

Integration of Ground Penetrating Radar (GPR) and Well Logging Data for Mapping Coal Seams in Pit "NS", South Palembang Sub-Basin

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Abstract

Coal seam continuity is an important aspect in coal exploration and mine planning, particularly in the Muara Enim Formation, South Sumatra Basin, which is one of Indonesia's major coal-bearing formations. This study aims to identify and evaluate the lateral and vertical continuity of coal seams in Pit "NS", South Palembang Sub-Basin, by integrating Ground-Penetrating Radar (GPR), drill, and outcrop data. GPR data were acquired along four survey lines with lengths of 418 m, 611 m, 158 m, and 517 m using a 25 MHz antenna. The data were processed through static correction, dewow filtering, gain application, bandpass filtering, background removal, running-average filtering, and depth conversion using an electromagnetic-wave velocity of 0.14 m/ns. The processed radargrams show strong, continuous, high-amplitude reflectors interpreted as coal seams, supported by drill and outcrop observations. The interpreted coal seams occur at depths of approximately 5–42 m, with thicknesses ranging from 8 to 12 m, varying across the survey lines. The integration of GPR with geological control data improves the reliability of coal seam interpretation and demonstrates that GPR is effective for evaluating shallow coal seam continuity in the study area.

Keywords: Coal; Drilling Data; Ground Penetrating Radar (GPR); Outcrop.

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Introduction

Coal constitutes one of Indonesia's strategic energy resources and remains an important commodity supporting domestic energy supply and industrial development. The South Sumatra Basin is recognized as one of Indonesia's major coal-producing regions, with the Muara Enim Formation hosting extensive, economically significant coal deposits (ESDM, 2023). Accurate delineation of coal seam geometry, thickness, and continuity is fundamental for resource estimation, mine planning, and operational decision-making. Although drilling and well logging provide reliable information regarding lithological

characteristics and coal seam occurrence, these methods are inherently limited to discrete observation points and often fail to adequately characterize lateral seam continuity between boreholes (Ramadhana et al., 2022).

Ground Penetrating Radar (GPR) has been widely applied as a near-surface geophysical technique for subsurface imaging due to its ability to detect electromagnetic property contrasts between geological materials. In coal-bearing environments, differences in dielectric permittivity between coal and surrounding

lithologies generate distinctive reflection responses that can be utilized to delineate seam boundaries and geometry. Previous studies have demonstrated GPR's capability to identify coal seam distribution, estimate seam thickness, and map shallow subsurface structures with high spatial resolution (Ibrahim et al., 2018; Wahidah & Basid, 2018).

Despite the proven effectiveness of GPR for coal exploration, most studies have focused primarily on interpreting radargram reflection patterns without comprehensive integration with geological control data. Consequently, uncertainties may arise in distinguishing coal-related reflectors from other subsurface features and in evaluating seam continuity beyond localized observations. Furthermore, studies integrating GPR interpretation with borehole logs and outcrop observations within the coal-bearing sequences of the Muara Enim Formation remain relatively limited. The integration of these datasets has the potential to improve the reliability of interpretation by combining continuous geophysical imaging with direct geological evidence.

Accordingly, this study employs an integrated approach involving GPR data, borehole logs, and outcrop observations to evaluate the depth, thickness, geometry, and lateral continuity of coal seams in Pit “NS” in the South Palembang Sub-basin. By combining geophysical and geological information, this approach is expected to enhance the accuracy of coal seam delineation and provide a more representative characterization of coal distribution both vertically and laterally. The results are anticipated to contribute to resource evaluation, exploration activities, and mine planning within the Muara Enim Formation.

Material and Methods

Geological Setting

The study area is stratigraphically located within the Muara Enim Formation, which represents the principal coal-bearing formation in the South Sumatra Basin (Figure 1). The formation is generally composed of interbedded coal seams, claystone, mudstone, siltstone, sandstone, and locally limestone deposits, reflecting deposition in fluvial, delta plain, and shallow marginal marine environments (Nasution & Nalendra, 2017; Ramadhana et al., 2022).

To support coal seam identification, this study employed GPR, a near-surface geophysical method that utilizes electromagnetic waves to detect contrasts in subsurface electromagnetic properties. The method provides high-resolution information on subsurface conditions both laterally and vertically. Previous studies have demonstrated that GPR is effective for identifying coal seam geometry, boundaries, and continuity by analyzing electromagnetic wave reflection responses and correlating them with borehole data (Ibrahim et al., 2018).

The application of GPR in coal-bearing environments is particularly effective because coal generally exhibits different electromagnetic properties from the surrounding lithologies, resulting in distinct reflection responses on radargrams. These contrasts enable the delineation of coal seam boundaries and continuity with relatively high spatial resolution. Therefore, the interpretation of GPR data in this study was based on the analysis of electromagnetic wave propagation, attenuation, reflection characteristics, and depth conversion principles, which are described in the following section.

Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is an active geophysical method that uses high-frequency electromagnetic waves, generally ranging from 10 MHz to 2 GHz, to image subsurface conditions (Čeru et al.,

2018). Ground Penetrating Radar has become one of the most widely applied near-surface geophysical methods because of its high resolution, rapid acquisition, and ability to characterize subsurface materials based on electromagnetic property contrasts (Rangole et al., 2024; Syam et al., 2019). In this study, a 25 MHz antenna was used because lower frequencies provide deeper penetration, allowing the method to reach depths of up to approximately 40 meters under suitable subsurface conditions. In GPR, there are various measurement configurations, one of which

is the Continuous Reflecting Profiling (CRP) used in this study. This method operates by moving the GPR device along a predetermined path, maintaining a constant distance between transmitter and receiver (Figure 2). When waves propagate, they are distorted by variations in the material's electromagnetic properties such as conductivity, permeability, and dielectric permittivity. The dielectric constant of the medium in GPR greatly affects the speed, attenuation, reflection, refraction, and transmission of electromagnetic waves (Feng, 2023).

