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Research Article

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Assessment of Coal-Bearing Formations Using Vertical Electrical Sounding in the Gerado Basin, North-Central Ethiopia

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ABSTRACT

Background: Ethiopia's growing energy demand has renewed interest in indigenous coal resources, yet subsurface characterization of coal-bearing formations in structurally complex volcanic terrains such as the Gerado Basin remains poorly constrained. **Objective:** This study aimed to delineate coal-bearing formations in the Gerado Basin, north-central Ethiopia, determine their thickness, depth, and lateral continuity, and produce a preliminary estimate of coal resources. **Methods:** A quantitative geophysical research design was applied. Five Vertical Electrical Sounding (VES) stations were surveyed using the Schlumberger electrode configuration (maximum $AB/2 = 440$ m). Apparent resistivity data were inverted into one-dimensional layered-earth models using IPI2Win and WinResist, calibrated against regional geological mapping. Interpreted layers were coded into six geoelectric classes, and descriptive, correlational, and Monte Carlo sensitivity analyses were applied to the interpreted thickness and resistivity data. **Results:** Six geoelectric layers were consistently resolved across the five stations. Two coal-bearing horizons were identified between the Lower and Middle Basalt formations, with a combined mean thickness of 5.13 m (SD = 1.06 m) and overburden thickness ranging from 0.54 to 14.2 m (mean = 5.07 m). Combined coal thickness correlated strongly with overburden thickness ($r = .96$, $p = .011$). Using an aerial extent of 102,500 m², an assumed seam thickness of 2.5 m, and a bulk density of 1.4 g/cm³, the estimated coal tonnage was 358,750 t (Monte Carlo 90% interval: 285,690–437,168 t). **Conclusion:** The Gerado Basin exhibits moderate, spatially variable coal potential concentrated within a shale-bounded interval between two basaltic units. The estimate is preliminary and should be upgraded through borehole verification, geochemical characterization, and higher-resolution geophysical imaging before economic development decisions are made.

Keywords: Gerado Basin; coal exploration; Vertical Electrical Sounding; electrical resistivity; Ethiopia; resource estimation; Monte Carlo simulation

1. Background of the study

In response to Ethiopia's rapidly increasing energy demand, exploration of alternative energy resources such as coal and oil shale has gained significant attention across several sedimentary basins, including the Gerado Basin. This initiative, supported by governmental and private stakeholders, aims to meet growing domestic and industrial energy needs while reducing the environmental degradation associated with heavy dependence on biomass energy, particularly deforestation (World Bank, 2022). Coal continues to play an important role in the global energy mix, especially in developing countries, where it remains a relatively affordable and accessible source for industrial applications (International Energy Agency [IEA], 2023). In Ethiopia, recent national energy strategies emphasise diversification through the exploration and development of indigenous coal resources (Ministry of Mines Ethiopia, 2021).

Accurate delineation and quantification of coal deposits require reliable subsurface investigation techniques. Conventional exploration methods such as drilling, although effective, are costly and provide limited spatial coverage. Geophysical methods have therefore become indispensable tools in mineral exploration owing to their cost-effectiveness, non-invasive nature, and ability to provide continuous subsurface information (Kearey et al., 2002; Reynolds, 2011). Among these, electrical resistivity techniques - particularly Vertical Electrical Sounding (VES) - are widely applied for subsurface characterisation because different lithological units exhibit distinct resistivity signatures (Telford et al., 1990). Coal-bearing formations typically display measurable resistivity contrasts relative to surrounding shale and clay layers, making resistivity methods especially suitable for coal exploration (Sharma, 1997).

Despite these advancements, a significant research gap remains in the Gerado Basin and similar underexplored regions of Ethiopia. Previous investigations have largely relied on regional geological mapping and limited drilling data, which provide insufficient resolution for accurate subsurface characterisation and coal resource estimation (Tesfaye & Gebretsadik, 2018). In particular, there is a lack of integrated geophysical studies that systematically delineate the geometry, depth extent, and continuity of coal-bearing formations. Furthermore, the spatial variability of coal seams and the influence of subsurface structural features on coal distribution have not been adequately addressed using modern resistivity techniques (Reynolds, 2011). A further methodological gap concerns resource reporting: prior regional assessments in comparable Ethiopian basins have generally presented single-value tonnage figures without explicit treatment of measurement or geometric uncertainty, which limits their usefulness for investment and drilling-prioritisation decisions.

Within this context, the present study investigates subsurface coal-bearing formations in the Gerado Basin using geophysical methods, with particular emphasis on VES. Specifically, this study intended to delineate the lateral and vertical extent of coal-bearing sedimentary units within the Gerado Basin; determine the thickness and depth distribution of coal seams and associated overburden layers; identify

subsurface structural features that may influence coal occurrence and continuity and integrate geophysical data with available geological information to evaluate the coal resource potential of the area and quantify the associated estimation uncertainty.

The findings of this study contributes to bridging the existing gap by providing a high-resolution, geophysically constrained interpretation of coal-bearing strata in the Gerado Basin. By explicitly coding geoelectric layers, statistically characterizing their lateral variability, and propagating measurement uncertainty into the resource estimate, the study offers a methodologically transparent basis for resource classification, exploration planning, and future drilling prioritisation, with a workflow that is transferable to other structurally complex, volcanic-interbedded coal basins in Ethiopia.

2. Conceptual Framework

The integration of geological and geophysical methods in coal exploration has gained increasing traction as an effective approach to identifying and evaluating coal deposits (Tesfaye & Gebretsadik, 2018). Determining the economic viability of coal deposits requires thorough geological and geophysical characterization, including the physical characterization of coal properties, reserve estimation, and analysis of depositional environments; such investigations are essential for assessing exploitable coal deposits and guiding resource management strategies (Kearey et al., 2002). Electrical resistivity methods are especially well suited to this task because coal, carbonaceous shale, clay, and basaltic rock exhibit sufficiently distinct resistivity ranges to be discriminated in a one-dimensional layered-earth inversion (Telford et al., 1990; Sharma, 1997).

Vertical Electrical Sounding operates by injecting direct current into the ground through a symmetric electrode array - most commonly the Schlumberger configuration - and progressively increasing the current-electrode spacing to sample increasing depths. The resulting apparent resistivity sounding curve is inverted to recover the true resistivity and thickness of each subsurface layer (Reynolds, 2011). Sounding curves are conventionally classified into standard types (A, H, K, and Q, and their multilayer combinations) according to the sequence of resistivity increases and decreases with depth; this classification provides a rapid, reproducible diagnostic of the layering style before full quantitative inversion (Telford et al., 1990). VES has been applied extensively in groundwater, engineering, and mineral exploration, and is increasingly used for coal-related characterization where seams are thin, laterally discontinuous, or interbedded with volcanic rock, conditions under which drilling alone provides poor spatial coverage.

Ethiopia's coal-bearing sedimentary interbeds occur mainly within volcanic sequences of the Trap Series, deposited during periods of volcanic quiescence under swampy or lacustrine conditions (Flores, 2008). Regional stratigraphic understanding builds on early classification by Blanford (1870), later revised by Kazmin (1972) and Zanettin and Justin-Visentin (1974), and consolidated in the national

geological map compiled by Mengesha et al. (1996). Site-specific geological investigations of northern Ethiopian coal occurrences (Tesfaye & Gebretsadik, 2018) have identified coal interbeds between basaltic units but have generally lacked the systematic geophysical resolution needed to constrain seam geometry away from outcrop and borehole locations. The present study addresses this gap directly for the Gerado Basin.

The conceptual framework (Figure 1) organizes the study around three input domains: regional/local geological setting, geomorphological context, and field-acquired VES resistivity data that feed into a central data-processing and interpretation stage. This stage encompasses geoelectric layer coding, inversion, lithological calibration, and statistical/uncertainty analysis, and produces three linked outcomes: delineation of coal-bearing horizons, a preliminary coal resource estimate with an explicit uncertainty range, and evidence-based exploration recommendations. Structural complexity, spatial variability of coal seams, and the absence of borehole control are treated as moderating factors that constrain how confidently the geophysical outcomes can be generalised across the basin; this is why the resource estimate is expressed as a probability-weighted range rather than a single deterministic figure.

