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Coal Rank Variation Induced by Igneous Intrusion in Pit A, Tanjung Enim, South Sumatra

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ABSTRACT

This study investigates the effect of igneous intrusion on coal quality variation in Pit A, PT Bukit Asam Tbk., Tanjung Enim, South Sumatra, with emphasis on calorific value (CV) as an indicator of coal rank alteration. The research utilized geological and coal quality data from nine exploration drillholes (DKP_01–DKP_09) intersecting four major coal seams (A1, A2, B, and C). The dataset included drilling records, geophysical logs (gamma ray and density), core descriptions, geological structure measurements, and proximate analysis results from coal samples located 70.9–1001.4 m from the interpreted intrusion body. Seam correlation and three-dimensional subsurface modeling were performed using Leapfrog software to evaluate spatial coal quality variation relative to intrusion proximity. The results indicate that coal located closer to the intrusion generally exhibits higher calorific values and fixed carbon content, accompanied by lower inherent moisture and volatile matter values, reflecting localized thermal alteration. Coal calorific values range from approximately 11,064 to 14,311 Btu/lb (GCV_MMMF) and show a general decrease with increasing distance from the intrusion. Spatial distribution mapping reveals a clear zonation pattern, with higher calorific values concentrated near the intrusion contact and lower values occurring farther from the heat source. Several anomalous values were identified and are interpreted to reflect local overheating effects and geological heterogeneity. Structural interpretation suggests that faults may have facilitated magma emplacement, although their direct influence on coal quality variation remains uncertain. Overall, the results indicate a strong spatial relationship between igneous intrusion proximity and localized coal rank enhancement within the study area.

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1. INTRODUCTION

Coal remains one of the most important fossil energy resources and continues to play a significant role in electricity generation and industrial activities worldwide. The maturity level of coal, commonly referred to as coal rank, is controlled by the coalification process and can be evaluated using parameters such as calorific value, moisture content, volatile matter, fixed carbon, mineral matter, and petrographic characteristics (Thomas, 2020). Among these parameters, calorific value is widely used as an indicator of coal quality because it generally increases with coal maturation, although it cannot solely represent coal rank, particularly in higher-rank coal (Zhang et al., 2024). Coal rank development is mainly influenced by temperature, pressure, and geological time during burial (Saghafi, 2017). In addition to regional burial processes, local geological factors may significantly modify coal properties and produce spatial variations in coal quality. One of the most important local factors is igneous intrusion, which can thermally alter coal seams and affect calorific value, moisture, volatile matter, and fixed carbon content (Singh et al., 2017).

Igneous intrusion can generate localized thermal anomalies that alter the physical and geochemical characteristics of surrounding coal seams. The magnitude of thermal alteration depends on factors such as intrusion geometry, intrusion thickness, residence time of heat, and distance from the intrusion contact. Previous studies reported that coal located closer to intrusive bodies generally experiences stronger thermal alteration, resulting in progressive increases in coal rank toward the intrusion contact (Zhang et al., 2026; Widodo et al., 2021). Thermal effects may also increase calorific value, fixed carbon, and vitrinite reflectance while reducing moisture and volatile matter contents (Li et al., 2020). Under intense heating conditions, thermal metamorphism may further modify coal texture and structure through devolatilization, cleat alteration, and partial coking, indicating advanced maturation processes near intrusion contacts.

The study area is located in Pit A, PT Bukit Asam Tbk., Tanjung Enim, South Sumatra, within the coal-bearing Muara Enim Formation of the South Sumatra Basin. The South Sumatra Basin has undergone a complex geological evolution involving multiple tectonic and magmatic events that influenced sedimentation patterns, structural development, and basin architecture (Barber et al., 2005; Hall, 2012). These geological processes created favorable conditions for the emplacement of igneous intrusions within coal-bearing sequences. In the study area, several faults and fractures are interpreted to have facilitated magma migration into the Muara Enim Formation, resulting in localized thermal alteration of adjacent coal seams. Consequently, the interaction between igneous intrusion and coal seams in Pit A provides an important opportunity to evaluate the spatial influence of thermal alteration on coal quality and rank variation.

The Muara Enim Formation constitutes the principal coal-bearing unit in the study area and contains several economically significant coal seams. The formation was deposited predominantly in fluvial to deltaic environments and hosts the A1, A2, B, and C coal seams investigated in this study (Suwarna et al., 2019). Understanding the stratigraphic distribution of these seams is essential because their relative positions to the intrusion body may influence the intensity of thermal alteration experienced by each seam. Therefore, stratigraphic relationships provide an important geological framework for evaluating coal quality variation associated with intrusive activity.

