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Application of Geophysical Methods in the Determination of Pb-Zn Mineralization in Abakaliki, Parts of the Southern Benue Trough, Nigeria

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ABSTRACT

To identify Pb-Zn mineralization in the Abakaliki province, an integrated strategy was used for the objective of this study. Particularly in the Nsuba, Oputumo, Amenyi, Nsobo, and Opuitumo lodes. This investigation was conducted using two methods: the resistivity method (Dipole dipole configuration) and induced polarization (IP). The apparatus utilized for this research is the Abem Terrameter SAS 4000. There were ten (10) Dipole dipole arrays installed in the research region, with electrode spacing ranging from five to twenty meters in a NW-SE direction and a maximum spread of two hundred meters. Findings from the study suggested that mineralized zones, resistivity values ranging from 0.4 to 1354 Ω-m and chargeability values from -877 to 813 ms were found. Positive magnetic anomalies were found in areas below the ground that had unusually high chargeability and relatively low resistivity structures. This suggested that Pb-Zn minerals might be present. The mineralization, characterized as a mildly disseminated stockwork, leans towards a relatively epigenetic nature.

1. Introduction

According to (Yusuf et al., 2022), lead-zinc (Pb-Zn) mineralization in Nigeria has a lengthy geological history that spans from the late Albian to the Turonian eras. The upper Benue Trough's sedimentary deposits are the main locations for mineralization, which is frequently correlated with clearly defined, sharply dipping fractures and faults that are orientated N-S (Ukwuteyinor and Ezeh, 2023). Most of these deposits are found in Cretaceous strata in the northern, central, and southern Benue Trough and are epigenetic (Fatoye et al., 2014; Haruna, 2017).

It is important to comprehend and identify Pb-Zn mineralization zones for both economic and geological reasons. During their exploration of southern Nigeria, (Ezeh and Ikegbunam, 2022) used geophysical methods including induced polarization and electrical resistivity tomography to find possible mineral-rich areas. Their results suggest that low to moderate resistivity and high chargeability values within the same width range may be signs of Pb-Zn mineralization. They do, in fact, advise testing drilling at the peculiar sites. In a similar spirit, (Eyankware, 2021) emphasized the economic potential of the Pb-Zn mineralization in the Benue Trough and indicated its significance for Nigeria's revenue generation. In mineral exploration, geophysical methods such as electrical resistivity and induced polarization are frequently employed (Nabighian, 2005; Janos, 2011; Moreira, 2012; Eyankware, 2019).

Pb-Zn-Ag sulfide deposits can be located and mapped using induced polarization (IP) tomography, as (Ali et al., 2023) described in detail in their paper. Moreover, geophysical studies are essential for fine-tuning prospective drilling locations and verifying surface geological findings.

Prospecting for different minerals is made easier by methods including induced polarization, seismic, magnetoteluric, magnetic, gravity, and electromagnetic surveys (Ali et al., 2023). For example, (Boivin, 2007) examined how Pb-Zn deposits might transform into minerals using induced polarization profiles and DC resistivity. They were able to decipher the meaning of geological characteristics from the contour maps, magnetic profiles, and three-dimensional surface maps. Geological investigations, in addition to geophysical approaches, offer important insights into Pb-Zn mineralization. Pb-Zn mineralization was linked to igneous intrusions, according to (Evrard et al., 2018) mapping of the Benue, Abakaliki and Ogoja districts.

In a similar vein, (Mbah and Aniwetal, 2015) located Pb-Zn deposits in Ishiagu in Abakaliki and highlighted their relationship to geological characteristics like the Asu River Group shale and NW-SE trending fractures. In general, the identification and characterization of Pb-Zn mineralization in Nigeria depend heavily on the combination of geophysical and geological techniques, which yields important data for both economic development and mineral exploration. In order to meet the global need for lead and zinc—essential minerals utilized in a range of industries, including battery production and construction—studying Pb-Zn deposits is crucial, according to (Yalçın,and Canlı, 2024) used the IP technique to spread sulfate ores and find gold. They used induced polarization profiles and DC resistivity. In order to find Pb-Zn mineralization, (Eze and Adaora, 2018) conducted a magnetic survey on the ground. Magnetic intensity profiles were made along seven profile lines over the target area. In order to find the position and depth of mineral rocks, (Ojo et al., 2014; Kayode and Adelusi, 2010; Dakir et al., 2019) carried out additional investigation.

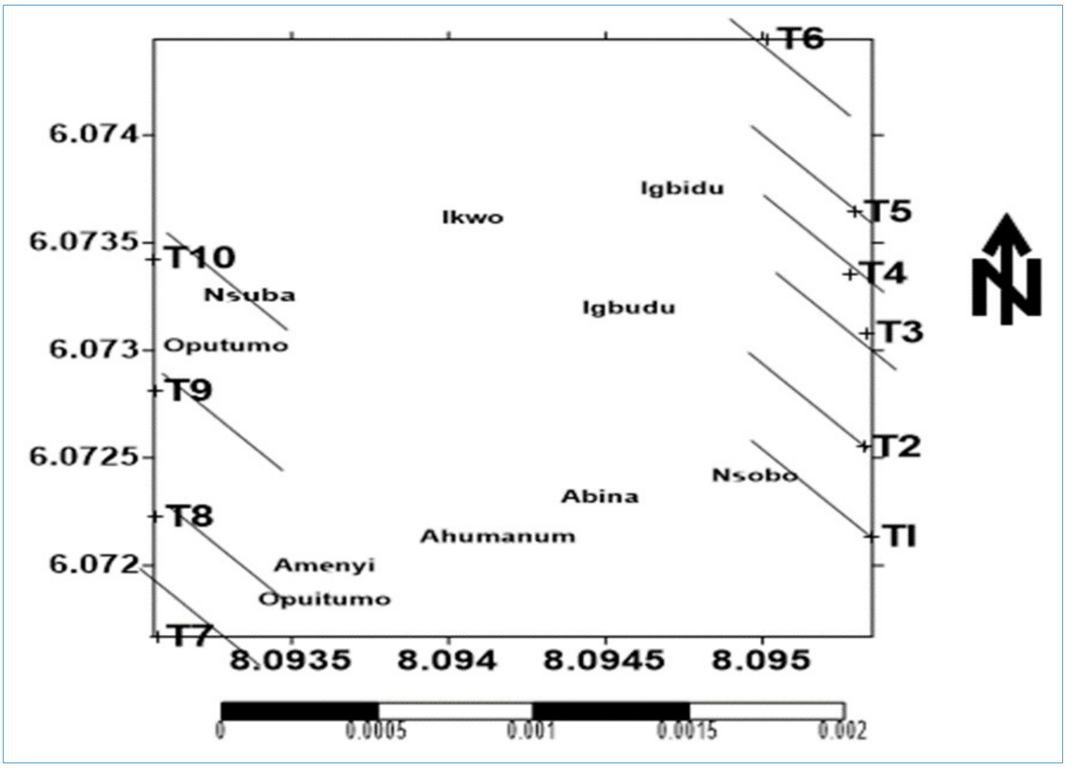


Fig. 1. Base Map of the study area

According to Victor et al. (2015) the southern limit of the Benue Trough's mineralization is represented by the Zurik Pb-Zn deposit in the Upper Benue Trough. As per (Victor et al., 2015) during the Cenomanian incursion phase of the Middle Albian, the Asu River Group bended somewhat. Later, during the Santonian tectonic phase associated with igneous activity, the strata underwent refolding (Nwachukwu, 1972; Ogundipe and Obasi, 2016). The area's igneous activity and the main volcanic band coexist with Pb-Zn mineralization (Oha et al., 2017).

