

Study of Porosity and Mechanical-Elastic Properties of the Potential Underground CO₂ Storage in Un-Mined Coal Seams from Well-log Data, South Sumatra Basin, Indonesia

Handoyo Handoyo^{1*}, Asido Saputra Sigalingging¹, Edlyn Yoadan Nathania¹, Dimas Astomo¹, Ramon Carbonell², Sondang Samsir³

¹Geophysical Engineering, Institut Teknologi Sumatera, South Lampung, 35365, Indonesia

²Geosciences Barcelona (GEO3BCN, CSIC), Barcelona, 08028, Spain

³Tiarabumi Petroleum, Jakarta, 12190, Indonesia

*Corresponding author: handoyo.geoph@tg.its.ac.id

Abstract

In CO₂ storage technology, particularly in coal seams, necessitates specialized research into numerous critical factors that are equivalent to coal seam characteristics, including porosity, permeability, rock strength (UCS: uniaxial compressive strength), Poisson ratio, and brittleness. Rock properties of the coal seam are responsible for the CO₂ storage capacity. In this study, we have core samples from the borehole and employed four well-logs (within an area ~ 1000 m × 875 m) that drilled in the coal mining project located in South Sumatra Basin, Indonesia. The goal of this study is to describe the coal seam C strata in the sub-surface that have the potential to be utilized for underground CO₂ storage. In this study, we identified coal seams C from low density and gamma rays from log response data. Then, we predict porosity values from data density, velocity (V_p and V_s), UCS values, and BI using petrophysical and rock physics approaches. The result of this study shows that the distribution of top depth coal seam C varies in depth 19 to 225 m with the porosity 0.086–0.138. The value of UCS 1150–1299 Pa and brittleness index 0.531–0.569 that are associated with a characteristic coal with low to medium strength and medium brittleness. The results of this preliminary analysis revealed that the coal seam layer in this region has a high potential for CO₂ storage in Sumatra, Indonesia.

Keywords

Brittleness, Coal Seam, CO₂ Storage, Porosity, UCS

Received: 23 September 2024, Accepted: 12 December 2024

<https://doi.org/10.26554/sti.2025.10.1.238-249>

1. INTRODUCTION

Carbon capture and storage aims to contribute to the reduction of the effect of global warming by capturing the CO₂ emissions of industrial processes prior to the release into the atmosphere and storage the CO₂ in underground facilities/suitable geologic formations. Geological storage of CO₂ involves injecting greenhouse gas into the subsurface (Aydin et al., 2010). Capturing CO₂ in aquifers located in geological formations is regarded as one of the most promising techniques for stabilizing CO₂ concentrations in the atmosphere (Figure 1).

In Figure 2b, the stratigraphic arrangement of Coal in Tanjung Enim is as follows (Tarsis, 2001; Adiwidjaja and Decoster, 1973; Amier, 1991; Muksin et al., 2012): (I) Petai Coal Seam (Coal Seam C): The thickness of this coal seam ranges from 3 to 4.5 meters, with shiny black characteristics containing impurities such as clay and silt with a thickness of around 10 to 15 cm. The interburden between coal layers C and coal B is characterized by layers of sandstone interbedded with siltstone with a thickness of about 20 to 40 m; (II) Upper Petai Coal

Seam (Coal Seam B2): The thickness of this coal seam ranges from 7 to 14.6 meters, is characterized by a shiny black color and contains the mineral pyrite in it. The interburden between coal seams B1 and B2 is characterized by dense claystone, sandstone with layers approximately 20 to 40 cm thick; (III) Suban Coal Seam (Coal Seam B1): This coal layer has a shiny black color around the intrusion area. Black and very hard pyrite and clay minerals with a thickness of less than 5 meters were found in it. The total thickness of this coal seam is estimated to be around 8–12 meters. The interburden between coal seams A2 and B1 is characterized by the presence of claystone and silty claystone, which are gray and dense and contain pyrite minerals. The thickness of this interburden ranges from 15 to 23 meters, and there is also a thin layer of coal called Suban Marker; (IV) Lower Mangus Coal Seam (Coal Seam A2): This coal layer has a thickness ranging from 9.8 to 14.7 meters, and there are claystone inserts as an impurity layer (clayband). Above the A2 coal seam, there is a layer of tuffaced siltstone and claystone with a thickness of between 0.5 and 4 meters; and (V) Upper Mangus Coal Seam (Coal Seam A1): This coal

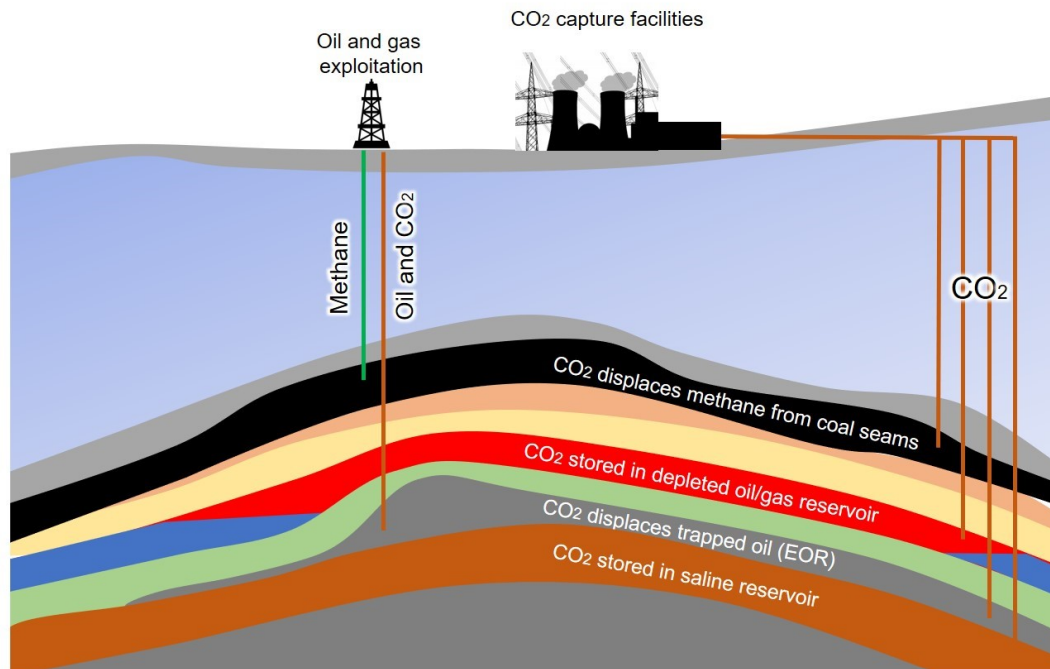


Figure 1. Illustration of a Geological CO₂ Storage Scenario (Adapted from Aydin et al. (2010), Ravagnani et al. (2009), Shi and Durucan (2005), Li and Fang (2014), Wu et al. (2023), and Gibbins and Chalmers (2008)). The CO₂ Can Be Stored in Several Geological Formations, for Instance, Coal Seams, Depleted Reservoirs, and Saline Reservoirs

seam has a thickness ranging from 5 to 13.5 meters. It is characterized by the presence of three white bands which are inserts of tuffaceous claystone. The overburden of this layer consists of dark greenish claystone, as well as very hard reddish-brown iron claystone. Above the A1 coal seam, there is a Hanging Seam or what is also called a hanging coal seam, but this coal seam is not mined because it has no economic value. Three different storage scenarios can be envisioned: 1) CO₂ can be stored in geological media by injection into depleted oil and gas reservoirs. The CO₂ is used in enhanced oil recovery (EOR) operations where CO₂ is injected into an oil field, causing it to swell, and thereby reduce its viscosity, maintaining or increasing the pressure in the reservoir. This keeps or increases flow of the hydrocarbon to the production wells. Part of the gas is stored in the reservoir rocks, part is extracted and re-injected (Ravagnani et al., 2009). 2) CO₂ can be injected into un-mined coal seams. Approximately 95-98% of the gas in the coal seam like methane (CH₄) is stored by sorption in the coal matrix. Three mechanisms act to trap/store the gas in coal: a) the gas compounds are physically adsorbed on the internal surfaces of coal (within the cleats); b) within the natural fractures and/or pores; and c) absorbed within the molecular structure (Shi and Durucan, 2005). The injection of CO₂ in coal seams can enhance coal-bed methane recovery. This CO₂-Enhanced Coal-Bed Methane Technology (CO₂-ECBM) has the poten-

