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Analysis of The Coal Depositional Environment on Total Coal Sulphur Content at Pt Baturona Adimulya, Musi Banyuasin Regency, South Sumatra

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ABSTRACT

PT Baturona Adimulya operates an open pit mining system. Field conditions indicate variations in coal quality that influence the overall quality of the coal. This study aims to analyze the relationship between the coal depositional environment and the distribution of total sulfur content, as well as to assess the effect of calorific value on moisture content, ash content, and total sulfur. The study uses petrographic (maceral), ultimate and proximate analysis, as well as interpretation based on the Tissue Preservation Index (TPI) and Gelification Index (GI) methods. The results show that seams S and T are dominated by vitrinite macerals consisting of Telocolinite (Tc) 2.2-10.0% and Desmocolinite (Dc) 78.4-87.0%, while Inertinite ranks second, consisting of Semifusinite (Sf) 8.0%-11.0% and Sclerotinite (Sc) 2.2%. Mineral matter is represented by Pyrite (Py) with a composition of 0.6%. In terms of coal quality, seam S has a total moisture content of 41.76–49.79%, a calorific value of 3,233–3,672 kcal/kg, and a sulfur content of 0.38–1.06%, whereas seam T has a total moisture content of 34.47–49.52%, a calorific value of 1,835–3,777 kcal/kg, and a sulfur content of 1.29–4.15%. Based on the maceral composition analyzed using the TPI and GI methods, the depositional environments of seams S and T are interpreted as transgressive limnic settings within the lower delta plain system. Furthermore, the VI and GWI values indicate that the coal forms in an ombrotrophic peat environment.

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INTRODUCTION

Coal is a fossil fuel formed from organic material through a long process of peat formation, diagenesis, and metamorphism, known as coalification. This process causes physical and chemical changes in peat to lignite, which then progresses to sub-bituminous coal, bituminous coal, and finally anthracite, before finally approaching graphite (O'Keefe et al., 2013). The characteristics of coal sedimented in various basins in Indonesia vary widely, particularly in its inorganic composition. This variation is strongly influenced by the coal's depositional environment. Indonesian coal generally has a low sulfur content (<1.0%), although in some areas, high sulfur content is found locally and does not represent the entire formation or basin (Herudiyanto 2007).

The sulfur content of coal is an important indicator of its quality and economics. High sulfur can form SO_2 during combustion, potentially causing acid rain and environmental damage, so low-sulfur coal has a higher selling price. Understanding the depositional environmental factors that influence sulfur content is important for predicting its quality and economic value early on (Webbink 1978) and (Luppens et al., 2009). Similar relationships between depositional environments and sulfur distribution have also been reported in previous studies, which indicate that marine influence and groundwater fluctuations can contribute to sulfur enrichment in coal (Sari et al., 2017; Dita Maulia n.d 2024). Coal deposit characteristics are divided into five categories based on moisture, pH, hydrogen ion concentration, food availability, and bacterial activity. Depositional environment analysis can be performed using the tissue preservation index (TPI) and gellification index (GI) parameters, which describe the level of tissue preservation and the gelification process of organic material. The TPI and GI values not only provide information on the coal's depositional facies but also relate to its potential sulfur content. Generally, coal formed in marine environments tends to have higher sulfur content, while coal from terrestrial environments tends to have lower sulfur content (Diessel 1992).

Coal quality is strongly influenced by its depositional environment, which is directly related to its total sulfur content, ash content, and calorific value. Higher sulfur content in coal indicates that the coal experienced sedimentation in a marine environment, while lower sulfur content in coal indicates that the coal experienced sedimentation in a terrestrial environment. The higher the ash content, the lower the calorific value of the coal, because calories are needed to burn the impurities in the coal. The higher the total water content in the coal, the lower the calorific value, because calories are needed for the evaporation of water (Bargawa 2012).

PT Baturona Adimulya exhibits variations in coal quality across the study area. Sulfur content is a key parameter affecting coal quality and its economic value; however, the influence of depositional environments on sulfur distribution in the study area has not been comprehensively evaluated. In addition, studies on coal facies using tissue preservation index (TPI) and gelification index (GI) parameters are still limited in this area. Therefore, this study aims to analyze the relationship between depositional environments and total sulfur content in coal at PT Baturona Adimulya. The results are expected to contribute to a better understanding of the geological controls on sulfur distribution and coal quality characteristics in the study area.

METHODOLOGY

This study was conducted at PT Baturona Adimulya, Musi Banyuasin Regency, South Sumatra. Data were collected through field observations, coal sampling, and sedimentary rock sampling from Seam S and Seam T. Coal quality was analyzed using proximate and ultimate analyses to determine moisture content, ash content, calorific value, and total sulfur content. Petrographic analyses of coal and sedimentary rocks were conducted to identify maceral composition, mineral matter, and sediment characteristics.

The depositional environment was interpreted using the TPI and GI proposed by Diessel (1992), as well as the vegetation index (VI) and groundwater index (GWI) proposed by Calder (1991). The results were then correlated with coal quality parameters to evaluate the influence of depositional environments on sulfur distribution and coal quality characteristics.

Regional geology

Regionally, the study area falls within the North Palembang sub-basin, which is part of the South Sumatra Basin. The South Sumatra Basin formed as a result of tectonic activity closely related to the north-to-northeast movement of the Indo-Australian Plate against the relatively stationary Eurasian Plate. The movement of several smaller plates (microplates) within this interaction zone contributed to the formation of various convergence zones of varying directions and shapes (Bishop 2001).

Physiographically, the South Sumatra Basin is divided into four parts: the South Sumatra Basin, the Bukit Barisan Basin, and the Lampung Highlands Basin, which encompasses the offshore area between the Sumatran mainland and the island clusters west of Sumatra, and the forearc ridge west of Sumatra, forming a non-volcanic arc (Luqman et al., 2019). The planned coal mining area of PT Baturona Adimulya is regionally included within the Palembang Geological Map Sheet, with the characteristics of each surrounding formation being the Air Benakat Formation (Tma), Muara Enim Formation (Tmpm), Kasai Formation (QTk), and Alluvial Deposits (Qa).

Tectonic events that play a role in the development of Sumatra Island and the South Sumatra Basin are: Compression Phase or Rifting Phase (Jurassic - Cretaceous), Tensional Phase (Late Cretaceous - Early Tertiary), Sagging Phase (Miocene or Intra Miocene Tectonic Phase) and Compression Phase (Miocene - Pliocene) (Pratiwi et al., 2013). The South Sumatra Basin has a complex tectonic history with transgression and regression cycles that produce a complete stratigraphic sequence starting from the Lahat, Talang Akar, Baturaja, Gumai, Air Benakat, to Muara Enim Formations (Adith et al., 2025).

Maceral analysis

According to Bustin et al. (1983), the liptinite maceral group exhibits a yellowish color due to the hydrogen content in the unsaturated bonds in coal. The fluorescent colors of the macerals decrease with increasing coal rank. Liptinite exhibits fluorescent intensity in low-rank coals. The internitite maceral group (except for micrinite) indicates oxidizing conditions during peat formation. Spores and pollen are commonly produced and preserved in reed and sedge plants in lake swamp environments. Cutinite is usually associated with vitrinite, which originates from wood.

Tissue preservation index and gelification index

The TPI (tissue preservation index) is the ratio between the preserved tissue structure and the altered tissue structure, while the GI (gelification index) is the ratio between the gelified component and the oxidized component (fusinification) (Diessel 1992). The TPI value indicates that the coal originates from woody plants and that the plant tissue is well-preserved. A low GI value indicates a high degree of oxidation. Furthermore, the GI value provides an indication of the dryness or wetness of peat formation conditions, as gelification occurs in humid conditions. It also serves as an indicator of relative pH, as microbial activity requires low acidity.

The TPI–GI analysis can be enhanced with a facies approach that utilizes the integration of well logs and seismic data to map changes in depositional environments (Alifah et al., 2025). Other research in the Jambi Sub-Basin, South Sumatra, also demonstrated the important role of transgression–regression cycles in the formation of delta front facies in the Air Benakat Formation (Utama 2021). Meanwhile, studies of the Oligo–Miocene stratigraphic sequence in Sarolangun link this cycle to the depositional regression process of the Muara Enim Formation (Lubis & Ramli 2021). These findings provide an important framework for understanding variations in coal quality, including sulfur content, at the study site.

