# INTEGRATED OFGEOMECHANICS WELLBORE STABILITY & SWEET SPOT ZONE ANALYSIS TO UNCONVENTIONAL WELL DRILLING OPTIMIZATION

Allen Haryanto Lukmana UPN "Veteran" Yogyakarta Email : <u>allenharyanto@upnyk.ac.id</u>

#### ABSTRACT

Central Sumatra Basin is one of the largest hydrocarbon producer basins in Indonesia. The largest hydrocarbons accumulation in this basin does not rule out the possibility of hydrocarbons also trapped in shale source rock. The potential for hydrocarbon shale is in the Brown Shale Pematang Group layer. The obstacle to development is the depth of the Brown Shale layer so deep that further case studies are needed. This study aims to analyze the geomechanical wellbore stability modelling for drilling and determination sweet spot zone supported by x-ray diffraction (XRD), brittleness index (BI), total organic carbon (TOC) analysis. The geomechanical wellbore stability modelling based on pore pressure, shear failure gradient/collapse pressure, fracture gradient, normal compaction trend, minimum horizontal stress, maximum horizontal stress and overburden gradient analysis. Brittleness index considers each parameter from XRD data which dominantly contains clay, quartz, and calcium. Based on XRD analysis of shale samples from Limapuluh Koto Area, it showed that the samples included the brittle shale group because of the dominant quartz, while the samples from Kiliran Jao were shale brittle because of dominant carbonate (carbonate-rich). From laboratory test results of 8 rock samples from Brown Shale Formation outcrop in Limapuluh Koto Area, it was obtained total organic carbon (TOC) value is 4-17% (average 8%). The shale thickness estimated > 30 m, the brittleness index shale estimated 0.71, and the gradient of over-pressure on Brown SahlePematang Group estimated 0.57 psi/ft& 0.53 psi/ft from log data analysis. So the output of this results the study is expected to get stable borehole, minimum of non-productive time (NPT), the problem when drilling such as caving and sloughing. Based on (Mt, 2013), the prospect criteria results can be concluded that the Brown Shale Formation has good unconventional hydrocarbon shale potential. It can be carried out with further research.

Keywords: brittleness index; shale hydrocarbon; sweet spot zone; wellbore stability

#### **INTRODUCTION**

Oil consumption which tends to coupled with a decline increase in production has made Indonesia experience an oil deficit since 2003. Indonesia's oil production in 2017 was only 949 thousand barrels per day while consumption increased to 1.65 million barrels so that it needed 702 barrels per day to meet domestic oil needs (Company, 2018). In addition to conventional hydrocarbons, explorationists began to aggressively search for unconventional hydrocarbons, one of which is shale hydrocarbon.

The United States is a pioneer in the development of exploration and exploitation of hydrocarbon shale. Several shale gas fields with reserves reaching hundreds of TCFs, such as the Barnett and Bakken Fields, have been successfully developed in the country (Widada, 2018).

The Central Sumatra Basin is one of the basins which have the potential shale hydrocarbon. Brown Shale Formation is the main target in the exploration of hydrocarbon shale which is composed of lacustrine sediments. Evidence shows that the majority of oil and gas produced from oil and gas fields in the Central Sumatra Basin comes from the Brown Shale Formation, reinforcing the belief that the formation has good potential as a source rock and a shale hydrocarbon reservoir. However, challenges of the exploration and development process is the Brown Shale Formation has a deep depth so that further studies are needed for the drilling problem. This study aims to analyze the geomechanical wellbore stability modelling for drilling and determination sweet spot zone supported by x-ray diffraction (XRD), brittleness index (BI), total organic carbon (TOC) analysis.

Research location is in Central Sumatra Basin, with a focus on studies of the Brown Shale Formation. This formation is a compiler of the Eocene-Oligocene Pematang Group which was deposited unconformably above bedrock. This Group is referred to as syn rift deposits. It is deposited in a fluvial and lacustrine environment with sediments from the surrounding height. In the fluvial environment the lithology consists of conglomerates, coarse sandstones, and colorful claystones(Heidrick, 1993). Whereas the lithology in the lacustrine environment consists of siltstone and intercalation of fine sandstone with lacustrine shales that are rich in organic material (Laing, 1994).

