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Review of Geoelectrical Methods in Geophysical Exploration

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ABSTRACT

In geoelectric methods, with the exception of self potential current is introduced into the ground or on the surface to study the differences of the electrical property of the materials beneath the earth. The current injected generates potential variations arising from the inhomogeneity of the subsurface that is measured. Geophysical methods applied in the investigation of earth's subsurface provide a relatively fast and cheaper means of getting information coverage of large expanse subsurface geology. Geoelectric method is adjudged the most suitable, efficient and economical method in subsurface investigation. It is presently employed in archeology, hydrology, mineral exploration, environmental and engineering investigations. The present review is aimed at reviewing geoelectric methods applied in geophysical exploration. The paper provides us with a comprehensive understanding of the principles, applications, and potentials of the geoelectrical methods. The advantages and challenges of different geoelctrical techniques were also discussed. The review also considered the recent developments and future perspectives in geoelectric surveys due to modern instrumentation, surveys designs, computer and software applications that have made a lot of improvements and changes in geoelectric investigations. The various results highlighted by different researchers have revealed the applicability of most of the geoelectric methods in geophysical explorations.

Keywords:
Anomaly,
Exploration,
Fractures,
Geoelectrical methods,
Resistivity.

INTRODUCTION

The application of Physics principles to study the earth is called Geophysics (Nazri, *et al*., 2012). It is majorly divided into Physics of the earth's interior and Applied Geophysics (Anderson and Ahmed, 2003). Geophysics is applied in exploration and exploitation of: hydrocarbons (CONSTABLE, 2010), mineral resources (Mosaad *et al*., 2023) and other materials having recognizable economic value in the subsurface. This deals with measurements at the surface of the earth or near to it to delineate the minerals and rocks in the subsurface of the earth by application of Physics principles, thereby considering the associated physical and chemical properties of materials of economic importance to humanity. The properties of interest that are sought for are: seismic velocity (Yilmaz, 2001), susceptibility of magnetic materials, electrical conductivity or resistivity (Herman, 2001), electrical polarizability, density (GARDNER ET AL., 1974) and radioactivity (Parasnis 2013). These properties most times suggest the most adequate geophysical approach to be employed in an investigation (Kearey *et al*., 2002). Geophysical methods applied in the investigation of earth's subsurface provide a relatively fast and cheaper means of getting information coverage of large expanse subsurface geology. Although geophysical data can sometimes be prone to ambiguities and uncertainties of interpretation particularly with magnetic and gravity methods, the advantages of geophysical methods still outweigh the limitations, particularly when compared with conventional methods such as drilling of boreholes and wells as the best alternatives with the associated high cost and limitation of information to a particular drilling point.

Geophysical methods are applied on investigations depending on the need of a particular study. These days the following geophysical techniques are most adopted: seismic, gravity, radiometric, electrical resistivity, magnetic, ground-probing radar and self-potential methods (Kearey *et al*., 2002). Irrespective of the method adopted, the study covers determination of overburden thickness, groundwater exploration (Mohamaden *et al.*, 2016), engineering site investigations, geological structure (shaft, fault, fractures; cavities) mapping, location of buried cables and pipes, location of clandestine graves as forensic tools, among others.

Geophysical techniques are classified in terms of the nature of their source fields which could be natural like earthquakes, gravity, magnetic, magnetotellurics and radiometrics or artificial such as seismic, electrical and electromagnetic. Electrical and electromagnetic techniques have both naturally and artificially generated sources of energy. The natural field methods are easier to handle in terms of logistics and provide information from greater depths; the artificial source methods give more detailed and higher resolution picture of the subsurface.

In geoelectric methods, with the exception of self potential current is introduced into the ground or on the surface to study the differences of the electrical characteristic of the materials under the earth. The current injected will generate potential variations that will be measured due to the inhomogeneity of the subsurface. These variations can be investigated using any of the following geoelectric methods: Induced Polarization (IP) and Resistivity while the study using Self Potential (SP) does not involve introduction of current into the ground. Electric resistivity survey is among the oldest method of geophysical exploration. It is generally employed in hydrology, environmental and engineering investigations (Cardenas and Wilson 2006), archeology (Griffiths and Barker 1994) and mineral exploration (Bauman 2005)

Many researchers, among who are Koefoed 1976; Odoh *et al*., 2012; Ojo and Olorunfemi 2013; Igboama *et al.*, 2021a have used electrical resistivity survey in the delineation of rock types and the mapping of rock boundaries and fractures. Some others including, Olayinka and Barker (1990); Al Garni (2005); Abubakar *et al.*, (2014); Alhassan *et al.*, 2017;Olorunfemi *et al.*, (2020), applied electrical resistivity survey to siting of wells, boreholes and groundwater studies. Park *et al.*, (2016);Uchegbulam and Ayolabi (2014) on the other hand, demonstrated the application of electrical resistivity imaging (ERI) in groundwater contamination monitoring. The duo of electromagnetic and resistivity techniques was combined by Hazell (1992) in locating aquifer in crystalline rocks in northern Nigeria.

Induced Polarization (IP) has been employed in the delineation of low-grade ore deposits such as disseminated sulfides and has found applications in areas like geotechnical engineering studies, hydro-geophysical investigations and environmental investigations, Haldar (2018). The improvement in instrumentation technology, automated and inversion techniques, computer and software applications, multiplexers and multichannel resistivity meters have impacted on geoelectric surveys. 2-D, 3-D and 4-D resistivity arrays are the current arrays in use unlike before when the traditional 1-D array was frequently used for geoelectric survey (Loke *et al.*, 2013).

The present study is aimed at reviewing geoelectric methods as applied in geophysical exploration in order to highlight recent developments, role of advancement in technology and future perspectives in the sector.

Background Theory

The basic principle of electrical methods is centered on the Ohm's law. This law states that, the electric current (I) flowing through a conductor varies proportionally to the potential difference (V) applied between the terminals provided temperature and other physical factors are constant.

The expression for the relation is as follows:

$$V = IR \qquad (1)$$

where R = resistance of the conductor measured in Ohm (Ω). The resistance has a reciprocal called the conductance and is measured in ohm (Ω^{-1}) variously called mho Siemens(S).

Also, a given material of resistance R ,is said to have a length L directly proportional and inversely proportional to the cross-sectional area A of the material. These relationships can be formulated as:

$$R = \rho \frac{L}{A} \ldots\ldots \qquad (2)$$

ρ is the resistivity of the conductor, also known as constant of proportionality. The reciprocal of the resistivity is known as the conductivity, σ of the material. Ohm-meter (Ωm) is the unit of resistivity while ohm-meter ($\Omega^{-1}m^{-1}$) is the unit of conductivity.

Substituting equation (2) into equation (1) gives,

$$\frac{V}{L} = \rho \frac{I}{A} \ldots\ldots.. \qquad (3)$$

The ratio $\frac{V}{L}$ can be equated to the electric field, $\boldsymbol{E}$**.** Also the ratio $\frac{I}{A}$ is the current per unit area of the conductor called current density, J. Substituting these parameters into equation (3) gives

$$\boldsymbol{E} = \rho \boldsymbol{J}$$

This is the form of Ohm's law use in calculating parameters used in resistivity methods of electrical surveying. In any case, the quantities measured in the field are difference in potential V and current I.

