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Geo-electrical Resistivity Investigation of Iron Ore Mineral Deposits in Mbeu Area, Meru County, Kenya

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Abstract

Global demand for iron and its products has increased in recent years due to the expansion of the housing, road, and railway sectors as well as machinery manufacture, making the search for additional iron ore deposits increasingly important. This study used two-dimensional electrical resistivity tomography (ERT) to characterise the subsurface of the Mbeu area, Meru County, Kenya (approximately 0°06'24"N, 37°50'49"E). Subsurface resistivity was measured at the ground surface using an ABEM Terrameter LS2 along eleven profiles, and the apparent resistivity pseudosections were quantitatively inverted using RES2DINV software. The results delineate two principal subsurface zones: alluvium and rock enriched with iron ore, and alluvium and rock containing disseminated iron ore. Resistivity values of 17.4–406 Ωm and 208–886 Ωm are interpreted as alluvium and rock enriched with iron ore, respectively, while values of 110–487 Ωm and 542–995 Ωm correspond to alluvium and rock containing disseminated iron ore. The Mbeu deposits constitute an extensive resource occurring at both shallow and deep levels, predominantly as granular magnetite mixed with alluvium and host rock, with magnetite identified as the dominant ore mineral. Ore-bearing alluvium and rock were detected at depths of approximately 1.25–65.6 m, and beyond 65.6 m on several profiles.

Keywords: Electrical resistivity tomography; iron ore deposits; subsurface characterisation; magnetite; resistivity pseudosections; RES2DINV; geophysical exploration

Statements and Declarations

Ethics, consent to participate, and consent to publish declarations

Not applicable

Clinical trial

Not applicable

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Competing Interests

The authors declare no competing financial or non-financial interests in relation to the work described.

Availability of Data and Materials

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

Author Contributions

J.M. conducted the fieldwork and data processing, and drafted the manuscript. A.O. and Z.W. supervised the study and reviewed the manuscript.

1. Introduction

Iron is an abundant element, accounting for about 5% of the Earth's crust, and is the most widely used metal once processed into steel. Steel is a key material in the construction, transportation, and manufacturing industries [1]. In nature, iron is bonded with oxygen, water, sulphur, and carbonates. The principal iron ores are magnetite, containing 74.2% Fe (black); hematite, containing 69.9% Fe (red); and limonite, containing 63% Fe (brown) [2], as summarised in Table 1.

Table 1 Major iron-bearing compounds (adapted from [2])

Name	Formula	% Fe
Hematite	Fe ₂ O ₃	69.9
Magnetite	Fe ₃ O ₄	74.2
Goethite/Limonite	HFeO ₂	~63
Siderite	Fe ₃ CO ₄	48.2
Chamosite	(Mg,Fe,Al) ₆ (Si,Al) ₄ O ₁₀ (OH) ₈	29.61
Pyrite	FeS	46.6
Ilmenite	FeTiO ₃	36.81

Iron ore deposits form through three main geological processes: direct sedimentation, producing bedded sedimentary deposits such as banded iron formations and ironstones; and deposits of igneous origin formed by magmatic segregation of iron-bearing minerals, occurring as veins and tabular bodies. Electrical resistivity surveying determines the subsurface resistivity distribution from measurements taken at the ground surface. In this study, rocks and alluvium exhibiting resistivity contrast relative to the surrounding material were delineated as potential ore bodies.

According to [3], the Mbeu area has been a target for mineral exploration since the 1940s. A granitic intrusion on the southern slopes of Nyambeni suggests the likelihood of valuable mineral occurrences in the area. Chemical analysis of sand and soil sediment samples from the valleys indicates that grained sand deposits contain up to 80% magnetite, while rocks contain 40–70% magnetite. A pilot study to establish the source of this magnetite found that it originates from localised iron deposits in the hilly parts of the area [4]. A magnetic survey of the area identified

zones of high magnetic susceptibility suspected to be of ferromagnetic iron ore origin, although the ground magnetic data were affected by high-magnitude, high-frequency anomalies from near-surface intrusive and extrusive outcrops, which can conceal or distort anomalies from deeper sources [5]. A gravity survey conducted in Mbeu identified areas of higher density contrast relative to the country rock, interpreted as possible iron ore reserves; however, small, grained magnetite bodies mixed with alluvium in low-lying areas could not be resolved at shallow depth, since gravity alone cannot distinguish a strong density contrast at depth from a more diffuse shallow contrast [6].

2. Literature Review

2.1 Electrical resistivity method

The electrical resistivity method involves passing an electric current into the ground through two electrodes; the resulting potential drop is measured by a second pair of electrodes placed between the current electrodes [7]. Current flows into the ground through current electrodes C1 and C2, producing a potential difference measured between electrodes P1 and P2 [8].

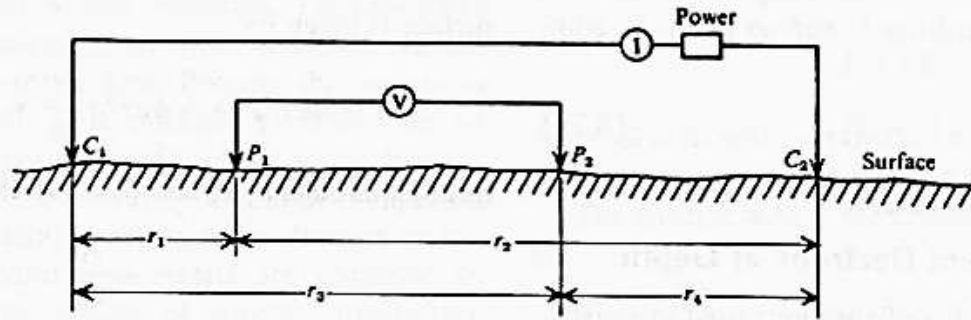


Fig. 1 Array of four electrodes: two current electrodes (C1, C2) and two potential electrodes (P1, P2), adapted from [8]

From the measured current (I) and voltage (V), an apparent resistivity (ρ_a) is calculated as $\rho_a = K(V/I)$, where K is a geometric factor that depends on the electrode arrangement [9]. Following [10], for a finite electrode spacing the potential due to C1 at P1 is $V_1 = -A_1/r_1$, where $A_1 = -I\rho/2\pi$; since the current at C2 is equal and opposite, the potential due to C2 at P1 is $V_2 = -A_2/r_2$, where $A_2 = I\rho/2\pi = -A_1$. Combining these gives $V_1 + V_2 = (I\rho/2\pi)(1/r_1 - 1/r_2)$. Introducing a second potential electrode at P2 gives the potential difference $\Delta V = (I\rho/2\pi)\{(1/r_1 - 1/r_2) - (1/r_3 - 1/r_4)\}$, which rearranges to give the apparent resistivity measured by the array: $\rho = (2\pi\Delta V/I) / \{(1/r_1 - 1/r_2) - (1/r_3 - 1/r_4)\}$. The value obtained is an apparent resistivity rather than the true subsurface resistivity; the relationship between the two is complex, and true resistivity is recovered by inversion of the measured apparent resistivity values using computer software [9].

2.2 Electrode configurations

The shape of the electrode array determines the apparent resistivity value obtained. The Schlumberger, Wenner, and dipole-dipole configurations are the three principal electrode arrangements, the first two named after their originators, Conrad Schlumberger and Frank Wenner.

Each configuration has its own advantages, limitations and sensitivities; the space available for the array, the labour intensity of the method, and susceptibility to lateral inhomogeneities influence the choice of array [11].