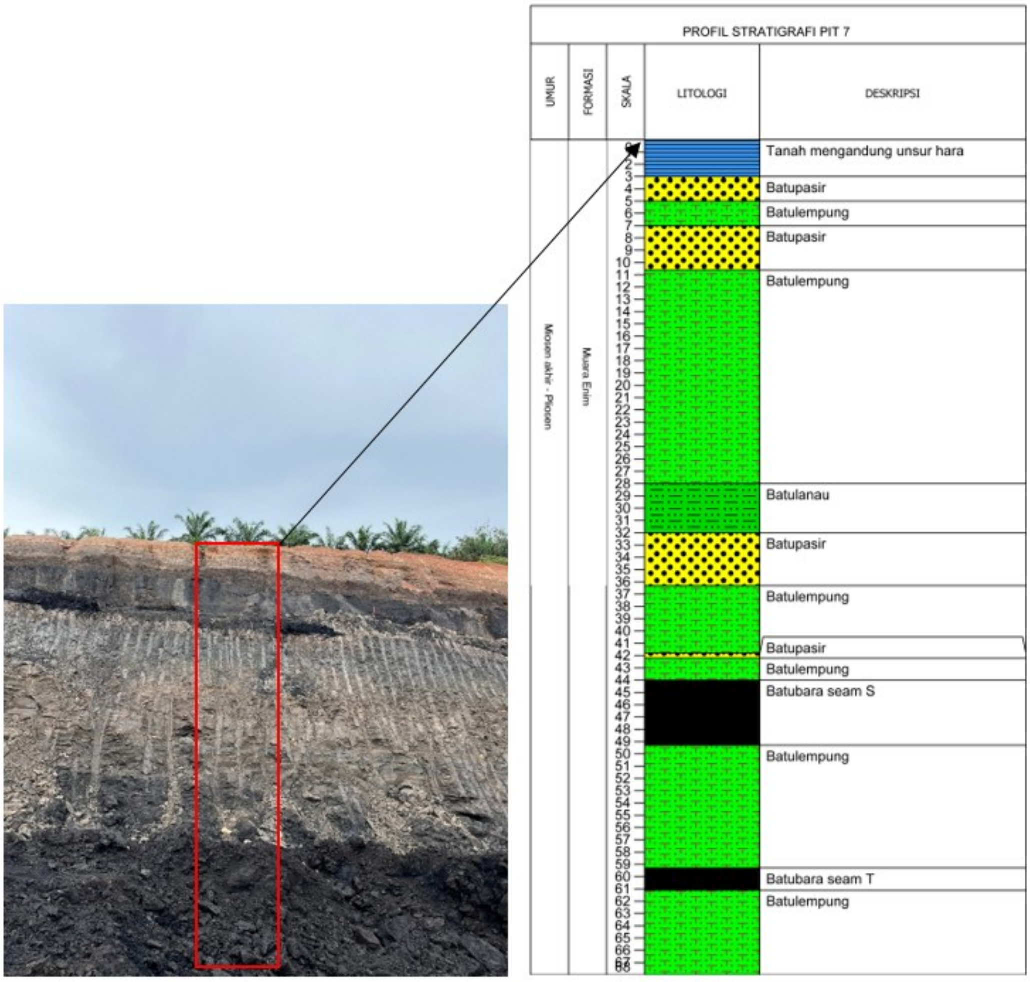
RESULT AND DISCUSSION

Stratigraphy of the research area

The research area is stratigraphically included in the Muara Enim Formation, which is of Late Miocene to Pliocene age. The stratigraphic sequence observed in PIT 7 shows dominant lithology consisting of claystone, sandstone, and coal. The stratigraphic sequence, from roof to floor, consists of topsoil, sandstone, claystone, siltstone, and two coal layers, the S-seam and the T -seam, as seen in (Figure 1). The coal in the S-seam exhibits a brownish-black color with a dull luster, is brittle, and contains pyrite. Meanwhile, the coal in the T-seam exhibits a brownish-black color with a dull to slightly light luster and exhibits brittle properties, as seen in (Figure 2).

Sampling position

This study conducted sampling on seam S and seam T in the PIT 7 area, Muara Enim Formation. Seam S has an average thickness of ± 6 meters and seam T ± 2 meters. Overall, this study collected 20 samples consisting of several types of tests. Of these, 2 samples were used for coal petrography (1 sample each from seam S and seam T) obtained from coal outcrops, then 4 samples were taken for sedimentary petrography (2 samples on seam S were taken from sedimentary rock outcrops and 2 seam T were taken from drill cores) as well as 14 coal quality sample points (7 sample points on



A B

Figure 1. A) Rock Outcrops at the Research Location; B) Stratigraphic Profile

(A) (B)

Figure 2. (A) S Seam Coal (B) T Seam Coal

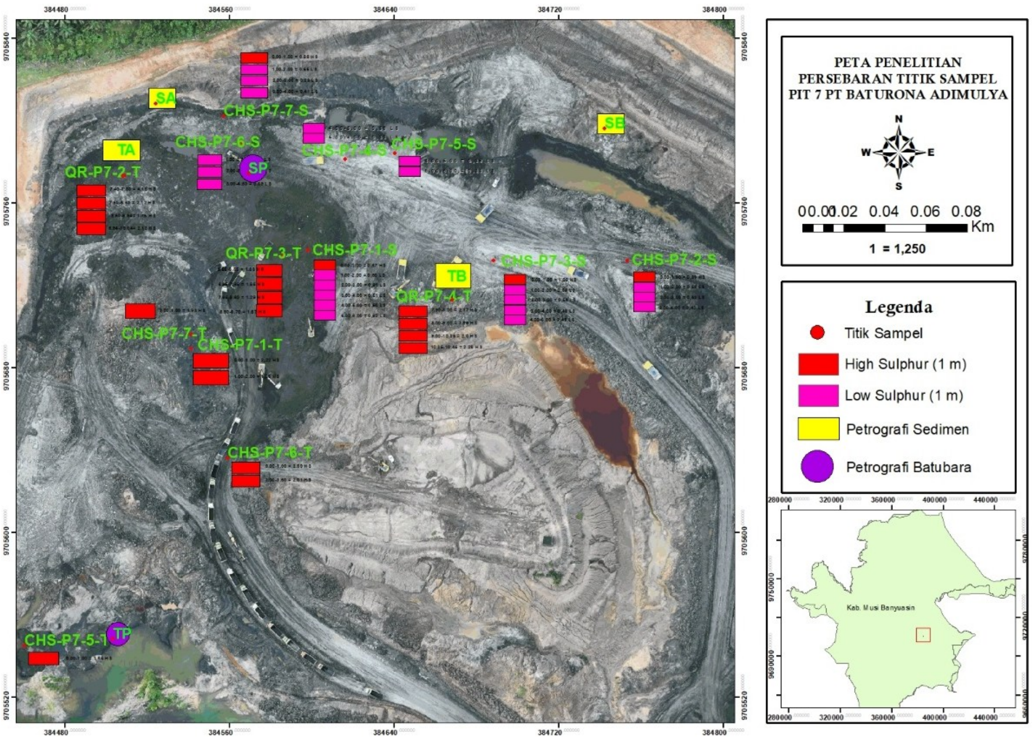


Figure 3. Sample Point Distribution Map

seam S and 7 sample points on seam T were obtained from outcrops and also drill cores). The distribution of sampling locations is shown in (Figure 3).

- Petrography of Sedimentary Rocks

The SA sample is a rock outcrop at the research location showing physical characteristics in the form of dark gray rock with a parallel laminated structure, fine texture, and is easily destroyed when wet, so that macroscopically it is classified as sandstone (Figure 4).

Based on microscopic observation of SA samples, it was done with a total lens magnification of 40x, 10x ocular lens magnification and 4x objective lens. In general, the rock section is brownish gray; clastic texture with a grain size of 1/4-1/8 which is included in the fine sand category; the grain shape is angular to rounded; well sorted; open packing. There are fragments in the form of Plagioclase (Pl) 16%, Opaque (Opq) 10%, Quartz (Qz) 52%, Hornblede (Hbl) 3%, Lithic (Lth) 14%, while the matrix is composed of 15% clay material. Based on the classification of Pettijohn (1975) the name of this rock is Arkose Wacke, which can be seen in the picture (Figure 5). The observed lamination is interpreted to reflect fluctuations in sediment supply and depositional energy during sedimentation. Periods of higher energy favored the deposition of coarser detrital material, whereas lower-energy conditions promoted the accumulation of finer clay-rich sediments.

Rock outcrops at the research site show a lithology consisting of brownish-gray sandstone with claystone intercalations. The sandstone has a fine to medium grain size with a fairly clear parallel layering structure. The claystone intercalations appear darker in color, have a fine texture, and are easily crushed when squeezed, indicating the typical plastic properties of clay, as seen in (Figure 6).

