

**DELINEATION OF GRAVES AND OTHER SUBSURFACE FEATURES
USING ELECTRICAL RESISTIVITY TOMOGRAPHY**

BY

KNUST

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(BSc. Materials Engineering)

**A Thesis Submitted to the Department of Physics, Kwame Nkrumah
University of Science and Technology in partial fulfillment of the
requirements for the degree of**

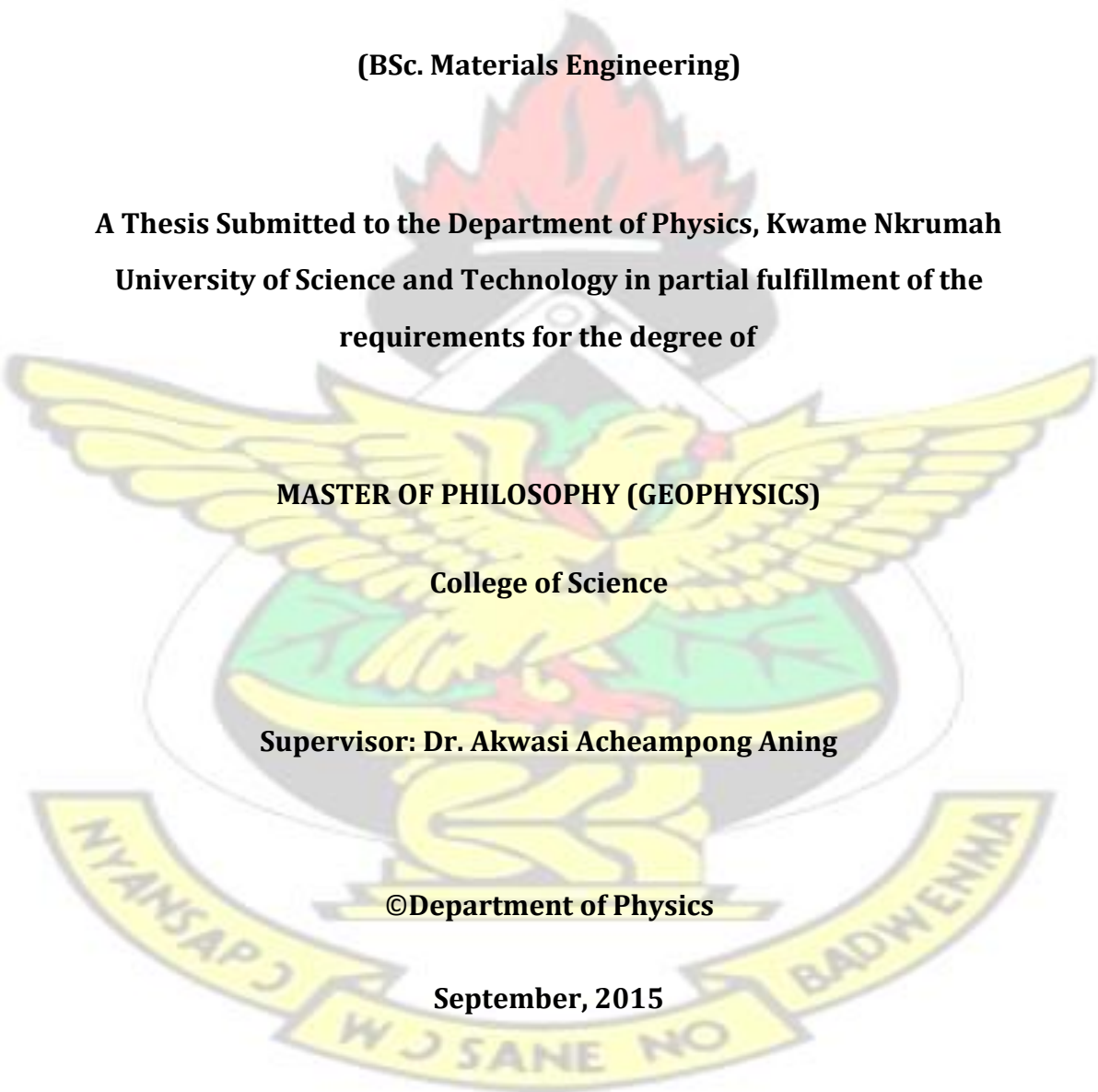
MASTER OF PHILOSOPHY (GEOPHYSICS)

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September, 2015



Declaration

I hereby declare that this submission is my own work towards the award of MPhil degree and that, to the best of my knowledge, it contains no material previously published by another person or material which has been accepted for the award of any degree of the University, except where due acknowledgement has been made in the text.

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Abstract

In response to rumours that the study area (a relatively flat ground) used to be a royal cemetery and for future developmental purposes, this study aimed at delineating graves and other subsurface features so that informed decisions can be made about the place if the need arises. The survey was conducted on a 10000 m^2 plot of land using the electrical resistivity method. The multi-electrode or CVES was combined with the roll along technique for data collection. With inter profile separation of 2 m, 51 profile lines were obtained. The data were acquired in 2D with a minimum electrode separation of 1 m and later collated to 3D. The gradient array was used taking the Grad4L8 and Grad4S8 protocols into consideration. Data processing with the RES2DINV and RES3DINV software indicated wide resistivity variations in the near subsurface suggesting a disturbance of the soil at this level. This might have been caused by digging (probably graves) and refilling activities. High and low resistivity anomalies relative to their backgrounds were identified within the first 4 m of the subsurface. These were suspected to be tombs because of their rectangular geometries, dimensions and resistivity contrast with the background materials. The linear arrangement of these anomalies similar to the arrangement of tombs in cemeteries heightened this suspicion. Other subsurface features observed were also associated with dykes, unweathered granite, cracks, voids etc.

Consequently, the study area could have been a cemetery but can still support infrastructural development since the entire place was not covered by the anomalies. A weak zone spotted between 26 and 58 m in the S-N direction and between 30 and 70 m in the E-W direction must however be taken into consideration when carrying out constructional projects in the study area.



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List of Symbols and Acronyms

5 Dirac delta function

π Pi

Ω Ohms

σ Conductivity ρ Resistivity ρ_a

Apparent Resistivity

φ Porosity

S Saturation

ρ_w Resistivity of ground water

$\mathbf{E}$ Electric field

$\mathbf{J}$ Current density

L Length A

Area m Metre

F Formation factor

R Resistance

J Jacobian matrix of partial derivative

I Current V

Voltage δ

Delta

K Geometric factor

1D One dimensional

2D Two dimensional

3D Three dimensional

4D Four dimensional

GPR	Ground penetrating radar
CVES	Continuous vertical electrical sounding
CST	Constant Separation Traversing
ERI	Electrical Resistivity Imaging
ERT	Electrical Resistivity Tomography
VES	Vertical Electrical Sounding



Acknowledgements

I am grateful to God Almighty for his ever presence in my life and for the successful completion of this work. I am also indebted to my supervisors, Dr. Akwasi Acheampong Aning and Prof. S. K. Danuor (who also doubles as the Head of the physics Department) for their contribution towards this work. Their technical pieces of advice, criticisms and encouragement produced the best in this work. The entire physics department and again the Head of Department are also deserving of my heartfelt gratitude for the financial support and the equipment that were released for the execution of this project. It must be mentioned at this point that Mr. Thomas Dwomoh (the geophysics lab technician) never relented in assisting with data collection and I so much appreciate his efforts. May God bless him. To all the lecturers in the department, thank you for imparting to my life. I am also grateful to my colleagues especially Mr. Obeng Aaron who left his work on several occasions and came to the field to help me collect data. I don't think I can ever return that favour. Thank you Messrs. Joshua Kpan and Alfred Bienibuor for always encouraging and motivating me to work hard. Also deserving commendation are the third and final year geophysics students who also assisted me on the field a number of times. I also pay tribute to my family without whose support I would not have been able to pursue this program. Thanks for always being there for me. Finally, a big thank you to the Association of African Universities (AAU) for their financial assistance.

Chapter 1

INTRODUCTION

1.1 Introduction

The global expansion of urban development has increased pressure on land, including abandoned cemeteries of historical and indigenous interest (Nobes, 1999). It may become important with time and progressive development, to find old, unmarked graves (Bevan, 1991) especially in historic cemeteries which are poorly maintained and often threatened by erosion, development and agricultural operations (Conyers, 2006). Sometimes they are accidentally encountered during construction and one wishes to determine the extent of the cemetery so that it can be preserved. In other cases, it might be necessary to locate individual burials so that they can be moved to another location.

For future constructional and other developmental purposes, graves and other subsurface features or structures are delineated in this study in a place rumoured to be an old cemetery even though there are no surface expressions of burials. It is also the objective of this study to respond to the rumour lingering about the study area. This knowledge will not only be of significance for constructional and other developmental purposes but also archaeological and historical purposes. For forensic reasons the mapping of graves using geophysical methods is also gaining popularity. While the location of graves can reveal some important archaeological information, their discovery together with such subsurface features as cavities, voids, fractures, sink holes etc. can help prevent engineering and environmental management problems.

Geophysical surveys provide a noninvasive and nondestructive means to determine the positions of previously unknown or unmarked graves and other subsurface features such as cavities, fractures, faults etc. Geophysical investigations of the earth involve

taking measurements at or near the earth's surface that are influenced by the internal distribution of physical properties. Analysis of these measurements reveals the vertical and lateral variations of the physical properties of the earth's interior (Kearey et al., 2002). The physical properties which include density, resistivity, electrical conductivity, elasticity, magnetic permeability, thermal conductivity, magnetic susceptibility, dielectric permittivity, abundances of radio nuclides and capacitance; are largely influenced by subsurface porosity, lithology, water saturation, structure and degree of pore connectivity.

The variation of the physical properties across the earth's subsurface has resulted in the evolution of different geophysical methods. These methods depend on the contrasts in one or more of the physical properties of the subsurface media (rocks, sediments, water, voids etc) and can be classified in two distinct types- passive and active. The passive methods detect variations within the natural fields such as the gravitational and magnetic fields of the earth. Contrastingly, the active methods are concerned with transmitting artificially generated signals into the ground and having them modified in ways that are characteristic of the materials through which they travel. The altered signals are measured by appropriate detectors whose output can be displayed and ultimately interpreted.

The geophysical methods in use include: gravity, magnetic, seismic, electrical resistivity, self-potential, electromagnetic, induced polarisation, radiometric, thermal conductivity etc (Reynolds, 1997). Generally, passive or the natural field methods can provide information on the earth's properties to significantly greater depths and are logistically simpler to carry out than artificial source methods. The latter, however, are capable of producing a more detailed and better resolved picture of the subsurface geology (Kearey et al., 2002). The type of geophysical method chosen for a particular survey depends on the objective of the survey relative to the sensitivity of the method, the resolution required, the prevailing conditions of the site, the time required for the survey, funds and computational resources available (Aizebeokhai et al., 2010).

Geophysical investigations have not only succeeded in building nations' economies but have also been phenomenal in restoring history and exposing crime.

Probably the first geo-archaeological investigation of its kind in Ghana, this study relies on an active geophysical method- the electrical resistivity - to investigate the subsurface in order to delineate subsurface features with a particular focus on graves in a place rumoured to be an old cemetery. This is done in consonance with Conyers' (2006) intimation that many historic cemeteries are poorly maintained and are often threatened by erosion, development and agricultural operations. Unmarked graves sometimes need to be identified so that human remains may be removed if a cemetery is threatened by construction, for instance.

The geophysical response of a grave will depend on the geology of the site and on the nature of the burials. The type of soil cover (whether clay or sand), the material property contrasts with the surrounding rock and soil and the degree of ground disturbance are other important factors. It is also dependent on whether the burials are done in a casket or not, whether the bedrock is sedimentary or volcanic and on the bedrock topography. Different responses can be obtained not only between burial sites, but within a specific burial site because methods of burial change with time (Nobes, 1999).

The most distinctive feature of a grave may, however, be the disturbed soil in the filled excavation. The first few metres of a grave shaft may have a significant change in soil. When the excavated earth is replaced, some topsoil may be sent to the bottom of the hole and subsoil sent to the top and spread on the surface. The topsoil can be higher in magnetic susceptibility than the subsoil. Also the electrical conductivity of the natural earth may increase or decrease with depth. The soil filling the grave shaft could therefore have a different electrical and magnetic stratification than the natural earth. These soil changes could last indefinitely. The contrast in electrical properties between them and the host medium will make them visible to the electrical resistivity method. Likewise, the electrical property differences between other subsurface structures and their host will also aid in their detectability by the Electrical Resistivity Tomography (ERT).

The direct current resistivity method is of recent a well-established geophysical technique, used routinely and successfully in the detection and mapping of concealed subsurface structures like walls, ditches and anthropogenic or natural cavities (Dahlin and Zhou, 2004). In archaeological geophysics, tombs comprise the most common subterranean manmade cavities of the greatest archaeological and historical importance. Several successful case studies in the detection of tombs have been reported, mainly where the investigated area is almost flat or with relatively small tomographic variation (Nyari and Kanli, 2007).

An electrical resistivity survey is a geophysical technique that investigates the subsurface resistivity distribution beneath an area of interest. Generally, electric current is injected into the ground and the resulting voltage differences are measured at the earth's surface. The current is generated by a battery or generator and injected via electrodes known as the current electrodes planted in the ground and the resulting potential difference determined by the potential electrodes. The potential difference patterns are indicative of the electrical properties of the subsurface and hence its nature. Inhomogeneities or anomalous conditions such as relatively conductive or resistive zones within the ground are deduced from the fact that they deflect the current and distort surface potential readings. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and the degree of water saturation in the rock.

Electrical resistivity surveys can be conducted using different electrode configurations or arrays. These include the Wenner array, Schlumberger array, dipole-dipole, poledipole, pole-pole, square and gradient arrays. Of these the gradient array is adjudged the best by Dahlin and Zhou (2006) in relation to multi-channel measurements because it is faster, resolves like or better than the wenner array and handles noisy data better than the dipole- dipole. It was for similar reasons the gradient array was considered in this study. Generally, the electrical resistivity method depends on the

resistivity contrast hence if the graves and subsurface features are to be detected they must have a significant resistivity contrast with the host rock.

This study will enable a better understanding of the nature of the subsurface. The knowledge obtained will also possibly end the rumour in circulation about the study area and influence future decisions regarding the use of the area. It is particularly an important step in this era when infrastructural development has taken centre stage in most universities in the country as they all try to accommodate their students.

1.2 Literature Review

Since its inception geophysics has received wide spread applications in various disciplines with some geophysical methods complementing each other to produce the desired results. Little wonder that new and challenging uses of these methods are emerging. Subsurface mapping of tombs or graves is one daunting task that many geophysicists and archaeologists have had to face; with the latter initially employing try and error methods until the former came along. It is frustrating and time-consuming locating graves especially in places where there are no surface expressions of burials. Popular among the geophysical methods for the detection of subsurface structures especially graves is the GPR but the electrical resistivity method also proves to be credible even though not widely used.

The application of geophysical methods to archaeological investigations as opposed to most parts of Europe and America, is less popular a practice in Ghana even though this has been around for long. The practice dates back to the early 1950s. According to Leucci and Greco (2012), the application of geo-archaeological and geophysical methods changed the starting point of scientific approaches towards archaeological investigations in the 20th century. The traditional methods that were used in archaeology resulted in limited and sometimes no information on unexcavated subsurface archaeological features. The pair went further to say that this technology that has developed rapidly over the past 20 years, has made the geophysical approach a reliable investigative tool, both

before and during excavation. In large scale reconnaissance surveys geophysical prospecting allows the physical parameters of the subsoil to be mapped but in specific cases, it can provide useful information on the depth and shape of the buried structures of anthropogenic origin and may help determine individual artefacts.

Butler (2008) wrote exclusively about subsurface cavities being anomalies or deviations from the surrounding or background geologic conditions but argueably the concept is also applicable to graves and some other subsurface features. According to him, they are anomalous due to the cavity space itself, the secondary effects around the cavity, and materials within the cavity. The anomalies representing all subsurface cavities have effective diameters larger than the physical dimensions of the cavity space itself due to the secondary effects around the cavity. This is called a "halo" effect and is caused by stress redistribution, cracking and fracturing, subsidence and induced groundwater flow. The effective size of the subsurface cavity anomaly is often larger by a factor of two than the cavity itself. Indeed the composition of the graves, fractures, sinkholes etc. makes them different from the surrounding geology and therefore easily detectable. Whether natural or man-made, cavities can be air-filled, water-filled or sediment-filled (van Schoor, 2002; Butler, 2008).

Though acclaimed as reliable investigative tools, the detectability of graves and other subsurface features using the geophysical methods depends on a number of factors. These include the magnitude and spatial wavelength of the anomaly, noise, sensitivity and depth of investigation of the measurement system. The magnitude of the surface anomaly is determined by the size of the subsurface anomaly, the depth to the anomaly, and the physical property contrasts. Surface spatial wavelength depends primarily on the depth to the anomaly and secondarily on its size. Noise sources affecting a set of geophysical measurements can be natural (e.g electrical in this case) or artificial. For optimum results, the anomaly magnitude should be greater than the noise level and the anomaly spatial extent and frequency (wavelength) should be distinctive from the characteristics of the noise sources. The anomaly cannot be detected if it is practically below the depth of

investigation of the geophysical instrument being used since the geophysical instruments have specific depths to which they can probe. The instrument must also have appropriate sensitivity and accuracy for the parameter magnitude else the anomaly will not be detected (Butler, 2008) .

Therefore the selection of the correct geophysical tool for the detection of subsurface cavities (van Schoor, 2002) and other subsurface features is not always easy due to the highly variable and unpredictable target characteristics. Graves, cavities (MartinezPagan et al., 2013), sinkholes (van Schoor, 2002) and some other subsurface features can be partially or completely water filled and, depending on the composition of the water, have a resultant conductivity ranging from highly conductive to relatively resistive compared to the host rock. Air- filled cavities on the other hand will have high resistivities with intermediate resistivities when filled with dry and loose sediments (porous).

It has, however, been severally reported that the electrical resistivity method is reliable and capable of delineating graves (Jervis and Pringle, 2014; Pringle and Jervis, 2010; Matias et al., 2006; Jervis et al., 2009) and subsurface cavities, fractures etc (van Schoor, 2002; Martinez-Pagan et al., 2013; Metwaly and AlFouzan, 2013; Panek et al., 2010) as well as other buried archaeological features. This method has also been used in combination with other methods (Hansen et al., 2014; Nobes, 1999; Bevan, 1991; Juerges et al., 2010) for the mapping of graves or tombs and buried archaeological features (Drahor et al., 2011).

Recently, Loke et al. (2013) lauded the major improvements in instrumentation, field survey design and data inversion techniques for the geoelectrical method over the past 25 years. They acknowledged the possibility of conducting large 2-D, 3-D and even 4-D surveys efficiently to resolve complex geological structures that were not possible with traditional 1-D surveys using multi-electrode and multi-channel systems.

Affirmatively Aning et al. (2013a) carried out a 2-D ERT survey using the multielectrode gradient array to determine the resistivity distribution around the

Bosumtwi Impact crater. In a separate survey, Aning et al. (2013b) used the same methods to determine the sediment/bedrock contact, impact related structures and the impact direction of the meteorite that crested the Bosumtwi Lake.

The detection and delineation of graves and other subsurface features using geophysical methods often result in information useful to the historical and archaeological communities as well as the construction industry. Undoubtedly the forensic scientists also benefit from such surveys.

The historians and the archaeologists benefited from geophysics when Matias et al. (2006) employed the resistivity methods for the detection of a tomb tentatively associated with, the prominent Portuguese humanist, Damio de Goes, who lived in the XVI century. The survey was carried out with the dipole-dipole, gradient and pole-pole arrays with the results from the inversions of the 2-D dipole-dipole data and 3-D gradient array showing high resistivity anomalies that were assigned to the walls of the tomb. The low resistivity anomalies observed in between the high resistivity ones were interpreted as due to the presence of water enriched by ions from the decomposition of human bodies. Excavation works carried out in accordance with the results of the geoelectrical investigation successfully found a tomb where several human bones had been collected.

The discovery of the tombs of Cleopatra and Mark Anthony in the temple of Osiris and Isis inside the Tap-Osiris Magna complex in Alexandria, Egypt was another breakthrough for them. Even though the GPR, electrical tomography and magnetic methods did not give them the desired results in an earlier research in the same place, the very low frequency electromagnetic method did it for Abbas et al. (2012). The failure of the three methods is indicative of the weaknesses of the various geophysical methods. They may not always work in every environment.

That aside, the electrical resistivity method has still been proven to be able to detect not only graves, but also the properties of tumuli filling materials and resolving buried archaeological structures inside the tumuli. Tumuli are small man-made hills constructed

to cover monumental tombs or burial chambers that belonged to great historical persons (Papadopoulos et al., 2010).

Additionally, the detection and delineation of graves and other subsurface structures are necessary if constructional projects are to be carried out especially in abandoned cemeteries and mining areas. The essence is to avoid buildings collapsing as a result of loose sedimentation, cavities and fractures below their foundations. The 2-D electrical resistivity method has wide applications in engineering, environmental and shallow surface investigations (van Schoor, 2002). It is based on assumptions that various entities like minerals, solid bedrock, sediments, air and water-filled structures have detectable electrical resistivity contrasts relative to the host medium (Panek et al., 2010). Ahead of constructional projects, the electrical resistivity method has been used in mining and abandoned mining areas (Martinez-Pagan et al., 2013; Martinez-Lopez et al., 2013) and limestone or dolomite dominant zones which are susceptible to cavity formation due to natural processes (van Schoor, 2002; Metwaly and AlFouzan, 2013). Subsurface cavities may also be surveyed to assess the likelihood of landslides in an area with the ERT (Panek et al., 2010). The ERT also stands out as an appropriate geophysical tool in terms of locating voids in karst areas. This was confirmed by (Farooq et al., 2012) after an ERT investigation in an attempt to solve a road construction problem that was encountered in Yongweol-ri, South Korea. It also saved them from the expensive, time-consuming and dangerous drilling to determine the extent of the karst voids.

The method is also capable of investigating the degree of fracturing and weathering of the subsurface and determining the groundwater potential of a site (Aizebeokhai et al., 2010). In other surveys, the electrical resistivity was used together with the GPR to delineate subsurface cavities (El-Qady et al., 2005) and investigate the floors of an old building for cracks and fractures (Leucci, 2006). Drahor et al. (2011) also combined the ERT with other methods to define subsurface characteristics inside and around the church of Agios Voukolos (Turkey) and searched for possible structural damage such as

cracks and fissures that may exist in the subfloor of the church. Investigations of the courtyard area indicated potential buried structures under the settling area of the church.

Furthermore, geophysics (may be to the surprise of many) is now gaining grounds in forensic studies as so much work has been done in that direction already using the electrical resistivity method. Pringle and Jervis (2010) exposed crime by using an electrical resistivity survey to discover a one year old clandestine burial of a murder victim in North Wales in the UK. The indicators were some seven anomalies that were identified and compared to anomalies derived from similar-aged, simulated clandestine burial surveys. These anomalies had sizes and amplitudes ($\pm 3 \Omega m$) comparable to those for the simulated surveys.

Having established that the electrical resistivity is useful for the detection of clandestine graves, Jervis and Pringle (2014) investigated the effects of seasonal changes of climate in the resistivity responses of graves. In this study, resistivity data collected over three years over three simulated graves were analysed in order to assess how the graves' resistivity anomalies varied seasonally and when they could most easily be detected.