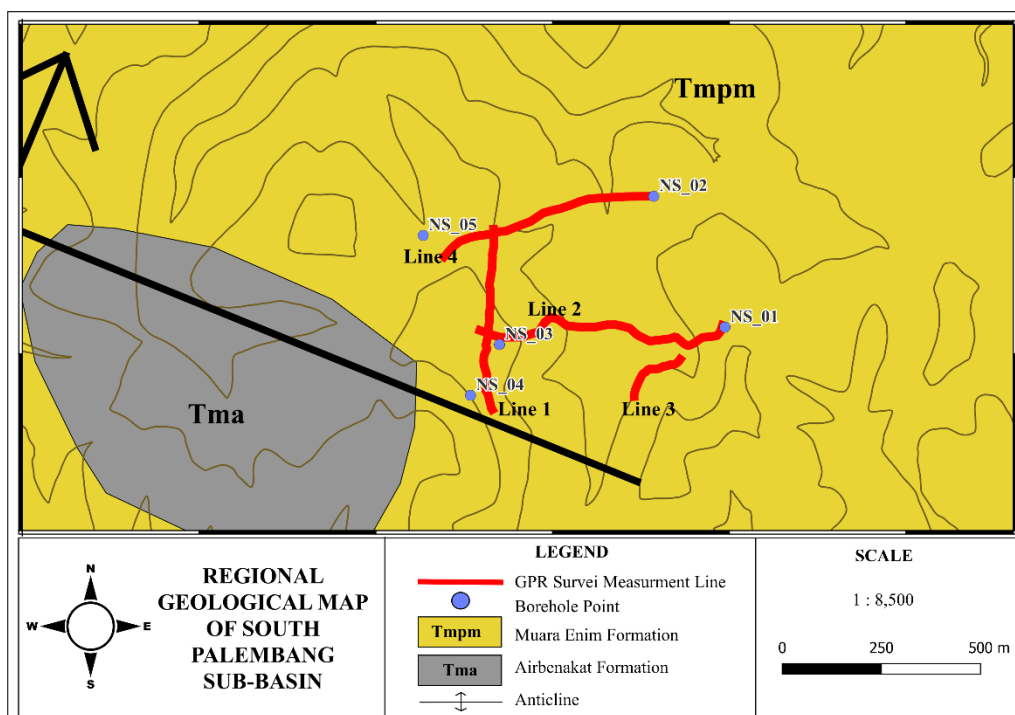


Figure 1. Regional geological map of South Sumatra showing the location of the 'NS' Field (Gafoer et al., 1986).

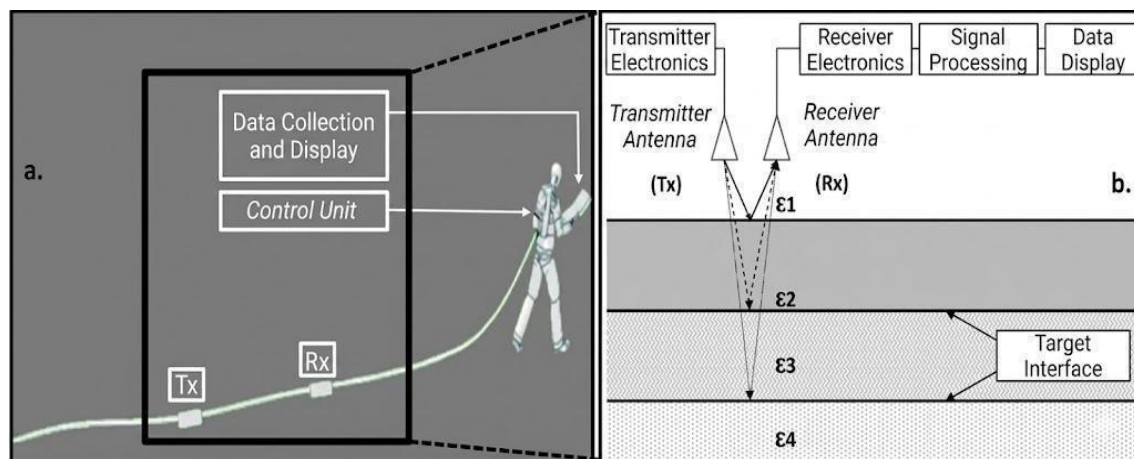


Figure 2. (a) Ground Penetrating Radar (GPR) data acquisition process in the field; (b) Schematic of the working principle of GPR based on the emission and reflection of electromagnetic waves (Daniels, 2004).

Electromagnetic waves used in Ground Penetrating Radar (GPR) are described by Maxwell's equations, which relate an electric field to a magnetic field. In the GPR method, the electromagnetic waves emitted propagate through the soil and reflect when they cross the boundary between layers with different electromagnetic properties. The difference in permittivity between the coal layer and the surrounding rocks produces a strong reflection on the radargram (Hamdaoui et al., 2020). Therefore, the interpretation of GPR data is based on analyzing reflection patterns to identify the presence and continuity of the coal seam. The conductivity of a material or rock can vary with time, temperature, pressure, and other environmental factors. In contrast to permittivity and electrical conductivity, permeability usually does not depend on the strength of the electric field but is more influenced by the magnetic field. The electromagnetic properties of a material are related to its composition and moisture content, which is the main controller of the propagation velocity and attenuation of electromagnetic waves in the material (Gao et al., 2021).