The Brown Shale Formation was deposited above the Lower Red Bed Formation but in some places shows the similarity of lateral depositional and is conformably covered by the Upper Red Bed Formation. The constituent lithology consists of well-laminated shale, rich in organic material, brown to black, indicating a depositional environment with calm water conditions such as lacustrine (Sefein, 2017) (Figure 1). In the deeper part of the basin, sandstone alternation which is predicted to be deposited by the turbidite current mechanism.

#### METHODOLOGY

The research methodology was started bycollecting data logs and cuttings (Figure 2). Data logs include GR log, sonic log, resistivity log, and density log to analyze overpressure mechanism. In this research, there is a well that representative of Brown Shale Formation to understand the save mud window. Data cuttings/ outcrop samples include XRD, TOC, and BI to determine interval Brown Shale Formation. It used samples in Limapuluh Koto Area and KiliranJao (Figure 3).From those analysis, it can determine sweet spot zone. Based on determination of save mud window and sweet spot zone, it could recommend save drilling and precision target for Brown Shale Formation.

## **Geomechanical Modelling**

Analysis of geomechanical modelling for wellbore stability based on determination of pore pressure gradient, fracture pressure gradient, in-situ stress (minimum & maximum horizontal stress) completely included friction angle, cohesion strength, and shear failure gradient caused hole collapse (Zoback, 2007). In other to the analysis of wellbore stability also determination of well orientation and safe operating of wellbore trajectory

## Sweet Spot Zone Analysis

Determination of sweet spot interval in unconventional reservoir shale needs to know the value of brittleness index. Determination of sweet spot intervals in unconventional reservoir shale needs to know the value of the Brittleness index. Brittle shale types are the target chosen for the sweet spot interval in the unconventional reservoir shale. That's because hydraulic fracturing is needed to produce oil and gas in unconventional reservoir shale for optimum results. Minimum pressure of fracture and fracture direction are needed to know in-situ stress that works on the field (Aris Buntoro, 2018).

In this research, the determination of the sweet spot zone is done by integrating analysis of TOC,Brittleness Index, XRD, and Geomechanical models in order to obtain the interval of shale layer that has the potential to produce oil and gas. The interval can be used as recommendations when drilling.

The Brittleness Index in this study uses the (Daniel M. Jarvie et al., 2007), method in which the process is based on the mineral composition of rocks and divides them into 3 constituent minerals, such as quartz,carbonate,andclay. The method is explained in the formula as follows:

BI Jarvie (2007) =  $\frac{Qz}{Qz+Ca+Cly}$ .....(1)

where Qz is fractional quartz content, Ca is calcite content, and Cly is clay content by weight in the rock.

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According to (Mt, 2013), There are several criteria for shale hydrocarbon that have the potential to produce oil and gas, such as the following:

	$\mathcal{O}$	
a.	Permeability	: greater
	than 100 nanodarcies	
b.	Porosity	: less than
	15%, more typically 4-7 %	
c.	Pressure	: above
	normal	
d.	TOC	:>1%
e.	Water saturation	: < 45%
f.	Shale thickness	: > 100 ft
g.	Moderate clay content	: < 40%
h.	Brittle Index shale	:>0,48

# **RESULT AND DISCUSSION**

#### **XRD Test and Brittleness Index**

From the XRD analysis conducted on shale samples in the Limapuluh Koto Area and KilaoJao Area (Table 1 and Table 2), most of them are dominated by quartz minerals. There is also a predominantly calcium, such as samples of B-22 (shale), B-21 (shale), B-7 (shale), B-15 (gastropod shale) at KiliranJao Area (Figure 4).

The KiliranJao shale samples have high clay content in the form of kaolinite and calcium content, while the Limapuluh Koto Area samples which have more illite and kaolinite and almost no calcium content. That is because the sample in the KiliranJao area contained gastropod fossil fragments thereby increasing the calcium (carbonate) content. Clay oriented analysis result from XRD at Limapuluh Koto Area samples (Table 3) show that the average value of 24.04% and KiliranJao samples (Table 4) show that average value of 16.33%. From samples of 2 locations have an average value of clay content less than 40%, this will not make the clay swell when it dissolves with water during the hydraulic fracturing process so that it is not a problem.