Based on observations on a polarizing microscope with a total lens magnification of 40x, 10x ocular lens and 4x objective lens for the SB sample shows gray to white, brown and black colors; clastic texture with a grain size of 1/4-1/8 mm; grain shape is angular to rounded; open packing (grain supported). There are fragments in the form of Plagioclase (Pl) 19%, Opaque (Opq)

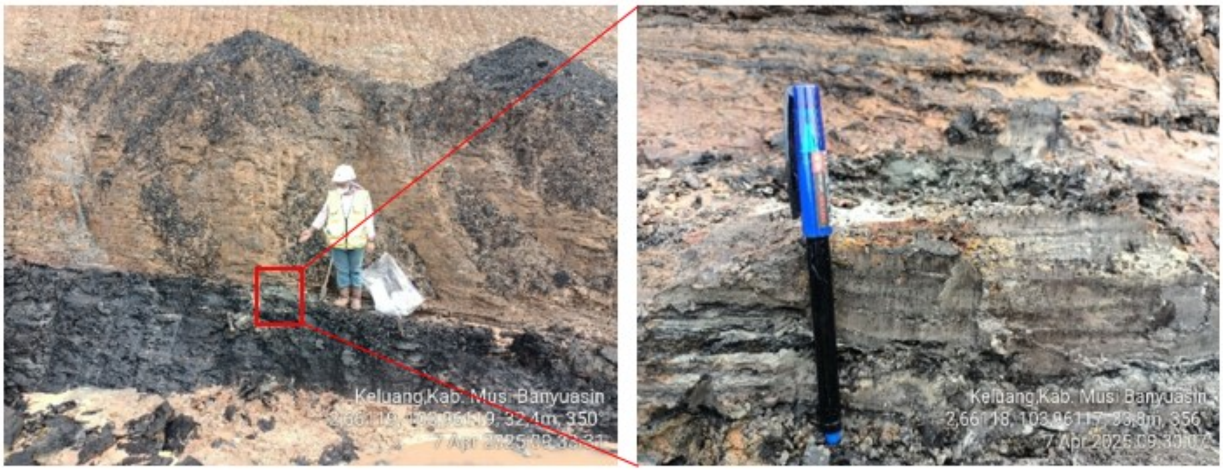


Figure 4. Appearance of sandstone outcrops in the field

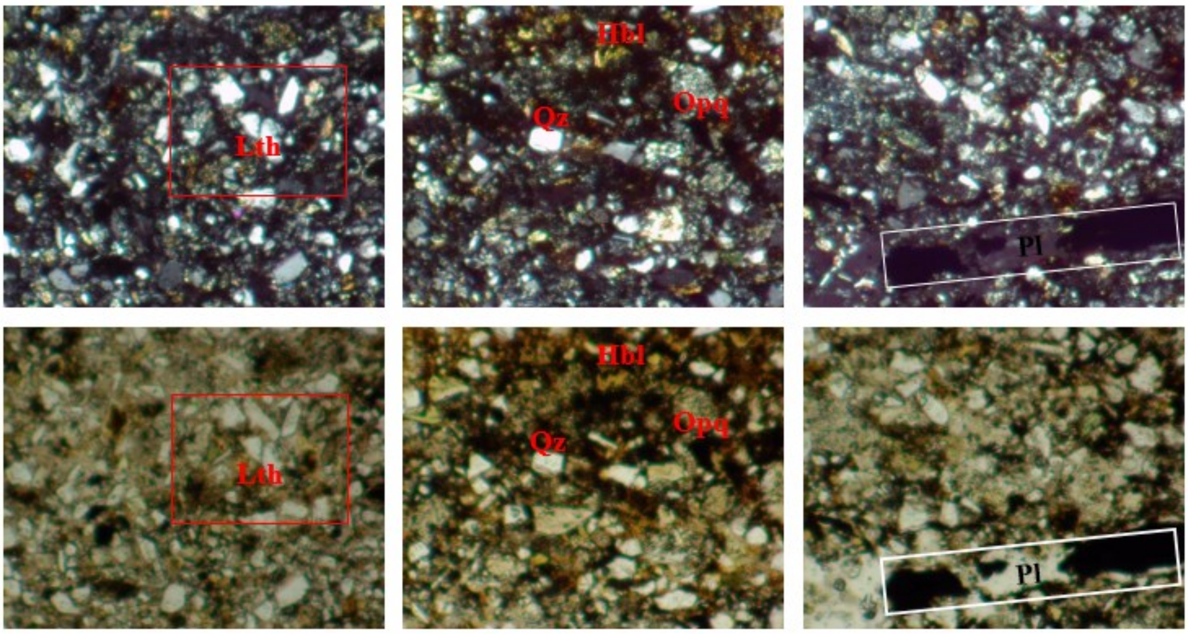


Figure 5. Petrographic appearance of SA section

10%, Quartz (Qz) 46%, Lithic (Lth) 13% and matrix (15%). Based on the classification of Pettijohn (1975) the name of this rock is Arkose Wacke, can be seen in (Figure 7).

Based on Pettijohn's (1975) classification, the rock name for the SA and SB samples is Arkose Wacke. This mineral composition indicates a supply of detrital material originating from land with a relatively high sedimentary energy level. This indicates that sedimentation occurred in the proximal part of the lower delta plain system, such as in the crevasse splay area or the edges of distributary channels (Diessel 1992).

TA samples, when viewed from macroscopic observations, the lithology at a depth interval of 05.44-06.40 m has a dark gray to blackish color, a slightly rough texture, and is plastic when wet, as can be seen in (Figure 8).

Based on observations on a polarizing microscope with a total lens magnification of 40x, 10x ocular lens and 4x objective lens for the TA sample shows a clastic texture with a grain size of 1/64-1/1289 (fine shale); slightly angular grain shape; packed (-). Rock fragments are composed of crystals/minerals in the form of Plagioclase (Pl) 5%, Quartz (Qz) 5%, Opaque (Opq) 5% and

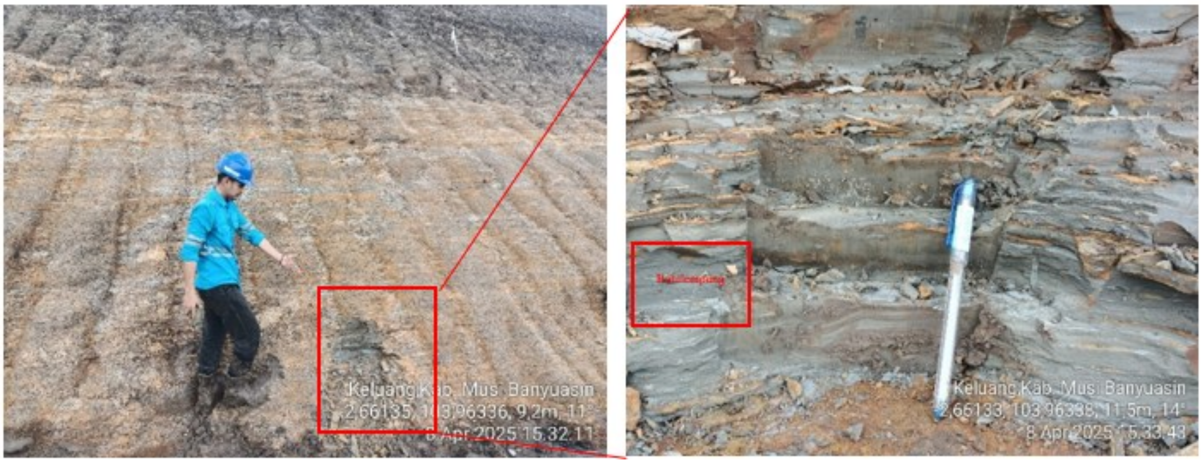


Figure 6. The appearance of sandstone outcrops containing mudstone inserts in the field