2.2.1 Schlumberger configuration

The Schlumberger configuration uses four electrodes arranged in a straight line on the ground surface: two current electrodes (spacing AB) and two potential electrodes (spacing MN). A power supply is connected to the current electrodes and a voltmeter to the potential electrodes [12].

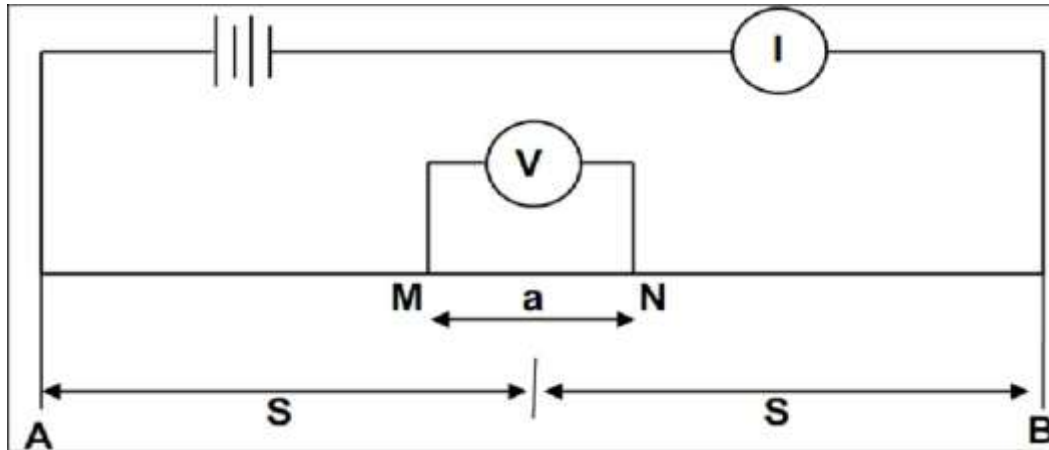


Fig. 2 Schematic of the Schlumberger electrode configuration, adapted from [13]

The configuration is founded on Ohm's law, whereby a material's electrical resistance is inversely proportional to its cross-sectional area and directly proportional to its length: a known current is passed through the subsurface between the current electrodes, and the subsurface resistivity is determined from the resulting potential difference [14]. The Schlumberger configuration is preferred because the current electrodes are positioned farther apart than the potential electrodes, producing a larger investigation depth that reduces the effect of near-surface heterogeneities and gives a more representative measurement of subsurface resistivity [11]. According to [15], the configuration is also versatile, suitable for both shallow and deep investigations across a range of subsurface conditions, making it a popular choice for geophysical surveys in varied geological settings.

2.2.2 The dipole-dipole configuration

The dipole-dipole array is a commonly used electrode configuration for electrical resistivity tomography (ERT) surveys [16].

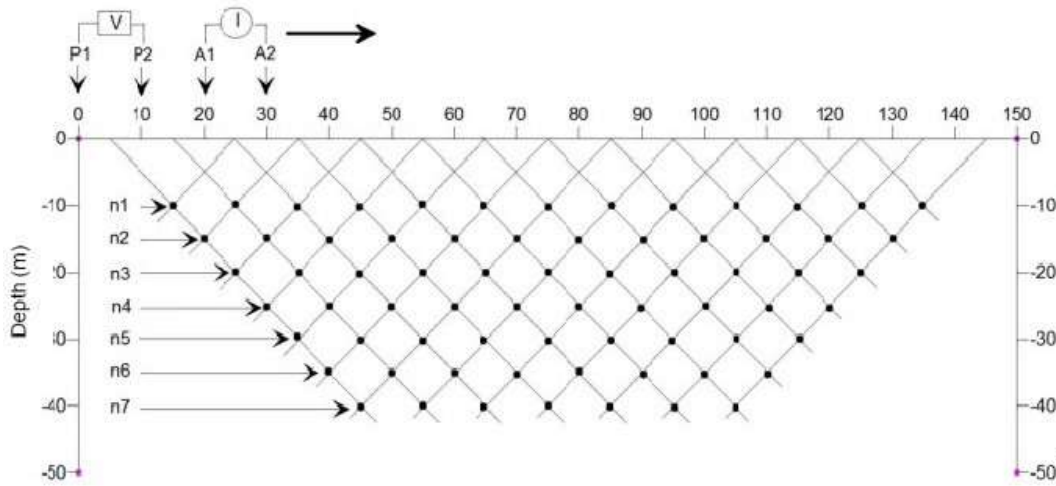


Fig. 3 Geometry of the dipole-dipole electrode configuration, adapted from [17]

In a dipole-dipole survey, electrodes are positioned on the ground surface with a current-electrode spacing typically of 1–10 m and a potential-electrode spacing of 2–20 m, chosen according to the required resolution and investigation depth. The configuration's ability to detect resistivity changes at different depths by varying electrode spacing makes it valuable for mineral exploration, groundwater mapping and environmental studies, and it is also sensitive to lateral resistivity changes [17]. Its main limitation is that it requires many electrodes, making it time-consuming and labour-intensive to deploy, and it is sensitive to noise, requiring careful data processing [18].

2.3 Modes of deployment

Electrode arrays can be deployed in two principal ways: vertical electrical sounding (VES), or depth sounding, which measures the vertical variation of resistivity using horizontal traversing to determine horizontal changes; and, for multi-electrode arrays, two-dimensional electrical resistivity tomography, which achieves very high resolution of the near-surface [11].

2.3.1 Vertical electrical sounding (VES)

Also known as electrical drilling or depth sounding, VES is appropriate where the subsurface comprises several horizontal strata of similar composition but differing resistivity [19]. In VES, the electrode array is expanded outward from a fixed centre point, and readings are obtained as the current penetrates to progressively deeper levels [20]. The penetration depth of the current increases as the spacing between the current electrodes increases [11].

The Wenner and Schlumberger arrays are the configurations most commonly used in depth sounding: the Schlumberger array is used for both shallow and deep prospecting, while the Wenner array is used mainly for shallow-depth exploration [21]. The Schlumberger array is most frequently used for VES measurements because only the current electrodes need to be relocated to change depth [22]; its current-electrode spacing is large relative to its potential-electrode spacing [10].

According to [23], although the spacing between electrode pairs varies, the midpoints of the potential and current electrode pairs coincide. If L and a represent the current- and potential-electrode spacing respectively, then $r_{AC} = r_{DB} = (L-a)/2$ and $r_{AD} = r_{CB} = (L+a)/2$.

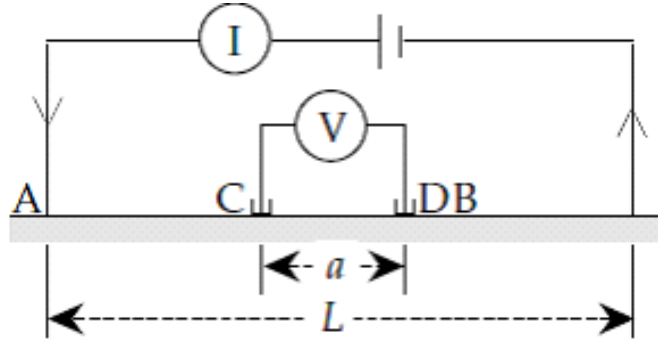


Fig. 4 Geometry of current and potential electrodes for the Schlumberger configuration, adapted from [23]

Substituting into the general apparent resistivity formula gives the apparent ground resistivity $\rho = (2\pi\Delta V/I) / \{(1/r_{AC} - 1/r_{CB}) - (1/r_{AD} - 1/r_{DB})\} = (\pi V/4I)(L^2 - a^2)/a$.

