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Coal Quality Distribution Analysis Based on Gamma Ray Log and Gamma-Gamma Ray Log in Area X, East Kalimantan

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ABSTRACT: This study was conducted in East Kalimantan with the objectives of identifying lithology from geophysical well-logging data, analysing the continuity of coal seams, analysing the distribution of coal quality based on proximate parameters, analysing the relationship between the most dominant proximate parameters and calorific value, and determining the rank of the coal. The data used included gamma-ray and density logs, lithological data from drilling, and proximate analysis data. Lithological interpretation was performed by integrating log responses with drilling data, while seam continuity was analyzed through borehole correlation. The results indicate that the study area consists of soil, silt, sand, mudstone, siltstone, coal, carbonaceous material, coaly shale, and sandstone. Correlation analysis identified six coal seams: S1, S2, S3, S4A, S4B, and S5. Coal quality analysis shows that Seam S4A has the highest Total Moisture (18.72%), Inherent Moisture (13.31%), and Fixed Carbon (41.40%). Seam S3 contains the highest Ash content (15.47%), Seam S2 has the highest Volatile Matter (42.55%), and Seam S5 records the highest Total Sulfur (3.55%) and Calorific Value (5887 kcal/kg adb). Correlation analysis reveals that ash content is the most influential proximate parameter affecting calorific value, showing a negative relationship: increasing ash content decreases calorific value. Based on ASTM D388 classification, seam S5 is classified as high-volatile C bituminous coal, whereas seams S1, S2, S3, S4A, and S4B are classified as subbituminous A coal.

KEYWORDS: coal quality, proximate analysis, gamma ray and density log

I. INTRODUCTION

Coal is one of the fossil fuel energy sources that remains widely utilised owing to its high economic value and energy potential. Coal quality is a critical factor in its utilisation, as it directly affects combustion efficiency, calorific value, and coal rank. Quality is generally determined through proximate analysis, which encompasses total moisture, inherent moisture, ash content, volatile matter, fixed carbon, total sulphur, and calorific value (Sukandarrumidi, 2006). Variations in these parameters can result in differences in coal quality across individual seams.

To understand these quality variations, information regarding subsurface conditions and coal seam characteristics is required. One commonly employed method is geophysical well logging, particularly gamma ray log and density log, which are capable of identifying lithology, coal seam boundaries, and seam continuity between boreholes (Lyanda et al., 2020). This information serves as a basis for analysing the spatial distribution of coal quality and the inter-seam relationships within the study area.

Several previous studies have assessed coal quality using proximate analysis and geophysical well-logging methods. Widodo and Anshariah (2017) conducted a coal quality analysis using moisture content, ash content, volatile matter, fixed carbon, and calorific value parameters, demonstrating that variations in these parameters influence calorific value and coal rank; higher moisture and ash contents tend to reduce calorific value, while increased fixed carbon contributes to higher calorific value. Subsequently, Amijaya and Harijoko (2019) characterized coal through proximate, ultimate, and petrographic analyses, showing that coal quality can be used to determine maturity level and coal rank. From a geophysical perspective, Khasanah et al. (2019) demonstrated that the combination of gamma ray log and density log is effective in identifying coal layers and their enclosing lithologies based on differences in rock physical responses. The same method was employed by Yuwanto et al. (2024) to interpret subsurface conditions and perform coal seam correlation, thereby obtaining information on seam continuity and spatial distribution. Furthermore, Nurlaili and Wibowo (2025) showed that coal quality in each seam may differ due to variations in geological conditions and the content of impurity materials affecting proximate parameters. Nevertheless, studies integrating coal seam interpretation based on geophysical well logging, coal quality distribution analysis, coal rank classification, and identification of the most dominant proximate parameter influencing calorific value remain relatively limited.

This study aims to identify lithology and analyze coal seam continuity based on geophysical well logging data, as well as to determine the distribution of coal quality using proximate analysis parameters comprising total moisture, inherent moisture, ash content, volatile matter, fixed carbon, total sulphur, and calorific value. Additionally, this study was conducted to determine the proximate parameter most significantly influencing calorific value and to classify coal rank based on the ASTM D388 standard.

A. GEOLOGY OF THE STUDY AREA

Regionally, the study area is included in the Samarinda geological map sheet, as shown in **Figure 1.**

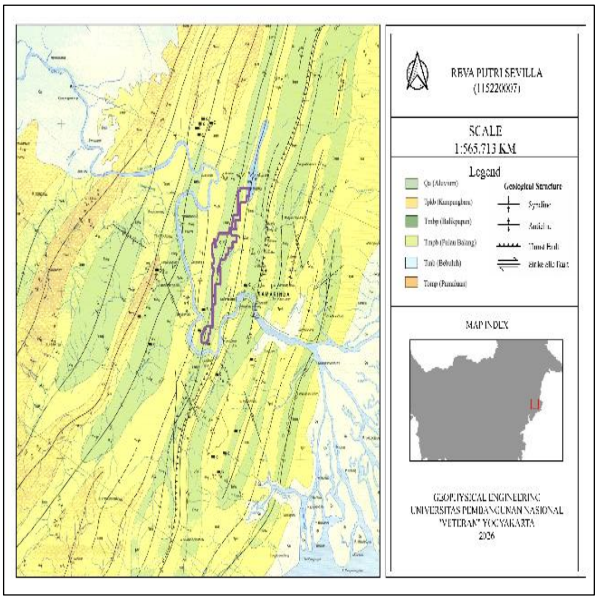


Figure 1. Regional geological map modified from the Samarinda sheet (Satyana, 1999); the purple line denotes the boundary of the data area.