tial to store large volumes of the greenhouse gas in relatively deep unmined coal formations, while improving the efficiency and potential profitability of CH₄ recovery (Li and Fang, 2014; Wu et al., 2023). Finally, 3) CO₂ can be injected into deep saline aquifers. Depths over 800 m to ensure that pressure and temperature conditions a close to the critical value for CO₂ (on the order, or above, 31°C and 100°C atmospheres) to push densities to 0.5 g/cc (Gibbins and Chalmers, 2008). Geological storage requires a conventional reservoir/seal structural sequence. A high porosity and permeability reservoir rock located under an overburden low porosity rock formation that acts as a seal. As a result, the use of the subsurface requires of profound and detailed knowledge. Therefore, direct and indirect multidisciplinary studies (e.g., geology, geophysics, rock physics, and petrophysics) are critical for understanding the characteristics of a rock formation that is expected to be a candidate for CO₂ storage, particularly in un-mined coal seams.

One of the prospective locations as a geological storage place for CO₂ is in Sumatra. Sumatra has long been known as a producer of oil, natural gas, and coal which are found in various types of rock reservoirs and coal seams such as in the North Sumatra Basin, Central Sumatra Basin and South Sumatra Basin (Bishop, 2001; Friederich et al., 2016; Koesoemadinata, 2002). In the coal mining field project in South

Sumatra Basin, density and gamma-ray logs are traditionally applied to investigate coal seams prospect (seam A and B), which have significant economic value. Meanwhile, coal seam C layer does not provide profit for the mining business. Coal seams C typically extend relatively deep (tens to hundreds of meters), thereby making mining challenging. Therefore, coal seam C has the potential to perform as an underground CO₂ storage site.

In this study, porosity and mechanical-elastic properties, such as UCS (uniaxial compressive strength), poisson ratio, and brittleness index (BI), were estimated using a density log that estimated by a mathematical relationships and a rock's physical properties. These parameters are very important in studying the potential for CO₂ storage in coal seams. Porosity and permeability are related to the ability to store and channel CO₂ in the coal seam layer through fractures in it (Wang et al., 2018; Zou et al., 2022). Rock strength UCS represents the strength of the rock when pressed (Pan et al., 2013; Perera and Ranjith, 2012; Tenthorey et al., 2019) and brittleness indicates the level of coal brittleness when fracturing is carried out, which has the same analogy as in unconventional shale gas or shale oil exploration (Zhang et al., 2021; Sampath et al., 2019; Kuang et al., 2023; Masoudian et al., 2014). It is hoped that this study will have potential and provide an overview to coal mining companies as a commitment to support controlling CO₂ emissions both in Sumatra (Indonesia) and in other locations throughout the world.

2. EXPERIMENTAL SECTION

2.1 Location

The study area is located in the Muara Enim area, where the Muara Enim Formation host a number of coal seams (Figure 2a). This formation consistently occurs above the Air Bekanat Formation, which consists of claystone, siltstone and tuffaceous sandstone. Then followed by the Talang Akar Formation and covered by the Kasai Formation. The youngest deposits are an alluvium unit consisting of sandstone, silt and clay. The Muara Enim Formation has been divided in sub-sections M1, M2, M3, and M4 (Figure 2b). The most economical and potential coal seams for exploitation are mainly found in sub-sections M2 and M4. In the M1 unit, the lowest layer of the Muara Enim Formation, includes two layers, namely the Keladi and Merapi Layers. M2 sub-section contains coal which is mostly exploited in the Tanjung Enim area (Tarsis, 2001; Adiwidjaja and Decoster, 1973).

In Figure 2b, the stratigraphic arrangement of Coal in Tanjung Enim is as follows (Tarsis, 2001; Adiwidjaja and Decoster, 1973; Amier, 1991; Muksin et al., 2012): (I) Petai Coal Seam (Coal Seam C): The thickness of this coal seam ranges from 3 to 4.5 meters, with shiny black characteristics containing impurities such as clay and silt with a thickness of around 10 to 15 cm. The interburden between coal layers C and coal B is characterized by layers of sandstone interbedded with siltstone with a thickness of about 20 to 40 m; (II) Upper Petai Coal Seam (Coal Seam B2): The thickness of this coal seam ranges

from 7 to 14.6 meters, is characterized by a shiny black color and contains the mineral pyrite in it. The interburden between coal seams B1 and B2 is characterized by dense claystone, sandstone with layers approximately 20 to 40 cm thick; (III) Suban Coal Seam (Coal Seam B1): This coal layer has a shiny black color around the intrusion area. Black and very hard pyrite and clay minerals with a thickness of less than 5 meters were found in it. The total thickness of this coal seam is estimated to be around 8-12 meters. The interburden between coal seams A2 and B1 is characterized by the presence of claystone and silty claystone, which are gray and dense and contain pyrite minerals. The thickness of this interburden ranges from 15 to 23 meters, and there is also a thin layer of coal called Suban Marker; (IV) Lower Mangus Coal Seam (Coal Seam A2): This coal layer has a thickness ranging from 9.8 to 14.7 meters, and there are claystone inserts as an impurity layer (Clayband). Above the A2 coal seam, there is a layer of tuffaced siltstone and claystone with a thickness of between 0.5 and 4 meters; and (V) Upper Mangus Coal Seam (Coal Seam A1): This coal seam has a thickness ranging from 5 to 13.5 meters. It is characterized by the presence of three white bands which are inserts of tuffaceous claystone. The overburden of this layer consists of dark greenish claystone, as well as very hard reddish-brown iron claystone. Above the A1 coal seam, there is a Hanging Seam or what is also called a hanging coal seam, but this coal seam is not mined because it has no economic value.

2.2 Borehole Geophysics: Data Constraints

The study area is a mining field in Tanjung Enim, South Sumatra Basin, Indonesia. This study involves four wells (DM-C, DM-G, DM-I, and DM-M) covering approximately 875.000 m² (Figure 3). Table 1 shows the petrophysical parameters for all boreholes, particularly depth (m), gamma-ray (API), and density (CPS: count per second).

Table 1. The Materials Used of This Study.

Well Name	Core Data	Density (cps)	Gamma Ray (API)
DM-C	✓	✓	✓
DM-G	✓	✓	✓
DM-I	✓	✓	✓
DM-M	✓	✓	✓

2.3 Methodological Aspects

This study analyzes layers in coal seam C, in three stages: (1) delineating the layer using gamma ray and density log data, (2) predicting porosity from density log data, and (3) estimating P-wave velocity (V_p), UCS, and brittleness index values. Once all physical properties was calculated, we analyze the rock physical depth trend and correlation between rock properties and coal seam characteristics.