In the propagation of electromagnetic waves, especially when passing through different mediums, the amplitude of the signal will be attenuated due to energy loss as expressed in Equation (1). This occurs as a result of the reflection and transmission events that occur when radar waves pass through the boundary plane between mediums.

$$\alpha \approx \frac{\sigma}{2} \sqrt{\frac{\mu}{\epsilon}}; \sigma < \omega\epsilon \quad (1)$$

where (σ) is the electrical conductivity, (μ) is the magnetic permeability, (α) is the dielectric permittivity, and (ω) is the angular frequency (Daniels, 2004).

The penetration capability of electromagnetic waves is commonly represented by skin depth (δ) using

Equation (2) defined as the depth at which the signal amplitude decreases to $1/e$ (37%) of its original value. Skin depth can be estimated using (Daniels, 2004):

$$\delta \approx 0,0053 \frac{\sqrt{\epsilon_r}}{\sigma}; \sigma < \omega\epsilon \quad (2)$$

When GPR waves arrive at the interface of two layers with different dielectric properties, some of the energy is reflected to the surface. Propagation velocity and amplitude of the electromagnetic wave signal reflected in the survey GPR are strongly influenced by the relative dielectric constant contrast between adjacent rock layers (Putro et al., 2019). The reflection coefficient between two subsurface layers is calculated using Equation (3). The value of this reflection coefficient depends on the difference in the relative dielectric constant (ϵ) between the first layer (ϵ_1) and the second layer (ϵ_2). The magnitude of the reflection coefficient can be calculated using the following equation:

$$R = \frac{\sqrt{\epsilon_2} - \sqrt{\epsilon_1}}{\sqrt{\epsilon_2} + \sqrt{\epsilon_1}} \quad (3)$$

The reflected signals recorded by the GPR system are initially represented in two-way travel time and must be converted into depth using an appropriate electromagnetic wave velocity model. The accuracy of depth estimation is strongly influenced by the selected propagation velocity (Ghazali et al., 2019). To obtain the actual depth of subsurface reflectors, the travel time must be converted into depth was performed using Equation (4). The depth conversion is expressed as:

$$z = \frac{v \cdot t}{2} \quad (4)$$

where (z) is the reflector depth (m), (v) is the electromagnetic wave velocity in the medium (m/ns), and (t) is the two-way travel time (ns). The division by two accounts for the travel path from the transmitting antenna to the reflector and back to the receiving antenna (Daniels, 2004). In this study, an average velocity of

0.14 m/ns was used based on the dielectric characteristics of coal and the surrounding lithologies.

Data and Processing Steps

This study was conducted in the operational area of PT "X", located within the South Palembang Sub-basin of the South Sumatra Basin. Stratigraphically, the study area belongs to the Muara Enim Formation, a Late Miocene–Pliocene coal-bearing unit that constitutes the principal coal-producing formation in the South Sumatra Basin. The formation is generally composed of interbedded claystone, siltstone, sandstone, carbonaceous mudstone, and coal seams deposited in fluvial to deltaic environments (Nasution & Nalendra, 2017). Locally, the main coal seam identified in the study area is Seam C (Petai Seam), with a thickness of 7.2 to 11.4 m and thin carbonaceous clay intercalations. The coal seam generally occurs at shallow to intermediate depths, while interpreted reflector depths from GPR data range from approximately 5 to 42 m, depending on topographic conditions and survey line orientation.

A total of 4 GPR survey lines were analyzed: Line 1 (418 m), Line 2 (611 m), Line 3 (158 m), and Line 4 (517 m). Data acquisition was performed using a 25 MHz Rough Terrain Antenna (RTA), selected for deeper penetration suitable for imaging coal seams to depths of approximately 40 m. Survey lines were determined based on borehole locations, interpreted seam continuity, and field accessibility conditions.

The penetration depth and resolution of GPR data are strongly influenced by antenna frequency. Lower-frequency antennas generally provide greater penetration depth but lower vertical resolution, whereas higher-frequency antennas provide higher vertical resolution but shallower penetration depth (Indelicato, 2017; Lombardi et al., 2022). Figure 3

describes the depth of penetration of GPR signals in various mediums.

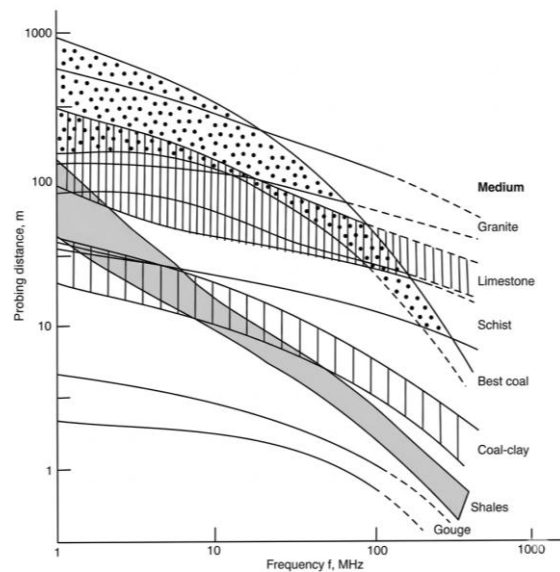


Figure 3. The depth of penetration of the GPR signal in the medium (Reynolds, 1997).

The use of 25 MHz antennas allows deeper penetration, but at the cost of lower vertical resolution. This causes the ability to distinguish thin layers to be limited, especially in layers with small thicknesses that have a reflection response like the surrounding lithology (Lai et al., 2018).

Meanwhile, the supporting data used are elevation data, aerial photos, outcrops, log borings, local geological maps, and local stratigraphic columns in the research area. The results of the GPR measurement will yield the resolution of the raw data, which will then be processed further to minimize the influence of any direct waves or tool-related errors during measurements in the research field.

