INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Vertical Fracability Model on Lithofacies Association of Brownshale Formation from Outcrop Analog Using Rock Mechanical and Mineralogy Correlation Method: A Preliminary Study of Shale Hydrocarbon Development in Bengkalis Trough, Central Sumatra Basin

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Manuscript received: August, 12, 2019; revised: April, 23, 2021;
approved: June, 3, 2021; available online: January, 7, 2022

Abstract - In the production stage of shale hydrocarbon with very low permeability, an in-depth analysis of the mechanism governing hydraulic fracking is required to open natural fractures, so that the fractures are connected to allow maximum flow of hydrocarbon fluids. This study is dedicated to create a vertical fracability model of shale hydrocarbon as a basis for planning the optimal position combination of horizontal well with multistage hydraulic fracking based on the correlation of rock mechanical and mineralogy analysis. Because in-situ core data is not available, this study uses shale core and shale sample data from outcrop analog (surface) as as a representative of the Brownshale Formation in the Central Sumatra Basin. At present, Indonesia has a very large potential for shale hydrocarbon, mainly from the Brownshale Formation of Pematang Group as the main source rock in the Central Sumatra Basin, which spread over several troughs, namely: Balam, Rangau, Kiri, Aman, and Bengkalis, where Bengkalis trough has the largest area compared to others, so it was chosen as the research target. In creating the vertical fracability model, information about the elastic rock properties, namely Young's Modulus (YM) and Poisson's ratio (PR) are needed as the basis for determining the depth interval of the formation with high fracability. Fortunately, at this time there was a very good outcrop analog at the coal mine site of PT. Karbindo in Kiliranjao, and there were also several outcrop analog locations in Limapuluh Koto area, West Sumatra. The vertical fracability model of shale hydrocarbon of the Brownshale Formation shows an interesting phenomenon, where the sweetspot fracable window interval is in the low YM - high PR zone, so it can be concluded that the low YM - high PR zone is a good candidate for hydraulic fracking. In contrast, the fracture barrier interval is in the high YM - high PR and low YM - low PR zones, where both are correlated with high Brittleness Index (BI), but the Fracability Index (FI) is low. I t can be concluded that high YM - high PR and low YM - low PR are inappropriate interval as a candidate for hydraulic fracking. This phenomenon is confirmed by the presence of a dominant carbonate mineral at the upper section as fracture barrier, while at the lower section as a sweetspot fracable window, which is more dominated by quartz mineral.

Keywords: fracability, lithofacies, rock mechanical, mineralogy, shale hydrocarbon, brownshale, Central Sumatra Basin

How to cite this article:
Buntoro, A., Prasetyadi, C., Wibowo, R.A., and Suranto, 2022. Vertical Fracability Model on Lithofacies Association of Brownshale Formation from Outcrop Analog Using Rock Mechanical and Mineralogy Correlation Method: A Preliminary Study of Shale Hydrocarbon Development in Bengkalis Trough, Central Sumatra Basin. *Indonesian Journal on Geoscience*, 9 (1), p.87-104. DOI: 10.17014/ijog.9.1.87-104

Introduction

In recent years, conventional hydrocarbon production in the world has decreased rapidly, and several countries, including the United States (US), Canada, and China have gradually developed unconventional hydrocarbon resources from the exploration phase to production (Bai, 2016). At present, Indonesia has an immense potential for shale hydrocarbon, where the Central Sumatra Basin is the biggest potential in Indonesia, especially from the Brownshale Formation of Pematang Group (Longley *et al.*, 1990; Katz, 1994). However, shale hydrocarbon development in Indonesia is still little studied and poorly understood (Geological Agency, ESDM, 2015).

In producing shale hydrocarbon formations with very low permeability, information about the elastic rock properties (rock mechanical parameters) is needed as a basis for determining the formation interval with high fracability (Deshpande, 2008; Berard, 2012; Jin *et al.*, 2014; Alzahabi, 2014; Bai, 2016 ; Jarzyna, 2017). Fracability is a function of the brittleness index, which can be calculated from Young's Modulus and Poisson's ratio (Goodway, 2007; Grieser and Bray, 2007; Enderlin *et al.*, 2011).

Sui *et al.* (2015) stated that fracability is a comprehensive reflection of geological and reservoir characteristics, especially those related to crustal stress, rock brittleness, brittle mineral content, clay content, shale strength, diagenesis, and natural fractures, where the fracability is a term that is currently used in selecting hydraulic fracking intervals. Mineralogical analyses using XRD (X-ray Diffraction) drill cutting data also can be used to determine the fracability model on shale rock (Jarvie *et al*., 2007; Perez and Marfurt, 2013)

Previously, many argued that only brittleness could characterize the fracture of unconventional shale reservoirs, assuming that formations with high brittleness would break easily (Sui *et al.*, 2015). Chong (2010 *in* Jin *et al.*, 2014) stated that brittleness alone is not enough to describe fracability, because formations with higher brittleness can also be a fracture barrier. To illustrate fracability, not only is the criterion "high bittleness" for creating a new fracture surface, but it must also consider the mineralogical aspects. For example, dolomite limestone with high brittleness (Jin, 2014), actually becomes a barrier to frac in the shale reservoir, because the fracture gradient in the shale formation is lower than the dolomitic limestone formation and with the same fracture pressure that cannot break it.

Formations with high brittleness are considered good candidates for hydraulic fracking. But this point of view is not entirely correct, because brittleness does not indicate rock strength (Jin *et al.*, 2014; Jinbu *et al.*, 2015). This can be found in the case of fracture barriers between the upper and lower Shale Barnett formations, namely the existence of dolomite limestone Forestburg Formation with higher brittleness, but instead becomes a fracture barrier (Jin *et al.*, 2014). To overcome the weaknesses of the high brittleness criteria in determining the hydraulic fracking interval, the fracability index (FI) parameter is introduced, which is by integrating brittleness and energy absorption during hydraulic fracking. This FI considers that a good hydraulic fracking candidate is not only high brittleness, but also requires less energy to create a new fracture surface.

The main problem in the development of shale hydrocarbon is the lack of subsurface data, especially core data used to determine static elastic rock properties (rock mechanical parameters), where the static elastic rock properties are used as a basis for determining the formation interval with high fracability (sweetspot fracable window). The use of outcrop analog (Carnell and Butterworth, 1997; Sunardi, 2015) for determination of shale rock properties can be used as a preliminary study of hydrocarbon shale development.

Thus, building a sweetspot fracable interval for the outcrop analog of Brownshale as the represetative Brownshale Formation model (Pematang Group) in Bengkalis Trough, Central Sumatra Basin, outcrop analog data (shale cores and samples) are used. Fracability model from this work can be applied to determine the location and formation interval in hydraulic fracking planning.

Studied Area and Stratigraphy of Central Sumatra Basin

Bengkalis Trough is located in three Regencies, *i.e.* Siak Sri Indrapura Regency, Bengkalis Regency, and Pelalawan Regency, Riau Province, Indonesia. Figure 1 shows the location of field observations and outcrop analog sampling carried out in two locations in West Sumatra Province, namely the Kiliranjao area, Sawahlunto Regency, and the Sarilamak-Batubalang area, Limapuluh Koto Regency. The Pematang Group Formation is only known below the surface, where its thickness reaches more than 1,800 m (Katz *et al.,* 1994). Stratigraphically, there are equivalent lacustrine rocks, which show the characteristics of oil source rock in the Ombilin Basin and the Kiliranjao Basin in the southwest area of the Bengkalis Trough (Katz *et al*., 1994; Carnell and Butterworth, 1997; Sunardi, 2015).