Delineation of coal seams C layers are identified on the base of their low gamma-ray values and density (Zhou and O'Brien,

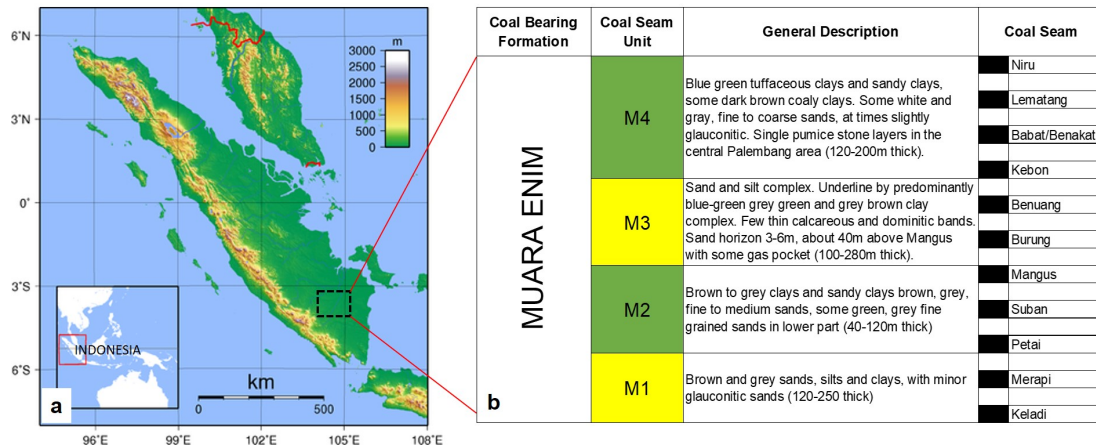


Figure 2. Study Area of South Sumatra Basin (Black Rectangle), (a) Topography Map of Sumatra Island, (b) Local Stratigraphy of Muara Enim (adapted from Tarsis (2001) and Adiwidjaja and Decoster (1973))

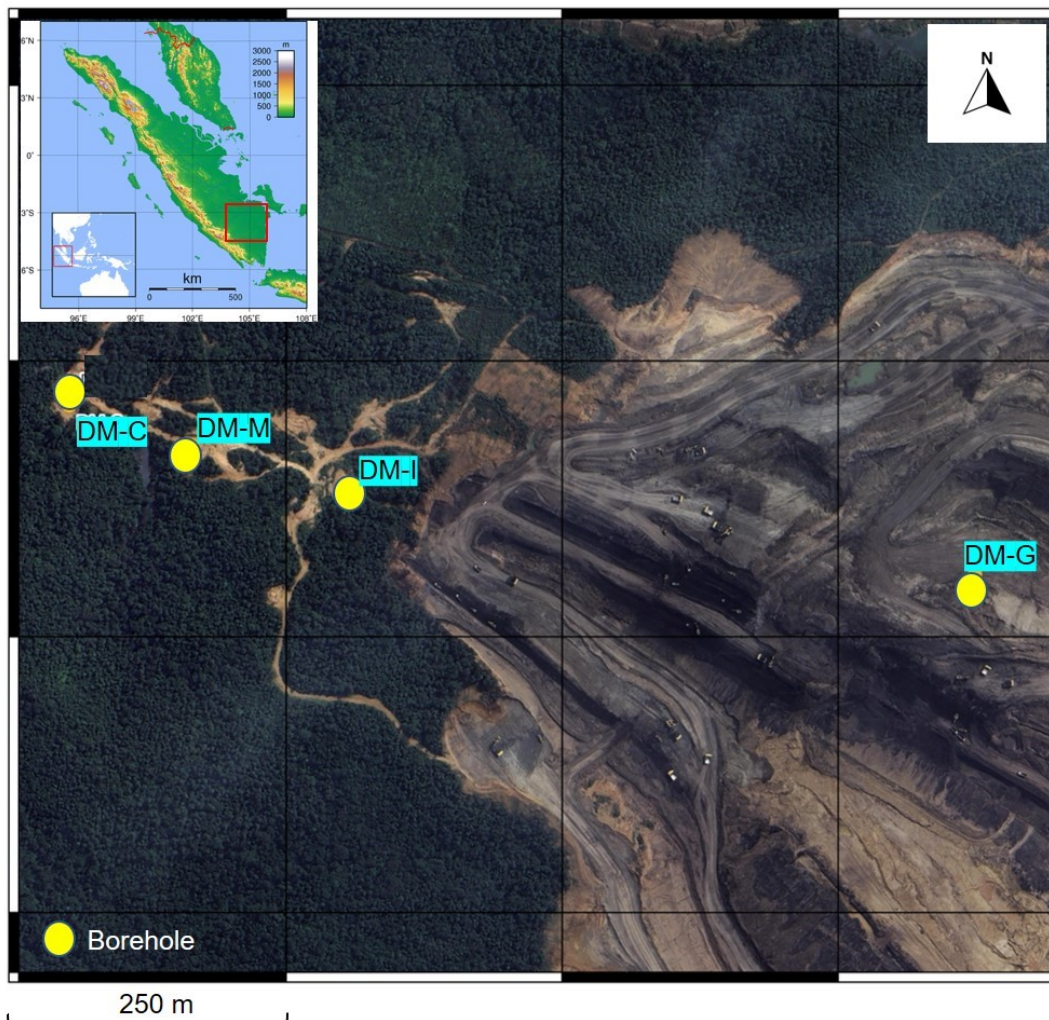


Figure 3. Basemap of the Study Area in Tanjung Enim mining field, There Are Five Location of Well-Log Data (Yellow Dots)

2016; Ghosh et al., 2014; Christoffel and Kayal, 1989). The density value in this study is in CPS (count per second) units, hence it needs to be translated to g/cc units. To accomplish this, Equation (1) (Christoffel and Kayal, 1989; Warren, 2002). is employed. Υ is the density value in CPS, while x is the density value in g/cc.

$$\Upsilon = 177598e^{-2.4325x} \quad (1)$$

Coal porosity values vary from 4.1 to 23.2% (Gan et al., 1972; Wang et al., 2024). In this study, the porosity values (Φ) are predicted using Equation (2) (Zanetta et al., 2021; Alberty, 1992). Where ρ_{ma} is the density of the coal matrix (1.1-2.2 g/cc) (Ünalın, 2010; Walker Jr et al., 1988; Chakravarty et al., 2020), ρ_b is the density log value from field measurement data, and ρ_f is the fluid density, which in this study is the water's fluid density (1.0 g/cc).

$$\Phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad (2)$$

Then, the uniaxial compressive strength (UCS) refers to the greatest axial stress that a rock can endure before failure. The value of UCS is estimated easily using Equation (3) (Gardner et al., 1974; Raymer et al., 1980). This UCS value is obtained by first calculating the velocity value in the coal seam C. The velocity of the coal seam (V_p) is derived from the density and porosity values. The velocity value is predicted using the average of the $V_p - density$ relationship by Gardner equation in Equation (4) and the $V_p - porosity$ empirical relationship by Raymer equation in Equation (5) (Gardner et al., 1974; Raymer et al., 1980; Kokowski et al., 2019). Where V_{solid} is the velocity of coal (~1900 m/s) and V_{fluid} is velocity in water (~1450 m/s) (Kokowski et al., 2019; McDowell, 2002).

$$UCS = 1277exp(-0.0367V_p) \quad (3)$$

$$\rho = 0.31V_p^{0.25} \quad (4)$$

$$V_p = (1 - \Phi)^2V_{solid} + \Phi V_{fluid} \quad (5)$$

Then, to get the brittleness index (BI), we first calculate the BI value from the Young's modulus (E) and poisson ratio (PR) approaches. Previously, the S-wave velocity value (V_s) was first calculated using the empirical relationship between V_p and V_s written by Equation (6) (Castagna et al., 1993).

$$V_s = 0.804V_p - 0.856\left(\frac{km}{s}\right) \quad (6)$$

The dynamic Modulus Young (E) and Poisson Ratio (PR) calculated by Equations (7) and (8). Then the value of the brittleness index is derived from Equations (9) and (10). Finally, the final BI value was calculated by Equation (11) (Grieser and

Bray, 2007; Aligholi et al., 2017).

$$E = \frac{\rho V_s^2(3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \quad (7)$$

$$PR = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \quad (8)$$

$$BI_E = \frac{E - E_{min}}{E_{max} - E_{min}} \quad (9)$$

$$BI_{PR} = \frac{PR - PR_{min}}{PR_{max} - PR_{min}} \quad (10)$$

$$BI_{Average} = \frac{BI_E + BI_{PR}}{2} \quad (11)$$

After all parameters were calculated from all well data, the simple interpolation technique by statistical Kriging algorithm was applied to characterize the distribution of mechanics, elasticity, and porosity in coal seam C.