Recent developments in GPR processing have shown that advanced signal enhancement techniques can significantly improve the reliability of reflector identification and interpretation (Afrasiabi et al., 2025). To obtain a reliable radargram for interpretation, the raw GPR data were processed using several sequential processing steps. The workflow employed in this study is presented in Figure 4.

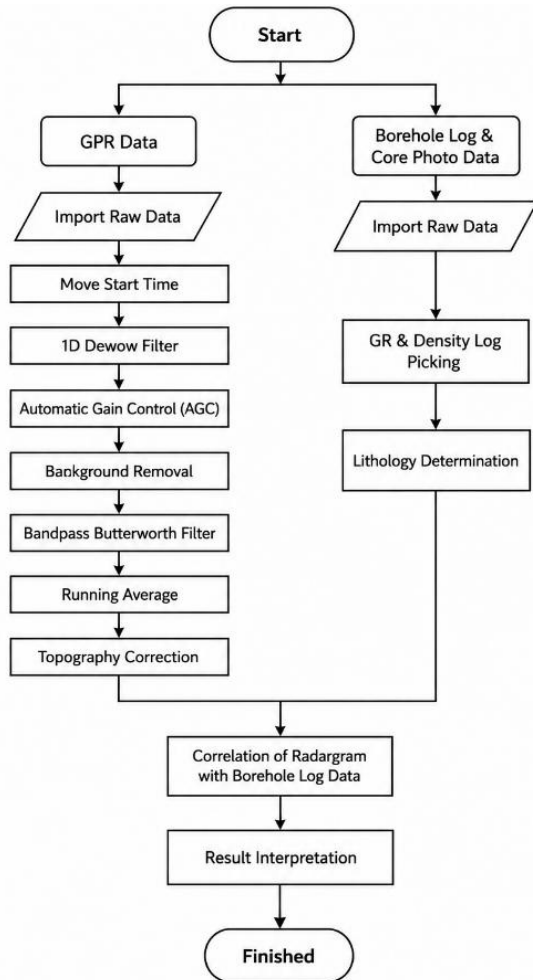


Figure 4. Workflow of integrated GPR and borehole log interpretation for coal seam analysis.

The processing workflow consisted of static correction, dewow filtering, Automatic Gain Control (AGC), bandpass filtering, background removal, running-average smoothing, and topographic correction. These procedures were applied to improve radargram quality and facilitate a more reliable interpretation of subsurface conditions. Overall, this processing stage aims to improve the quality of the data radargram so that the interpretation of subsurface conditions can be carried out more accurately (Afrasiabi et al., 2025; Rumansah et al., 2025; Zadhoush & Giannopoulos, 2021).

The GPR method for coal seam estimation applications is based on measuring electromagnetic wave reflection, which is directly proportional to the difference in dielectric permittivity (ϵ) of the underlying

medium. Electromagnetic waves are reflected when they encounter boundaries between materials with contrasting electromagnetic properties, allowing subsurface objects and lithological contacts to be identified from radargram reflections (Sugiarto et al., 2018). Depth conversion was performed using an average electromagnetic wave velocity of 0.14 m/ns based on the dielectric characteristics of coal and the surrounding lithologies. The value of 0.14 m/ns was selected based on previous Ground Penetrating Radar (GPR) investigations conducted in the same coal mining area of Tanjung Enim by Ibrahim et al. (2007). The study demonstrated that an electromagnetic wave velocity of 0.14 m/ns provided a representative approximation for coal-bearing formations and associated lithologies in the area. The following are the characteristic values for the Earth's material (Table 1).

Table 1. Characteristic values of dielectric constants (K) and velocity (v) for earth materials (Daniels, 2004).

Material	K	v (m/ns)
Air	1	0.3
Clay (wet)	8 – 15	0.086 – 0.11
Clay (dry)	3	0.173
Sandstone (wet)	6	0.112
Coal	4 – 5	0.134 – 0.15

Table 1 presents the dielectric permittivity and electromagnetic wave velocities of common subsurface materials used as references for GPR interpretation. Differences in the electromagnetic properties of coal and its surrounding lithologies generate reflection contrasts that can be identified on radargrams. Based on these characteristics, coal seams are generally interpreted as continuous, high-amplitude reflectors resulting from dielectric contrasts at lithological boundaries (Daniels, 2004).

To improve interpretation reliability and reduce ambiguity in reflector identification, GPR data were validated against borehole logs. Borehole logs provide direct

information on lithological variations and the occurrence of coal seams in the subsurface. In addition, well-log responses can be used to support lithological discrimination and depositional environment interpretation in coal-bearing formations (Setiawan et al., 2025). In this study, Borehole log interpretation was carried out using WellCAD software. Gamma-ray and density logs were analyzed to identify lithological boundaries and coal-bearing intervals by characterizing variations in radioactivity and bulk density. Gamma-ray logs are commonly used to distinguish clay-rich formations from cleaner lithologies, whereas density logs provide information on bulk density variations across different rock types. Coal intervals are typically characterized by low gamma-ray and density responses compared with surrounding sedimentary rocks, making them distinguishable from claystone and sandstone units (Setiahadiwibowo, 2017). In contrast, claystone generally exhibits high gamma ray values and higher density responses, while sandstone is characterized by relatively lower gamma ray values and moderate to high density responses. These characteristic log responses were used as reference markers for coal seam identification prior to correlation with GPR radargrams.

The integration of GPR, borehole logs, and outcrop observations enabled the validation of interpreted reflectors and provided a more reliable assessment of coal seam geometry, thickness, and lateral continuity throughout the study area.