VES data are plotted as a resistivity curve, typically on a logarithmic scale with depth increasing from left to right. A steeply sloping curve indicates a sharp resistivity change, possibly a geological boundary or change in material type; a flat curve suggests a relatively uniform subsurface; and a curve with multiple peaks and troughs may indicate several structures or strata. Curve matching is a technique used to interpret these resistivity curves [18].

2.3.2 Electrical resistivity tomography (ERT)

The development of efficient software and affordable, fast computers has enabled new techniques such as time-lapse ERT, which repeats surveys over the same area to track subsurface changes through time, and 3D ERT, which uses many electrodes and more complex processing to produce a three-dimensional subsurface image with greater precision and detail [9].

ERT is applied widely in environmental and engineering studies and in mineral exploration to map ore bodies and groundwater. In environmental studies it can identify and map contaminant plumes, monitor groundwater flow, and assess landfill integrity; in engineering applications it can locate buried utilities, map bedrock and soil layers, and assess slope and foundation stability [24].

The ERT method provides more precise resistivity measurements of horizontal variation along the survey line, assuming resistivity changes do not occur perpendicular to the line. The dipole-dipole array is the most appropriate array for ERT owing to its high sensitivity to horizontal resistivity changes and its superior horizontal data coverage compared with the Wenner and Schlumberger arrays [25].

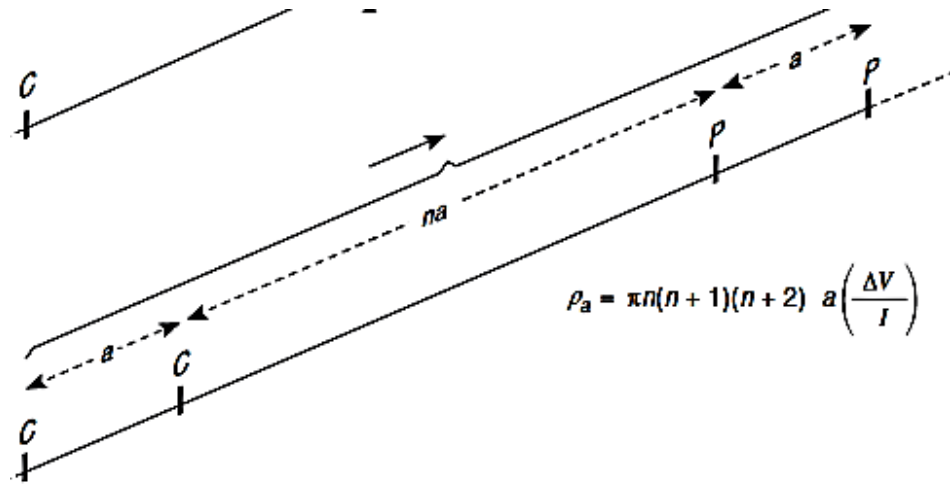


Fig. 5 Dipole-dipole array configuration used in electrical resistivity tomography, adapted from [20]

In the dipole-dipole array, all four electrodes are fixed along the line at measured separations: current electrodes C1 and C2, and potential electrodes P1 and P2, are separated by a distance a from the current dipole and by na from each other [26]. In this study, 42 electrodes attached to a multi-core cable were used for the 2D ERT survey; the cable was connected to an ABEM Terrameter LS2, which selects the appropriate four electrodes for each measurement [24]. Following [8], the apparent resistivity for a dipole-dipole array is given by $\rho_a = 2\pi n^3 a (\Delta V/I)$.

A pseudosection is used to study the electrical structure of a horizontally extensive body; pseudosections are typically inverted using RES2DINV software to recover the true subsurface resistivity [20]. ERT is a widely used method for shallow subsurface imaging, with applications in engineering, hydrogeology and mining prospecting [27].

3. Materials and methods

3.1 Study site

The Mbeu area lies north-east of Meru town on the eastern slopes of Mt Kenya, within the Nyambeni range in Tigania Sub-county, at approximately 1,500 m above sea level and coordinates 0.047185° N, 37.80138° E.

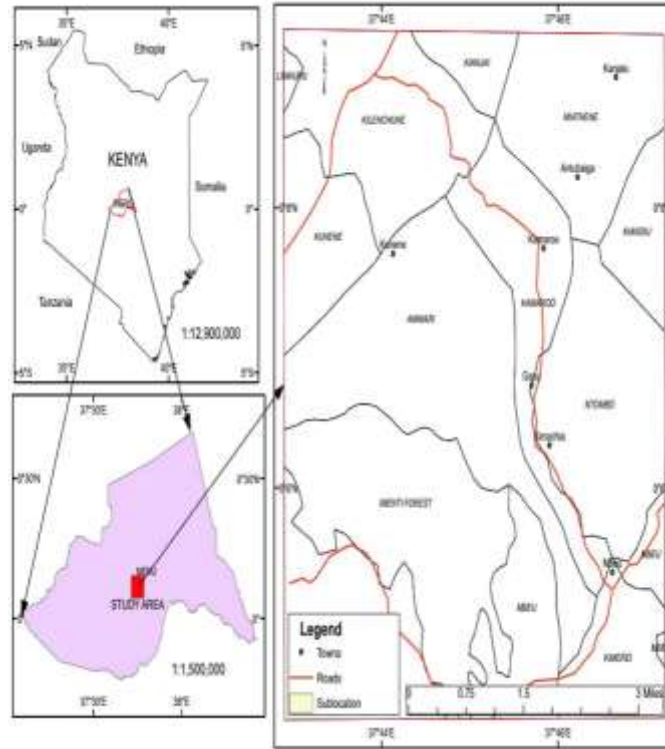


Fig. 6 Location of Meru and Mbeu area within Kenya, adapted from [28]

The area lies within a series of volcanic hills forming a conspicuous scenic landscape. Weathering and erosion have exposed large rock outcrops previously covered by vegetation, thick soils and volcanic material, revealing indications of iron ore and other mineral deposits. The local rocks comprise schist, granulites and heterogeneous gneisses of varying composition, predominantly quartzo-feldspathic gneisses containing variable proportions of biotite, and are frequently intensely veined by quartz and feldspar stringers, with some layers and lenses of pegmatitic texture [4].

3.2 Field equipment

Ground electrical resistivity was measured using an ABEM Terrameter LS2. Other equipment used included current and potential electrodes, a 12 V DC battery, coiled wires, a tape measure, a hammer, and a GPS receiver.



Fig. 7 Geophysical instrumentation used for ground resistivity measurement [29]

The Schlumberger and dipole-dipole configurations were both used for 2D resistivity imaging in this study.

3.3 Data acquisition

3.3.1 Schlumberger method

Following identification of the field site, the Schlumberger configuration was used for VES investigations to observe the variation of resistivity with depth. For asymmetric Schlumberger sounding, the current-electrode spacing (A, B) was increased in a succession of logarithmically near-equal increments, and the corresponding apparent resistivity calculated from the general apparent resistivity equation; the potential-electrode spacing (M, N) was held fixed for each successive current-electrode spacing.