Because of the lack of subsurface data, especially core data used to determine rock static elastic properties (rock mechanical parameters), the use of outcrop analog for determining shale rock properties can be used as a preliminary study of shale hydrocarbon development in Bengkalis Trough, Central Sumatra Basin.

Lithostratigraphically, the area consists of Pretertiary basement, Paleogene sedimentary unit, and Holocene deposits, but the study is more emphasized in the Pematang Group of the Paleogene sediments (Figure 2).

The Pematang Group is the main source of hydrocarbon rock in the Central Sumatra Basin, and is the oldest sedimentary layer in Paleogene. Syn-rift sediments of the Pematang Group is deposited unconformably the half graben.

According to Heidrick and Aulia (1993), the discovery of fossils of ostracods, fresh water gastropods, spores, pollen, dinoflagellates, algae, and fern debris on core rock samples and cutting powder in all major troughs, and the absence of foraminifera provides an indication of the non-marine depositional environment in humid and tropical environments.

Based on its lithological characteristics, the Pematang Group is divided into three formations, namely Lower Red Bed Formation, Brownshale Formation, and Upper Red Bed Formation.

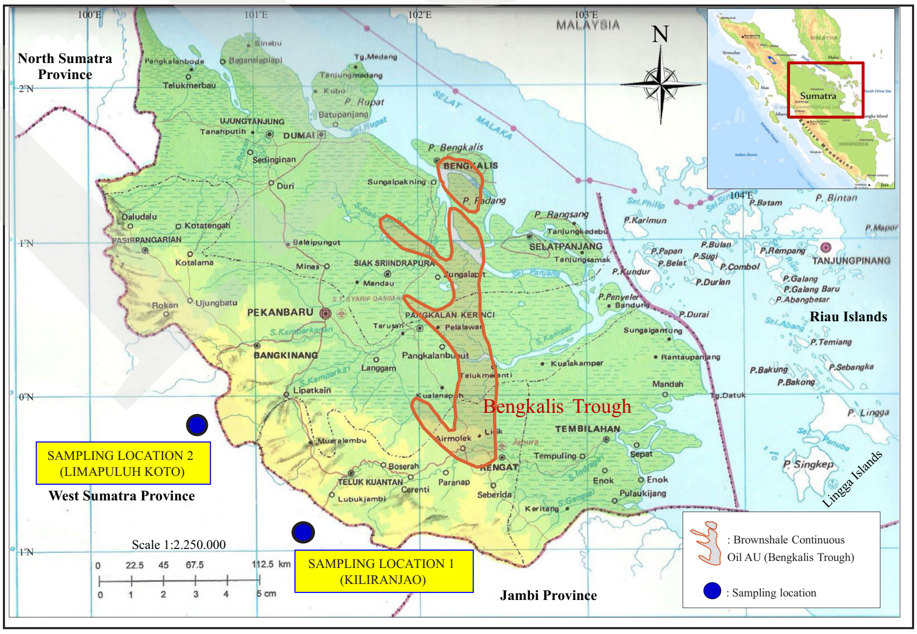

Figure 1. Locations of outcrop analog are in Kiliranjao and Limapuluh Koto, West Sumatra Province, because the Brownshale Formation of Pematang Group is not exposed on the surface (Modified from Katz *et al*., 1994; Carnell and Butterworth, 1997; Sunardi, 2015; N.N, 2015).

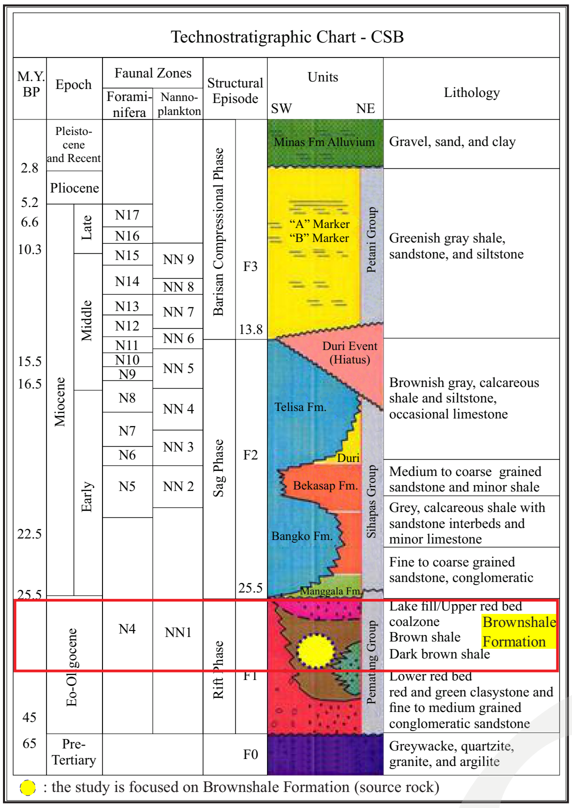

Figure 2. Stratigraphy of Central Sumatra Basin (Heidrick and Aulia, 1993).

Lower Red Bed Formation

This formation consists of claystone, siltstone, arcosic sandstones, and few conglomerates deposited in the alluvial plains and fluvial environments. The lower part of this formation in several deep basins can reach a thickness of 3,000 m. Sandstones in this formation have poor quality as a reservoir, because they are still very close to the source and have poor sorting.

Brownshale Formation

As the name implies, this formation consists of brownshale deposited conformably on the Lower Red Bed Formation with a lacustrine depositional environment. Shale in this formation is rich in organic matter, and has a fairly good laminae which indicates that the shale was deposited in fairly calm water conditions. This formation is also composed of deltaic and turbidite fan deposits. Turbidite deposits formed by granular flow mechanisms have been used as exploration targets which generally have stratigraphic trap types.

Based on a geochemical analyses, it shows that only the Brownshale Formation of the Pematang Group is the main source rock in Central Sumatra Basin, which spread over several sub-basins (troughs), namely: Balam, Rangau, Kiri, Aman, and Bengkalis (Katz, 1994). The formation was deposited in a lacustrine environment, and lithologically it comprises brown laminated shales, rich in organic matter, indicating a depositional environment with calm water conditions (Haris *et al*., 2017)

From the results of a previous research, it was stated that in general, the Brownshale Formation has good prospects for the development of hydrocarbon shales, supported by several parameters, including: TOC (fair - very good), kerogen type II/III, brittleness index greater than 0.48, and rock compressive strength below 70 MPa (Haris *et al*., 2017).

Upper Red Bed Formation

This formation is was deposited in the final stage of F1 phase tectonics. Increasing the speed of sedimentation and clastic supply caused the basin to become full and the environment to become fluvial and alluvial. The lithology of this formation is in the form of red-green sandstones, conglomerates, and claystones. Sandstone in this formation is an exploration target.

Research Methods

Figure 3 shows the workflow for constructing a vertical fracability model on Lithofacies Association of Brownshale Formation from outcrop analog by correlating the results of the rock mechanical, mineralogy (XRD) and TOC analyses through several stages to obtain a fracture barrier and fracable zone interval model.