The resistance of a geological formation due to current flow is measured by the terrameter (resistivity meter). The apparent resistivity ρ_a of the geologic formation is given by:

$$\rho_{a=} 2\pi \frac{V}{I} k \qquad (4)$$

where, k = the geometric factor, V = potential difference and I= current.

Geometric factor, k depends on the electrode's arrangement and the distances between the electrodes (Raji, 2014).

There is an established relationship that exists between the fluid saturation factor and of a porous rock resistivity. The relationship is known as Archie's law. This law holds for some rocks and sediments, precisely those with low clay content. Generally, the resistivity of a rock material is dependent on the following factors:

i. fractional pore volume (porosity, φ)
ii. water saturation (S)
iii. saturated water resistivity (ρ_w)
iv. type and amount of minerals dissolved and salts contained in the water

By Archie's equation

$\rho = a\rho_w/\varphi^m S^n$ (5), Loke (2001)

where φ and S are fractions between 1 and 0, a has values between 0 and 2.5, m has values between 1.3 and 2.5 and n = 2; a, m and n are constants. Different properties of rocks and the fluids contained result to different conductivity or resistivity signatures.

Self Potential (SP) Method

Self-potential anomalies are most times interpreted based on simple geometric models or qualitatively. This can take the form of profile shape, amplitude, polarity (+ or -) or contour pattern. Trends related to elongation of an ore body could be revealed by visual inspection of mapped anomalies while crowding of contour lines can be an indication of its orientation. Though, the method is fast and cheap and can be used in rapid subsurface analysis for base metal deposits, a good quantitative interpretation is not always possible. Studies have shown that intensity of SP anomalies are increased by rain (Revil and Jardani 2013), hence, site meant for SP investigation is advised to be artificially irrigated occasionally.

The Self Potential method is employed in different areas of geophysics including mining (Biswas and Sharma 2016; Eppelbaum 2019), environmental (Gusev *et al.*, 2018; Oliveti and Cardarelli 2019) and archaeological investigations (Shevnin *et al.*, 2014; De Giorgi and Leucci, 2017). However, according to Wynn and Sherwood (1984), self-potential method gives abnormal response over archeological anomalies in fields where other geophysical methods do not show unusual result.

Utilization, Advantages and Challenges

This method permits non-intrusive investigation and imaging of disturbances in electrical currents of conductive subsurface materials. Its use is not limited to mapping of fluid flow in the subsurface of the Earth but has risen to detection of preferential flow paths in earth dams and embankments.

The self-potential method is very fast with low cost of data acquisition (Nyquist and Corry, 2002; Eppelbaum, 2021), making surveying of large areas of land faster and cheaper. Mobility is a top notch with light-weight technique, thus making data acquisition in rough and challenging terrain, such as volcanoes doable, (Grobbe and Barde-Cabusson, 2019).

The main disadvantage of SP method is largely on data interpretation, this makes it more challenging than other geophysical techniques. Like magnetic and gravity methods, SP measurements are purely passive, making it difficult to adjust source parameters in order to identify signals of interest.

Induced Polarization Method

A sudden switch off of current, in a standard 4-electrode resistivity spread in a direct current mode does not cause the variation in potential difference between the electrodes to run to zero instantly rather, at the beginning, there is a large reduction in voltage, followed by a gradual decay that may last for many seconds before it falls to zero. The reverse occurs when the current is switched on, a sharp rise in voltage occurs, the voltage increases gradually over a specific period of time until it reaches a steady state. The ground stores electrical charge and behaves like a capacitor; thereby becoming electrically polarized. The ground capacitance stops the flow of direct currents and conveys alternating currents with rising performance as the frequency increases. Using, a variable low-frequency AC source than a DC source for the resistivity measurement results to an increase in frequency as the apparent resistivity of the subsurface decreases.

Utilization, Advantages and Challenges

The initial purpose and major application of induced polarization, is prospecting for ores and other metals underneath the surface of the earth. However, it has found its use in groundwater exploration, engineering, and environmental investigations (Ustra and Elis, 2018). IP tends to be the most accurate geophysical device when compared with conductivity, resistivity meters and GPR (Carlson *et al.*, 1999).The method has been shown to be very successful in the location of low-grade ore deposits like sulphides particularly in base metal exploration (Langore *et al.*, 1989).

IP equipment uses more current than does a resistivity spread and is similar to resistivity apparatus but bulkier and elaborate. Another limitation for the application of this technique is the presence of electro-metallic salts contained in lithologies (Biosca *et al.*, 2020). These salts can produce anomalies of chargeability that mask those due to non-aqueous phase liquids.

Electrical Resistivity Methods

There are a number of geoelectric measurement techniques adopted for geophysical investigations with different configurations of potential and current electrodes. These include Schlumberger, Wenner, double Dipole, Pole-Dipole, Pole-Pole Sounding Methods. The aim of a survey and how complex is the study area geologically, to a large extent determines the configuration to be adopted or a combination of the techniques needed for successful results.

The geoelectric resistivity method has been employed by many researchers to solve problems in geophysical exploration like: investigation of contamination or pollutants due to industrial waste (Rockhold *et al.*, 2020); assessing aquifers hydraulic parameters (De Clercq et al 2020); investigation of groundwater aquifers (Greggio et al. 2018); characterization of seawater intrusions and or saline/freshwater interface (Adegoke *et al.*, 2018; Niculescu and Andrei 2021).

Information on lateral variation of rocks properties at near surface depth are provided by Horizontal Resistivity Probing or profiling (HRP) while Vertical Electrical Sounding (VES), probes into deeper subsurface than HRP (Loke 1999). The depth of the current injected varies proportionally with distance separating the current electrodes, hence, increasing the distance between the current electrodes leads to deeper penetration of the current, Figure 1.

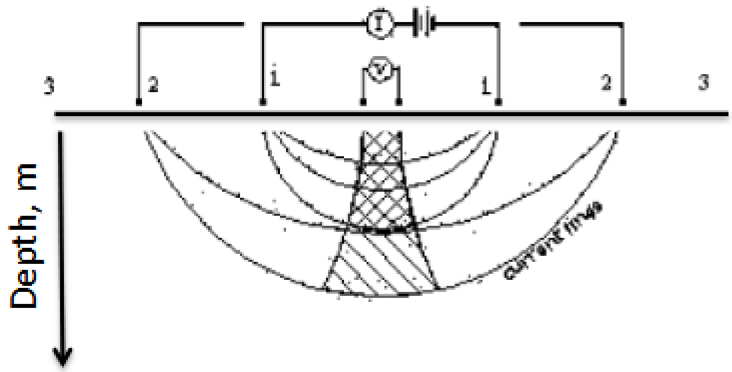

Figure 1: Schematic diagram of Vertical electrical sounding

In resistivity methods, the artificial electrical currents generated are put into the ground and the consequent voltages are measured at the surface. The electrical current supplied is controlled through two electrodes while the potential difference between the two is measured on the surface through the potential electrodes.

