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GEOPHYSICAL EVALUATION OF COAL DEPOSITS IN PART OF NORTHERN ANAMBRA BASIN NIGERIA, USING ELECTRICAL RESISTIVITY AND BOREHOLE DATA

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Abstract
This study integrates geophysical and borehole methods to evaluate coal deposits in part of the Northern Anambra Basin, Nigeria using vertical electrical sounding (VES) and 2D electrical resistivity imaging (ERI) in conjunction with borehole data. The geoelectric survey reveals five to nine distinct lithological layers, comprising of sandy soil, clay, shale, sandstone, sandy shale, shaly sandstone, interbedded sandstone and shale bed and coal. The coal seam is embedded within the alternating sandstone and shale beds. Coal seam thickness ranges from 0.5 to 6.1 meters, with thicker deposits concentrated in the southwestern and northwestern regions. Geoelectric sections were correlated with borehole lithologic logs for subsurface validation and structural interpretation. Utilizing the relationship between resistivity and coal properties, the coal core samples obtained from borehole intersections were subjected to proximate and ultimate analyses, enabling the identification of high-quality coal zones. Overburden thickness varies from 5 meters in the east to 140 meters in the west, influencing mining method selection. Open-pit mining is feasible in the eastern section, while underground mining is preferable in deeper western deposits. Structural controls, including monoclines and potential faults, influence coal thickness and geoelectric layer continuity, while groundwater intrusion affects the coal seam resistivity and moisture content. The study also presents 2D resistivity models, which visually depict coal seam geometry, overburden variations, and groundwater-influenced zones. A total coal resource of approximately 23.86 million metric tonnes is estimated, with an overall strip ratio of 22.63. The study concludes that the identified high-quality coal zones with moderate overburden suggest viable extraction opportunities, while areas with deep overburden require strategic mining plans.

Keywords: *Vertical Electrical Sounding, 2D Electrical Resistivity Imaging; Coal Seam, Mamu Formation and Ajali Formation*

Introduction

Coal is a significant global energy resource, primarily used for electricity generation (Schnapp and Smith, 2012). It consists mainly of carbon, with varying amounts of hydrogen, sulfur, oxygen, nitrogen, and trace elements, including mineral matter (Onoduku, 2014). It is more cost-effective than oil or natural gas and easier to transport, making it a vital energy source for various industries, including iron and steel production. Despite increasing global efforts of transition to renewable energy sources, coal remains a key component in power generation, especially in developing countries (Coal Industry Advisory Board, 2008). In many countries, coal is the primary source of energy (Tutmez*et al.*, 2013; Saini *et al.*, 2016), and it contributes to economic development, promoting a high standard of living for people.

Despite its economic benefits, coal utilization poses significant environmental challenges. The processes involved in coal storage, transportation, combustion, and processing release harmful trace elements such as Cu, Pb, Hg, Mo, and F into the environment (Baruah and Khare, 2010; Xiao *et al*., 2016). These contaminants necessitate effective mitigation strategies before coal utilization (Rajak *et al*., 2019). While the environmental and health concerns surrounding coal are well documented, policymakers in newly industrializing countries often emphasize the importance of coal for industrial development in specific regions (Kalkuhl *et al*., 2019). However, urgent climate change action requires a rapid reduction in coal use without carbon capture and storage (Luderer *et al*., 2018).

In Nigeria, coal production has declined significantly in recent decades, posing challenges to economic growth. The country's energy crisis could be mitigated by utilizing coal as an alternative power source. Historically, coal supported key industries such as cement production, railway transportation, and electricity generation (Odesola *et al*., 2013). Nigeria is endowed with extensive coal deposits, primarily located in the Anambra Sedimentary Basin (Obaje *et al*., 1994). These deposits, which include lignite, sub-bituminous, and bituminous coal, have been found suitable for boiler fuel, gas production, domestic heating, and chemical manufacturing including waxes, resins, adhesives, and dyes (Ministry of Mines and Steel Development, 2010).

The coal deposits in the Anambra Basin, particularly in locations such as Ogboyoga and Okaba (Kogi State), Owukpa (Benue state) and Enugu coal, represent the largest and most economically viable reserves in the country (Fatoye and Gideon, 2013). Nigeria possesses substantial coal reserves, yet they remain largely underutilized. Given the limitations of gas-fired and diesel-powered generation, coal presents a viable alternative for increasing Nigeria's electricity supply.