3. RESULT AND DISCUSSION

In this section, we present the result and discussion of this study that related to the physical properties of coal and the potential CO₂ storage in coal seam. We organize the result and discussion following: (i) Delineation of coal seam C and porosity estimation; (ii) Mechanical and elasticity estimation; (iii) Physical properties depth trends; (iv) Correlation between rock properties and coal seam characteristics; and (v) Limitation of this study.

3.1 Delineation of Coal seam C and Porosity Estimation

Coal seams in nature exhibit relatively low gamma-ray. In this field, we can quickly detect coal seams on gamma-ray when the values are < 20 API. Then, the coal seam density is also low and can be accurately determined in every well-log.

In Figure 4, coal seams C in Well DM-C is identified by gamma-ray values < 20 API and density values > 450 CPS. The coal seams C is identified at the depths 20-26 m and 28-32 m this is confirmed by core samples from these depths. Coal seams C in this location are described as having a glossy black color with clay intercalations in brittle bands. The average porosity of the coal seams in this well is of 0.138.

In Figure 5, deepest coal seams C in Well DM-G were characterized at depth 225-235 m interpreted from gamma-ray values < 10 API and density values within the range 520-780 CPS. The brittle coal seams C in this location are also described as having a dark to shiny black color with clay and silt contents. Then, the average porosity of the coal seams in this well is relatively low, measuring on the order of 0.086.

Furthermore, coal seams C in Well DM-I were identified through gamma-ray values of less than 10 API and density values of more than 450 CPS at a depth of 137-162 m (Figure 6). In the marker data in the form of a core image, the coal seam C sample has a glossy black color with brittle characteristics. The average porosity of coal seams in these wells is 0.104.

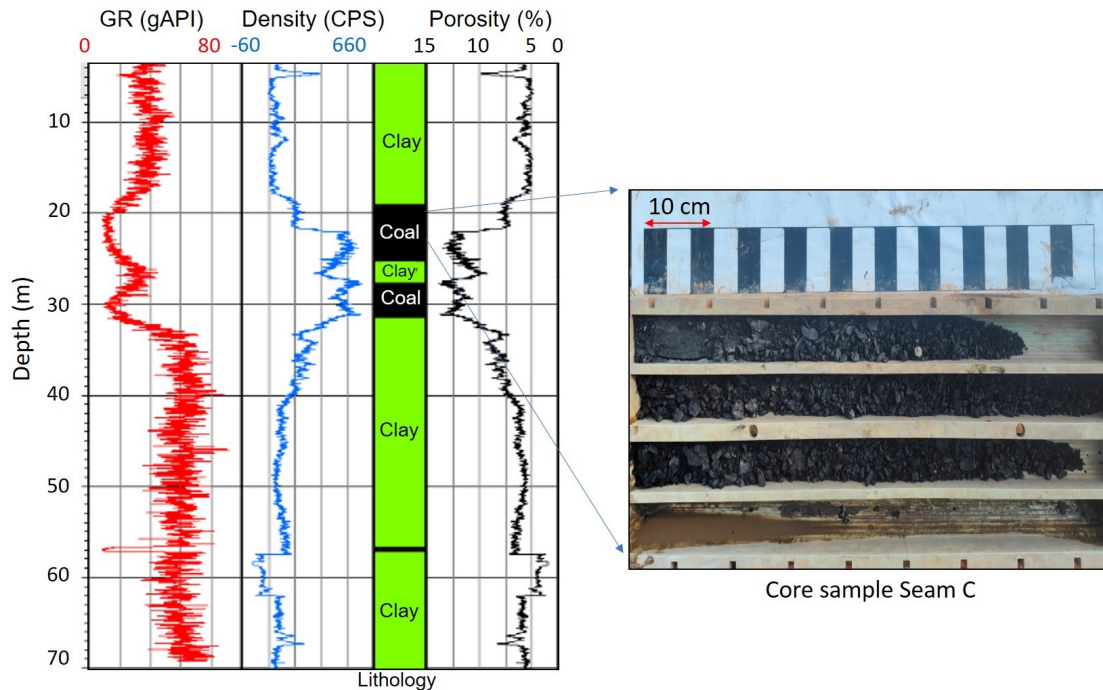


Figure 4. Interpretation of Coal Seams C in Well DM-C and the Image of Coal Sample in This Depth ~20 m.

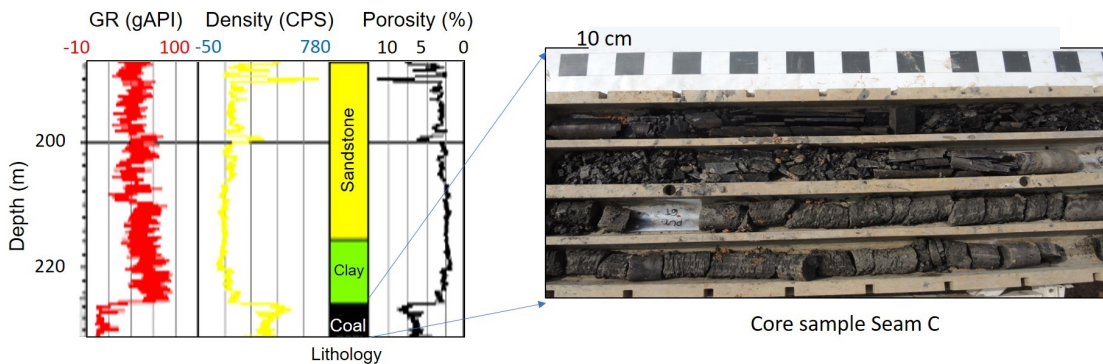


Figure 5. Characterization of Coal Seams C in Well DM-G, Including Image of Coal Sample at a Depth of Approximately 250 m

Finally, in Figure 7, coal seams C in Well DM-M were identified through gamma-ray values of < 10 API and density values of > 400 CPS at a depth of 42-75 m. In the marker data in the form of a core image, the coal seams C sample has a glossy black color with brittle characteristics and the average porosity 0.112.

3.2 Mechanical and Elasticity Estimation

In this section, we determined the rock physical parameters of coal seam C employing the equations from the previous section's in basic theory. First of all, the density value using Equation (2). The average density in Well DM-C is 1.369

g/cc, 1.955 g/cc in Well DM-G, 1.871 g/cc in Well DM-I, and 1.627 g/cc in Well DM-M. Then, the value of P-wave velocity was calculated by the averaging Equations (4) and (5). Consecutively, the V_p values from Well DM-C to DM-M are of 1432 m/s, 2190 m/s, 2112 m/s, and 1820 m/s. then, the S-wave velocity values derived from Equation (6) are 916 m/s, 1195 m/s, 1176 m/s, and 1010 m/s.

The mechanical and elastic properties of coal seams C are then calculated in order to identify their geomechanically features. The average value of bulk modulus of Well DM-C is 4.317 GPa, Well DM-G 11.221 GPa, Well DM-I 7.122 GPa, and Well DM-M 8.569 GPa. Then, the shear modulus are

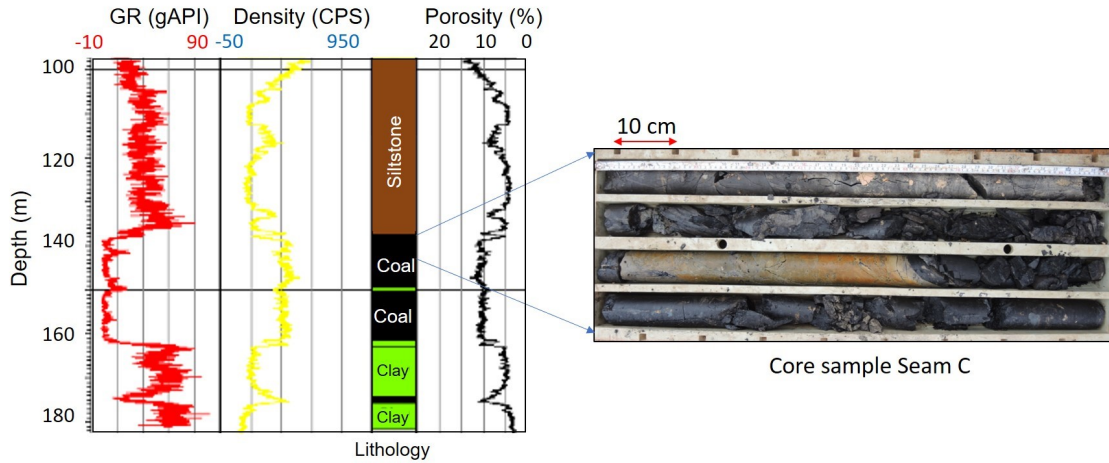


Figure 6. Identification of Coal Seams C in Well DM-I, Including Image of Coal Sample at a Depth of ~145 m