The earth's resistivity is not unconnected to geological parameters of the subsurface like porosity, void ratio, grain size fraction, level of saturation, type of rock and soil (Samouëlian *et al.*, 2005). It is important to know the quantity of current supplied to be able to determine the distribution potential, the path current flows in a homogenous soil. Inhomogeneities (anomalies) in the soil are detected because they deflect currents and cause variation in potentials (Al-Khafaji and Al-Dabbagh 2016).

The resistivity methods have been widely applied in areas such as: investigation of conductive bodies such as Ore bodies; saline/freshwater interface; groundwater; delineation of water saturation from Oil and gas saturation e.t.c.

Common Arrays

The setup is made of two pairs of electrodes: one for current and another pair for potential electrodes connected as in Figure 2. The electrodes A and B are source and sink respectively for current (Lowrie 2007). The electrode C, has the potential $+\rho I/(2\pi r_{AC})$, while the electrode D has potential $-\rho I/(2\pi r_{CB})$. The sum of potential at C is given by

$$U_C = \frac{\rho i}{2\pi}\left(\frac{1}{r_{ACc}} - \frac{1}{r_{CB}}\right) \quad \ldots\ldots\ldots\ldots \quad (6)$$

Also, the combined potential at D is

$$U_D = \frac{\rho i}{2\pi}\left(\frac{1}{r_{AD}} - \frac{1}{r_{DB}}\right) \ldots\ldots\ldots\ldots \quad (7)$$

The difference in potential between C and D measured by voltmeter as connected gives

$$V = \frac{\rho I}{2\pi}\left\{\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}}\right) - \left(\frac{1}{r_{AD}} - \frac{1}{r_{DB}}\right)\right\}. \quad (8)$$

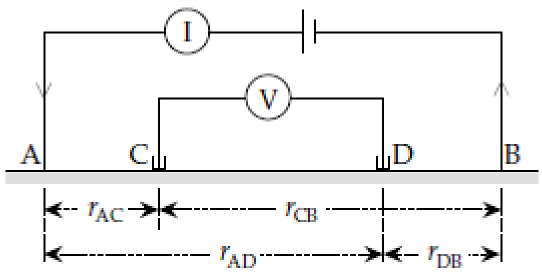

Figure 2: Four-electrode array for resistivity measurement

With the exception of resistivity ρ every other quantity in equation (8) can be obtained at the ground surface.

$$\rho = 2\pi \frac{V}{I}\{\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}}\right) - (\frac{1}{r_{AD}} - \frac{1}{r_{DB}})\}^{-1} \qquad (9)$$

Configurations like Wenner, Schlumberger and double-dipole arrangements are mostly used.

Common Arrays and their Characteristics

Table 1 presents some peculiar characteristics relating to: signal sensitivity, depth of penetration, and sensitivity to horizontal or vertical structures as they relate to particular configurations.

Table 1: Common Arrays and their characteristics (Samouëlian *et al*., .2005;Riwayat *et al*.,. 2018)

	Schlumberger	Wenner	Dipole-dipole	Pole-pole	Pole-dipole
Sensitivity of the array horizontal structures	++	++++	+	++	++
Sensitivity of the array vertical structures	++	+	++++	++	+
Depth of investigation	++	+	+++	++++	+++
Horizontal data coverage	++	+	+++	++++	+++
Spinal strength	+++	++++	+	++++	++

The legends are grouped from (+) to (++++) representing poor sensitivity to high sensitivity for the different configurations

Wenner configuration

In this configuration (Figure 3), the potential and current electrodes have the same mid-point while the adjacent electrodes have same distances in between, that is, $r_{AC} = r_{DB} = a$ and $r_{CB=} r_{AD} = 2a$. Substituting these values into equation. (9), gives

$$\rho = 2\pi \frac{V}{I}\{\left(\frac{1}{a} - \frac{1}{2a}\right) - (\frac{1}{2a} - \frac{1}{a})\}^{-1} \quad . \qquad (10)$$

$$\rho = 2\pi a \frac{V}{I} \qquad (11)$$

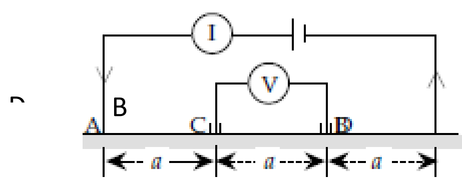

Figure 3: Wenner Arrangement

Utilization, Advantages and Challenges

The Wenner configuration method is the commonest technique used for soil resistivity measurements.

With Wenner array, the apparent resistivity is deducted easily in the field and the instrumental sensitivity is not as important as with other array geometries (Hassan *et al.*, 2017). Also, the magnitude of current needed to produce measurable potential differences is small.

The disadvantage of the Wenner array configuration is that the four electrodes will be moved to a new position each time measurement is to be taken. Hence, handling of the longer current cables and electrodes makes it cumbersome especially in difficult terrain (Hassan *et al*., 2017; Joel et al., 2019). Deeper electrical responses may be skewed due to sensitivity of Wenner array to near surface inhomogeneties.

Schlumberger array

Like in Wenner configuration, the Schlumberger array (Figure 4) has a pair of electrodes each for the current and potential and a common mid-point, though the separation between adjacent electrodes are not the same. Let the distance between the current electrodes to be *L* and potential electrodes to be *a*.

Hence, $r_{AC} = r_{DB} = \frac{L-a}{2}$ and $r_{AD} = r_{CB} = \frac{L+a}{2}$. Putting these values into equation (7), (the general relation), gives

$$\rho = 2\pi\frac{V}{I}\{\left(\frac{2}{L-a} - \frac{2}{L+a}\right) - \left(\frac{2}{L+a} - \frac{2}{L-a}\right)\}^{-1}$$

$$\rho = \frac{\pi V}{4I}\left(\frac{L^2-a^2}{a}\right). \quad (12)$$

Using Schlumberger configuration, the distance between the current electrodes A and B is longer than that between C and B ($L \gg a$). Applying these variables equation (10) becomes

$$\rho = \frac{\pi V}{4I}\left(\frac{L^2}{a}\right) \quad (13)$$

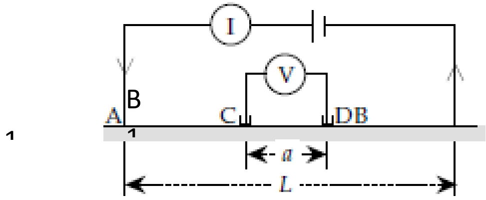

Figure 4: Schlumberger Array

Utilization, Advantages and Challenges

The Schlumberger array using vertical electrical sounding (VES) technique found its application mostly for groundwater and aggregate minerals.

With Schlumberger array, fewer and shorter potential electrodes need to be moved for each sounding. Schlumberger sounding generally has better resolution (Hassan et al., 2017), greater probing depth, and takes less time than Wenner array method.

Its limitation is that, it requires long current electrodes, the recording device is not very sensitive and the cables may be confusing among the crew.

