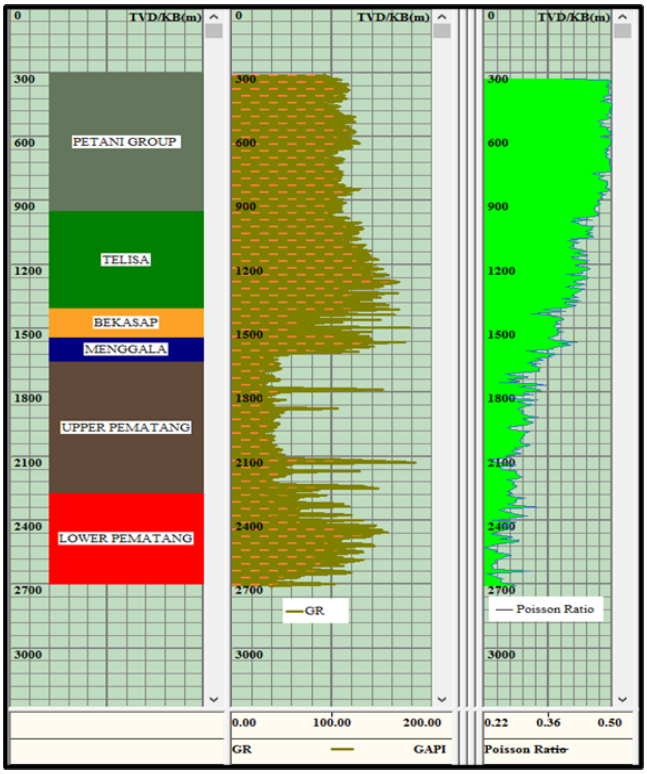

Fig. 8. Chart of Poisson's Ratio, GR log and lithology

C. Brittleness Average

The concept of rock brittleness is to combine Poisson's ratio and modulus Young's. Both components represent ability of rocks from damage when subjected to stress (Poisson's ratio) and resistance of fractures (Young's modulus). For this reason, Poisson's ratio data and Young's modulus of rock be needed which be obtained from calculation of rock mechanical properties. The method used to calculate the brittleness index with a geomechanically approach is by the method of Grieser and Bray [10]. After getting the results from the geomechanically calculation, it is necessary to correlate the price of the brittleness index obtained from the core test in the laboratory with the method of Jin, X, and Shah, S. [5] and Medina, L. A. et.al [13]. Laboratory tests be carried out by testing rock samples (XRD) to obtain the composition of mineral contents such as quartz, calcite, dolomite, and clay.

The following is an example of calculating the brittleness average at a depth of 2280 m:

- E = 37.369 Gpa
- E_{max} = 59.0332 Gpa
- E_{min} = 0.0491 Gpa
- υ = 0.27611 fraction
- υ_{max} = 0.49812 fraction
- υ_{min} = 0.22095 fraction

1. Calculate Young's brittleness modulus with Equation 6

$$E_{brittleness} = \frac{E - Emin}{Emax - Emin}$$

$$E_{brittleness} = \frac{37.369 - 0.0491}{59.0332 - 0.0491}$$

$E_{brittleness}$ = 0.63271 fraction

2. Calculates poisson ratio brittleness with Equation 7

$$\upsilon_{brittleness} = \frac{\upsilon - \upsilon_{max}}{\upsilon_{min} - \upsilon_{max}}$$

$$\upsilon_{brittleness} = \frac{0.27611 - 0.49812}{0.22095 - 0.49812}$$

$\upsilon_{brittleness}$ = 0.8009 fraction

3. Calculate the brittleness index with Equation 8

$$BI_{avg} = \frac{E_{brittleness} + \upsilon_{brittleness}}{2}$$

$$BI_{avg} = \frac{0.63271 + 0.8009}{2}$$

BI_{avg} = 0.7168 fraction

From the results obtained in Fig. 9, which will later be calibrated with the value of the brittleness index obtained in the XRD laboratory as shown in Table 1 to see the mineral content of rocks. Based on the results in Table 1, it could be seen that the brittleness value obtained by the geomechanically approach with the brittleness index value obtained from the core test in the laboratory (XRD) has a harmonized value, thus calculation of the brittleness index with a geomechanically approach has represented the actual rock state. From Fig. 10, the brown shale formation brittleness value which shows the sweet spot area in the reservoir shale is the brittleness value> 0.48 [2].