Previous investigations have demonstrated that calorific value generally decreases with increasing distance from igneous intrusion, indicating a negative correlation between coal quality and intrusion proximity (Zhang et al., 2024; Singh et al., 2017; Magfira et al., 2026; Marfian et al., 2023). However, the thermal influence of intrusion is often complex and may be modified by lithological heterogeneity, overburden thickness, structural controls, seam geometry, and intrusion characteristics (Li et al., 2020). Although the effects of igneous intrusion on coal rank have been widely documented, the quantitative spatial relationship between intrusion proximity and coal quality variation within individual coal seams in Pit A has not been comprehensively evaluated. In particular, the distribution of calorific value relative to intrusion geometry and the extent of thermal influence throughout the subsurface remain poorly constrained. Furthermore, differences in thermal response among seams A1, A2, B, and C have not been systematically assessed using integrated subsurface modeling and coal quality data. These limitations indicate the existence of a research gap regarding the spatial extent and intensity of intrusion-induced coal rank alteration in the study area.

To address these gaps, this study integrates coal quality data, intrusion-distance analysis, geological interpretation, and three-dimensional subsurface modeling to evaluate the influence of igneous intrusion on coal rank variation in Pit A. The study aims to analyze the relationship between calorific value and intrusion proximity and to examine the spatial distribution of coal quality across individual coal seams. It is hypothesized that coal located closer to the intrusion body exhibits higher calorific values and greater coal rank enhancement due to stronger thermal effects, whereas coal located farther from the intrusion experiences weaker thermal alteration. The novelty of this study lies in the integration of coal quality analysis, quantitative intrusion-distance evaluation, and three-dimensional spatial modeling to characterize intrusion-induced coal rank variation within the Muara Enim Formation. The results are expected to improve understanding of geological controls on coal quality distribution and provide valuable information for coal resource evaluation and mine planning in intrusion-affected coal deposits.

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2. METHOD

2.1. Materials and Data

The research method integrates geological data analysis and coal quality evaluation to assess the influence of igneous intrusion on coal rank variation based on calorific value. The study used secondary data from exploration drillholes in Pit A, including lithological and geophysical logs, core descriptions, and laboratory coal quality analyses from coal seams within the Muara Enim Formation. Nine exploration drillholes, DKP_01 to DKP_09, were used. Coal quality analyses on four main seams, A1, A2, B, and C, yielded 33 validated data points after screening. The dataset removed incomplete, duplicate, uncertain, and physically unrealistic records; one FC_DMMF value exceeding 100% was excluded, as fixed carbon cannot physically exceed 100%.

The geophysical data include gamma ray and density logs, which were used to identify coal seam boundaries, lithological contacts, and potential intrusion intervals. Core descriptions were conducted systematically by observing lithology, coal texture, color changes, contact characteristics, evidence of thermal alteration, and the occurrence of igneous material within or adjacent to coal seams. Intrusions were identified based on distinctive core characteristics, including massive igneous textures, sharp intrusive contacts, baked zones, and anomalous log responses compared to surrounding sedimentary units. Coal quality data were evaluated using proximate analysis results, particularly calorific value, inherent moisture, volatile matter, ash, and fixed carbon. All coal quality parameters were first checked according to their analytical basis, including ADB, DB, DAF, MMMF, and DMMF, to avoid inconsistency in coal rank classification.

2.2. Coal Rank Classification

Coal rank classification in this study refers to the ASTM D388 standard, which classifies coal maturity using calorific value together with fixed carbon and volatile matter parameters, depending on the coal rank range (ASTM, 2021). The classification diagram according to ASTM D388 (Figure 1) illustrates the transition from lignite, sub-bituminous, bituminous, to anthracite coal. In this study, gross calorific value on a moist mineral-matter-free basis (GCV_MMMF) was used as the primary parameter for lower-rank coal classification, whereas fixed carbon on a dry mineral-matter-free basis (FC_DMMF) and volatile matter were used to support the interpretation of higher-rank coal categories. Therefore, variations in calorific value, fixed carbon, and volatile matter associated with intrusion proximity were interpreted as indicators of localized coal maturation and thermal alteration within the study area (Zhang et al., 2024; Zhang et al., 2026). Samples with inconsistent analytical bases or unrealistic converted values were not used to assign coal rank, although they were retained as notes for data-quality evaluation.