However, detailed exploration and evaluation of Nigeria's coal reserves, particularly in the Anambra Basin, remain insufficient. Many awarded exploration blocks have yet to undergo thorough geological assessment. The absence of comprehensive geophysical and geochemical data further hampers coal development. While geophysical methods (electrical resistivity) are effective in mapping coal seams, their relationship with geochemical parameters (for example, ash content, fixed carbon, calorific value, moisture content) are not well established in existing literature. This study seeks to bridge this gap by employing an integrated approach involving field mapping, electrical resistivity surveying, and exploratory core drilling data to assess the coal potential of the study area.

Location and Geologic setting of the Study Area

The study area lies within Latitudes 7° 41' 20'' to 7° 43' 17.7'' and Longitudes 7° 10' 49.6'' to 7° 12' 14.6'' in the Northern Anambra Sedimentary Basin, Southeastern Nigeria (Fig. 1). The area, approximately 9 km², is accessible via the Ankpa-Otukpa road, located 9 km from Otukpa town.

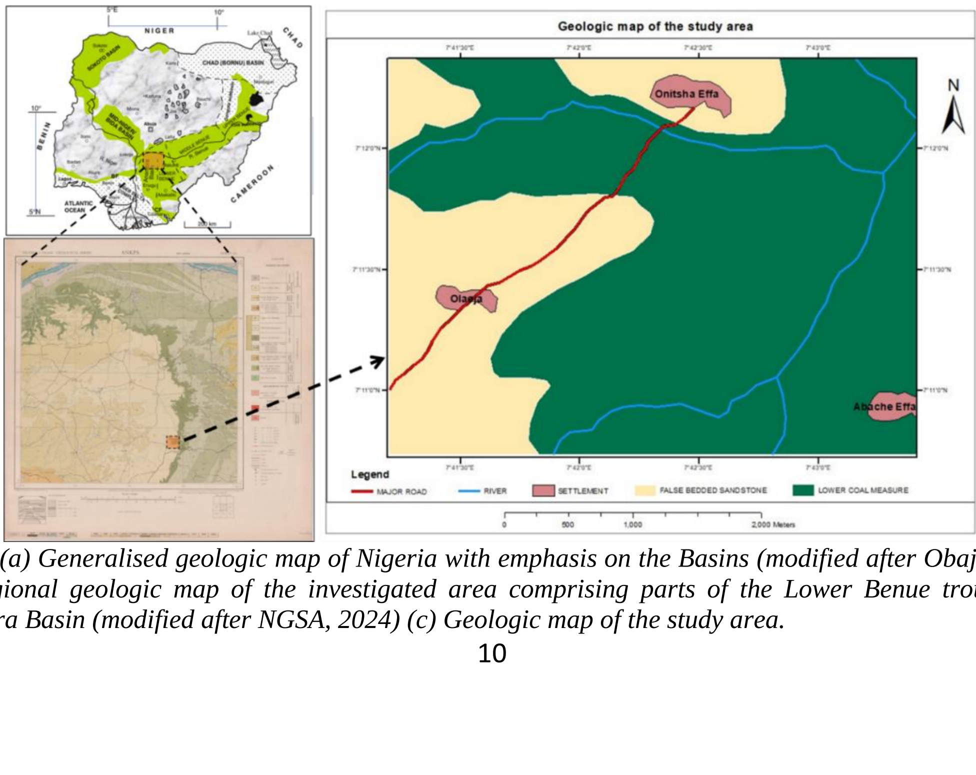

Fig. 1: (a) Generalised geologic map of Nigeria with emphasis on the Basins (modified after Obaje, 2009) (b) Regional geologic map of the investigated area comprising parts of the Lower Benue trough and Anambra Basin (modified after NGSA, 2024) (c) Geologic map of the study area.