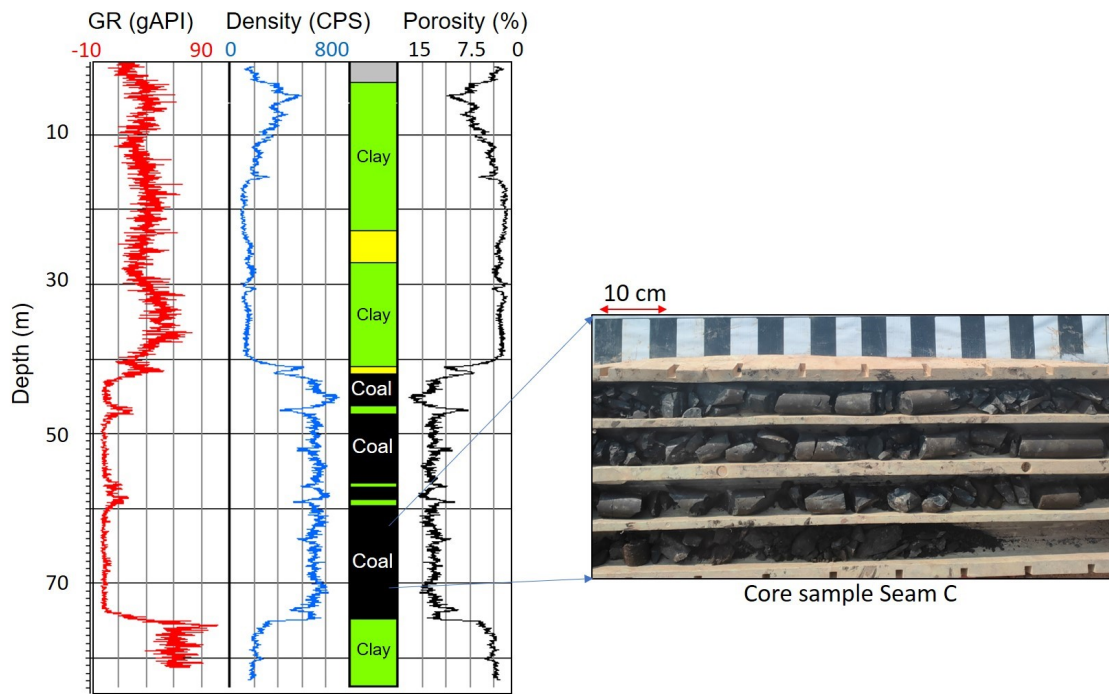


Figure 7. Identification of Coal Seams C in Well DM-M, Including Image of Coal Sample at a Depth of ~70 m

2.433 GPa, 3.831 GPa, 3.495 GPa, and 3.764 GPa. Then, the Poisson Ratio for each well respectively is 0.524, 0.497, 0.536, and 0.479. The rock brittleness index for each well is 0.573, 0.531, 0.565, and 0.569. Finally, the rock strength values for each well are of 1150 Pa, 1299 Pa, 1275 Pa, and 1233 Pa. In summary, the results of the overall physical parameter estimation for all wells are shown in Table 2.

After all petrophysical, elastic and mechanical parameters are calculated, we create a lateral distribution by interpolating all well data. The most common and familiar interpolation is the Kriging interpolation technique. The results of the in-

terpolation to see the lateral distribution are shown in Figure 8. The interpolated parameters are averages for each well in the hope of representing the true value of each coal seam C. In Figure 8a, from NW to SE, the depth distribution of top coal seams C broadens deeper from Well DM-C, which has an average depth of 19 m, to Well DM-G, which has a depth of 225 m. Figure 8b shows that the density value increases with depth. The identical situation occurs for the UCS value, which increases as one moves further southeast (Figure 8e). On the other hand, the *BI* level decreased from northwest to southeast (Figure 8d).

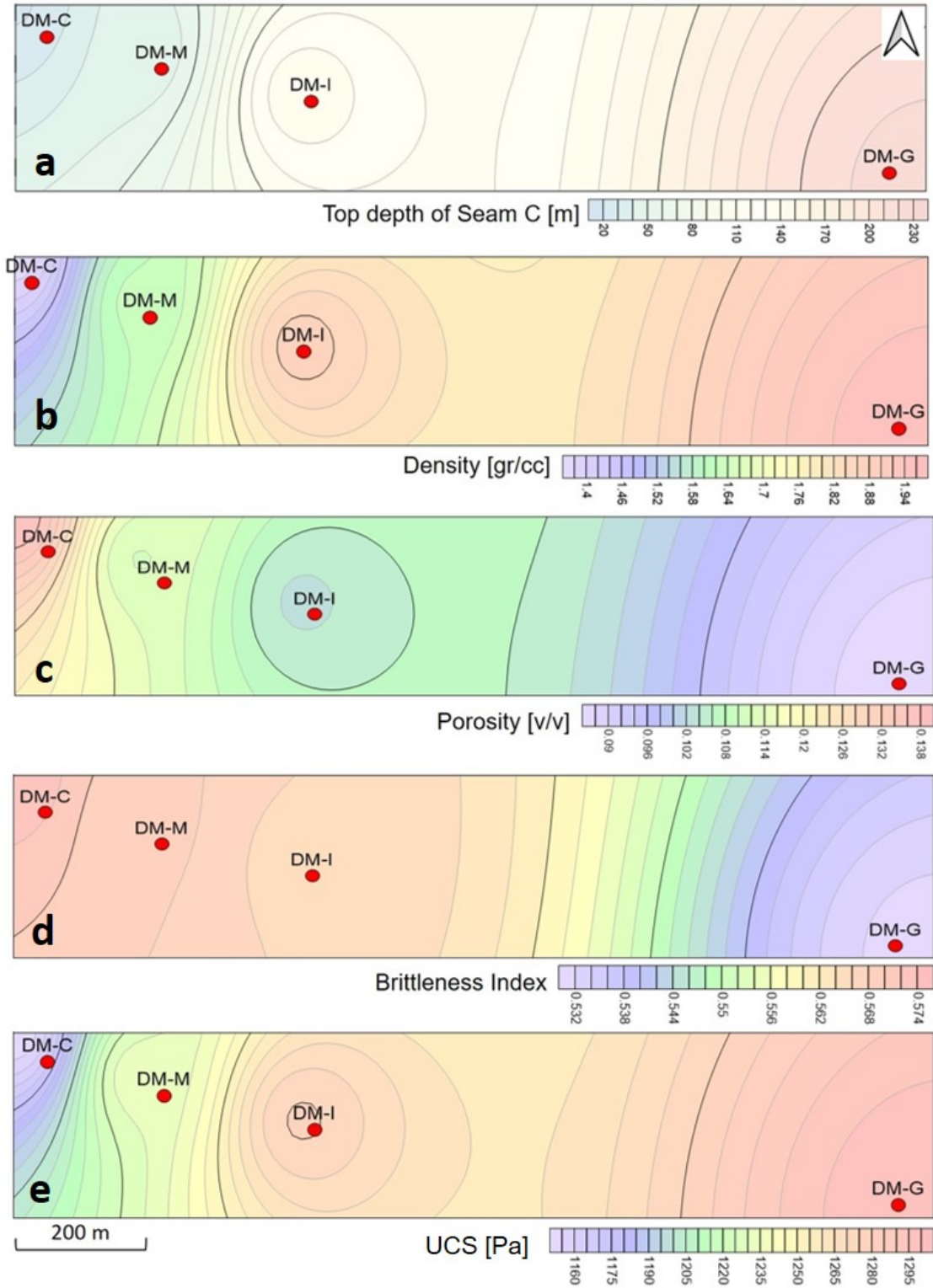


Figure 8. Map of the Physical Properties in Coal Seams C in Tanjung Enim, a) Map of the Depth of the Coal Seams C, b) Map of Density Distribution, c) Map of Porosity Value, d) Map of Brittleness Index *BI*, and e) Map of Rock Strength UCS