Fieldwork

Location 1: Kiliranjao Area

Kiliranjao Area is administratively located in Sungai Tambangan Subregency, Sawahlunto Regency, West Sumatra Province, and geographi-

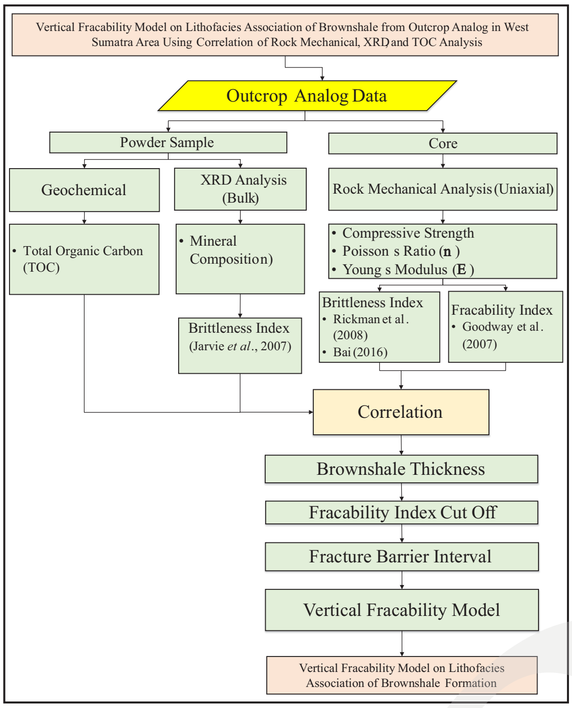

Figure 3. Workflow of the method to construct a vertical fracability model by correlating the results of the rock mechanical, XRD, and TOC analyses.

cally located at 101.348^0 east longitude and 0.848^0 south latitude.

Outcrop analog located in the coal mine of PT. Karbindo Abesyapradhi is in a fresh outcrop condition, but at the time of observation some parts of the outcrop was submerged by water, therefore some facies units could not be observed. The outcrop is divided into three parts, namely the outcrop in the southwest (SW) estimated as the coal zone and to the northeast (NE) which is estimated as brownshale zone, where both outcrops are limited by the normal fault zone or the third part that forms the coal zone at the bottom of the brownshale zone (Carnell and Butterworth, 1997; Sunardi, 2015). Figure 4 shows the outcrop analog at Karbindo (Kiliranjao) which can be divided into three zones, *i.e*: coal zone, fault zone, and brownshale zone. This study is focused on brownshale zone outcroping in the northeast as shown in Figure 5.

The brownshale zone outcrop has a thickness of about 56 m composed of four facies units, namely (from the oldest to the youngest) Unit E, interbedded red shale "siderite" and grey shale; Unit F interbedded red shale "siderite" and grey gastropod shale and insertion of brown gastropod shale; Unit G interbedded thin red shale "siderite" and grey shale; and Unit H of thin brownshale and grey shale (Figure 5).

Unit E comprises alternating red shale "siderite" and grey shale. Shale is red and grey, clay - silt in size, carbonates, and locally contains sand grains. This layer shows a very thin layer of parallel lamination, graded bedding, and slump structure.

Unit F is composed of interbedded red shale "siderite" and grey gastropod shale and insert of brown gastropod shale. Shale is red, grey to brown, clay - silt in size, calcareous, a lot of gastropods at the bottom that begins to decrease

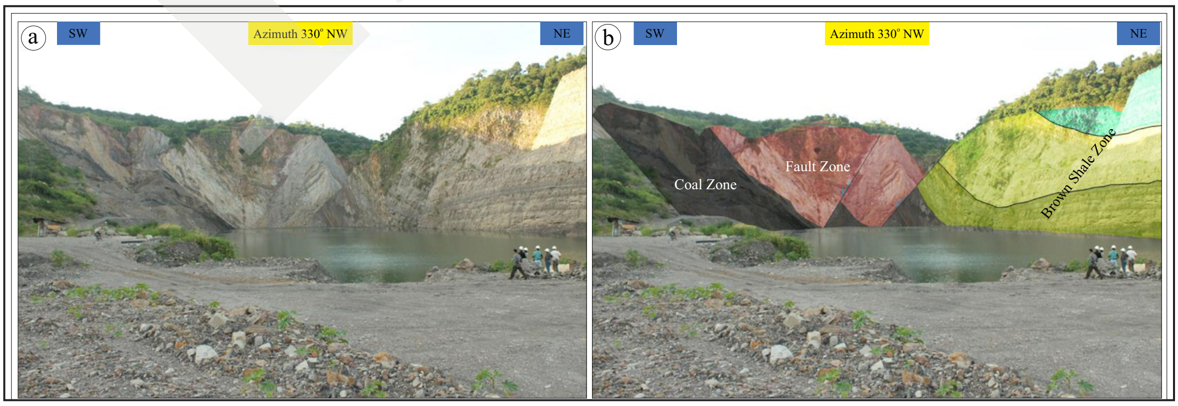

Figure 4. Field photograph of: (a). Brownshale Formation outcrop at Karbindo, Kiliranjao; (b). The outcrop profile can be divided into three zones, those are coal zone, fault zone, and brownshale zone.

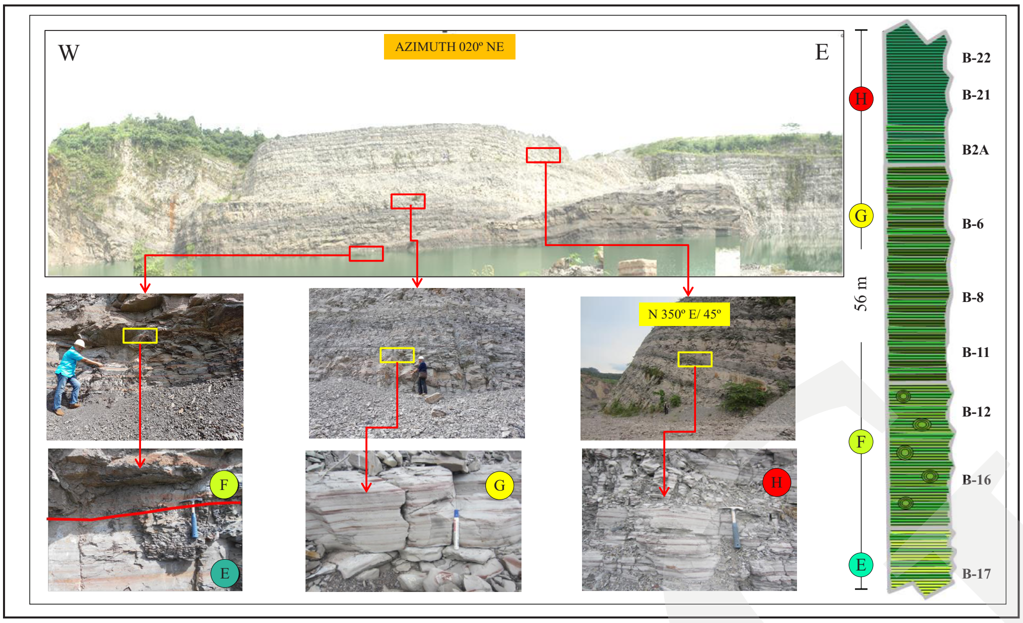

Figure 5. Field photograph of Brownshale Formation outcrops at Karbindo (Kiliranjao) which can be divided into four units (E, F, G, and H) with a thickness of about 56 m.

upwards and sometimes found intercalations with no gastropods.

Unit G consists of thin red shales "siderite" and grey shale. Shale is red and grey, clay - silt in size, calcareous, and locally contains sand grains. Red shale decreases upward and sedimentary structures are found in the form of parallel and graded bedding and local slump structure.

Unit H is made up of thin brown shale intercalations and grey shale. Shale is grey and brown, clay - silt in size, calcareous, and contains sand grains in part. The sediment structure occurring as parallel and local laminations was found in a slump structure. Samples taken in this unit contain oil odour.

Based on the analyses of physical aspects in brownshale zone combined with the deposition model (Sunardi, 2015), Unit E was deposited in a lake within offshore area, Unit F was in the margin slope area, Unit G was in the distal area - lacustrine turbidite, and Unit H was in the proximal region - lacustrine turbidite.