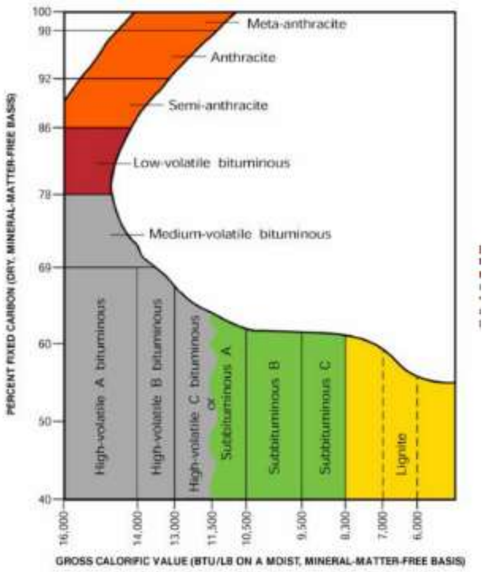

Figure 1. Coal rank classification diagram based on calorific value and coal rank categories (modified from Schweinfurth and Finkelman, 2003).

2.3. Data Processing and Spatial Modeling

The data processing stage includes coal seam correlation to evaluate seam continuity and the spatial distribution of igneous intrusions using drillhole correlation and subsurface modeling. Geophysical log interpretation, particularly gamma ray and density logs, was integrated with core descriptions to identify coal seam boundaries and intrusion intervals. Coal quality analysis was subsequently conducted to evaluate variations in calorific value, moisture, volatile matter, fixed carbon, and ash content relative to intrusion proximity. The distance between coal sample locations and intrusion contacts was calculated based on three-dimensional spatial relationships derived from drillhole coordinates and modeled intrusion geometry using the UTM coordinate system of the study area. Spatial interpolation and distribution modeling were performed using Leapfrog software with the radial basis function (RBF) interpolation method to generate calorific value zonation maps across individual coal seams.

Structural geological interpretation was also conducted to assess the role of faults as potential magma migration pathways and controls on local heat distribution (Widodo et al., 2021). To reduce interpretation uncertainty, cross-validation was performed between geophysical logs, core observations, laboratory results, and seam correlation models, while anomalous data were evaluated based on local geological conditions and possible excessive thermal alteration. The integrated workflow of the study is summarized in the research flowchart shown in Figure 2.

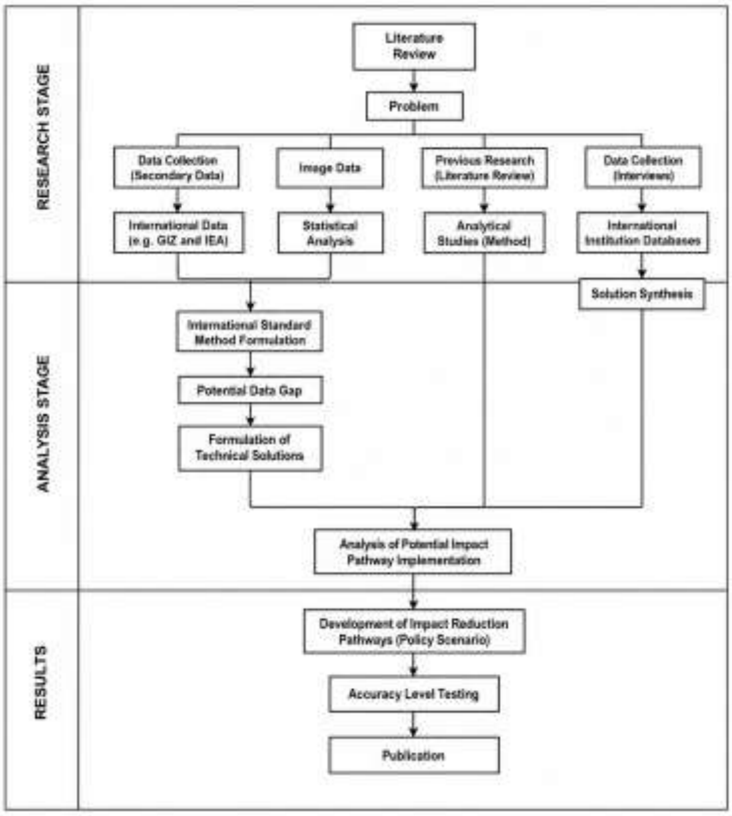

Figure 2. Research Flowchart

2.4. Statistical Analysis

Correlation and regression analyses were applied to evaluate the relationship between calorific value and distance from intrusion, where negative correlation trends were interpreted as evidence of thermal influence on coal maturation. Regression analysis was conducted separately for each seam using the validated dataset, and the strength of the relationship was evaluated using the correlation coefficient, coefficient of determination, p-value, and 95% confidence interval. Only validated GCV_MMMF and FC_DMMF values were used for coal rank interpretation, while physically unrealistic values, including FC_DMMF greater than 100%, were excluded from rank classification.