Hansen et al. (2014) for the same reason of detecting clandestine graves in support of forensic investigations, performed a control experiment using a pig carcass or cadaver. The cadaver was buried naked in one grave and buried wrapped with a tarpaulin in another grave. An empty grave was also obtained and the resistivity responses of all three cases measured. They reported high ground water conductivity and therefore low resistivity in graves containing the naked carcass and high resistivity in the tarpaulin wrapped carcass grave attesting that clandestine graves can be detected using this method. The method, however, did not detect the disturbed soil in the empty grave.

Whiles Juerges et al. (2010) combined the electrical resistivity method and the GPR for the detection of clandestine graves in contrasting burial environments, Jervis and Pringle (2014) used them to determine unmarked graves in different but also contrasting

burial environments. Alone or in combination with the GPR (Pellicer and Gibson, 2011), the ERT also functions in the determination of the lithological composition and detailed internal architecture of the subsurface, the characterisation and description of the geology of a site and understanding of depositional processes.

As geophysical technology has advanced so have the difficulties of the requirements (Butler, 2008). In agreement with Butler, the easy delineation of graves especially those in old cemeteries with no surface indications of burials and other subsurface features remains a hurdle to jump. Even though the GPR has received wide spread usage in surveys such as this, it is also important that alternative methods are identified. The electrical resistivity method has been tested and proven to be capable but not widely used for the delineation of old graves. It is therefore the objective of this study to use the electrical resistivity to delineate graves and other subsurface features in an area alleged to be an old cemetery for future developmental purposes. The knowledge will also confirm and preserve history. Using published literature as evidence, it is probably the first survey using a geophysical approach to delineate graves in Ghana.

1.3 Problem Statement

Though a relatively flat land with no surface expressions of burials, the study area is rumoured to have been used as a royal cemetery over sixty years ago. Therefore, locating graves or tombs in such an old cemetery can be challenging since there are no surface expressions of burial locations. The infilling material of grave shafts may also result in a complex stratigraphy difficult to identify. The complexity may come from the mixture of soil, sand and gravel laid in layers of irregular thicknesses and geometries. In cases where there are even markers and headstones over graves, they may be wrongly positioned. The challenge is to explore the subsurface with such complex stratigraphy without disturbing the soil. This therefore necessitates a geophysical approach since the claims cannot also be responded to by visual inspection.

Beyond responding to the rumours, the place could be considered for developmental purposes someday especially in this era when socio-economic development is an absolute necessity. This coupled with the daily emergence of new challenges in terms of infrastructure, water, health, food and other social amenities, it is anticipated that someday there will be a scramble for space and land and even cemeteries will not be spared. Places for burial are already difficult to come by in some parts of the world (Hansen et al., 2014) which is the reason why some people settle for cremation instead of interment or burial. Africa and specifically Ghana could be faced with this challenge in the not too distant future.

Following the global trend, the Kwame Nkrumah University of Science and Technology (KNUST) -yet a developing university- may find it necessary in the future to add to the existing structures and provide other facilities in order to cater for the ever increasing student and staff population. Consequently what appears to be unused land now (of which the study area is part) may be relied on as remedy to the situation. This necessitates the delineation of other subsurface features in addition to the graves so that informed decisions can be made about the place in the near future.

Thus, the possibility of using the site for developmental purposes coupled with the adverse environmental and health impacts cemeteries may have on humans informed my decision to carry out this survey to either confirm or refute this allegation.

1.4 Research Objectives

The main objective of this project is to use the electrical resistivity method to delineate graves or tombs in the area if indeed the site was a cemetery and other subsurface features in the study area.

The specific objectives are to:

- Map near subsurface features such as cavities, voids, fractures, faults etc

- Determine thicknesses of overburden
- Determine the spatial distribution of graves or tombs if they exist
- Determine the geometry of subsurface features

1.5 Research Hypothesis

It is expected that a geophysical study will be able to unravel the uncertainty surrounding the study area. Since the physical properties of a disturbed subsurface and those of an undisturbed subsurface are not the same, the survey results will provide the necessary answers. Bevan (1991) opines that the most distinctive feature of a grave may be the disturbed soil in the filled excavation. When the excavated soil is replaced some topsoil may be sent to the bottom of the hole and some subsoil brought on top and may spread across the surface. Thus, the soil filling the shaft of the grave could have different electrical, magnetic and dielectric stratification than the natural earth.

Similarly the presence of other subsurface features, natural and artificial voids, cavities, sinkholes etc. (whether filled with water, air or sediments) will result in a distinct resistivity contrast between them and the surrounding compact material. The response of subsurface materials to the electrical current that will be injected will thus facilitate the achievement of the research goals.

1.6 Significance Of The Research

Graveyards whether ancient or modern are culturally important and must be treated with sensitivity and care (Nobes, 1999). This might be an old cemetery but could no doubt be not only culturally vital but also economically valuable. Thus the need for a geophysical approach to unravel the myth since this is capable of delineating subsurface structures and revealing vital information about the nature of the subsurface without disturbing

materials underground. The results of this survey will end an age long rumour and avail information that will foster decisions regarding the future use of the study area.

Places of burial are already becoming increasingly scarce in the west due to infrastructural development emanating from the need to further expand to cater for current and unborn generations (Hansen et al., 2014). This may have influenced some westerners' decision to be cremated after their death.

For now this may not be a pressing issue in Ghana but it will catch up with us soon considering the spate of infrastructural development in the country especially in the cities and some institutions. Locally, KNUST is erecting new structures every now and then because the existing structures are not enough to accommodate the number of students and staff present. The possibility of the students population even increasing in the future makes this situation closer than we think. It is therefore imperative that a place with such a history on the KNUST campus be investigated so as to put it to appropriate use when the need arises. If, for instance, it is to be used for structural development it will be important to dig and remove the bones, dig the foundation to a certain depth and as well put in other measures that will prevent the building from sinking or collapsing due to the irregularities in the subsurface. It may also be unwise to sink a borehole in the area since nobody knows how the bodies of the deceased were prepared for burial and even how they died though they were buried a long time ago. This knowledge will certainly protect the inhabitants against the adverse effects of cemeteries.

In another view, there may be some important archaeological information associated with the buried remains. Generally, tombs have great archaeological and historical importance and may even be economically valuable where looting has not taken place. If it is so with this study area the information becomes readily available and obtainable when the facts are ascertained.

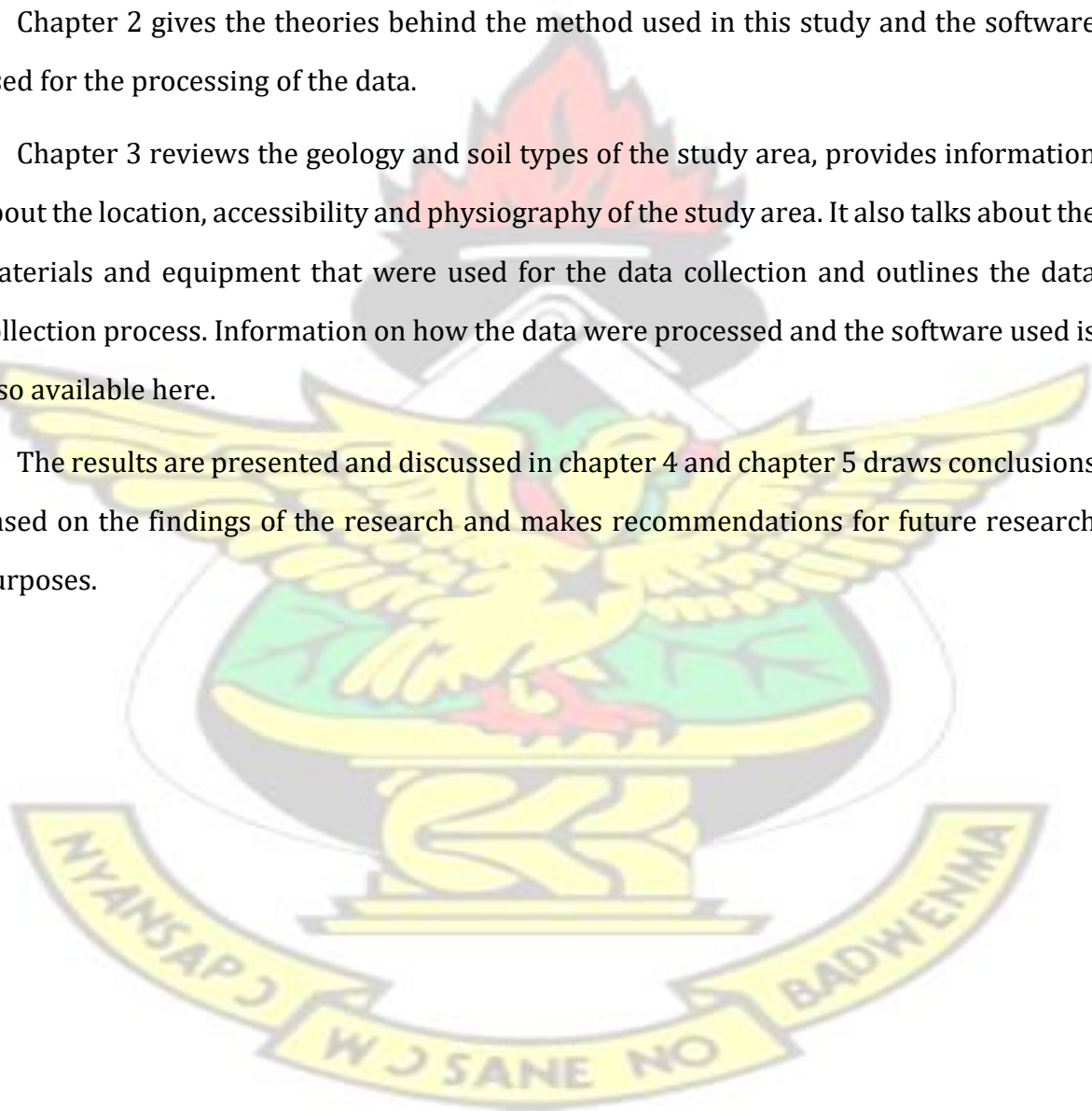
1.7 Thesis Layout

This thesis consists of five chapters and each of them addresses a major component of the thesis. Chapter 1 is basically the introduction and under it, the topic is introduced and the background as well as the objectives of the study stated. It then hypothesises a method that can help achieve the research goals and indicates the significance of such a research. Literature related to the study is also reviewed in this chapter.

Chapter 2 gives the theories behind the method used in this study and the software used for the processing of the data.

Chapter 3 reviews the geology and soil types of the study area, provides information about the location, accessibility and physiography of the study area. It also talks about the materials and equipment that were used for the data collection and outlines the data collection process. Information on how the data were processed and the software used is also available here.

The results are presented and discussed in chapter 4 and chapter 5 draws conclusions based on the findings of the research and makes recommendations for future research purposes.



Chapter 2

THEORITICAL BACKGROUND OF THE METHOD

2.1 Theory and basic principles of Electrical Resistivity

The purpose of electrical resistivity surveys is to determine the subsurface resistivity distribution by taking measurements on the ground surface. This is achievable based on the principle that the distribution of electrical potential in the ground around a currentcarrying conductor depends on the electrical resistivity and distribution of surrounding soils and rocks. The potential difference patterns supply information on the form of subsurface inhomogeneities and their electrical properties (Kearey et al., 2002; Loke, 1999). Detection of subsurface structures is easier if there is a sharp contrast in electrical properties between the soil matrix and the heterogeneity or anomaly.

Ohm's law is the basic theory governing electrical resistivity surveys. It controls the flow of current through a conducting medium. This law states that the current (I) flowing through a conductor between two points is directly proportional to the potential difference (V) across the two points (Fig. 2.1B). The resistance to the flow of current through the conductor, R is the constant of proportionality and is therefore expressed as the ratio of the potential drop to the applied current.

Consider an electrically homogeneous cube of side length L through which current is flowing (Fig. 2.1A). Conduction of electricity through the cube is resisted by the material within it resulting in a potential drop (V) between opposite faces. The resistance, R is proportional to the length (L) of the resistive material and inversely proportional to the

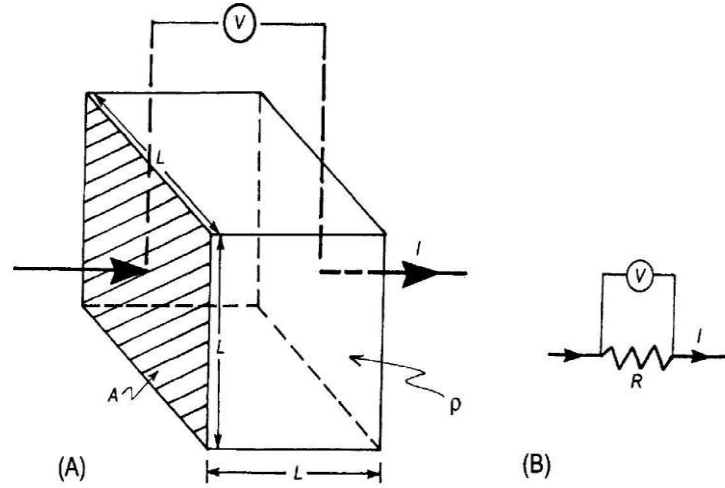


Figure 2.1: (A) Basic definition of resistivity across a homogeneous block. (B) The electrical circuit equivalent where R is a resistor (Reynolds, 1997)

cross-sectional area (A); the constant of proportionality is the true resistivity ρ . It is the resistance of a unit cube to current flowing between opposite faces. Resistivity is measured in ohm-metres (Ωm) and the opposite of it, conductivity, σ is measured in Siemens per metre (S/m) = $1 \Omega^{-1}m^{-1}$. This is equivalent to mhos/metre ($\Omega^{-1}m^{-1}$) (Kearey et al., 2002; Reynolds, 1997; Milsom, 2003).

Mathematically, Ohm's law is expressed as $V \propto I$

$$V = IR \quad (2.1)$$

From the electrically uniform cube (Fig. 2.1A),

$$R \propto \frac{L}{A} \Rightarrow R = \frac{\rho L}{A} \quad (2.2)$$

where ρ is the constant of proportionality. Therefore

$$\frac{V}{I} = \frac{\rho L}{A} \quad (2.3)$$

Making ρ the subject,

$$\rho = \frac{VA}{IL} \Omega m \quad (2.4)$$

This is the formula for calculating the resistivity of a material. All symbols have the same meaning as above.

Conductivity which is the opposite of resistivity is expressed mathematically as

$$\sigma = \frac{1}{\rho} \quad (2.5)$$

Alternatively, Ohm's law can be written in terms of the electric field strength, E (volts/m) and the current density, J (amps/m²) as follows:

$$\rho = \frac{1}{\sigma} = \frac{E}{J} \Omega m \quad (2.6)$$

Implying

$$J = \sigma E \quad (2.7)$$

But the physical parameter which is measured in the field is the electric potential, V and is related to the electric field as:

$$E = -\nabla V \quad (2.8)$$

Thus

$$J = -\sigma \nabla V \quad (2.9)$$

The current density in any direction within a material is generally given by the negative partial derivative of the potential in that direction divided by the resistivity.

2.1.1 Current flow in homogeneous ground

Current flows away radially from a point source (Fig. 2.2A) at the surface of a uniform ground of resistivity, ρ_a like ripples of water flowing away from the point where a stone has been dropped in the water. The current injected from a single electrode planted at the surface experiences a drop in voltage or potential difference between any two points on the surface of the medium. This is termed the potential gradient $\left(\frac{\delta V}{\delta r}\right)$ and is negative

because the potential decreases in the direction of the current flow. In the process of this movement, lines of equal voltage known as 'equipotentials' intersect lines of equal current at right angles forming a hemispherical shell around the point electrode source.

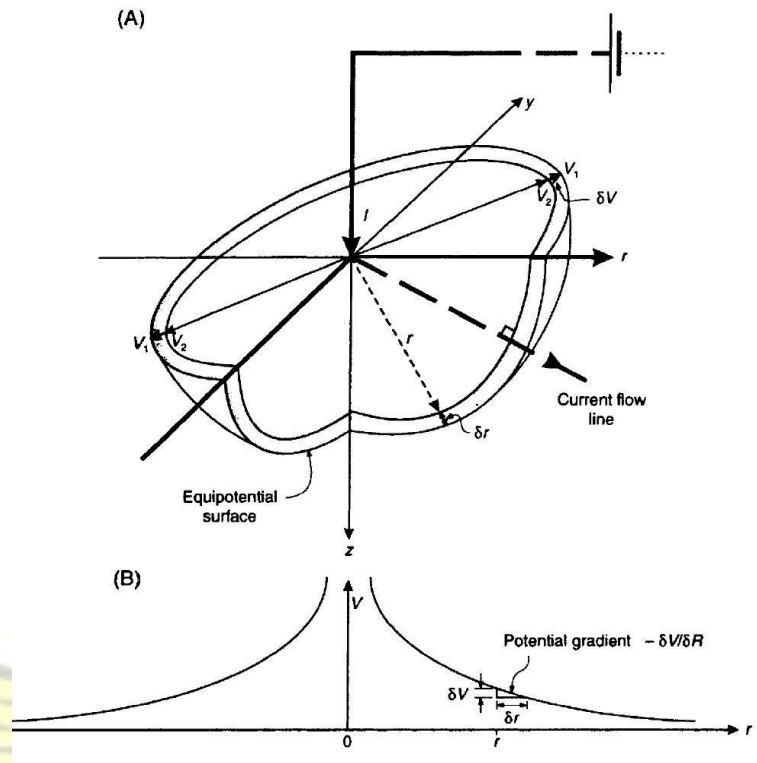


Figure 2.2: (A) 3-D representation of a hemispherical equipotential shell around a point electrode on a semi-infinite, homogeneous medium. (B) Potential decay away from the point electrode (Reynolds, 1997)

The potential difference δV across a hemispherical point of incremental thickness δr is given by:

$$\frac{\delta V}{\delta r} = -\rho J \quad (2.10)$$

J which is the current density is the ratio of the current flowing to the area of the hemispherical surface. That is

$$J = \frac{I}{2\pi r^2} \quad (2.11)$$

The potential gradient decreases with increasing distance from the source. Therefore,

$$\frac{\delta V}{\delta r} = -\rho \frac{I}{2\pi r^2} \quad (2.12)$$

Integrating the above equation, the potential or voltage, V_r at a distance r from the point current source, I is obtained. Thus

$$V_r = \delta V = - \int \frac{\rho I}{2\pi r^2} \delta r \quad (2.13)$$

where, the constant of integration is zero since $V_r = 0$ when $r = \infty$

Therefore,

$$V_r = \frac{\rho I}{2\pi r} \quad (2.14)$$

A new potential distribution occurs when a current sink is added to the point current electrode source or when two current electrodes are used to inject current into the ground resulting in a modification of the above expression. For a current source at point A and sink at point B with potential electrodes at points E and F (Fig. 2.3), the voltage at any point, P in the ground is the sum of the potentials from the two electrodes such that $V_P = V_A + V_B$ where V_A and V_B are the potential contributions of the two electrodes, A(+I) and B(-I) respectively. From equation 2.14 above the potentials at electrodes E and F are:

$$V_E = \frac{\rho I}{2\pi} \left(\frac{1}{AE} - \frac{1}{EB} \right) \quad (2.15)$$

and

$$V_F = \frac{\rho I}{2\pi} \left(\frac{1}{AF} - \frac{1}{FB} \right) \quad (2.16)$$

The potentials measured by the two potential electrodes may not be the same; therefore the potential difference is what is used in resistivity surveys. The potential difference, δV_{EF} is thus equal to

$$\delta V_{EF} = V_E - V_F = \frac{\rho I}{2\pi} \left(\left[\frac{1}{AE} - \frac{1}{EB} \right] - \left[\frac{1}{AF} - \frac{1}{FB} \right] \right) \quad (2.17)$$

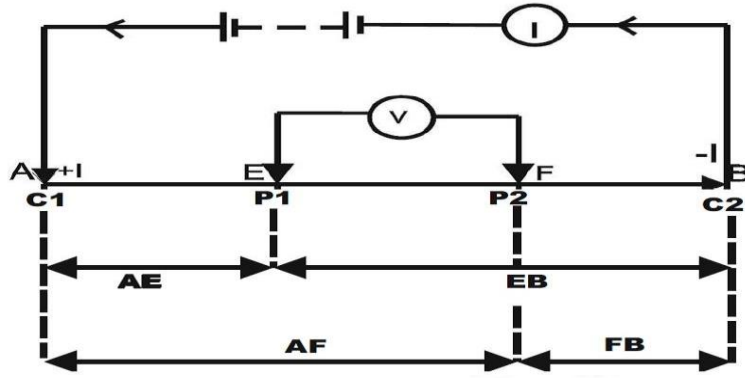


Figure 2.3: Generalised form of the four electrode configuration in resistivity surveys

2.1.2 Electrode configurations and Geometric factors

An electrode configuration or array is the arrangement of electrodes for resistivity surveys whiles geometric factors are numerical multipliers defined by the positions of the electrodes relative to one another. Conventionally, four electrodes are used for the surveys; one pair acting as current electrodes injecting current into the ground and the other pair known as the potential electrodes responsible for measuring the potential difference that results. It is unwise to use a single pair of electrodes to inject current and also measure the resulting potential difference because of contact resistances which depend on the ground moisture and contact area. By the arrangement of electrodes, subsurface resistivity variations both vertically and laterally can be determined to different extents and depths. The resistivity so obtained on the field is the apparent resistivity and not the true resistivity because of ground inhomogeneity. It would be true resistivity if the ground were homogenous; which in reality is not so.

Making ρ the subject (equation 2.17), the apparent resistivity, ρ_a in the case of heterogeneous ground is:

$$\rho_a = \frac{2\pi\delta V_{EF}}{I} \left(\left[\frac{1}{AE} - \frac{1}{EB} \right] - \left[\frac{1}{AF} - \frac{1}{FB} \right] \right)^{-1} \quad (2.18)$$

This can be rewritten as

$$\rho_a = K \frac{\delta V_{EF}}{I} \quad (2.19)$$

K is the geometric factor expressed as

$$K = 2\pi \left[\frac{1}{AE} - \frac{1}{EB} - \frac{1}{AF} + \frac{1}{FB} \right]^{-1} \quad (2.20)$$

This describes the geometry of the electrode configuration being used.

Thus the value of the apparent resistivity depends on the geometry of the electrode configuration as defined by the geometric factor. The apparent resistivity is the product of the resistance, R measured and the geometric factor, K of the electrode array in use. Its unit of measurement is the Ωm . True resistivity values are only obtained after field resistivity data have undergone computer-based inversion. It must be noted that the apparent resistivity is not the physical property of the subsurface but the true resistivity.

2.2 Basic electrode arrays or configurations

Electrodes for resistivity surveys are differently configured to meet various survey objectives. The differences in these arrays come from their arrangement and the separation of the electrodes (current and potential electrodes). The choice of an array for a particular survey depends on the space available, labour intensity, dipping interfaces, sensitivity to lateral inhomogeneities, level of background noise, sensitivity of the instrument and the structure to be delineated (Loke, 2001; Reynolds, 1997; Habberjam and Watkins, 1967; Barker, 1981; Broadbent and Habberjam, 1971).

Named after their originators, the Wenner and the Schlumberger arrays were about the first to be used for resistivity surveys. The later additions include the dipole-dipole, pole-dipole, pole-pole, gradient and square arrays.