Location 2: Limapuluh Koto Area

In Limapuluh Koto area, there are two outcrop analog locations, namely Sarilamak Area and Batubalang Area.

Sarilamak area is administratively located in Harau Subregency, Limapuluh Koto Regency, West Sumatra Province, geographically located at 100,685^0 East longitude and 0.154^0 South latitude. The outcrops are located on the side of the road opposite to the location of brick making community, slightly fresh and have a geometry of 12 m long and 10 m wide. The rocks are composed of two facies units, namely (from the oldest to the youngest) Unit I shale and Unit J of kaolinite claystone (Figure 6).

Unit I is composed of grey to blackish brown shale, clay - silt in size, massive, contains sand and grains between soft shale and hard shale.

Unit J consists of pink kaolinite claystone (fresh condition), clay-sized grained, massive, very weathered and soft. The red colour of claystone is thought due to the rich in iron content.

Based on the results of the analyses of the physical aspects of this outcrop combined with the sedimentation model (Sunardi, 2015), Unit I and Unit J were deposited in the low-gradient area of a lake shore.

Batubalang area is administratively located in Harau Subregency, Limapuluh Koto Regency, West Sumatra Province, geographically located at 100,684^O East longitude and 0.175^O South latitude.

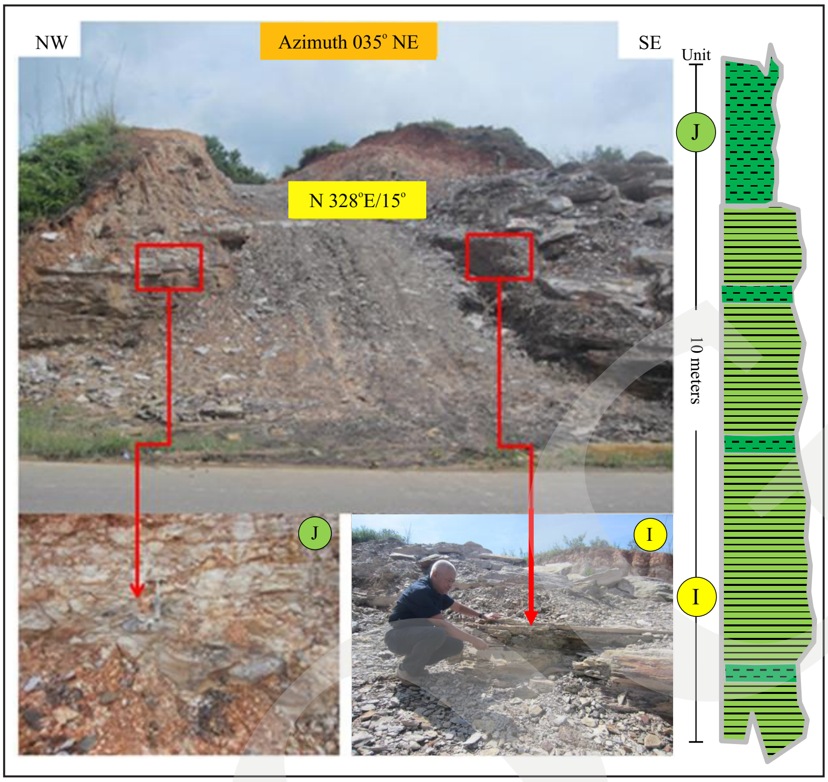

Figure 6. Outcrops of claystone and shale and their profiles (Unit I and Unit J) in Sarilamak area.

Outcrops are located on the side of the road opposite to the location of brick making community. The outcrop is rather fresh, and has a geometry of 21 m long and 15 m wide. It is consists of three facies units, namely (from the oldest to the youngest) Unit K coal, Unit L shale, and Unit M of shale and claystone (Figure 7). Unit K is composed of black, hard, bright gloss - dull coal, blocky to subconchoidal fractions, locally rich in pyrite minerals. Unit L is made up of grey and black shale, grain ranges from clay - silt, massive, hard, and contains sand. Unit M consists of shale and claystone intervals. Shale is brown and black, the size of grain ranges from clay - silt, laminated and soft - hard. Claystone is brown, clay-sized grain, massive, very weathered and hard.

Based on the analyses of physical aspects of this outcrop combined with the sedimentation model (Sunardi, 2015), Unit K was deposited in a shallow-marsh lake (palutrine mudflat) area, whilst Unit L and Unit M were deposited in a low-gradient lake shore area.

Literature Review

Rock Mechanical Analyses

The mechanical properties of rocks, such as compressive strength, Young's modulus and Poisson's ratio, can be tested in the rock mechanic laboratory. Tests to determine the mechanical properties of rocks can be carried out by uniaxial testing.

Uniaxial testing (testing of unconfined compressive strength) uses a press machine to press a sample of cylindrical, beam or prism in one direction (uniaxial). The displacement of the rock samples both axial (Δl) and lateral (ΔD) during the test was measured using a dial gauge or electric strain gauge. From the results of the compressive strength test, a stress-strain curve for each rock example can be described. Then from this curve, it can be determined the mechanical properties of rocks:

- Compressive strength (σc)
- Young's Modulus, E

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

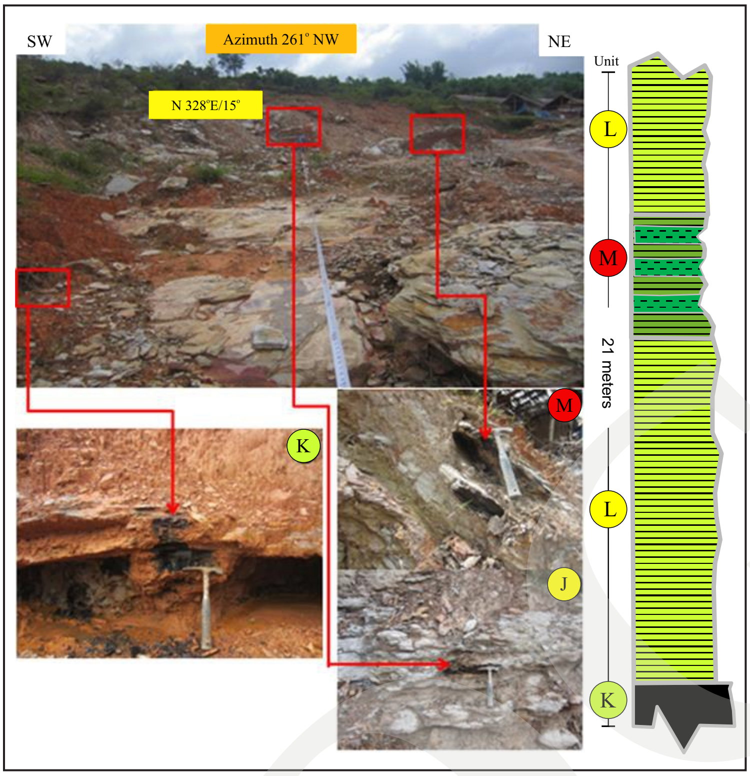

Figure 7. Coal outcrop, shale, and claystone intersection along with its profile (Unit K, Unit L, and Unit M) in Batubalang area.

- Poisson's Ratio, v

$$v = \frac{\varepsilon l}{\varepsilon a} \quad \text{...} \quad (2)$$

where Δσ is stress, Δεa is strain, εl is lateral strain, and εa is axial strain.