The lithological characteristics summarized in Table 2 were subsequently used to correlate borehole log responses with GPR reflection patterns and outcrop observations.

Table 2. Rock log characteristics (Adrian & Mulyatno, 2020).

Material	Log characteristics	
	Gamma ray	Density
Sandstone	Slightly Low	Moderate
Coal	Low	Low
Clay	Moderate	Moderate

Results and Discussions

Well logging data are interpreted to identify the lithology and characteristics of the subsurface layer based on the rock's physical responses to specific parameters, such as gamma-ray values and density (Sujiman & Ramadhani, 2023). Based on gamma-ray log interpretation, coal seams are characterized by relatively low gamma-ray values, indicating a lower concentration of naturally radioactive materials compared to clay-rich lithologies. In addition, density logs show lower density values for coal than for the surrounding claystone and sandstone units, enabling clear seam identification (Farahdila & Setiawan, 2023).

The interpretation of borehole logs at NS-01 and NS-03 was conducted using gamma ray and density log responses to identify lithological boundaries and coal seam intervals. The interpreted lithological sequence and coal seam distribution for both boreholes are presented in Figure 5.

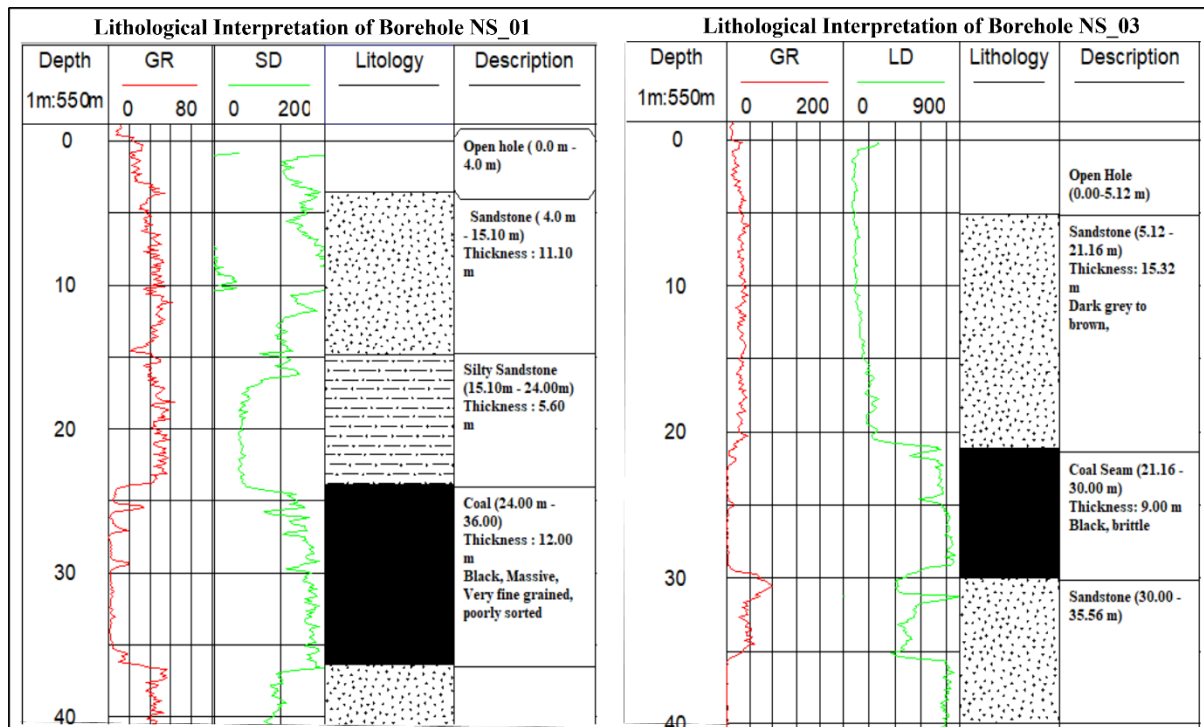


Figure 5. Lithological interpretation of boreholes NS-01 and NS-03 derived from gamma ray and density logs, indicating the depth and thickness of the interpreted coal seams.

The borehole log interpretation successfully identified coal seam intervals based on characteristic low gamma-ray and low-density responses. Coal seams and surrounding lithologies identified in the borehole logs were verified through visual examination of the corresponding core photographs. The validation process involved correlating the interpreted GPR reflectors with the depth and thickness of coal seams observed in the borehole records and confirmed by core documentation. These data provide reliable information regarding coal seam depth, thickness, and lithological variations at each borehole location. However, borehole logs capture vertical conditions at discrete points and cannot fully capture the lateral continuity of the coal seam between boreholes. Therefore, GPR data were integrated to extend the interpretation laterally and evaluate coal seam geometry and continuity throughout the study area. The processed GPR radargrams provide two-dimensional images of subsurface reflection patterns, with the vertical axis representing two-way travel time and depth, and the horizontal axis representing survey distance along

each profile. Coal seams are interpreted as continuous high-amplitude reflectors resulting from contrasts in electromagnetic properties between coal and the surrounding lithologies. Similar interpretation approaches based on reflector continuity and amplitude contrast have been successfully applied in previous GPR studies (Jannah et al., 2024). Variations in reflector continuity, depth, and geometry observed along the survey lines are influenced by topographic conditions, survey-line orientation relative to seam strike, and local geological factors such as erosion and structural deformation. The interpretation results for each survey line are presented in the following sections.

Line 1 is oriented south–north and located in the western part of the study area, with a survey length of 418 m running subparallel to the coal seam strike (Figure 6). Three high-amplitude reflector zones were identified at depths of approximately 21–30 m and interpreted as Seam C based on reflector continuity, amplitude characteristics, and correlation with borehole NS_03 and outcrop data. The

seam has an estimated thickness of approximately 9 m.