2.2.1 Wenner Array

The Wenner array has a linear arrangement of equally spaced electrodes as shown in figure 2.4 and operates by moving electrodes along the profile for lateral resistivity measurements or increasing the electrode spacing about a fixed point for resistivity variation with depth. It is very effective in resolving horizontal structures (sensitive to vertical changes in the subsurface) but less effective when it comes to the resolution of vertical structures (less sensitive to horizontal changes). It also covers an intermediate depth range, shows moderate sensitivity to near surface lateral effects and has an intermediate resolution. Milsom (2003) acclaims the Wenner array as very widely used and supported by a vast amount of interpretational literature and computer packages. He also describes it as the foundation stone on which all the array types have been developed. The apparent resistivity of the Wenner array is given by:

$$\rho_a = 2\pi a \frac{\delta V}{I} \quad (2.21)$$

Where δV is the potential difference, $2\pi a$ is the geometric factor and I is the applied current.

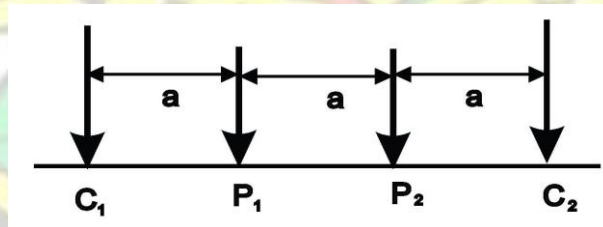


Figure 2.4: The Wenner array: C_1 and C_2 are the current electrodes; P_1 and P_2 are the potential electrodes; a is the electrode spacing

2.2.2 Schlumberger Array

This type of array has unevenly spaced electrodes with the potential electrodes in the middle and the current electrodes at the extreme ends (Fig. 2.5). The distance between the two potential electrodes is much smaller than the distance between a current

electrode and a potential electrode. Only the current electrodes are moved when determining resistivity variations which makes it suitable for depth soundings. The current electrode spacing is expanded symmetrically about the centre of the spread while the potential electrodes remain fixed. However, when the current electrodes are too wide, the potential electrode spacing will have to be increased for quality readings. The schlumberger array penetrates deeper and resolves vertical structures better than the wenner (Milsom, 2003). The apparent resistivity for the Schlumberger array is given by:

$$\rho_a \approx \frac{\pi}{2l} \frac{(L^2 - x^2)^2}{L^2 + x^2} \left(\frac{\delta V}{I} \right) \quad (2.22)$$

This array is often used symmetrically, that is $x = 0$, in which case the equation reduces to

$$\rho_a = \frac{\pi L^2}{2l} \left(\frac{\delta V}{I} \right) \quad (2.23)$$

The geometric factor, K is thus

$$\frac{\pi}{2l} \frac{(L^2 - x^2)^2}{L^2 + x^2} \text{ or } \frac{\pi L^2}{2l} \quad (2.24)$$

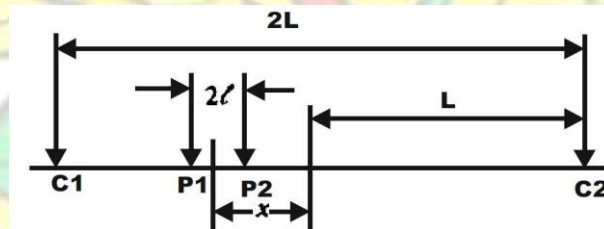


Figure 2.5: The schlumberger array: 2l is the potential electrode spacing and 2L is the current electrode spacing. x is the distance between the centre of the potential electrodes and the centre of the spread

2.2.3 Dipole-Dipole Array

This array has the current pair of electrodes on one side and the potential pair on the other side of the profile line as shown in figure 2.6. It is sensitive to horizontal changes

(resolving vertical structures) in the subsurface but less sensitive to vertical changes (resolving horizontal structures). This array has low signal strength. By varying 'n' information can be obtained at different depths. In principle the larger the value of 'n', the deeper the penetration of the current paths sampled. The double dipole array is commonly used for induced polarization (IP) because the complete separation of the current and voltage circuits reduces the vulnerability of inductive noise.

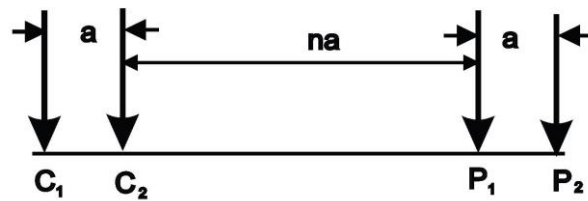


Figure 2.6: Dipole-Dipole array

The apparent resistivity of this type of array is calculated using the following formula:

$$\rho_a = \pi n a (n+1)(n+2) \left(\frac{\delta V}{I} \right) \quad (2.25)$$

n ranges from 1 to 5.

2.2.4 Pole-Dipole Array

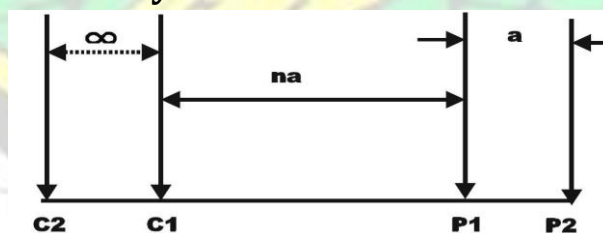


Figure 2.7: Pole-Dipole array

Figure 2.7 shows the arrangement of electrodes when using the pole-dipole array. One current electrode is placed at such a great distance from the other three that it is considered to be at infinity. This array has higher signal strength than the dipole-dipole. According to Milsom (2003), it produces asymmetric anomalies that are consequently

more difficult to interpret than those produced by symmetric arrays. Peaks are displaced from the centres of conductive or chargeable bodies and electrode positions have to be recorded with special care. It has an apparent resistivity of:

$$\rho_a = 2\pi na(n+1)\left(\frac{\delta V}{I}\right) \quad (2.26)$$

2.2.5 Pole-Pole Array

The two-electrode array has the second current electrode and second potential electrode placed far away from the other two (Fig. 2.8). The distance is not more than twenty times the separation between the first current and potential electrodes. It has the deepest depth of investigation but with a very poor resolution. This array is very popular in archaeological work because it can easily be carried out by one person (Milsom, 2003). The array has an apparent resistivity of :

$$\rho_a = 2\pi a\left(\frac{\delta V}{I}\right) \quad (2.27)$$

It has the same geometric factor as the Wenner, $2\pi a$

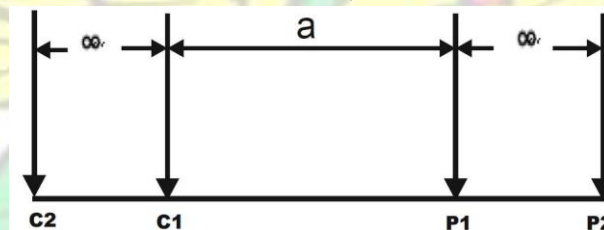


Figure 2.8: Pole-Pole array

2.2.6 Square Array

This has four electrodes positioned at the corners of a square and are variously combined into voltage and current electrodes (Fig. 2.9). Resistivity variations with depth are determined by expanding the square. The entire array is moved laterally when carrying out surface measurements of resistivity. It can provide vital information about ground anisotropy and inhomogeneity. The square array is the least sensitive of all the electrode

configurations to steeply dipping interfaces; thus it can cope in situations where the subsurface media are not horizontally layered (Broadbent and Habberjam, 1971). The square array is a special form of equatorial dipole-dipole array for $n=1$. It is particularly good for determining lateral azimuthal variations in resistivity. This is done by swapping

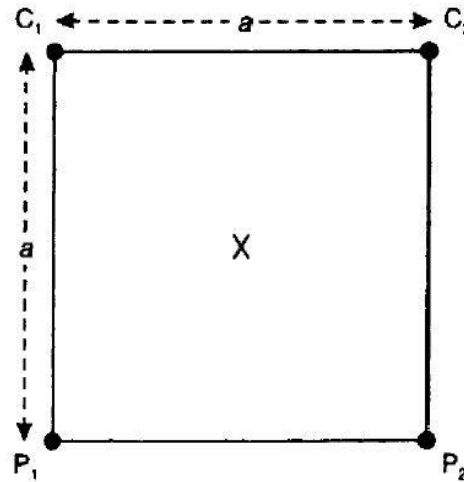


Figure 2.9: Square array

P_1 and C_2 so that the square rotates through 90° and hence the apparent resistivity can be determined for two orthogonal sections. It also lends itself to rapid grid mapping (Reynolds, 1997).

Its apparent resistivity is:

$$\rho_a = \frac{2\pi a}{2 - \sqrt{2}} \left(\frac{\delta V}{I} \right) \quad (2.28)$$

2.2.7 Gradient Array

Similar to the schlumberger array, the gradient array has the current electrodes at the extreme ends and the potential electrodes within them (Fig. 2.10). The potential pair is moved within the current pair when taking measurements. It is widely used for reconnaissance. If powerful generators are available large numbers of readings can be taken on parallel traverses without moving the current electrodes. The gradient array is

faster and more cost effective when used for multi-channel measurements than the wenner which is only one channel. It is said that its resolution is better than or as good as that of the wenner (Dahlin and Zhou, 2006). The duo further reported that the gradient array is a better option for multi-channel measurements as compared to the dipole-dipole because the latter suffers from higher noise levels for longer electrode separations.

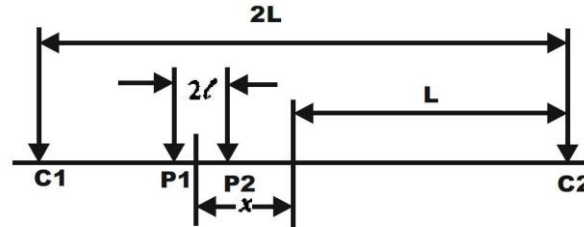


Figure 2.10: Gradient array

This array has an apparent resistivity of:

$$\rho_a \approx \frac{\pi (L^2 - x^2)^2}{2l (L^2 + x^2)} \left(\frac{\delta V}{I} \right) \quad (2.29)$$

Therefore the geometric factor

$$K = \frac{\pi (L^2 - x^2)^2}{2l (L^2 + x^2)} \quad (2.30)$$

According to Dahlin and Zhou (2006), the current is injected, when using the gradient array, into the subsurface using a separation of $(s+2)a$ and all the corresponding voltages with potential electrodes spacing of a are measured simultaneously. s gives the maximum number of potential readings for a current injection. It is an integer and also gives the maximum separation between the potential electrodes. The midpoint of the potential electrodes, m relative to the current electrodes is given as:

$$m = \frac{(x_M + x_N)/2 - (x_A + x_B)/2}{(x_N - x_M)} = \frac{(x_{MN} + x_{AB})}{a} \quad (2.31)$$

where x_A , x_B , x_M and x_N are the positions of the current and potential electrodes; $x_B > x_A$, $x_N > x_M$; x_{AB} and x_{MN} are the midpoints of the respective dipoles. m can also be calculated from

the relation $m = n - (s + 1)/2$, for $x_{MN} \leq x_{AB}$ ($m \leq 0$) and $m = n + (s + 1)/2$ for $x_{MN} \geq x_{AB}$ ($m > 0$). m and n are negative or positive integers.

For all the arrays C_1 and C_2 are current electrodes and P_1 and P_2 are potential electrodes. The different types and styles of electrode arrays have particular advantages, disadvantages and sensitivities.

2.3 Resistivity of Earth's Materials

The resistance of the earth to underground current depends on several geological factors including the mineral and fluid content, porosity and degree of water saturation in the rock. The degree of fracturing in rocks also contributes largely to ground resistivity (Loke, 1999). Such electrical properties of rocks and minerals as conductivity or the reverse, resistivity, electrical potentials and dielectric constants play key roles in electrical prospecting. Of these, electrical conductivity or resistivity is the most important.

Electric current can be conducted through a rock in three ways: electrolytic, electronic (ohmic) and dielectric conduction. Electrolytic conduction occurs by the relatively slow movement of ions within an electrolyte and depends on the ion type, ionic concentration and mobility. The process by which metals, for example, allow electrons to move rapidly carrying a charge is electronic conduction. Insulators or very weakly conducting materials conduct dielectrically when an external alternating current is applied. This causes atomic electrons to be shifted slightly with respect to their nuclei. Conduction in most rocks is by way of pore fluids acting as electrolytes with the actual mineral grains contributing very little to the overall conductivity of the rock. It is however not the case where the grains are themselves good electronic conductors. Sedimentary rocks are the most conductive of all the rock types because of their high porosity and hence high fluid content. Igneous rocks on the other hand have high resistivities while metamorphic rocks have intermediate but overlapping resistivities. The age of the rock may also influence its resistivity; older rocks may have higher resistivities than younger ones because of prolonged exposure to secondary infilling of interstices by mineralisation and

compaction decreasing the porosity and permeability. The resistivities of particular rock types may also vary with lithology since this also affects rock porosity and the salinity of the water content (Reynolds, 1997; Telford et al., 1990). Geological materials have resistivities ranging from $1.6 \times 10^{-8} \Omega m$ for native silver to $10^{16} \Omega m$ for pure sulphur as shown in figure 2.11.

The enormous influence of porosity and water as well as other pore fluids on the resistivities of rocks and minerals compelled Archie (1942) to establish a relationship

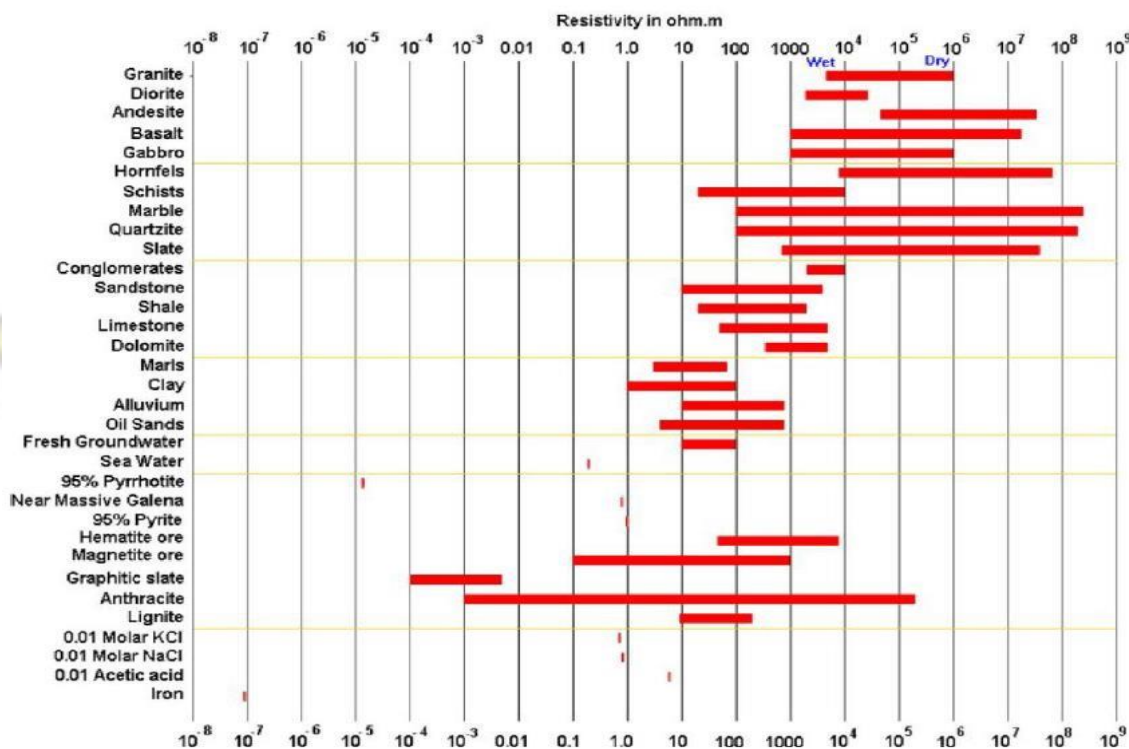


Figure 2.11: Resistivities of rocks, soils and minerals (Loke, 2012)

mathematically (known as the Archie's law) between rock resistivity and its geological factors. Archie's view is that the resistivity of many rocks is roughly equal to the resistivity of the pore fluids divided by the fractional porosity. Consequently, the law states that resistivity is inversely proportional to fractional porosity raised to a power varying between 1.2 and 1.8 according to the shape of the matrix grains (Milsom, 2003; Telford et al., 1990).

The resistivity of a porous rock varies with the volume and arrangement of the pores and even more with the conductivity and amount of contained water (Telford et al., 1990).

The relationship between rock resistivity and water filling the pores and the volume of the pores as postulated by Archie from empirical evidence is given by:

$$\rho = \frac{a\rho_w}{\phi^m S^n} \quad (2.32)$$

ρ is the effective rock resistivity; which is the combined resistivities of the rock and pore fluids; ρ_w is the resistivity of ground water; ϕ is the porosity or fractional pore volume; S is the volume fraction of pores with water; a , n and m are empirical constants and vary considerably according to the quantities and conductivities of dissolved materials. $n \approx 0$, $1.3 \leq m \leq 2.5$ and $0.5 \leq a \leq 2.5$.

The formation factor (F) which is a function depending only on the properties of the porous medium (ie porosity and pore geometry) is given in terms of only porosity as:

$$F = \frac{a}{\phi^m} \quad (2.33)$$

In terms of resistivities of the formation and pore fluid, it is expressed as:

$$F = \rho\rho_w^{-1} \quad (2.34)$$

2.4 Depth of penetration

The popular opinion regarding homogeneous grounds is that the depth to which current penetrates the subsurface is dependent on the current electrodes spacing- the wider the separation between the current electrodes the deeper the current goes and vice versa. It must be noted, however, that the nature of subsurface layers also wields some influence on the depth of penetration. The combination of these two factors limits practically the depths of penetration attainable by normal resistivity methods because of the difficulty

in laying long lengths of cables and generating sufficient power (Telford et al., 1990; Kearey et al., 2002). Figure 2.12 demonstrates how the depth of current penetration increases with increasing current electrode separation in a homogeneous medium.

It shows from the graph that when the electrode separation, $L = Z$ about 30% of the current flows below Z but when $L = 2Z$ about 50% of it flows below Z . It is therefore clear that as electrode separation increases depth of current penetration also increases.

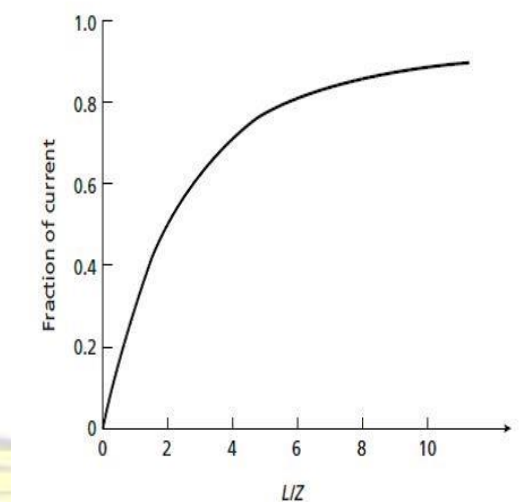


Figure 2.12: The fraction of current flowing below a depth Z for a current electrode separation L (Kearey et al., 2002)

2.5 Modes of Resistivity Measurements

Generally electrical resistivity surveys aim at determining the subsurface variation in resistivity but considering that this physical property may vary both horizontally and vertically, two main techniques have been developed to cater for both instances. These two methods are resistivity profiling or Constant Separation Traversing (CST) or electrical resistivity traversing and the Vertical Electrical Sounding (VES). The former measures the lateral variation in resistivity whereas the latter measures resistivity variation with depth.

The different modes of resistivity measurements are therefore based on the approach adopted when implementing these two techniques. On this premise, the modes of measurements include the conventional resistivity surveys, the computer-controlled multielectrode systems and continuous measurement systems.

2.5.1 Conventional resistivity surveys

The resistivity profiling and vertical electrical sounding are the fundamental resistivity survey types and conventionally have been designed to operate with four electrodes; two current electrodes for injection or transmission of current into the ground and two potential electrodes which measure the potential difference.

The electrical resistivity profiling method (Fig. 2.13) measures the lateral resistivity variations by varying the midpoint of the array while keeping the electrode separation constant. All four electrodes are moved along the entire profile during measurements. The depth of investigation may only vary with subsurface layering since array parameters are constant. The data collected from this survey can be presented as a profile or as a contour map and interpreted qualitatively.

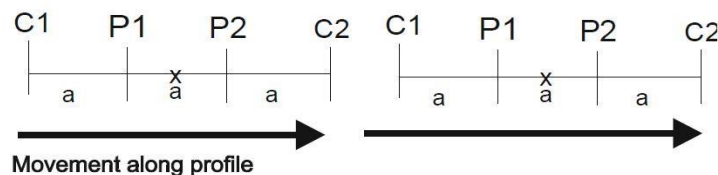


Figure 2.13: Resistivity Profiling

The preferred arrays for resistivity profiling are those that can be easily moved. Based on this the gradient array and the two pole array may be recommended even though these may not give the best resolution (Milsom, 2003).

Conversely, VES (Fig. 2.14) is achieved by systematically increasing the distance between the current electrodes and occasionally the potential electrodes about the

midpoint of the array. Current is driven deeper into the subsurface as electrode separation is increased. Consequently, resistivity variation with depth is obtained. The position of measurement is the midpoint of the profile. The depth of penetration depends on the array type, the resistivity and the nature of subsurface layers. The Wenner and Schlumberger arrays are popular in depth sounding. The data obtained are plotted on a log-log graph or interpreted using computer based interactive modelling.

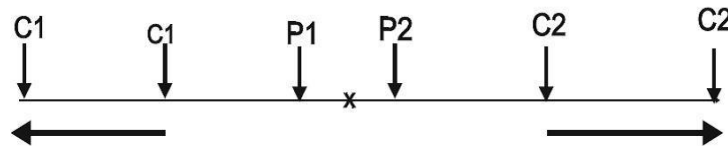


Figure 2.14: VES mode of data collection

Interpretation of VES data suffers from nonuniqueness arising from problems known as equivalence and suppression. The problem of equivalence is indicated by identical bellshaped or basin-shaped resistivity curves for different layered models while suppression is evidenced by the progressive increase or decrease in apparent resistivity with electrode spacing on the resistivity curves (Reynolds, 1997).

Resistivity data may also be collected in a circular pattern using a method called the azimuthal rotation (Fig. 2.15). With this the midpoint of the array or one end of the array is kept in a fixed location while successive apparent resistivity measurements are taken. Like the other two the current and potential electrodes are arranged linearly and the entire array pivoted about the stationary point in increments of 10° to 20° through a complete sweep of 180° or 360° . The spacing between electrodes remains constant. When the complete sweep of 180° or 360° apparent resistivity measurements are taken, the entire electrode array is moved to another stationary pivot point where a new set of azimuthal measurements are made. This method is employed to quantify the directional components of resistivity (resistivity anisotropy) which may provide information on the presence and trends of aligned features in the subsurface. Apparent resistivity

measurements from an azimuthal rotation survey are plotted on a polar coordinate graph.

Generally, the conventional survey methods are time consuming which is one of the reasons why the other modes of resistivity measurements have been developed. A lot of energy is also involved as two or all four electrodes with long spreads of wire attached will have to be moved for every measurement.