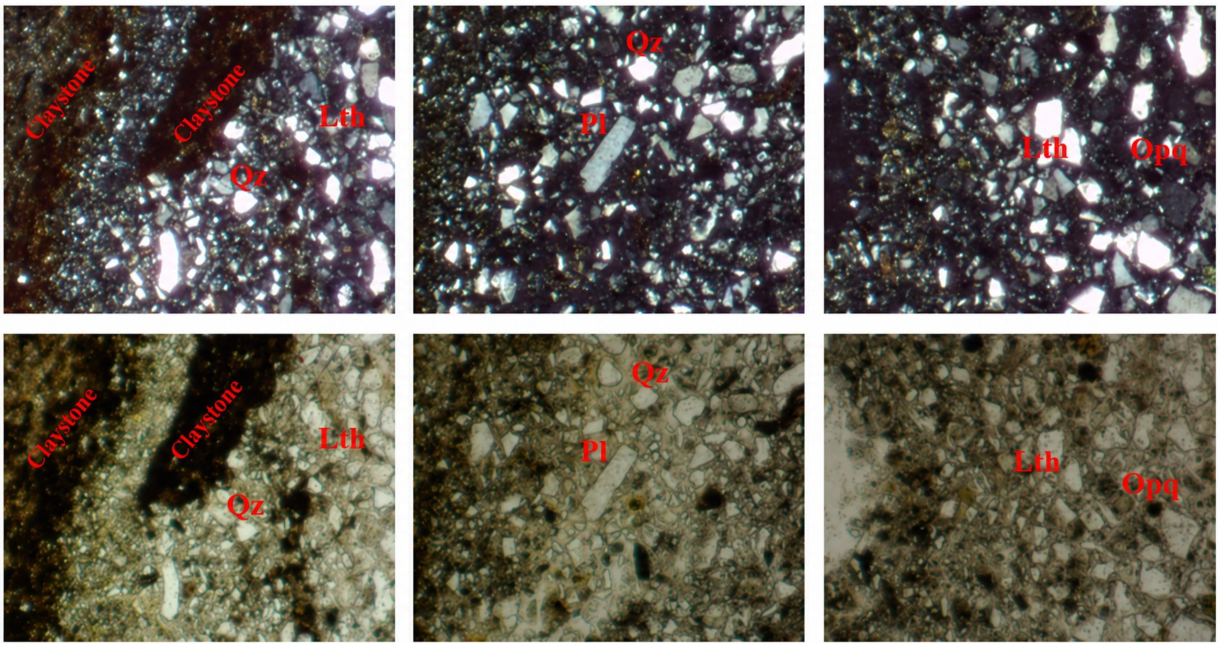


Figure 7. Petrographic appearance of SB section

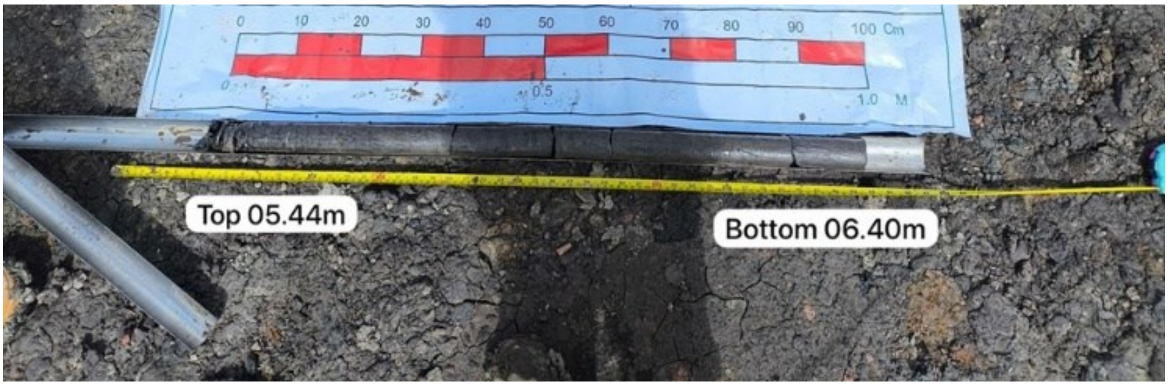


Figure 8. Appearance of shale drill core in the field

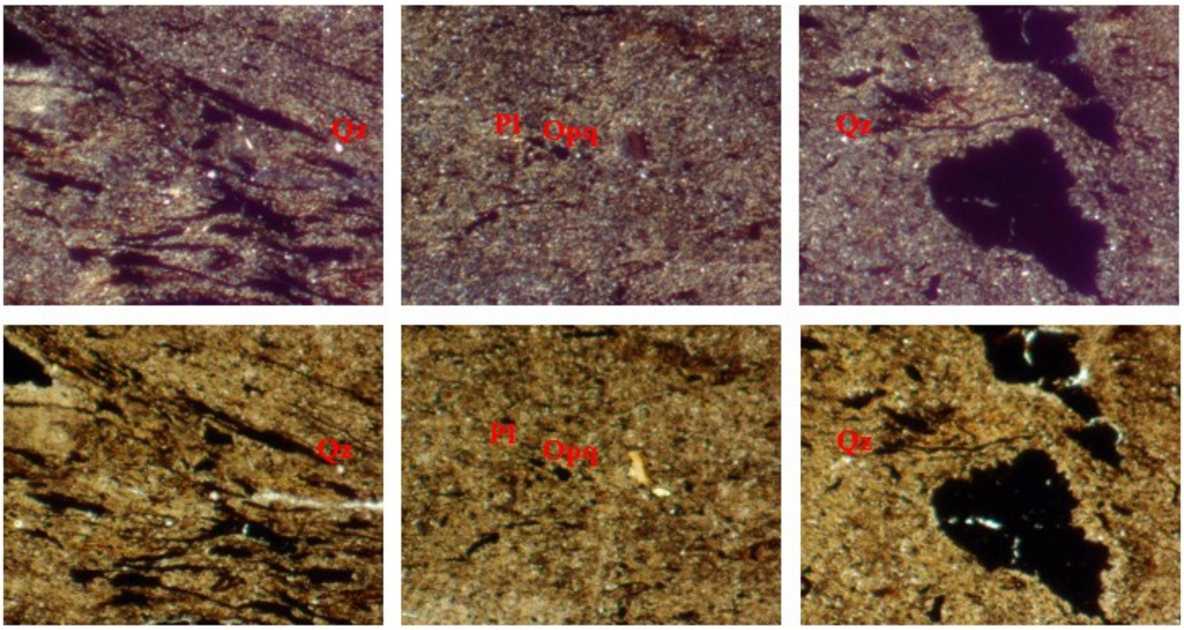


Figure 9. Petrographic appearance of TA section

Matrix 83%. Based on the classification of Pettijohn (1975) this rock is classified as shale, as can be seen in (Figure 9).

The TB sample is a drill core sample that shows a lithological change from sedimentary rock to coal. At a depth of 6.50-7.90 meters, the lithology is dominated by blackish-gray to dark-colored rocks, with a fine texture and plasticity when wet, as seen in (Figure 10). Based on observations on a polarizing microscope with a total lens magnification of 40x, 10x ocular lens and 4x objective lens for TB samples, the dominant color is gray, brown to black; clastic rock texture with a grain size of 1/512-1/1024 mm fine clay, the grain shape is slightly angular to rounded; closed packing (matrix supported). The mineral composition is Plagioclase (Pl) 4%, Quartz (Qz) 6% and Opaque (Opq) 3% and matrix. The remaining 87% is the matrix that binds the clastic grains. Based on the classification of Pettijohn (1975) this rock is classified as mudstone, as can be seen in (Figure 11).

Based on microscopic observations, the TA sample is classified as shale, while the TB sample is classified as mudstone (Pettijohn 1975), indicating fine-grained material deposited in a still-water environment. These rock types reflect more enclosed depositional conditions, such as swamps or interdistributary bays in the lower delta plain (Diessel 1992).

- Coal Petrography

  Based on the results of petrographic analysis using a microscope, in (Figure 12 (A)), Semifusinite (Sf) macerals are seen associated with Desmocolinite (Dc). Semifusinite is present in a percentage of 11.0%, while Desmocolinite dominates with a percentage of 78.4%. Desmocolinite is part of the vitrinite sub-group which originates from the hard part of wood tissue embedded in moist water seepage (Santoso, 2015). Furthermore, in (Figure 12 (B)), Pyrite (Py) minerals are seen together with Telocolinite (Tc) macerals. Pyrite is found in relatively small amounts, around 0.6%, but its presence is important for understanding coal genesis. Meanwhile, Telocolinite has a percentage of 10.0% and belongs to the vitrinite sub-group.

In (Figure 13 (A)), the presence of Semifusinite (Sf) macerals associated with Pyrite (Py) and Desmocolinite (Dc) is visible. Semifusinite was found at 8.0%, while pyrite was found in small amounts of 0.6% and Desmocolinite remained dominant with a percentage of around 87%. Then, in (Figure 13 (B)) Desmocolinite (Dc) macerals were again clearly associated with Sclerotinite (Sc). Sclerotinite was present in small amounts of around 2.2%, and is part of the inertinite group which originates from the same plant parts as vitrinite, but differs in its coalification process. Inertinite macerals are formed from fire, oxidation by microbial activity and dehydration in an aerobic environment as well as biochemical changes (Santoso 2015).

- Coal Quality

  The depositional environment is a key factor influencing the coal formation process. To interpret this influence, coal quality analysis is performed using four parameters: total moisture content (TM), ash content (ASH), calorific value (CV), and total sulfur (TS). These four parameters are interrelated in providing an overview of coal characteristics, as can be seen in Table 1.

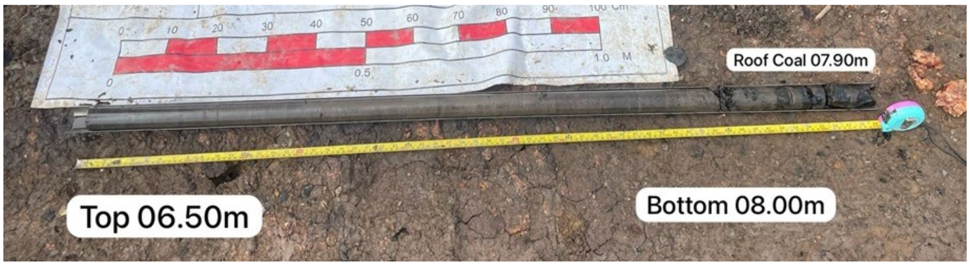


Figure 10. Appearance of claystone drill core in the field

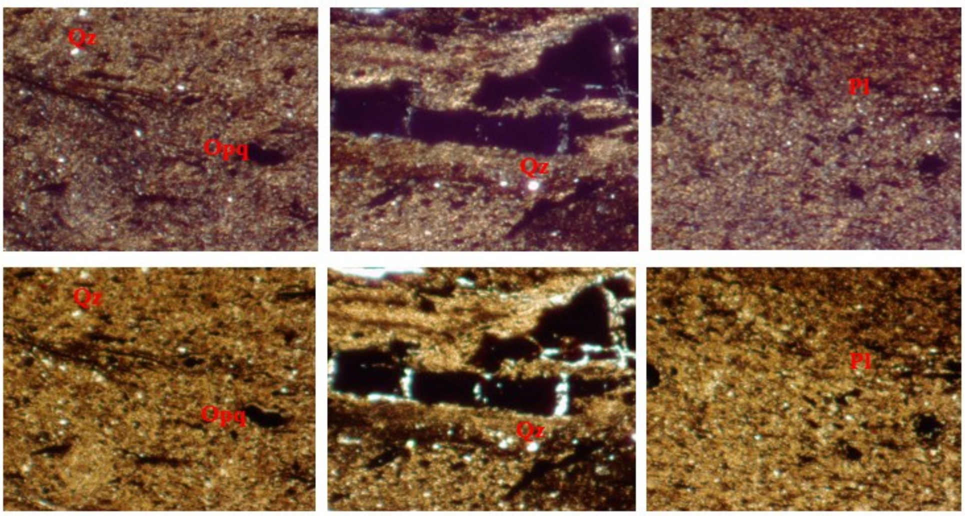


Figure 11. Petrographic appearance of TB section

Table 1. Results of coal quality analysis of Seam S and Seam T.