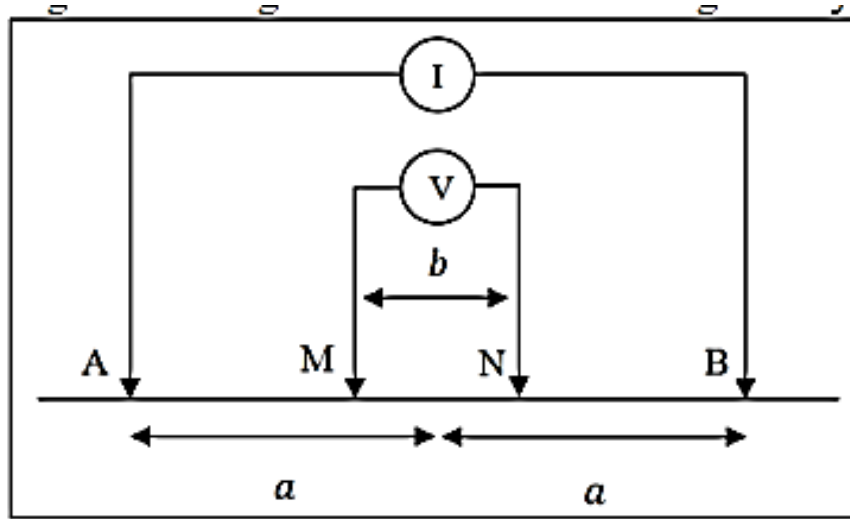


Fig. 8 Schlumberger array used for vertical electrical sounding, adapted from [30]

The survey was carried out with an ABEM Terrameter LS2 and accessories, using a continuous vertical electrical sounding (CVES) system to cover a wide area. Two multi-core cables were laid on the ground with 42 electrodes at 10 m spacing. GPS was used to record the coordinates and elevation of each survey point. Ten VES stations were established across the study area, with a maximum current-electrode separation of 400 m and an investigation depth of 65.6 m; these steps were repeated at each station. After all connections were made, the Terrameter was powered on and a contact-resistance test performed to confirm good electrode-ground contact, after which a survey scan was carried out and the data stored on external memory for interpretation.

3.3.2 Electrical resistivity tomography (ERT)

A dipole-dipole array was used for ERT, since it offers high signal strength and greater sensitivity to horizontal and vertical structures.

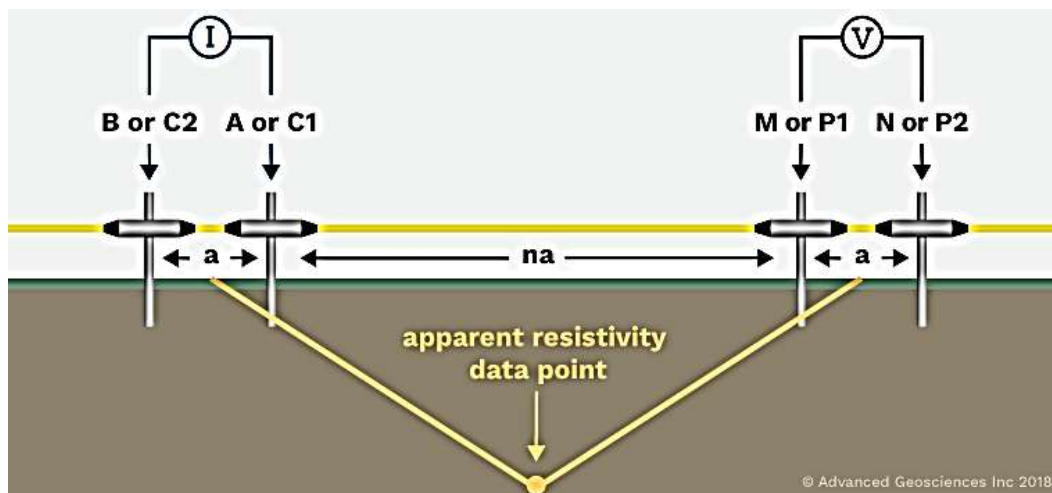


Fig. 9 Dipole-dipole array used in electrical resistivity tomography [31]

Data were acquired using the ABEM Terrameter LS2 across the survey sites. A GPS receiver recorded the coordinates of each survey point prior to acquisition. Two multi-core cables were laid along each survey line, with 42 electrodes inserted at the designated take-outs. A contact-resistance test confirmed that all electrodes were properly connected, after which the survey name, electrode spacing and dipole-dipole configuration were entered into the Terrameter and data acquisition initiated. Acquired data were processed and stored on an external storage device for subsequent analysis and interpretation.

3.4 Data analysis, representation and interpretation

3.4.1 Quantitative interpretation

Interpretation of the ERT data was a crucial step in understanding the subsurface and identifying targets for further investigation. RES2DINV software was used to process and interpret the data collected from the ERT survey as follows: the ERT data collected in the field were imported into RES2DINV; the software plotted the values on a 2D grid, with the x-axis representing distance along the survey line and the y-axis representing depth; data refinement was performed to remove noise and anomalies, producing a clearer subsurface image; and, following generation of the apparent-resistivity pseudosections, an inversion procedure was applied to compute the true subsurface resistivity from the observed data.

In the resulting resistivity models, colour is used to distinguish geological layers with similar geo-electric properties: red represents high-resistivity layers and blue represents low-resistivity layers [9]. Eleven profiles, using the dipole-dipole and Schlumberger configurations, were carried out and are discussed in Sections 4.1.1 to 4.1.11. Most profiles were measured at the foot of the hills, in areas of accumulated weathered rock and alluvium.

4. Results and discussion

4.1 Quantitative interpretation

To delineate the mineralisation zones of the study site and determine the heterogeneity of the subsurface, resistivity models depicting the subsurface structure were obtained for eleven profiles using the dipole-dipole and Schlumberger configurations, discussed in Sections 4.1.1 to 4.1.11. Most profile measurements were made at the foot of the hills, in areas of accumulated weathered rock and alluvium.

4.1.1 Profile one

This profile was located on coordinates 0° 3.1988'N, 37° 47.078'E, elevation 1,134–1,149 m ASL, profile length 420 m.

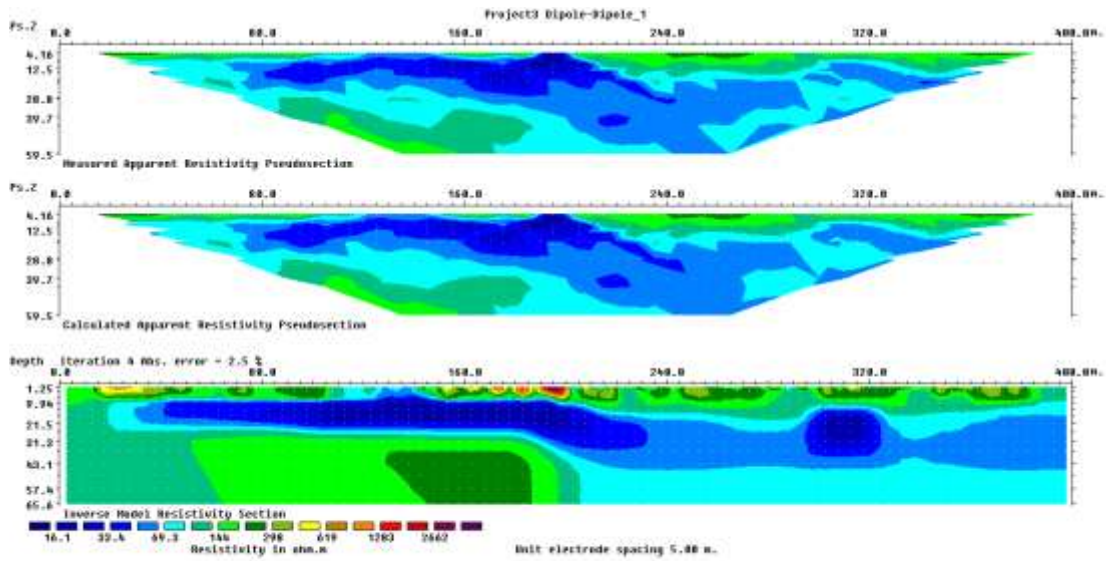


Fig. 11 Electrical resistivity image, subsurface of profile two

The inverse model gives true subsurface resistivities of a low-lying area containing alluvial deposits of weathered rock from the surrounding hills; iron ore occurs as grained magnetite mixed with alluvium and soil. Since the resistivity of magnetite ranges from 0.01 to 1,000 Ωm [32], layers with resistivity 104–212 Ωm at 1.25–31.3 m depth between 50–260 m horizontal distance are interpreted as alluvium rich in grained iron ore. An oval-shaped region with resistivity 212–433 Ωm is a magnetite-rich rock boulder. A further magnetite-rich rock, with resistivity 433–658 Ωm , occurs at 21.5 m depth between 330–390 m lateral distance [33]. The dark-blue patch with resistivity 13.5–27 Ωm is alluvium with high groundwater concentration [34].