The majority of researchers have looked into other communities in the province of Abakaliki, including Ishiagu (Usman et al., 2014; Okonkwo et al., 2014; Mbah et al 2015), Enyigba (Eyankware et al., 2019; Ema et al., 2018), Ameri (Orajaka, 1965) and Ameka (Orajaka, 1965). However, no research on Pb-Zinc mineralization has been published in other towns in the same province, like Nsuba, Oputumo, Amenyi, Nsobo, and Opuitumo. This study uses 2D Dipole dipole profiling and the integrated IP approach to assess the Pb-Zn mineralization in Abakaliki province for both exploration and economic viability. The following objectives were selected to accomplish this: determining the coordinates, traverses, and field data collection layout of the study area; acquiring information on the chargeability and resistivity of the IP to examine the polarization potential, which can reveal the presence or absence of Pb-Zn mineralization because of its unique properties; and identifying potential Pb-Zn mineralization locations throughout the research area in order to excavate or pit them in the future.

2. Location, Accessibility, Climate and Geology of the Study Area

The study area's location is depicted on a map in Fig. 1. The region spans longitudes 8°4'E to 8°8'E and latitudes 6°1'N to 6°5'N (Fig. 2). It's in the Nigerian state of Ebonyi. The area is located in the lower Benue Trough geological complex in Southeast Nigeria, near the southwest corner of the Abakaliki Basin. It is made up of sedimentary terrain that is lower lying and has some intrusions from various episodes, according to (Eyankware et al., 2022). The terrain is made up of low, level terrain with few trees, uneven streambeds, and tiny trees that have little or no leaves.

3. Geology of the Study Area

Baked clays and shale define the lithology. The Abakaliki Basin's Asu River Group of the Benue Trough is home to the Abakaliki geology (Fig. 2). It is mostly composed of poorly sorted bedded shale and splintery, unevenly sized metamorphosed mudstones. The sandstone and sandy limestone lenses have been badly cracked and combined. The earlier volcanic rocks in the Abakaliki Basin experienced faulting and metamorphism due to compressional tectonic stresses. Shallow aquifers were formed as a result of considerable weathering of the region's pyroclastic rocks

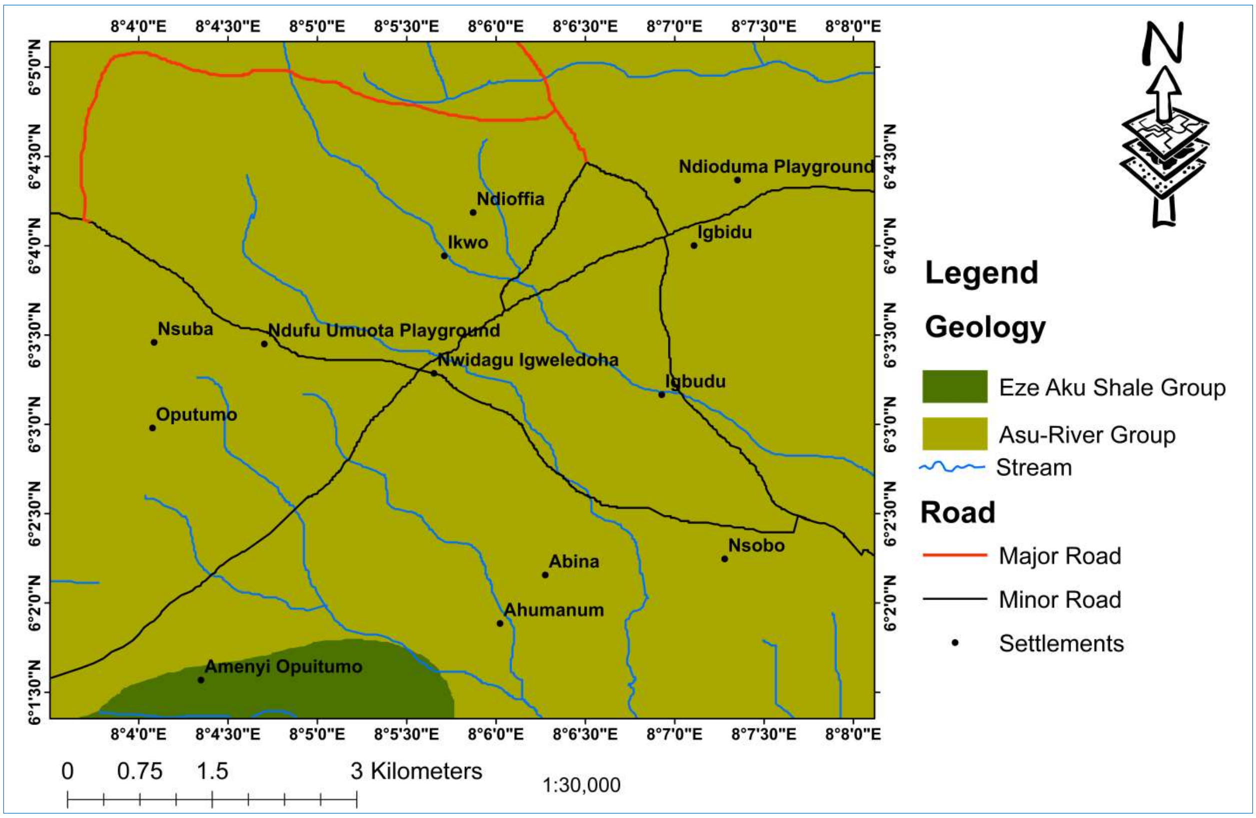


Fig. 1. Geology map of the study area

Phaleserite and quartz were deposited at temperatures between 102-175°C, according to fluid inclusion studies conducted on vein minerals from the Abakaliki and Ishiagu ore complexes. About 1725 equivalent weight percent of NaCl is the typical salinity of the ore fluid. The trace element contents in galena and sphalerite, as reported in Eze and Adaora (2018), are also in line with an epigenetic origin and low formation temperature; the southern Benue Trough's epigenetic Pb-Zn deposit is housed in the Cretaceous layers of an intra-cratonic rift basin.

The geotectonic setting, the prevalence of muddy conditions, and the fluid inclusion characteristics point to connate brines—produced by high geothermal gradients that triggered continental drifting—as the source of mineralization. Mineral deposition is induced by reactivity with wall rocks or quick cooling from mixing with descending or low-salinity meteoric waters, according to Eze and Adaora (2018).