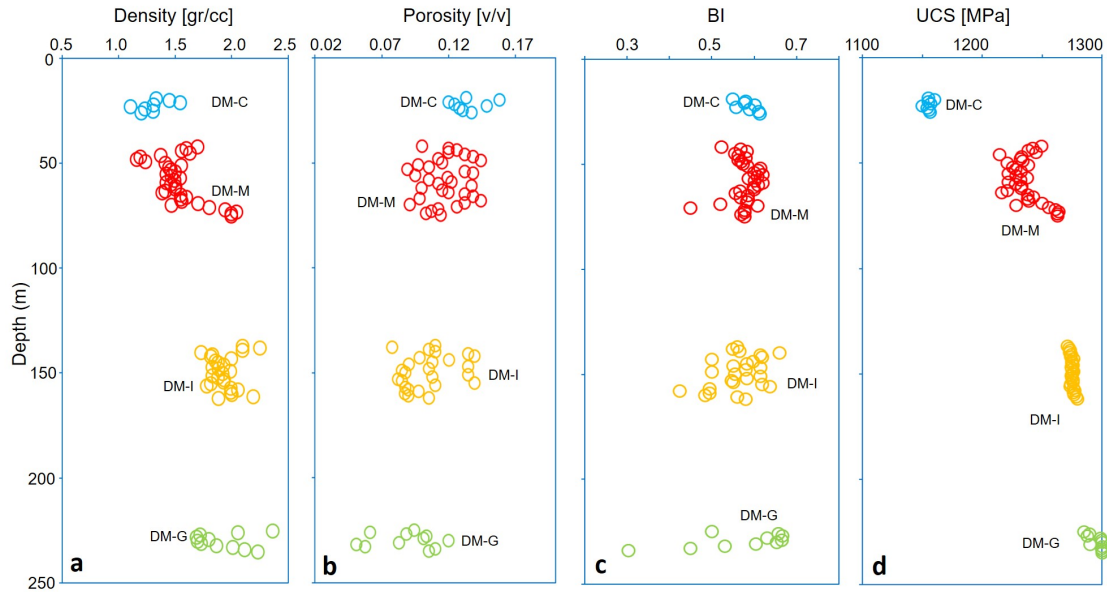


Figure 9. Depth Trend of the Petrophysical and Physical Properties of Coal Seams C in Tanjung Enim

Table 2. The Summary of Petrophysical and Physical Properties of Coal Seams C.

UCS [Pa]	BI	PR	K [GPa]	G [GPa]	Porosity [v/v]	V_s [m/s]	V_p [m/s]	Density [g/cc]	Thickness [m]	Top Depth [m]	Well Name
1150	0.573	0.524	4.317	2.433	0.138	916	1432	1.369	7	19	DM-C
1299	0.531	0.497	11.221	3.831	0.086	1195	2190	1.955	10	225	DM-G
1275	0.565	0.536	7.122	3.495	0.104	1176	2112	1.871	25	137	DM-I
1233	0.569	0.479	8.569	3.764	0.112	1010	1820	1.627	33	42	DM-M

3.3 Physical Properties Depth Trends

Rock physical properties such as density and porosity naturally perform trends that can be connected to increasing depth. For example, porosity decreases as depth increases (Ramm et al., 1997; Bohnsack et al., 2020). In contrast, the density will rise as the depth increases (Lu et al., 2020; Mariucci et al., 2024). This effect is caused by increased levels of compaction and cementation, which typically increase with depth (Ramm et al., 1997; Bohnsack et al., 2020; Lu et al., 2020; Mariucci et al., 2024).

In this study, in Figure 9a, the density value at a depth of 20-32 m (Well DM-C) has quite wide variations in values ranging from 1.1-1.6 g/cc. Then, at a depth of 42-75 m (Well DM-M) it has a value of 1.2-2.1 g/cc, at a depth of 137-162 m (Well DM-I) it has a density value of 1.6-2.2 g/cc, and at a depth of 225-235 m (Well DM-G) has a very wide density range ranging from 1.4-2.4 g/cc. In general, the density value of coal seams C in Tanjung Enim is increased as the depth value increases. Figure 8b shows the porosity values at the corresponding depth intervals. Well DM-C has the highest porosity with a value interval of 0.11-0.16, followed by Well DM-M with 0.08-0.13, Well DM-I with 0.07-0.14, and Well DM-G with a porosity interval of 0.03-0.12. In general,

the average porosity value in this investigation decreases with increasing depth.

In Figure 9c, the BI value at each depth is relatively uniform at an interval of 0.5-0.6. This shows that the brittleness index for coal seams C is relatively uniform. In Figure 9d, the UCS rock strength value increases with increasing depth. Well DM-C has an average UCS value of 1150 Pa, Well DM-M is 1233 Pa, UCS with an average of 1275 Pa in Well DM-I, and the highest UCS value is in Well DM-G with an average value 1299 Pa. In general, the UCS value in this study is proportional to the increase in depth value.

3.4 Correlation between Rock Properties and Coal Seam Characteristics

One factor to consider when determining the ideal location of a rock layer formation as a site to store CO₂ below the surface is the rock layer's ability to hold the amount of CO₂ it contains. Therefore, the porosity and permeability of the coal seam layer must be relatively high in order to store the maximum quantity of CO₂. In this study, the porosity value of coal seams C at the Tanjung Enim Mine varied from 8.6% to 13.8%. This amount is regarded optimal since it has the capacity to store significant volumes of CO₂ in the coal seams C layer. Previous research

has shown that coal seams with porosity levels ranging from 5-10% can be used to store CO₂ and methane gas (Yan et al., 2020; Sander, 2014; Mwakipunda et al., 2023). In addition, the thickness of the C coal seam, which is around 7-33 m, is expected to increase the volume of the coal seam so that the volume of CO₂ that can be stored will also be more significant.

Then, in an effort to inject CO₂ into the coal seams, it is related to the level of brittleness and strength of the coal, which is related to the *BI* and UCS values. The *BI* value can provide information on whether the coal seams are brittle or ductile and the UCS value can provide information for the purposes of the drilling process. In this research, the UCS value of Tanjung Enim C coal seams is between 1150-1229 Pa which requires relatively low pressure to crush it (Speight, 2015; Gonzatti et al., 2014).