4.1.3 Profile three

This profile was located on coordinates 0° 3.763'N, 37° 48.268'E, elevation approximately 1,170–1,199 m.

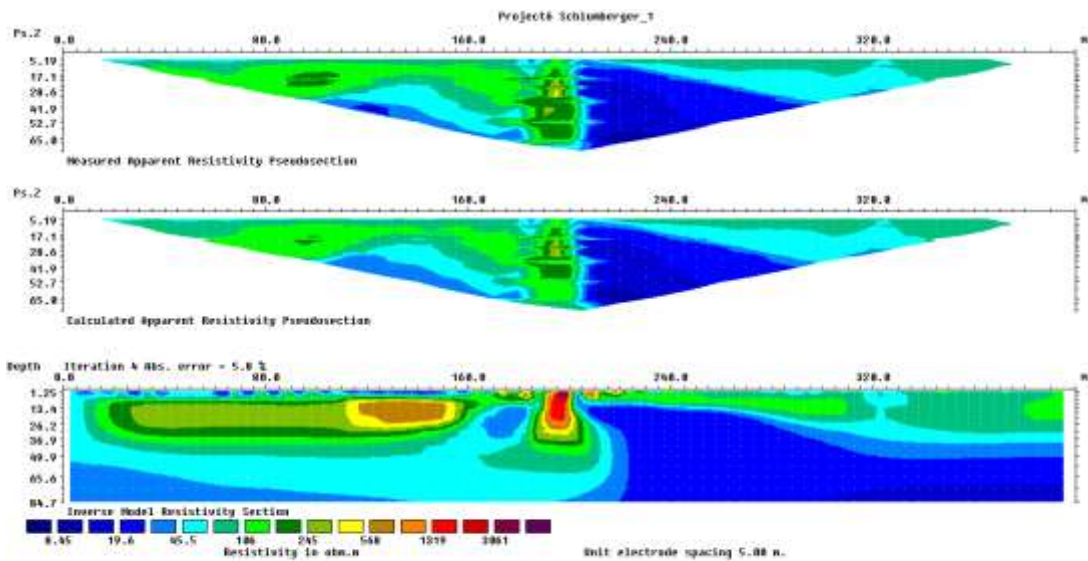


Fig. 12 Electrical resistivity image, subsurface of profile three

The model reveals alluvium with resistivity 19.6–406 Ωm and a rock patch with resistivity 406–940 Ωm at 20 m depth over 115–150 m horizontal distance. A high-resistivity region (568–3,061 Ωm) at 190–200 m distance corresponds to a borehole drilled into the subsurface [35]. The top layer, with resistivity 19.6–75 Ωm at 1.25–10 m depth over 10–180 m distance, is alluvium rich in grained iron deposits, and the underlying layer at 10–84.7 m depth across the whole profile (resistivity 19.6–406 Ωm) is likewise alluvium rich in grained iron ore, sourced from magnetite-bearing rock weathered from the surrounding hills over a long period [4]. Layers with resistivity 4.11–19.6 Ωm are saturated with groundwater [34].

4.1.4 Profile four

This profile was located on coordinates 0° 3.794'N, 37° 48.016'E, elevation 1,180–1,190 m ASL.

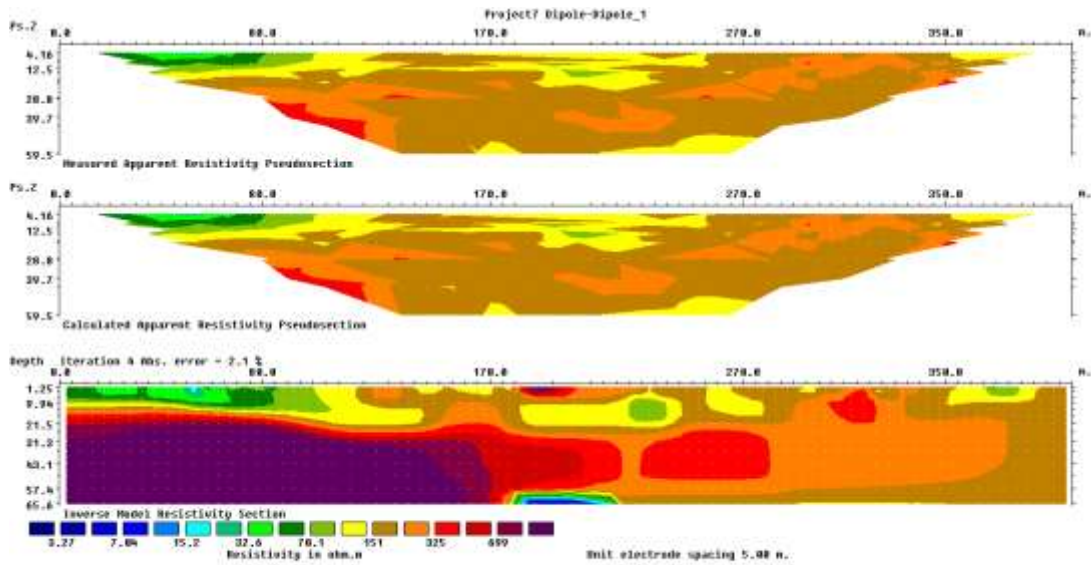


Fig. 13 Electrical resistivity image, subsurface of profile four

The model reveals alluvium and rock; since magnetite is typically a poor conductor in massive form but its individual crystals are highly conductive [11], the layer with resistivity 325–886 Ωm at 15–65.6 m depth over 5–210 m lateral distance is interpreted as massive magnetite-rich rock. Layers with resistivity 32.6–110 Ωm at 1.25–9.94 m and 2.5–20 m depth between 10–100 m distance are alluvium rich in grained magnetite, while layers with resistivity 110–325 Ωm contain disseminated magnetite.

4.1.5 Profile five

This profile was located on coordinates 0° 07.30'N, 37° 46.72'E, elevation 1,277–1,327 m ASL.