4. Methodology

4.1. Data and Methods

4.1.1. Electrical Resistivity Tomography

Using the apparent resistivity of the variation, the vertical and lateral extent of the Pb-Zn mineralization was determined using the electrical resistivity method (Dipole Dipole Array). Along the previously occupied TR1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 at variable (5, 10, 15, and 20 m) electrode spacing in a NW-SE orientation with a maximum spread of 200 m, Terrameter ABEM 4000, GPS, and compass clinometer were moved to the site. Traverse lines must be laid across the direction of dipping fractures and faults in the study region because lead-zinc mineralization in the upper Benue Trough is limited to well defined steeply dipping fractures and faults striking in a N-S direction (Ukwuteyinor and Ezeh, 2023).

There were different numbers of traverses carried out in each of the communities since the lines chosen were determined by the amount of space available to lay the traverses in the research region. Readings from field measurements were kept in a field notebook. 2D Dipole dipole profiling was employed in both the electrical resistivity and the induced polarization surveys. It was chosen to detect the potential difference rather than the contact resistance between the two electrodes while using two extra electrodes. This is not relevant, given the small amount of current the voltmeter is meant to draw. Per Ohm's law, a little current differential across the contact resistances translates into a small potential difference. The sign (V) stands for the potential difference (pd) between the electrodes that have potential. The signal-to-noise ratio in magnetism is enhanced via stacking.

4.1.2. Induced Polarization Data

Induced polarization (IP) is a delayed voltage response observed in earth materials (Sumner, 2012; Albi et al., 2010). The cause of it is stimulation by current. Neguyen (2020) suggests that this technique can locate hidden subsurface mineral deposits. Ion movement and chemical reactions are the two key factors that determine how rapidly the polarization potential rises or lowers. Polarization is limited to materials that carry electricity (Sumner, 2012; Airo, 2015). In earth materials, "induced polarization" refers to an electrical or resistive blocking effect that occurs primarily in fluid-filled pores near metallic minerals (Alilou et al., 2014; Revie et al., 2015). The IP effect is therefore most noticeable in close proximity to rocks that include metallic-luster minerals. In regions with distributed mineralization, where conventional geophysical exploration techniques prove unproductive, induced polarization serves as a useful instrument (Shah, 2013; Adagunodo et al., 2015). During the IP scan, current was sent into the subsurface using a pair of non-polarizing electrodes (Binley, 2015; Clement, 2021). Because the primary voltage (v) between a second pair of non-polarizing potential electrodes did not return to zero but instead formed into a secondary voltage (Vs) that steadily declined, an IP effect occurred in the time domain when the current was abruptly shut off. The outcome is an apparent chargeability (Clement, 2021). A lead-zinc deposit is characterized by low resistivity and strong chargeability (Yusuf et al., 2022). A Pb-Zn deposit may therefore be present if low resistivity regions on the Dipole dipole profile line up with high chargeability sites on IP.