TABLE 1. CALCULATION RESULTS OF BRITTLENESS INDEXS LOG AND CORE

Depth (m)	Brittleness Index (Core)	Brittleness Index (Log)
2642.89	0.87	0.655864
2643.96	0.25	0.705663
2644.54	0.75	0.734564
2645.97	0.75	0.812288
2647.22	0.88	0.888857
2648.19	0.95	0.954755

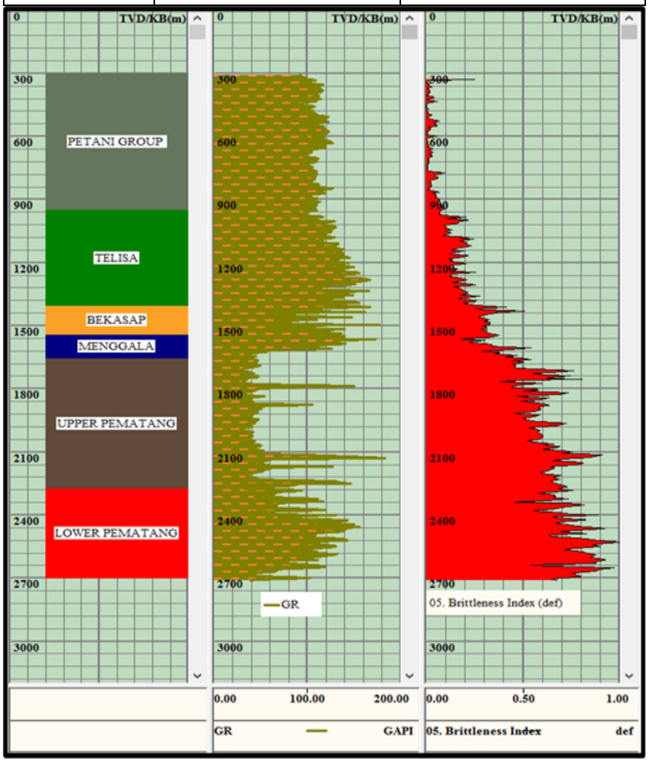

Fig. 9. Chart of brittleness, GR log and lithology

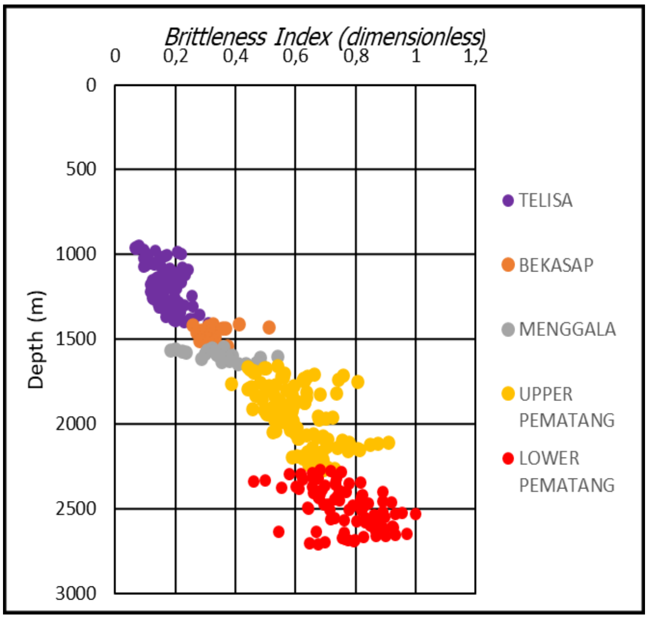

Fig. 10. Brittleness index vs depth

Based the results, it is shown that the brown shale formation found in the Central Sumatra Basin has the potential be developed as a shale reservoir. To find out the sweet spot on the shale reservoir, it is necessary to predict the parameters, namely brittleness. To know with certainty the brittleness of the rock needs be tested for cores in rock mechanics laboratories and XRD laboratories, because of the availability of cores due to the high cost of coring activities, only a few depths could be tested for brittleness. Therefore, a geomechanically approach be taken to determine the value of brittleness that consider the nature of rock elasticity such as Young's modulus and Poisson's ratio.

Determination of Young's modulus and Poisson's ratio has done using data logging such as sonic log and density log. From the comparison of the results of brittleness obtained using log data, it looks close to or has the same value as brittleness with laboratory tests. Young's modulus value gets deeper and higher, this is consistent with the deeper rock modulus value, the Young's modulus will get higher due to the more compact rock. The Lower Pematang as a brown shale formation has a large Young's modulus compared to other formations as shown in Fig. 6. Thus, it could be said that the rock in brown shale is brittle. On the other hand, Poisson's ratio gets deeper and smaller, this is consistent with the deeper rock, where Poisson's ratio will decrease due to rock compaction.

The Lower Pematang as a brown shale formation has a small Poisson's ratio compared to other formations as shown in Fig. 8, thus it could be said that the rock in brown shale is brittle. For brittleness value to be considered as brittle rock which has a brittleness value > 0.48. If the value of brittleness is between 0 - 0.16 then the rock is ductile, the brittleness value is between 0.16 - 0.32 then the rock is less ductile and if the brittleness is between 0.32 - 0.48 then the rock is less brittle.

V. CONCLUDING REMARKS

The mechanical properties of rocks from the brown shale formation at a depth of 6979.8 ft - 8869.1 ft showed the Young's modulus value was high between 2.92 x 106 psi - 8.55 x 106 psi, and the relatively low Poisson's ratio between 0.22 - 0.33. For the brittleness value obtained by the average brittleness method, it is 0.46-1 which indicates that the brown shale formation be categorized as brittle rock. It could be predicted that fractures that occur during hydraulic fracturing are complex fractures or fractures that occur will spread widely.

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