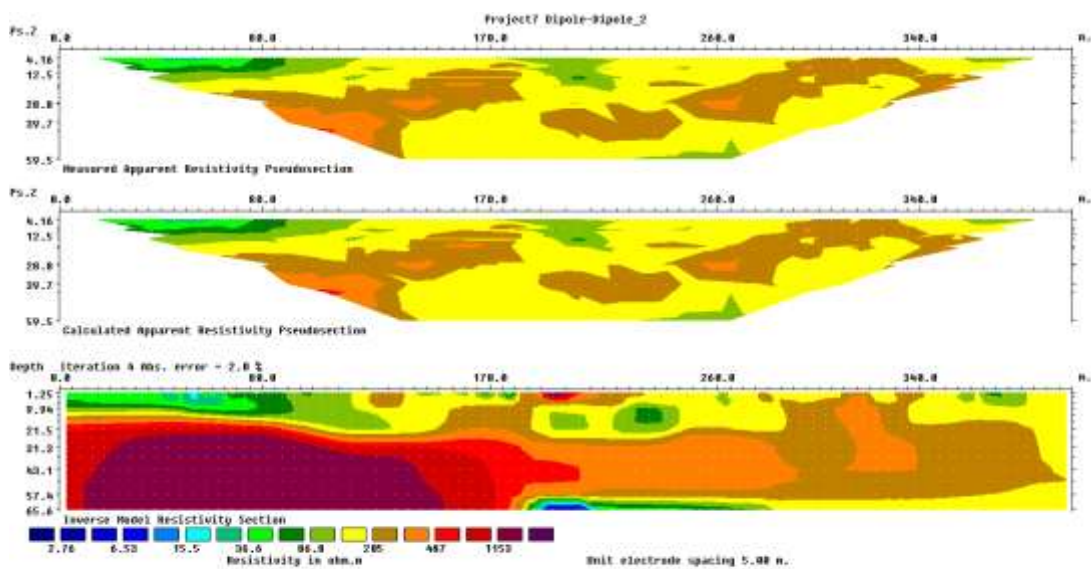


Fig. 14 Electrical resistivity image, subsurface of profile five

High-resistivity regions indicate coarse sandstone [36]. The layer with resistivity 487–2,000 Ωm at 12.8–65.6 m depth over 0–280 m distance is coarse sandstone. Since alluvium rich in magnetite typically ranges from 34–738 Ωm , layers with resistivity 30.6–205 Ωm at 1.25–35 m depth across the whole profile are alluvium rich in iron ore.

4.1.6 Profile six

This profile was located on coordinates 0° 07.28'N, 37° 46.67'E, elevation 1,263–1,312 m ASL.

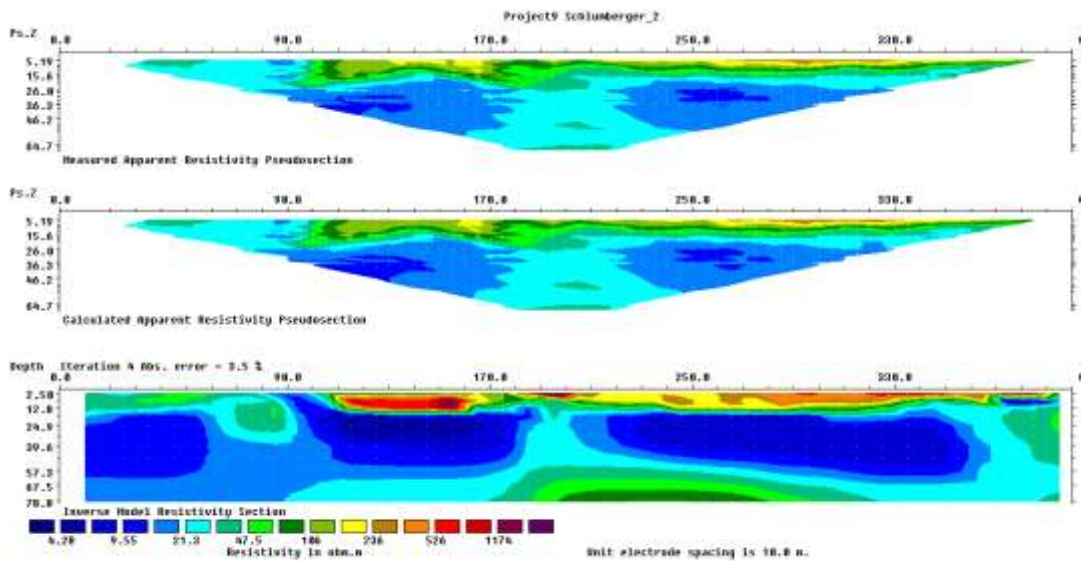


Fig. 15 Electrical resistivity image, subsurface of profile six

The top layer, at 2.5–12.8 m depth over 180–390 m distance, is alluvium and rock patches with resistivity 170–1,300 Ωm ; the rock patches (236–1,300 Ωm) are rich in magnetite [37]. Layers with resistivity 21.3–236 Ωm at 2.5–20 m and 8–26.5 m depth over 10–85 m and 160–390 m distance are alluvium rich in grained iron ore, while the blue layers with resistivity 4.28–21.3 Ωm at 20–58 m, 12.8–62 m and 20–57.3 m depth are wet alluvium [38].

4.1.7 Profile seven

This profile was located on coordinates 0° 5.1542'N, 37° 48.86'E, elevation 1,172–1,203 m.

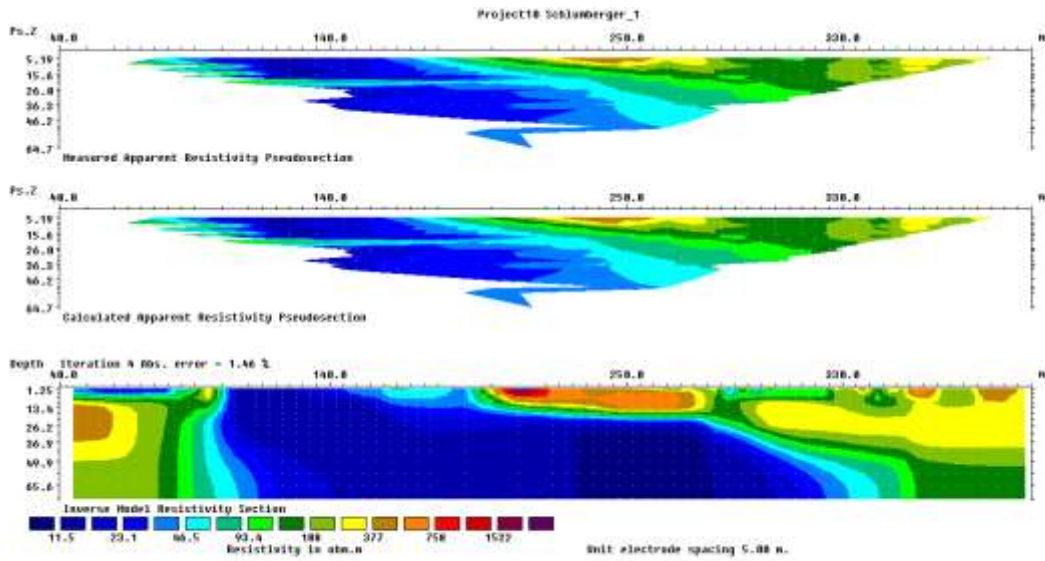


Fig. 16 Electrical resistivity image, subsurface of profile seven

The subsurface comprises low-resistivity rock and alluvium. The layer with resistivity 377–758 Ωm at 1.25–13.4 m depth over 180–390 m distance is low-resistivity rock rich in magnetite [11]. The light- and dark-blue layers (3.39–20 Ωm) are water-saturated [38], and layers with resistivity 23.1–377 Ωm are weathered rock and alluvium containing grained iron ore.

4.1.8 Profile eight

This profile was located on coordinates 0° 5.25'N, 37° 48.993'E, elevation approximately 1,190–1,205 m ASL.