From the results of the ternary diagram of the brittleness level, it was found that shale samples in the Limapuluh Koto Area are included in the brittle quartz rich, while the Kilian Jao Area shale samples are divided into 3 zones, the most dominant being in the brittle quartz rich zone. From this diagram, it shows that shale samples from 2 locations have brittle and quartz rich characteristics making it suitable for hydraulic fracturing of the Brown Shale Formation layer.

From the Brittleness index calculation according to (Daniel M. Jarvie et al., 2007) with consideration of the content of quartz, calcium, and clay, the results obtained for the BI value in the KiliranJao samples have an average of 0.48 and the BI in the Limapuluh Koto Area samples have an average of 0.71 (Tables 1 and Table 2).

#### **Total Organic Carbon (TOC)**

The results of the Total Organic Carbon (TOC) in the shale sample in the Limapuluh Koto Area are shown in Table 5. Based on the results of the plot between TOC vs S1 + S2 it is found that the organic content in the samples have very good potential as source rock (Figure 5). Where the TOC value has a range of 4.2-17.3% and S1 + S2 values with a range of 16.45 - 58.84 mg/g.

#### Geomechanical Model (1). Inputing Data mud log

In the 1D Geomechanics analysis of the drill holes stability in the Pematang Group formation in the Central Sumatra basin, some mud log input data is needed to reconstruct the safe mud window design which is expected to reduce drilling problems such as caving, sloughing, pipe sticking due to swelling, tight hole spot, pack-off and reduce non-productive time based on parameters of rock mechanics such as stress profile, pore pressure (overpressure), elastic properties, and rock strength analysis.(Al Hajer, 2017). In its application in the analysis of the stability of boreholes, some primary mud log data that need to be input are gamma ray logs, resistivity logs, sonic logs, and density logs. (Ahmed K. Abbas, 2018). While there are also secondary mud log data such as Neutron log and spontaneous (SP) log. The primary data can be seen in Figure 6.

In the 1D Geomechanics analysis of mud log primary data using software. The output of gamma ray log is shale base line, sonic log is normal compaction trend, resistivity log is normal resistivity trend, and density log is overburden gradient. From the 4 primary data, analysis of vertical stress (Sv), pore pressure fracture gradient (PPFG), In-principal magnitude situ stress, and shear failure gradient (SFG) will be performed. In other to, also analysis of geostress determination in safe wellbore stability such as safe well trajectory analysis and safe operating analysis based on 1D Geomechanical modeling software.

# (2). Determination of vertical stress (overburden stress)

In the vertical stress (Sv) analysis, an empirical method is needed to calculate the bulk density obtained from the density log using the Miller's equation.

 $\rho = \rho_{matrix}(1-\phi) + \rho_w \phi$  where .....(2)

$$(\phi = \phi_a) + \phi_b \exp\left[-K(depth)^{1/n}\right]$$

The Miller's equation is a method of analyzing bulk density and porosity sediment which cannot be analyzed using only seismic interval velocities derived from seismic data (Zhang & Yin, 2017). However, there are several coefficient parameters that refer to core data in the Deepwater Gulf of Mexico, therefore it is necessary to change the coefficient according to the core data in the group formation of the Central Sumatra basins.

knowing the After bulk density sediment value, an analysis of the of overburden gradient calculation calculation using bulk density values is then corrected parameters such as water depth, water density, and average density of the formation between seabed and top of data. Results of corrections to the calculation of overburden gradient can be seen in the figure 7. The result of overburden gradient is used in determining vertical stress / overburden pressure in units (psi).

# (3). Pore Pressure Using Eaton's Method

In the drilling case, many things need to be understood as a drilling engineer to determine the gradient of pore pressure based on each of the gradient on formation that is drilled. The reason, the pore pressure prediction is very useful for prediction on wellbore stability analysis that can be influences on formation pressure stability. (Al Hajer, 2017). As for determining the pore pressure in the oil industry, it is divided

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into two, namely the direct and indirect method. The measurement of direct methods are usually derived from the results of well tests such as drill stem tests (DST) and also repeated formation tests (RFT) (Hamid Roshan et al., 2011). The different measurements of using indirect methods (empirical equations) are derived from several petrophysical well logs data that were developed for prediction of pore pressure (Adam, 1985). In this case, to determine the pressure prediction using the indirect method with the calculation of Eaton's empirical equation. The Eaton's empirical equation to study the prediction of geopressured magnitudes from mud / well logs and these equations were used with resistivity logs, conductivity logs, sonic travel-time logs, and corrected "d" exponent plots (A.Eaton, Ben, 1975). On this measurement of pore pressure prediction using resistivity logs and sonic data logs.