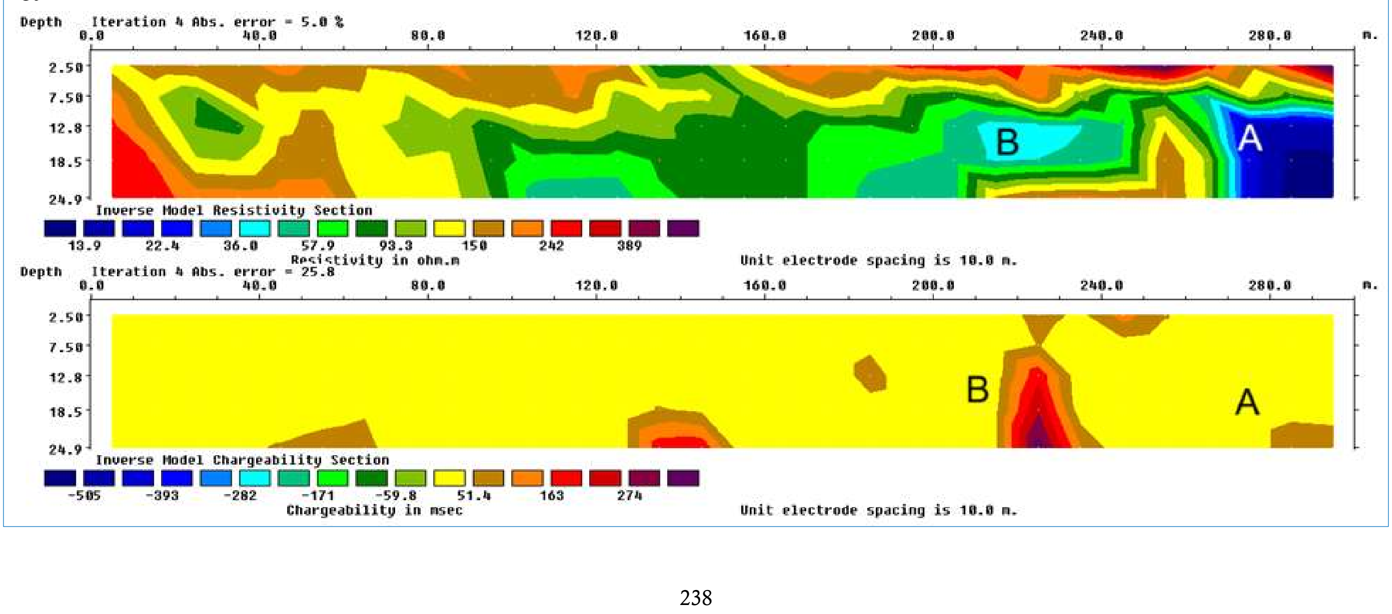
5. Results and Discussion

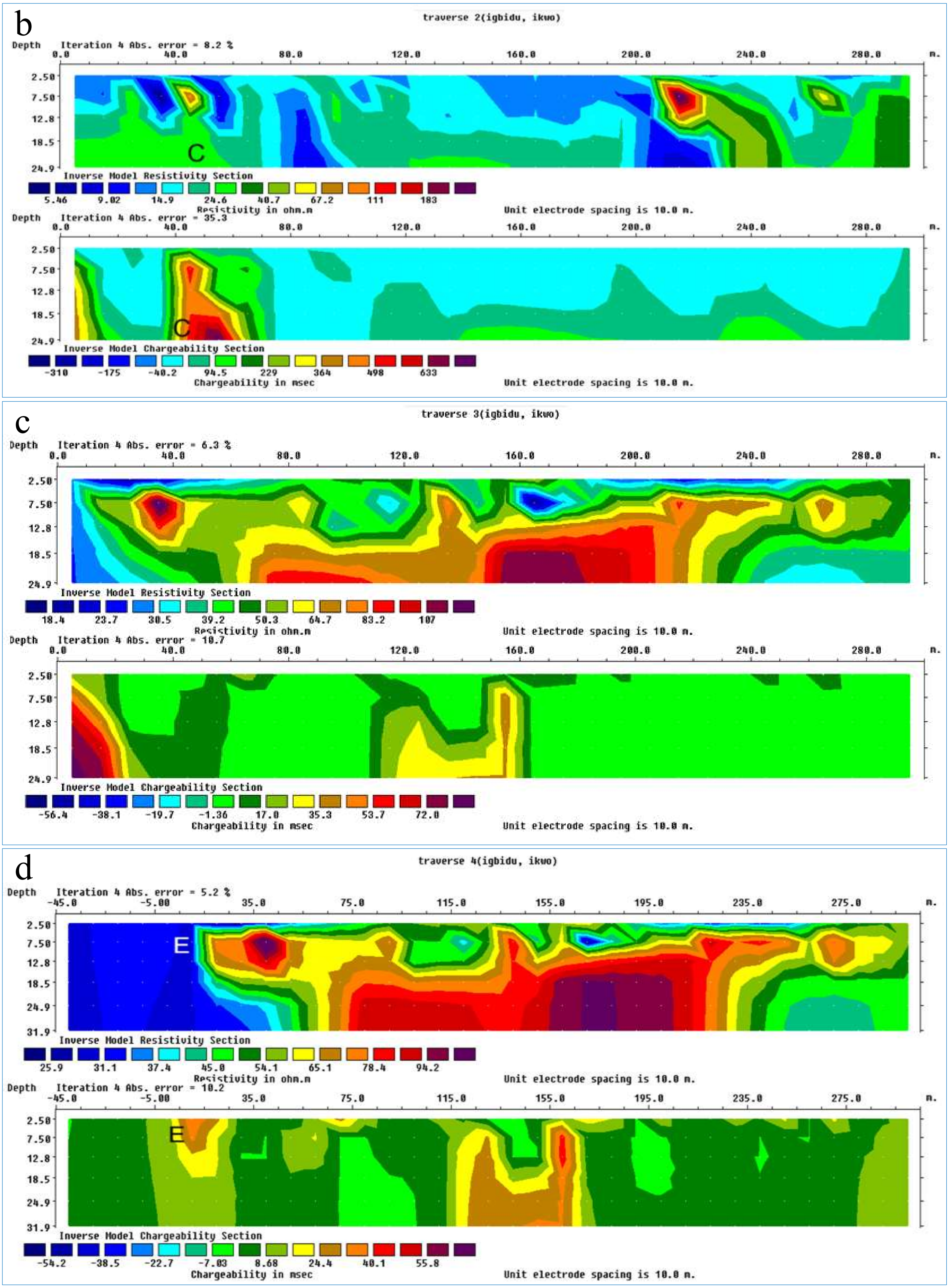
5.1. Induced Polarization and Electrical Resistivity Surveys

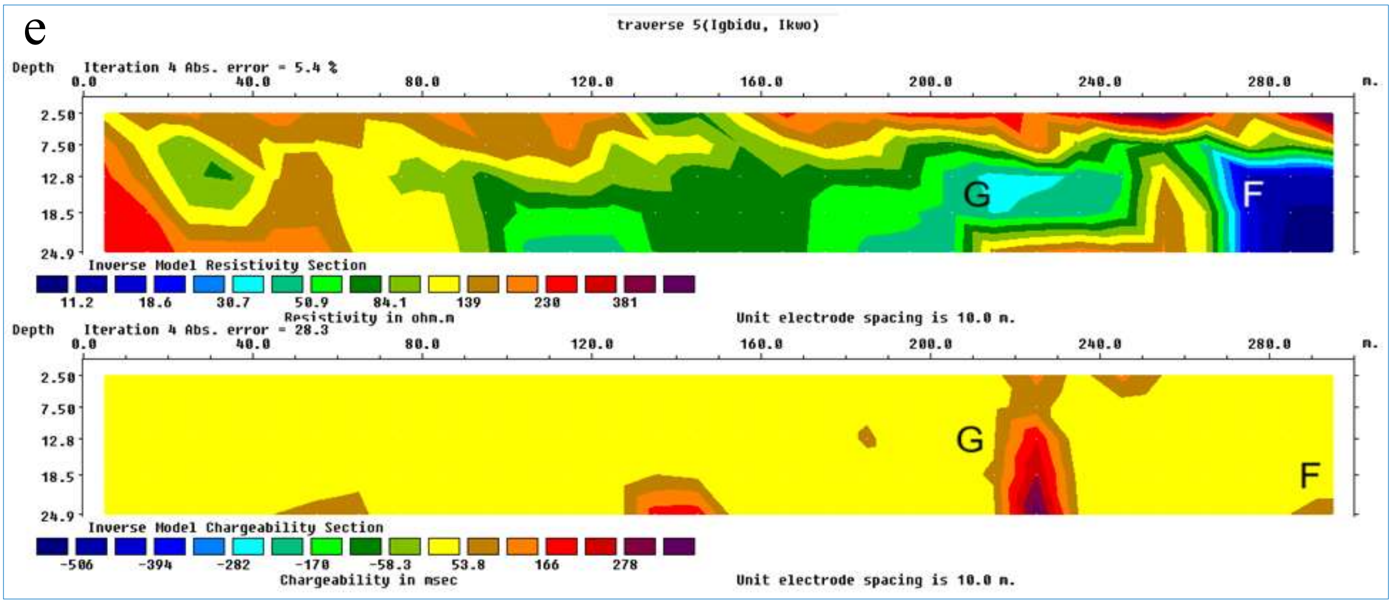
Figs. 3a–3i show 2D resistivity plots of the ten interpreted traverses and their associated induced polarization results. The 2D resistivity data was processed using the RES2D Inversion program. To characterize the study area, geophysical methods were used. Fig. 3a reveals two major chargeability bodies (A and B) with chargeability values between 242 ms and 389 ms and resistivity values of 36 Ωm and 320 Ωm, respectively. The resistivity and chargeability structures were mapped along traverse 1 NW–SE, with a distance of 200 m in the study area. A total depth of 24.9 m was imaged, and the resistivity varied from 13.9 Ω-m to 389 Ω-m. The results align with the research carried out by Vieira et al. (2016) and Grygory et al. (2021). A high-chargeability body C with chargeability values ranging from 450 to 633 ms and a low resistivity value of 24.6Ωm is shown in Fig. 3b.