The Anambra Basin's sedimentary fill occurred between the Late Santonian and Danian, spanning approximately 11 million years (Nwajide, 2005). Gravity measurements estimate the basin's sediment thickness to range from 1,000 to 4,500 m (Ladipo *et al*., 1992), with 3,000-3,500 m deposited during the Late Cretaceous (Late Campanian to Maastrichtian).The Campanian-Maastrichtian stratigraphic succession in the Anambra Basin includes; Nkporo Shale Group (Campanian) which consists of three Formations, namely; Nkporo Shale (composed of dark shales and mudstones interbedded with thin sandy shale and sandstone layers, (Kogbe, 1976); Enugu Shale(primarily composed of carbonaceous shales and coals, deposited in floodplain and swamp environments according Ladipo *et al*. (1992); Owelli Sandstone (composed of the major sand unit of the Enugu Shale, forming elongated, northeast-trending shoestring sand bodies that indicate fluvial/distributary channel deposition).

This is overlain by Mamu Formation (Early to Late Maastrichtian), which according to Umeji (2002) contains three lithologic units: 1) Lower Unit: which contains black carbonaceous marine shales overlain by sandy shoreface deposits with heterolithic wave-rippled and flaser-bedded fine white sandstones interlaminated with dark grey mudstones; 2) Middle unit:Coal-bearing facies and 3) Upper unit: Fine to medium-grained sandstones with climbing ripple lamination. The studied section lies within the upper part of the coal-bearing facies.

Following this is the Ajali Sandstone (Middle to Late Maastrichtian): which is composed of thick, friable, poorly sorted sandstones, typically white but sometimes iron-stained (Reyment, 1965). Hence, the Nsukka Formation (Late Maastrichtian to Danian) conformably overlies the Ajali Sandstone. It consists of alternating sandstone, dark shale, and sandy shale with thin coal seams (Simpson, 1954). Thin limestone beds occur towards the top (Reyment, 1965).

Methodology

Electrical resistivity surveying was carried out employing the vertical electrical sounding (VES) technique using Schlumberger electrode configuration at forty-three locations (Figure 2) in east-west and north-south azimuth in the study area. VES point separation is between 400 m to 800 m such that the total area surveyed is approximately 9 km^2. A total of 43 VES were conducted with a minimum current electrode separation of 1.0 m and a maximum current electrode separation range of 300 - 400 m. The potential electrodes were made to remain fixed while the current electrodes spacing expands symmetrically about the centre of the spread. For large values of current electrode spacing the separation of the potential electrodes were also increase in order to maintain measurable potential at all times. The ground resistance R measured at each current electrode sampling point were recorded and inserted into the equation below to obtain the corresponding apparent resistivity (ρ_a) values.

$$\rho_a = GR$$

Where: G= Geometric factor.

The apparent resistivity data computed were plotted against one half of the current electrodes spacing (AB/2) on a bi-logarithmic graph and interpreted using an iterative computer software called WinResist software (Udo *et al*., 2024). The contrasts in electrical resistivity existing between lithological sequences in the subsurface (Lashkarripour, 2003; Udo *et al*., 2021) were used in the delineation of geoelectric layers. The resistivity and depths values obtained were used to produce geologic section in the study area.

More so, a total of twenty-eight 2D ERI were conducted using dipole-dipole array. Figure 2 shows the locations of the 2D ERI profile lines. A resistivity meter called ABEM Tarameter LS (multielectrode imaging unit), with 64 electrodes connected to the resistivity meter through a multi-core reversible cable was used in the study. The survey objective was defined and the appropriate electrode array (dipole-dipole) was selected. The electrodes are laid out in straight lines and cables connected to the instrument such that the minimum traverse length was 315m for a 5m electrode intervals and maximum 630m for a 10m electrode interval. The survey setting was configured and the automated data acquisition were done in all locations and saved. The downloaded resistivity datasets were processed, filtered and inverted using the Earth Imager software technique to determine the distribution of 2D resistivity and inverse model images in the subsurface. The measured apparent resistivity data were inverted by comparing it with a calculated model and an inverted 2D inverted resistivity sections were generated. The inverted 2D Electrical resistivity section is presented in a color coded format which shows the lateral and vertical subsurface distribution based on its electrical resistivity representation. The vertical scale on the 2D electrical resistivity section is the investigated. The lateral scale represents the horizontal distance on ground and the resistivity range of each color is presented as a logarithmic color scale bar. The resistivity images were then used to characterize the subsurface and delineate the coal deposit and water bearing zone in the area. High-definition pseudo sections with dense sampling of apparent resistivity variations at depth (> 100 m) were obtained in a short time.