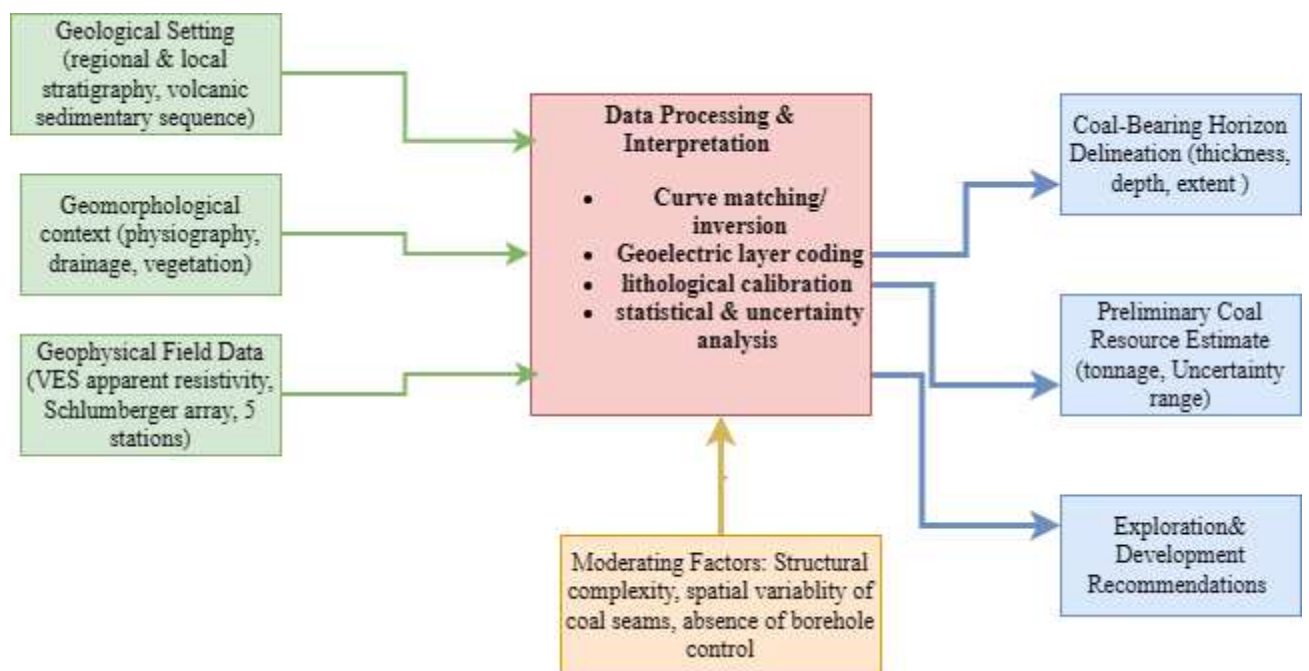


Figure 1. Conceptual framework linking geological/geomorphological inputs, geophysical data processing, and resource-evaluation outcomes.

3. Description of the Study Area

3.1 Location and Accessibility

The study area lies within the Amhara National Regional State, positioned relative to the major urban centres of Dessie and Addis Ababa. The site is situated in Kutaber Woreda, specifically within Berkana Kebele, approximately 3 km east of Berkana settlement. Access is via the main asphalt road from Dessie to Kutaber, continuing along a gravel road connecting Kutaber to Berkana.

The concession boundary of the project area is defined using Universal Transverse Mercator (UTM) coordinates (Adindan Datum, Zone 37N), ranging from 553,398 m to 554,294 m Easting and 1,243,651 m to 1,244,349 m Northing, enclosing an area of approximately 285,000 m² (Table 1). Five VES stations (V1-V5) were distributed across the study area for subsurface investigation (Table 2).

Table 1. Geographic coordinates of the concession boundary.

Point	Easting (m)	Northing (m)	Elevation (m)
B1	554190	1243947	2248
B2	553924	1244150	2239
B3	553703	1244349	2201
B4	553657	1244291	2187
B5	553398	1244271	2151
B6	553398	1244271	2151
B7	553418	1244098	2143
B8	553480	1244049	2156
B9	553654	1244035	2151
B10	553757	1243955	2144
B11	553655	1243821	2189
B12	554139	1243651	2199
B13	554294	1243829	2261

Area = 285,000 m²

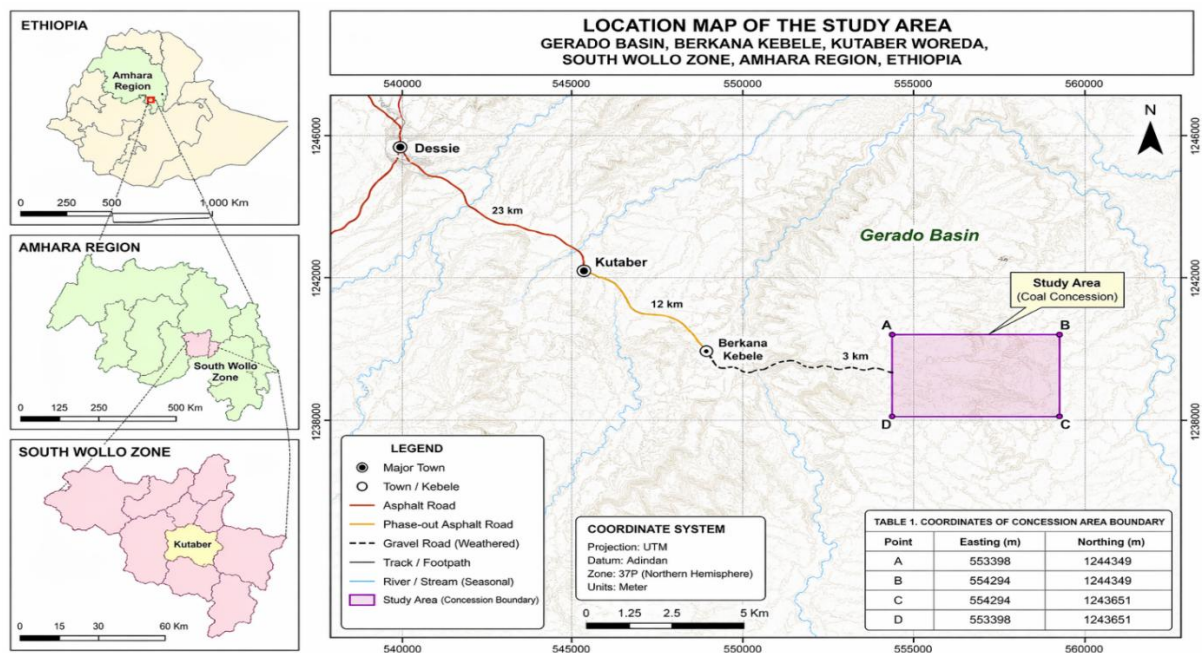


Figure 2: Location Map.

3.2 Physiography and Drainage

The Gerado Catchment, located in north-central Ethiopia within the Blue Nile River Basin, is characterized by a complex physiographic and drainage system reflecting its long-term geological and geomorphological evolution. The terrain is predominantly rugged, comprising elevated plateaus, steep escarpments, and deeply incised valleys, with elevation ranging from approximately 1,897 to 3,264 m above sea level. This marked topographic variation exerts strong control on local climatic conditions, surface runoff, and hydrological processes. The drainage system is mainly dendritic, governed by the underlying volcanic and sedimentary formations, and is well integrated into the broader hydrological framework of the Blue Nile Basin, where numerous tributaries merge into the main river system. Hydrological flow is strongly seasonal, with peak discharge during the rainy season. The interaction between rugged physiography and dendritic drainage significantly influences erosion, sediment transport, and depositional processes within the catchment, which are of particular importance for interpreting the geomorphological development of the area and evaluating its coal occurrences.