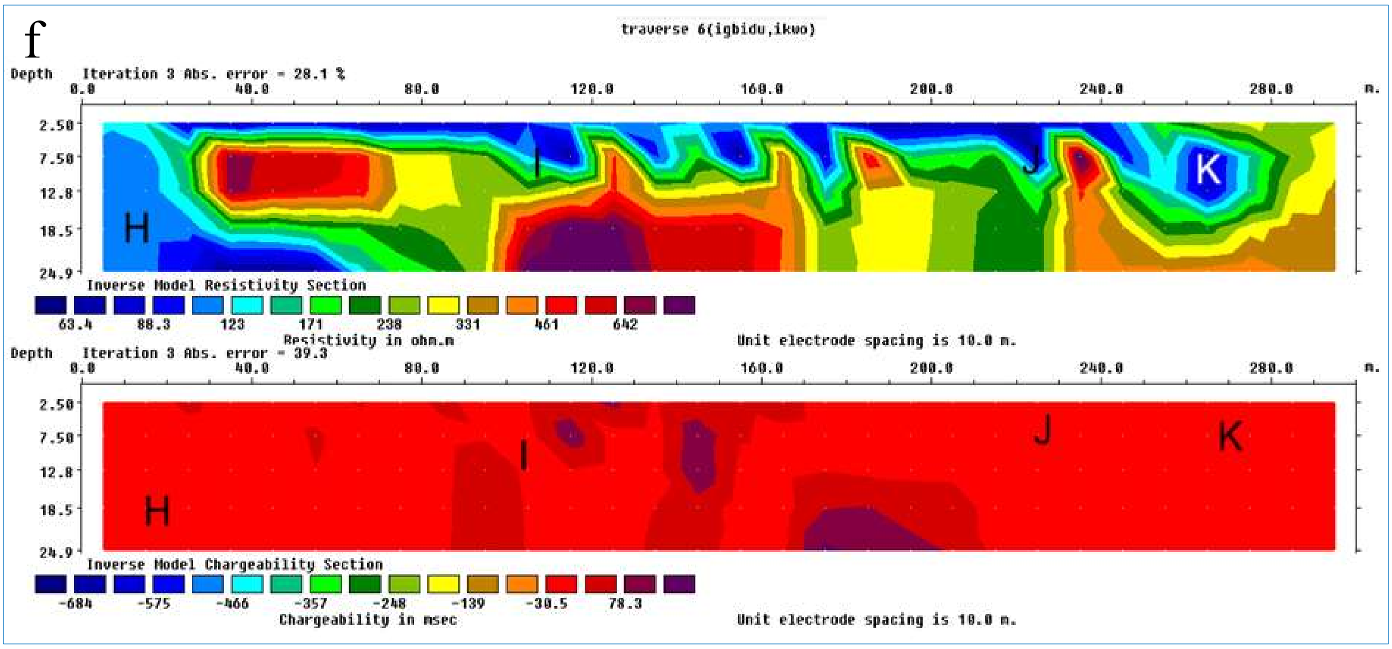
As per reference Yusuf et al. (2022), the presence of a high chargeability and a similarly low resistivity is indicative of metallic mineralization. Electrode polarization, an overvoltage phenomenon of electrical reactance between metals or metallic minerals and an electrolyte, is the cause of this high chargeability. It is suspected that Pb-Zn mineralization exists in this subsurface region. This is consistent with research by Grygory et al. (2021), who believed that low resistivity and high chargeability indicate the existence of metallic minerals. Fig. 3c revealed a major chargeability body D with chargeability values ranging from 50 ms to 72 ms and resistivity values ranging from 23.7 Ω-m to 30.5 Ω-m.

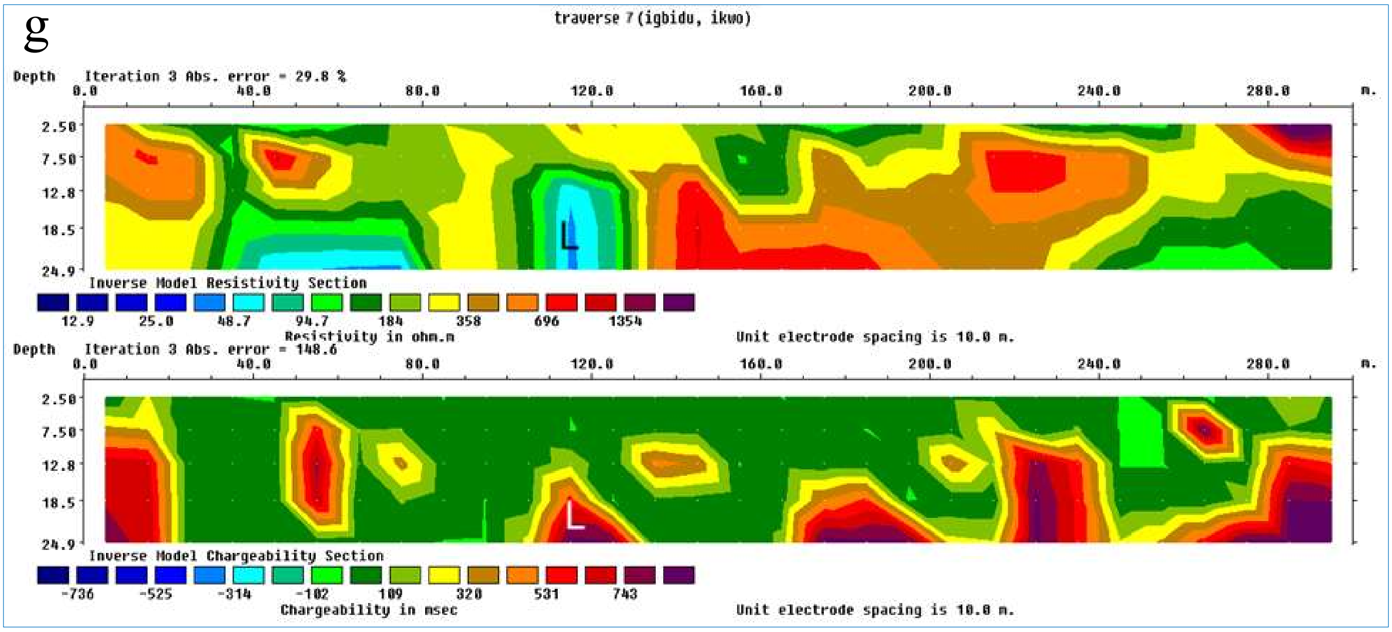
a




b
traverse 2(igbidu, ikwo)
Depth Iteration 4 Abs. error = 8.2 %
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
C
Inverse Model Resistivity Section
5.46 9.02 14.9 24.6 40.7 67.2 111 183
Resistivity in ohm.m
Unit electrode spacing is 10.0 m.
Depth Iteration 4 Abs. error = 35.3
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
C
Inverse Model Chargeability Section
-310 -175 -40.2 94.5 229 364 498 633
Chargeability in msec
Unit electrode spacing is 10.0 m.
c
traverse 3(igbidu, ikwo)
Depth Iteration 4 Abs. error = 6.3 %
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
Inverse Model Resistivity Section
18.4 23.7 30.5 39.2 50.3 64.7 83.2 107
Resistivity in ohm.m
Unit electrode spacing is 10.0 m.
Depth Iteration 4 Abs. error = 10.7
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
Inverse Model Chargeability Section
-56.4 -38.1 -19.7 -1.36 17.0 35.3 53.7 72.0
Chargeability in msec
Unit electrode spacing is 10.0 m.
d
traverse 4(igbidu, ikwo)
Depth Iteration 4 Abs. error = 5.2 %
-45.0 -5.00 35.0 75.0 115.0 155.0 195.0 235.0 275.0 m.
2.50 7.50 12.8 18.5 24.9 31.9
E
Inverse Model Resistivity Section
25.9 31.1 37.4 45.0 54.1 65.1 78.4 94.2
Resistivity in ohm.m
Unit electrode spacing is 10.0 m.
Depth Iteration 4 Abs. error = 10.2
-45.0 -5.00 35.0 75.0 115.0 155.0 195.0 235.0 275.0 m.
2.50 7.50 12.8 18.5 24.9 31.9
E
Inverse Model Chargeability Section
-54.2 -38.5 -22.7 -7.03 8.68 24.4 40.1 55.8
Chargeability in msec
Unit electrode spacing is 10.0 m.