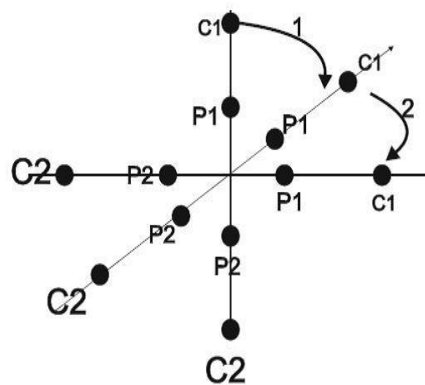


Figure 2.15: Azimuthal rotation

2.5.2 Computer-controlled Multielectrode Systems

This mode of measurement is also called The Electrical Resistivity Tomography (ERT) or the Continuous Vertical Electrical Sounding (CVES) (Fig. 2.16a). It is so called because it uses equally spaced electrodes in several multiples unlike the conventional mode which uses only four electrodes; all connected to a multi-core cable in a straight line. The cable is either connected directly to a resistivity meter or connected to a selector which in turn is connected to the resistivity meter. The resistivity meter then automatically determines the electrode separation and the current and potential pairs of electrodes. The separation between the current and potential electrodes varies depending on the type of array used. By this apparent resistivities are measured using a range of different electrode separations and midpoints. The desire for high resolution subsurface resistivity

information in 2-D and 3-D in most geophysical applications of late necessitated the development of a method which would combine both profiling and sounding techniques. The ERT or CVES thus provides a solution since it combines both lateral and vertical resistivity variations in one measurement and produces images in either 2-D or 3-D depending on how the data is acquired.

This method allows noisy data to be identified and removed and apparent resistivity values are normally presented in pictorial form using pseudo sections. This gives ap-

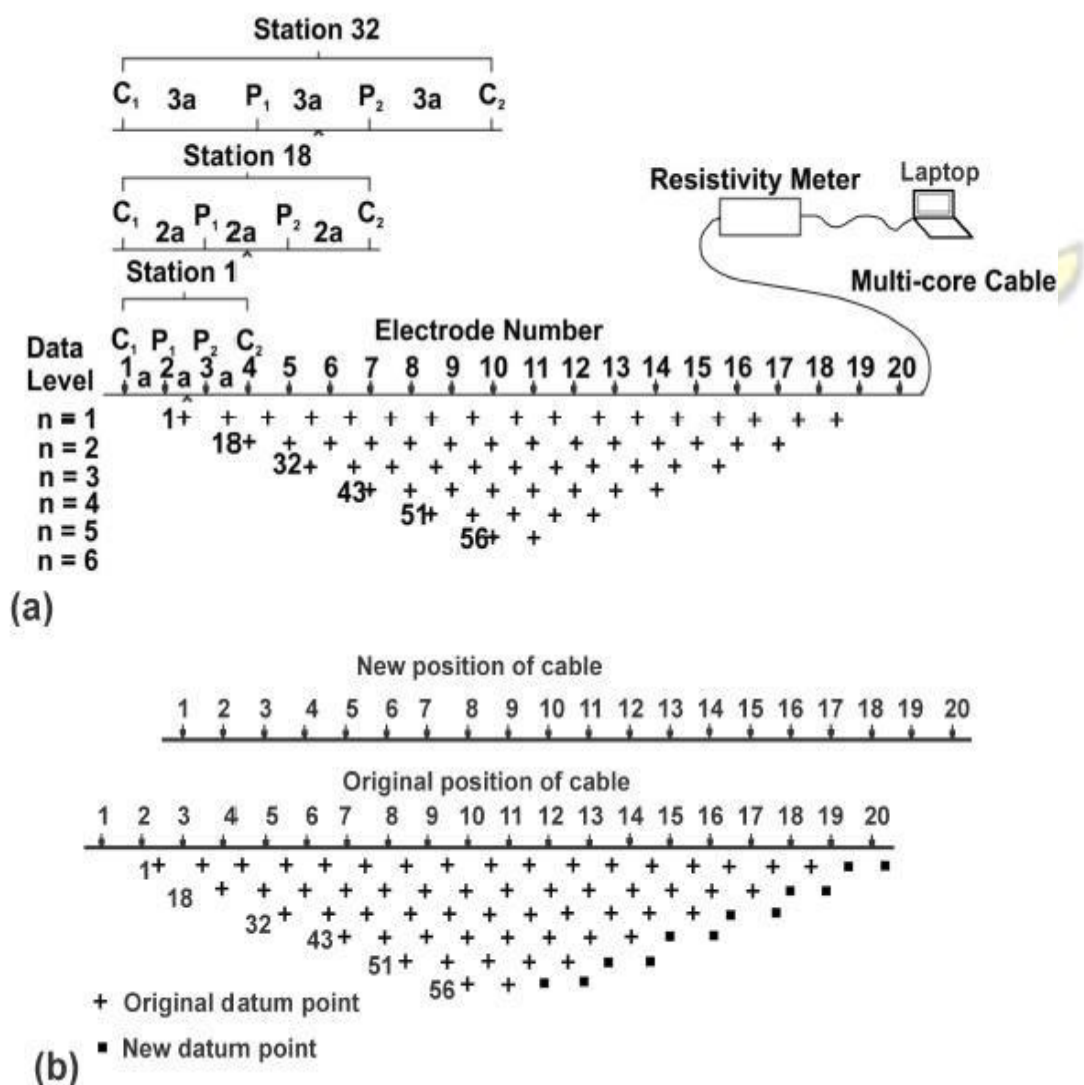


Figure 2.16: (a) Arrangement of electrodes for 2-D electrical survey and the sequence of measurements used to build up a pseudo section. (b) Roll-along technique

proximate pictures of subsurface resistivity distribution. Depending on the array used pseudo section contours may vary in shape. Data analysis and quantitative data interpretation are done using the model sections. ERT surveys can be done using different electrode configurations such as the gradient, Schlumberger, dipole-dipole, Wenner and square arrays.

If for a particular ERT survey, the profile line is longer than the available cables and electrodes can cover, a technique known as roll-along (Fig. 2.16b) is deployed to do the job. This is done by moving a cable past one end of the line by several units of electrode spacing after the first set of measurements. Because the number of data to be collected is less as a consequence of data overlap and only data which do not overlap are measured, measurements are usually faster for roll-along stations than the first station.

This study was carried out combining CVES and the roll-along techniques.

Even though faster than the conventional mode the ERT is also slower than the continuous measurement systems. Because of its quite time consuming factor, there might be the temptation to reduce the data density in order to save expensive field operation time which may adversely affect the quality of resistivity images.

2.5.3 Continuous Measurement Systems

Noticing that the CVES was only an improvement on the conventional surveys and not a remedy to the time consuming problem of these surveys, the continuous systems were developed. These which are devoid of planting electrodes and pulling them out at some points and replanting are faster than the two methods discussed above. Based on the manner in which current is supplied to the ground, the continuous resistivity techniques

can be divided into two types: one adopts the capacitive-coupling approach and the other the galvanic contact approach.

With galvanic contact resistivity, the electrodes are in direct contact with the ground and there is a direct transfer of current between the electrodes and the soil. Resistivity measurements are made continuously by a computer mounted on a truck and moved along the profile line.

The capacitive-coupling approach allows currents coming from electric fields within insulated conductors to flow in the ground without direct contact. Resistivity can then be measured continuously since the aeriels are dragged along the ground. This can be done either mechanically or manually (Milsom, 2003).

2.6 Data Processing

A number of software exist and several others being tested for the processing of resistivity data but popular among them are the RES2DINV and RES3DINV. The RES2DINV and RES3DINV are computer programs that automatically determine respectively the 2D and 3D resistivity models of the data obtained. They do this by inversion of the data. Inversion is the process of dividing the data into rectangular blocks. The blocks are tied to the distribution of the data and the depth of the blocks is equal to the depth of investigation. In alternative terms, inversion reconstructs the subsurface resistivity distribution based on a measured apparent resistivity pseudosection. The inversion is made possible with the Gauss-Newton least squares equation which allows the model resistivity values to change in a smooth and gradual manner. The Gauss-Newton least squares equation is shown below.

$$(J^T J + \lambda F) \Delta q_k = J^T g - \lambda F(q_{k-1} - q_0) \quad (2.35)$$

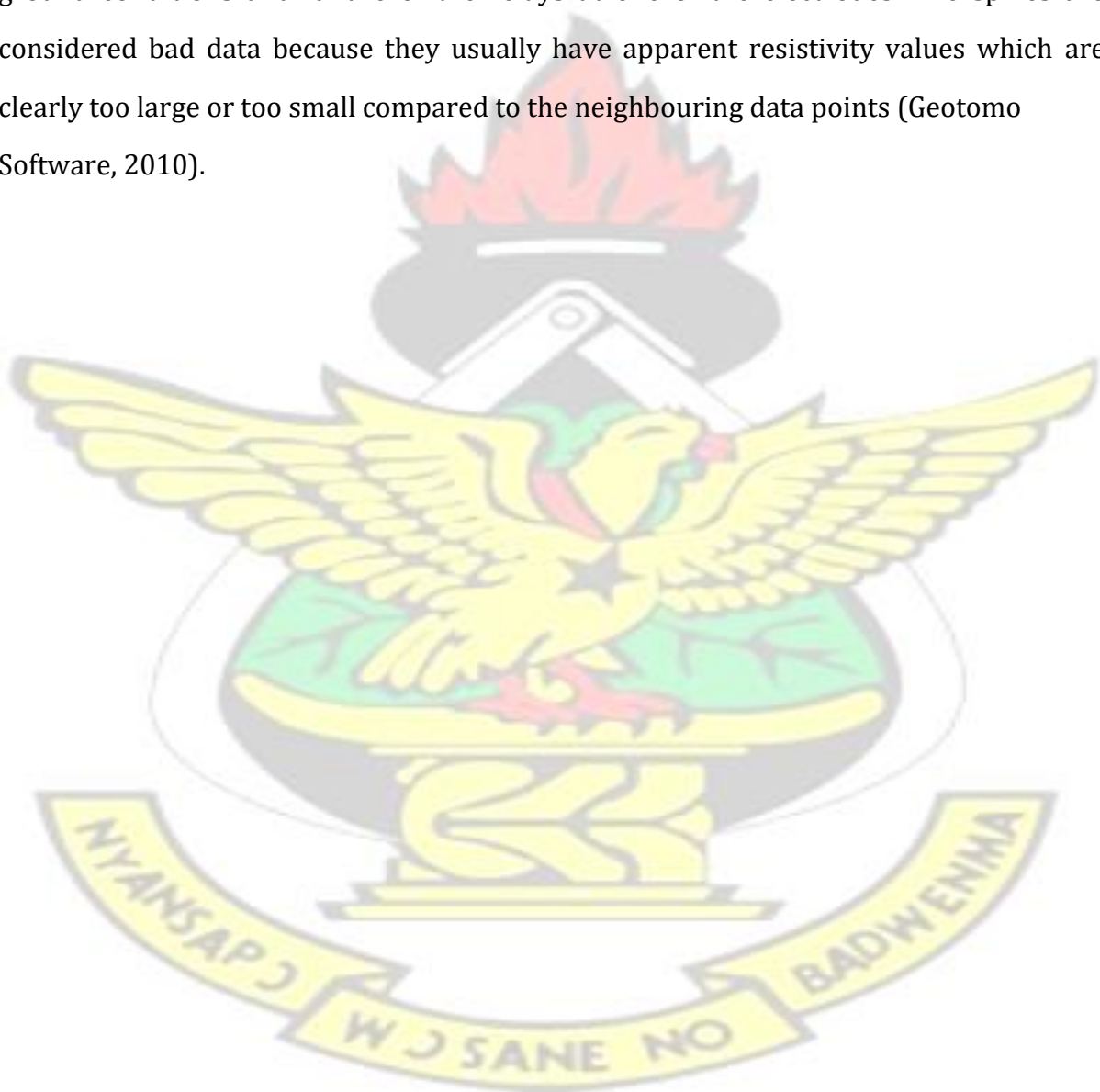
where

$$F = \alpha_x C_x^T C_x + \alpha_y C_y^T C_y + \alpha_z C_z^T C_z \quad (2.36)$$

Δq_k is the change in model parameters for iteration k, q_{k-1} is the model parameter vector (the logarithms of the model resistivity values) at the iteration k-1, q_0 is a homogeneous half space reference model. g is the discrepancy vector (the difference between the logarithms of the measured and calculated apparent resistivity values). J is an $m \times n$ Jacobian matrix of partial derivatives. C_x, C_y and C_z are the smoothing matrices in the x-, y-

and z-directions. α_x , α_y and α_z are the relative weights given to the smoothness filters in the x-, y- and z-directions (Loke, 2012). These software usually work with a device called dongle connected to the computer.

The inversion process is, however, preceded by editing of the data. Bad data points which often occur as spikes are exterminated from the data. Spikes may result from poor electrode-ground contact due to dry soil, or shorting across the cables due to very wet ground conditions and failure of the relays at one of the electrodes. The spikes are considered bad data because they usually have apparent resistivity values which are clearly too large or too small compared to the neighbouring data points (Geotomo Software, 2010).



Chapter 3

MATERIALS AND METHODS

3.1 Project Site Description

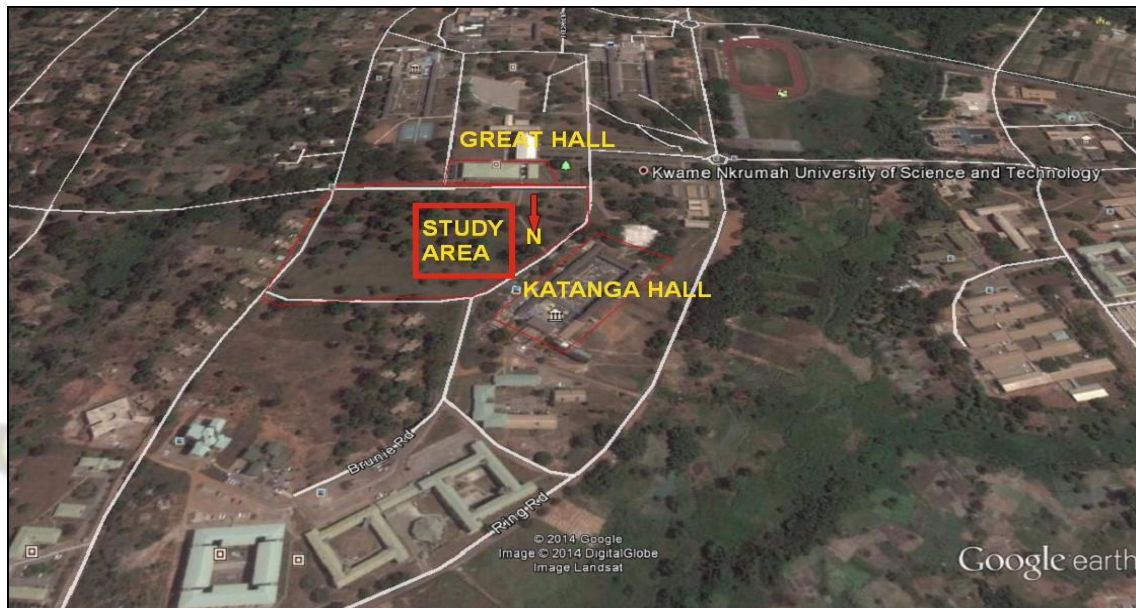


Figure 3.1: Map of the Study area

The research area (Fig. 3.1) is located on the KNUST campus and bounded by the Great Hall, the University Hall (Katanga), the main Administration Block and some bungalows for lecturers. It is a nearly flat ground and largely inhabited by tall trees and grasses. The part of it close to the Great Hall serves as a car park to visitors and some staff. Even though there are no signs of burials in the place, history has it that it was used as a cemetery before the inception of the school. That was over sixty years ago.

Only a $100 \times 100 \text{ m}^2$ plot of this parcel of land was investigated. It is centered on latitude $6^{\circ}41'07.68''\text{N}$ and longitude $1^{\circ}43'06.28''\text{W}$.



Figure 3.2: Different sections of the project site

3.1.1 Geology of the Study Area

The Kumasi Metropolitan area of which KNUST is part is dominated by the middle Precambrian rocks and forms part of Eburnean Plutonic Suite (Fig. 3.3). These were formed approximately within the upper and lower ages of 2.172 and 2.116 million years ago. The Precambrian rocks and the Eburnean plutonic suite are also composed mainly of biotite (+/- hornblende), granite and minor granodiorite and K-feldspar porphyritic.

There are Birimian sequences in the area characterised by a transition in the sedimentary facies from the central part of the basin to the margins. Sediments deposited in the central part consist of a thick sequence of dark grey to black argillites that are interbedded with subordinate siliciclastic metasediments. The argillites grade laterally or horizontally away from the centre of the basin into a thick sequence of interbedded

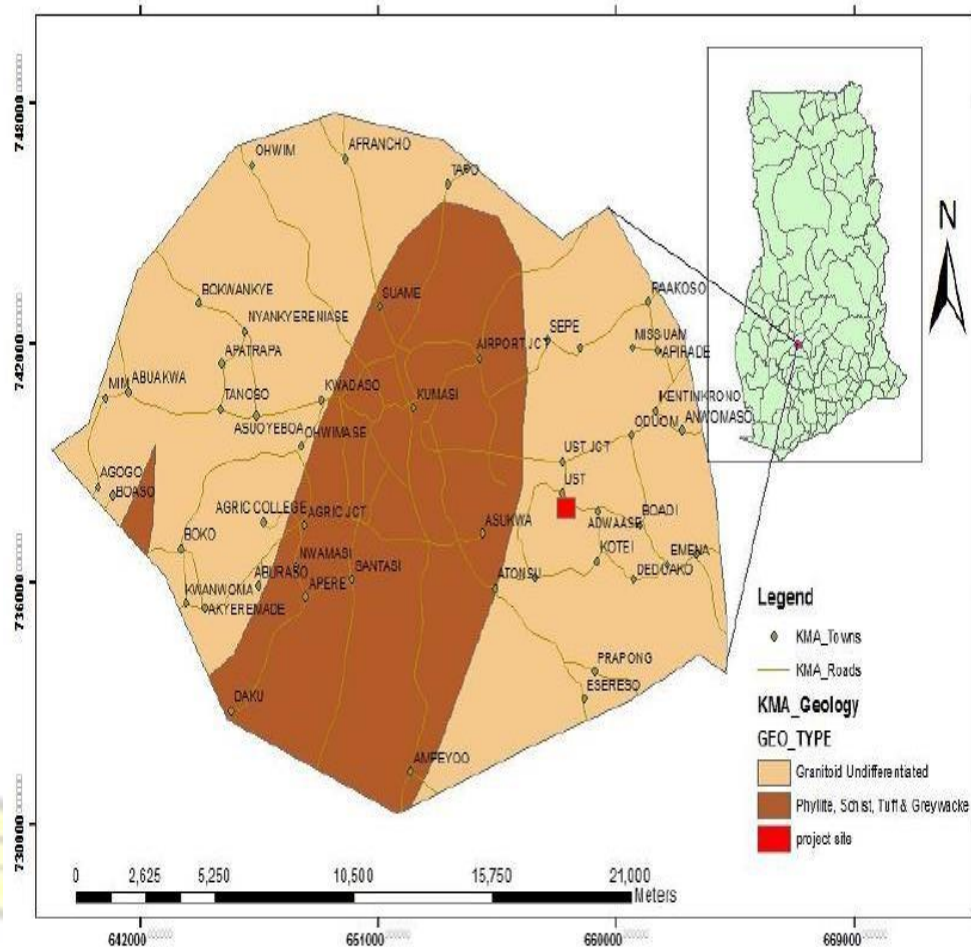


Figure 3.3: Geological map of the Kumasi Metropolis showing the study area in red (Ghana Geological Survey , 2009)

argillite/volcaniclastic units and to volcaniclastics interbedded with subordinate argillites, tuffs and volcanics. A narrow belt (up to 3 km wide) underlain by interbedded volcaniclastic and coarse arenaceous sediments such as wackes, arkose, conglomerates, quartzite etc also occurs (Moon, 1962). These clastic and volcaniclastic units feature high radiometric potassium (K) levels and appear to be somewhat distinctive from most of the typical interbedded volcaniclastic and marine sedimentary units as well as the Tarkwaian clastic sediments (Griffis, 1998). According to Kesse (1969, 1972), the Kumasi granitoid complex dominates much of the basin area and contains large roof pendants of metasedimentary schists. This is a basin-type granitoid massive intrusive complex and

ranges in composition from intermediate (granodiorite/tonalite) to more felsic (granite) phases. The construction industry in the metropolis has come to stay because of the existence of the Precambrian rocks.

The geology of the study area is mainly granitoid undifferentiated.

3.1.2 Major Soil Types

Obeng (2000) identifies the major climatic differences as the factors responsible for the classification of soils in Ghana. These also account for the two major vegetation belts forest and savannah- in the country. The major soil type in the forest belt to which the Kumasi metropolis belongs is the ochrosol. This type of soil has high concentration of organic matter in the surface horizon due to the abundant leaf-fall from vegetation cover and also as a result of the slow oxidation of humus. These have strongly leached lower horizons. Weathering products of metamorphosed and basic intrusive rock, mainly, granites, phyllites, quartzites, sandstones, epidiorites, greenstones, basalt and upper birimian phyllites are the principal components of this type of soil. Forest ochrosols are red, brown and yellowish brown, to imperfectly drained soils occurring on summits, upper, middle and lower slopes.

3.1.3 Location and Accessibility

The KNUST campus is characterised by a perfect network of tarred roads and directional boards. Consequently these will help in smoothly locating the study area between the Great Hall and the University Hall (Katanga). Specifically the study area is bounded by a pavement that leads to the Katanga hall from the Great hall, a road that runs from campus through the Great hall to Ahinsan (a suburb of Kumasi) and some lecturers' bungalows. It is also separated from the main Administration Block of the University by a road that passes by Katanga Hall from campus.

Generally, all towns and villages within the Kumasi metropolis have a good network of both tarred and untarred roads making it easier for people to travel around the metropolis and even beyond. It is therefore easier accessing the study area irrespective of a person's location.

3.1.4 Physiography

The Kumasi metropolis is described by dissected plateau, probably representing a mid to late tertiary peneplain with elevations in the range 225 to 300 m above mean sea level. Also in the metropolis are a number of rounded and flat-topped hills that crest at elevations of 400 to 460 m above sea level. These appear to represent mid to early tertiary regional erosional surfaces (Griffis et al., 2002). It is largely occupied by secondary forest and cultivated farms due to the relatively dense population. The site under study (Fig. 3.2) is considered relatively flat because of insignificant topographic changes.

3.2 The ABEM LUND Imaging System



Figure 3.4: The ABEM LUND Imaging System

The ABEM Lund Imaging system (Fig. 3.4) consists of terrameter SAS4000, an electrode selector and four drums of cables. The set up for any geoelectrical survey also includes a battery, metal electrodes, tape measures, hammers, connectors and cable jumpers.

It is an automatic electric imaging system specially designed for electrical resistivity surveys. It is capable of collecting data in both profiling and sounding modes. Other electrical survey methods such as induced polarization and self-potential can also be conducted using the ABEM LUND imaging system.