Double-Dipole Array

The spacing of the electrodes in the double-dipole array (Figure 5) is a in each pair while L is the separation between their mid-points which is by far larger than a. The potential detection electrode D is closer to current sink B. In this case, $r_{AD} = r_{BC} =$ L, $r_{AC} = L + a$ and r_{BD} = L-a. Resistivity of the arrangement is measured as

$$\rho = 2\pi\frac{V}{I}\{\left(\frac{1}{L} - \frac{1}{L-a}\right) - \left(\frac{1}{L+a} - \frac{1}{L}\right)\} \quad (14)$$

$$\rho = \pi\frac{V}{I}\left(\frac{L(L^2-a^2)}{a^2}\right) \quad (15)$$

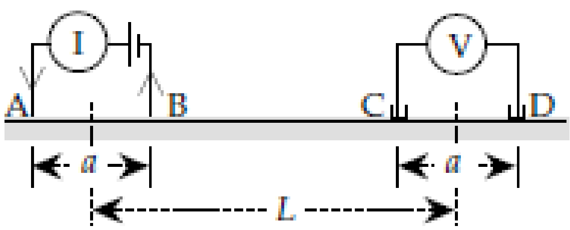

Figure 5: Double-Dipole Array

Utilization, Advantages and Challenges

The dipole-dipole resistivity survey has found its application in resistivity monitoring of a producing geothermal field and in delineating reservouir.

The main advantage of the dipole-dipole arrays is its multi-channel capability and high resolution; its provision of a very detailed image of the subsurface. Another advantage is that it is ease to deploy in the field sequel to shorter cable lengths.

The disadvantage of this array is that the dipoles do lose the signal when placed too far apart, thereby decreasing the power to see deeper into the earth (Ohaegbuchu *et al*., 2019). Also, large generator may be needed to transmit a greater amount of current for the measurements, especially for deeper results.

Pole-Dipole

The Pole-dipole configuration is made up of four electrodes, a pair of current electrodes (C_1, C_2) and another pair of potential electrodes (P_1, P_2) as in Figure 6, arranged in a straight line fixed on the ground surface, the last current electrode (C_2) is fixed at far distance from the configuration about five to ten times of the expected penetration depth at an effective infinity distance from the array. The array is like the Dipole-dipole array; only that, it is used when the depth of penetration needs to be deeper (Farooq, *et al*., 2012).

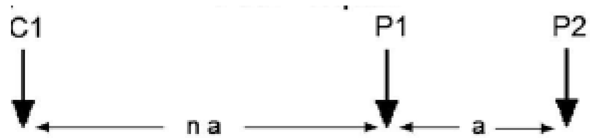

Figure 6: Pole-Dipole Array

Utilization and Challenges

The principal application of pole-dipole array most often is for mineral and ore exploration, like dipole-dipole array.

The major limitation of this array is that the signal strength decreases as distance between the dipole pair increases.

Pole-Pole Array

The pole-pole array has one current and one potential electrode (poles) traversed or successively expanded on a survey line (Figure 7). The second current and potential electrodes are located at a far distance (at infinity) that their location has insignificant effect on the measurements.

Figure 7: Pole-Pole

Utilization, Advantages and Challenges

Pole-pole array is commonly used in 3-D geo-electrical resistivity surveys because it has the widest horizontal coverage as well as the highest number of possible independent measurements.

Pole-pole surveys are cost effective, able to penetrate deeper depth, flexible, resolve vertical and horizontal subsurface structures and can be used in tracking the movement of contaminants.

The main concern of the pole-pole array is space—this problem makes it less visible and less frequently used than both the dipole-dipole and the pole-dipole arrays.

Interpretation of Resistivity Data

Resistivity data can be interpreted qualitatively and quantitatively. In practice, preceding the data collection is the plot of the apparent resistivity against the electrode separation in a linear graph. With VES data, the spacing is obtained by dividing the current electrode spacing by 2 (half) and both axes are plotted in log scale. The plots obtained are noted in terms of resistivity variation with depth. The sections with low or high resistivity are noted for discussion either showing the availability or absence of anomalous (minerals) bodies below the point of observation.

With this data (VES), curve types obtained are in relation to the resistivity variation, are noted i.e. weather it increases or decreases continuously with depth as follows:

i. A-type ⇒ continuous increase of resistivity (ρ) with depth
ii. Q-type ⇒ continuous decrease of resistivity (ρ) with depth
iii. H-type ⇒ (3 layers in which $\rho 1 > \rho 2 < \rho 3$)
iv. K-type ⇒ (3 layers in which $\rho 1 < \rho 2 > \rho 3$)

Layers 1, 2 and 3 are associated with resistivities ρ_1, ρ_2 and ρ_3 respectively.

The identification of the observed resistivity sounding curve as A, Q, K and H results in the estimation of the number of layers (2, 3, 4, 5, e.t.c). The resistivities of different layers and their thicknesses are obtained by curve matching. These processes are carried out these days on computer systems using soft wares.

Case Studies

Here few case studies are presented to demonstrate the applicability of the different methods in real live situation by some researchers.

Wahab *et al.*, 2021 carried out a study to detect groundwater aquifer and its associated electrical properties at Ito Campus, Kyushu University (Fukuoka, Japan). They determined the electrical resistivity distribution of the subsurface using the Code Division Multiple Transmission (CDMT) equipment- a device of high-speed resistivity made of three main parts: the power supply system, transmitter of 24 channel amplifier and the receiver (Rx). The CDMT equipment is designed to handle pole–pole configuration with apparent resistivity relation as in Equation (17).

$$\rho_a = \frac{V}{I}(2\pi a) \quad (17)$$

Figure 8 is a pseudo-section as obtained by the authors.

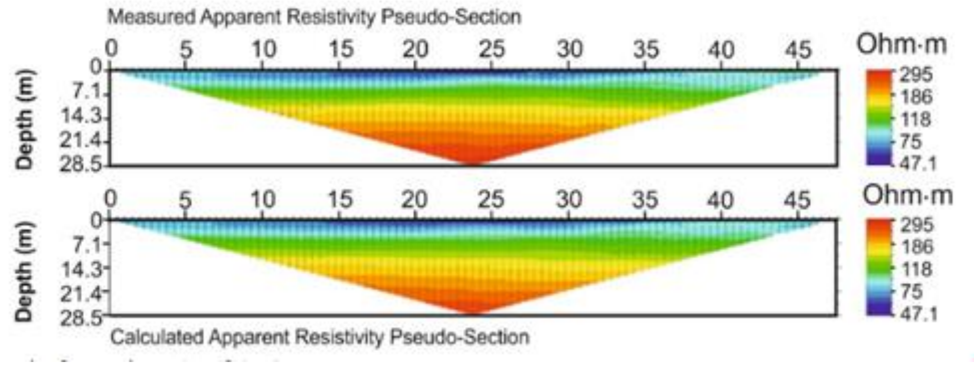

Figure 8: Pseudo-section of Line3, Wahab et al. 2021.