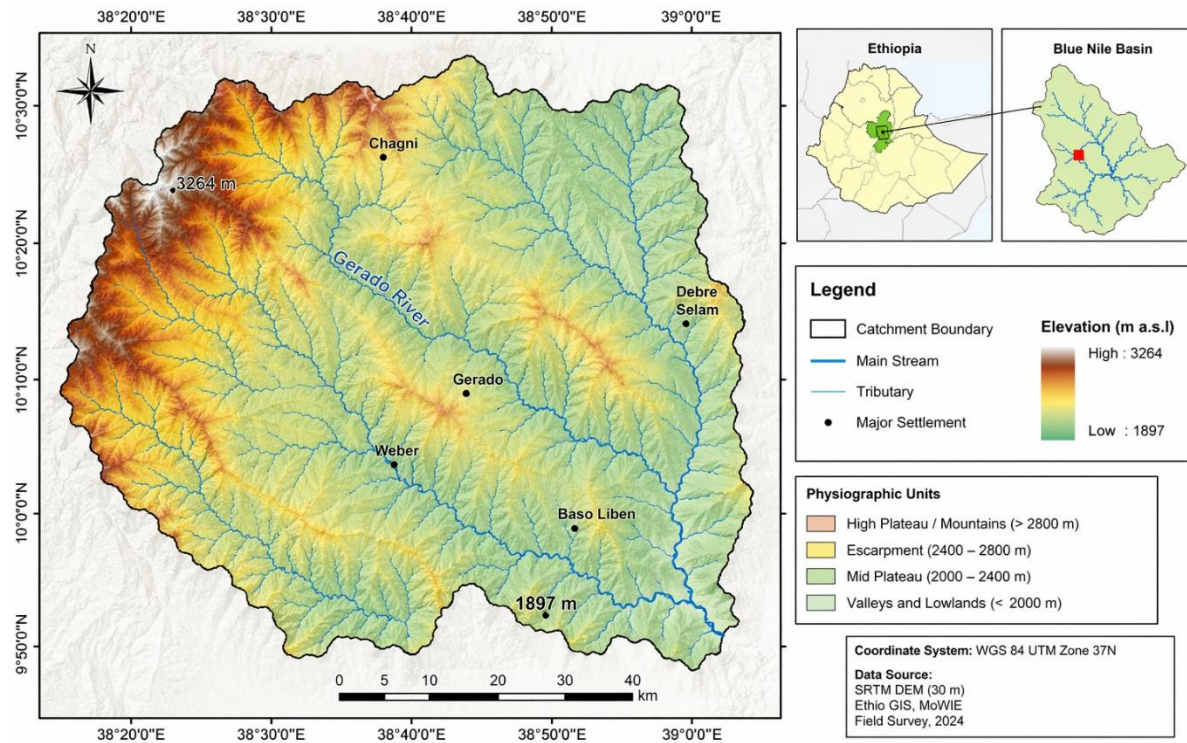


Figure 2: Physiographic and Drainage pattern of the area.

Figure 3: Physiographic and Drainage pattern of the area

3.3 Climate and Vegetation

The Gerado Catchment is characterised by a tropical highland climate with distinct seasonal variability, exhibiting a clear bimodal pattern with a rainy season from May to September and a prolonged dry season for the remainder of the year (World Bank, 2021). Mean annual rainfall ranges from approximately 800 to 1,200 mm, with spatial variability strongly controlled by elevation and the influence of the Intertropical Convergence Zone (National Meteorological Agency [NMA], 2020). Temperature is likewise elevation-dependent, with mean monthly values ranging from about 10°C in high-altitude zones to approximately 25°C in lower-lying areas, consistent with broader patterns described for the Upper Blue Nile basin (Conway, 2000).

Vegetation cover reflects the combined influence of climatic gradients, topography, and human activity. Montane forests and woodlands dominate at higher elevations, while mid- to low-altitude zones are characterised by grasslands and shrublands. Extensive anthropogenic activity - particularly agricultural expansion, settlement, and livestock grazing - has modified the original vegetation cover (Food and Agriculture Organization [FAO], 2020), contributing to habitat fragmentation and localised soil degradation consistent with regionally documented land-degradation processes in the Ethiopian highlands (Hurni, 1988). These vegetation and erosion patterns regulate surface hydrology and soil moisture retention, and provide indirect evidence relevant to interpreting the palaeo-environmental conditions under which coal-bearing sediments accumulated.

3.4 Regional Geology

The study area is located within the central Ethiopian Plateau, near the western margin of the East African Rift System escarpment. Its geological evolution reflects successive tectonic, volcanic, depositional, and erosional events. The area is predominantly covered by extensive fissural flood basalts with subordinate acidic volcanic units belonging to the Ethiopian Trap Series, which account for approximately 90% of the surface geology, reflecting the dominance of Cenozoic volcanism in the region.

The volcanic stratigraphy of Ethiopia is broadly divided into the Trap Series Volcanics (pre-rift to early-rift stage) and the Aden Series Volcanics (post-rift stage). The Trap Series, the oldest and most extensive volcanic episode, is associated with uplift and initial fracturing of the Horn of Africa and is mainly composed of thick flood-basalt sequences with intercalated trachyte and rhyolite. In the central Ethiopian Plateau these sequences attain thicknesses of up to approximately 3 km (Mengesha et al., 1996).

Based on lithology, age, and tectonic evolution, the volcanic rocks are further subdivided according to major eruptive phases. Field investigations and regional correlations indicate three principal basaltic units - the Lower, Middle, and Upper Basalt. Early classification by Blanford (1870) grouped these rocks into the Ashenge and Magdala series; Kazmin (1972) later reclassified them into the Ashenge and Shield groups; and Zanettin and Justin-Visentin (1974) introduced a more detailed subdivision identifying the Lower Basalt (Ashenge Basalt), Middle Basalt (Aiba Basalt), and Upper Basalt (Alaji Basalt together with associated ignimbrites). Post-emplacement tectonic activity, erosion, and sedimentation have locally disrupted the continuity of these volcanic units, producing lithological variation and structural deformation that are directly relevant to geophysical interpretation and coal resource evaluation in the study area.

4.5 Local Geology

The project area comprises three major units: Quaternary sediments, volcanic rocks of varying age (Lower and Middle Basalt), and sedimentary deposits (shale, mudstone, and coal-bearing units). The lithological sequence from top to bottom includes alluvium, Upper Basalt, Middle Basalt, sedimentary units, and Lower Basalt, most of which are depicted on a 1: 100,000-scale geological map derived from a 1: 250,000-scale regional map (Demissie et al., 2010).

Quaternary alluvial sediments are distributed along river channels, floodplains, and valley bottoms as discontinuous, unconsolidated deposits of clay, silt, sand, gravel, and occasional boulders, generally a few metres to about 10 m thick; owing to their limited extent they do not form a continuous mappable unit at regional scale but remain important for recent geomorphic processes.

The coal-bearing sedimentary unit occurs as localised interbeds within the volcanic sequence, particularly between the Lower and Middle Basalt formations. This unit, mainly exposed in the Gerado catchment, consists of carbonaceous shale, silty clay/mudstone, reworked volcanic material, and thin, discontinuous coal seams. The presence of coal layers suggests episodic low-energy depositional environments - such as swampy or lacustrine conditions - during volcanic quiescence (Flores, 2008). The unit exhibits both lateral and vertical lithological variation and generally dips gently toward the southeast.