Brittleness Index from The Rock Mechanic Laboratory Test

Some empirical correlations have been developed for rock brittleness. In this paper, Rickman's approach was used. Based on measurements in the rock mechanic laboratory, Rickman *et al.* (2008) have correlated the brittleness of formations with Young's modulus and Poisson's ratio according to the following equation:

$$Br = \frac{50}{7}\,(E_{static} - 28v_{static} + 10.2) \quad \text{........................} (3)$$

where Br is the rock brittleness index.

Based on fracture mechanics, brittle rocks are targeted for hydraulic fracking, because it is easier to fracture than ductile rocks due to their predominant elastic deformation (Bai, 2016).

Having calculated the static properties for Young's modulus and Poisson's ratio, the brittleness of both moduli is required to quantify rock brittleness. Young's modulus brittleness (E_{BRIT}) is a function of static Young's modulus and is expresses in Equation 4.

$$E_{BRIT} = \frac{E_{static} - 1}{7} x100 \quad \text{..............................} \quad (4)$$

Poisson's ratio brittleness (V_{BRIT}) is a function of static Poisson's ratio and the relationship is shown in Equation 5.

$$V_{BRIT} = \frac{v_{static} - 0.4}{-0.25} x100 \quad \text{................................} \quad (5)$$

The rock brittleness index is an average of Young's modulus brittleness and Poisson's ratio brittleness as expressed in Equation 6.

$$Br = \frac{E_{BRIT} + V_{BRIT}}{2} \quad \text{....................................} \quad (6)$$

Fracability Index (FI) from The Rock Mechanic Laboratory Test

Fracability is another major index used in conjunction with brittleness index analyses to verify intervals of risk of fracture. The two essential parameters in calculating the fracability index are the Lame parameters of lambda (λ, psi) and mu (μ, psi). Lambda can be termed incompressibility (Equation 7; Crain, 2000) and mu is rigidity (Equation 8; Zhang, 2016) and their ratio (λ / μ) is the rock fracability index (Fr, Equation 9). According to Goodway *et al.* (2007), low incompressibility and high rigidity indicate a brittle zone.

$$\lambda = \frac{E_{static} v_{static}}{\left(1+v_{static}\right) \times \left(1-2v_{static}\right)} \quad \text{...........................} (7)$$

$$\mu = \frac{E_{static}}{2\left(1+v_{static}\right)} \quad \text{...} (8)$$

$$Fr = \frac{\lambda}{\mu} \quad \text{..} (9)$$

The fracability index for a fracable interval was found to range between 0 and 1. A rock may fail to fracture when the fracability index is greater than 1 due to the rock becoming more ductile. Hence, it should not be taken as a potential candidate. Plotting both brittleness and fracability index in one chart can provide significant information about possible fracable intervals, which can vary over the thickness of the target reservoir (Alsaif *et al*. 2017).

XRD Analyses

X-Ray Diffraction (XRD) analyses is conducted to identify the types of minerals contained in each rock sample using the bulk analyses method. In bulk analyses, shootings are carried out with shooting angles of 3^o up to 90^o. After getting the results of shooting or running samples using the XRD tool, the results of the analyses are presented in the form of peaks from the XRD reading chart, and the types of minerals present in the sample can be determined based on determinant peaks (Bladh *et al*., 2001, http://www.handbookofmineralogy.org /).

The type of mineral that has been identified is carried out a semiquantification analyses to determine the percent of minerals in each depth sample. The mineral percentage is calculated using Equation 10.

$$\text{Percentage of minerals A} = \frac{I_A}{\left(I_A + I_B + \ldots I_n\right)} \times 100\% \; \cdots (10)$$

where I is the determinant peak intensity of one type of mineral, while A, B, ... n are the types of minerals identified in each sample.

Brittleness Analyses from The XRD Laboratory Test

Brittleness is the measurement of stored energy before failure, and is the function of rock strength, lithology, texture, effective stress, temperature, fluid type, diagenesis, and TOC. Brittleness Index (BI) is the most widely used parameter for the quantification of rock brittleness (Perez and Marfurt, 2013).

In recent years, brittleness has been used as a descriptor in selecting formation zone intervals for hydraulic fracking (Jarvie *et al*., 2007; Rickman *et al*., 2008). Therefore, brittleness is one of the most important rock-mechanical properties, and is used in determining prospecting of shale hydrocarbon.

Brittleness index based on the results of XRD analyses can be calculated using a formula from Equation 11 (Jarvie *et al*., 2007), as follows:

$$BI_{(jarvie,\ 2007)} = W_{qtz} / W_t \quad \text{..............................} (11)$$

where W_{qtz} = weight of quartz; and W_t = total mineral weight

Total Organic Carbon (TOC) Analyses

Determination of the total original organic carbon (TOC_o) from source rock provides a quantitative means for estimating the total volume of hydrocarbons that can be produced depending on the type of kerogen. Broadly, explored areas generally have mature source rocks, so it is not easy to determine the original values. Consideration of the TOC component helps in understanding how to restore highly mature TOC to TOC_o (Jarvie *et al*., 2007).

Hydrocarbon Shale Development Criteria

The development of shale hydrocarbon, depending on several parameters that can be produced commercially, includes several criteria, as shown in Table 1.

Rock Mechanical, Mineralogy (XRD), and TOC Analyses

Samples from fieldwork at Location 1 (Kiliranjao) and Location 2 (Limapuluh Koto), which had been labelled with "Sample ID", were then tested in the rock mechanical, XRD, and geochemical laboratory. The elastic rock properties, mineral content, and Total Organic Carbon (TOC) can be determined to identify the Brownshale Formation outcrop prospection, which assumed to represent the presence of Brownshale Formation (Pematang Group) in Bengkalis Trough, Central Sumatra Basin.

At Location 1 (Karbindo, Kiliranjao), rock sampling and coring can be done, because at certain intervals shale rock outcrops are quite compact, but at Location 2 rock coring cannot be done, because shale outcrops both in Sarilamak and Batubalang Area are very brittle.

Outcrop analog of brownshale zone at Karbindo Coal Mine (Kiliranjao) has a thickness of about 56 m and is composed of four facies units, namely (from the oldest to the youngest) Unit E interbedded shale red "siderite" and shale grey, Unit F interbedded shale red "siderite" and shale grey gastropods and insertions of brown gastropod shale, and the G units comprise interbedded thin shale red "siderite" and greyshale, and unit of thin brownshale and grey shale (Figure 4).

The rock mechanical test was selected from several shale core samples from the results of the coring on the outcrop at Karbindo Coal Mine (Kiliranjao) representing each unit of the shale hydrocarbon facies (Browshale Formation), namely:

- Unit E, including: core B-17 (shale), assuming the equivalent of core B-11 (shale gastropod), B-12 (shale gastropod), and B-16 (shale gastropod)
- Unit F, including : core B-11 (shale gastropod), B-12 (shale gastropod), and B-16 (shale gastropod)
- Unit G, including : core B-2A (shale), B-6 (shale), dan B-8 (shale)
- Unit H, including : core B-22 (shale), assuming the equivalent of core B-21 (shale)

The rock mechanical test results from several shale core samples of the outcrop at Karbindo (Kiliranjao) are shown in Table 2.