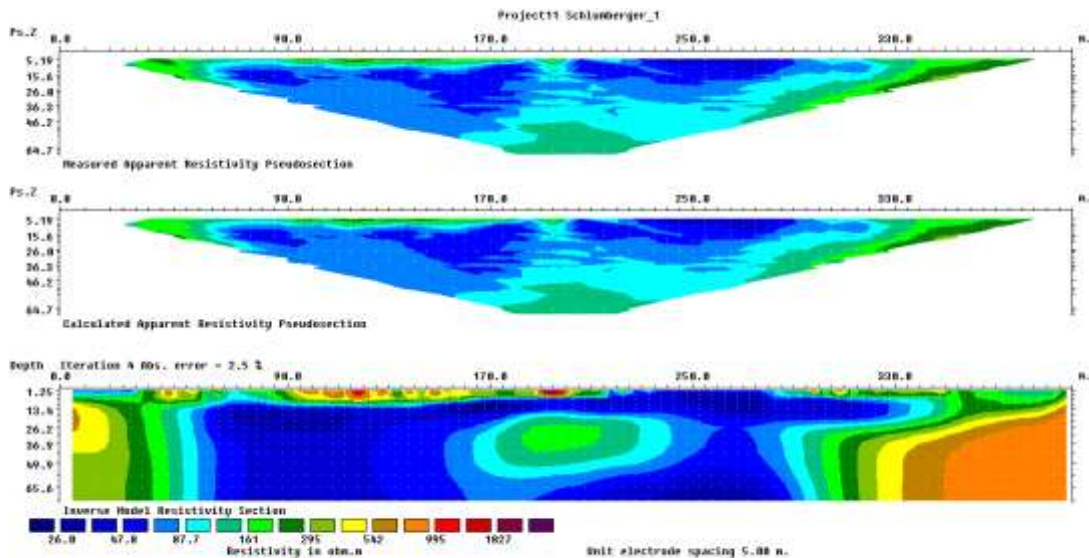


Fig. 17 Electrical resistivity image, subsurface of profile eight

The profile comprises alluvium (resistivity 26–542 Ωm). At 1.25–65.6 m and 1.25–12.8 m depth over 10–60 m, 280–390 m and 45–230 m distance, resistivity of 87.7–161 Ωm indicates alluvium rich in grained iron ore. Layers at 12.8–65.6 m depth over 50–330 m distance, with resistivity 26–87.7 Ωm , are wet alluvium [38]. Rock with resistivity 542–995 Ωm at 13.4–45 m and 12.8–65.6 m depth over 0–15 m and 330–390 m distance contains disseminated iron ore deposits surrounded by relatively low-resistivity iron-bearing layers [33].

4.1.9 Profile nine

This profile was located on coordinates 0° 5.555'N, 37° 49.01'E, elevation 1,177–1,191 m ASL.

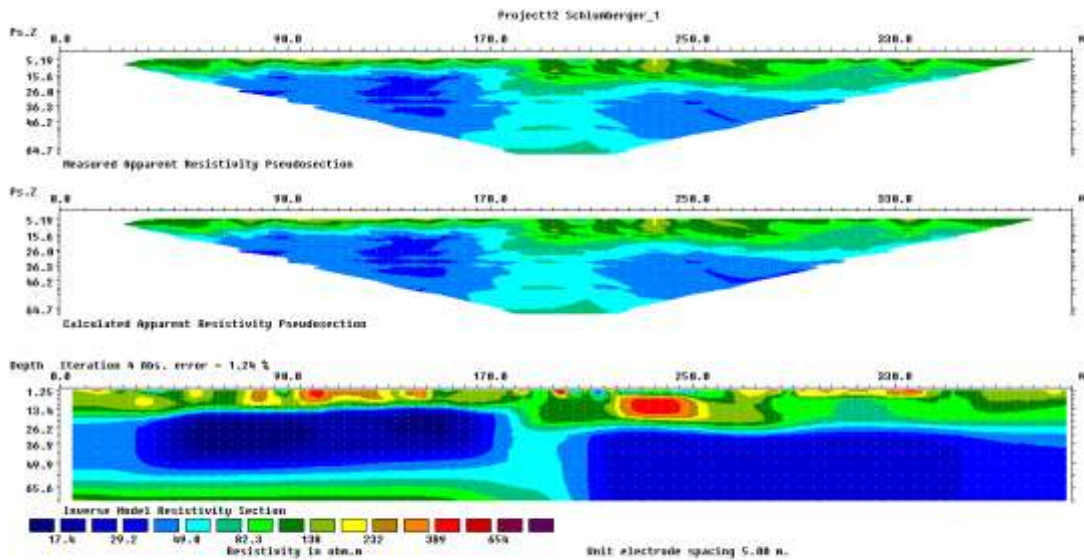


Fig. 18 Electrical resistivity image, subsurface of profile nine

The profile comprises alluvium, low-resistivity rock patches, and groundwater-saturated alluvium. At 2.5–20 m depth over 10–340 m distance, low-resistivity rock (232–389 Ωm) is rich in magnetite [32]. Across the whole profile at 1.25–65.6 m depth, alluvium with resistivity 17.4–232 Ωm is rich in grained iron ore, and at 20–57.3 m depth a layer of wet alluvium (17.4–65 Ωm) is likewise rich in grained magnetite [39].

4.1.10 Profile ten

This profile was located on coordinates 0° 5.515'N, 37° 49.224'E, elevation 1,155–1,215 m ASL.

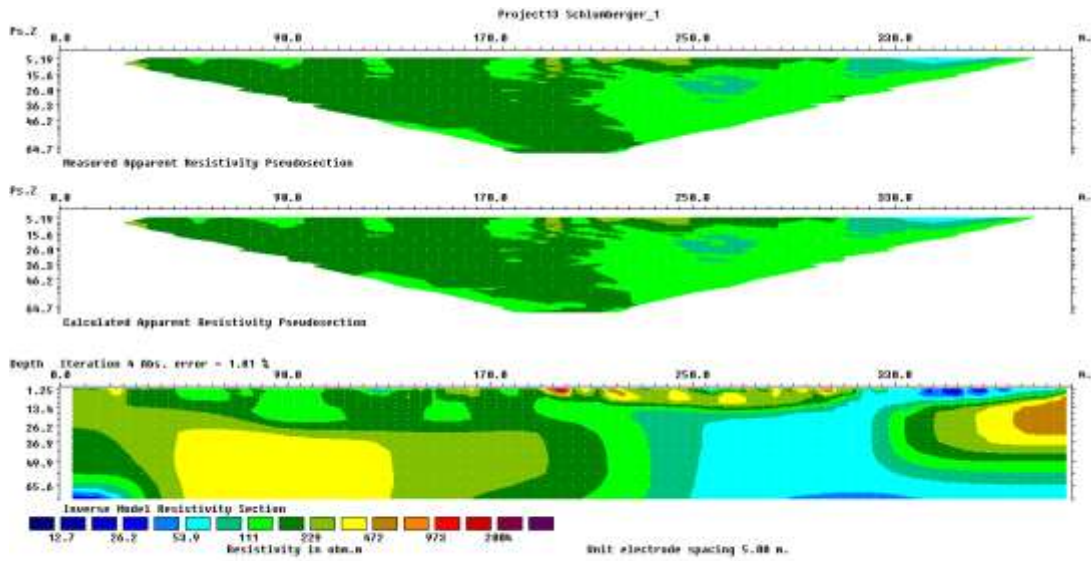


Fig. 19 Electrical resistivity image, subsurface of profile ten

The profile comprises rock and alluvium. Layers with resistivity 111–229 Ωm at 1.25–65.6 m and 1.25–12.8 m depth over 10–30 m and 190–310 m distance are alluvium with disseminated magnetite [33]. The zone with resistivity 229–603 Ωm at 13.4–65.6 m depth over 10–190 m distance is a massive magnetite-rich rock [40], and rock with resistivity 208–472 Ωm at 5–34 m depth over 320–380 m distance is also magnetite-rich [41]. Layers with resistivity 53.9–111 Ωm at 1.25–65.6 m depth over 250–390 m distance are wet alluvium [38].