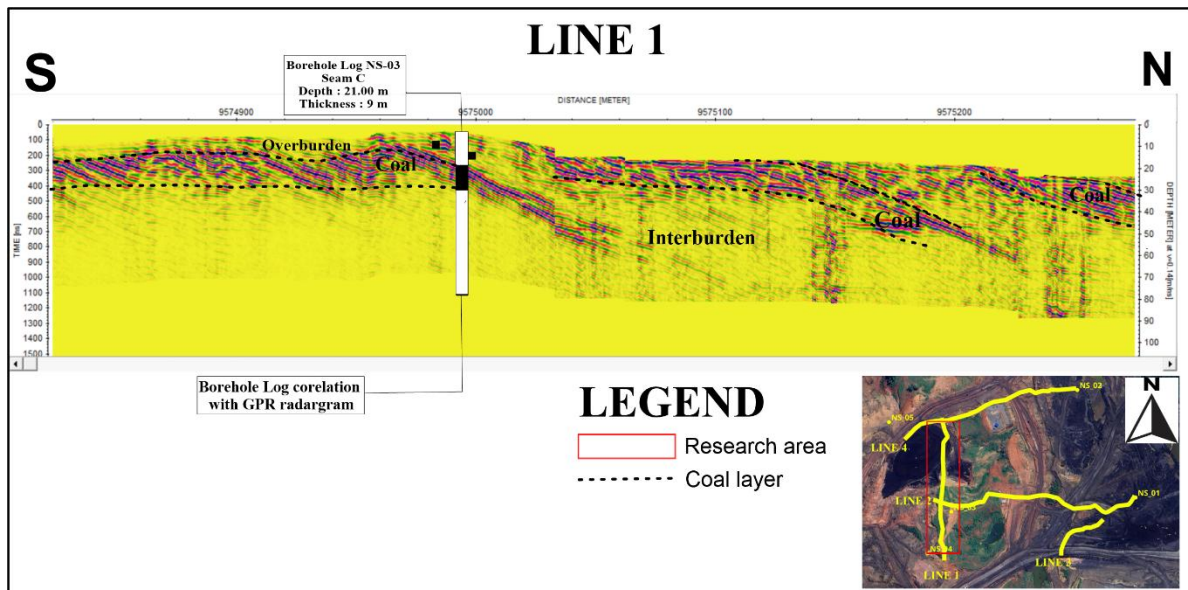


Figure 6. Interpretation of the GPR radargram of Line 1 showing strong amplitude reflectors interpreted as coal seams at depths of 21–30 m.

The strong, continuous reflections are attributed to the significant dielectric contrast between coal and the surrounding claystone and mudstone units, which serve as overburden and interburden. Coal exhibits lower dielectric permittivity and conductivity, producing a more distinct reflection response than the adjacent lithologies. Correlation with borehole data shows a depth difference of only 1–2 m, indicating good agreement between GPR interpretation and subsurface geological conditions. Reflector continuity decreases in the central part of the profile, while strong reflections persist in the southern and northern sections. This pattern is interpreted as the result of local erosion and topographic variation near the outcrop zone, suggesting that the seam was originally continuous but has been partially modified by post-depositional processes.

Line 2 is oriented west–east with a survey length of 611 m and exhibits a laterally continuous high-amplitude reflector zone at depths of approximately 24–36 m (Figure 7). Based on reflector continuity, amplitude

characteristics, and correlation with borehole data NS_01 this reflector is interpreted as Seam C with an estimated thickness of 11–12 m. The strong reflection response is attributed to the significant dielectric contrast between coal and the surrounding claystone and mudstone units, allowing the coal seam to be clearly distinguished from the overburden and interburden lithologies.

The interpreted seam exhibits better lateral continuity than that observed along Line 1, suggesting relatively stable depositional conditions and limited erosional influence. Similar high-amplitude and continuous reflector patterns associated with coal seams have been reported in previous GPR studies (Ibrahim et al., 2018). The reflection response becomes weaker toward the eastern part of the profile, which is interpreted as the effect of increasing topographic elevation and mining excavation activities in the mine front area. These conditions cause the coal seam to occur at greater relative depths and locally affect reflector continuity on the radargram.