The study area is situated within the Kutai Basin, one of the largest sedimentary basins in Indonesia, composed of Tertiary deposits with a total thickness of approximately 14.000 m (Jamaluddin & Rahmawati, 2024). This basin was formed as a result of extensional processes along the southern margin of the Eurasian Plate and constitutes one of the major hydrocarbon and coal-producing basins in Indonesia (Allen & Chambers, 1998). Geologically, the study area belongs to the Pulaubalang Formation, which is dominated by coarse to very coarse sandstone interbedded with claystone and coal layers deposited in a fluvial to deltaic environment as shown in **Figure 2**. The presence of coal layers within this formation indicates depositional conditions rich in organic material, which has the potential to form coal seams with varying quality characteristics (Amijaya & Harijoko, 2019).

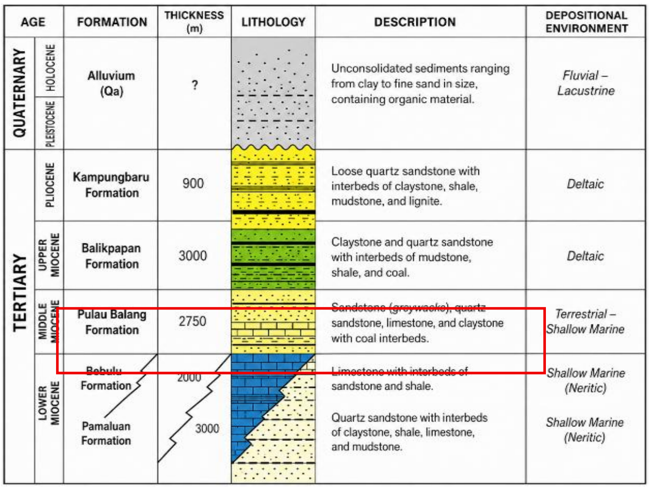


Figure 2. Stratigraphic column of the study area within the Kutai Basin; the red box indicates the formation of the study area (Sukardi et al., 1995).

II. RESEARCH METHODS

Well logging is a method of measuring physical properties of rocks as a function of borehole depth, intended to obtain continuous subsurface characteristic information (Sunarti et al., 2020) as shown in **Figure 3**.

The gamma ray log is employed to measure the natural gamma radiation emanating from radioactive elements in the rocks along the borehole (Lai et al., 2022). Elevated gamma ray values generally indicate clay-rich lithologies such as shale or claystone, whereas low values correspond to lithologies such as sandstone and coal (Sunarti et al., 2020). These contrasting responses are exploited to identify coal layers and differentiate them from the enclosing rocks.

The gamma-gamma ray log (density log) is used to measure rock density by utilizing a gamma radiation source (Rahmayanti et al., 2019). Its operating principle is based on the emission of gamma rays into the rock formation and the measurement of energy returning to the detector following interaction with electrons in the rock. The greater the energy reduction recorded at the detector, the higher the density of the rock (Sunarti et al., 2020).

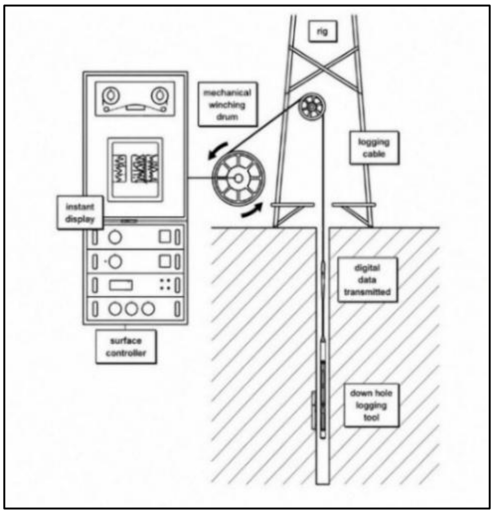
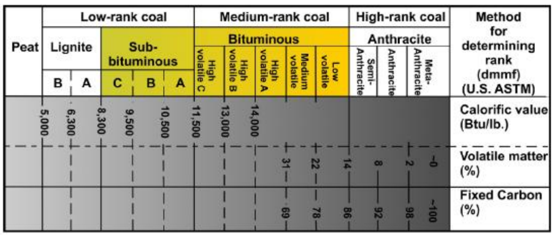


Figure 3. Logging process (BPB, 1981).

Coal quality refers to the physical and chemical characteristics that determine its economic value and potential for utilization as an energy source. Quality is generally evaluated through proximate analysis comprising moisture, ash content, volatile matter, fixed carbon, and calorific value (Sukandarrumidi, 2006). In addition to quality evaluation, proximate parameters also serve as the basis for coal rank classification according to the ASTM D388 standard (Salsabilla et al., 2022), as presented in **Table 1.**

Table 1. Schematic diagram illustrating coal classification and ranking (ASTM, 1999), modified after Kentucky Geological Survey (Sajid et al., 2022).