3. RESULTS AND DISCUSSION

3.1. Coal Rank Analysis

Based on the calorific value analysis presented in Table 1, coal in the study area generally ranges from Sub-bituminous B to Sub-bituminous A according to the ASTM D388 classification. Several localized samples situated near igneous intrusion contacts exhibit relatively higher calorific values that approach the High Volatile Bituminous rank range. This rank transition demonstrates that coal quality in Pit A is not controlled only by regional burial coalification, but also by localized thermal alteration associated with igneous intrusion. Similar intrusion-related coal-rank enhancement has been reported in coal seams affected by contact metamorphism, where magmatic heat increases organic maturity and modifies proximate characteristics near the intrusion contact (Singh et al., 2017; Zhang et al., 2026).

Variations in coal quality are reflected across seams A1, A2, B, and C. Seam A1 is dominated by lower calorific values characteristic of sub-bituminous coal, whereas Seam A2 shows localized increases in calorific value near intrusion zones. Seam B generally exhibits relatively higher calorific values compared to the other seams, while Seam C shows moderate to high calorific values in several samples located closer to the interpreted intrusion body. The increase in calorific value is accompanied by lower inherent moisture and volatile matter and higher fixed carbon content, indicating progressive thermal maturation. This trend is consistent with previous studies showing that thermal alteration commonly promotes moisture loss, devolatilization, and relative fixed-carbon enrichment in coal affected by igneous intrusion (Zhang et al., 2024; Li et al., 2020; Tang et al., 2020).

Although several samples show values approaching higher-rank categories, coal-rank interpretation must be treated cautiously because ASTM D388 requires consistent analytical bases, particularly GCV_MMMF and FC_DMMF, for reliable classification (ASTM, 2021). Therefore, samples with physically unrealistic conversion results, particularly FC_DMMF values exceeding 100%, were excluded from rank interpretation. This data-screening step is essential because overestimated fixed carbon values could lead to artificial assignment of anthracitic or semi-anthracitic rank and weaken the validity of the geological interpretation.

Table 1. Coal Rank Analysis Data

Seam	Number of validated samples	Distance from intrusion (m)	GCV_MMMF range (Btu/lb)	FC_DMMF range (%)	Dominant rank	Localized higher rank
A1	9	70.9–1001.4	11,064–12,486	43.0–95.9	Sub-bituminous B	High-volatile bituminous C to Semi-anthracite*
A2	8	70.9–1001.4	11,363–12,615	53.0–89.1	Sub-bituminous B to A	High-volatile bituminous C to Semi-anthracite*
B	8	394.9–1001.4	11,170–13,617	55.0–97.6	Sub-bituminous A	High-volatile bituminous C to Anthracite*
C	8	394.9–1001.4	11,363–14,311	54.0–92.3	Sub-bituminous A to B	High-volatile bituminous C to Anthracite*

* **Note**: Coal rank was classified based on ASTM D388 using validated GCV_MMMF and FC_DMMF values. Samples with FC_DMMF > 100% were excluded from rank interpretation because such values are physically unrealistic and may indicate conversion, input, or analytical-basis errors. Ranks marked with an asterisk (*) should be interpreted cautiously because high-rank classification requires confirmation using vitrinite reflectance or petrographic analysis.

3.2. Correlation Between Calorific Value and Distance from Intrusion

The correlation between calorific value and distance from the intrusion demonstrates a consistent negative relationship across all analyzed coal seams, indicating that calorific value generally decreases with increasing distance from the intrusion contact. This result provides quantitative evidence that intrusion proximity is a major spatial control on coal quality variation in the study area. The observed negative relationship agrees with previous studies showing that coal closer to intrusive bodies commonly records stronger thermal alteration and higher calorific value than coal located farther from the intrusion (Singh et al., 2017; Zhang et al., 2024; Zhang et al., 2026; Liu et al., 2020). Linear regression analysis was conducted to quantify the thermal influence of the intrusion on coal quality variation. The summary of regression statistics for each coal seam is presented in Table 2.