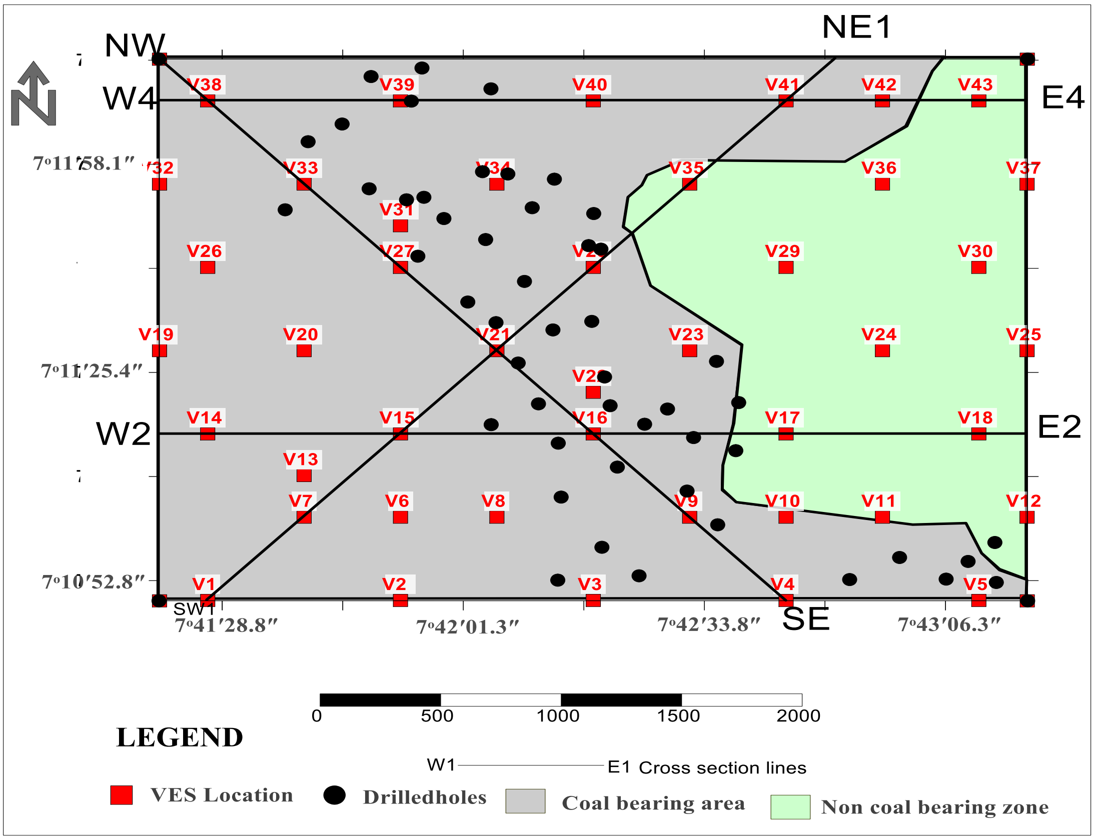

Fig.2: *Data acquisition map of the study area*

Results and Discussion

The qualitative interpretation of computer-generated model data curves reveals the presence of five to nine geoelectric layers. Some of the modeled curves are presented in Fig. 3.