This study utilized geophysical well logging data from 7 boreholes to identify lithology and subsurface characteristics, as presented in **Figure 4.** However, coal quality distribution analysis was performed on only 6 boreholes, as one borehole lacked proximate analysis quality data. The spatial distribution of boreholes exhibits considerable variation in spacing, ranging from 1 m between DH02 and DH02R (indicating a redrill operation) to 591 m between DH06 and DH07.

Table 2. Geophysical well logging values for lithological interpretation at each borehole.

Based on the interpretation results at borehole DH01, as shown in **Figure 5**, a siltstone lithology was identified at the depth interval of 12.80–13.60 m, with moderate gamma ray and density values of 30 CPS and 2.3 gr/cc, respectively. At the interval of 13.60–17.35 m, mudstone was identified with high gamma ray and density values exceeding 50 CPS and 3 gr/cc. Furthermore, a coal seam was identified at borehole DH01 at a depth interval of 17.35–17.75 m with a thickness of approximately 0.40 m. This seam exhibits a low gamma ray response (0–15 CPS) and a density value of 1.8–2.0 gr/cc, reflecting the characteristic properties of coal with relatively

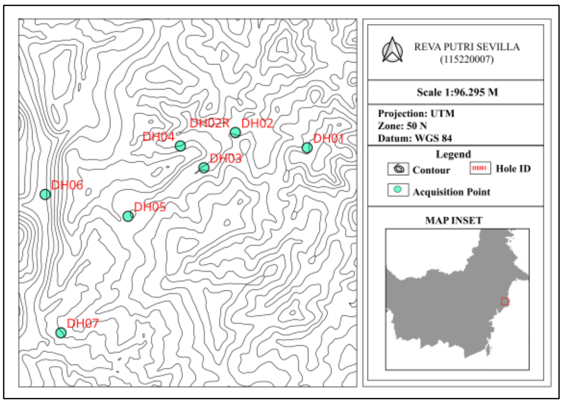


Figure 4. A map of the research survey design, with blue dots indicating the research drilling sites

The data employed in this study include survey data comprising borehole ID and coordinates, core data consisting of depth and lithological descriptions, and geophysical well logging data in the form of gamma ray and density logs for subsurface lithological identification. Proximate analysis data comprising total moisture, inherent moisture, ash content, volatile matter, fixed carbon, total sulphur, and calorific value were also utilized to analyze quality distribution and determine coal rank in the study area.

III. RESULTS AND ANALYSIS

A. Geophysical Well Logging Analysis Results

Lithological interpretation was performed using a combination of gamma ray log and density log to differentiate coal layers from the enclosing rocks. Coal is characterized by low gamma ray values (<15 CPS) and low density (1.2–1.8 gr/cc), whereas enclosing rocks such as mudstone generally exhibit higher gamma ray and density values. Based on these characteristics, both logs were employed to identify lithology and coal seam boundaries, as summarized in **Table**

No	**Classificatio n**	***Gamm a* Ray (Cps)**	***Density* (gr/cc)**	**Litholog y**
1	Very Low	<15	<1.8	Coal
2	Low	15–30	2 – 2.2	Sandston e
3	Medium	30–50	2.2–2.3	Siltstone
4	High	>50	>2.3	Mudston e

low density. In the lower portion of the log (interval 58.60–60.20 m), sandstone was identified, exhibiting low gamma ray values (30 CPS) but high density (>2.3 gr/cc).

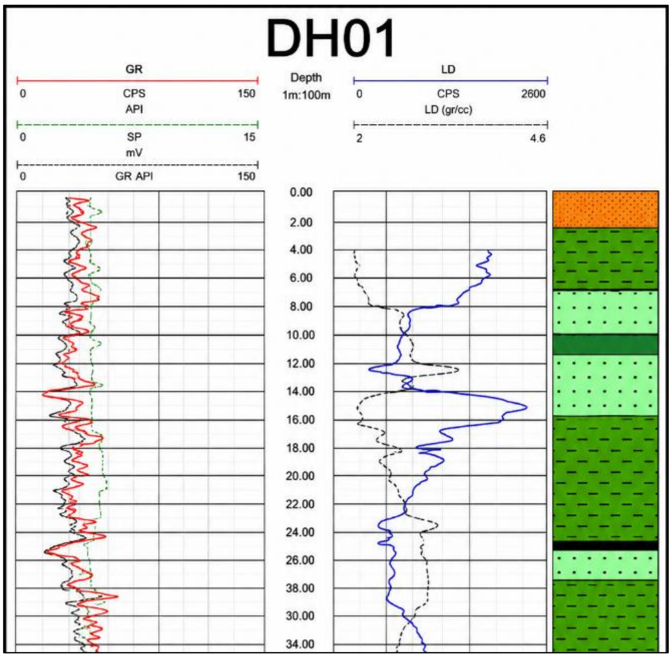


Figure 5. Lithological interpretation at borehole DH01 based on gamma ray log and density log values.