Figure 9 presents the top-soil with thickness of about 1 to 8 m comparatively thin layer with materials of resistivity. Figure 9 (a, b), having a resistivity ranging between 30 and 50 Ωm, was considered as having high water-saturation and very conductive clay layer. Two different layers appeared below this shallow layer. The first layer with resistivity of 70 and 170 Ωm represents the phreatic aquifer while the second geoelectric layer with resistivities ranging from 300 Ωm and increasing as the depth increases was described as resistive layer and represents the bedrock.
Line 2, showed also a thin layer topsoil with materials of high resistivity of about 2 m thick and resistivity of more than 250 Ωm. The next layer is considered conductive with thickness of 3 to 8 m and resistivity ranging between 16 to 50 Ωm. Beneath the second layer, is another one with depth of 8 to 18 m with resistivities ranging from 50 to 150 Ωm and identified as an aquifer layer.
The authors concluded that, the 2 D inversion result using the pole–pole resistivity array depicted three geoelectric layers with different resistivities and thicknesses that showed the location of the aquifer. These findings are bases for future groundwater exploration at Ito Campus, Kyushu University (Fukuoka, Japan) and have helped in localization of drilling water wells in the area.

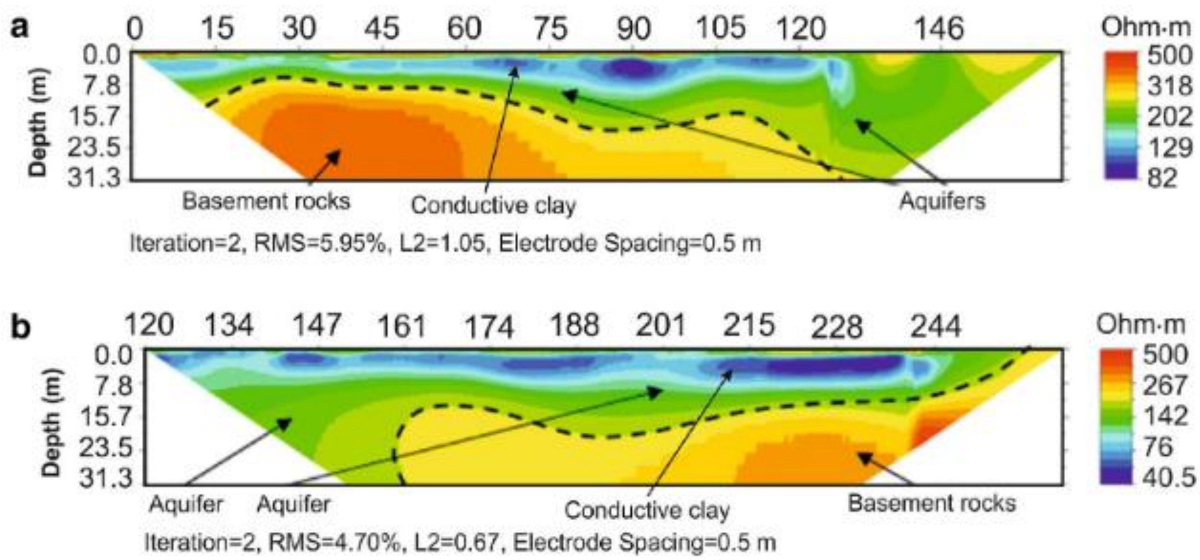

Figure 9: Inverted sections of data from Line 1 sections A and B, Wahab et. 2021.

The study by Adagunodo et al. 2018 at Aaba area in Akure, Nigeria used Schlumberger configuration to conduct a geophysical survey. The survey employed VES configuration as it is effective, simple (Sunmonu et al. 2012; Anomohanran et al. 2017) and easy to interpret (Adelusi et al. 2014; Sunmonu et al. 2016). Current was introduced to the subsurface through current electrodes and the difference in potential was measured. This was done repeatedly by increasing the electrode spacing at predetermined fixed points to probe deeper into the subsurface giving different resistivity values and 16 VES stations were established in the investigation.

The study produced a number of model curves i.e. Q, K, A and H-types representing different layers with their respective resistivities and thicknesses. They showed that, topsoil resistivity varied from 59.5 to 491.6 Ωm having thickness of 0.4 to 2.1 m. The overburden thickness ranged between 4.2 to 47.1 m. The northwest and western regions of the study area in particular, showed thick overburden that could translate to probable high groundwater potential. Few VESes were enclosed with thin overburden, leading to low yield of groundwater. Figure 10 is the Overburden Isopach map (Adagunode et al. 2018.). The authors affirmed that the aquifer units in Aaba were made of weathered layer and fractured bedrock.

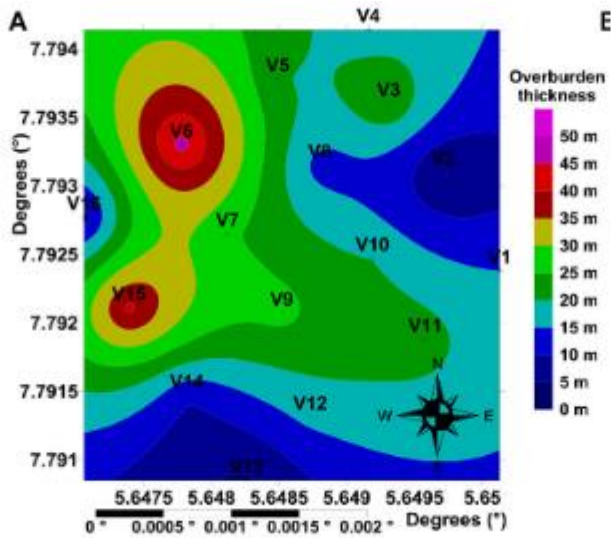

Figure 10: Overburden Isopach Map of Aaba, Akure after Adagunode et al. 2018.

The study showed three to four geoelectric sections, identified as topsoil, lateritic soil, sandy clay/clayey, sand/clay/weathered rock and the bedrock. Figure 11 is a typical geoelectric section that showed the areas within VES 1and 2of Aaba, Akure, as the most appropriate area for groundwater prospection. According to Adagunodo , 2018, the weathering in the area was very thick and it could be due to deep seated fracture. They recommended boreholes of 18.0 m depth in the area or more for good yield on this zone.

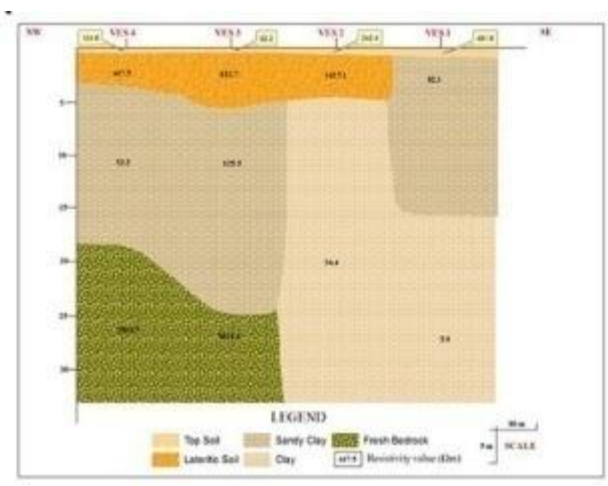

Figure 11: Geoelectric Section along Traverse 1, Adagunodo et al. 2018.

In conclusion, the authors found that the basement depression resulting to thick overburden is translated to sustainable groundwater potential in the area hence; the zone should serve as collecting channel for groundwater exploitation in Aaba.