As shown in Table 2, Seam A1 yielded the regression equation $y = -1.067x + 8648.40$ with $r = -0.786$, $R^2 = 0.618$, and $p = 0.012$, indicating a statistically significant negative correlation between calorific value and intrusion distance. Similarly, Seam A2 exhibited the equation $y = -1.243x + 8721.60$ with $r = -0.787$, $R^2 = 0.620$, and $p = 0.020$, suggesting that intrusion proximity exerts a significant influence on coal quality. The strongest relationship was observed in Seam B, represented by the equation $y = -1.714x + 9175.19$, with $r = -0.944$, $R^2 = 0.891$, and $p < 0.001$. Seam C also showed a strong negative correlation, characterized by the equation $y = -1.433x + 9059.39$, $r = -0.941$, $R^2 = 0.885$, and $p < 0.001$. The high R^2 values in Seams B and C indicate that 89.1% and 88.5% of calorific-value variation, respectively, can be statistically explained by distance from the intrusion. This suggests that these seams experienced more systematic thermal influence than Seams A1 and A2, where lower R^2 values indicate stronger interference from other geological factors.

Table 2. Summary of Linear Regression Statistics Between Calorific Value and Distance from Intrusion for Each Coal Seam

Seam	Regression Equation	r	R^2	p-value	95% CI	n
A1	$y = -1.067x + 8648.40$	-0.786	0.618	0.012	-1.817 to -0.317	9
A2	$y = -1.243x + 8721.60$	-0.787	0.620	0.020	-2.214 to -0.271	8
B	$y = -1.714x + 9175.19$	-0.944	0.891	< 0.001	-2.314 to -1.114	8
C	$y = -1.433x + 9059.39$	-0.941	0.885	< 0.001	-1.949 to -0.917	8

Overall, the statistical analysis supports the interpretation that intrusion proximity is an important factor influencing calorific value distribution within the study area. The negative slopes indicate a measurable increase in calorific value toward the intrusion body, which is consistent with the development of a thermal aureole around intrusive rocks. In such a system, coal rank generally increases toward the heat source because organic matter receives greater thermal input near the intrusion contact (Singh et al., 2017; Zhang et al., 2026; Yulianto & Firmansyah, 2022). However, the relationship is not entirely linear, indicating that additional geological factors, including seam geometry, lithological heterogeneity, and localized thermal conditions, may also contribute to variations in coal quality between drillholes. This non-linearity is important because it shows that intrusion distance alone cannot fully explain coal-quality variation; rather, heat transfer is also controlled by intrusion geometry, seam thickness, lithological barriers, and structural pathways (Li et al., 2020; Widodo et al., 2021).

Several anomalous data points deviate from the general regression trend. In Seam A2, drillhole DKP-04 exhibits relatively higher calorific values compared to neighboring drillholes located at similar intermediate distances from the intrusion. This anomaly is interpreted to be associated with lower inherent moisture and ash content, which may increase calorific value despite the greater intrusion distance. This finding indicates that calorific value is sensitive not only to thermal maturity, but also to coal composition and analytical basis. Moisture and mineral matter can suppress or enhance apparent calorific value, thereby producing local deviations from the expected intrusion-distance trend (Thomas, 2020; Zhang et al., 2024). In contrast, drillhole DKP-02, which is located close to the intrusion contact, shows slightly lower calorific values than expected. This condition may reflect excessive heating, partial coking, or local textural alteration that changes the coal structure and causes calorific value to deviate from the ideal maturation trend (Singh et al., 2017; Li et al., 2020).

Additional deviations were identified in Seam B, particularly at DKP-06, where calorific values remain relatively high despite being situated farther from the intrusion compared to DKP-03 and DKP-04. This condition is interpreted to reflect local geological heterogeneity, including seam thickness variation and possible uneven heat distribution related to intrusion geometry. Variations in overburden thickness may also have influenced local heat retention and cooling rates, resulting in different thermal responses between drillholes. Structural discontinuities may also facilitate magma migration and redistribute heat along preferential pathways, resulting in localized coal-rank enhancement away from the main interpreted intrusion boundary (Widodo et al., 2021). Therefore, although intrusion proximity represents the primary control on coal rank variation, the observed anomalies demonstrate that calorific value distribution is also influenced by coal composition, seam characteristics, and local geological conditions.