Kualitas Batubara Seam S							
No	**Kode Sampel**	**% As received**		**% Air dried basis**			
		TM	**CV**	**IM**	**ASH**	**TS**	**CV**
1	CHS-P7-1 A	46,81	3.405	17,67	4,82	0,87	5.270
2	CHS-P7-1 B	46,18	3.392	16,94	4,48	0,65	5.235
3	CHS-P7-1 B	47,95	3.341	20,41	4,99	0,61	5.108
4	CHS-P7-1 C	49,19	3.313	22,54	3,91	0,51	5.051
5	CHS-P7-1 D	49,79	3.275	22,75	4,26	0,50	5.038
6	CHS-P7-1 E	49,31	3.251	20,63	4,69	0,62	5.090
7	CHS-P7-1 F	47,53	3.403	18,70	4,77	0,89	5.273
8	CHS-P7-2 A	45,70	3.521	15,79	5,24	0,58	5.460
9	CHS-P7-2 B	45,90	3.401	16,18	6,71	0,43	5.269
10	CHS-P7-2 C	45,79	3.561	17,37	4,49	0,43	5.428
11	CHS-P7-2 D	47,99	3.263	20,65	5,16	1,06	4.978
12	CHS-P7-3 A	47,99	3.263	20,65	5,16	1,06	4.978
13	CHS-P7-3 B	45,51	3.511	15,04	4,67	0,66	5.474
14	CHS-P7-3 C	49,00	3.233	22,02	5,47	0,54	4.944
15	CHS-P7-3 D	47,93	3.264	20,55	4,80	0,46	4.980
16	CHS-P7-3 E	43,98	3.369	14,26	8,44	0,45	5.157
17	CHS-P7-4 A	41,76	3.672	11,41	5,65	0,82	5.586
18	CHS-P7-4 B	45,81	3.376	16,25	5,87	0,52	5.218
19	CHS-P7-5	44,83	3.485	15,21	5,53	0,62	5.356
20	CHS-P7-6 A	45,36	3.500	15,68	5,97	0,43	5.402
21	CHS-P7-6 B	47,69	3.389	18,86	4,43	0,53	5.257
22	CHS-P7-6 C	47,82	3.380	20,46	4,85	0,59	5.152
23	CHS-P7-7 A	46,95	3.433	19,21	4,75	0,88	5.227
24	CHS-P7-7 B	47,15	3.399	19,28	5,74	0,55	5.191
25	CHS-P7-7 C	46,25	3.522	17,56	4,13	0,38	5.402
26	CHS-P7-7 D	46,83	3.432	18,04	4,83	0,41	5.291

Table 1. Results of coal quality analysis of Seam S and Seam T. (Continued)

Kualitas Batubara Seam T							
27	CHS-P7-1 A	40,40	3.777	9,52	2,80	2,22	5.734
28	CHS-P7-1 B	43,25	3.556	13,14	3,54	1,55	5.442
29	QP7-2-RC1	34,47	1.835	1,60	50,19	4,15	2.755
30	QP7-2-BC1-A	43,61	3.251	13,08	14,46	2,12	5.012
31	QP7-2-BC1-B	46,52	3.487	18,32	5,37	1,76	5.326
32	QP7-2-FC1	45,78	3.474	17,35	5,98	2,12	5.295
33	QP7-3-RC	43,88	3.234	15,06	14,71	1,83	4.895
34	QP7-3-BC1-A	47,25	3.337	20,48	7,44	1,55	5.030
35	QP7-3-BC1-B	48,91	3.329	21,72	5,13	1,29	5.101
36	QP7-3-FC	49,52	3.273	23,39	5,20	1,57	4.967
37	QP7-4-RC	47,04	3.300	18,74	8,45	2,17	5.063
38	QP7-4-BC1-A	48,12	3.254	20,27	8,25	1,89	5.000
39	QP7-4-BC1-B	46,01	3.490	17,53	6,02	2,00	5.330
40	QP7-4-FC	37,82	2.429	5,22	38,14	2,28	3.702
41	CHS-P7-5	45,54	3.409	15,95	5,77	1,84	5.261
42	CHS-P7-6-A	44,61	3.529	15,74	4,70	3,80	5.368
43	CHS-P7-6-B	45,94	3.346	15,27	8,38	2,01	5.245
44	CHS-P7-7	48,60	3.407	21,17	4,00	1,93	5.226

Table 2. TPI and GI values of the research area

Sampel	TPI	GI
SP	0,27%	8036%
TP	0,14%	8745%

Relationship between depositional environment and total sulfur content based on TPI-GI

The depositional environment of coal can be represented by a tissue preservation index (TPI-GI). The Tissue Preservation Index (TPI) shows the ratio of preserved tissue structure to decomposed tissue structure. The Gelification Index (GI) is the ratio of gelified components to fusinized components. The results of the TPI and GI values for S seam and T seam research show that the TPI values are close to each other, namely 0.1-0.2% and the GI value is 8% (Table 2).

The results of plotting the TPI and GI values of seam S and seam T on the Diessel Diagram indicate coal in a limnic depositional environment. Limnic is a dome-shaped peat or raised bog where the peat is mostly submerged in water and the water table follows the development of the dome. The water table is the boundary between the water-saturated zone (submerged in water) and the water-unsaturated zone (dry), as can be seen in (Figure 14).

Based on the TPI–GI analysis (Diessel 1992), the S seam and T seam are located in a transgressive

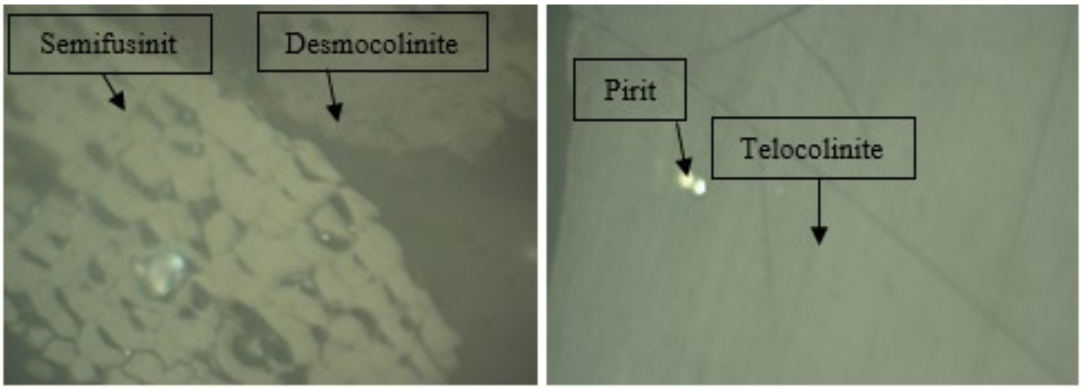


Figure 12. Maceral and mineral appearance in SP Sample: (A) semifusinite and desmocolonite; (B) pyrite and telocolinite.

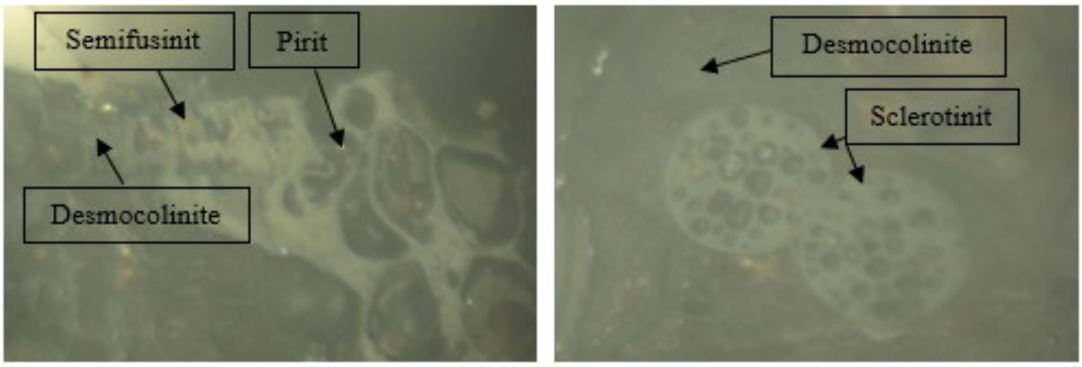


Figure 13. Maceral and mineral appearance in TP Sample: (A) semifusinite, desmocolinite and pyrite; (B) desmocolinite and sclerotinite.