Recently**,** Igboama et al. (2021b) conducted an investigation in Onibueja area, Osogbo, Nigeria on groundwater contamination emanating from Osogbo Central Dumpsite by employing geoelectrical and hydro-physicochemical analysis methods. Analysis of the survey presented geoelectric sections with H, KH and QH resistivity curves. Pseudo-sections were computed for the profiles that showed the resistivities, geoelectric sections and thickness of each geo-electric layer. Fig.12 is a modeled curve for VES 2 of the study area showing a KH ($\rho1<\rho2>\rho3<\rho4$) resistivity curve. The geo-sections obtained were revealed as top soil, lateritic soil, highly weathered basement and fresh basement.

The study identified highly weathered basement (leachate contamination) with low resistivity values that translated to percolation or clay with low resistivity values. The low resistivity values and closeness of VES 1 and VES 3 to the dumpsite was adjudged to be responsible for accumulated leachate contamination with saturated clay. This result of low resistivity values correlating to leachate pollution was in agreement with Barker (1990).

The weathered layer was considered to be associated with contaminant (leachate) from the dumpsite with high saturated and conducting material, Igboama *et al.*, (2021b). The study showed the applicability of electric resistivity (VES) using Schlumberger configuration on groundwater contamination investigation in a basement complex terrain, Osogbo, Nigeria.

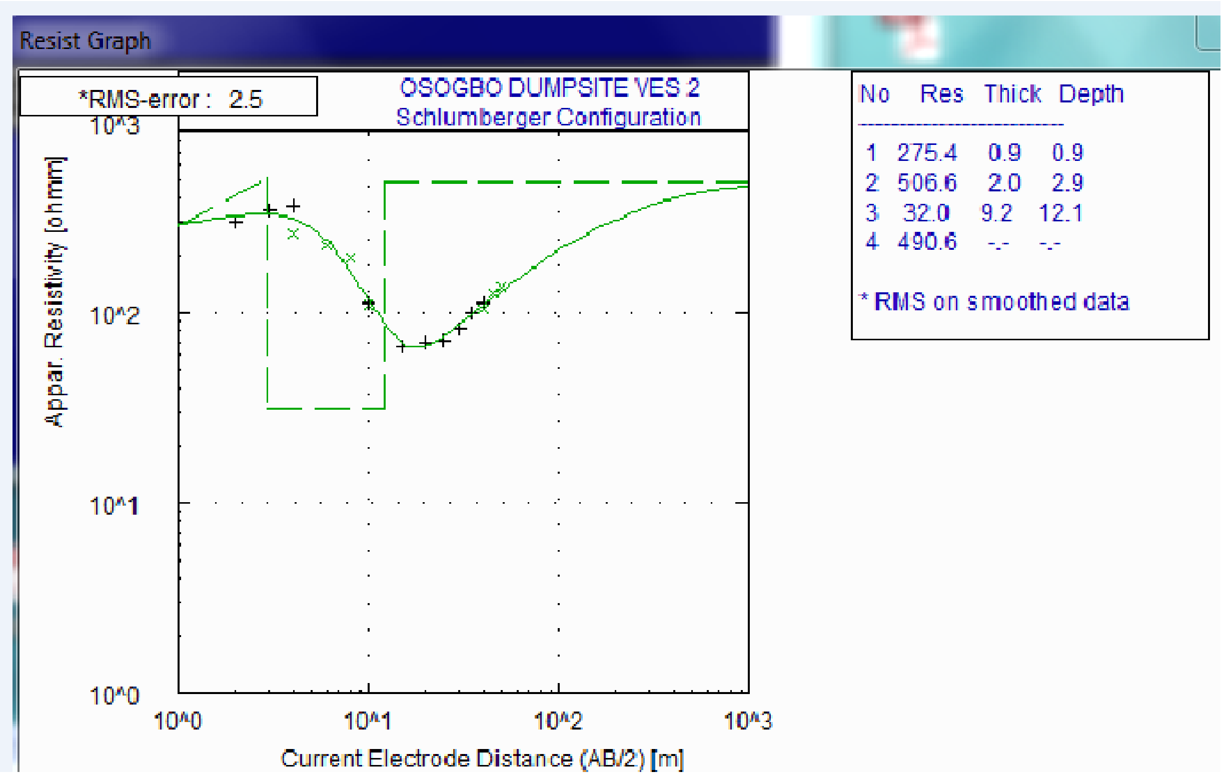

Figure 12: Modeled curve for VES 2 of the Study, Igboama *et al.*, 2021b

Akingboye et al. (2020) conducted a study on potential failures and subsurface defects of the substrate along Etioro-Akoko highway, Southwestern Nigeria using electrical resistivity tomography (ERT) technique. Geophysical traverses were established along the identified sections of the high way that were defective. Using Wenner array, the ABEM Lund Resistivity Imaging System was employed and two traverses were established.

Figure 13 is the subsurface inversion model of resistivity section along Traverse 1. The model is characterized by four different subsurface layers having different resistivities. Traverse 2 equally showed four distinct subsurface layers with different resistivity values. The two model resistivity sections delineated four different subsurface layers as: thin clayey topsoil characterized by resistivity of below 150 ohm-m and thickness of about 2 m; saturated clayey to sandy weathered layer having resistivity of 10–325 ohm-m and 0.5–12.5 m thickness; partially weathered/fractured bedrock with resistivity values of 205–800 ohm-m and thickness ranged from the near surface to above 24 m and the fresh bedrock whose resistivity is above 1000 ohm-m

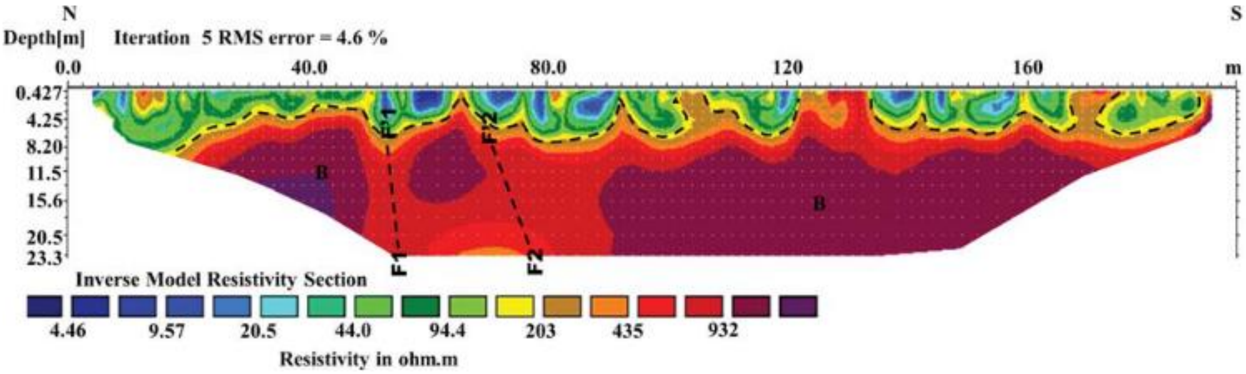

Figure13: 2D Inverse model resistivity section of Traverse 1, Akingboye et al.2020.