e
traverse 5(Igbidu, Ikwo)
Depth Iteration 4 Abs. error = 5.4 %
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
G
F
Inverse Model Resistivity Section
11.2 18.6 30.7 50.9 84.1 139 230 381
Resistivity in ohm.m
Unit electrode spacing is 10.0 m.
Depth Iteration 4 Abs. error = 28.3
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
G
F
Inverse Model Chargeability Section
-506 -394 -282 -170 -58.3 53.8 166 278
Chargeability in msec
Unit electrode spacing is 10.0 m.


f
traverse 6(igbidu,ikwo)
Depth Iteration 3 Abs. error = 28.1 %
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
H
I
J
K
Inverse Model Resistivity Section
63.4 88.3 123 171 238 331 461 642
Resistivity in ohm.m
Unit electrode spacing is 10.0 m.
Depth Iteration 3 Abs. error = 39.3
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
H
I
J
K
Inverse Model Chargeability Section
-684 -575 -466 -357 -248 -139 -30.5 78.3
Chargeability in msec
Unit electrode spacing is 10.0 m.


g
traverse 7(igbidu, ikwo)
Depth Iteration 3 Abs. error = 29.8 %
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
L
Inverse Model Resistivity Section
12.9 25.0 48.7 94.7 184 358 696 1354
Resistivity in ohm.m
Unit electrode spacing is 10.0 m.
Depth Iteration 3 Abs. error = 148.6
0.0 40.0 80.0 120.0 160.0 200.0 240.0 280.0 m.
2.50 7.50 12.8 18.5 24.9
L
Inverse Model Chargeability Section
-736 -525 -314 -102 109 320 531 743
Chargeability in msec
Unit electrode spacing is 10.0 m.

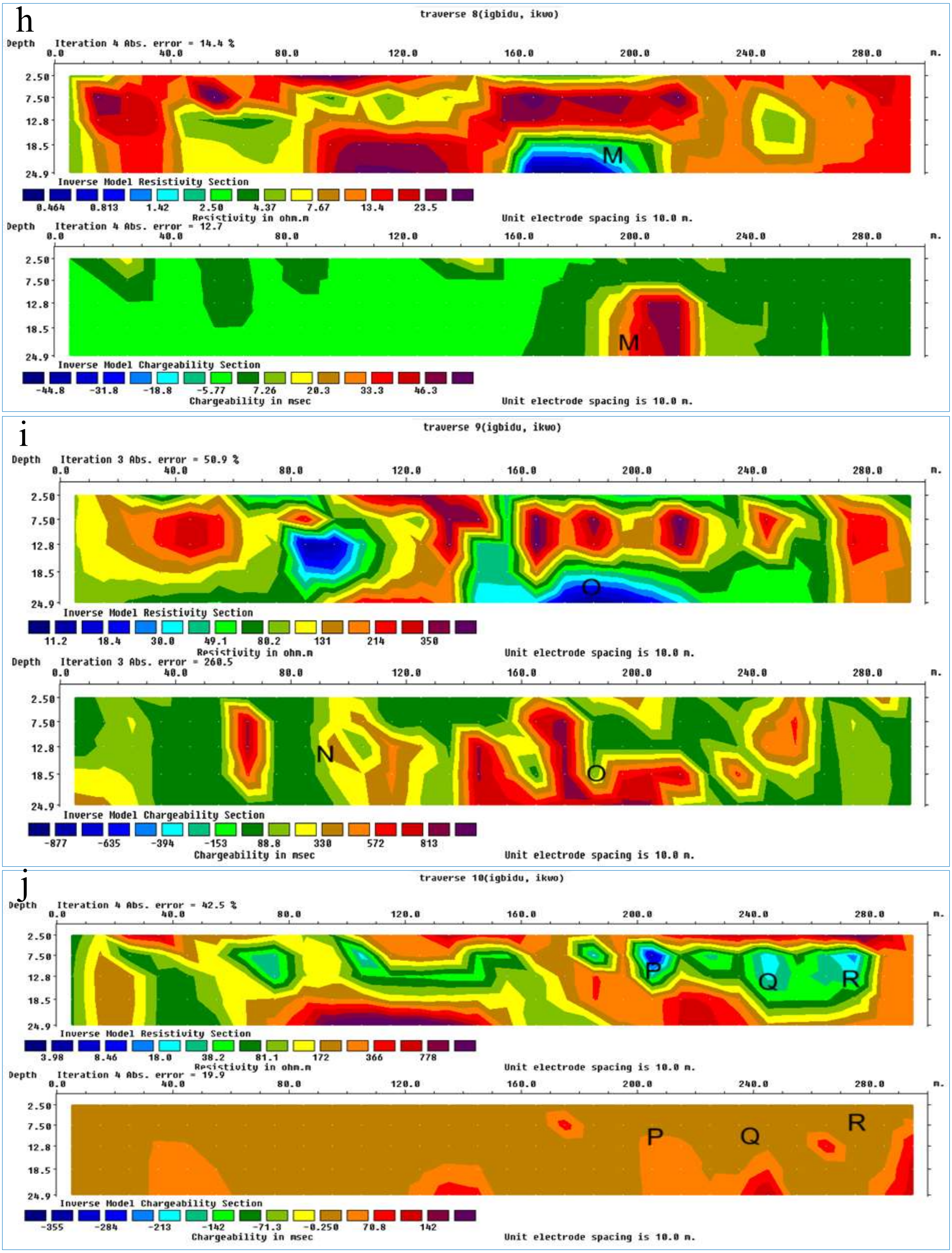


Fig. 3. Resistivity and chargeability structure for (a) traverse 1 (TR-1), (b) traverse 2 (TR-2), (c) traverse 3 (TR-3), (d) traverse 4 (TR-4), (e) traverse 5 (TR-5), (f) traverse 6 (TR-6), (g) traverse 7 (TR-7), (h) traverse 8 (TR-8), i) traverse 9 (TR-9) and (j) traverse 10 (TR-10)

The resistivity and chargeability structure along traverse 4 in NW are presented in Fig. 3d. A low resistivity of 25.9 Ωm to 37.7 Ωm and an abnormal body E with chargeability values between 48.1 and 55.8 ms define the figure. This finding is consistent with the high peak positive magnetic anomaly region, which is typically thought to contain mineral potential (Grygory et al., 2021). This location has been linked to possible Pb-Zn mineralization. The shape of Fig. 3e is moving toward NNW-SSE, and it has two strange spots (F and G) that have chargeability values between 166 and 278 ms and low resistivity values of 11.2 Ωm and 30.7 Ωm, respectively. Fig. 3f revealed that the entire study area is characterized by high chargeability values ranging from -30.5 to 70.3 and corresponding pockets of low resistivity values of 88Ωm to 123 Ωm at points H, I, J, and K. For this traverse, the chargeability value decreased when compared to Fig. 3e. Fig. 3f revealed the resistivity and chargeability structure along TR-6 NNW. A depth of 18.5 m was imaged, and the resistivity ranged from 461 Ω-m to 642 Ω-m. Chargeability values ranged from -38.5 to 78 ms; at a distance of 18.5-24.9 m, there is an anomalous chargeability. A high chargeability anomaly L was seen in the middle of the profile (along transverse (TR) NNW-SSE), with values ranging from 400 to 743 ms. Low resistivity values, which ranged from 25 to 48.7 Ωm, corresponded to it. Fig. 3h showed a medium to low resistivity value ranging from 1.42Ωm to 0.6Ωm, which corresponded to a high chargeability anomaly M ranging from 33.3 to 46.3 ms. In Fig. 3h, the resistivity and chargeability structure are presented by Traverse (TR8) NNW-SSE. The resistivity and chargeability structure along traverse (TR-9) NNW-SSE in the research area are displayed in Fig. 3i. With values ranging from 338 to 813 ms for its two high anomalous chargeability bodies (N and O), it has a low resistivity value between 18.4 Ω and 30.0 Ωm. The resistivity ranged from 11.2 Ωm to 350 Ω-m at a total depth of 24.9 m that was documented. Along the traverse, chargeability varied from -877 to 813 ms. Along the traverse of NNE, Fig. 3j displays pockets of high chargeability bodies (P, Q, and R) of 120 ms, which correlate too low to medium resistivity values of 3.89Ωm to 18 Ωm. This study is in line with the research conducted by Ukwuteyinor and Ezeh (2023)in the study area.