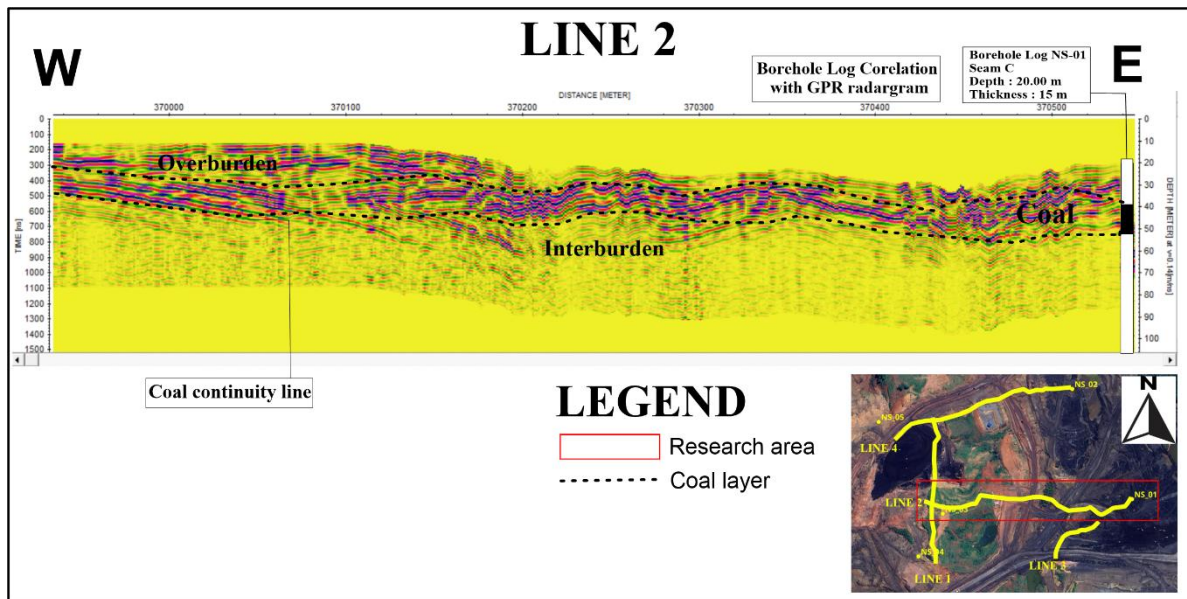


Figure 7. Interpretation of the GPR radargram of Line 2 showing a relatively continuous high-amplitude reflector interpreted as a coal seam at depths of 24–36 m with an estimated thickness of 11–12 m.

Line 3 has a survey length of 158 m and identified two potential coal zones at depths of approximately 5–13 m, characterized by medium- to high-amplitude reflectors (Figure 8). These reflections are interpreted as coal-bearing intervals due to their relatively strong amplitudes compared to the surrounding overburden and interburden lithologies. One reflector zone is supported by field observations and is therefore interpreted with higher confidence, whereas the second zone remains tentative because of its limited lateral continuity. Compared to Lines 1 and 2, reflector continuity along Line 3 is relatively poor. This is primarily attributed to changes in survey orientation, which shifts from south–north to southwest–northeast along the profile. Such variations reduce the consistency of reflector imaging and complicate seam correlation along the survey line. Consequently, although potential coal-bearing zones can be identified, Line 3 is considered less representative for evaluating coal seam geometry and continuity.

Line 4 has a total length of 517 m and is oriented approximately west–east, intersecting the coal seam strike direction.

Field measurements indicate a strike of 350° and a dip of 8° , suggesting that the coal seam trends nearly north–south and dips gently (Table 3). Because the survey line is oriented nearly perpendicular to the strike direction, the radargram provides a representative cross-sectional view of the coal seam geometry and depth variation along the profile.

Table 3. Strike and Dip measurements along GPR survey Line 4.

Strike ($^\circ$)	Dip ($^\circ$)
350	8

Two coal zones characterized by strong and continuous reflection contrasts were identified in the western and eastern sections of the radargram (Figure 9). Correlation with borehole data shows that the interpreted reflector depths differ by less than 1 m from the drilled coal seam intervals, indicating good agreement between GPR interpretation and subsurface lithology. The interpreted coal seam thickness ranges from approximately 10 to 11 m and is further supported by outcrop observations that confirm the upper and lower boundaries of Seam C.

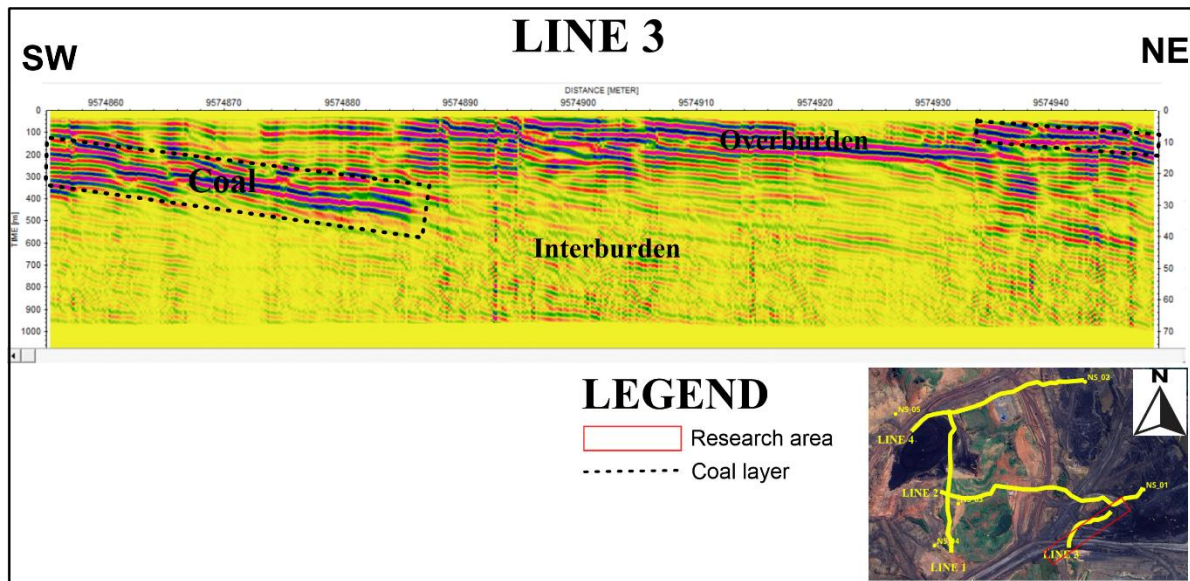


Figure 8. Interpretation of the GPR radargram of Line 3 two coal zones characterized by medium to high amplitude reflectors at depths of approximately 5–13 m.