The authors also delineated three deep-penetrating fractures in the area. Fractured sections in the bedrock along the section of the road investigated serve as channels for groundwater/seepage zones. These features pose problems to the substrate of the road.

The failures along Etioro-Akoko highway according to the authors was due to the poor sub-base/substrate soil materials. They also attributed the failures of the highway to reduction in load-bearing ability; stress from heavy traffics. This study confirms the application of geoelectric technique in civil engineering and environmental studies.

Another study carried out in Irare, Oye-Ekiti, Southwestern Nigeria by Igboama *et al.*, (2021a) adopted geophysical methods to map rock contact for the purpose of delineating rock boundaries and structures favourable for groundwater exploration. Irare, Oye-Ekiti, is within the basement complex terrain of Nigeria. The following geophysical methods were used: electrical resistivity and electromagnetic methods employing Horizontal profiling (HP) (Wenner array) of inter electrode spacing 5 m, 2-D profiling (dipole-dipole array) and Vertical Electrical Sounding (VES).

The horizontal profiling (Wenner array) resistivity and electromagnetic conductivity results were presented in profile form. Areas with high conductivity values or peaks in the EM plot were considered as delineations of fracture systems or geologic structures. This conforms to low resistivity of horizontal profiling and weathered area of the geoelectric section, (Figure 14). Figure 14 showed the correlation between the different geophysical methods adopted. The authors conclusively stated that the correlation of results revealed the presence of high conductivity boundary between the basement rocks, which could serve as groundwater aquifer in the area.

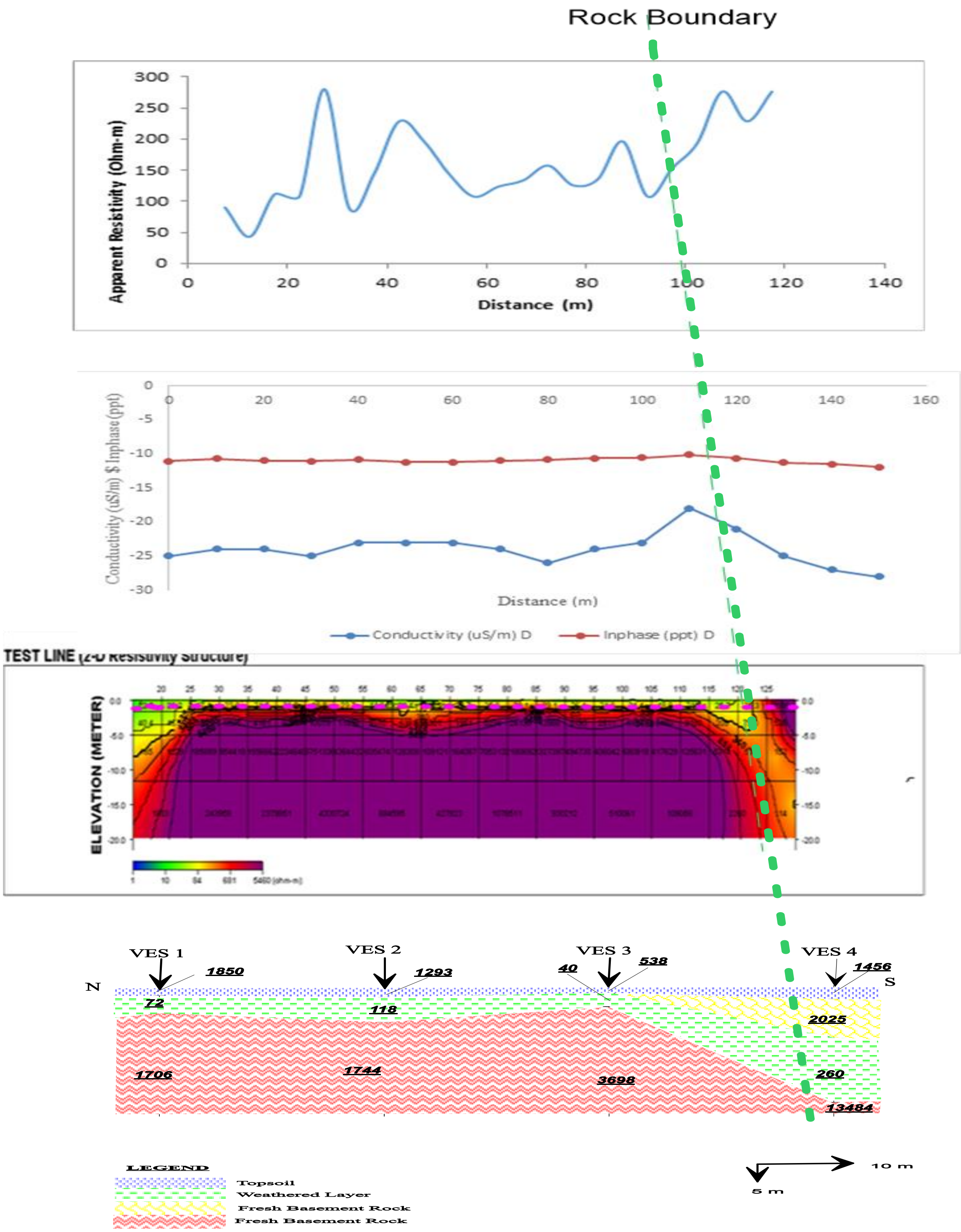

Figure14: Correlation of the Geophysical methods and Geoelectric section along the traverse, Igboama et al. 2021a

Dakir et al., 2019 applied electrical resistivity and induced polarization methods to locate metalliferous veins at Ougnat Mountains Morocco. The different structural contacts were obtained using electrical tomography to identify alignment of mineralized veins in barite and galena while pseudo-sections were obtained using induced polarization in delineating the zones of anomalies encountered.

The authors established 5 profiles in the study. Figure 15 is the pseudo-section of profile 3 that showed a zone with mineral at point 85 m from the beginning of the profile, with a climax at about10 m with chargeability value above 100 msec. The second zone with mineral was connected to fracking anomaly zone with resistivity of the order 130 ohm-m and within the profile (80 msec). The profile showed water accumulation on the two sides of the fracturing anomaly area. In Taroucht area, the pseudo-section models from the chargeability and resistivity compared favourably and led to the delineation of zones of anomalies linked to where the baryte veins (BaS_{O4}) were located.

Mineralized zones were delineated at the end of the investigation. The fissured sandstone formations were concealed as mineralized zone. The study was able to locate and align the mineralized veins.