The dominant lithological units are the Lower and Middle Basalt. The Lower Basalt forms the basal volcanic unit and is typically more weathered and fractured, whereas the Middle Basalt is relatively fresh, massive, and forms prominent ridges and elevated terrain; these flows largely control the rugged topography and structural framework of the area. The Lower Basalt (Ashenge Group, Eocene) is the oldest volcanic unit in the region, exposed in the north-western lowlands, and consists of multiple cyclic flows marked by reddish-brown soil horizons and tuff layers indicating time gaps between eruptions. Fresh rock is dark grey, while weathered zones show light grey, pinkish, or reddish-brown hues; the unit displays columnar joints, aphanitic to micro-porphyrific textures, and feldspar and pyroxene phenocrysts, with morphological expression as stratified cliffs and escarpments.

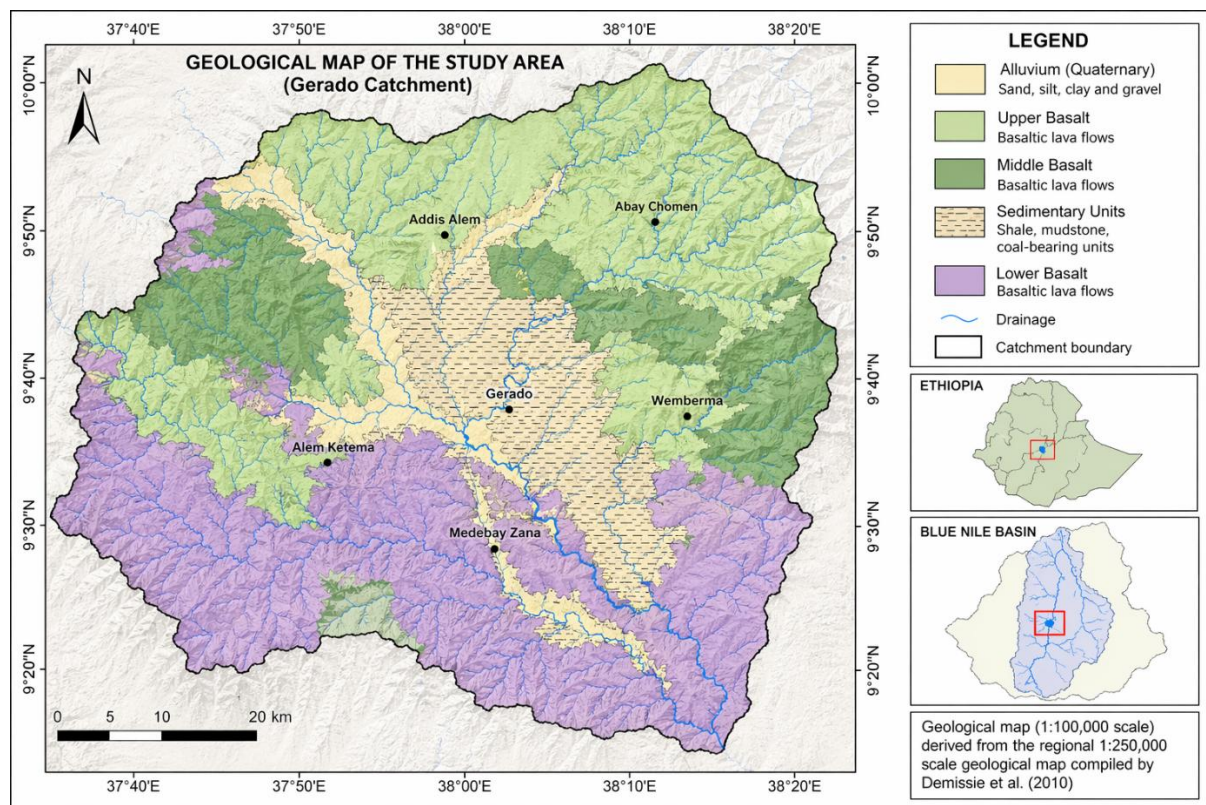


Figure 4: Simplified Geological Map of the Study Area.

3.6 Materials and Methods

3.6.1. Research Design

This study adopts a quantitative, field-based geophysical research design, integrating primary VES field data with secondary geological and geomorphological information. The design follows a sequential explanatory structure: (i) acquisition of primary resistivity data at five stations; (ii) structured coding and classification of the resulting layer sequences; (iii) inversion and geological calibration; (iv) statistical and uncertainty analysis of the coded data; and (v) synthesis into a resource evaluation model. This design was chosen because the research questions concern the geometry and quantifiable extent of a physical subsurface feature (coal-bearing horizons), for which a quantitative, measurement-based approach is appropriate, while the limited number of stations ($n = 5$) motivates transparent uncertainty quantification rather than reliance on a single point estimate.

3.6.2. Data Acquisition and Instrumentation

The geophysical investigation was conducted using a portable integrated resistivity meter (Tetrameter SAS 1000) powered by an external 12 V battery, applying the VES technique to characterise subsurface electrical properties and delineate geological formations (Reynolds, 2011). Prior to field acquisition, a conceptual analysis of the local geology and geomorphology was carried out collaboratively by a geologist and a geophysicist to establish the geological framework and identify suitable measurement locations; survey traverses and electrode azimuths were selected accordingly.

Electrical current was injected into the ground through stainless-steel electrodes arranged in a Schlumberger configuration, and the resulting potential differences were measured to determine apparent resistivity. Measurements were recorded at progressively increasing electrode spacing (maximum $AB/2 = 440$ m), with data plotted in real time on log-log graphs to verify curve consistency and detect anomalies. Data acquisition followed predefined traverses to ensure systematic, spatially representative coverage, generating the dataset used to construct the geoelectric sections presented in Section 6.

3.6.3. Data Coding Procedures

Because VES interpretation ultimately reduces a continuous resistivity sounding curve to a small number of discrete, comparable layer parameters, an explicit coding procedure was applied to ensure that layer identification was systematic, reproducible, and comparable across the five stations, in the same way a coding scheme structures qualitative or mixed-methods data. Two complementary coding layers were applied.

Geoelectric layer coding

Each inverted sounding was decomposed into six geoelectric layers, coded L1-L6, based on inflection points in the resistivity-depth curve and cross-checked against known local lithology:

Code	Layer description	Typical resistivity (Ωm)	Assigned lithology
L1	Uppermost layer	5 - 663 (site-dependent)	Overburden: soil, mudstone, or weathered basalt
L2	Second layer	72 - 331	Upper coal-bearing unit
L3	Third layer	1 - 26	Clay-rich parting / sediment
L4	Fourth layer	124 - 808	Lower coal-bearing unit (intercalation)
L5	Fifth layer	1 - 48	Sedimentary unit (clay/silt)
L6	Basal layer (open-ended)	133 - 1,476	Lower Basalt (basement)

Layers were coded independently by the interpreting geophysicist and cross-checked against the geological log for each station; disagreements in code assignment (e.g., where a thin parting could plausibly be merged with an adjoining coal layer) were resolved by consulting the resistivity contrast threshold (a factor of at least 3x relative to the adjoining layer) as the coding rule, consistent with standard practice for distinguishing coal from clay-rich sediment (Telford et al., 1990).

VES curve-type coding

In addition to layer-level coding, each station's six-layer resistivity sequence was coded into a standard sounding-curve type by comparing successive layer resistivities ($\rho_1 \dots \rho_6$): a K-code was assigned where $\rho_i < \rho_{i+1} > \rho_{i+2}$ (resistive layer sandwiched between conductive layers), an H-code where $\rho_i > \rho_{i+1} < \rho_{i+2}$ (conductive layer sandwiched between resistive layers), an A-code for a monotonically increasing sequence, and a Q-code for a monotonically decreasing sequence (Telford et al., 1990). This produced a composite curve-type code for each station, which serves as a rapid diagnostic cross-check on the layer-coding scheme: a coal-bearing interval coded as L2 or L4 should coincide with a K-segment (resistive coal flanked by conductive clay), and any station for which this did not hold was flagged for re-inspection of the inversion.