3.3 Data Acquisition

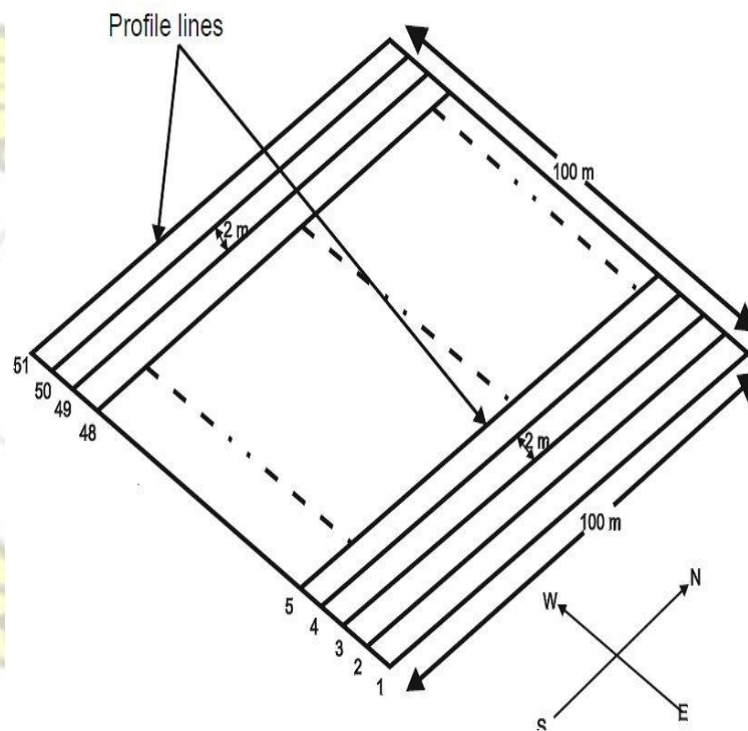


Figure 3.5: Layout of survey area indicating profile lines

The data were obtained using the computer-controlled multi-electrode system or the

Continuous Vertical Electrical Sounding (CVES) together with the roll-along technique (Fig. 2.16) since the cables and electrodes available could not cover the entire profile length. The entire data acquisition period lasted for fifteen (15) working days; running from the 8th to the 28th of October 2014. A 100 × 100 m² plot of land (Fig. 3.5) was surveyed producing a total of 51 profile lines since the inter-profile spacing was 2 m. The profile lines were oriented south-north.

The data acquisition was however preceded by a reconnaissance survey during which the study area was demarcated and profile lines marked with pegs totalling 102. The plot was carefully chosen so as to eschew interference from visitors and some staff who parked their vehicles on the part of the study area close to the road and yet meet the survey objectives. Permission was also sought from the unit taking care of the place. The necessary protocols were also decided at this stage based on the objectives of the survey.

3.3.1 Resistivity Data Acquisition with the ABEM Terrameter

Computer-controlled multi-electrode system or CVES and the roll-along techniques were combined in this study for the collection of the resistivity data. The gradient array was used. Since the survey area was a 100×100 m² plot each profile line was 100 m long and the inter-profile spacing was 2 m. The resistivity data collection therefore began with laying of tapes along the profile lines up to 100 m. Metal electrodes were then planted on the ground with the help of hammers at equal intervals of 2 m up to 60 m of the profile. This was followed by the laying of three cables, each 20 m long. With the help of jumpers, the electrodes were connected to the cables at the red take out positions. Each cable has twenty-one (21) take outs which are 1 m apart with alternating colours of red and blue. This means that any two closest take outs with the same colour are 2 m apart and have as their midpoint a take out of the other colour. Where necessary, cables were joined together with connectors and the entire set up connected to a selector which was also connected to the terrameter. A 12 V car battery was then connected to the terrameter to

make current flow through the ground when the terrameter was turned on and put in measurement mode. The selector automatically chooses the current and potential electrodes.



Figure 3.6: Data acquisition with the ABEM Terrameter on different profiles

When all the connections were done, the protocols were set. For this survey the gradient array was used taking into consideration the Grad4L8 and Grad4S8 protocols. At each station, the long measurements (Grad4L8) were taken first followed by the short (Grad4S8) which was to supplement the Grad4L8 data. The amount of current passed into the ground was 100 mA and the minimum electrode spacing was 1 m. The minimum and maximum numbers of stacks were respectively 2 and 4. The machine was instructed to wait between protocols.

Following the setting of the protocols as well as the other parameters, the terrameter was made to begin resistivity measurements first with the Grad4L8 which covered a length of 60 m and subsequently with the Grad4S8 which covered a length of 40 m when

the terrameter was placed at the 20 m spot. This was considered to be the centre of the first spread assuming that there was a 20 m cable with electrodes before the point where each profile began but were skipped. Measurements, however, did not begin until after the electrode check was done to ensure that all the electrodes were connected and working properly. While the Grad4L8 measurements were being taken; electrodes were planted and connected to the blue take outs up to 40 m for the first spread. This was for the Grad4S8 measurements. After this a fourth cable (also 20 m long) was layed which therefore covered up to 80 m of the profile and electrodes again planted first at intervals of 2 m and connected to the red take outs. When both measurements were done for the first 60 m, this last cable was connected to the first three via a connector and the terrameter was moved to the 40 m spot where the next set of measurements was taken. The Grad4L8 measured from 0 to 80 m and the Grad4S8 from 20 to 60 m. when the long measurements (Grad4L8) were done and the short (Grad4S8) being taken, the first cable was removed and connected at the last 20 m of the profile (that is from 80 m to 100 m). Same connections as those in the previous cases were followed. The centre of measurement was then moved to the 60 m spot and the next set of measurements taken. The long measurements ran from 20 to 100 m and the short from 40 to 80 m in this case.

Following these measurements one of the cables was removed and the last three were used for the final measurements on the first profile. Here it was also assumed that there was another cable with electrodes after the 100 m mark which were also skipped. Measurements were taken at the 80 m spot with the long covering 40 m to 100 m and the short 60 m to 100 m.

All the measurements were conducted from the south to the north. That is the profile lines ran from south to north (Fig. 3.5). The procedure described above was carried out on all 51 profile lines. The methods used in this study allowed both lateral and vertical apparent resistivity variations to be measured simultaneously.

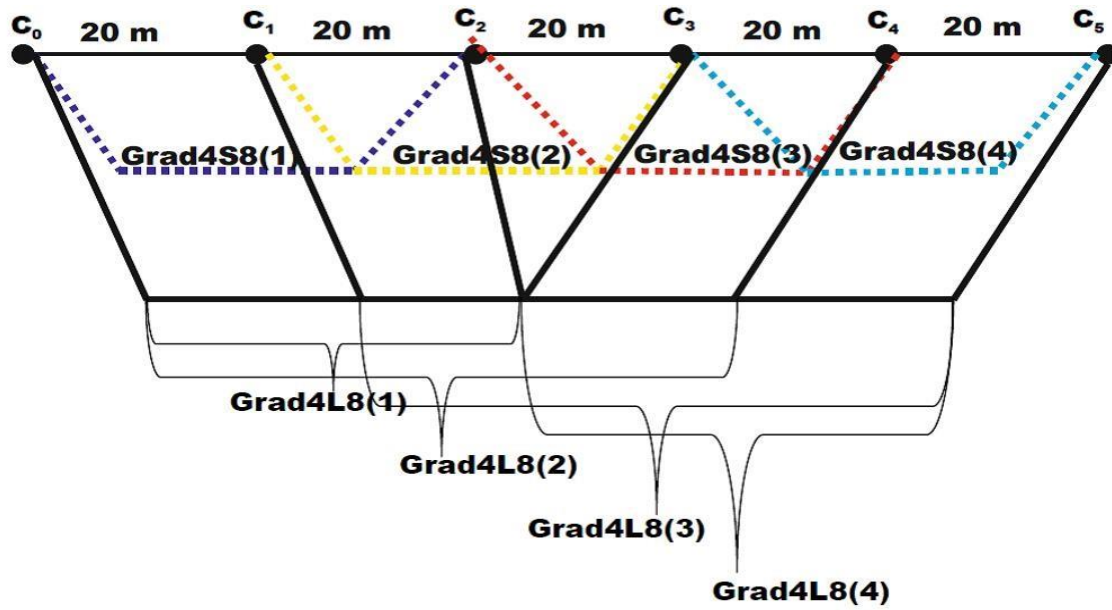


Figure 3.7: Illustration of the data acquisition process: C1, C2, C3 and C4 are the measurement positions.

3.4 Field Data Processing

Usually the data obtained from the field are apparent resistivity values and must therefore be converted to the true resistivity whose variation in the subsurface is being sought.

This conversion from apparent resistivity to true resistivity is made possible with the RES2DINV software. Since the data were collected in 2D, they were first processed with the RES2DINV and later converted to 3D using the RES3DINV.

3.4.1 2D Data Processing

Data processing with the RES2DINV was carried out by first reading into the software the field data and editing the data by exterminating bad data points which usually occur as spikes.

The edited data were reread into the software and the L2-norm inversion was commenced. Under inversion, model discretization was chosen followed by model

refinement where the option 'use models with half electrode spacing' was applied. This option checks

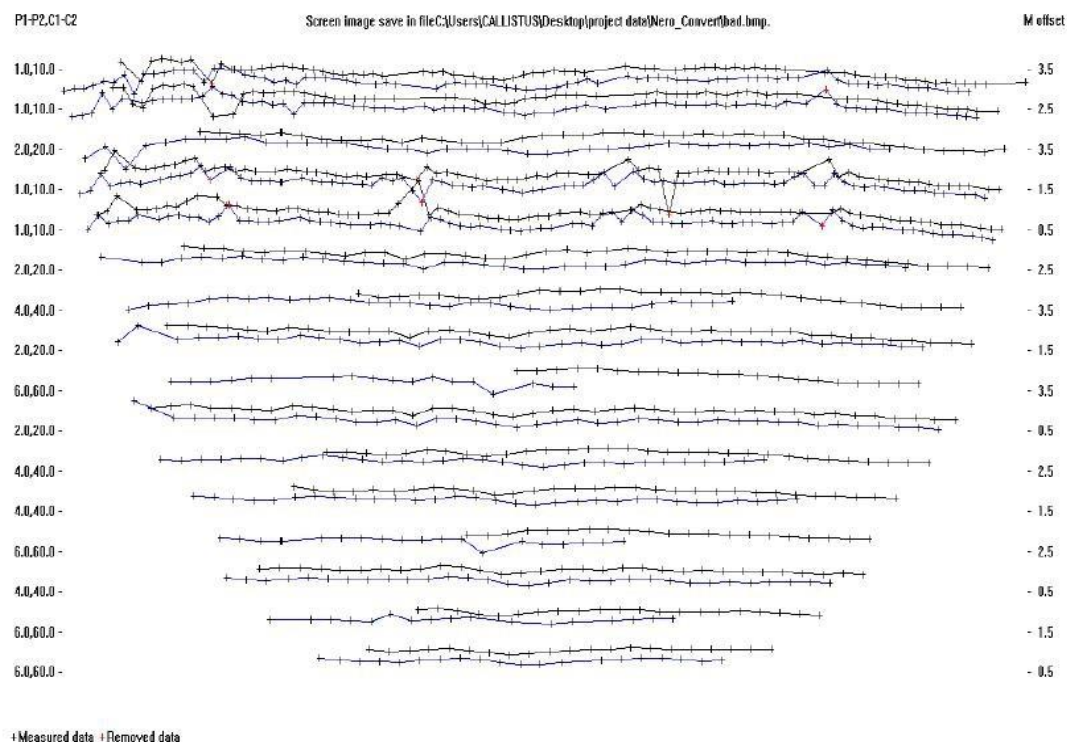


Figure 3.8: Pseudo section showing bad data points (spikes)

large surface resistivity variations which was the case with this data. The inversion results were then displayed after a number of iterations were done. Following this the data and model sections were also displayed using the user defined logarithmic contour intervals option. This last step produces even contour values and spacing on the resistivity models for all the profile lines so that they could be easily compared.

3.4.2 3D Data Processing

The interest was also to image the subsurface in 3D which involved converting the 2D data into 3D. A script of the edited 2D data line parameters was compiled. The line parameters included the name of a file, its location, the first electrode position on each line and direction of the profile line as well as the polarity of the line. The output file was

in RES3DINV format. The script was next collated with the RES2DINV software and read into the RES3DINV software. Inversion began afterwards using the model discretization and the model refinement options. After several iterations, the results were displayed using the user defined logarithmic contour intervals option. The models so obtained are 3D resistivity models.



Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The 2D data were processed and inverted into resistivity models showing the vertical and lateral distribution of subsurface resistivity. The 2D data were also collated into 3D and inverted to obtain the 3D models. In both cases the model sections were displayed using the user defined logarithmic contour intervals so that contours with the same resistivity value will have the same colour for easy comparison. The absolute error of inversion ranged between 1.22 and 9.9 % for the 2D models and 3.84 and 4.12 % for the 3D models. The information contained in the model sections will subsequently lead to knowledge of the nature and types of materials comprising the subsurface. The models have also been interpreted in this chapter based on the resistivity variation across the subsurface and the knowledge of the geology.

4.2 2D Resistivity Models

The results indicated a wide variation of subsurface resistivity ranging from 9.34 to 1196 Ωm in all the profiles. At a depth of about 1 m down the subsurface a high lateral variation in resistivity was observed suggesting either a disturbance of the near subsurface, variations in soil moisture, variations in electrode-ground coupling or a combination of these. But the resistivities at this depth fall between 37.4 and 299 Ωm in most profiles which may be as a result of a mixture of topsoil and gravel caused by digging (probably graves) and refilling activities. Generally, subsurface materials further down the earth had higher resistivities than those at the near surface as expected. Some anomalies were also observed at depths beyond 1 m. These were either structures of high

resistivity within materials of lower and uniform resistivity or structures of low resistivity within materials of higher and uniform resistivity. These resistivity anomalies are indicative of the properties of subsurface materials.

It is known that open, dry voids or cavities and fractures are highly resistant to electric current because of the dielectric property of the air filling the vacuum. Intact or compact rocks also exhibit high electrical resistivity. However, cavities and fractures may be conductive or less resistant to electric current if they are moist or filled with water because of the presence of ions in water. The presence of a conductive substance other than water in a cavity can also cause lower resistivities in such structures.

With regard to graves, it is generally recommended that graves should be 6 ft deep which is about 1.83 m but some people may dig deeper or shallower for various reasons. While this is very likely in our part of the world where most people don't use any standard measuring instruments but their discretion when digging graves, for reasons of grave looting some people especially royals and the rich who often bury their dead with expensive ornaments may dig their graves deeper. Outrageously bigger coffins may also require deeper and wider graves than the standard dimensions. On the other hand, extremely hard ground and limited time may result in graves shallower than 6 ft. Besides the tumuli that is often used to cover graves adds an extra layer and so makes graves deeper than 6 ft if surveyed from the surface of the earth. It is thus not to be expected in this study that all graves must fall within 6 ft; they may be deeper, shallower or within the required limits. According to the International Cremation, Cemetery and Funeral Association, a standard grave has a length of 8 ft (2.44 m) and a width of 2.5 ft (0.76 m). A standard coffin has height, length and width of 23 in (0.58 m), 84 in (2.13 m) and 28 in (0.71 m) respectively.

Also deserving consideration in this analysis are the geology of the study area and the period within which the place ceased to be used as a cemetery. Though the geology may be of little significance as far as the objectives of this research are concerned, knowledge of it will help explain some of the resistivity anomalies observed. In this regard the

geology of the study area is largely granitoid undifferentiated which may be less conductive suggesting that highly conductive anomalies may stem from other factors than geological.

On the latter factor, it is expected that no burials would have taken place in the study area since the inception of the school (from the Kumasi College of Technology to KNUST). Therefore a lot including deposition of new sedimentary strata would have happened from 1951 to now due to human activities. Consequently graves or tombs could also be located at deeper depths than 6 ft.

Now considering all of the aforementioned factors in the analysis of the resistivity models, the geometries of the resistivity anomalies, the depths at which they occurred, their dimensions, the history of the study area and importantly the resistivity contrast with the background materials qualify some of these anomalies as tombs or graves. Others may be voids caused by the burrowing of the subsurface by certain organisms. The resistivity models below will thus be discussed in line with these factors.

The features or structures labelled 'A' in figure 4.1 are possible tombs or graves partly due to the sharp contrast in resistivity from the background materials. These anomalies have resistivities $\geq 600 \Omega\text{m}$ against background resistivities of $598 \Omega\text{m}$ and below. Being a royal cemetery, these high resistivity anomalies may be tombs that were built with bricks or even cement. Such tombs may have some slabs over them which could be responsible for the high resistivities. Burials done with coffins may also show high electrical resistance than the surrounding geology if the coffins are not completely decomposed. A partially collapsed coffin could result in air-filled voids in the grave which will also be seen as a highly resistive anomaly because of the dielectric properties of air.

The marked anomalies in figure 4.1 are most likely tombs because of their rectangular

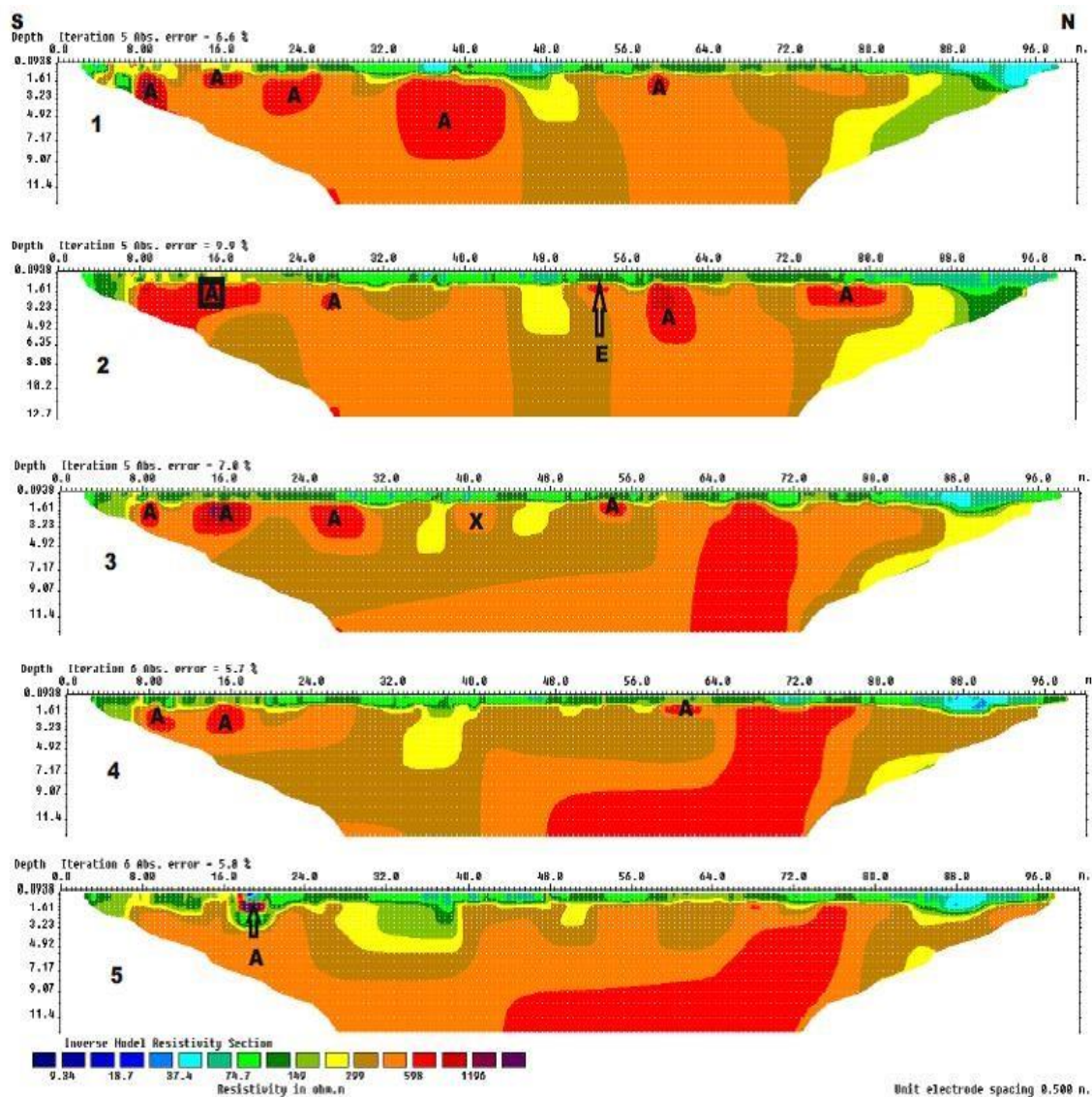


Figure 4.1: 2D Resistivity models of Profiles 1 to 5

shapes and depths of occurrence. Most of them are located within the first 3 m of the subsurface and a few at deeper depths. It is possible to have tombs at deeper depths than 3 m since additional sedimentary layers could be deposited on the tombs after such a long time. They had dimensions ranging from 3 m × 2 m to 10 m × 6 m. Grave dimensions may deviate from normal because social classes still persist even at death. The rich may want their graves and coffins deeper and larger because of the size of the coffins and the materials that accompany the dead. The anomaly that is 10 m long and

6 m wide appears too big for a grave nonetheless, it could still be one taking a cue from Butler's (2008) assertion that the dimensions of anomalies due to cavities may be larger by a factor of 2 than the actual size of the cavity. It could also be a double grave. The anomaly labelled E seems to be an extension of the anomaly between 48 m and 56 m of profile 3 since the two are directly opposite. Besides the profile lines are 2 m apart and the anomaly is about 3 m long and 2.5 m wide. This anomaly is therefore thought of as a tomb oriented parallel to the profile lines with a small portion of it extending into profile 2.

The 'X' anomaly is probably a grave with totally decomposed content. It may, however, contain a few air-filled pores which account for its slightly higher resistivity than the background material.