In the XRD analyses selected several shale samples from the outcrop sampling at Karbindo Coal Mine (Kiliranjao) representing each of the Brownshale Formation facies units, namely:

- Unit E, including: sample B-17 (shale)
- Unit F, including: samples B-11 (shale gastropod), B-12 (shale gastropod), and B-16 (shale gastropod)
- Unit G, including: sample B-2A (shale), B-6 (shale), and B-8 (shale)

Tabel 1. Criteria in The Commercial Development of Shale Hydrocarbon (Modified from McKeon, 2011; Jin *et al.*, 2014)

No	Parameter	Criteria
1	Total Organic Carbon (TOC), wt.%	> 1 wt.%
2	Shale thickness, ft	> 100 ft (30,48 m)
3	Moderate clay content, %	< 40 %
4	Brittleness Index of shale, dimenssionless	> 0.48
5	Fracability Index of shale, dimenssionless	
	- Fracable	> 0.55
	- Not Fracable (hard to frac)	≤ 0.55

Table 2. Rock Mechanical Test Results on Several Shale Cores at Karbindo (Kiliranjao)

No	Sample ID	Unit	TOC (%)	Rock Mechanics Test Result		
				CS (MPa)	v	E (MPa)
1	B-22 Shale	H	2,46	19,04	0,18	2.444,93
2	B-21 Shale	H	6,33	19,04	0,18	2.444,93
3	B-2A Shale	G	2,65	26,56	0,10	3.261,23
4	B-6 Shale	G	6,08	14,50	0,05	784,62
5	B-8 Shale	G	8,73	14,00	0,13	710,28
6	B-11 Shale Gastropod	F	7,78	5,92	0,21	301,79
7	B-12 Shale Gastropod	F	4,50	5,92	0,21	301,79
8	B-16 Shale Gastropod	F	7,51	5,92	0,21	301,79
9	B-17 Shale	E	13,70	5,92	0,21	301,79

- Unit H, including: sample B-21 (shale) and B-22 (shale)

The results of the mineralogy (XRD) analyses of several shale samples in outcrop at Karbindo Coal Mine (Kiliranjao) are shown in Table 3.

Meanwhile, the Brownshale Formation outcrop in Sarilamak area has a thickness of 10 m, consisting of four facies units, namely (from the oldest to the youngest) Unit I which is composed of shale grey to blackish brown, and Unit J comprising of pink kaolinitic claystone (Figure 5). The Brownshale Formation outcrop in Batubalang area has a thickness of 21 m, consisting of three facies units, namely (from the oldest to the youngest) Unit K composed of shale near coal, Unit L comprising shale, and Unit M is made up of shale and claystone (Figure 6).

In the XRD laboratory test, several shale samples are selected from the outcrop sampling at Location 2 (Limapuluh Koto) representing each unit of the shale hydrocarbon facies (Brownshale Formation), namely:

- Unit I and J, including: sample SH 6.1 Upper, Middle, and Lower (shale)
- Unit K, including: sample BH 6.4 Shale near coal
- Unit L, including: sample BH 6.3 Upper, Middle, and Lower (shale)

The results of the mineralogy (XRD) analyses of several shale samples in the outcrop at Location 2 (Limapuluh Koto) are shown in Table 4.

Results and Discussion

In this study, there are two locations of outcrop analogs of Brownshale Formation, namely Location 1 (Karbindo Coal Mine, Kiliranjao) and Location 2 (Sarilamak and Batubalang

Table-3. Results of Mineralogy (XRD) Analysis of Several Shale Samples at Karbindo (Kiliranjao)

No	Sample ID	Unit	TOC (%)	Quartz (%)	Calcite (%)	Clay (%)	Other Mineral				Total
							Feldspar (%)	Feox (%)	Pyrite (%)	Dolomite (%)	
1	B-22 Shale	H	2,46	17,86	69,32	3,35	0,00	9,47	0,00	0,00	100,00
2	B-21 Shale	H	6,33	27,44	51,88	6,08	0,00	9,07	5,53	0,00	100,00
3	B-2A Shale	G	2,65	29,55	44,24	16,87	0,00	0,00	4,77	4,58	100,00
4	B-6 Shale	G	6,08	29,86	36,94	21,07	0,00	0,00	6,49	5,64	100,00
5	B-8 Shale	G	8,73	32,11	24,34	28,67	0,00	4,38	5,87	4,62	100,00
6	B-11 Shale Gastropod	F	7,78	49,38	31,68	18,94	0,00	0,00	0,00	0,00	100,00
7	B-12 Shale Gastropod	F	4,50	76,84	0,00	17,39	0,00	0,00	5,77	0,00	100,00
8	B-16 Shale Gastropod	F	7,51	71,25	11,74	17,01	0,00	0,00	0,00	0,00	100,00
9	B-17 Shale	E	13,70	67,98	0,00	32,02	0,00	0,00	0,00	0,00	100,00

Table 4. Results of Mineralogy (XRD) Analysis of Several Shale Samples at Location 2 (Limapuluh Koto)

No	Sample ID	Unit	TOC (%)	Quartz (%)	Calcite (%)	Clay (%)	Other Mineral			
							Feldspar (%)	Feox (%)	Pyrite (%)	Dolomite (%)
1	SH 6.1 Upper Shale	I	5,68	**85,83**	0,00	**14,17**	0,00	0,00	0,00	0,00
2	SH 6.1 Middle Shale	J	-	**74,08**	0,00	**19,80**	0,00	**6,12**	0,00	0,00
3	SH 6.1 Lower Shale	J	6,08	**74,50**	0,00	**20,11**	0,00	**5,39**	0,00	0,00
4	BH 6.3Upper Shale	L	4,23	**69,66**	0,00	**22,20**	0,00	**8,14**	0,00	0,00
5	BH 6.3 Middle Shale	L	-	**66,10**	**3,64**	**26,45**	0,00	0,00	**3,82**	0,00
6	BH 6.3 Lower Shale	L	7,59	**79,39**	0,00	**16,59**	0,00	0,00	**4,02**	0,00
7	BH 6.4 Shale	K	-	**57,59**	0,00	**36,55**	0,00	0,00	**5,86**	0,00
8	BH 6.4 Near Coal	K	-	**57,09**	0,00	**36,42**	0,00	0,00	**6,49**	0,00

areas, Limapuluh Koto). Shale samples from each location represent a unique mixture of mineralogy**.** The nature of brittle rocks can be determined using ternary diagrams based on the main mineral content (quartz, clay, and carbonate) from the mineralogy (XRD) analyses results. The ternary diagram plot of the mineralogy (XRD) analyses results of Brownshale Formation from Location 1 (Karbindo Coal Mine, Kiliranjao) and Location 2 (Limapuluh Koto) is shown in Figure 8.

From the Figure 8, it can be seen that the main minerals (quartz, carbonate, clay) of the XRD analyses results of Brownshale Formation from Location 1 (Karbindo, Kiliranjao) and Location 2 (Limapuluh Koto) are distributed between Zone 1 to Zone 4, where the spread of Zone 1 is more dominant. This can be classified, as follows:

- Zone 1: quartz dominant – clay and carbonate minor (Brittle quartz rich), Limapuluh Koto and Kiliranjao shale samples
- Zone 2: carbonate dominant – quartz and clay minor (Brittle carbonate rich), Kiliranjao shale samples
- Zones 3 and 4: quartz and carbonate are nearly balanced – clay minor (ductile, hard to frac), Kiliranjao shale samples.