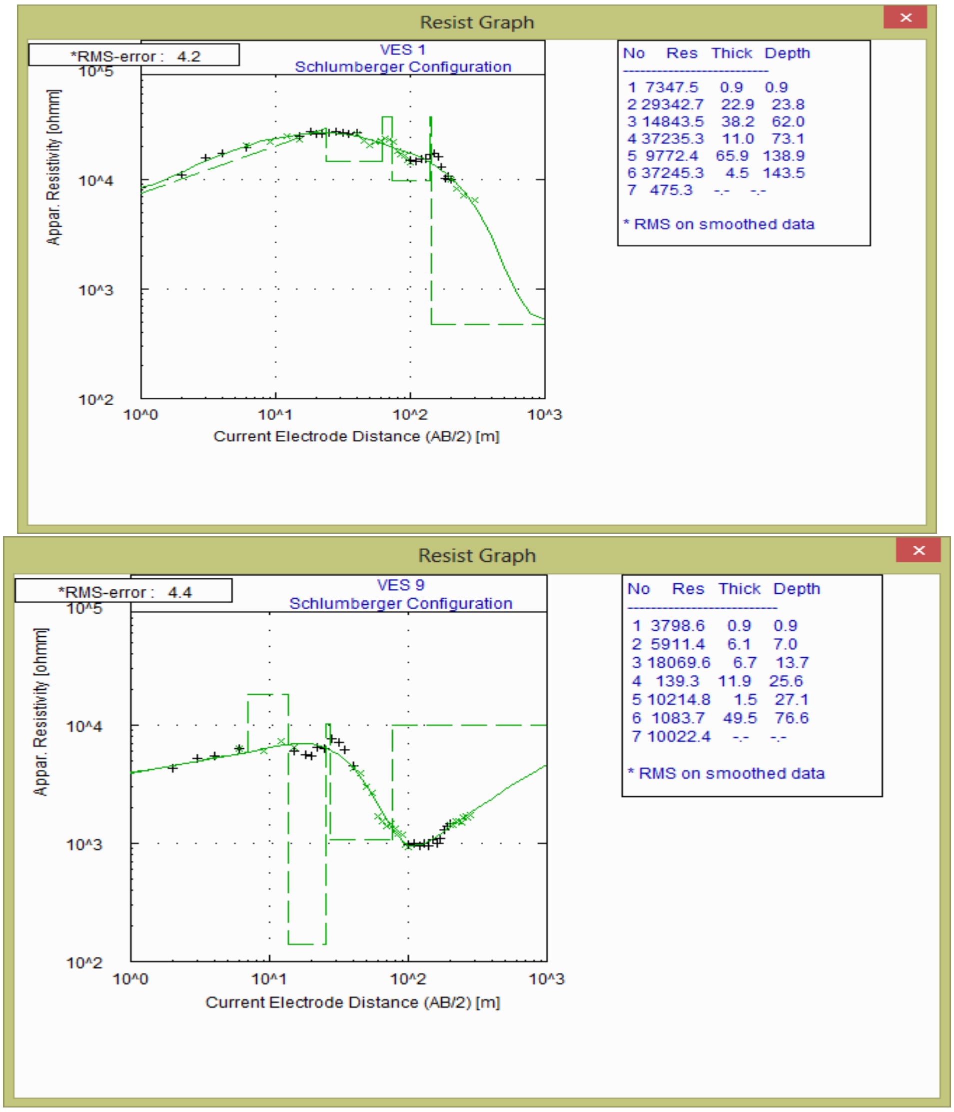

Fig. 3: Computer generated model data curves for VES 1 and 9

Geoelectric Sections and Stratigraphic Models

Geologic sections were generated based on interpreted layer resistivity values, layer thickness, and inferred lithology of the study area as discussed by Anakwuba *et al.* (2017). Fig. 4 illustrates the correlation between a vertical electrical sounding point (VES-31) and a borehole (OTA-232), serving as ground truth for validating the interpretation of other data within the study area. Geologic sections (Fig. 5) indicate the presence of five to nine geologic layers composed of sandy soil, sand, clay, clay-shale, shale, sandstone, coal, sandy shale / shaly sandstone, interbedded shale and sandstone.

Selected results of the 2D ERI resistivity inversion in the study area are presented in Figs. 6-8. The inverted resistivity model displays a variation in resistivity distribution, with high and low resistivity zones ranging from 1.0 to 100,000 Ω-m. Low resistivity zones (1.0-316 Ω-m), represented by deep blue to blue-green coloration, indicate groundwater saturation at depths. High resistivity zones (48,690–100,000 Ω-m), represented by red coloration, signify dry sand, compacted sandstone/shale. In most cases, the coal layer intersects the saturated zones along the profiles. Based on VES results and borehole data, the coal seam was delineated. However, the presence of groundwater intrusion has altered the resistivity values and generally disrupted the lateral continuity of the geoelectric layers. The shapes of the saturated zones suggest upward and lateral migration of groundwater in the study area.