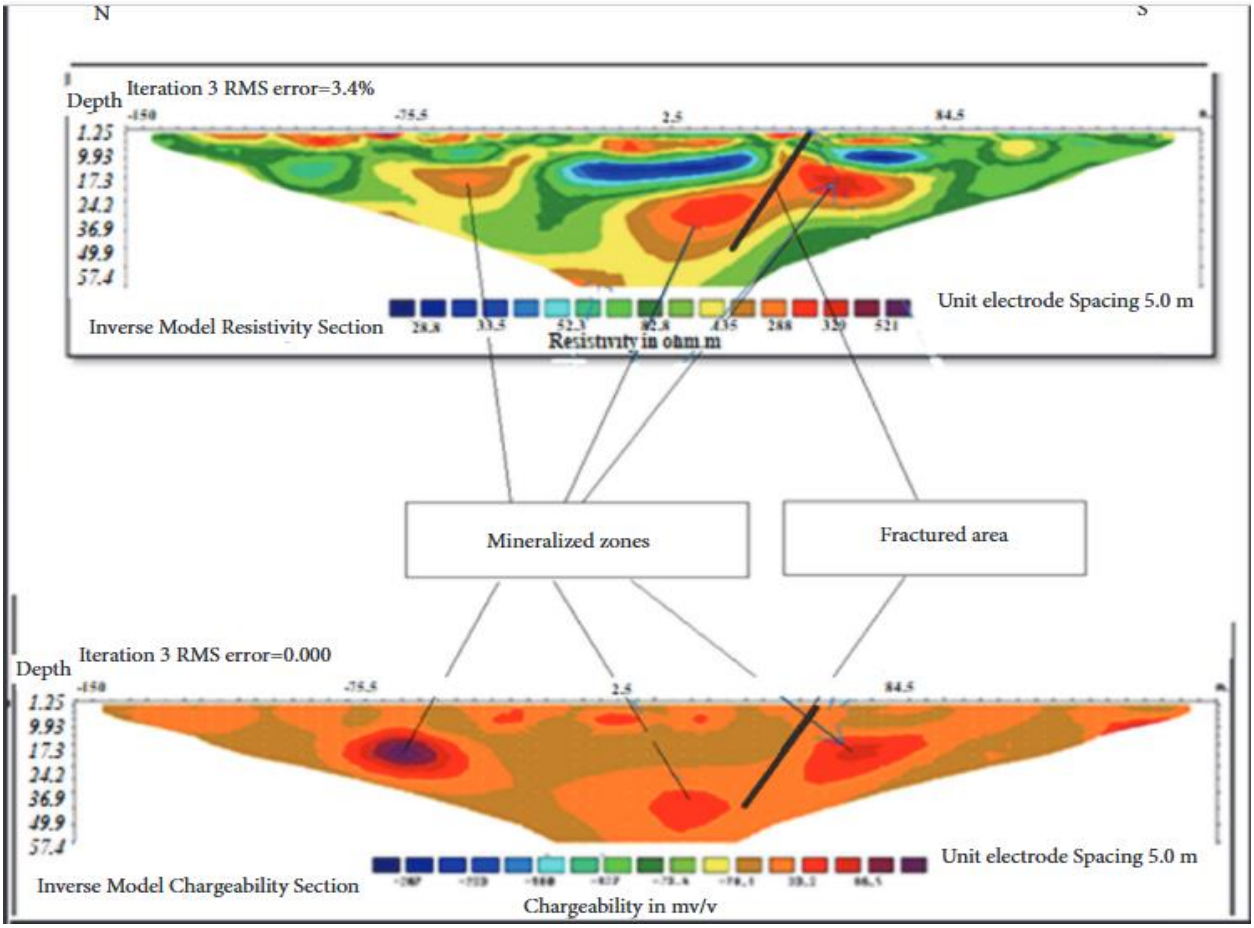

Figure 15: Inverse model resistivity and chargeability sections, Dakir, *et al*. (2019).

Improvement in Technology

Time-Lapse electrical imaging is possible today, particularly in environmental and engineering applications because measurements can now be repeated many times to monitor changes in subsurface parameters (Whiteley *et al.*, 2019). This is applicable in monitoring groundwater contamination and movement of fluids in reservoirs. Also, there has been emphasis on high-resolution imaging techniques in the recent past (Loke *et al.*, 2013). This enables detection of smaller and more detailed geological features during investigations. It involves the use of multi-electrode arrays that provide better spatial resolution and deeper penetration.

Furthermore, inversion algorithms are more sophisticated now than before, leading to better interpretations of subsurface data. The algorithms can create 2D or 3D models of subsurface structures using measured electrical resistivity data. The improvement in this area enables one to deal with complex geological settings and also get more accurate results. Advancement in sensor technology has also, given room for efficient data collection in the field. These devices are more user-friendly and robust these days thereby making geoelectrical surveys accessible to more users. Another area of improvement is the integration of machine learning and data analytics into geoelectrical data processing and interpretation leading to a change in the sector (Bahramian et al., 2022). These technologies have improved the speed and accuracy of subsurface modeling through automation of data analysis.

The emergence of new software tools for field data acquisition has simplified the setup and execution of geoelectrical investigations. Some of these tools came with quality control features coupled with real-time data visualization parameters. In addition, combination of geoelectrical techniques with other geophysical methods, like gravity, seismic surveys have brought more insight to subsurface information. It gives a better understanding of the structures and properties of the subsurface. More so, geoelectrical methods are applied in various fields these days; such as in contaminant investigations (environmental studies), mineral exploration, pre and post foundation investigations in civil engineering, and groundwater studies. This has made geophysical methods to be more versatile than other techniques of investigations.

Future Perspectives

It is expected that there will be more efficient and precise data acquisition tools and methods. This may come in form of improved measurement devices, electrodes and sensors to provide faster data collection and higher resolution systems. Advancing hardware and computational techniques will further develop 3D and multi-dimensional models of the subsurface properties. This will in turn make available detailed and better representation of geological features. Geoelectrical methods are now used in various sectors like mineral exploration, groundwater resource management, civil engineering investigation, and environmental studies. There is tendency that in the nearest future there will be more specialized fields of applications. Furthermore, combination of different geoelectrical methods such as gravity, magnetic, seismic and electromagnetic methods is presently giving a better understanding of the subsurface structures. It is likely there will be more integration of these methods for reliable results in the future. Another spectacular and interesting development is the advent of machine learning algorithms and artificial intelligence in geoelectric data analysis, thereby providing more meaningful geologic patterns. These will result in improved interpretation of the subsurface and reduction in manual interpretation. Most importantly is the ability to carry out geoelectrical investigations in real-time or near real-time as it has gained general acceptance. This is necessary in monitoring changes in subsurface situations particularly where measurements are to be repeated like contaminant investigations. Future applications are expected to increase tremendously in this aspect.

CONCLUSION

The paper highlighted the background theory of the general principle of electrical methods and an overview of some case studies (histories) to showcase the application of the different methods adopted in geoelectrical investigation. Reasons for different interpretation based on anomaly signatures and geological structures were equally portrayed along the case studies. The case studies presented, showed that geoelectric methods can successfully be applied by geoscientists in mapping and exploring of groundwater, engineering site and environmental investigations, location of geological structures, pipes and recently locating clandestine graves as forensic tools. The roles of advancement in measuring devices, application of multiplexer and multi-channel systems for data acquisition, software applications in data management and analyses have changed the place of geoelectric methods in geophysical explorations. Most of the techniques are effective and efficient in terms of cost, time, data coverage and interpretation. Most times, integration of geophysical methods is advised so that hidden targets can be revealed in order to characterize the study area for better interpretation of observed anomalies. In field applications, guidance and help of geophysicists is required for their expertise advice.

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