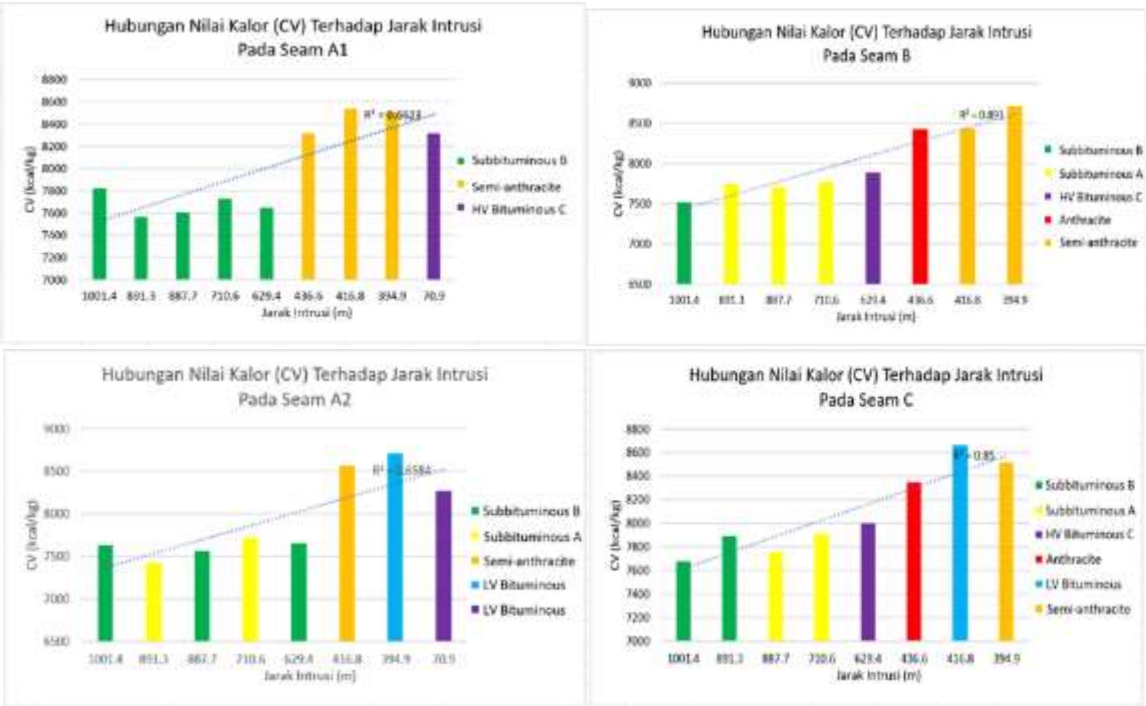

Figure 3. Relationship between calorific value (CV) and distance from intrusion for a) Seam A1, b) Seam A2, c) Seam B, and d) Seam C.

3.3. Distribution of Coal Calorific Value

Based on Figure 4, the calorific value distribution exhibits a clear west-to-east zonation pattern. The map was generated from coal quality data obtained from nine drillholes, DKP-01 to DKP-09, and interpolated using the Radial Basis Function method in Leapfrog software. The map shows low calorific values in the western area, moderate values in the central area, and high values concentrated in the eastern area near the interpreted intrusion boundary. This spatial zonation provides visual and geological support for the regression results, because the highest calorific-value zones are spatially associated with areas closest to the interpreted intrusion. This pattern is consistent with intrusion-affected coal deposits where thermal maturity increases toward intrusive contacts (Singh et al., 2017; Zhang et al., 2026).

Drillholes DKP-07, DKP-08, and DKP-09 are located within low calorific value zones situated relatively far from the intrusion, whereas DKP-04 to DKP-01 occur within moderate- to high-calorific value zones positioned closer to the intrusion contact. This spatial trend supports the interpretation that calorific value generally increases toward the intrusion due to localized thermal alteration. However, the interpolation results remain subject to uncertainty associated with limited drillhole density, uneven sample distribution between seams, and potential geological heterogeneity such as seam thickness variation, fault influence, and local lithological changes.

Therefore, Figure 4 should be interpreted as a spatial trend model rather than an exact deterministic representation of coal quality. This interpretation is more appropriate because interpolation results depend strongly on data density, borehole distribution, and the accuracy of the modeled intrusion boundary.

When analyzed by seam, Seam B exhibits the most distinct and continuous gradational pattern from low to high values, reflecting the most consistent thermal influence. Seams A2 and A1 also show an increasing trend toward the east, although the zonal boundaries appear slightly more irregular and less homogeneous compared to Seam B. Meanwhile, Seam C displays a relatively simpler distribution, dominated by moderate to high calorific values in the central to eastern areas. The difference among seams indicates that the intrusion did not affect the coal-bearing succession uniformly. Instead, each seam responded differently depending on its stratigraphic position, continuity, thickness, lithological barriers, and proximity to the heat source. This interpretation agrees with the concept that intrusion-related coal alteration is controlled by both heat-source characteristics and host-rock heterogeneity (Li et al., 2020; Widodo et al., 2021).