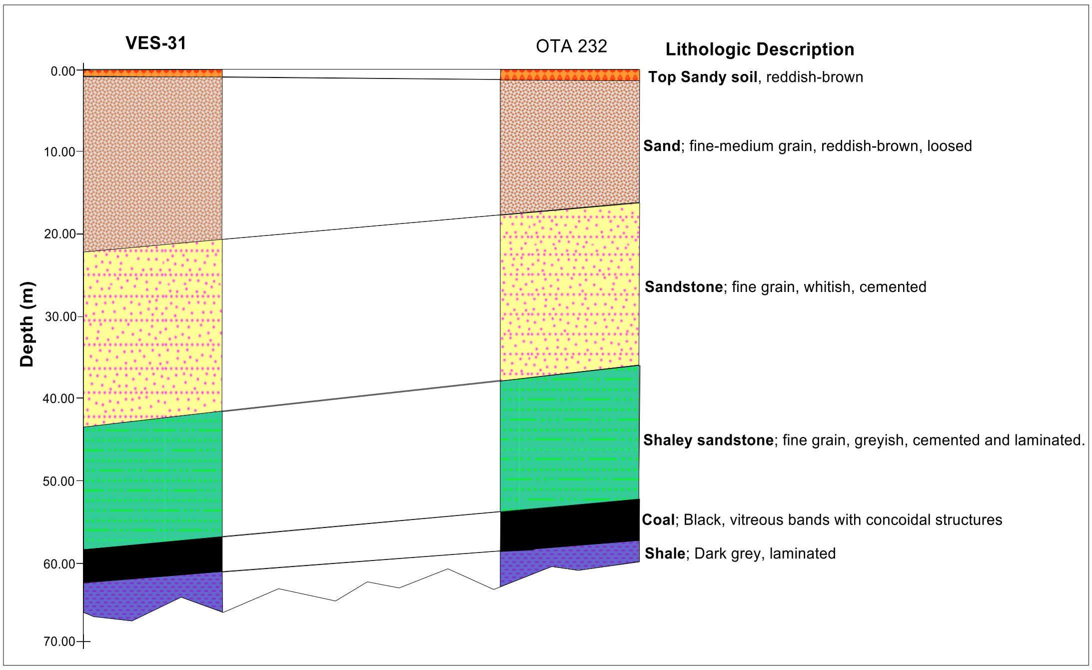

Fig. 4: Correlation of geoelectric section with borehole for ground-truthing in the study area.