Figure 4.2 has highly resistive anomalies ($\geq 1196 \Omega\text{m}$) labelled 'B', low resistivity anomalies ($\leq 37.4 \Omega\text{m}$) labelled 'C' and the other anomalies denoted 'F'. The 'B' and 'C' anomalies are possible tombs or graves with the former being probably dry and empty and the latter probably filled with water or some other conductive substance presumably secretions from the decomposed buried remains. These, when they mix up with the soil can increase its conductivity because of the salt and chemicals in humans. While the 'B' anomalies may also be grave stones, the 'C' anomalies may be partially filled graves which are porous and saturated resulting in the low resistivity. Burials in the 'C' anomalies may have been done without coffins. All of them are located within the first 4 m of the subsurface and have geometries and dimensions similar to graves. The anomalies labelled 'F' may be dry and possibly hardpan. The dimensions of these structures especially the widths are lower than the standard width of a coffin or grave. Their higher resistivities could also imply that they are cracks filled with air coming from the surface of the earth since they are not too far from the surface. Human activities such as digging could result in cracks in some parts of the subsurface which can expand with time due to the movement of water and activities by subsurface organisms. Such a structure, if dry and air filled, can show high resistance to current. Large high resistivity regions ($\geq 1196 \Omega\text{m}$)

observed at depths 5 m and beyond (Fig. 4.2) could be dykes because of their resistivity and geometry. One is located between 76 m and 83 m of profile 7 and extends to profile

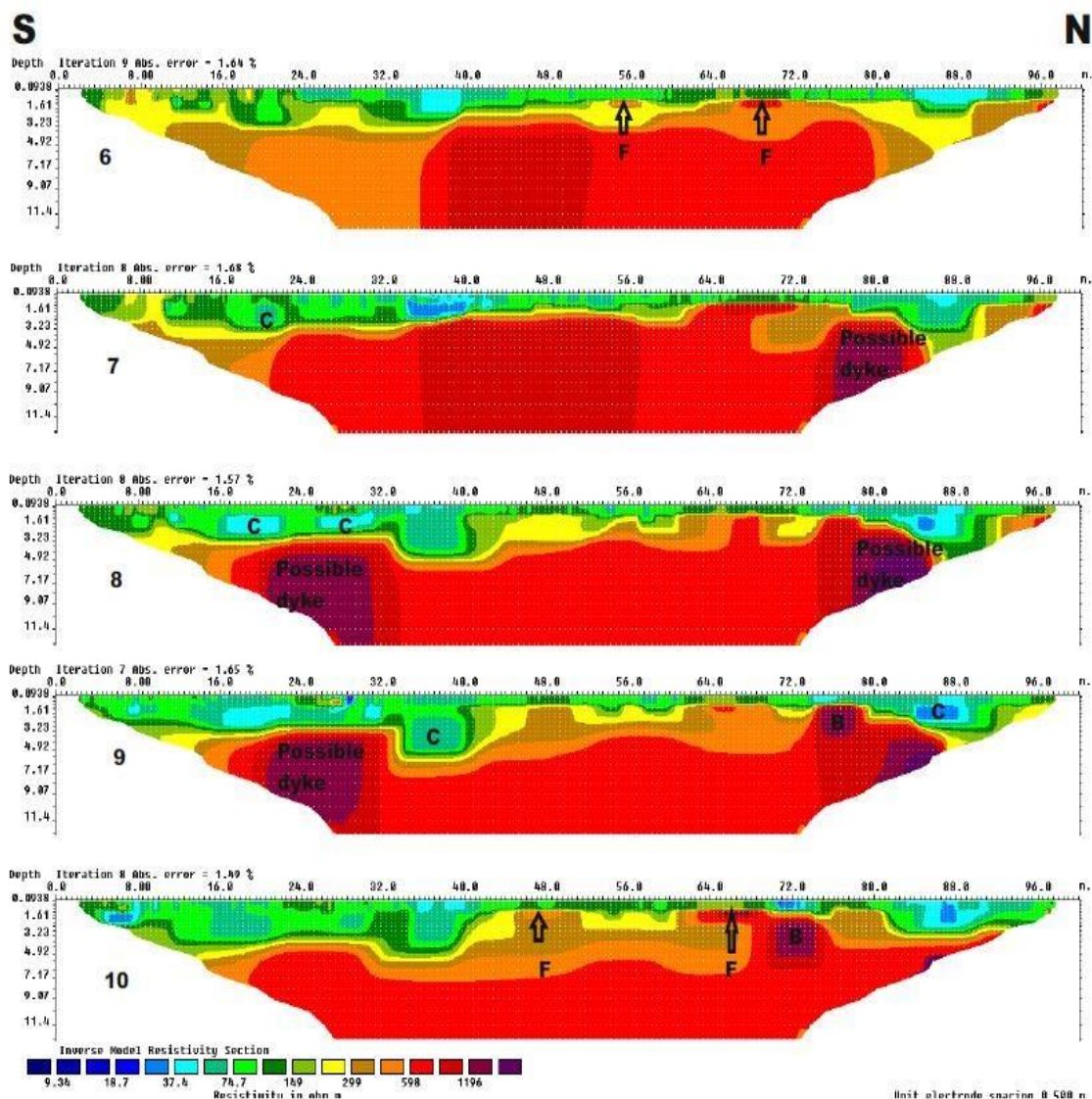


Figure 4.2: 2D Resistivity models of Profiles 6 to 10

9. Another one is observed to extend from profiles 8 to 9. Such an igneous intrusion, typical of igneous rocks, is highly resistive.

The anomalies marked T and G in figure 4.3 with resistivities $\geq 299\Omega\text{m}$ could be tombs which are gradually filling up. These tombs may have collapsed and have sediments fallen into them but not consolidated. Consequently they may have high porosities but contain

little or no water which accounts for their moderate resistivities. These may also be burials without coffins. Similarly the anomalies (labelled C) in the same figure may also

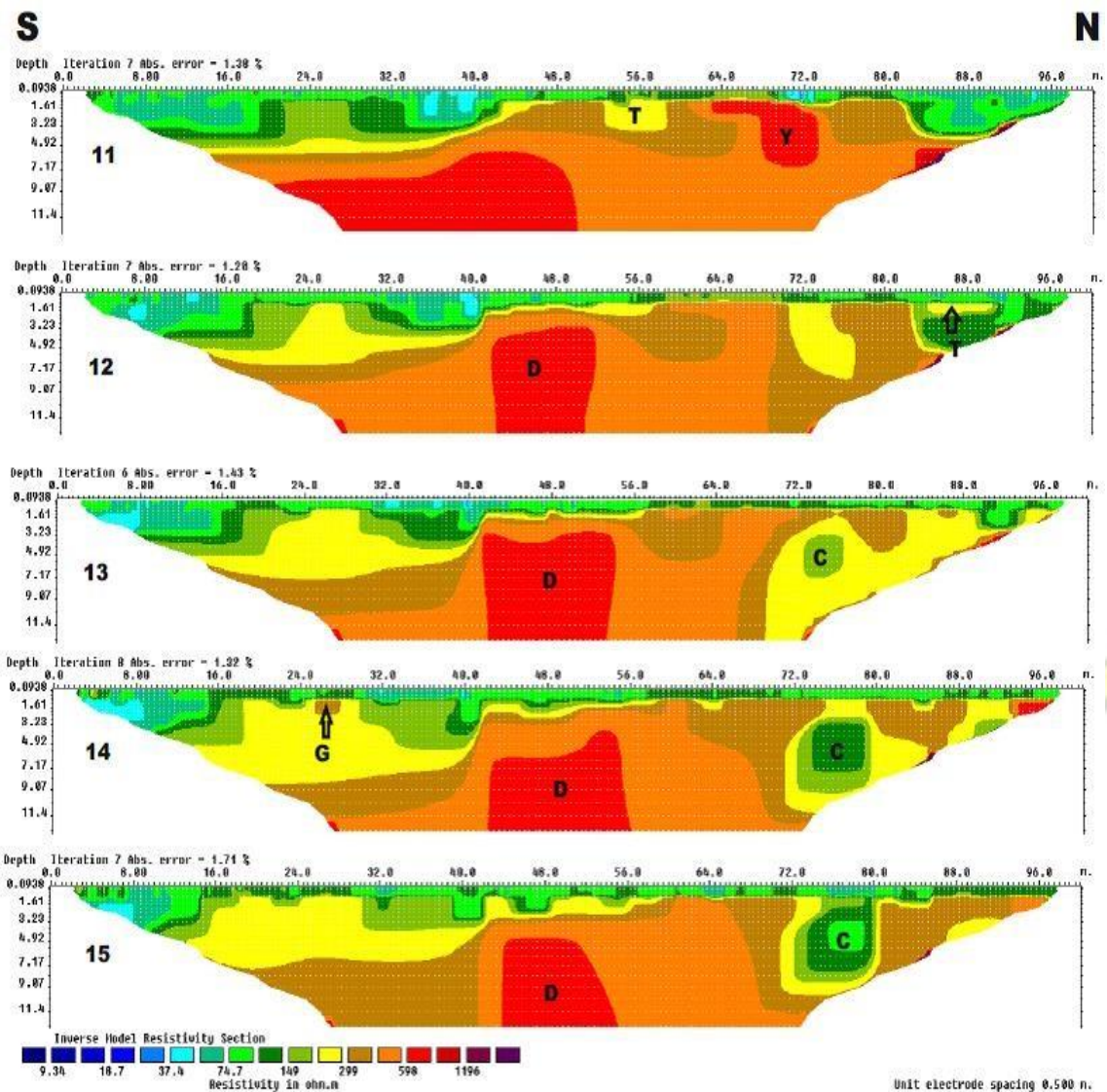


Figure 4.3: 2D Resistivity models of Profiles 11 to 15

be tombs but these are more conductive. Their conductivities are most likely influenced by underground fluids or rain water and fluids from decomposed buried bodies. Two of such conductive anomalies appeared between 72 and 80 m of both profiles 14 and 15 suggesting either a tomb that is perpendicular to the profile lines or two separate tombs directly opposite each other and parallel to the profile lines. The anomaly marked 'Y'

could possibly be a tomb and the extension up to 64 m could be a hardpan. Such a tomb might be dry and contain probably only air. The high resistivity anomalies labelled 'D' from profiles 12 to 15 appear to be a large rock running across all four profiles. This might be the unweathered bedrock (granite).

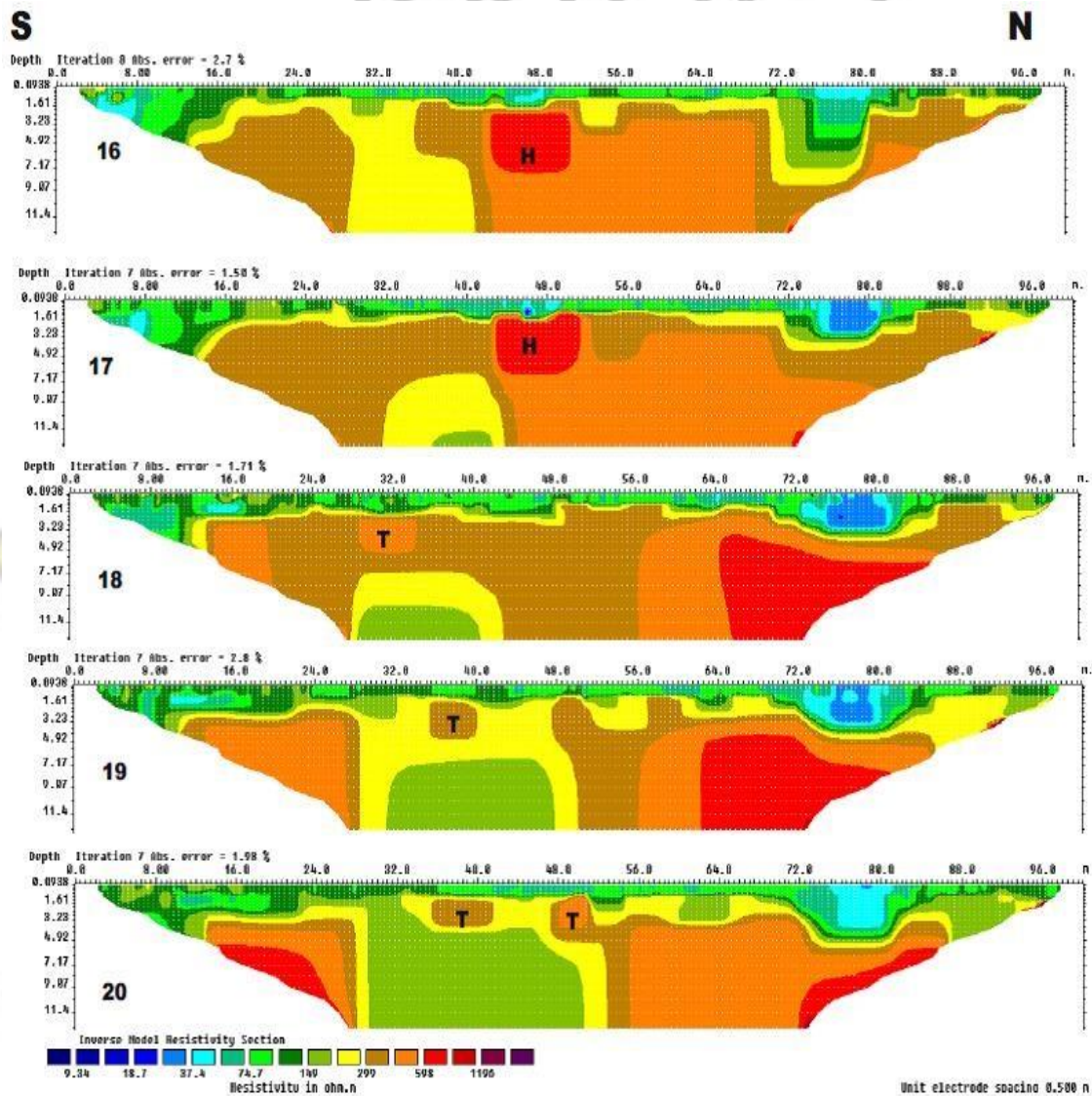


Figure 4.4: 2D Resistivity models of Profiles 16 to 20

High resistivity anomalies (indicated H) in relatively low resistivity backgrounds in figure 4.4 may be tombs or graves. Located about 4 m below the earth's surface, these are likely to be two separate tombs lying along the profile lines per their geometry and

dimensions. These may also have a hard material probably a hardpan resulting in the high resistivity. As discussed earlier the presence of air-filled voids in the grave could also give high resistivity values because of the dielectricity of air. The arrangement of these anomalies further serves as evidence since most cemeteries have this linear arrangement of tombs. Their rectangular shapes and dimensions further prove this point.

Anomalies marked 'T' and observed to exist in relatively low resistivity backgrounds may have resulted from loosely packed sediments in graves yet filling up. These may be dry or slightly moist which is the cause of the moderate resistivities of these structures. Most of them are around 5 m × 3 m in size and rectangular in shape which to some extent confirm these structures as tombs. These may be naked burials and are totally decomposed.

The 'K' anomalies in relatively low resistivity backgrounds in figure 4.5 may be tombs. Again these may be tombs comprising loosely packed sediments which are dry or only slightly moist and so are able to exhibit neither complete conductivity nor complete resistivity. The other anomalies in this figure are labelled 'J'. These have very low resistivities (lower than those of the background materials) and could be broken tombs that are saturated or moist. The conductive property of water limits the resistivity of the material which explains the relatively low resistivities of these structures. All the anomalies are located within the first 4 m of the subsurface and are rectangular in shape. Most of these anomalies (K and J) are 3 m × 2.5 m in size and two of them have dimensions of 6.5 m × 3 m. The 'F' anomaly may be a conductive void or crack. This cavity was probably filled with water at the time the measurements were taken.

Anomalous structures with resistivities between 18.7 and 149 Ωm denoted 'L' in figure 4.6 are considered tombs because of their similarities with them in terms of geometry, dimensions and depth. The resistivity contrast with their backgrounds is also an important consideration. Their high conductivities are therefore thought to have come from water which probably filled the tombs since there were a few rains during the data taking period. For example it rained on the night before the data were taken. A

decomposing body also influences the conductivity of the soil around it by virtue of the salt in mammals. An embalmed body also adds extra chemicals to the soil which can all change the chemistry of the soil and therefore its response to electric current.

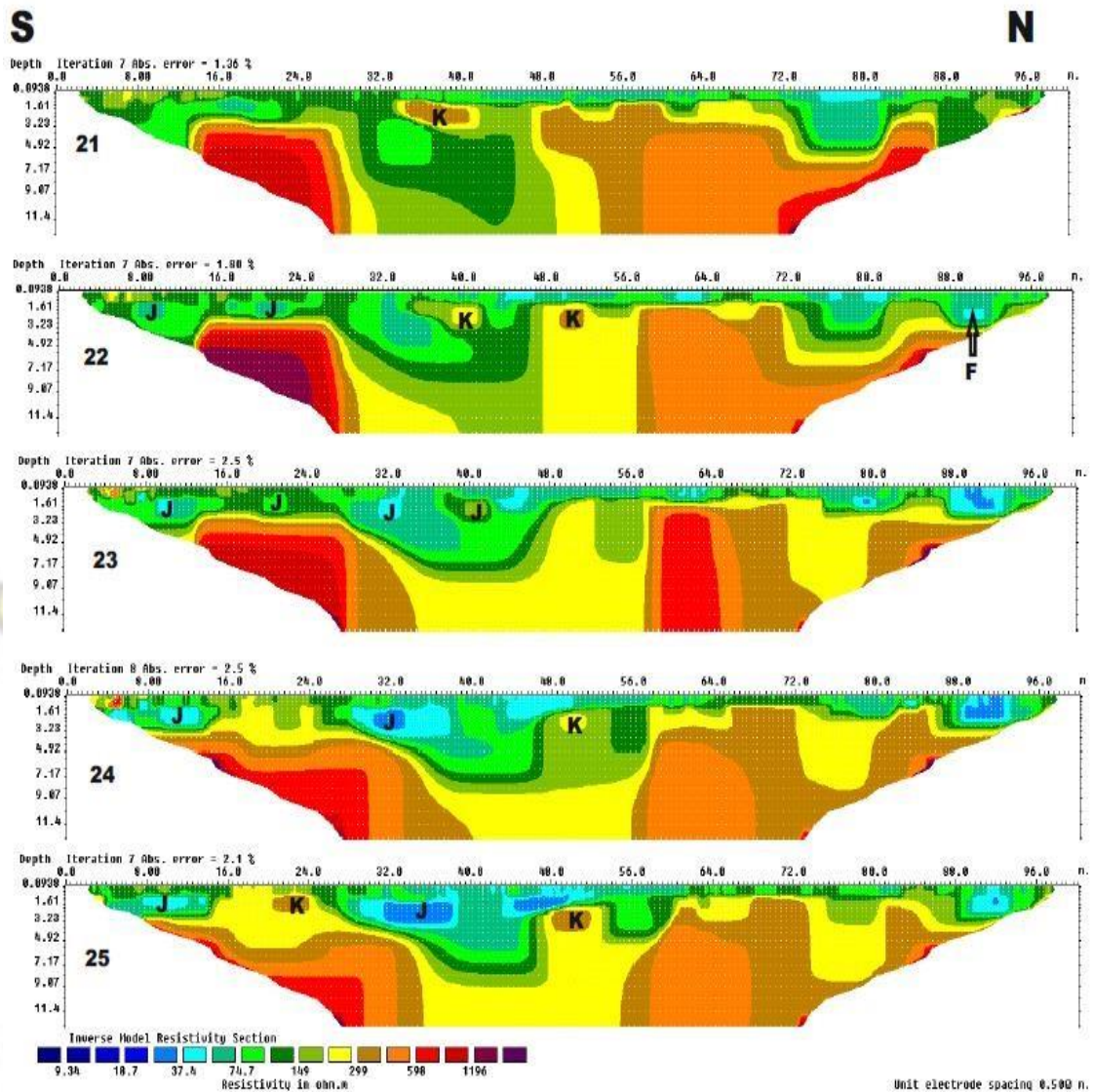


Figure 4.5: 2D Resistivity models of profiles 21 to 25

According to Konefes and McGee (1996), arsenic, which was the main ingredient in embalming fluids from the civil war to the 19th century, is toxic and persistent, and elemental arsenic will never degrade into harmless by-products. It effectively killed or halted the micro-organisms responsible for decomposition. This suggests that an arsenic

embalmed body can last for as long as possible depending on the concentrations of arsenic used for the embalment. Arsenic can thus alter permanently the electrical properties of the soil.

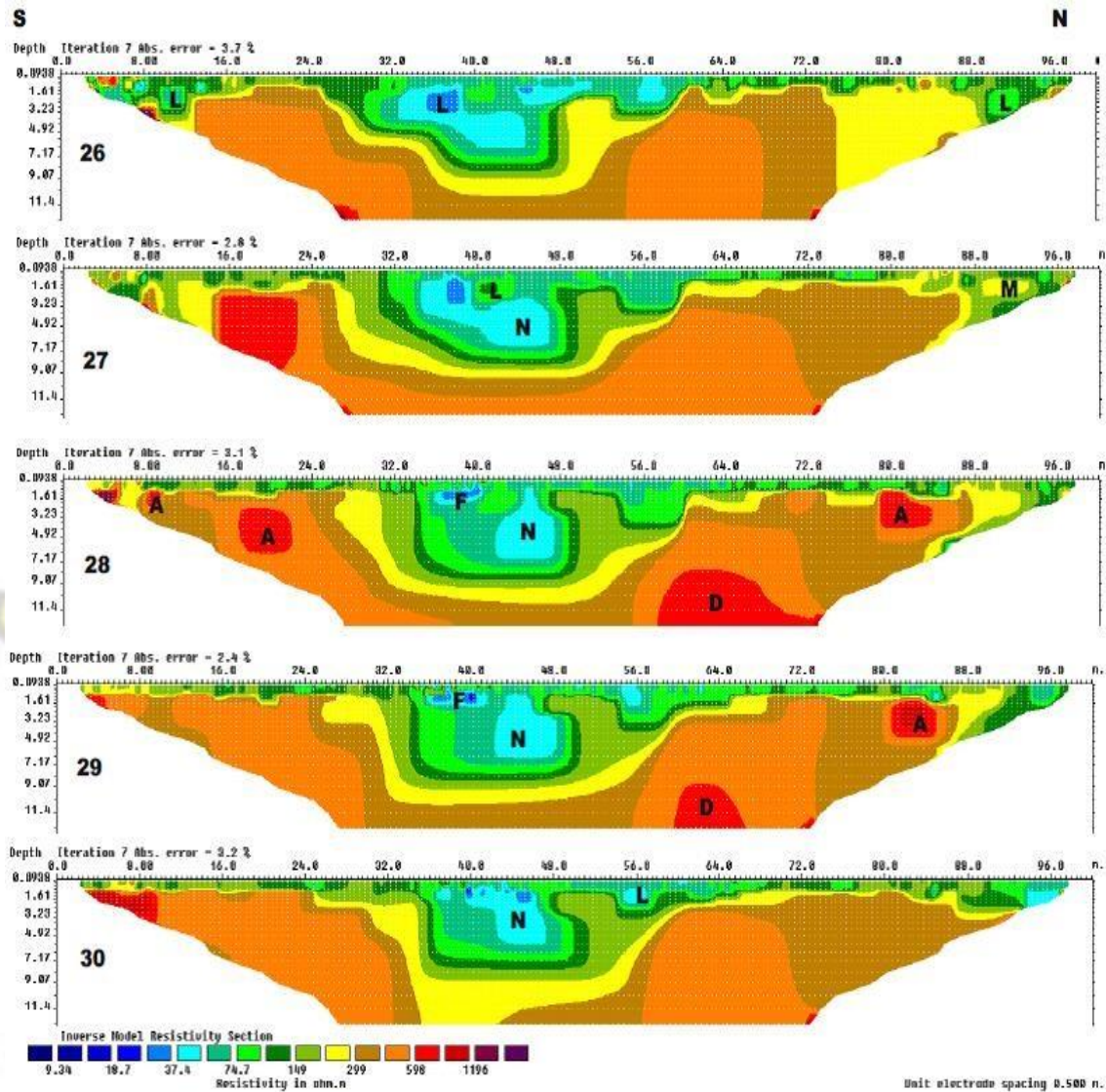


Figure 4.6: 2D Resistivity models of Profiles 26 to 30

The moderate resistivity anomaly ($\leq 299\Omega\text{m}$) denoted 'M' (Fig. 4.6) is also considered as being a tomb that is neither completely empty nor completely filled. Possibly, it has a few air-filled pores allowing the structure to exhibit neither high electrical resistivity nor

high conductivity. Residing in relatively low resistivity background and also coupled with the geometry, depth at which it is located and dimensions, it qualifies as a tomb.

The anomalies marked 'N' appear a large cavity running across profiles 26 to 30. Its low resistivity means that it was probably filled with water or heavily damp at the time of measurements. It could also contain clay. The 'F' labelled anomalies may be fractures or cracks which were also filled with water or wet clay which explains their high conductivities. The 'A' anomalous zones may be tombs. Their high resistivity is caused by the probable dryness and air filling the cavities or a hardpan over the tomb. Such tombs may still have in them partially decomposed coffins or some current resistant objects such as glass since the dead were buried with several things those days. The dielectricity of air results in high resistivities. These are also rectangular in shape and occurred at depths within 4 m. The anomaly 'D' may be some hard rock extending into profile 29 from 28. It is probably the unweathered granite.