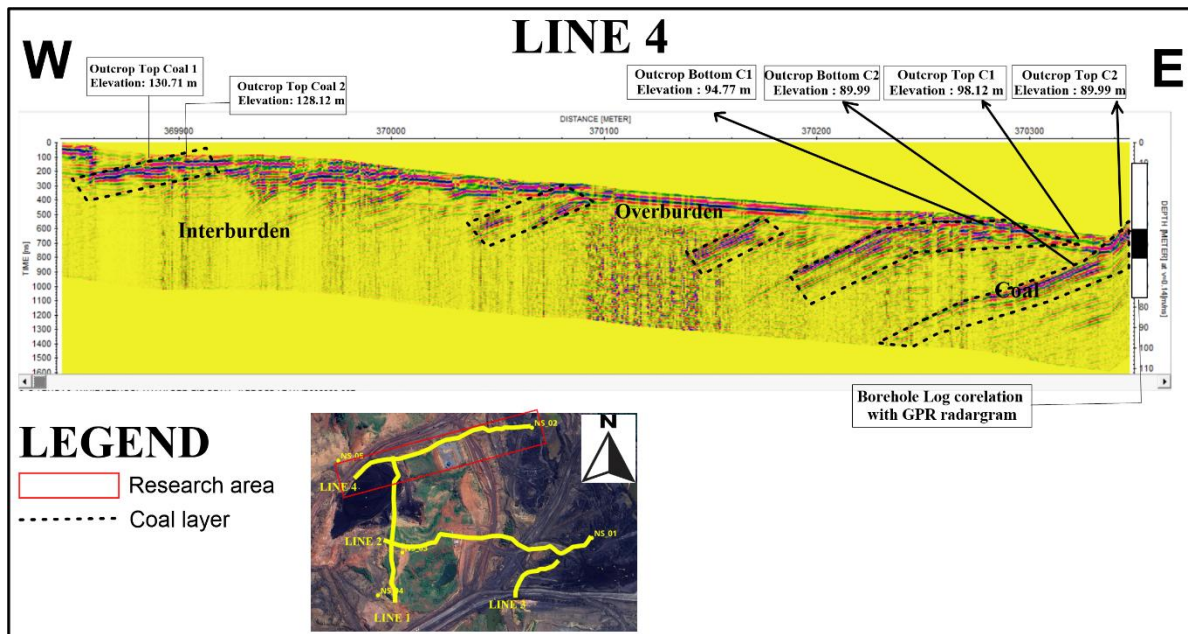


Figure 9. Interpretation of the GPR radargram of Line 4 showing strong amplitude reflectors interpreted as coal seams with an estimated thickness of 10–11 m.

The measured dip angle of 8° indicates that the coal seam is relatively gently inclined, which is consistent with the generally continuous reflector geometry observed along the profile. However, the absence of a strong reflector in the central portion of the radargram suggests an interruption in seam continuity. This discontinuity is interpreted as associated with topographic erosion rather than significant structural deformation, as the low dip value indicates only a minor bedding inclination. The

decreasing topography along the survey line likely contributed to erosion of the coal seam in the central section, leading to the apparent separation of the western and eastern coal zones.

Overall, the interpretation of the four GPR survey lines indicates that Seam C is present throughout the study area with varying depths and lateral continuity (Table 4). The interpreted coal seam occurs at depths of approximately 5–42 m and has a

thickness of about 8–12 m. Comparison with borehole log data shows good agreement in both seam depth and thickness, confirming the reliability of the interpreted reflectors. Variations in reflector continuity observed along several survey lines are interpreted to be influenced

by local topographic conditions and erosional processes. These results demonstrate that integrating GPR and borehole data provides a representative characterization of coal seam geometry and continuity within the study area.

Table 4. Interpretation of Coal Layer Geometry.

Survey Line	Direction	Line Distance (m)	Coal Seam Interpreted from GPR		Coal Seam Interpreted from Log	
			Depth (m)	Thickness (m)	Depth (m)	Thickness (m)
1	N – S	418	21 – 30	9 – 10	21.16 – 30	9
2	W – E	611	24 – 36	11 – 12	24 – 36	12
3	SW – NE	158	5 – 13	8 – 10	–	–
4	W – E	517	31 – 42	10 – 11	31.22 – 42.88	11.66

Conclusion

This study demonstrates that Ground Penetrating Radar (GPR) successfully identified and delineated Seam C within the Muara Enim Formation by detecting continuous high-amplitude reflectors generated by contrasts in electromagnetic properties between coal and surrounding lithologies. The interpreted coal seam was identified at depths of 5–42 m, with an estimated thickness of 8–12 m, indicating that GPR can image the geometry and continuity of near-surface coal seams.

The interpreted reflector depths show very good agreement with borehole logs, cores, and outcrop data, with depth discrepancies generally less than 1 m. This result indicates a high level of correlation between GPR interpretation and geological observations, confirming the reliability of the interpreted coal seam boundaries and reducing uncertainty in subsurface characterization.

Unlike previous studies that primarily focused on coal seam detection based on radargram responses, this study emphasizes evaluating coal seam continuity through the integration of GPR, gamma-ray, and density logs, core data, and outcrop observations. The integrated interpretation not only confirms the presence of coal but also provides a more representative

characterization of seam geometry, lateral continuity, and distribution patterns.

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Author Contribution

Neta Gresiana Santi Siregar was responsible for studying conceptualization, the research, data processing and analysis, and writing the manuscript, and Andri Yadi Paembonan supervised the research, provided critical guidance throughout the research process, and contributed to the interpretation of the results. Putu Pradnya Andika provided expertise in data analysis, contributed to

data interpretation, and provided valuable insights during manuscript preparation. M. Alamshah provided the data and served as field supervisor during the data acquisition process. All authors contributed to the writing and revision of the manuscript.

Conflict of Interest

The authors declare that they have no conflicts of interest relevant to the content of this publication.

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