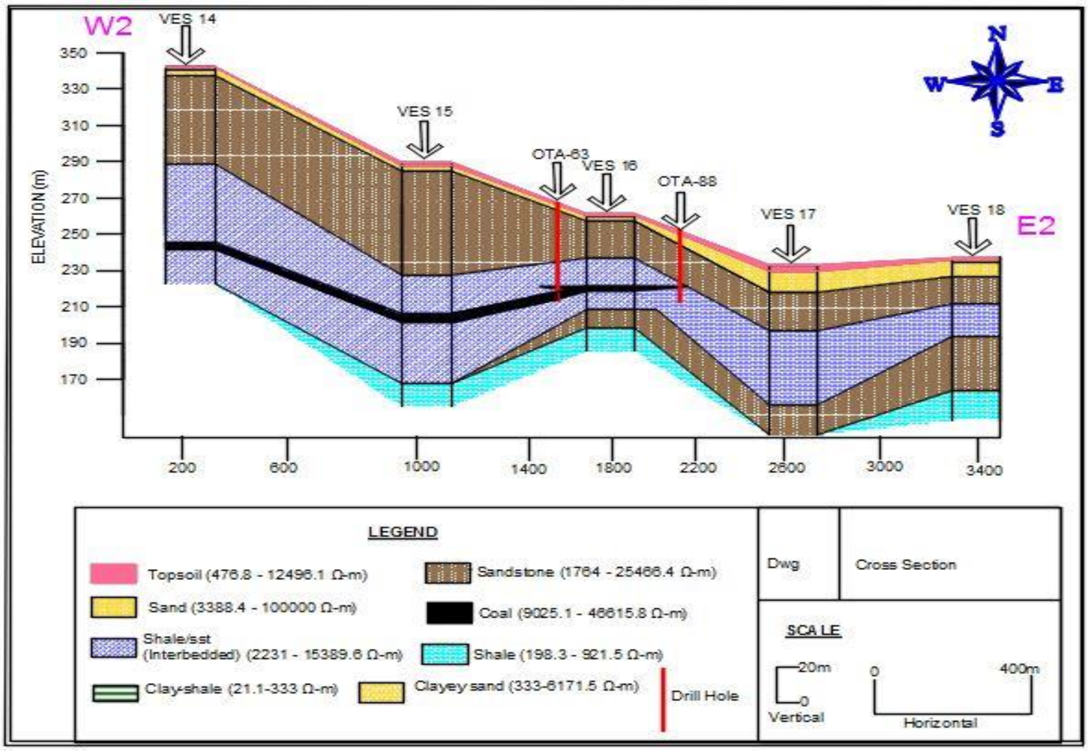

Fig. 5: Geologic section along W2-E2 traverse

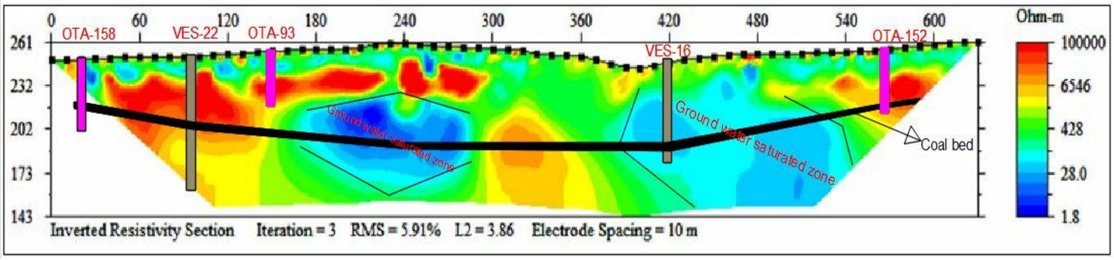

Fig. 6: 2D resistivity structure and pseudosection for profile 1 (in Block A)

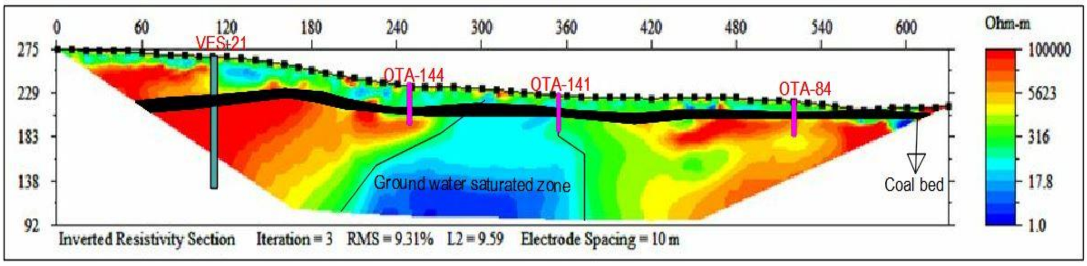

Fig. 7: 2D resistivity structure and pseudosection for profile 2 (in Block B)

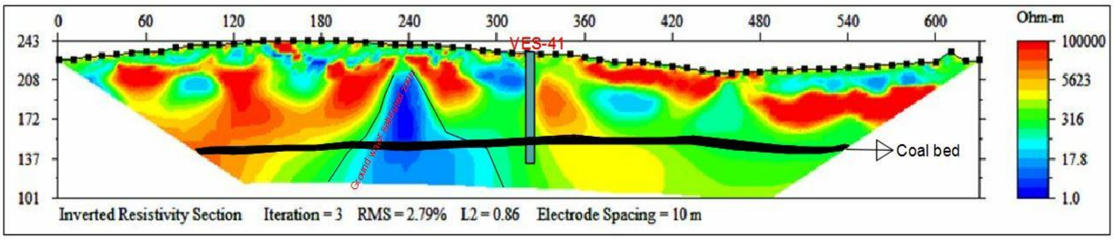

Fig. 8: 2D resistivity structure and pseudosection for profile 2 (in Block C)

Overburden versus Coal Thickness Analysis

Overlaying the overburden contour lines on the coal thickness contour map (Fig. 9) reveals spatial relationships that inform mining feasibility. The central eastern zone**,** where the coal seam is thick **(**>3.5m**)** and the overburden is relatively thin **(**15 - 30m), presents the most promising area for open-pit mining due to reduced stripping costs. The southwestern and northwestern regions**,** despite having significant coal thickness **(**up to 5m**), s**how higher overburden (>50m**)**, making surface mining less feasible but potentially viable for underground mining**.**