The anomalies marked 'C' and 'T' in figure 4.7 are probable tombs. While the 'C' anomalies resided in relatively high resistivity backgrounds, the 'T' anomalies occurred in low resistivity backgrounds. Apparently these are indications of the presence of features or materials other than the background materials in those positions. Per their geometry, dimensions and depth of occurrence, both types of anomalies could be tombs but the difference in resistivity may stem from their compositions. The presence of water or some other conductive substances in the tombs may give rise to the high conductivities where as slightly porous structures as a result of partial filling of the tombs may result in the moderate resistivities.

There were no indications of tombs in profile 32 (Fig. 4.7) even though there were lateral and vertical variations in subsurface resistivity. The variations may be due to changes in subsurface stratigraphy.

Some two fractures or cracks (anomalies labelled 'F') were identified too. The one in profile 31 appears empty and air-filled and the other in profile 34 partially filled because of their high and intermediate resistivities respectively. Human activities on the surface

of the earth are capable of causing loosely held rocks to slip resulting in subsurface fractures and cracks. This is highly possible in this area which is under constant pressure from vehicular movements.

The 'D' anomaly may be a large granitic rock lying perpendicularly to profiles 31,

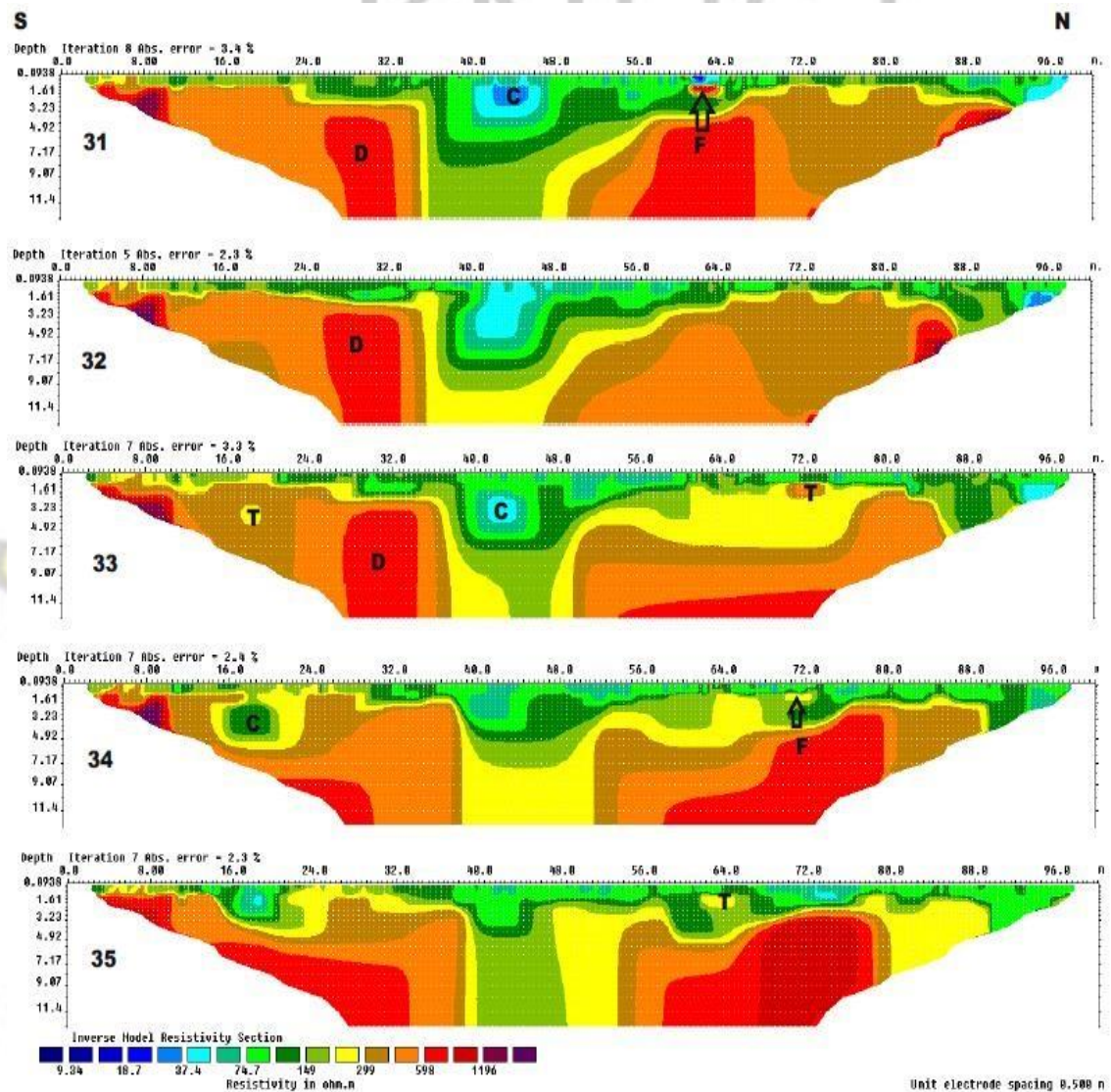


Figure 4.7: 2D Resistivity models of Profiles 31 to 35

32 and 33. Such a rock will be devoid of water-filled cracks and fractures in order to be highly resistant.

Between 32 and 48 m of profiles 21 to 36 (figs. 4.5 - 4.8), relatively lower resistivity zones were identified. In most cases these zones extended to about 8 m down the earth but went beyond 11 m in profiles 21, 31, 35 and 36. These may be composed of less consolidated sediments or may be fracture zones and so weak and cannot support infrastructural development.

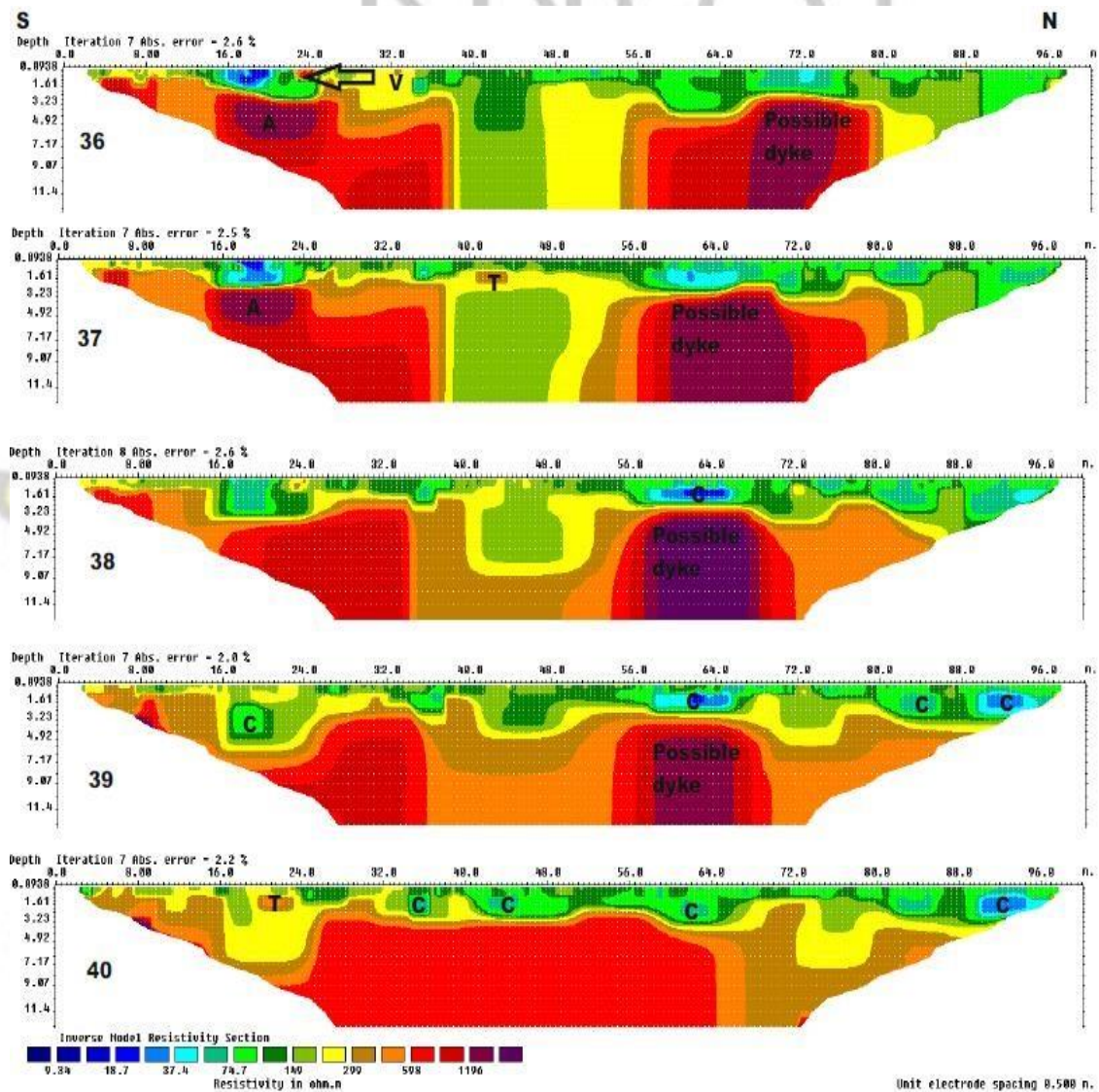


Figure 4.8: 2D Resistivity models of Profiles 36 to 40

The high resistivity anomalies, A ($\geq 1196 \Omega\text{m}$) observed in figure 4.8 may be dry tombs. Because air is dielectric, its presence in the tomb could produce such a high

resistivity value. Besides, the shape of the anomalies, the depth at which they occurred and their dimensions also exemplify tombs. These could have gravestones over them or air-filled voids from perforated coffins. The linear arrangement of tombs observed in most cemeteries is portrayed here in these profiles. By their dimensions they are two separate tombs oriented along the profile lines. An anomaly labelled 'T' in profile 37 (Fig. 4.8) may also be a tomb by virtue of its dimensions and depth of occurrence. This however is less resistive than the 'A' anomalies.

Less than a metre down the subsurface was a highly resistive small anomaly (V) in profile 36 (Fig. 4.8) which may be regarded as a void probably caused by burrowing subsurface organisms. A possible dyke seems to extend from profiles 36 to 39 since it is located at nearly the same point in all three profiles but narrows down a bit in profile 39. It could be an igneous intrusion and therefore having a higher resistivity than the surrounding material.

Profiles 38 to 40 (Fig. 4.8) were largely characterized by high conductivity (low resistivity) anomalies, C ($< 149 \Omega\text{m}$) probably influenced by water occupying subsurface cavities which are likely to be tombs because of the geometries and depths of these anomalies. The moderately resistive anomalies, T ranging between 299 and 598 Ωm may also describe a tomb characterised by slightly consolidated sediments. The contents of the tombs may be completely decomposed thus causing only a slight distinction from the background material.

Profiles 41 and 42 of figure 4.9 recorded high conductivity anomalies (labelled 'O') and moderate resistivity (P) anomalies. There were also anomalies suspected to be cracks (F), voids (V) and dykes. With a resistivity of 37.4 Ωm against a background resistivity of 74.7 Ωm and rectangular dimensions, the 'O' anomalies are likely to be tombs containing conductive substances. The moderately resistive anomaly, P may also be a sediment-filled but dry and porous tomb. Cracks may have resulted from human activities on the surface of the earth and voids caused by burrowing organisms or some natural processes.

Still from figure 4.9, profiles 43, 44 and 45 do not seem to possess graves or tombs but there is a clear observation of lateral and vertical variations in resistivity corresponding to changes in subsurface stratigraphy and lithology. Two conductive anomalies labelled 'F' were identified on profile 43 and a possible dyke on profiles 44 and 45. Water or wet clay is thought to be responsible for the conductivity of the 'F' anomalies and the igneous properties of dykes could explain the high resistivity of the structures identified as possible dykes.

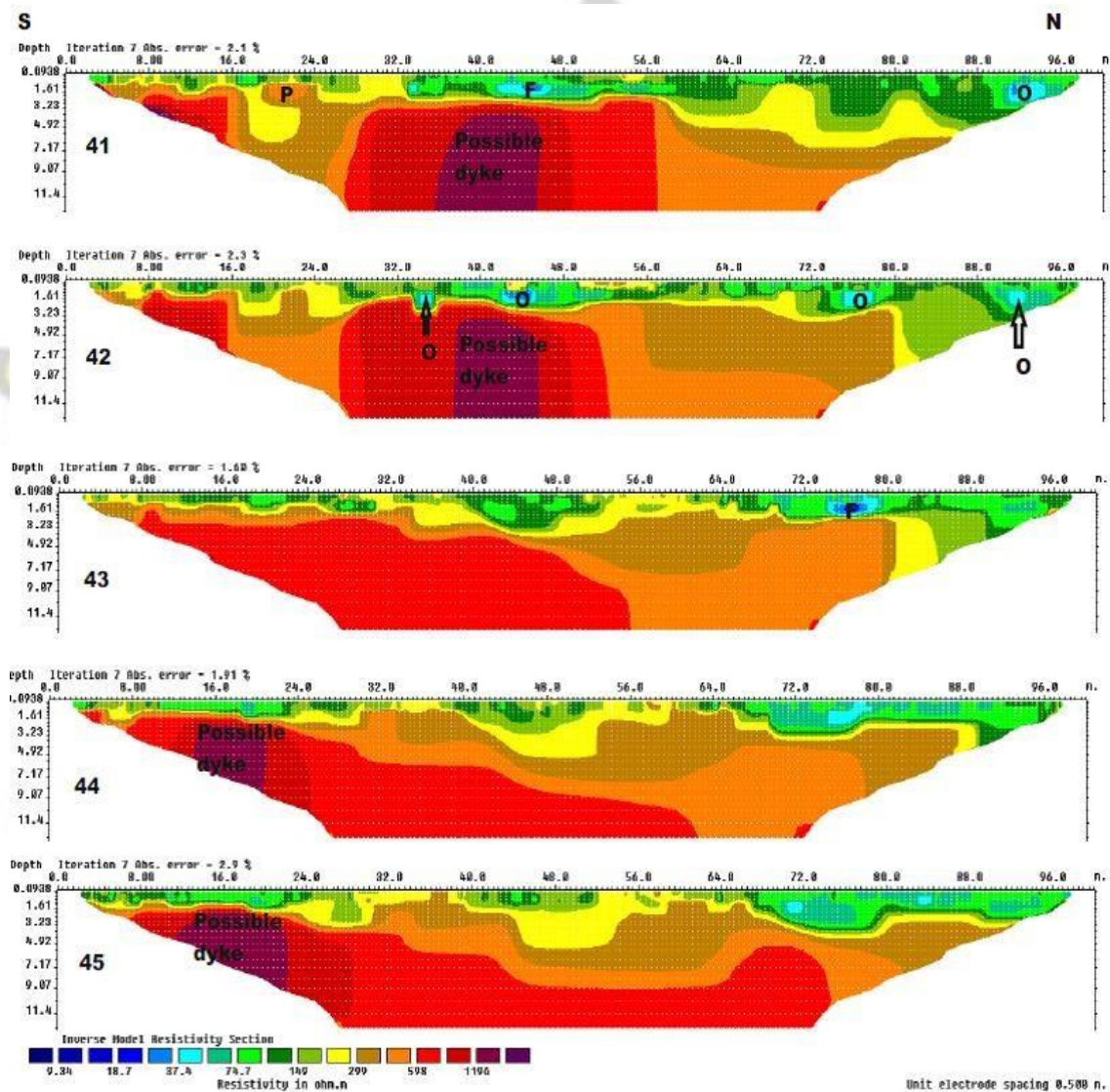


Figure 4.9: 2D Resistivity models of Profiles 41 to 45

Similarly, profiles 48, 49 and 51 (Fig. 4.10) do not show any remarkable anomalies that may be regarded as tombs. They also display subsurface stratification and lithological changes. They are, however, characterised by moderate to highly conductive fractures or cracks (F) and voids (V).

Profiles 46 and 47 (Fig. 4.10) displayed less resistant anomalies (O) in relatively more resistant backgrounds and profile 50 (Fig. 4.10) displayed a remarkably highly resistant anomaly (A) in relatively low resistivity background which are considered as tombs for

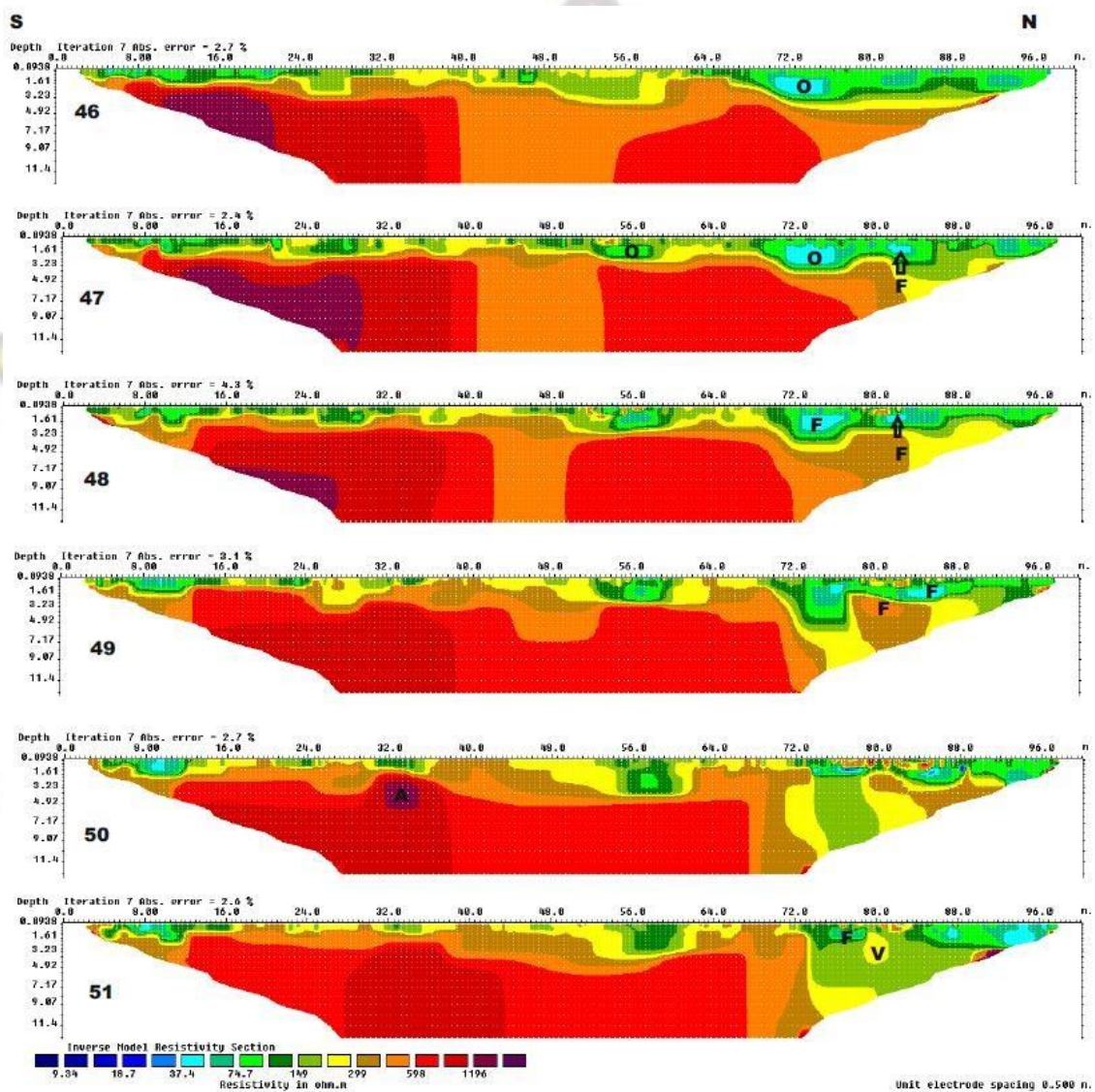


Figure 4.10: 2D Resistivity models of Profiles 46 to 51

similar reasons as explained above. Profile 47 has possibly a conductive fracture or crack (F) as well.

Generally, the thicknesses of the overburden varied from 1.5 to about 4 m and tomblike anomalies were at least 2 m apart. As seen in figures 4.1 to 4.10, the tomb-like anomalies were not evenly distributed across the study area. While some profiles recorded up to 5 of these anomalies, others had only one or none at all. Linear patterns of these anomalies were also observed in both S-N and E-W directions which may be indicative of the linear arrangement of tombs in cemeteries.

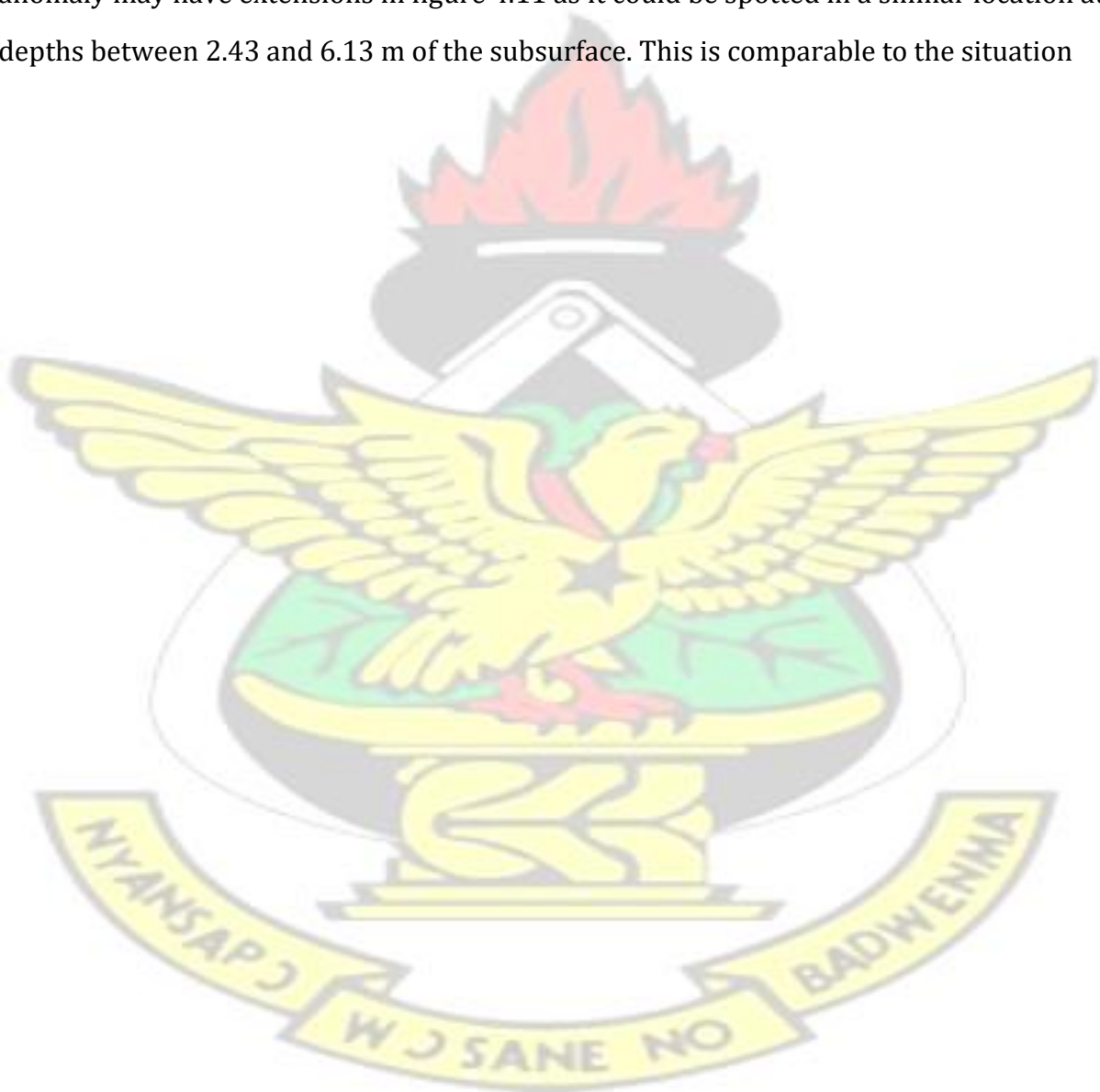
4.3 3D Resistivity Models

The results presented are up to a depth of 6.13 m because tombs are expected only within this range. The 3-D resistivity models are displayed as horizontal slices through the earth showing vertical and lateral resistivity variations (Figs. 4.11 and 4.12). Because the data size was too large for inversion with the RES3DINV software, the data was divided into two and inverted separately. Figure 4.11 is the model for the first 58 m of the study area and was obtained from the first 30 profile lines. Figure 4.12, which is the model from 42 m to 100 m of the study area, is composed of profiles 22 to 51. The reason for the overlap of data was to ensure that each model section had the same data size and more importantly that no data was lost. These models depict the appearance of the subsurface when viewed from the surface of the earth.