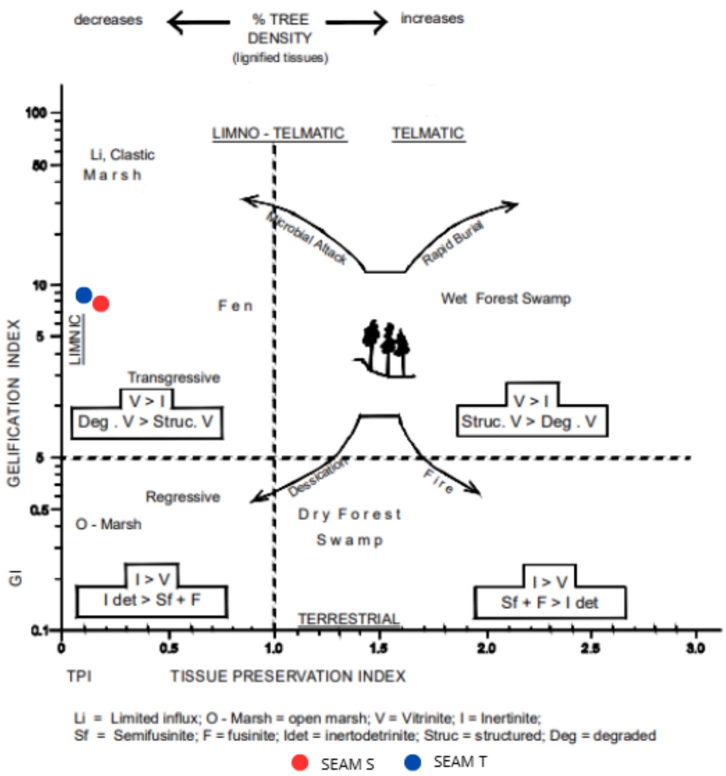


Figure 14. Plotting results on the TPI-GI diagram (Diessel 1992).

limnic zone, which describes a freshwater swamp in a continental environment affected by sea level rise (transgression). This transgression process can occur through limited seawater intrusion or groundwater level rise triggered by regional sea level changes. This intrusion brings sulfate ions (SO_4^{2-}) into the swamp, which under reducing conditions will be reduced by sulfate-reducing bacteria to pyrite (FeS_2), thereby increasing the sulfur content of the coal.

In this study, GI appears to have a greater influence on sulfur accumulation than TPI. Although both seams show relatively similar TPI values, the consistently high GI values indicate waterlogged peat conditions that favor gelification processes and sulfate reduction. These conditions enhance pyrite formation and sulfur enrichment within the coal seam. Therefore, sulfur distribution in the study area is interpreted to be more strongly influenced by GI than by TPI.

The effect of vegetation and groundwater level on total sulfur content in coal

To determine the type of peat in the depositional environment, one method can be used, namely the diagram introduced by Calder (1991), which uses two parameters, namely the level of groundwater influence and the degree of vegetation. The level of groundwater influence is expressed as GWI (ground water index), which states the comparison between strongly gelified components, usually vitrinite macerals formed from decaying tissue in wet conditions, to weakly gelified components, namely inertinite and oxidized plants. The degree of vegetation is expressed as VI (Vegetation Index), which is used to describe the type of coal-forming plants, whether dominant forests of trees and woods or marginal aquatic vegetation such as swamps, shrubs and aquatic plants.

The calculated GWI and VI values for seam S and seam T are shown in Table 3 as a reference for interpreting the facies and types of coal-forming peat. Plotting VI and GWI values on a Calder diagram (1991) indicates that the Seam S and Seam T coals are located in the ombrotrophic zone (Figure 15). Based on previous interpretations of the TPI and GI diagrams, the coal deposition occurred in a limnic environment, a stagnant freshwater swamp. Under these conditions, the peat should be rheotrophic, meaning it is rich in nutrients. However, the VI-GWI diagram shows ombrotrophic peat, which is nutrient-poor and dominated by herbaceous vegetation.

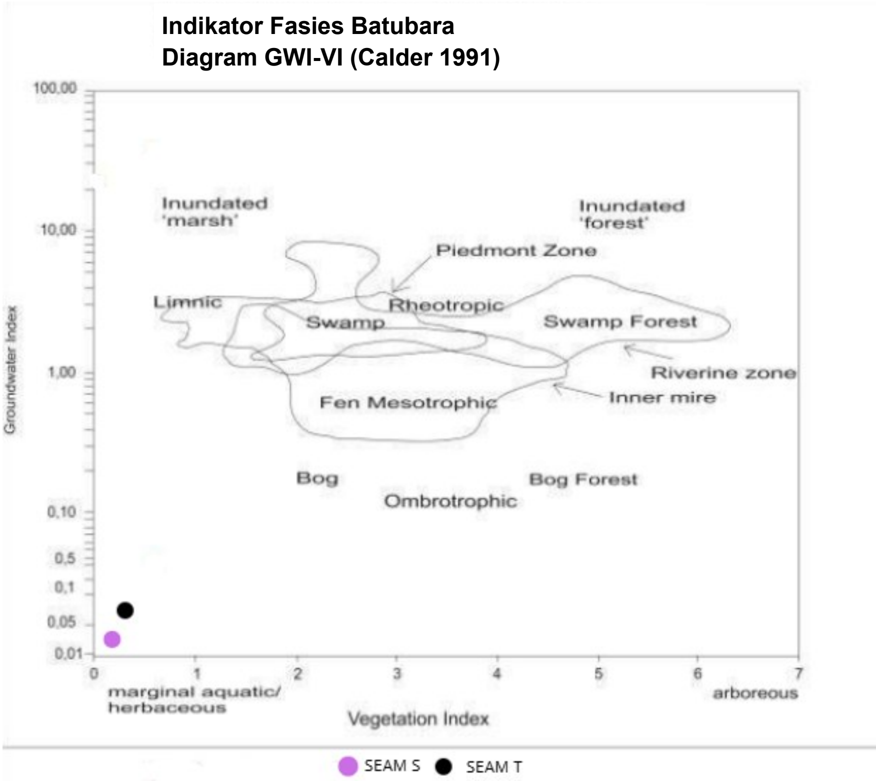


Figure 15. Results of plotting the GWI-VI diagram (Calder 1991)

While this may seem contradictory, the limnic (waterlogged swamp) conditions of ombrotrophic peat are not uncommon. This occurs because when upland peat forms, the water table rises, following the peat surface. During the rainy season, this inundation creates conditions similar to limnic (waterlogged) conditions, as the water source remains primarily rain, resulting in a nutrient-poor, or ombrotrophic, environment. This phenomenon is commonly found in Indonesian geological history and is in line with research by (Anggayana et al., 2014) and (Amijaya & Littke 2005).

Swamp or herbaceous vegetation rich in organic matter and sulfate tends to produce coal with a high sulfur content, due to the plant tissue being more easily decomposed and the availability of sulfate ions from the aquatic environment. Conversely, hardwood and nutrient-poor vegetation produces coal with a lower sulfur content (Wiranata et al., 2019). In addition to vegetation, the water table also significantly influences sulfur formation. A water-saturated environment (high water table) creates anaerobic conditions that support the activity of sulfate-reducing bacteria to form the mineral pyrite (FeS_2), thereby increasing the total sulfur content. Conversely, under low and oxidative conditions, pyrite formation is reduced, leading to a lower total sulfur content. This reaction causes changes in the total sulfur content of each coal seam (Chou 2012).

The relationship between calorific value and total sulfur, total moisture content and Ash content in coal

- Total sulfur

  The correlation between the calorific value and total sulfur in the S-seam is shown in (Figure 16), with a coefficient of determination of R2=0.0005. This value indicates a very weak correlation between the two parameters, with only 0.05% of the variation in calorific value being explained by changes in sulfur content. In other words, changes in sulfur content in the S-seam do not significantly affect the calorific value of coal; instead, it is controlled by other factors such as ash content, moisture content, and organic composition.

Table 3. GWI and VI values of the research area.

Sampel	GWI	VI
SP	0,034%	0,117%
TP	0,006%	0,267%

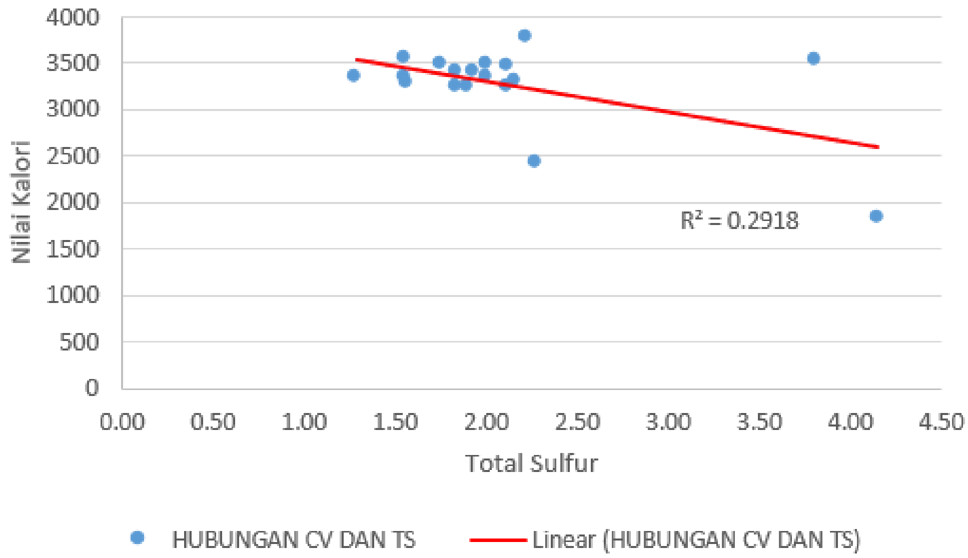


Figure 16. The relationship between calorific value and total sulfur in Seam S coal.