B. Coal Seam Continuity Analysis Results

Coal seam correlation is conducted primarily to ensure the continuity of coal layers between drill holes. Through correlation, it can be determined whether a seam is the same layer, has thinned, thickened, or split.

On-strike coal seam correlation is performed to ensure the continuity of the coal seam along the strike direction, as the seam may thin, be interrupted, transform into carbonaceous material, or be replaced by non-coal lithology

Interpretation of geophysical well logging data reveals that the study area contains five principal coal seams, namely Seam S1, S2, S3, S4, and S5. Splitting was observed in Seam S4, causing it to be

divided into Seam S4A and Seam S4B due to the presence of a parting layer between them. To determine the continuity and spatial distribution of coal seams in the study area, on-strike and on-dip correlations were conducted between boreholes.

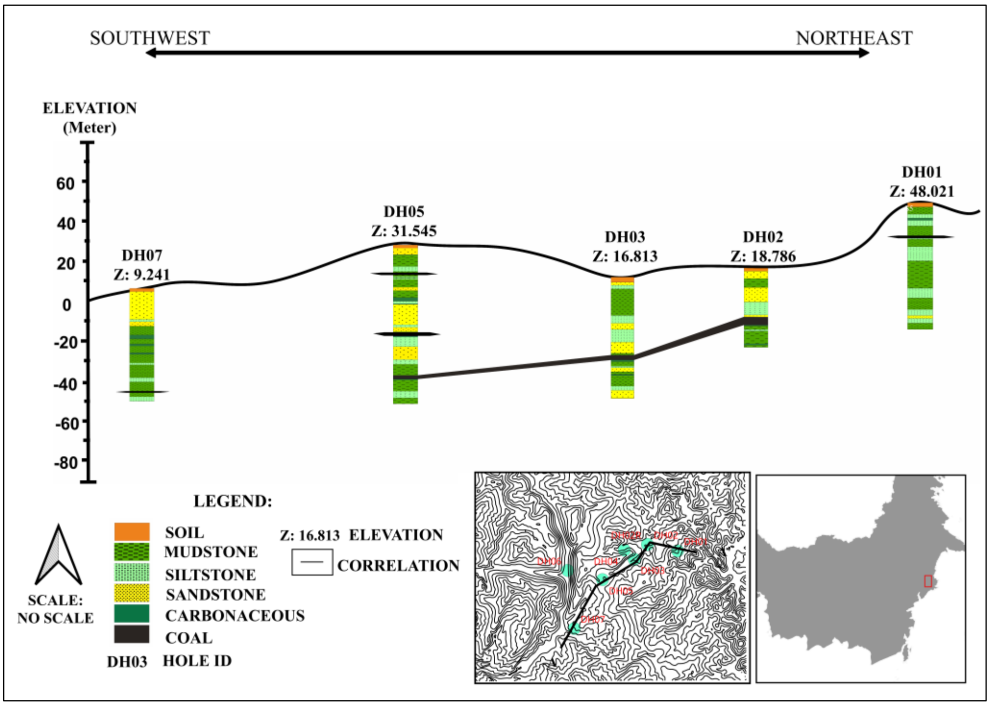


Figure 6. On-strike coal seam correlation along section A–A’ comprising boreholes DH07, DH05, DH03, DH02, and DH01 oriented from southwest to northeast; the continuous black line indicates the continuity of Seam S4.

Section A–A', as presented in **Figure 6**, represents the on-strike correlation among boreholes DH01, DH02, DH03, DH05, and DH07. The results indicate that only Seam S4 is continuous throughout the section, making it the most suitable reference seam (marker seam). Meanwhile, Seams S2 and S3 were not identified at DH02 and DH03, suggesting that these seams do not extend toward the locations of these two boreholes, presumably due to thinning to the point of disappearance (pinch-out) or replacement by parting or non-coal lithology.