## a. Resistivity Logs Data Using Eaton's EmpiricalMethod

Based on well logs data, the resistivity logs

can be used in pressure detection. The log's response is based on the rock matrix and the fluid-filled porosity as total sample on each depth of formation which has high porosities and high pressures (Adam, 1985).

$$PP = OBG - (OBG - PP_N)(\frac{R_o}{R_N})^x....(3)$$

From the equation, it is then applied to the software 1D Geomechanics wellbore stability. accordance with In the determination of the eaton's resistivity equation which requires shale point analysis, normal pore pressure gradient, and eaton exponent in the formation group bund to get pore pressure gradient. Please note, normal pore pressure gradient using fresh water gradient is (0.433 psi / ft or 8.33 ppg), Eaton exponent around 0.08 (obtained the coefficient from the trial and error analysis in software simulation 1D Geomechanics), also using analysis of normal and compaction trend resistivity manually based on assumed the validity parameters to predict pore pressure with normal pressure (0.433 psi/ft) from its field in Central Sumatra Basin . From Eaton's empirical

method, the formation of pore pressure (psi) (Figure 8).

So there are any differents formation pore pressure (PP), normal pore pressue along  $(PP_N)$ , and overburden pressure (OBG) along with total depth on well TM-01.

## b. Sonic Logs Data Using Eaton's Empirical Method

The analysis of pore pressure by using sonic logs data are for to determine the difference in travel times between high porosity of overpressure zones, low porosity, and normal pore pressure zones. Noted that to know about overpressure zones, the needed compaction trend was to extrapolated throughout the pressure region, also estimated of overpressure or abnormal pressure based on sonic logs data. (Adam, 1985). Also sonic log data is to identify of the shale acoustic which has the function for determination of pore pressure gradients along with total depth (A.Eaton, Ben, 1975) (Figure 9).

The eaton's empirical method are explaining about an empirical calculations based on analysis of the normal compaction trend (NCT) that used for. Some of compaction trend has a several empirical equation of methods using Miller's sonic or interval velocity, Bower's sonic or interval velocity, and Skagen sonic or interval velocity. Beside that from its empirical, in this case, the authors using analysis of normal compaction trend sonic manually based on assumed the validity parameters to predict pore pressure with normal pressure (0.433 psi/ft) from its field in Central Sumatra Basin.

After analysis for normal compaction trend on sonic logs data, then the eaton's empirical method can be succesfully applied in software 1D Geomechanics wellbore stability to identify an overpressure zones by analysed of normal compaction trend as nomal interval transit time  $(DT_N)$ , normal pore pressure gradient (PP<sub>N</sub>), overburden gradient (OBG), and set of eaton exponent around 1.2 (obtained the coefficient from analysis trial and error in software simulation 1D Geomechanics) based on Figure 10.

 $PP = OBG - (OBG - PP_N)(\frac{DT_N}{DT_0})^x....(5)$ 

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Based on this calculation from eaton's empirical mehod, the result of formation pore pressure included (OBG) is overburden gradient .(PP<sub>N</sub>) is normal pore pressure gradient, (DT<sub>N</sub>) is normal interval transit time ,(DT<sub>0</sub>) is observed interval transit time, and (x) is eaton exponent. There is any different pressure on normal pore pressure and formation pore poressure along with total depth, the high of formation pore pressure up to 4000 psi on pematang group formation. So from sonic logs data by using eaton's empirical method succesfully approved of pore pressure analysis.

#### (4). Fracture Pressure Gradient

Hubbert and Willis says that the study the fracture gradient determination of principles as a function from overburden pressure, pore pressure and the relationship of in situ stress (minimun stress and maximum stress horizontal) in wellbore stability. Fracture pressure gradient is to identify about the mechanism of mud losses while drilling because of hydrostatic pressure is higher than fracture pressure from imprecision to predict between fracture gradient and pressure gradient, so it would be many causes of mud losses such as seepage mud loss, small loss, partial loss, partial loss and total loss in natural fractures (Zhang & Yin, 2017). There were any ways to determination of fracture gradient with utilizing on field geological structures, leak off tests (LOT), or logging methods. Based on well TM-01 that has mud/well logs to use for identification of fracture gradient supported empirical methods such as eaton's & Matthews and Kelly equations.