The relationship between calorific value and sulfur in the T-seam is shown in (Figure 17), with a coefficient of determination of R2=0.2918. This value indicates that approximately 29.18% of the variation in calorific value can be explained by changes in sulfur content, while the remaining 70.82% is influenced by factors other than sulfur content. This relationship is negative, meaning that an increase in sulfur content tends to be followed by a decrease in the calorific value of the coal.

When compared with seam S (R2=0.0005) and seam T (R2=0.2918), a difference in the relationship between sulfur content and calorific value is observed in the two seams. This difference indicates changes in depositional environmental conditions, namely changes in the influence of seawater during deposition. Higher total sulfur values reflect stronger seawater influence during deposition, while lower sulfur values indicate decreasing marine influence (Pamekas et al., 2019). Consequently, sulfur accumulation in seam S is lower (<1%) and its variation is not directly related to calorific value. This finding confirms that the intensity of transgressive influence in transgressive limnic environments plays a significant role in determining sulfur content. Although both seams formed in the lower delta plain environment, differences in sulfur levels between them also affect the energy quality of the coal. Furthermore, high sulfur content not only reduces calorific value but also has the potential to cause significant environmental impacts.

- Total water content

  In (Figure 18) shows that the coefficient of determination R2 is 0.6696, which indicates that approximately 66.96% of the variation in calorific value can be explained by changes in total water content, while the remaining 33.04% is influenced by other factors such as ash content, sulfur and other elements. The relationship between the two variables is negative, which means that the higher the total water content, the lower the calorific value of the coal. This is in accordance with the basic properties of coal, where high water content can reduce combustion efficiency because water does not contribute to energy release, but instead absorbs some of the energy during evaporation

In (Figure 18) the graph shows the relationship between the calorific value and total water content in the T seam with a coefficient of determination value of R^2=0.4542. This value indicates that approximately 45.42% of the variation in calorific value can be explained by changes in total water content, but the relationship between the two is not very strong. In general, the positive relationship seen in this graph is likely caused by variations in other factors such as ash and sulfur content, because

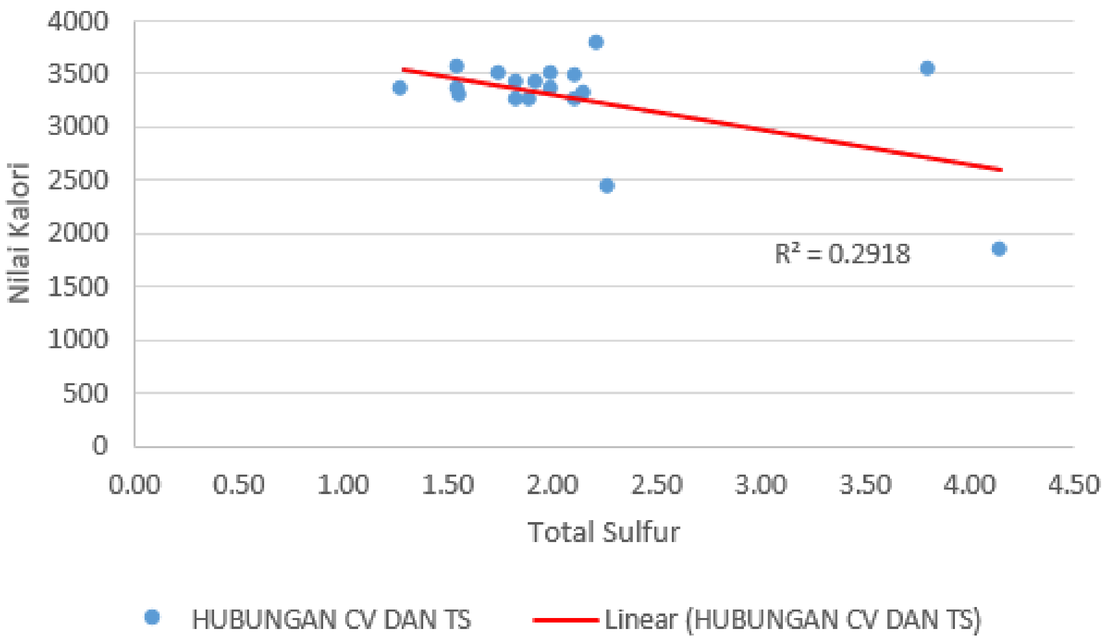


Figure 17. The relationship between calorific value and total sulfur in Seam T coal

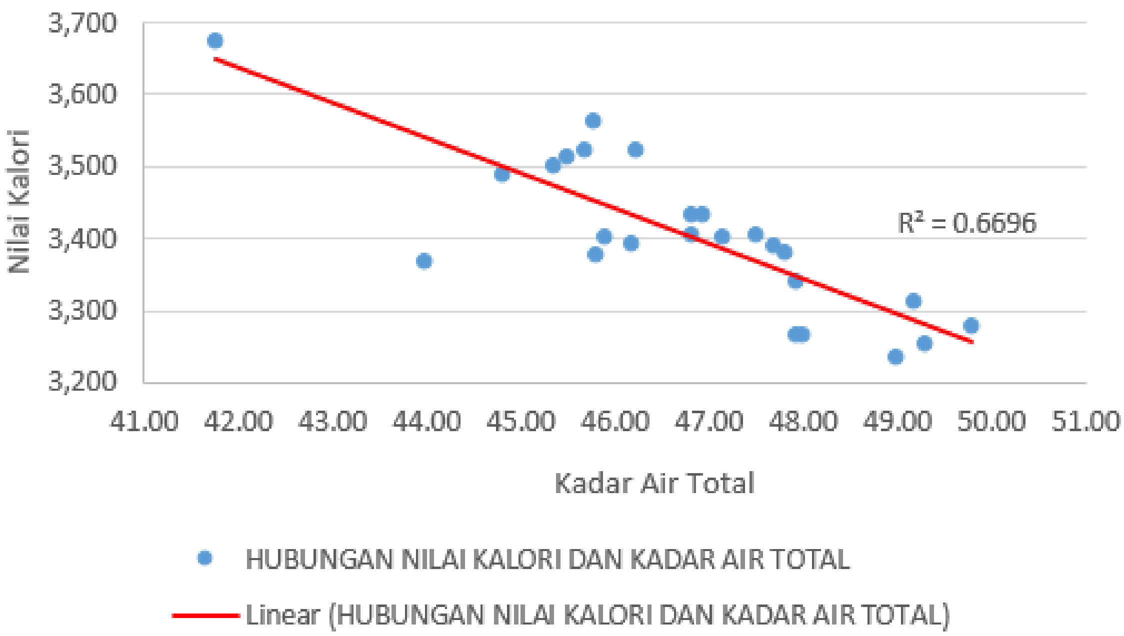


Figure 18. The trend of the relationship between calorific value and total water content of Seam S.

theoretically high water content tends to reduce the calorific value of coal.

The difference in correlation between calorific value and total water content in seam S and seam T indicates variations in depositional environmental conditions. Seam S formed during a weaker transgression phase in a transgressive limnic environment of the lower delta plain (Anggayana et al., 2014). Under these conditions, the swamp is relatively isolated from marine influences, resulting in high porosity and low permeability of the peat. These conditions allow water content to persist more easily until the coalification stage, thus contributing significantly to the reduction in calorific value. Conversely, seam T formed during the peak transgression phase with stronger marine influences, resulting in greater transport of fine clastic minerals and sulfur into the peat. The presence of these materials increases the mineral matter content and affects the density and porosity of the coal (Amijaya & Littke 2005) and (Talla 2018). In addition to impacting coal quality, water content also directly influences aspects of coal mining and management.

- Ash Content

  Calorific value is a primary indicator of coal quality because it reflects the energy released during combustion. In general, ash content plays a role in reducing the calorific value because inorganic materials do not produce energy (Sukandarrumidi 2009). In seam S (Figure 20), the relationship between ash content and calorific value is very weak, with a coefficient of determination (R^2) of 0.0035. This value indicates that only about 0.35% of the variation in calorific value can be explained by ash content. This condition indicates that ash content does not have a significant effect on calorific value. This is likely due to the low input of inorganic minerals during the weak transgression phase, so other factors such as water content or coal maturity play a greater role in controlling calorific value (Amijaya & Littke 2005).

In contrast, in seam T (Figure 21), the relationship between ash content and calorific value shows a very strong negative correlation with R^2=0.9462. Increasing ash content significantly decreases the calorific value of coal. The high ash content in this seam is likely related to depositional conditions during the peak transgression phase, when the supply of fine clastic material and inorganic minerals to the peat was more intense. This finding is in line with research by (Amijaya & Littke 2005) and (Talla 2018) which explains that mineral matter content plays a significant role in reducing coal quality in swamp environments affected by transgressive processes.