6. Conclusion

In conclusion, the various chargeability and resistivity variations observed across the study area.

- Chargeability bodies A and B exhibit values between 242 ms and 389 ms, with corresponding resistivity values of 36Ωm and 320Ωm while a high-chargeability body C is observed with values ranging from 450 to 633 ms and a low resistivity value of 24.6Ωm, indicating suspected Pb-Zn mineralization.
- Major chargeability body D has values ranging from 50 ms to 72 ms, with resistivity values ranging from 23.7 Ω-m to 30.5 Ω-m and an anomalous body E is characterized by chargeability values ranging from 48.1 to 55.8 ms and low resistivity values of 25.9 Ωm to 37.7 Ωm, also indicating suspected Pb-Zn mineralization.
- Strange spots F and G have chargeability values between 166 and 278 ms and low resistivity values of 11.2 Ωm and 30.7 Ωm, respectively while Traverse 6 (TR-6) reveals high chargeability values ranging from -30.5 to 70.3 ms, with corresponding pockets of low resistivity values of 88 Ωm to 123 Ωm.
- Anomalous chargeability anomaly L is observed in the middle of the profile, with values ranging from 400 to 743 ms, matched by low resistivity values ranging from 25 to 48.7 Ωm and High chargeability anomaly M ranging from 33.3 to 46.3 ms corresponds to medium to low resistivity values ranging from 1.42 Ωm to 0.6 Ωm.
- High anomaly chargeability bodies N and O have values between 338 and 813 ms, with low resistivity values between 18.4 Ωm and 30.0 Ωm and Pockets of high chargeability bodies P, Q, and R of 120 ms correspond to low to medium resistivity values of 3.89 Ωm to 18Ωm along the traverse of NNE.

These findings align with previous research and suggest potential areas of interest for further exploration, particularly regarding metallic mineralization such as Pb-Zn.

Authors Contribution
The research was done by I.F.C., the manuscript was written by O. O. Wasiu and it was evaluated by A. F. Zephaniah, I. C. Fidelia and O. O. Wasiu.

Data Availability Statement
My manuscript has associated data in a data repository.

References

Adagunodo, T.A., Sunmonu, L.A., Adeniji, A.A., 2015. An overview of magnetic method in mineral exploration. Journal of Global Ecology and Environment 3, 13-28.

Airo, L, 2015. Geophysical signatures of mineral deposit types in Finland. Geol Surv Finl Spec Paper 58, 9-70.

Alabi, A.A., Ogungbe, A.S., Adebo, B., Lama, O., 2010. Induced polarization interpretation for subsurface characterisation: A case study of Obadore, Lagos State. Archives of Physics Research (3), 34-43.

Ali, M.A.H., Mewafy, F.M., Qian, W., Alshehri, F., Ahmed, M.S., Saleem, H.A., 2023. Integration of Electrical Resistivity Tomography and Induced Polarization for Characterization and Mapping of (Pb-Zn-Ag) Sulfide Deposits. Minerals 13, 986. https://doi.org/10.3390/min13070986.

Alilou, K., Norouzi, G.H., Doulati, F., Abedi, M., 2014. Application of magnetometry, electrical resistivity and induced polarization for exploration of polymetal deposits, a case study. Halab Dandi, Zanjan, Iran. In: 2nd International conference on advances in engineering sciences and applied mathematics ICAESAM, 2014 May 1-5, Istanbul, Turkey.

Binley, A., 2015. Tools and techniques: electrical methods G. Schubert (Ed.), Treatise on Geophysics (second ed.), Elsevier (2015), pp. 233-259.

Boivin, M., 2007. Advances in geophysics and technology for VMS exploration. In: Ore deposits and exploration technology proceedings of exploration 07: ffth decennial international conference on mineral exploration edited by Milkereit, pp 731–739, MB Geosolutions, Quebec City, Quebec, Canada Paper 50.

Clement, W.P., 2021. Geophysical site characterization David Alderton, Scott A. Elias (Eds.), Encyclopedia of Geology (second ed.), Academic Press (2021), pp. 805-814.

Dakir, I., Benamara, A., Aussonumi, H., Ouallali, A., Bahammou, Y.A., 2019. Application of induced paleomagnetism and resistivity to determine the location of metalliferous veins in the taroucht and Tabesbati area (Eastern Anti-Atlas Morocco). International Journal of Geophysics Article ID 5849019, 1-11. https://doi.org/10.1155/2019/5849019.

Ema, M.A., Daniel, A.M., Ndidiamaka, N.E., 2018. Mapping Geological Structures Controlling Mineralization in Enyigba Area, South Eastern Nigeria, using Magnetic Inversion Technique. International Journal of Mining Science 4, 31-39.

Evrard, M., Dumont, G., Hermans, T., Chouteau, M., Francis, O., Pirard, E., Nguyen, F., 2018. Geophysical Investigation of the Pb-Zn Deposit of Lont-zen-Poppelsberg, Belgium. Minerals 8, 233. https://doi.org/10.3390/min8060233.

Eyankware, M.O., 2019. Integrated Landsat Imagery and Resistivity Methods in Evaluation of Groundwater Potential of Fractured Shale at Ejekwe Area, southeastern Nigeria, Unpublished PhD Thesis.

Eyankware, M.O., Akakuru, C.O., Eyankware, E.O., 2022. Interpretation of hydrochemical data using various geochemical models: a case study of Enyigba mining district of Abakaliki, Ebonyi state, SE. Nigeria. Sustainable Water Resources Management 8, 33 (2022). https://doi.org/10.1007/s40899-022-00613-4.

Eyankware, M.O., Aleke, G., 2021. Geoelectric investigation to determine fracture zones and aquifer vulnerability in southern Benue Trough southeastern Nigeria. Arabian Journal of Geosciences. 14, 2259. https://doi.org/10.1007/s12517-021-08542-w.

Eze, C.L., Adaora G.A., 2018. Ground magnetics survey over lead-zinc mineralization in Edor Cross River State Nigeria. Advances in Physics Theories and Applications 70, 1-5.