The correlation of rock mechanical, mineralogy (XRD), and TOC analyses with lithofa-

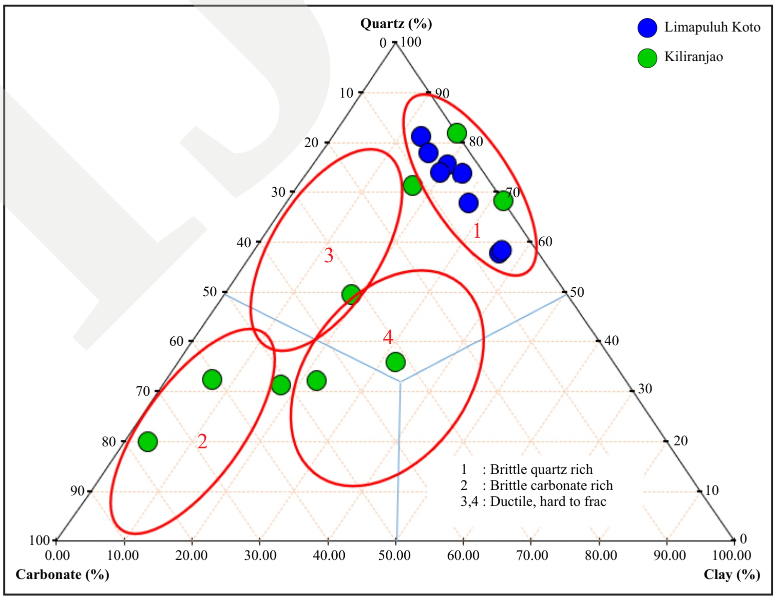

Figure 8. Ternary diagram plot of mineralogy (XRD) analysis results of Brownshale Formation at Location 1 (Karbindo Coal Mine, Kiliranjao) and Location 2 (Limapuluh Koto).

cies association Brownshale Formation model, represented by shale samples from Location 1 (Karbindo, Kiliranjao) consist of Unit E, Unit F, Unit G, and Unit H, is shown in Figure 9 as vertical fracable model.

It can be seen from Figure 9 that the correlation of TOC and brittleness with Lithofacies Association Brownshale Formation at Karbindo (Kiliranjao) shows the TOC of each facies unit is high (TOC > 1%), and the brittleness index calculation (Jarvie *et al*., 2007) shows some intervals of facies units < 0.48 (less brittle). Then, it can be concluded that Lithofacies Association Brownshale Formation Model at Karbindo (Kiliranjao) eventhough the TOC value is high, there is a fracture barrier if applied with hydraulic fracking.

Figure 9 shows that the G Unit and H Unit (upper section) are dominated by calcite (carbonate) mineral, the brittleness index (Jarvie *et al*., 2007) is low (< 0.48), but the brittleness index (Rickman *et al*., 2008) is high (> 0, 48, brittle carbonate rich). On the other hand, units E and F (lower section) are dominated by quartz minerals, the brittleness index (Jarvie *et al.*, 2007) is high (> 0.48, brittle quartz rich), but the brittleness index (Rickman *et al*., 2008) is low (<0.48).

This proves that the criteria for "high brittleness" as a descriptor in determining the fracable zone interval is not accurate, because the presence of a dominant carbonate mineral will become a fracture barrier in the shale reservoir, so a new descriptor is needed to select a more accurate fracable zone interval, namely the "fracability index". In determining the sweetspot fracable window, based on the correlation of the results of lithofacies, rock mechanical, and mineralogy (XRD) analyses of the Brownshale Formation at Location-1 (Karbindo Coal Mine, Kiliranjao), it can be concluded that the results of rock mechanic analyses from core samples (static data) are the most reliable, where the results of the calculation of the fracability index (static) can be used as a descriptor for drawing the limits of the fracable zone interval and fracture barrier interval with the criteria of fracability index > 0.55.

Figure 9 also shows that the vertical fractability model of the Lithofacies Association Brownshale Formation from the outcrop analog is correlated with elastic rock properties, where the limit of the fracable zone interval is based on the value of the high fracability index (FI > 0.55), as the descriptor is at the zone with Low YM - High PR values. On the other hand, the fracture barrier interval is in the High YM - Low PR zone.

In the vertical fracability model of the Lithofacies Association of Brownshale Formation from outcrop analog, there is an interesting phenomenon, namely the fracture barrier interval in the High YM - High PR and Low YM - Low PR zones, where both are correlated with High BI, but Low FI. So, it can be concluded that the High YM zone - High PR and Low YM - Low PR is a shale hydrocarbon interval which is not suitable as a candidate for hydraulic fracking.

From the analyses of lithofacies shown in Figure 9, it can be seen that there is a strong relationship between the fracable zone interval and the sand-shale series interval. So, it can be concluded that the sand-shale series is a suitable interval for hydrocarbon shale as a candidate for hydraulic fracking.

While the correlation of mineralogy (XRD) and TOC analyses with Lithofacies Association Brownshale Formation model is represented by shale samples from Location 2 (Limapuluh Koto) that consists of Units I, J, K, L, and Unit M, shown in Figure 10 which cannot be used as a vertical fracable model.

Determining the sweetspot fracable window, based on mineralogy (XRD) analyses for the Lithofacies Association Brownshale Formation model at Sampling Location-2 (Limapuluh Koto), is only based on the value of the brittleness index (BI avg > 0.48), the entire facies unit profile interval is a fracable sweetspot zone, because there is no core data.