## a. Resistivity logs and Sonic logs using Matthews & Kelly method

The well TM-01 has the several mud logs that can be applied in software 1D Geomechanics of wellbore stability to identify of fracture pressure gradient by calculate the overburden gradient, pore pressure gradient who has been explained on previous chapter. The equation of Matthews and Kellymethod explained a variable of the "matrix stress coefficient  $(K_i)$ " with the degree of compaction in South Texas Gulf of Coast and Lousiana Gulf of Coast .(Adam, 1985) with the following formula for sedimentary formations :

 $FG = PP + (OBG - PP)K_i....(6)$ 

The value of matrix stress coefficient  $(K_i)$  as a function of effective stress based on resistivity logs around 0.675 and from sonic logs around 0.67 (obtained the coefficient from analysis trial and error in software simulation 1D Geomechanics)alongwith total depth in pematang group formation. In other to, (PP) is the pore pressure, (OBG) is overburden gradient, and (FG) is fracture gradient.

The comparison of fracture pressure gradient (FPG) based on sonic and resistivity logs by Matthews & Kelly empirical method with determined of pore pressure (PP), normal pore pressure ( $PP_N$ ), and overburden pressure (OBP) (Figure 11).

#### b. Resistivity logs and Sonic logs using Eaton's method

Ben A. Eaton was developed on Matthews and Kelly equation with introduce poisson' ratio as equivalent to fracture pressure gradient. The poisson's ratio (PR) and overburden stress gradient (OBG) are the same variable for simplification in different rocks formation which can be calculated on field data but not all same on some areas in the world. (A.Eaton, 1969). The following formula is showed from eaton's method :

 $FG = PP + (OBG - PP)\left(\frac{V}{1-V}\right)....(7)$ 

Based on eaton's empirical method that the parameter such as (PP) is pore pressure, (OBG) is overburden gradient, and (v) is poisson's ratio which calculated from sonic logs data.Brocher, empirical method represent about correlation for P-wave sonic velocity ( $V_p$ ) and Poisson's ratio on its lithologies and depths which assumed every each formations represent water-saturated rocks (Gary Mavko, Tapan Mukerji, Jack Dvorkin, 2009):

v=0.8835-0.315Vp+0.0491Vp2-0.0024Vp3

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Where (v) is Poisson's ratio and the value of  $(V_p)$  P-wave velocity has range of validity,  $1.5 < V_p < 8.5$ . So, the coefficient of poisson's ratio is appropriated along with total depth to the pematang group formation. The comparison of fracture pressure gradient (FPG) based on sonic andresistivity logs by Eaton's empirical method with determined of pore pressure (PP), normal pore pressure (PPN), and overburden pressure (OBP) (Figure 12).

So the authors are comparing two methods to analyse of fracture pressure gradient which has the correct criteria. The result by analyse them that the Matthews and Kellys empirical method is the correct equation and can applied on pematang group formation with has coefficient matrix stress  $(K_i)$  around 0.675 for resistivity logs and 0.67 for sonic logs because the fracture pressure gradient (FPG) is higher than the minimum horizontal stress  $(Sh_{min})$  as in situ stress based on Figure 13.(Zhang & Yin, 2017).

# (5). In Situ Stress (Minimum and Maximum)

Minimum and maximum horizontal stress are the principal stress in surround of wellbore conditionproblems in drilling operations caused the high of mud weight which not consideration with mechanism of principal stress (Zoback, 2007) (Figure 14). In other words, as the drilling engineer should to know about principal stress  $(Sh_{min} \text{ and } SH_{max})$  in wellbore trajectory because the maximum horizontal stress is described about rock strength formation excess of the fracture gradient in wellbore towards of mud weight or hydrostatic pressure. The mud weight exceeded in direction of maximum horizontal stress actually is fracture gradient and the formation would be "breakout" condition. This condition became caution for the drilling engineers to decreasing the mud weight, if without principal stress, the circulation was lost and would be wellbore instability. So to achieve the wellbore stability was drilled in the direction of (SH<sub>min</sub>) minimum horizontal stress. The authors analyse of in situ stress toward the mud weight and fracture gradient, the result

is successfully to design wellbore stability based on Figure 15

#### (6). Shear Failure Gradient using Mohr-Coulomb Criteria

Based on previously chapter which been explained, the "washout" have condition caused unpredictable of determining in-situ stress condition. In this chapter, the wellbore instability can be detected from hole collapse caused shear failure gradient. It is such as caution to the drillers which the mud weight almost reach of pore pressure gradient. On this handbook by (Zoback, 2007) showed that the mechanism would be "breakout" condition where appear of hole collapse such as (caving, sloughing, etc) (Figure 16). The determination of Shear failure gradient based on Mohr-Coulumb as determining of failure criterion. the following formula :