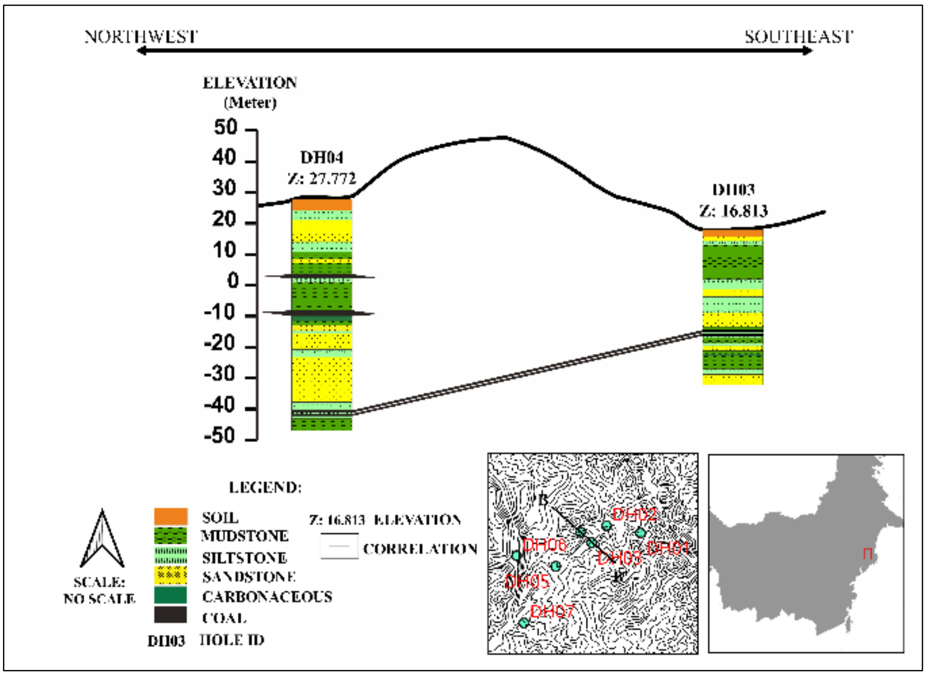


Figure 7. On-dip coal seam correlation along section B–B' comprising boreholes DH03 and DH04 oriented from southeast to northwest; the continuous black line indicates the continuity of Seam S4.

Cross-section B–B' between DH03 and DH04 with a spacing of 136 m, as illustrated in **Figure 7**, reveals increasingly apparent inter-seam relationships, particularly for Seam S4, which begins to exhibit splitting, as evidenced by the appearance of Seams S4A and S4B. This splitting generally occurs in the central to southeastern portion of the section, indicating changes in depositional environmental conditions such as the influx of non-coal material. However, no correlation was established for Seams S2 and S3 in this section, confirming that S2 and S3 undergo thinning or transition to non-coal material at DH03.

C. Coal Quality Distribution Analysis Results

Coal quality distribution analysis was conducted for all seams identified in the study area using proximate parameters comprising total moisture (TM), inherent moisture (IM), ash content, volatile matter (VM), fixed carbon (FC), total sulphur (TS), and calorific value (CV). However, the discussion in this study is focused on Seams S2, S3, S4A, and S4B, as Seams S1 and S5 were identified at only one borehole each, and the available data are therefore insufficient to characterize spatial quality distribution patterns.

The iso-quality map for Seam S2, as presented in **Figure 8**, indicates that coal quality is predominantly developed in the northwestern to central portions of the study area, particularly around DH04, DH05, and DH06. Total moisture and inherent moisture values range from 15.90–16.50% and 12.40–12.43%, respectively, with a tendency to increase toward the northwest. Ash content ranges from 5.74–7.76% and is relatively higher around DH05–DH06, indicating greater accumulation of inorganic material. Meanwhile, volatile matter, fixed carbon, total sulphur, and calorific value range from 42.68–43.05%, 36.78–39.18%, 2.67–3.96%, and 5512–5697 kcal/kg, respectively. The highest values of volatile matter, fixed carbon, and calorific value are concentrated around DH04, where the highest total sulphur values are also found. In Seam S2, the central portion of the study area exhibits higher coal quality than the northwestern portion, as reflected by higher calorific values and carbon content with relatively lower ash content.

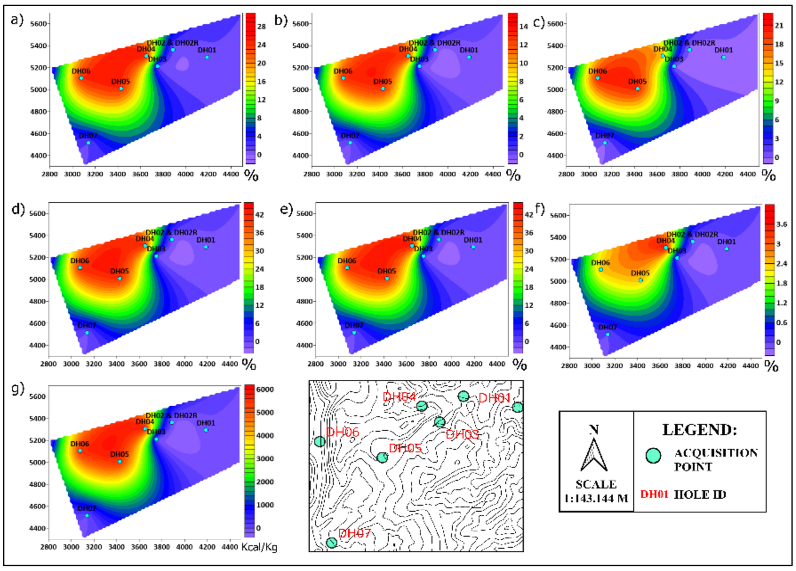


Figure 8. Iso-quality maps for Seam S2 encompassing the following parameters: a) Total Moisture, b) Inherent Moisture, c) Ash Content, d) Volatile Matter, e) Fixed Carbon, f) Total Sulphur, g) Calorific Value.