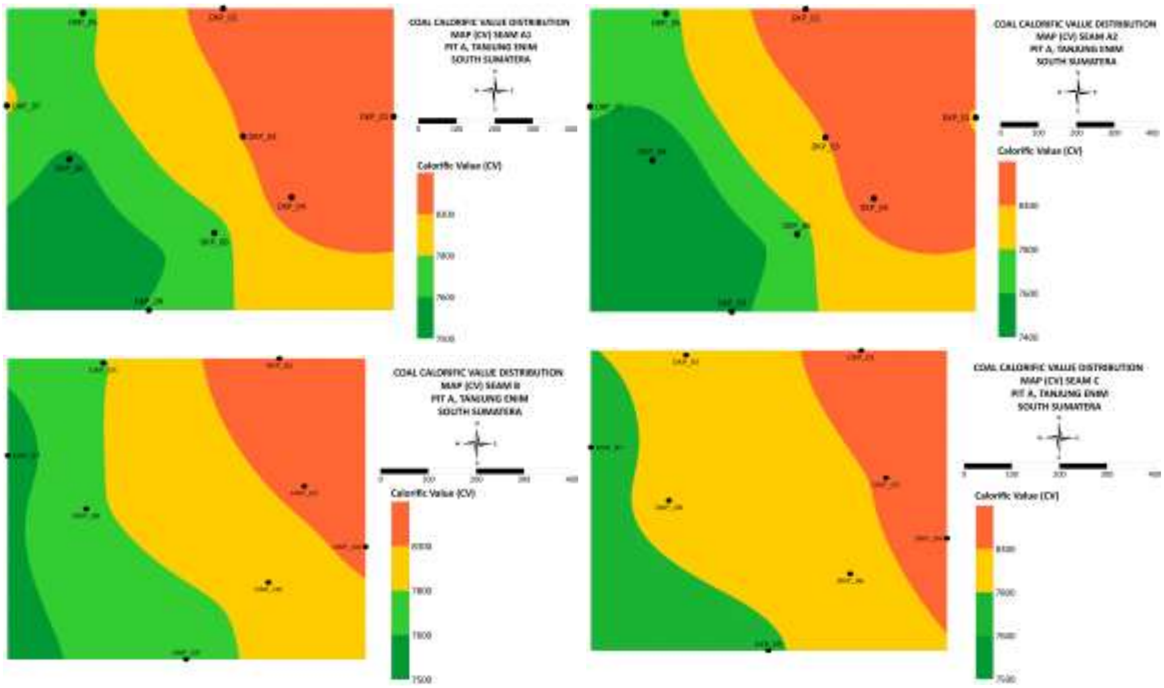

Figure 4. Spatial distribution of calorific value (CV_DAF, kcal/kg) generated using RBF interpolation from drillhole data (DKP-01 to DKP-09): a) Seam A1, b) Seam A2, c) Seam B, and d) Seam C. The maps are displayed in the UTM coordinate system at a scale of 1:3,000 and illustrate the spatial relationship between calorific value distribution and the interpreted intrusion boundary.

3.4. Effect of Igneous Intrusion on Coal Rank

Based on the integration of calorific value data, intrusion–drillhole distance analysis, regression trends, and spatial distribution mapping, the results indicate a consistent spatial association between intrusion proximity and increased coal calorific value within the study area. Coal samples located closer to the interpreted intrusion zones generally exhibit higher calorific values than those located farther away, suggesting localized thermal alteration related to igneous intrusion. This pattern is particularly evident in Seams B and A2, where several samples proximal to the intrusion display calorific values approaching the high sub-bituminous to bituminous rank range. The integrated evidence confirms that the intrusion acted as a localized heat source capable of modifying coal quality and enhancing coal rank within the affected zone. This mechanism is consistent with contact metamorphism, in which magmatic heat accelerates coal maturation and changes the physical and chemical properties of coal adjacent to intrusive bodies (Singh et al., 2017; Zhang et al., 2026).

The observed increase in calorific value near intrusion zones is supported by proximate-analysis results, which generally show lower moisture and volatile matter contents accompanied by higher fixed carbon content in samples located closer to the intrusion. These variations are consistent with localized thermal maturation associated with igneous intrusion. During thermal alteration, coal commonly loses moisture and volatile components, whereas fixed carbon becomes relatively enriched. This process increases calorific value and produces a higher apparent coal rank, particularly in zones exposed to stronger heat input (Zhang et al., 2024; Li et al., 2020; Tang et al., 2020). Nevertheless, the relationship is not entirely uniform across all seams and drillholes, indicating that additional factors such as seam heterogeneity, intrusion geometry, overburden variation, and local lithological conditions may also influence coal quality variation. Thus, intrusion proximity can be interpreted as the dominant spatial control, but not the sole factor controlling coal-rank variation in Pit A.