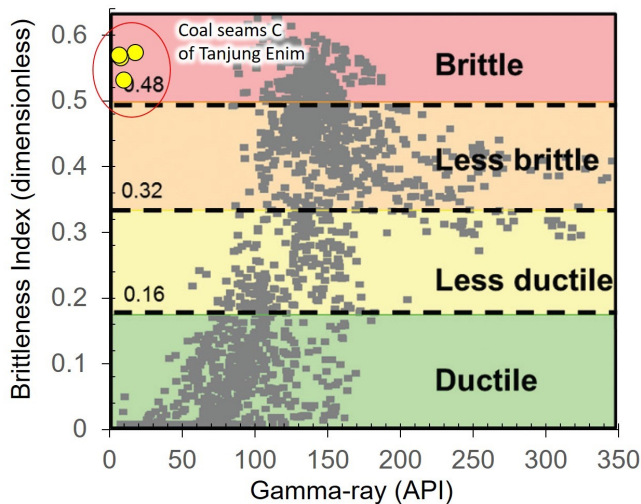


Figure 10. Interpretation of the Brittleness Index of Coal Seams C Tanjung Enim (Yellow Dots Data) Based on the Perez and Marfurt Classification (Modified from Perez Altamar and Marfurt (2014))

In order to increase connectivity between pores in coal seams, which usually have a closed pore type, fracturing efforts are needed to create secondary porosity in the coal seams layer, so that the permeability value can increase. To create fractures in coal seams, information is needed regarding the type of coal, whether brittle or ductile, therefore the *BI* value is important information to know. In this study, the *BI* value of coal seams C Tanjung Enim ranged from 0.531-0.569. After being correlated with the relationship diagram between gamma-ray and *BI* adapted from Perez Altamar and Marfurt (2014) classification (an analogy from his research on shale), it can be predicted whether the coal seams are brittle or not (Figure 10). In Figure 10, we plotted the value of gamma-ray and *BI* of all well data in coal seams C Tanjung Enim. Based on the Perez and Marfurt classification, the C coal seams at this location are classified as brittle coal seams. This result corresponds to the appearance of

the core sample image in each well (Figures 4-7) which is relatively incomplete (fragmented). Therefore, the potential for fracturing the Tanjung Enim C coal seams layer is promising.

3.5 Limitation of This Study

In this study, the porosity, *BI*, UCS, and Vp-Vs values did not have log data or core analysis in the lab. The values of these parameters are predicted from theoretical (mathematical) approaches and empirical studies. Therefore, it is hoped that future studies will have information on these parameters in situ, both from log data and laboratory studies. In situ information is needed as a marker so that the predictions made are more accurate.

Furthermore, further research is also expected to involve other geophysical methods such as seismic methods in order to provide information on the lateral distribution of thickness of coal seams C, which is a limitation of log data in the form of 1D information. Moreover, seismic data can provide information regarding the existence of geological structures (faults) that may be present in the research area. It is hoped that advanced seismic techniques such as inversion and attributes can also be applied to distribute the parameters that we have calculated (density, porosity, *BI*, UCS, and Vp-Vs) laterally and volumetrically (2D/3D) (Pan et al., 2015; Lepore and Ghose, 2015).

4. CONCLUSIONS

This study is a preliminary look into feasible options for CCS in un-mined coal seams in Tanjung Enim, South Sumatra Basin which was carried out based on information obtained from four data wells spread across the research location. The results of this study illustrate the estimated 2D map of the depth to the top of the coal seam C which ranges from 19 m to 225 m, with possible CO₂ storage dimensions represented by a thickness of 7-33 m and a widely range in porosity of 8.6-13.8%. Then, the UCS value of 1150-1299 Pa and the Brittleness index of 0.531-0.569, which are related with the distinctive coal with low to medium strength and brittleness. Further investigations are required in order to have a more extensive supporting data set (for example seismics, additional well-logs.). This additional information will allow for more thorough study on the 2D/3D geometry of the CCS coal seam reservoir. In concluding remark, coal seams C in Tanjung Enim's un-mined coal field is a possible target for testing and carrying further research on CCS in coal seams.

5. ACKNOWLEDGMENT

Thank you to PT Bukit Asam for providing permission to use well data in this research. This research was funded by LPPM Institut Teknologi Sumatera, grant number 1539j/IT9.2.1/PT. 01.03/2024.

REFERENCES

- Adiwidjaja, P. and G. L. Decoster (1973). Pre-Tertiary Paleotopography and Related Sedimentation in South Sumatra. *Indonesian Petroleum Association*; 89–103
- Alberty, M. (1992). *ME 10: Development Geology Reference Manual*, chapter Standard Interpretation: Part 4. Wireline Methods. American Association of Petroleum Geologists (AAPG), pages 180–185
- Aligholi, S., G. R. Lashkaripour, and M. Ghafoori (2017). Strength/Brittleness Classification of Igneous Intact Rocks Based on Basic Physical and Dynamic Properties. *Rock Mechanics and Rock Engineering*, **50**; 45–65
- Amier, R. I. (1991). *Coals, Source Rocks and Hydrocarbons in the South Palembang Sub-Basin, South Sumatra, Indonesia*. Master's thesis, University of Wollongong
- Aydin, G., I. Karakurt, and K. Aydiner (2010). Evaluation of Geologic Storage Options of CO₂: Applicability, Cost, Storage Capacity and Safety. *Energy Policy*, **38**(9); 5072–5080
- Bishop, M. G. (2001). *South Sumatra Basin Province, Indonesia: The Lahat/Talang Akar-Cenozoic Total Petroleum System*. US Geological Survey, Denver, Colorado, USA
- Bohnsack, D., M. Potten, D. Pfrang, P. Wolpert, and K. Zosseder (2020). Porosity-Permeability Relationship Derived from Upper Jurassic Carbonate Rock Cores to Assess the Regional Hydraulic Matrix Properties of the Malm Reservoir in the South German Molasse Basin. *Geothermal Energy*, **8**; 1–47
- Castagna, J. P., M. L. Batzle, T. K. Kan, and M. M. Backus (1993). Rock Physics-The Link Between Rock Properties and AVO Response. *Offset-Dependent Reflectivity-Theory and Practice of AVO Analysis: SEG*, **8**; 135–171
- Chakravarty, S., K. Chakravarty, V. Mishra, S. Chakladar, A. Mohanty, and M. Sharma (2020). Characterization of Chemical Structure with Relative Density of Three Different Ranks of Coal from India. *Natural Resources Research*, **29**; 3121–3136
- Christoffel, D. A. and J. R. Kayal (1989). Coal Quality from Geophysical Logs: Southland Lignite Region, New Zealand. *The Log Analyst*, **30**(05)
- Friederich, M. C., T. A. Moore, and R. M. Flores (2016). A Regional Review and New Insights into SE Asian Cenozoic Coal-Bearing Sediments: Why Does Indonesia Have Such Extensive Coal Deposits? *International Journal of Coal Geology*, **166**; 2–35
- Gan, H., S. P. Nandi, and P. L. Walker Jr (1972). Nature of the Porosity in American Coals. *Fuel*, **51**(4); 272–277
- Gardner, G. H. F., L. W. Gardner, and A. Gregory (1974). Formation Velocity and Density—The Diagnostic Basics for Stratigraphic Traps. *Geophysics*, **39**(6); 770–780
- Ghosh, S., R. Chatterjee, S. Paul, and P. Shanker (2014). Designing of Plug-In for Estimation of Coal Proximate Parameters Using Statistical Analysis and Coal Seam Correlation. *Fuel*, **134**; 63–73
- Gibbins, J. and H. Chalmers (2008). Carbon Capture and Storage. *Energy Policy*, **36**(12); 4317–4322
- Gonzatti, C., L. Zorzi, I. M. Agostini, J. A. Fiorentini, A. P. Viero, and R. P. Philipp (2014). In Situ Strength of Coal Bed Based on the Size Effect Study on the Uniaxial Compressive Strength. *International Journal of Mining Science and Technology*, **24**(6); 747–754
- Grieser, B. and J. Bray (2007). Identification of Production Potential in Unconventional Reservoirs. *SPE Oklahoma City Oil and Gas Symposium/production and Operations Symposium*; SPE-106623
- Koesoemadinata, R. P. (2002). Outline of Tertiary Coal Basins of Indonesia. *Berita Sedimentologi*, **17**(1); 2–13
- Kokowski, J., Z. Szreder, and E. Pilecka (2019). Reference P-Wave Velocity in Coal Seams at Great Depths in Jastrzebie Coal Mine. *E3S Web of Conferences*, **133**; 01011
- Kuang, N. J., J. P. Zhou, X. F. Xian, C. P. Zhang, K. Yang, and Z. Q. Dong (2023). Geomechanical Risk and Mechanism Analysis of CO₂ Sequestration in Unconventional Coal Seams and Shale Gas Reservoirs. *Rock Mechanics Bulletin*, **2**(4); 100079
- Lepore, S. and R. Ghose (2015). Carbon Capture and Storage Reservoir Properties from Poroelastic Inversion: A Numerical Evaluation. *Journal of Applied Geophysics*, **122**; 181–191
- Li, X. and Z. M. Fang (2014). Current Status and Technical Challenges of CO₂ Storage in Coal Seams and Enhanced Coalbed Methane Recovery: An Overview. *International Journal of Coal Science & Technology*, **1**(1); 93–102
- Lu, Y., C. Li, Z. He, M. Gao, R. Zhang, C. Li, and H. Xie (2020). Variations in the Physical and Mechanical Properties of Rocks from Different Depths in the Songliao Basin under Uniaxial Compression Conditions. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, **6**; 1–14
- Mariucci, M. T., P. Montone, and P. Balossino (2024). Comparative Analysis of Bulk and Velocity-Derived Density Data in Deep Wells in the Adriatic Region (Italy). *Annals Of Geophysics*, **67**(2); GT212–GT212
- Masoudian, M. S., D. W. Airey, and A. El-Zein (2014). Experimental Investigations on the Effect of CO₂ on Mechanics of Coal. *International Journal of Coal Geology*, **128**; 12–23
- McDowell, P. W. (2002). *Geophysics In Engineering Investigations*. The Geological Society
- Muksin, N., D. Yusmen, R. Waren, A. Werdaya, and D. Djuhaeni (2012). Regional Depositional Environment Model of Muara Enim Formation and Its Significant Implication for CBM Prospectivity in South Sumatra Basin, Indonesia*. *American Association of Petroleum Geologists, Search and Discovery Article*; 80272
- Mwakipunda, G. C., Y. Wang, M. M. Mgimba, M. R. Ngata, J. Alhassan, C. N. Mkono, and L. Yu (2023). Recent Advances in Carbon Dioxide Sequestration in Deep Unmineable Coal Seams Using CO₂-Ecbm Technology: Experimental Studies, Simulation, and Field Applications. *Energy & Fuels*, **37**(22); 17161–17186
- Pan, J., Z. Meng, Q. Hou, Y. Ju, and Y. Cao (2013). Coal