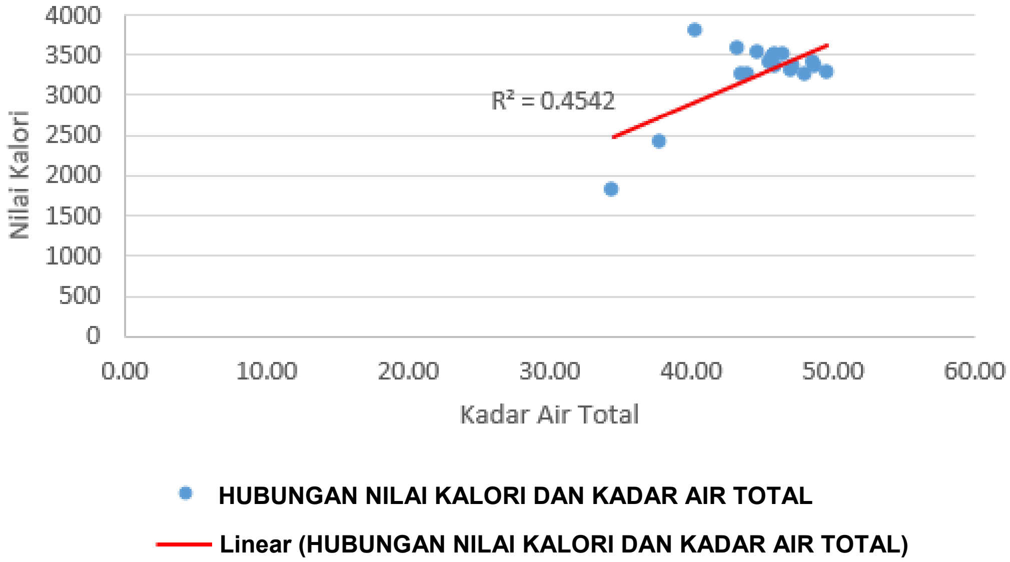


Figure 19. Trend of the relationship between calorific value and total water content of Seam T.

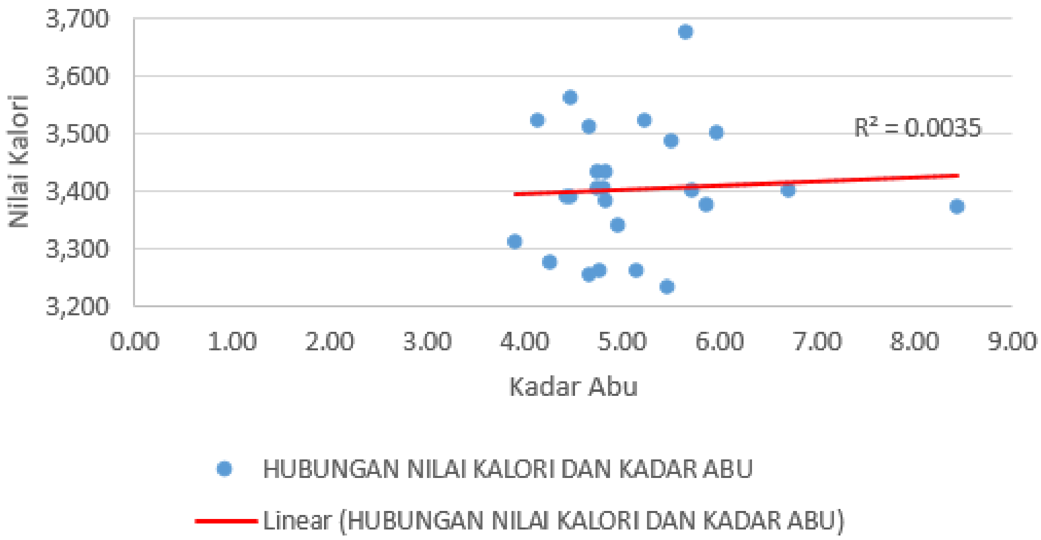


Figure 20. Trend of relationship between calorific value and ash content in Seam S

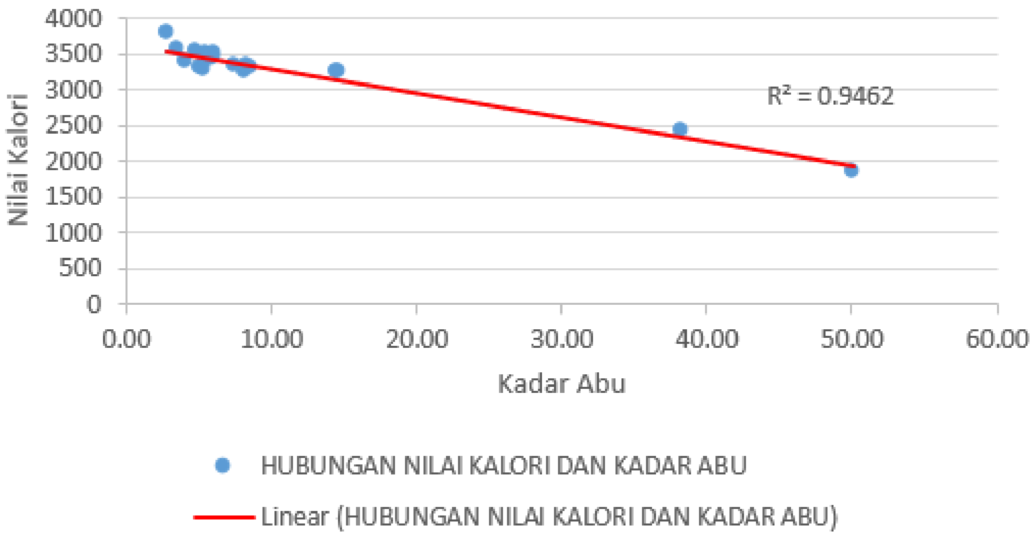


Figure 21. Trend of relationship between calorific value and ash content in Seam T.

Thus, the differences in the characteristics of the relationship between ash content and calorific value between seam S and seam T reflect variations in the intensity of transgression within a single depositional system. Seam S formed under conditions with minimal input of mineral impurities, resulting in a relatively small effect of ash content on calorific value. Conversely, seam T records a stronger transgressive phase, which led to an increased supply of fine clastic material and the accumulation of inorganic minerals within the peat layer. These conditions make ash content a primary controlling factor in coal quality in seam T. In addition to influencing energy value, ash content also has important implications for environmental aspects and mining activities, such as the potential for increased solid waste from combustion and coal processing costs.

Overall, the variations in the relationship between calorific value and total sulfur, total water content, and ash content in seam S and seam T indicate the influence of different depositional environments. Seam S formed during a weak transgressive phase with low clastic input, resulting in a high water content but low sulfur and ash content, while seam T formed during a strong transgressive phase, enriching both sulfur and ash. This confirms that the characteristics of the depositional environment play a significant role in determining coal quality in the study area.

CONCLUSION

Based on the tissue preservation index (TPI) and gelification index (GI) values of coal and sedimentary petrography data, S and T seam coals were formed in a transgressive limnic environment that supports sulfur accumulation due to seawater intrusion and reductive conditions. Based on the Vegetation Index (VI) and Ground Water Index (GWI), coal forms in the ombrotrophic zone, which causes changes in the total sulfur content in each coal seam. Based on the analysis, the relationship between calorific value and total sulfur, total water content, and ash content in S-seam and T-seam coal indicates the influence of different depositional environments. S-seam, formed during the weak transgression phase, is characterized by high water content and low sulfur and ash content, while T-seam, formed during the strong transgression phase, shows increased sulfur and ash content.

Further research is recommended to identify the forms of sulfur (organic and inorganic) in coal. This is important because each form has a different origin and influences the potential for environmental pollution and the characteristics of the coal and Further research should expand the scope to include technical aspects of mining and environmental management, so that research findings can be applied to efficient, safe, and sustainable coal mining systems.

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DECLARATION

Author contribution

I.N. Azizah: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing original draft, writing review & editing. H.W. Utama: Supervision, conceptualization, methodology, validation, writing review & editing. J. Wiratama: Supervision, methodology, validation, writing review & editing.

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Competing interest

The authors declare that this research was conducted independently and that no financial or personal interests influenced the design, analysis, or reporting of the study.

The use of AI or AI-Assited

During the preparation of this manuscript, the authors used ChatGPT and Grammarly solely to improve the quality, clarity, and grammatical accuracy of the English language. The use of these AI-assisted technologies was limited to language refinement and did not influence the research design, data collection, data analysis, interpretation of results, or the scientific conclusions presented in this manuscript. The authors carefully reviewed and verified all revisions and assume full responsibility for the accuracy and integrity of the final manuscript.

GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Description	Unit
TPI	Tissue Preservation Index	
GI	Gelification Index	
VI	Vegetation Index	
GWI	Groundwater Index	
ASTM	American Society for Testing and Materials	
Opq	Opaque	
Qz	Quartz	
Lth	Lithic	
Sf	Semifusinite	
Dc	Desmocolinite	
Sc	Sclerotinite	
Tc	Telocolinite	
Py	Pyrite	
XPL	Cross-Polarized Light	
PPL	Plane-Polarized Light	
TM	Total Moisture Content	
ASH	Ash Content	
TS	Total Sulphur	
CV	Calorie Value	

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