The iso-quality map for Seam S3, as presented in **Figure 9**, similarly shows that coal quality is predominantly developed in the central to northwestern portions of the study area, particularly around DH04, DH05, and DH06. Total moisture and inherent moisture values range from 16.44–23.00% and 12.06–13.62%, respectively, with a tendency to increase toward the northwest. Ash content ranges from 10.95–21.69% and reaches its highest value around DH05, indicating greater accumulation of inorganic material in the central portion of the study area. Volatile matter, fixed carbon, total sulphur, and calorific value range from 34.44–38.97%, 31.19–38.65%, 1.03–2.12%, and 4782–5106 kcal/kg, respectively. The highest values of volatile matter and fixed carbon are concentrated around DH06, while the highest total sulphur and calorific values are found at DH04. The northwestern portion exhibits higher organic material content, whereas the central portion shows relatively better calorific values. However, the elevated ash content around DH05 results in relatively lower coal quality at that location compared with other areas.

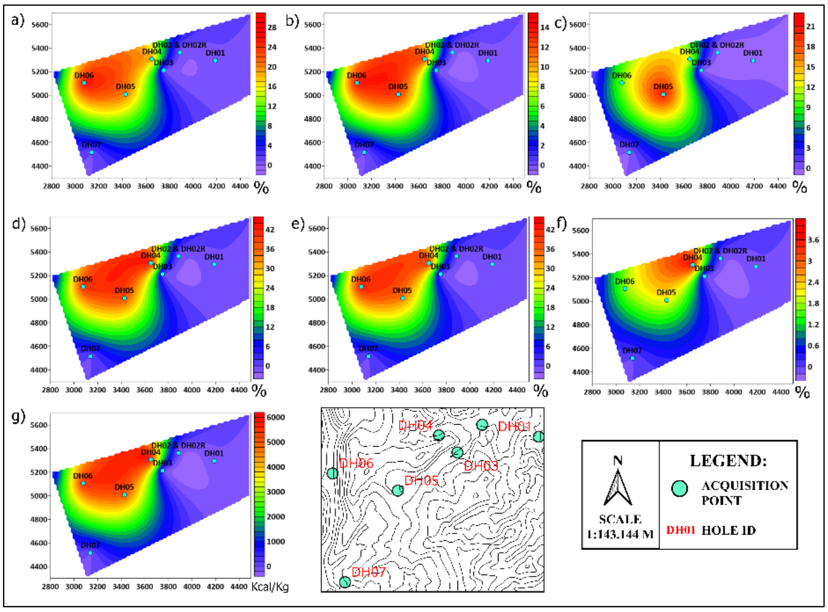


Figure 9. Iso-quality maps for Seam S3 encompassing the following parameters: a) Total Moisture, b) Inherent Moisture, c) Ash Content, d) Volatile Matter, e) Fixed Carbon, f) Total Sulphur, g) Calorific Value.

The iso-quality map for Seam S4A, as presented in **Figure 10**, shows the coal quality distribution at boreholes DH02, DH02R, DH03, DH04, DH05, and DH06. Total moisture and inherent moisture values range from 15.81–28.69% and 12.92–13.68%, respectively, with total moisture values exhibiting an increasing tendency toward the northwest. Ash content ranges from 2.19–7.10% and is generally low, indicating that Seam S4A is less influenced by inorganic material compared with other seams. Volatile matter, fixed carbon, total sulphur, and calorific value range from 39.50–42.06%, 40.10–44.14%, 0.37–1.06%, and 4679–5870 kcal/kg, respectively. The highest volatile matter values are found around DH05, while relatively high fixed carbon and calorific values are predominantly observed in the eastern portion of the study area. Seam S4A exhibits the best coal quality among all seams, characterized by low ash and sulphur contents and relatively high fixed carbon and calorific values.

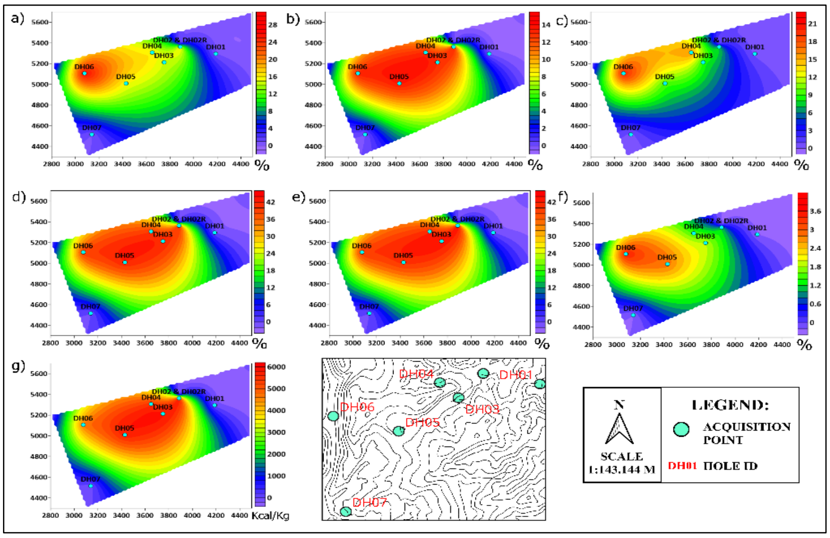


Figure 10. Iso-quality maps for Seam S4A encompassing the following parameters: a) Total Moisture, b) Inherent Moisture, c) Ash Content, d) Volatile Matter, e) Fixed Carbon, f) Total Sulphur, g) Calorific Value.