The thermal influence of the intrusion is not uniform across all seams and locations because each seam exhibits different geological characteristics that control heat transfer and coal maturation processes. Seam B shows the most distinct and consistent increase in calorific value, which is interpreted to be related to its stratigraphic position, relatively greater seam continuity, and stronger exposure to intrusion-related heat. In contrast, Seam A2 exhibits more fluctuating variations despite showing localized increases in calorific value near intrusion zones. This variability may reflect heterogeneous seam thickness, the presence of clay-rich partings and interburden layers, and uneven intrusion geometry that caused irregular heat distribution within the seam. Clay-rich partings and interburden layers may act as lithological barriers or thermal buffers that modify heat transfer, resulting in heterogeneous coal-rank development even at comparable distances from the intrusion (Li et al., 2020; Widodo et al., 2021).

Meanwhile, Seams A1 and C display relatively more variable calorific value patterns, which may indicate differences in stratigraphic position, overburden condition, lithological barriers, or original coal composition. Differences in the initial moisture, mineral matter, and organic composition of coal may also have influenced the thermal response of each seam. These findings show that intrusion-induced coal-rank variation is controlled by the combined influence of intrusion proximity, seam geometry, lithological heterogeneity, and coal composition. Therefore, the main contribution of this study is the integration of regression analysis, coal-quality parameters, and spatial modeling to explain how intrusion-related heat modifies coal-rank distribution at the seam scale.

From a practical perspective, the results are important for mine planning and coal-quality management in intrusion-affected deposits. Zones located closer to intrusion bodies may contain higher-calorific-value coal, but they may also exhibit greater quality variability due to overheating, coking, or local geological heterogeneity. Therefore, spatial coal-quality modeling should be integrated into pit design, selective mining, coal blending, and quality-control strategies to reduce uncertainty in resource evaluation.

Despite these contributions, the interpretation remains limited by the absence of independent maturity indicators such as vitrinite reflectance and detailed petrographic analysis. These parameters are commonly used to verify coal-rank changes, especially for higher-rank coal where calorific value alone may not provide a complete maturity assessment (Diessel, 1992; Thomas, 2020). Accordingly, the present study should be interpreted as strong evidence of spatial association between intrusion proximity and coal-quality variation, rather than definitive proof of all mechanisms controlling coal-rank transformation. Future work should integrate petrographic, geochemical, and more detailed structural data to better constrain the thermal history and rank evolution of coal seams in Pit A.

4. CONCLUSIONS

Based on the integration of coal quality data, intrusion-distance analysis, regression modeling, and spatial distribution mapping, this study demonstrates that igneous intrusion exerts a significant influence on coal rank variation in Pit A, PT Bukit Asam Tbk., Tanjung Enim, South Sumatra. Coal located closer to the interpreted intrusion body generally exhibits higher calorific values, lower moisture and volatile matter contents, and higher fixed carbon contents, indicating localized thermal maturation associated with intrusion-related heating.

Regression analysis revealed significant negative correlations between calorific value and distance from intrusion for all analyzed seams, with the strongest relationships observed in Seam B ($R^2 = 0.891$; $p < 0.001$) and Seam C ($R^2 = 0.885$; $p < 0.001$). Spatial distribution mapping further confirmed a progressive increase in calorific value toward the intrusion boundary, supporting the interpretation that intrusion proximity is a major control on coal quality distribution within the study area.

This study demonstrates that the combined application of coal-quality analysis, intrusion-distance evaluation, and three-dimensional spatial modeling provides an effective approach for assessing intrusion-induced coal-rank variation at the seam scale. The results support the hypothesis that coal located closer to the intrusion body experiences greater coal-rank enhancement due to stronger thermal effects. These findings contribute to a better understanding of geological controls on coal quality and provide valuable information for resource evaluation, mine planning, selective mining, and coal-quality management in intrusion-affected coal deposits.

Although a strong spatial association between intrusion proximity and coal-rank variation was identified, further studies incorporating vitrinite reflectance, petrographic analysis, geochemical characterization, and detailed structural investigations are recommended to better constrain the mechanisms and extent of intrusion-related thermal alteration in the study area.

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