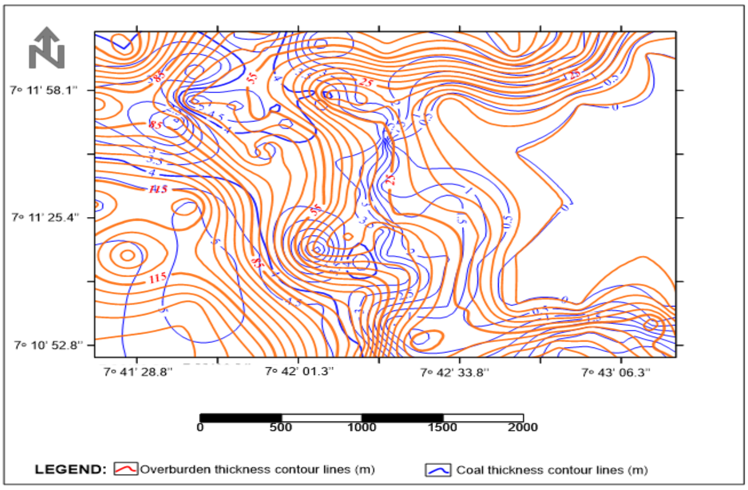

Fig.9: Overburden versus coal thickness contour map overlaid

Relationship between Resistivity and Coal Quality Variation

The geophysical resistivity map, when compared with the coal quality maps (proximate and ultimate analysis), provides insights into the correlation between resistivity anomalies and the coal characteristics. The resistivity anomalies observed in the study area correlate well with coal quality variations (Fig. 10). The southwestern to northwestern part of the study area shows high resistivity values (16000 - 46000 Ω-m). The eastern part of the study area is non-coal-bearing and represents the in-crop area. Higher resistivity values in the southwest could indicate coal seams with lower moisture and higher carbon content, given the known relationships between resistivity and coal properties.

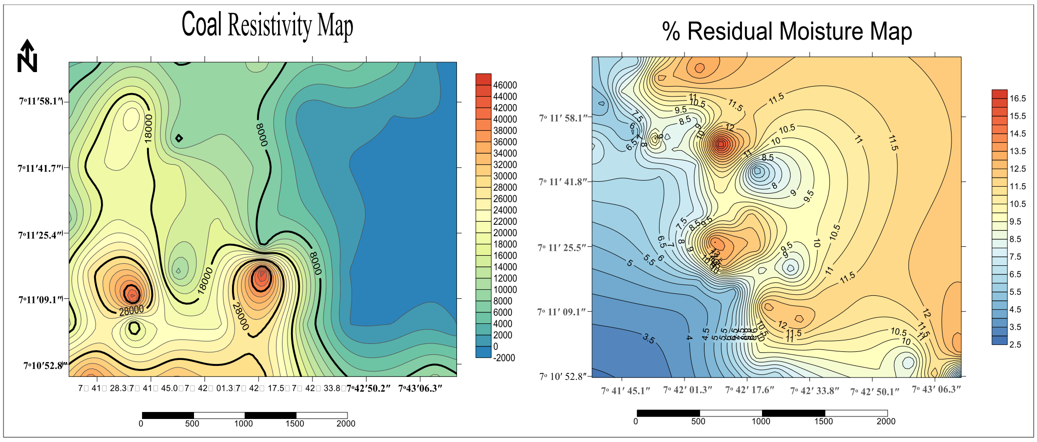

Fig. 10: Resistivity versus percentage moisture content map

Conclusion

This research successfully delineated coal seams using integrated geophysical and borehole methods, providing a robust framework for coal exploration and resource estimation in the Anambra Basin. The overburden thickness varies significantly across the area, ranging from 5 m in the east to 140 m in the western part. Resistivity data revealed distinct coal seams embedded within alternating sandstone and shale beds. The coal-bearing layers exhibit resistivity values between 4,854.1 and 46,615.8 Ω-m**,** a range influenced by moisture content, mineral impurities, and compaction. The result also reveals that resistivity data can serve as a predictive tool for assessing coal quality across different locations.

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