The iso-quality map for Seam S4B, as presented in **Figure 11**, shows the coal quality distribution at boreholes DH02, DH02R, DH03, DH04, DH05, and DH06. Total moisture and inherent moisture values range from 15.76–25.25% and 11.00–13.50%, respectively, with values tending to increase toward the northwest. Ash content ranges from 3.00–21.00%, with lower values concentrated in the eastern to central portions around DH02 and DH03, while the highest values are found at DH06. Volatile matter, fixed carbon, total sulphur, and calorific value range from 34.75–41.14%, 33.25–42.93%, 0.60–2.61%, and 4049–5808 kcal/kg, respectively. The highest volatile matter and fixed carbon values are concentrated around DH03, while the highest total sulphur and lowest calorific values are found at DH06. Coal quality in Seam S4B is superior in the eastern to central portions of the study area, characterized by lower ash and sulphur contents and higher calorific values, whereas the northwestern portion exhibits relatively lower quality due to elevated ash content.

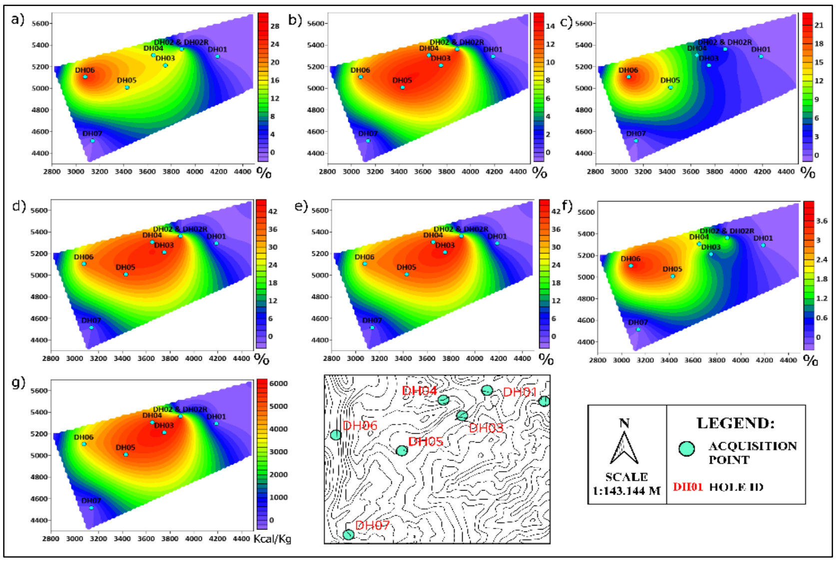


Figure 11. Iso-quality maps for Seam S4B encompassing the following parameters: a) Total Moisture, b) Inherent Moisture, c) Ash Content, d) Volatile Matter, e) Fixed Carbon, f) Total Sulphur, g) Calorific Value.

Overall, the coal quality distribution reveals that the central portion of the study area exhibits relatively superior quality, particularly in the zone dominated by Seams S4A and S4B. This zone is characterized by low ash and total sulphur contents and relatively high fixed carbon and calorific values. In addition, Seam S2 exhibits the highest volatile matter content, while Seam S5 demonstrates the best values of total moisture, inherent moisture, and calorific value. However, interpretation of Seam S5 remains limited given that it is supported by data from only one borehole. Conversely, coal quality in Seam S3 tends to be lower due to elevated ash content, which contributes to a reduction in calorific value. Therefore, the central portion of the study area can be regarded as the zone with relatively superior coal quality compared with other areas.

D. Analysis of Quality Parameters on Calorific Value

Regression analysis results indicate that ash content is the parameter with the greatest influence on calorific value across all analyzed seams, as summarized in **Table 3**. Ash content exhibits the highest coefficient of determination (R^2) compared with other parameters, and the relationship formed is negative, whereby an increase in ash content is accompanied by a decrease in coal calorific value. The magnitude of the influence of ash content on calorific value is related to the nature of ash as a non-combustible inorganic material. Ash content in coal generally originates from impurity minerals such as clay minerals, quartz, carbonates, and other minerals incorporated during the process of coal formation and deposition. The higher the ash content, the smaller the proportion of organic material that functions as the energy source during combustion. As a result, the thermal energy generated is lower, thereby reducing the calorific value (Fadhili & Ansosry, 2019).

An increase in mineral matter and ash content in coal leads to a deterioration in coal quality, as a portion of the coal mass is composed of material that does not contribute to heat energy generation and instead contributes to increased fouling, wear, and corrosion of the equipment through which it passes (Sepfitrah, 2016).

Table 3. Proximate parameters with the greatest influence on calorific value.