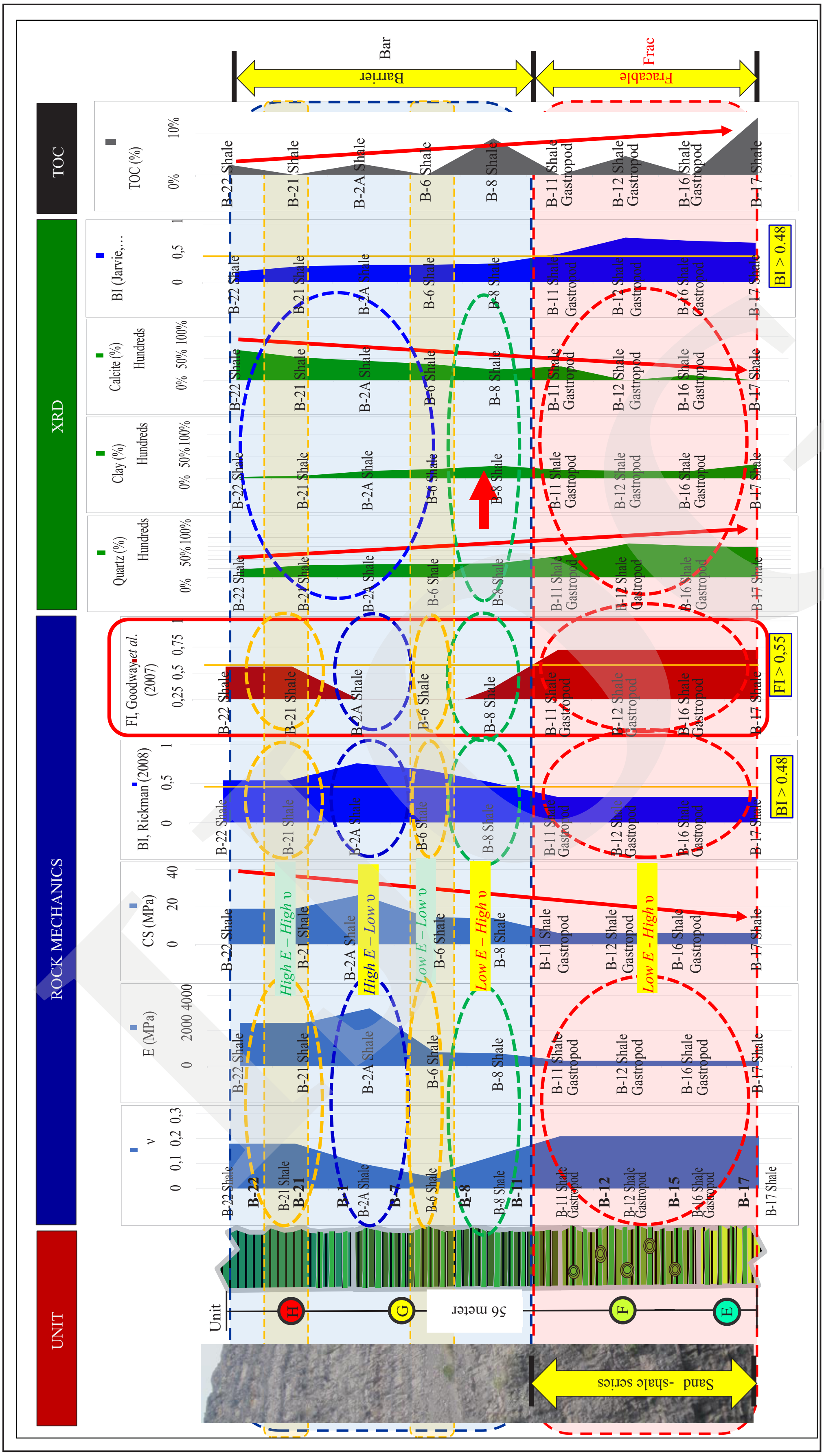

Figure 9. Correlation of rock mechanical, mineralogy (XRD), and TOC analyses with Lithofacies Association Brownshale Formation Model at Karbindo (Kiliranjao) as a Vertical Fracability Model.

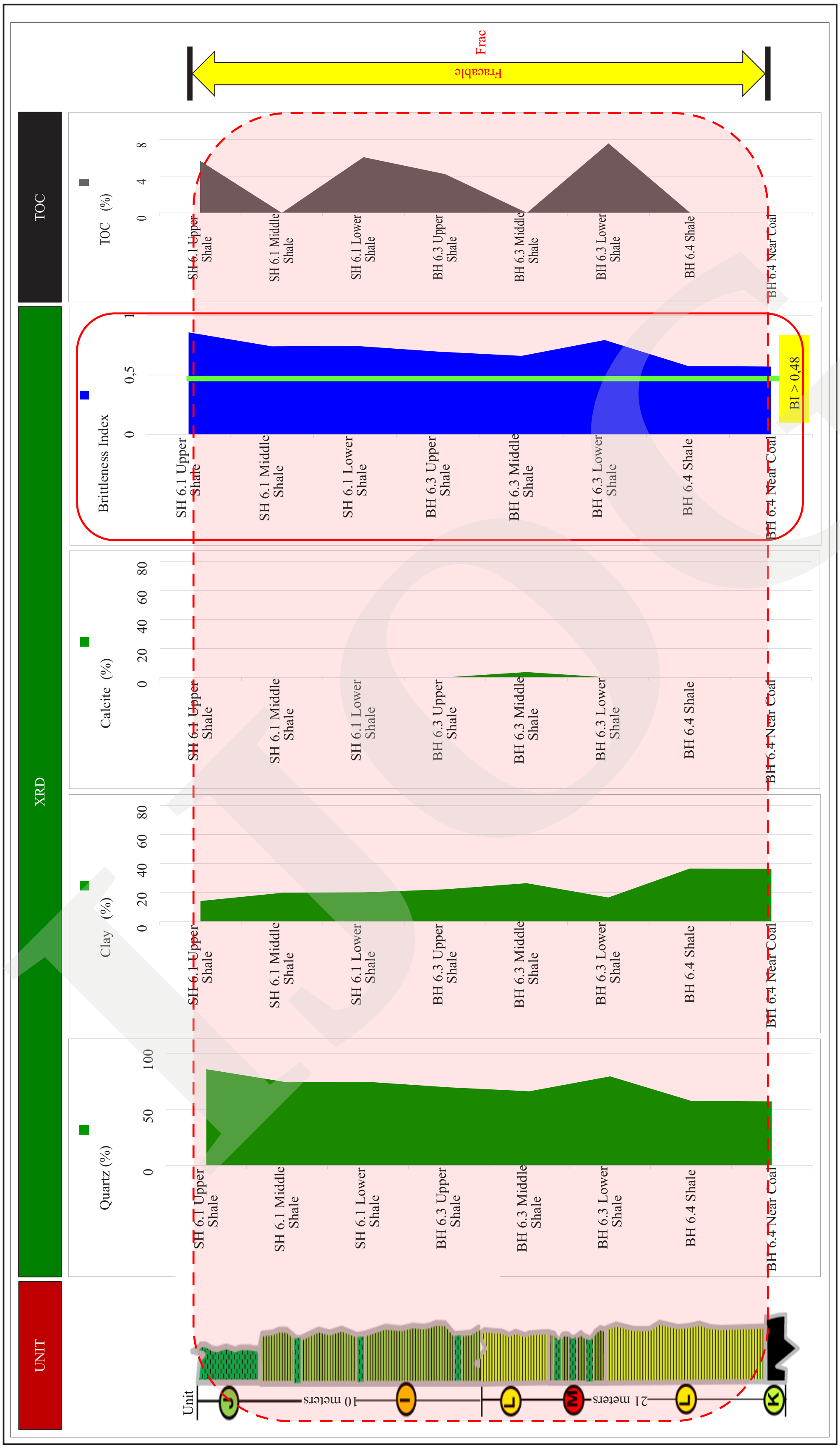

Figure 10. Correlation of mineralogy (XRD) and TOC analyses with Lithofacies Association Brownshale Formation Model at Location 2 (Limapuluh Koto).

Conclusions

Previous researchers have shown that Tertiary lithostratigraphic units exposed at the Karbindo Coal Mine (Kiliranjao) are an equivalent part of the Pematang Group Formation, because the Pematang Formation is not exposed on the surface, where the Karbindo Coal Mine is located southwest of the studied area (Bengkalis Trough). This provides a valuable information to support the exploration stage of shale hydrocarbon. The equivalent Pematang Formation exposed at Karbindo called as Brownshale consists of four units, *i.e*. E, F, G, and H Units with a thickness of about 56 m.

The hypothesis that the Brownshale Unit at Karbindo is an equal part of the Pematang Group Formation, so that the vertical fracability model of the Lithofacies Association of Brownshale Formation from outcrop analog can be used as a preliminary study of shale hydrocarbon development in Bengkalis Trough, Central Sumatra Basin. From the results and discussion, it can be concluded as follows:

- From the ternary diagram of the mineralogy (XRD) analyses results of the Lithofacies Association of Brownshale Formation from outcrop analog samples at Karbindo and Limapuluh Koto, it shows variations in the distribution of the main mineral composition of Q-C-C (quartz-clay-calcite) due to variations in the mineral composition of each facies unit.
- The vertical fracability model of the Lithofacies Association of Brownshale Formation from outcrop is influenced by lithofacies, where there is a strong relationship between the fracable zone interval and the sand-shale series interval, so it can be concluded that the sand-shale series is a suitable interval for hydrocarbon shale as a candidate for hydraulic fracking.
- A high brittleness index value does not always correlate with a high fracability index, but can be inversely proportional, due to the influence of mineral content in shale rocks.
- In the vertical fracability model of the Lithofacies Association of Brownshale Formation from outcrop analog, there is an interesting phenomenon, namely the fracture barrier interval in the High YM − High PR and Low YM − Low PR zones, where both are correlated with High BI, but Low FI. So, it can be concluded that the High YM zone − High PR and Low YM − Low PR is a shale hydrocarbon interval which is not suitable as a candidate for hydraulic fracking.

Acknowledgment

The authors would like to thank the PHE & BSP Consortium for the Joint Study of Non-Conventional Oil and Gas (JS MNK) on the CPP Block for contributing data and permission to publish this paper. The authors also thank P.T. Karbindo Abesyapradhi for sampling and coring access.

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