- Strength and Young's Modulus Related to Coal Rank, Compressional Velocity and Maceral Composition. *Journal of Structural Geology*, **54**; 129–135
- Pan, R., H. Gao, K. Lei, and Z. Zhu (2015). Quantitative Prediction Of Coalbed Gas Content Based On Seismic Multiple-Attribute Analyses. *Journal Of Engineering & Technological Sciences*, **47**(4)
- Perera, M. S. A. and P. G. Ranjith (2012). Carbon Dioxide Sequestration Effects on Coal's Hydro-Mechanical Properties: A Review. *International Journal of Energy Research*, **36**(10); 1015–1031
- Perez Altamar, R. and K. Marfurt (2014). Mineralogy-Based Brittleness Prediction From Surface Seismic Data: Application To The Barnett Shale. *Interpretation*, **2**(4); T255–T271
- Ramm, M., A. W. Forsberg, and J. S. Jahren (1997). Porosity-Depth Trends In Deeply Buried Upper Jurassic Reservoirs In The Norwegian Central Graben: An Example Of Porosity Preservation Beneath The Normal Economic Basement By Grain-Coating Microquartz. *AAPG Memoir 69: Reservoir Quality Prediction in Sandstones and Carbonates*; 177–199
- Ravnani, A. G., E. L. Ligerio, and S. B. Suslick (2009). CO₂ Sequestration through Enhanced Oil Recovery in a Mature Oil Field. *Journal of Petroleum Science and Engineering*, **65**(3-4); 129–138
- Raymer, L. L., E. R. Hunt, and J. S. Gardner (1980). An Improved Sonic Transit Time-to-Porosity Transform. *SPWLA Annual Logging Symposium*; SPWLA-1980
- Sampath, K. H. S. M., M. S. A. Perera, P. G. Ranjith, and S. K. Matthai (2019). CO₂ Interaction Induced Mechanical Characteristics Alterations in Coal: A Review. *International Journal of Coal Geology*, **204**; 113–129
- Sander, R. (2014). *The Economics of CO₂ Storage in Coal Seams with Enhanced Coalbed Methane Recovery (CO₂-ECBM)-Development of Screening Criteria*. Ph.D. thesis, UNSW Sydney
- Shi, J. Q. and S. Durucan (2005). CO₂ Storage in Deep Unminable Coal Seams. *Oil & Gas Science and Technology*, **60**(3); 547–558
- Speight, J. G. (2015). *Handbook of Coal Analysis*. John Wiley & Sons
- Tarsis, A. D. (2001). Penyelidikan Batubara Bersistem Dalam Cekungan Sumatera Selatan Di Daerah Benakat Minyak Dan Sekitarnya, Kabupaten Muara Enim Propinsi Sumatera Selatan. Technical report, Sub Direktorat Batubara, Jakarta
- Tenthorey, E., T. Richard, and D. N. Dewhurst (2019). A Continuous, Proxy-Based Rock Mechanical Approach for Developing Mechanical Frameworks at CO₂ Storage Sites. *International Journal of Greenhouse Gas Control*, **85**; 36–45
- Ünalın, G. (2010). *Kömür Jeolojisi*. Maden Tetkik ve Arama Genel Müdürlüğü
- Walker Jr, P. L., S. K. Verma, J. Rivera-Utrilla, and A. Davis (1988). Densities, Porosities and Surface Areas of Coal Macerals as Measured by Their Interaction with Gases, Vapours and Liquids. *Fuel*, **67**(12); 1615–1623
- Wang, D., H. Hu, T. Wang, T. Tang, W. Li, G. Zhu, and X. Chen (2024). Difference Between of Coal and Shale Pore Structural Characters Based on Gas Adsorption Experiment and Multifractal Analysis. *Fuel*, **371**; 132044
- Wang, L. L., M. Vandamme, J. M. Pereira, P. Dangla, and N. Espinoza (2018). Permeability Changes in Coal Seams: The Role of Anisotropy. *International Journal of Coal Geology*, **199**; 52–64
- Warren, J. (2002). *Well Logging*. API, USA
- Wu, M., Y. Qin, Y. Zhang, S. Zhu, G. Zhang, F. Lan, and Y. Qin (2023). Influence Factors and Feasibility Evaluation on Geological Sequestration of CO₂ in Coal Seams: A Review. *ACS Omega*, **8**(19); 16561–16569
- Yan, H., J. Zhang, S. S. Rahman, N. Zhou, and Y. Suo (2020). Predicting Permeability Changes with Injecting CO₂ in Coal Seams During CO₂ Geological Sequestration: A Comparative Study Among Six SVM-Based Hybrid Models. *Science of the Total Environment*, **705**; 135941
- Zanetta, E. V., H. Handoyo, F. Fatkhan, A. Laesanpura, and H. Y. Hutami (2021). Analisis Parameter Elastisitas untuk Interpretasi Litologi dan Fluida Pori Reservoir Batupasir Formasi Intra Gumai Cekungan Sumatera Selatan. *Jurnal Geofisika*, **19**(2); 45–50
- Zhang, G., P. G. Ranjith, Z. Li, M. Gao, and Z. Ma (2021). Long-Term Effects of CO₂-Water-Coal Interactions on Structural and Mechanical Changes of Bituminous Coal. *Journal of Petroleum Science and Engineering*, **207**; 109093
- Zhou, B. and G. O'Brien (2016). Improving Coal Quality Estimation Through Multiple Geophysical Log Analysis. *International Journal of Coal Geology*, **167**; 75–92
- Zou, G., Q. Zhang, S. Peng, J. She, D. Teng, C. Jin, and Y. Che (2022). Influence of Geological Factors on Coal Permeability in the Sihe Coal Mine. *International Journal of Coal Science & Technology*, **9**(1); 6