No	Seam	Parameter with the Greatest Influence on CV	R^2 Value	Relationship
1	S2	*Ash*	0.9467	Negative
2	S3	*Ash*	0.8067	Negative
3	S4A	*Ash*	0.9059	Negative
4	S4B	*Ash*	0.8633	Negative

Based on the ash content iso-quality maps presented in **Figure 12**, the spatial distribution of ash content across all seams shows an increasing trend from east to west toward the central portion of the map, followed by a decrease toward the east, with the highest values found in Seam S3 at 21.69% at DH05 and in Seam S4B at 21% at DH06. In general, the distribution pattern of ash content shows a decreasing trend from west to east across the study area, influenced by the influx of impurity materials, the coal formation process, and data limitations in the eastern area. Elevated ash content values are generally associated with lower coal quality, as they can reduce calorific value and combustion efficiency.

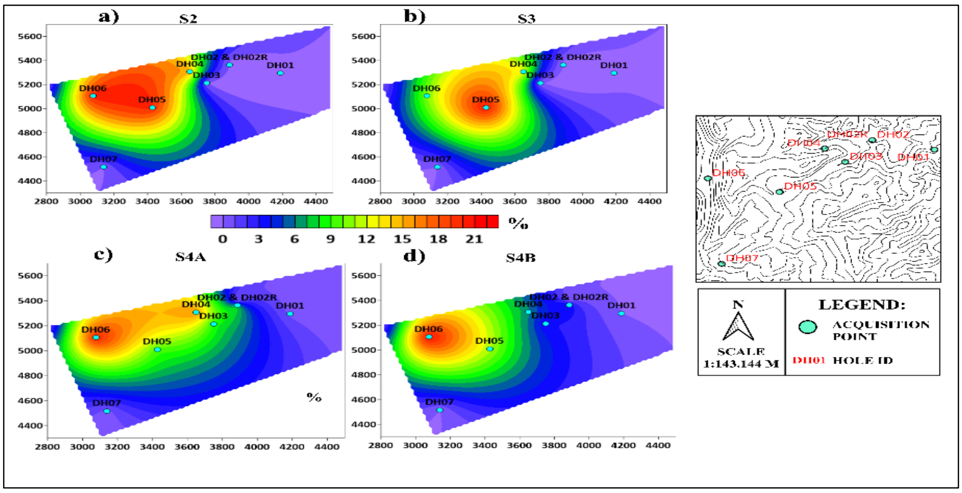


Figure 12. Comparative iso-quality maps of ash content for multiple seams: a) Seam S2, b) Seam S3, c) Seam S4A, d) Seam S4B.

E. Coal Rank Analysis

The relatively uniform calorific values among seams suggest that the degree of coal maturity in the study area does not differ significantly, as presented in **Table 4**. This is supported by relatively high total moisture and inherent moisture values, which are general characteristics of low- to medium-rank coals. Based on the ASTM D388 classification, the majority of seams fall within the subbituminous A coal rank. However, Seam S5 exhibits a higher calorific value than the other seams and is therefore classified as high volatile C bituminous coal. These results indicate that, in general, the coals in the study area possess a relatively uniform degree of maturity.

Table 4. Coal seam ranks based on ASTM D388 classification.

No	Seam	TM	IM	ASH	VM	FC	TS	CV	CV	*Rank*
		Ar	Adb	Adb	Adb	Adb	Adb	Adb	Dmmmf	ASTM
		%	%	%	%	%	%	KCal/Kg	Btu/lb	
1	S1	16.78	12.96	11.48	38.40	37.16	2.55	5485	11206	*Subbituminous A Coal*
2	S2	16.15	12.42	7.06	42.39	37.60	3.10	5824	11256	*Subbituminous A Coal*
3	S3	18.75	12.72	15.47	36.79	35.03	1.52	5106	11036	*Subbituminous A Coal*
4	S4A	19.66	13.31	4.34	40.55	41.79	0.69	5933	11275	*Subbituminous A Coal*
5	S4B	16.32	12.95	6.13	39.99	40.94	1.39	5837	11274	*Subbituminous A Coal*
6	S5	13.19	9.01	10.39	42.39	38.20	3.55	5892	11806	*High Volatile C Bituminous Coal*

IV. CONCLUSIONS

Based on the interpretation of geophysical well logging data, the lithologies encountered in the study area consist of soil, silt, sand, mudstone, siltstone, sandstone, coal, coaly shale, and shaly coal. Inter-borehole correlation results indicate that the coal seams dip at approximately 10–15° toward the southwest, with relatively uniform seam thicknesses, although several seams tend to thin toward the southeast. Coal quality analysis reveals that Seam S4A possesses the highest total moisture and inherent moisture contents of 18.72% and 13.31%, respectively, while the lowest values are found in Seam S5 at 13.19% and 9.01%. The highest ash content was recorded in Seam S3 at 15.47%, while the lowest was found in Seam S4A at 4.34%. The highest volatile matter value is in Seam S2 at 42.55%, while the highest fixed carbon value is in Seam S4A at 41.40%. The highest total sulphur content was found in Seam S5 at 3.55%, and the highest calorific value was also recorded in Seam S5 at 5887 kcal/kg adb. Among all analyzed parameters, ash content is the most dominant factor influencing calorific value, whereby an increase in ash content results in a decrease in coal calorific value. Based on the ASTM D388 classification, Seam S5 is classified as high volatile C bituminous coal, while Seams S1, S2, S3, S4A, and S4B are classified as subbituminous A coal.

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