3.6.4. Data Processing and Presentation

Sounding data were processed and interpreted using electrical resistivity inversion software, including IPI2Win and Win Resist, complemented by ArcGIS, Surfer, and Global Mapper for spatial analysis and presentation. During processing, geoelectric layers were identified and their thicknesses and resistivity values determined by calibrating observed resistivity against known local geological units, providing a reliable framework for subsurface stratigraphic interpretation. Processed VES data were presented as resistivity curves and geoelectric sections, forming the basis for the physical characterisation of coal properties and the calculation of coal reserves.

3.6.5. Data Analysis Framework

Following data coding, four linked analytical stages were applied to the coded dataset (Figure 5): (i) descriptive statistical analysis of layer thickness and resistivity across the five stations (mean, standard deviation, coefficient of variation), used to quantify lateral homogeneity/heterogeneity of each coded layer; (ii) construction of geoelectric cross-sections along three transects (V1-V2-V3, V1-V2-V5, and V3-V4) to visualise lateral continuity; (iii) deterministic coal tonnage calculation using the conventional area x thickness x density model; and (iv) Monte Carlo uncertainty propagation, in which the area, mineable seam thickness, and coal density are each represented as triangular probability distributions (reflecting boundary-delineation uncertainty, the observed range of combined coal thickness across stations, and the published density range for sub-bituminous coal, respectively) and combined through 200,000 simulation draws to generate a full tonnage probability distribution rather than a single point estimate.

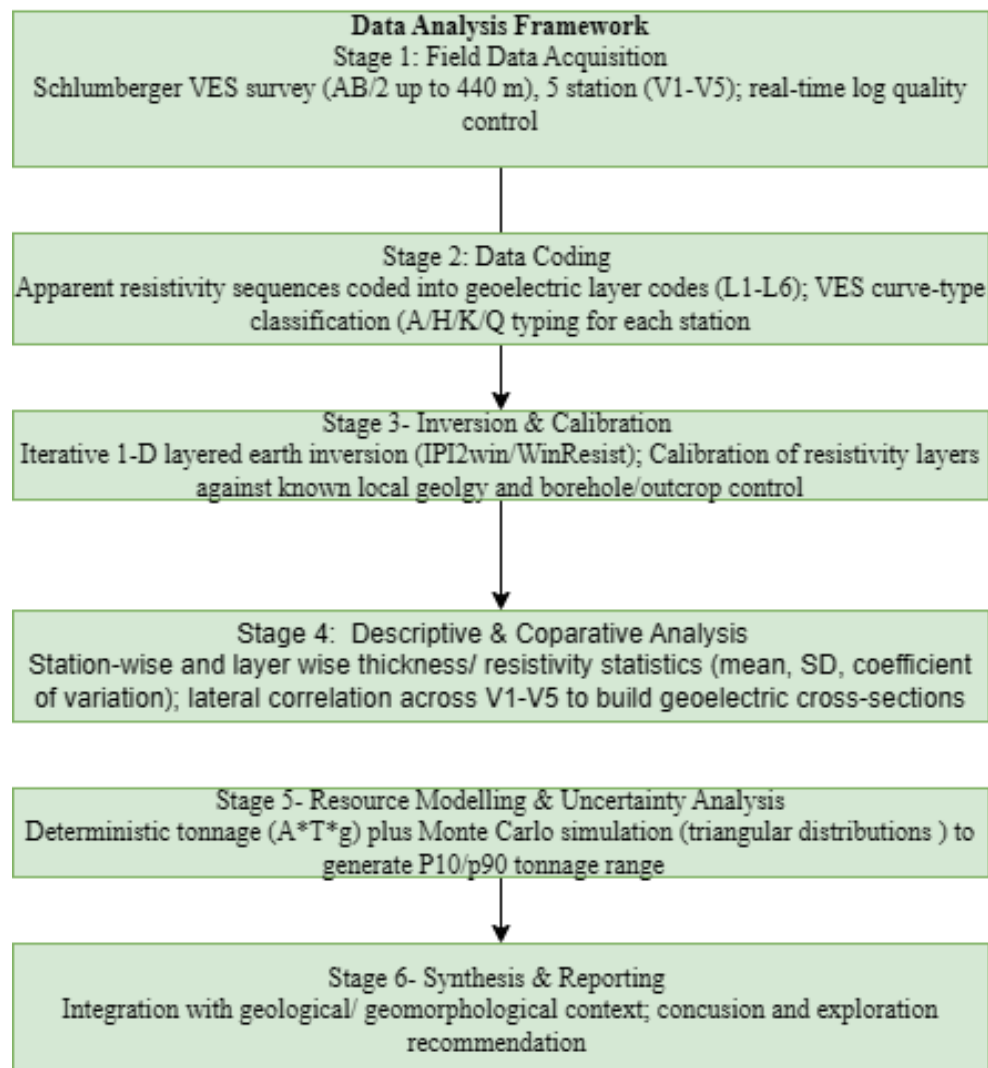


Figure 5. Data analysis framework applied to the coded VES dataset, from field acquisition through resource-uncertainty modelling.

3.6.6. Coal Resource Estimation Model

The deterministic resource estimate follows the standard tonnage formula for tabular deposits:

$$\text{Tonnage (t)} = A \times T \times g$$

where A is the probable potential area delineated from the geophysical survey (m²), T is the considered average coal-bed thickness (m), and g is the specific gravity (bulk density) of sub-bituminous coal (t/m³). For the Monte Carlo model, A, T, and g were each sampled from a triangular distribution parameterized by a minimum, most-likely (mode), and maximum value, and the resulting tonnage distribution was summarized using the P10, P50 (median), and P90 percentiles, a reporting convention consistent with standard mineral-resource uncertainty communication.

4. Results

The primary objective of the geophysical survey was to investigate the subsurface characteristics of the coalfield: identifying lithologies, estimating the extent and thickness of coal seams, and locating structural features influencing the geology (Tesfaye & Gebretsadik, 2018). VES was employed as the principal method for determining the thickness and lateral extent of formations, identifying structural features, and characterising subsurface layers (Reynolds, 2011). The Schlumberger array configuration was applied at five stations across the concession area (Table 2), providing data on overburden thickness, stratigraphic units, resistivity values, and inferred rock types.

Table 2. VES station coordinates.

Station	Easting (m)	Northing (m)	Elevation (m)
V1	553796	1243938	2145
V2	553786	1243975	2140
V3	553735	1244120	2154
V4	553552	1244214	2135
V5	553514	1244110	2147

4.1 Summary of Interpreted Geoelectric Layers

Interpretation of the inverted VES curves identified six geoelectric layers, coded L1-L6 as described in Section 3.6.3, consistently recognisable at all five stations (Table 3).

Table 3. Summary of interpreted geoelectric layers by station.

Station	Code	Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred lithology
V1	L1	78	0.54	0.54	Mudstone & soil
	L2	309	1.44	1.98	Upper coal-bearing unit

Station	Code	Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred lithology
	L3	3	1.78	3.76	Clayey sediment
	L4	124	2.36	6.12	Lower coal-bearing unit
	L5	1-42	4.38	10.50	Sedimentary unit
	L6	1,126-1,476	-	-	Lower Basalt
V2	L1	360	0.87	0.87	Mudstone & soil
	L2	72	3.47	4.34	Upper coal-bearing unit
	L3	26	1.21	5.55	Sediment
	L4	220	1.16	6.71	Lower coal-bearing unit
	L5	2-48	3.79	10.50	Sedimentary layer
	L6	133-1,126	-	-	Lower Basalt
V3	L1	22-207	14.2	14.2	Weathered basalt, mudstone & soil
	L2	331	2.6	16.8	Upper coal-bearing unit
	L3	2	1.7	18.5	Clayey sediment
	L4	776	4.1	22.6	Lower coal-bearing unit
	L5	5	7.0	29.6	Sedimentary unit
	L6	219-880	-	-	Lower Basalt
V4	L1	11-663	4.54	4.54	Upper basalt, mudstone & soil
	L2	241	2.43	6.97	Upper coal-bearing unit
	L3	3	1.43	8.40	Sediment
	L4	518	2.80	11.20	Lower coal-bearing unit
	L5	6	8.80	20.00	Sedimentary layer
	L6	228-847	-	-	Lower Basalt
V5	L1	5-207	5.21	5.21	Mudstone & soil
	L2	220	1.89	7.10	Upper coal-bearing unit
	L3	1	3.60	10.70	Clayey sediment
	L4	808	3.40	14.10	Lower coal-bearing unit
	L5	4	14.90	29.00	Sedimentary unit
	L6	227-534	-	-	Lower Basalt

4.2 Descriptive Statistics and VES Curve-Type Classification

To quantify lateral homogeneity of each coded layer across the five stations, descriptive statistics (mean, standard deviation, and coefficient of variation, CV) were computed for layer

thickness and resistivity (Table 4). The coal-bearing layers (L2, L4) show moderate variability (thickness CV of 32.5% and 40.2%, respectively), while overburden (L1) is highly heterogeneous (CV = 108.8%), consistent with its interpretation as a weathered, erosively modified surface unit rather than a laterally continuous stratum.