4.1.11 Profile eleven

This profile was located on coordinates 0° 07.133'N, 37° 46.233'E, elevation 1,288–1,298 m ASL.

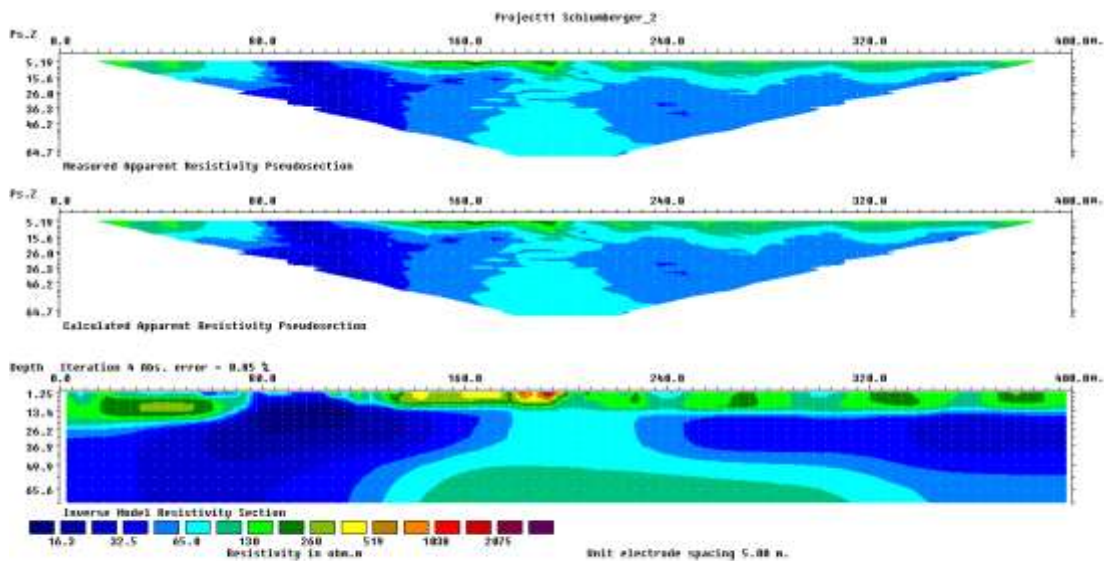


Fig. 20 Electrical resistivity image, subsurface of profile eleven

The profile comprises wet alluvium, low-resistivity rock patches, and dry loamy topsoil. Rock patches within the topsoil layer, at 1.25–15 m depth over 10–70 m and 110–390 m distance, have resistivity 400–750 Ωm and are presumed rich in magnetite. Most of the subsurface is covered by wet alluvium (resistivity 16.3–130 Ωm at 1.25–65.6 m depth), likely rich in grained magnetite deposited from the surrounding hills [33].

5. Conclusion and recommendations

5.1 Conclusion

The electrical resistivity method successfully located small and large isolated rock bodies and shallow deposits rich in magnetite that could not be resolved by either magnetic or gravity methods, owing to their low density contrast and magnetic susceptibility, respectively. Inversion of the measured apparent resistivity values yielded the true subsurface resistivities summarised in Table 2. Ground resistivities range from 229–3,000 Ωm for rock and 19.6–487 Ωm for alluvium.

Table 2 Summary of resistivity, geometry and interpreted lithology across the eleven survey profiles

Profile	Resistivity (Ωm)	Lateral distance (m)	Depth (m)	Interpreted lithology
1	122–460	10–390	1.25–9.94	Top loamy soil / sandstone
1	460–3000	10–390	1.25–9.94	Wet alluvium rich in grained magnetite
1	33.4–144	10–390	9.94–65.6	Wet alluvium with disseminated magnetite
2	104–212	50–260	1.25–31.3	Alluvium rich in grained iron ore
2	212–650	90–250	9.94–31.3	Magnetite-rich rock
2	50.9–212	–	1.25–65.6	Wet alluvium with disseminated magnetite
3	19.6–406	10–190	1.25–55	Alluvium rich in grained magnetite ore
3	406–940	115–150	20	Magnetite-rich rock
4	325–886	10–210	15–65.6	Magnetite-rich rock
4	32.6–110	10–100	1.27–9.94	Alluvium with grained iron ore
4	110–325	170–390	1.25–65.6	Alluvium with disseminated magnetite
5	322–2000	0–280	12.8–78.8	Magnetite-rich rock
5	61.7–322	0–390	2.5–20	Alluvium with grained iron ore
5	22.21–26.4	310–390	7–78.8	Wet alluvium containing magnetite
6	487–2000	5–190	1.25–65.6	Coarse sandstone

6	30.6–205	5–190	1.25–35	Alluvium rich in grained iron ore
6	205–487	130–390	1.25–65.6	Alluvium with disseminated magnetite
7	377–758	180–390	1.25–13.4	Rock rich in magnetite
7	26–286	270–390	1.25–65.6	Alluvium with grained iron ore
8	87.7–161	10–60; 280–390; 45–230	1.25–65.6	Alluvium rich in grained iron ore
8	542–995	5–15; 330–390	13.4–45; 12.8–65.6	Sandstone with disseminated iron ore
9	232–389	10–340	1.25–20	Rock rich in magnetite
9	17.4–232	10–390	1.25–65.6	Alluvium rich in grained iron ore
10	111–229	10–30; 190–310	1.25–65.6; 1.25–12.8	Alluvium rich in magnetite
10	229–603	10–190	13.4–65.6	Rock rich in magnetite
11	400–750	10–70	1.25–15	Rock rich in magnetite
11	16.3–130	110–390	5–390; 1.25–65.6	Wet alluvium with grained magnetite patches

This study quantitatively characterised alluvium and rock using electrical resistivity tomography and vertical electrical sounding across the valleys and hills of the study area. Subsurface layers in the valleys and low-lying areas, with resistivity 17.4–206 Ωm , are alluvium enriched with grained iron ore accumulated from weathered sandstone and magnetite-bearing rock in the surrounding hills. Small and large rock patches with resistivity 208–886 Ωm are magnetite-rich rocks distributed within the hills and valleys of Mbeu, and zones of alluvium and rock with resistivity 205–995 Ωm contain disseminated iron ore. Iron ore in Mbeu therefore occurs as grained deposits mixed with alluvium, as magnetite-rich rock, and as sandstone rock with disseminated iron ore.

The quantitative interpretation of the 2D resistivity models indicates that ore bodies extend from a shallow depth of 1.25 m to beyond the maximum probing depth of 65.6 m on profiles 1, 3, 4, 5, 7, 8 and 9, and occur at depths of 30 m to beyond 65.6 m on profile 10, while ore rock and deposits appear at shallow depth on profiles 2 and 6. The similarity of results across profiles at different locations indicates that the ore rock and alluvium deposits are not localised but extend over a wide area of Mbeu. Profiles 8 and 11, carried out in the Kimachia area 10 km north-west of the study area, produced results similar to those within Mbeu, indicating that the iron deposits extend beyond Mbeu into the Kimachia area.

5.2 Recommendations

Subsurface investigation of mineral ores benefits from complementary geophysical methods. A magnetotelluric survey should be integrated, as it uses natural time variations in the Earth's magnetic and electric fields to delineate deeply buried ore bodies at depths from a few metres to more than a kilometre. Drilling should be carried out at the identified targets to obtain direct

evidence of iron ore mineralisation, with drill-hole locations guided by the geophysical anomalies to increase the likelihood of intersecting ore bodies at depth. An induced-polarisation survey, which can effectively delineate alluvium and rock layers with disseminated iron ore and distinguish mineral-rich clay from water-saturated clay, should also be integrated into future work.

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