Ezeh, C.C., Ikegbunam, I.C., 2022. Delineation of potential zones of lead-zinc mineralization in Uburu Ohaozara L.G.A South Eastern Nigeria, using electrical resistivity tomography and induced polarization methods. International Journal of Physical Sciences 17 (3), 121-130. https://doi.org/10.5897/IJPS2022.5013.

Fatoye, F.B., Ibitomi, M.A., Omada, J.I., 2014. Lead-Zinc-Barytes mineralization in the Benue Trough, Nigeria: their geology, occurrences and economic perspective. Advances in Applied Science Research 5 (2), 86-92.

Haruna, I.V., 2017. Review of the basement geology and mineral belts of Nigeria. Journal of Applied Geology and Geophysics 5 (1), 37-45.

Janos, F., 2011. Geological interpretation of results provided by geophysical methods in mineral exploration. Mineral exploration Digital Egyetem copyright 4.1.2-08/1/A-200-0033, pp. 1-20.

Kayode, J.S., Adelusi, A.O., 2010. Ground magnetic data interpretation of Ijebu-Jesa area, Southwestern Nigeria, using total component. Research Journal of Applied Sciences, Engineering and Technology 2 (8), 703-709.

Mbah, V.O., Onwuemesi, A.G., Aniwetalu, E.U., 2015. Exploration of Lead-Zinc (Pb-Zn) Mineralization Using Very Low Frequency Electromanetic (VLF-EM) in Ishiagu, Ebonyi State. Journal of Geology & Geosciences 4, 214. https://doi.org/10.4172/2381-8719.1000214.

Moreira, C.A., Borges, M.R., Vieira, G.M., Fillio, W.M., Montanheiro, M.A.F., 2012. Geological and geophysical data integration for delimitation of mineralized areas in a supergene manganese deposits. Geofísica Internacional 53, 199-210

Nabighian, M.N., Grauch, V.J.S., Hansen, R.O., LaFehr, T.R., Li, Y., Pearson, W.C., Peirce, J.W., Phillips, J.D., Ruder, M.E., 2005. The historical development of the magnetic method in exploration. Geophysics 70, 33-61. https://doi.org/10.1190/1.2133784.

Nguyen, H., Drebenstedt, C., Bui, X.N., Bui, D.T., 2020. Prediction of blast-induced ground vibration in an open-pit mine by a novel hybrid model based on clustering and artificial neural network. Natural Resources Research 29 (2), 691-709. https://doi.org/10.1007/s11053-019-09470-z.

Nwachukwu, S.O., 1972. The tectonic evolution of the southern portion of Benue Trough Nigeria. Geological Magazine 99, 411-419.

Ogundipe, I., Obasi, R., 2016. Geology and mineralisation in the Albian Sediments of the Benue Trough, Nigeria. British Journal of Earth Sciences Research 4 (3), 1-15.

Oha, I.A., Onuoha, K.M., Dada, S.S., 2017. Contrasting styles of lead-zinc-barium mineralization in the Lower Benue Trough, Southeastern Nigeria. Earth Sciences Research Journal 21 (1), 7-16. http://dx.doi.org/10.15446/esrj.v21n1.3970.

Ojo, A.O., Omotoso, T.O., Adekunle, O.J. 2014. Determination of location and depth of mineral rocks at Olode, village Ibadan Oyo state, Nigeria using geophysical methods. International Journal of Geophysics 14, 1-14. https://doi.org/10.1155/2014/306862.

Okeke, O.C., Dioha, E.C., Umeorizu, I.B., Merole, M.C.N., Nwankwasi, J.T., Ekere, L. 2016. Physicochemical an bacteriological characteristics and quality assessment of groundwater from shallow aquifers in Abakaliki Town, southeastern Nigeria. International Journal of Advanced Academic Research/Sciences, Technology & Engineering 2, 60-75.

Okezie, C.N., 1957. The igneous rocks of Izekwe Ominyi and Nkpumeakwa Okuku districts of Ogoja Province. Interim Report No 2 on the mapping of the cretaceous igneous districts of southeastern Nigeria. Geological Survey of Nigeria Report No: 1380.

Okonkwo A.C., Okeke P.O., Opara A.I., 2014. Evaluation of self-potential anomalies over sulphide ore deposits at Ishiagu, Ebonyi State, Southeastern Nigeria. International Research Journal of Geology and Mining 4 (1), 9-19.

Orajaka, S., 1965. Geology of Enyigba, Ameri and Ameka lead-zinc mines. Journal of Geology 3, 49-51.

Revil, A., Florsch, N., Mao, D., 2015. Induced polarization response of porous media with metallic particles—Part 1: a theory for disseminated semiconductors Geophysics 80 (5) 525-538.

Shah, A.K., Bedrosian, P.A., Anderson, E.D., Kelley, K.D., Lang, J., 2013. Integrated geophysical imaging of a concealed mineral deposit: a case study of the world-class Pebble porphyry deposit in southwestern Alaska. Geophysics 78 (5), B317-B328.

Sikakwe, G.U., Amah, J.I., 2021. Application of integrated geophysical techniques in investigating Pb–Zn sulphide ore mineralization potential in part of the Benue Trough. Environmental Earth Sciences 80, 692. https://doi.org/10.1007/s12665-021-10009-w.

Sumner, J.S., 2012. Principles of Induced Polarization for Geophysical Exploration Elsevier (2012), p. 248.

Ukwuteyinor B.U., Ezeh, C.C., 2023. Assessment of depth to Lead-Zinc de posit in parts of Southern Benue Trough using integrated geophysical methods. Journal of Geology and Mining Research 15 (1), 1-9.

Usman, A.O., Omada, J.I., Omali, A.O., 2014. Application of Vlf-Em Geophysical Method in Delineating Pb-Zn Mineralization in Ishiagu Area, Ebonyi State, Nigeria. IOSR Journal of Applied

Geology and Geophysics 2 (4), 38-46.

Vieira, L.B., Moreira, C.A., Corte,s A.R.P., Luvizotio, G.L., 2016. Geophysical modelling of the manganese deposit for induced polarization method in Itapira (Brazil). Geofísica Internacional 55, 107-117. Victor, M.O., Onwuemesi, A.G., Emmanuel, U., 2015. Exploration of Pb-Zn mineralization using very low frequency electromagnetic (VLF-EM) in Ishaigu, Ebonyi State. Geology & Geosciences 4 (4), 1-7. http://dx.doi.org/10.4172/2329-6755.1000214.

Yalçın, C., Canlı, H., 2024. IP/Resistivity methods for Pb-Zn deposit exploration: A case study in Sudöşeği, (Simav-Kütahya, Türkiye). Engineering Applications 3 (1), 27-35.

Yusuf, S.N., Faruk, M.U., Imagbe, L.O., Yohanna, O.M., Yusuf, I., Onoshagbegbe, A., Kamal, M., Jacob, T.T., 2022. Integrated geophysical investigation for lead and zinc mineralization in Wase, middle Benue Trough, Nigeria. Heliyon. 2022 Dec 21;8(12):e12541. doi: 10.1016/j.heliyon.2022.e12541. PMID: 36593845; PMCID: PMC9803722.