Table 4. Descriptive statistics of layer thickness and resistivity across VES stations V1-V5 (n = 5).

Layer	Description	Mean thickness (m)	SD	CV (%)	Mean resistivity (Ωm)	SD	CV (%)
L1	Overburden	5.07	5.52	108.8	165.6	119.0	71.9
L2	Upper coal-bearing	2.37	0.77	32.5	234.6	101.9	43.4
L3	Clay-rich parting	1.94	0.95	49.0	7.0	10.7	152.2
L4	Lower coal-bearing	2.76	1.11	40.2	489.2	312.5	63.9
L5	Sedimentary unit	7.77	4.47	57.5	12.2	10.0	81.8

Applying the curve-type coding scheme of Section 5.3.2 to the six-layer resistivity sequence at each station produced the classification in Table 5. Four of the five stations (V1, V3, V4, V5) show an identical KHKH-type sequence, indicating a consistent resistive-conductive-resistive-conductive layering style across most of the survey area; V2 shows a QHKH sequence, reflecting a locally thicker, more resistive overburden layer at that station. In all five stations, both coal-bearing layers (L2, L4) coincide with a K-segment (resistive layer flanked by conductive layers), confirming internal consistency between the layer-coding and curve-type-coding schemes.

Table 5. VES curve-type classification by station.

Station	Curve-type code	Interpretation
V1	KHKH	Resistive-conductive-resistive-conductive; both coal layers coincide with K-segments
V2	QHKH	Monotonically decreasing overburden segment, then resistive-conductive-resistive-conductive
V3	KHKH	Resistive-conductive-resistive-conductive; thickest overburden (14.2 m) among all stations
V4	KHKH	Resistive-conductive-resistive-conductive
V5	KHKH	Resistive-conductive-resistive-conductive

4.3 Geoelectric Cross-Sections

Geoelectric cross-sections were constructed along three transects using the layer thickness and depth data in Table 3, plotted to true scale from the interpreted VES results (rather than schematically), to visualise lateral continuity of the coal-bearing horizons. Figure 4 presents a south-to-north section through V1, V2, and V3; Figure 5 presents a southeast-to-northwest section through V1, V2, and V5; and Figure 6 presents an east-to-west section through V3 and V4.

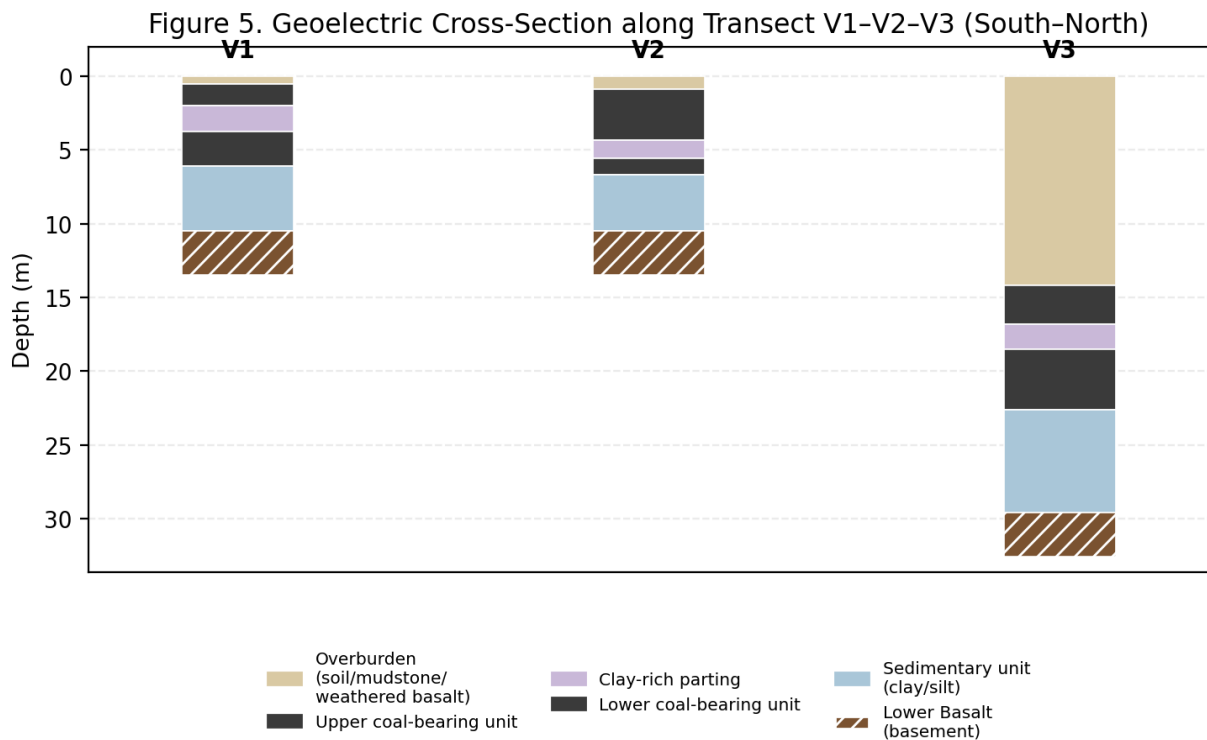


Figure 6. Geoelectric Cross-Section along Transect V1-V2-V5 (Southeast-Northwest)