$ au_{max}$	=	$\sigma_{min} \frac{1+\sin\phi}{1-\sin\phi} +$
$\frac{2CScos\phi}{1-\sin\phi}\dots\dots$	(9)	

Where  $\sigma_{max}$  and  $\sigma_{min}$  are the maximum and minimum effective stresses, ( $\phi$ ) is the friction angel derived from calculate data, (S<sub>o</sub>) is the cohesion strength derived from sonic log which calculate of P-wave sonic velocity (V<sub>p</sub>) specifically on shale strength correlations (Lal, 1999).

$$\phi = \sin^{-1} \left( \frac{V_p - 1}{V_p + 1} \right)....(10)$$
  
$$S_0 = \frac{5(V_p - 1)}{\sqrt{V_p}}....(11)$$

So, all of parameters that describe how the rock strength varies with its stress conditions such as shear failure gradient on wellbore trajectory.

# (7). Determination Design of Safe Wellbore Trajectory Analysis

Inputing data from sonic logs and resistivity logs data into 1D gemochanical modeling based on previos chapter to design of safe wellbore trajectory included parameter of overburden gradient, pore pressure, minimum of horizontal stress, maximum horizontal stress, and shear failure gradient completely of friction angle and cohesion strength. The output result of safe wellbore trajectory based on Figure 17 and Figure 18. The figures explained the most appropriate to safe wellbore caused instability in the direction of  $(Sh_{min})$  minimum horizontal stress with angle of inclination around 60°-120° which resulted the interval of mud safe window 10.6-10.9 ppg from resistivity logs and 11.2 – 11.6 ppg from sonic logs.

#### (8). Determination Design of Safe Operating Analysis

The final result by analysis on 1D geomechanics wellbore stability based on safe operating wellbore trajectory . So from Figure 19 and Figure 20, there were described about the optimum of mud weight which needed to balance between the pore pressure, minimum and maximum horizontal stress, fracture pressure gradient and also shear failure gradient caused hole collapse. The recommendation range of optimum mud weight is the best to design the safe wellbore stability based on safe mud window or safe pressure window.

## 4.4 Sweet Spot Zone Analysis

Based on the comparison between 1D geomechanical modelling and Brittleness Index, X-ray Diffraction (XRD) analysis, TOC (Total Organic Carbon) in Pematang Group Formation resulting determination the depth of overpressure gradient for resistivity logs at 2600 m around 4523 psi and sonic logs at 2640 m around 4891 psi (Figure 22). The overpressure from sonic and resistivity logs are to use for uplifting fluids (hydraulic fracturing) because based on XRD data >0.48 (contained moderately clay content <40% and TOC > 1% which resulted the shale thickness > 30 m and the unconventional resources deeper than conventional resources.

# CONCLUSIONS

The comparison and determination in the brown shale of Pematang Group Formation has the good prospect criteria for reservoir unconventional resources, based on:

1. Analysis of 1D geomechanics modelling for wellbore stability with indirect drilling measurement by identified of well log data to get the optimum of safe mud or pressure window based on geostress analysis as the new drilling technology for optimization.

- 2. Overpressure prediction analysis on shale brown from sonic logs and resistivity logs around 4891 psi and 4523 psi. So, by identify the overpressure on interval depth of brown shale can be useful for uplifting fluids (hydraulic fracturing).
- Total Organic Carbon (TOC) from outcrop data in Pematang Group Formation has excellent potential containing of oil type I from kerogen type. The TOC values have range of 4-17%. It was good potential based on McKeon (2011) criteria.
- XRD analysis resulted that shale samples have brittle and quart rich characteristic which containing of clay content < 40 %. It can be concluded that Brown Shale Formation dominantly brittle by calculate (BI) brittleness index using Jarvie equation.

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