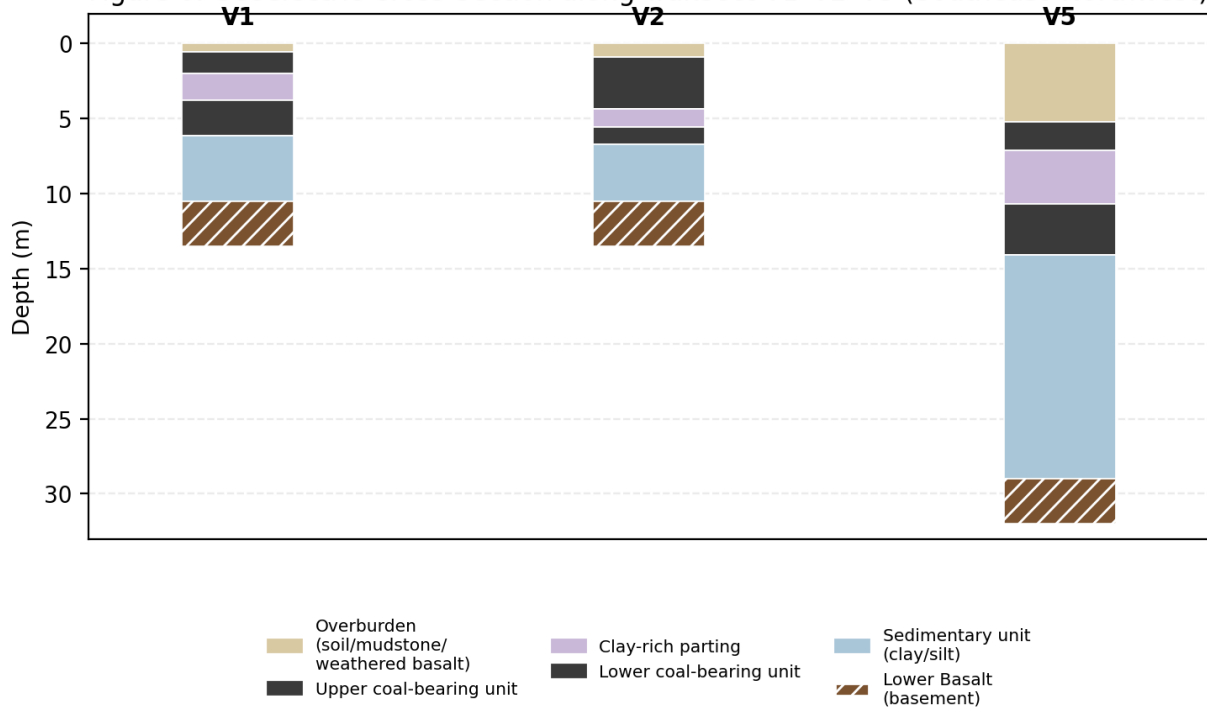
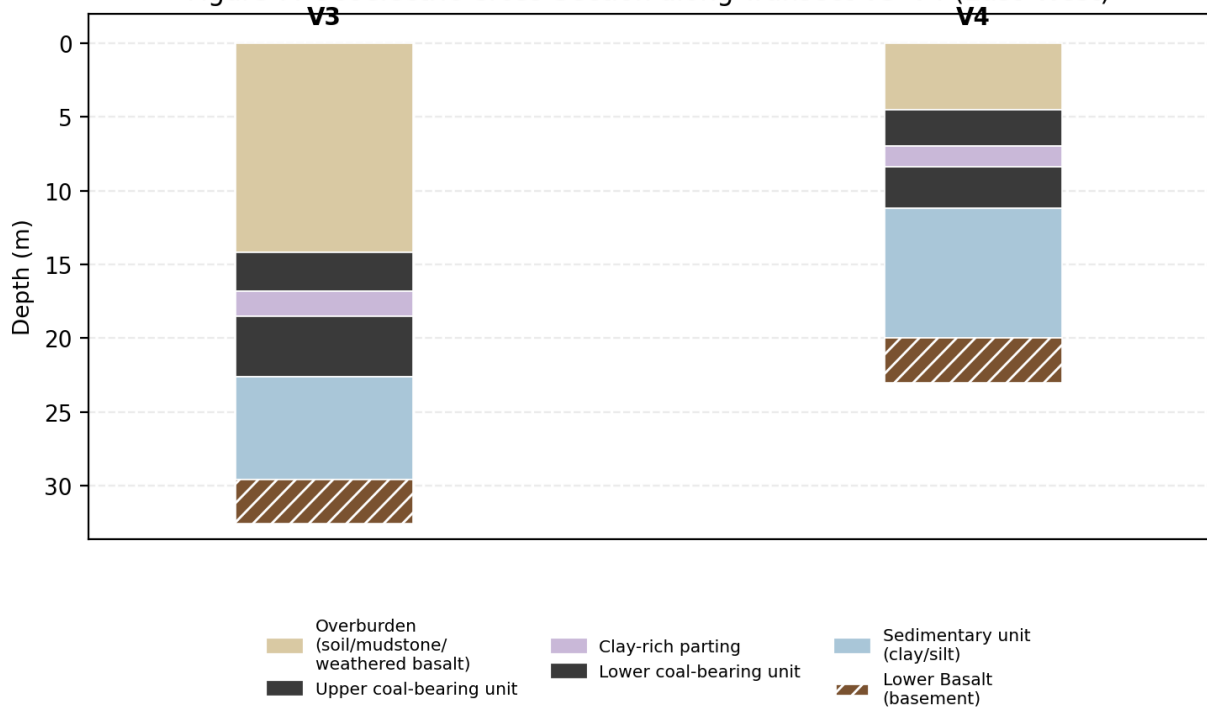


Figure 7. Geoelectric Cross-Section along Transect V3-V4 (East-West)



The sections show that both coal-bearing horizons persist across all sampled stations, but their thickness and depth vary considerably: the combined overburden-plus-parting package is thickest at V3 (consistent with its distinct QHKH-adjacent, thick-overburden signature), while the coal horizons themselves are thickest at V2 (upper layer) and V3 (lower layer). This lateral variability is consistent with deposition in discontinuous, structurally influenced swampy or lacustrine sub-basins rather than a single laterally continuous seam.

4.4 Probable Potential Coal-Bearing Sediments

Based on interpretation of the VES results, two probable coal-bearing horizons were identified within the sedimentary sequence interbedded between the Lower and Middle Basalt units, corresponding to the stratigraphic interval between the Ashenge and Aiba formations. These horizons are interpreted as upper (L2) and lower (L4) coal-bearing sedimentary layers, characterised by intermediate-to-high resistivity and lateral continuity across the survey points (Table 6).

Table 6. Estimated thickness of probable potential coal-bearing sediments by station.

Station	Upper coal-bearing layer (m)	Lower coal-bearing layer (m)	Combined thickness (m)
V1	1.44	2.36	3.80
V2	3.47	1.16	4.63
V3	2.60	4.10	6.70
V4	2.43	2.80	5.23
V5	1.89	3.40	5.29
Mean (SD)	2.37 (0.77)	2.76 (1.11)	5.13 (1.06)

4.5 Coal Resource Evaluation

Despite the structural and stratigraphic complexity of the concession area, the interpreted geoelectric data provided a reasonable basis for preliminary coal resource evaluation. The deterministic evaluation (Table 7) uses the interpreted coal-bearing thickness, the areal extent derived from geophysical coverage (Figure 2; Table 8), and an assumed coal density consistent with sub-bituminous coal.

Table 7. Deterministic resource evaluation of the coal-bearing sediment.

Parameter	Value
Average coal-bearing layer thickness from geoelectric analysis (m)	5.13
Average coal-bed thickness considered for mining, T (m)	2.5
Probable potential area, A (m ²)	102,500
Specific gravity of sub-bituminous coal, g (t/m ³)	1.4
Deterministic tonnage = A x T x g (t)	358,750

Table 8. Geographic coordinates of the probable potential coal-bearing area.

Point	Easting (m)	Northing (m)	Elevation (m)
B1	553373	1244078	2140
B2	553418	1244246	2140
B3	553555	1244222	2140
B4	553760	1244111	2160
B5	553867	1243986	2159
B6	553744	1243849	2170

Area = 102,500 m²

The deterministic figure above treats A, T, and g as fixed values, which does not reflect the measurement and geometric uncertainty inherent in a five-station survey. A Monte Carlo simulation (200,000 draws) was therefore run using triangular distributions for each input parameter: A between 92,250 and 112,750 m² (mode 102,500 m², reflecting +/-10% boundary-delineation uncertainty); T between 2.0 and 6.7 m (mode 2.5 m, spanning the observed range of combined coal thickness in Table 6); and g between 1.25 and 1.50 t/m³ (mode 1.40 t/m³, spanning the published density range for sub-bituminous coal). The resulting tonnage distribution (Figure 7; Table 9) has a median (P50) of approximately 504,000 t, with a P10-P90 range of approximately 350,000-753,000 t, indicating that the original single-value estimate of 358,750 t sits toward the lower end of the plausible range once parameter uncertainty is propagated.

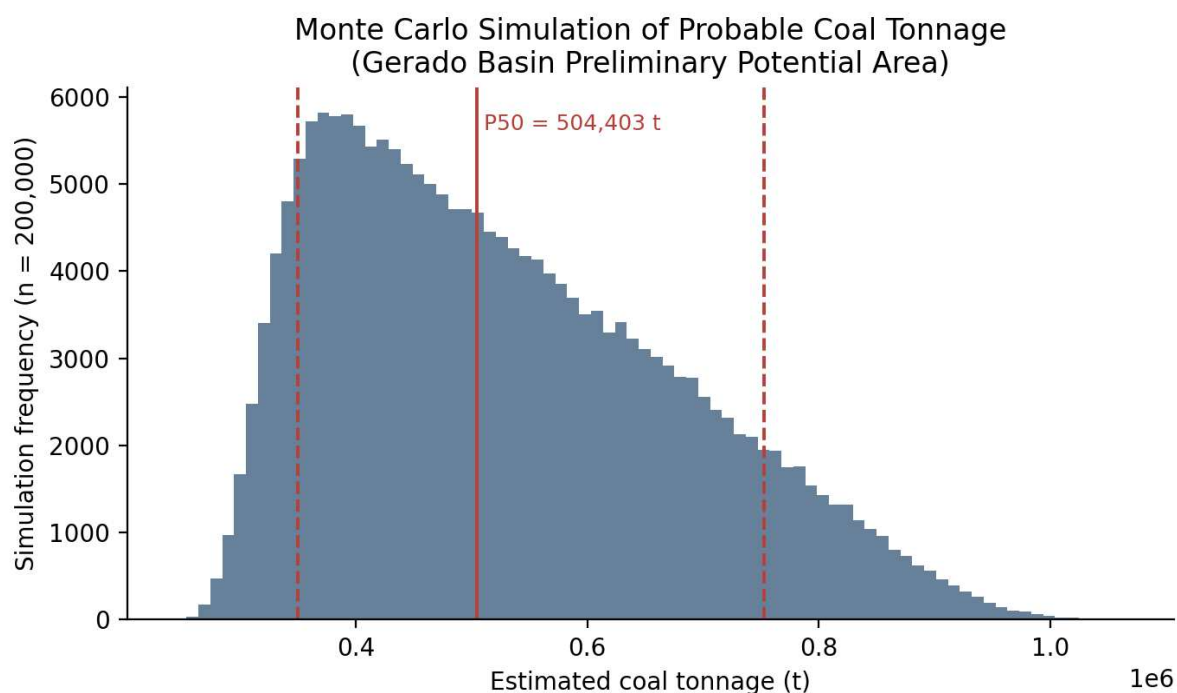


Figure 7. Monte Carlo simulation (n = 200,000) of probable coal tonnage, showing the P10, P50, and P90 percentiles.

Table 9. Monte Carlo resource uncertainty summary.

Statistic	Tonnage (t)
P10 (90% probability of exceeding)	349,971
P50 / median	504,403
P90 (10% probability of exceeding)	752,600
Simulation mean	529,506
Simulation SD	152,276

5. Discussion

The results confirm that two coal-bearing horizons are consistently present across the surveyed portion of the Gerado Basin, interbedded between the Lower and Middle Basalt formations, with a mean combined thickness of 5.13 m (SD = 1.06 m; CV = 20.7%). This moderate coefficient of variation indicates that, unlike the highly heterogeneous overburden (CV = 108.8%), the coal-bearing interval itself is comparatively laterally persistent across the five-station transect network, which is encouraging for continuity but should not be over-interpreted given the small sample size.

The near-uniform KHKH curve-type classification at four of five stations (Table 5) provides an internally consistent, independent cross-check on the layer-coding scheme described in Section 5.3: because both coal-bearing layers systematically coincide with the resistive limbs

of the K-segments, the coding procedure is unlikely to be an artefact of an arbitrary inversion choice. The one station showing a different curve type (V2, QHKK) coincides with the thickest overburden-adjacent resistive package, plausibly reflecting locally variable weathering or a near-surface volcanic clast horizon rather than a fundamentally different coal-bearing sequence, since its L2 and L4 layers still code consistently as coal-bearing K-segments.

The resource evaluation illustrates why single-value tonnage estimates can be misleading in early-stage, sparse-station surveys. The original deterministic estimate of 358,750 t corresponds closely to the lower quartile of the Monte Carlo distribution (P10-P50 range), meaning that a reader relying on the point estimate alone would substantially underestimate the resource's most likely value (P50 ~ 504,000 t) while also underappreciating the possibility of a materially larger or smaller resource (P10-P90 range of roughly 350,000-753,000 t). This uncertainty is driven jointly by the areal-delineation assumption, the choice of mineable seam thickness relative to the larger combined coal thickness observed geophysically, and the density range reported for sub-bituminous coal; drilling-based validation of seam thickness would be the single most effective way to narrow this range, since T contributes proportionally more to the spread than either A or g in the simulation design used here.

These findings should be interpreted in light of the study's methodological limitations. First, coal, carbonaceous shale, and clay-rich mudstone can present overlapping resistivity signatures, so lithological identification from resistivity contrast alone carries inherent ambiguity that only borehole calibration can resolve (Sharma, 1997). Second, the five-station network, while adequate for a first-pass reconnaissance survey, is too sparse to resolve seam pinch-outs, faulting, or small-scale facies changes between stations; the geoelectric sections in Figures 4-6 interpolate linearly between measured points and should be read as first-order approximations of the true subsurface geometry. Third, the density and thickness ranges used in the Monte Carlo model are informed by regional literature values and the observed VES thickness range rather than site-specific laboratory measurements, and should be refined once core samples become available.

6. Conclusion & Recommendations

This study integrated geological interpretation with Vertical Electrical Sounding to characterise coal-bearing formations in the Gerado Basin, applying an explicit data-coding procedure (geoelectric layer coding and VES curve-type classification) and a structured data-analysis framework that combines descriptive statistics with Monte Carlo uncertainty propagation. Six

geoelectric layers were consistently identified at five VES stations, with two coal-bearing horizons occurring between the Lower and Middle Basalt formations at a mean combined thickness of 5.13 m and overburden ranging from 0.54 to 14.2 m. Four of five stations exhibit a consistent KHKH sounding-curve type, supporting the internal reliability of the layer-coding scheme.

The probable potential coal-bearing area, covering approximately 102,500 m², yields a deterministic tonnage estimate of about 358,750 t; explicitly modelling the uncertainty in areal extent, mineable thickness, and coal density instead yields a P50 estimate of approximately 504,000 t within a P10-P90 range of roughly 350,000-753,000 t. Taken together, these results indicate that the Gerado Basin possesses moderate coal potential with possible economic significance, but the estimate remains preliminary, geophysically constrained rather than geologically confirmed, and subject to the absence of borehole control.

To improve the reliability of the subsurface interpretation and further assess the economic viability of the coal deposit, the following are recommended:

1. Exploratory drilling: Shallow boreholes at selected VES locations to validate interpreted lithological boundaries, confirm coal-seam thickness, and determine lateral continuity of the coal-bearing horizons, and to directly constrain the T parameter used in resource modelling.
2. Detailed geological mapping: High-resolution geological mapping to refine the structural and stratigraphic framework and improve correlation with geophysical results.
3. Geochemical and petrographic analysis: Laboratory analysis of coal and associated sediment samples to determine ash content, calorific value, moisture content, and rank classification.
4. Advanced geophysical surveys: Complementary methods such as seismic refraction or 2D/3D electrical resistivity tomography (ERT) to enhance subsurface resolution and structural interpretation, particularly across the V2 anomaly.
5. Integrated resource evaluation and reporting: A comprehensive resource model integrating geological, geophysical, and drilling data, reported with an explicit uncertainty range rather than a single deterministic tonnage figure, to support upgrading the resource classification from inferred to indicated or measured categories.

Declarations

Ethics, Consent to Participate, and Consent to Publish declarations: Not applicable.

Competing Interests: The authors declare that they have no competing interests.

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Author Contributions

To be completed by the authors following standard CRediT taxonomy (e.g., conceptualization, methodology, field investigation, formal analysis, writing - original draft, writing - review and editing, supervision).

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