Resistivities within the first 1.5 m of the subsurface are more diverse portraying the inhomogeneity of the near subsurface. The soil at this depth is probably a mixture of different soil types and other materials. Further down, larger anomalous zones were observed. They are anomalous in the sense that their resistivities vary from those of their backgrounds. This suggests that there are features in these locations different from the background geology. Based on the resistivity contrasts and the geometry, some of these anomalies are enclosed in rectangular boxes (Figs. 4.11 and 4.12) and said to be possible

graves or tombs. Conductive anomalies may be moist or saturated graves while highly resistive anomalies may be graves containing air-filled voids or some hard material over them.

Between 26 and 58 m in the x-direction and 42 and 70 m in the y-direction of the study area (Fig. 4.12), a high conductivity region (enclosed with a white line) was observed to run from the surface of the earth to a depth of about 6.13 m and probably beyond. This anomaly may have extensions in figure 4.11 as it could be spotted in a similar location at depths between 2.43 and 6.13 m of the subsurface. This is comparable to the situation



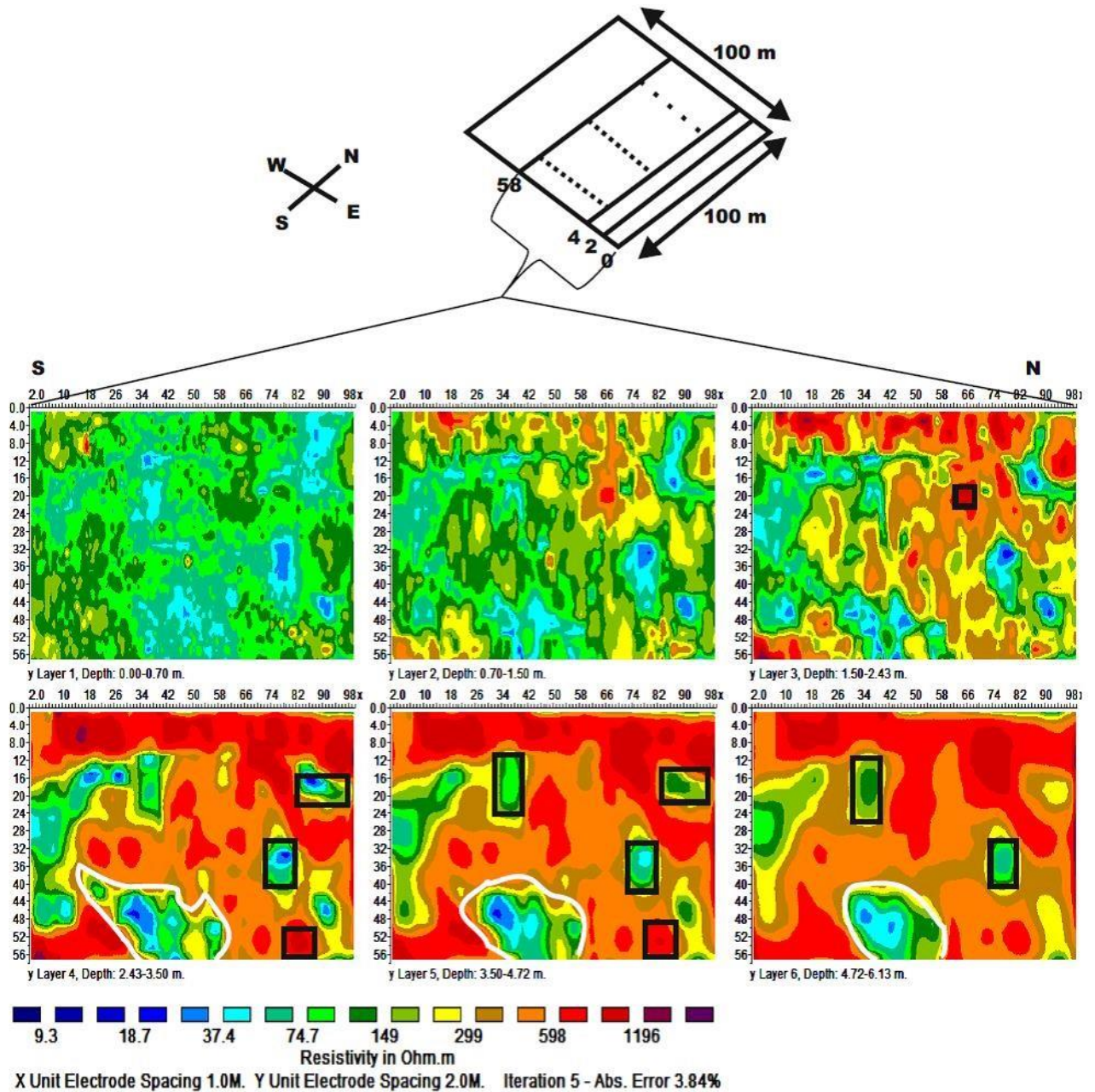


Figure 4.11: The 3-D resistivity model obtained from the inversion of the data from 0 to 58 m (profiles 1 to 30) of the study area and displayed as horizontal slices through the earth.

observed between 32 and 48 m of profiles 21 to 36 (Figs. 4.5 to 4.8) as this region may also contain saturated or moist sediments or even fracture zones. This weak zone may not successfully support any building structure on it.

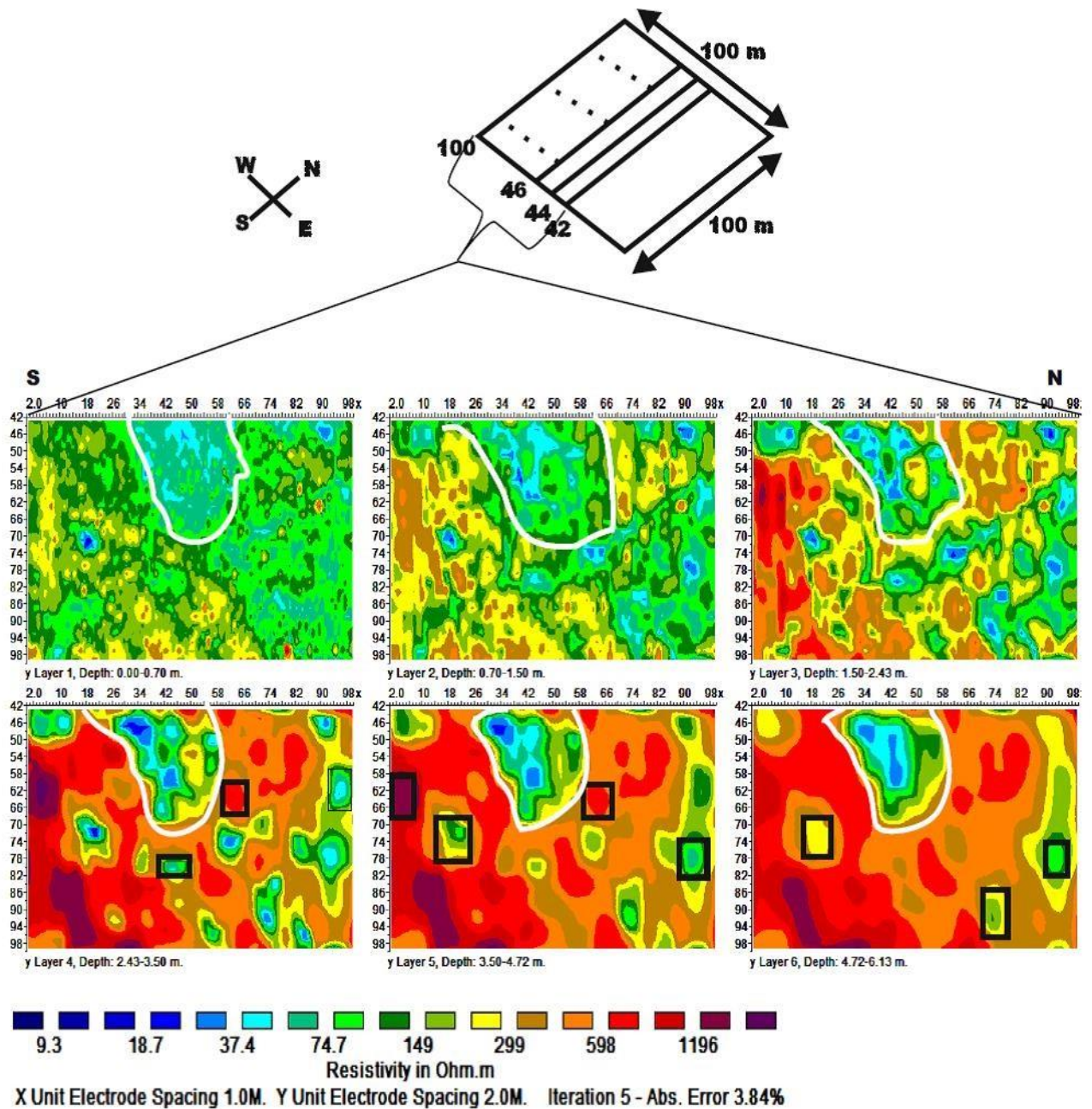


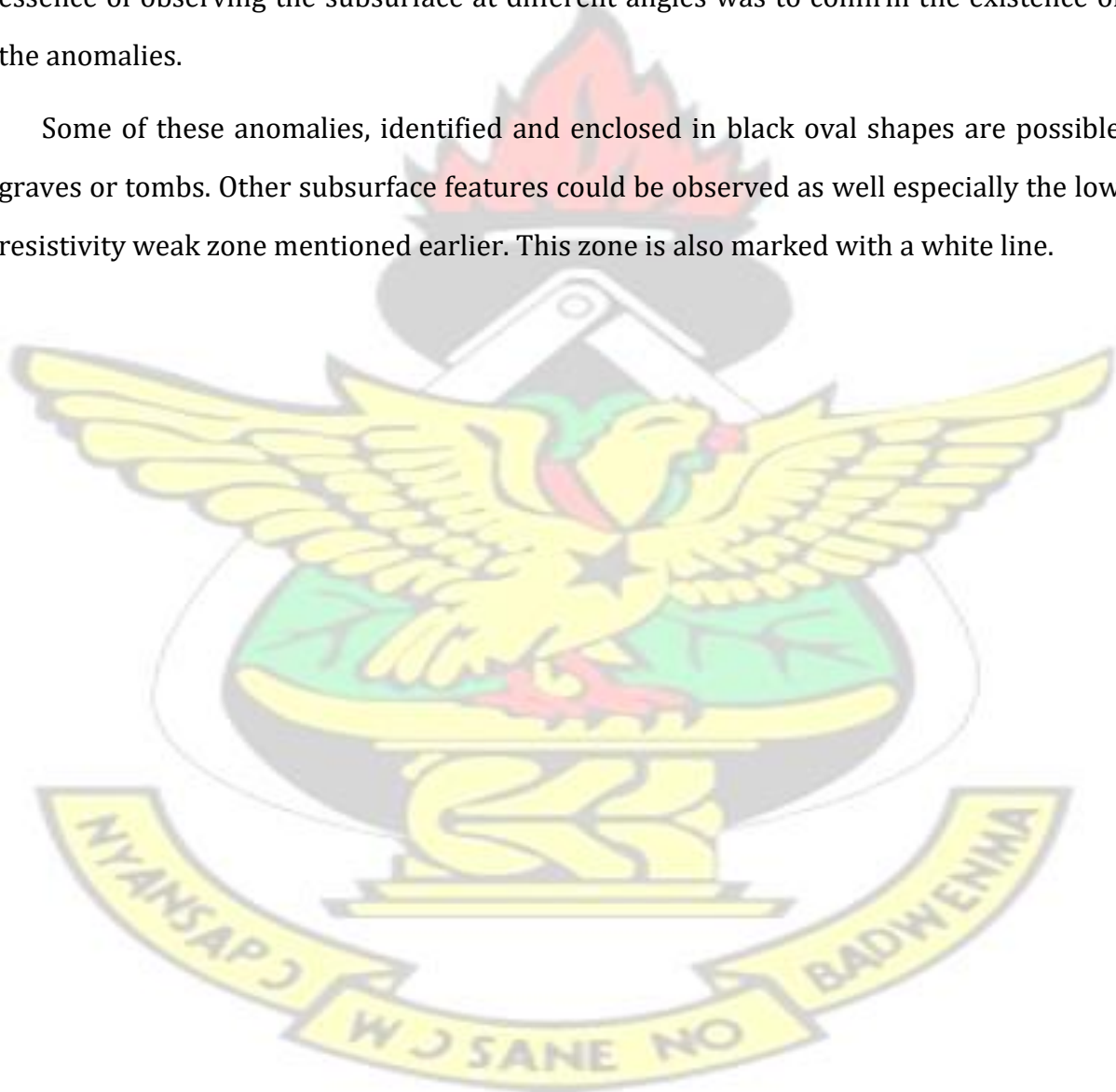
Figure 4.12: The 3-D resistivity model obtained from the inversion of the data from 42 to 100 m (profiles 22 to 51) of the study area and displayed as horizontal slices through the earth.

Figures 4.13 to 4.16 are vertical sections of the earth displaying its appearance when observed from the 'belly' of the earth. Different views are realised depending on the

position from which one looks at it. Figures 4.13 and 4.14 are observations from the x-z plane and figures 4.15 and 4.16 are views from the y-z plane.

In the x-z plane, it is assumed that vertical slices of the earth are cut from south to north and viewed in the E-W direction. On the other hand, the y-z plane has vertical slices of the earth cut from east to west and viewed in the S-N direction. Irrespective of the direction from which the subsurface was viewed, anomalies were still noticed. The essence of observing the subsurface at different angles was to confirm the existence of the anomalies.

Some of these anomalies, identified and enclosed in black oval shapes are possible graves or tombs. Other subsurface features could be observed as well especially the low resistivity weak zone mentioned earlier. This zone is also marked with a white line.



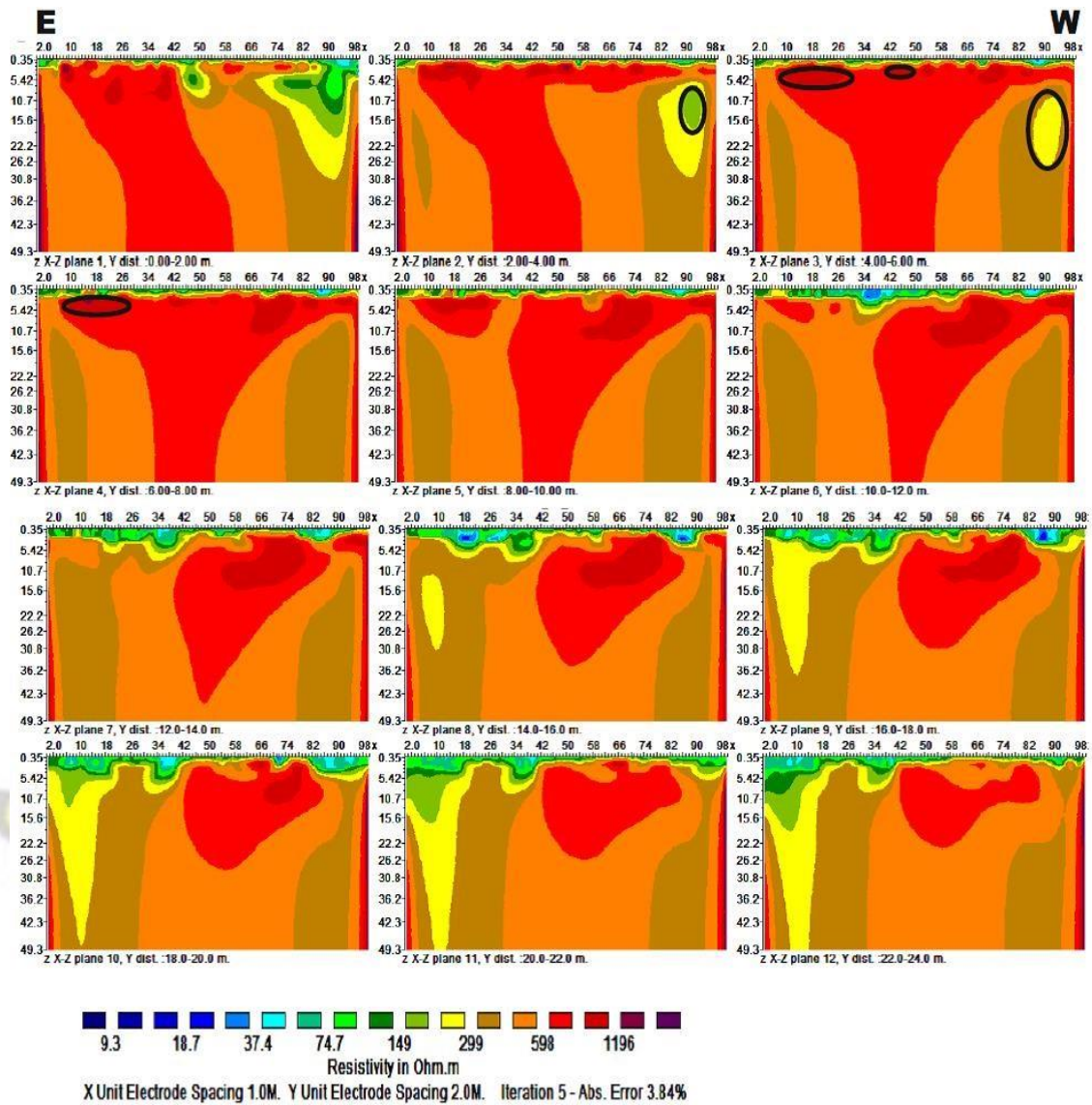


Figure 4.13: The 3-D resistivity model obtained from the inversion of the data from 0 to 58 m of the study area and displayed as vertical slices through the earth.

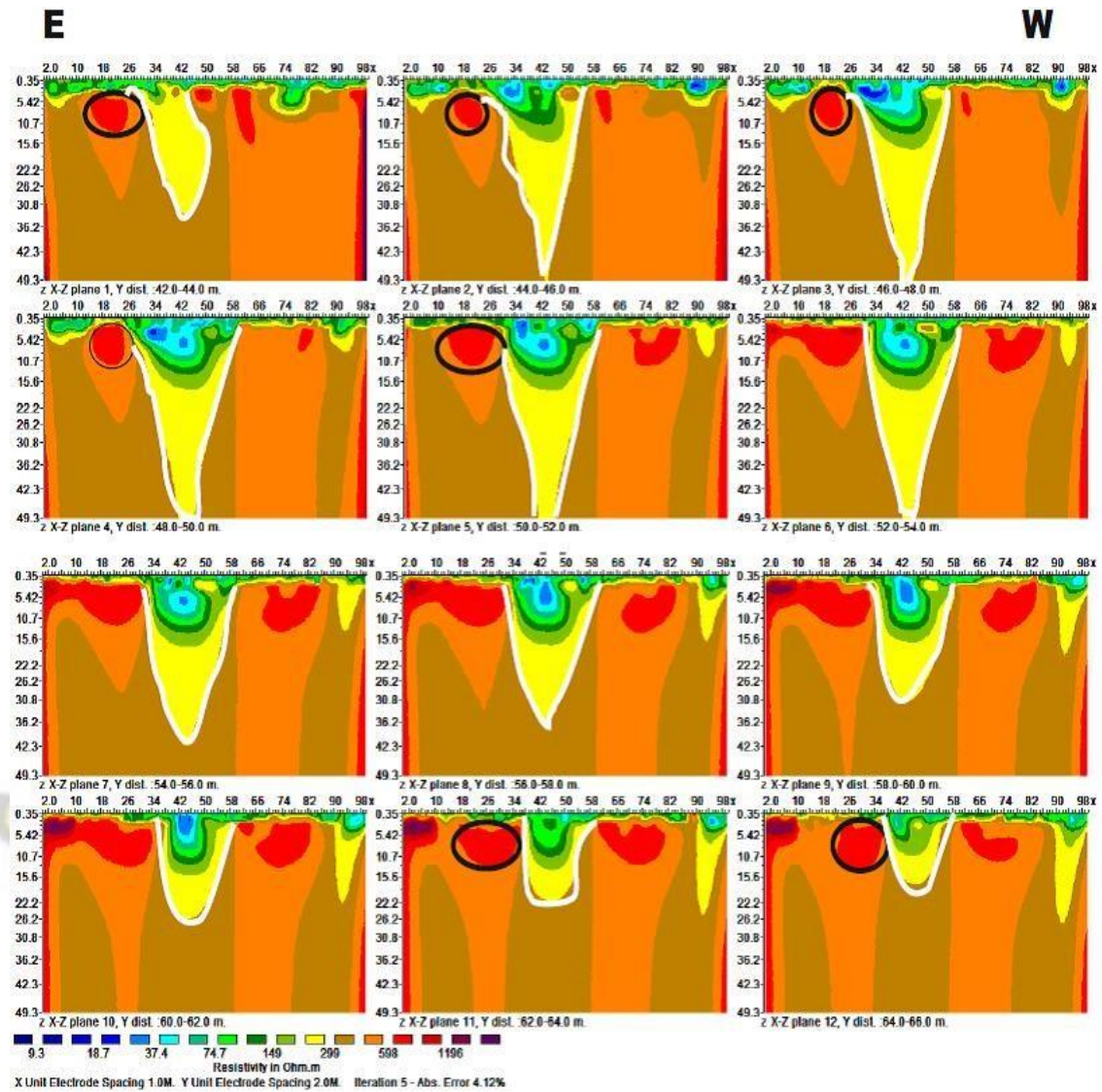


Figure 4.14: The 3-D resistivity model obtained from the inversion of the data from 42 to 100 m of the study area and displayed as vertical slices through the earth.

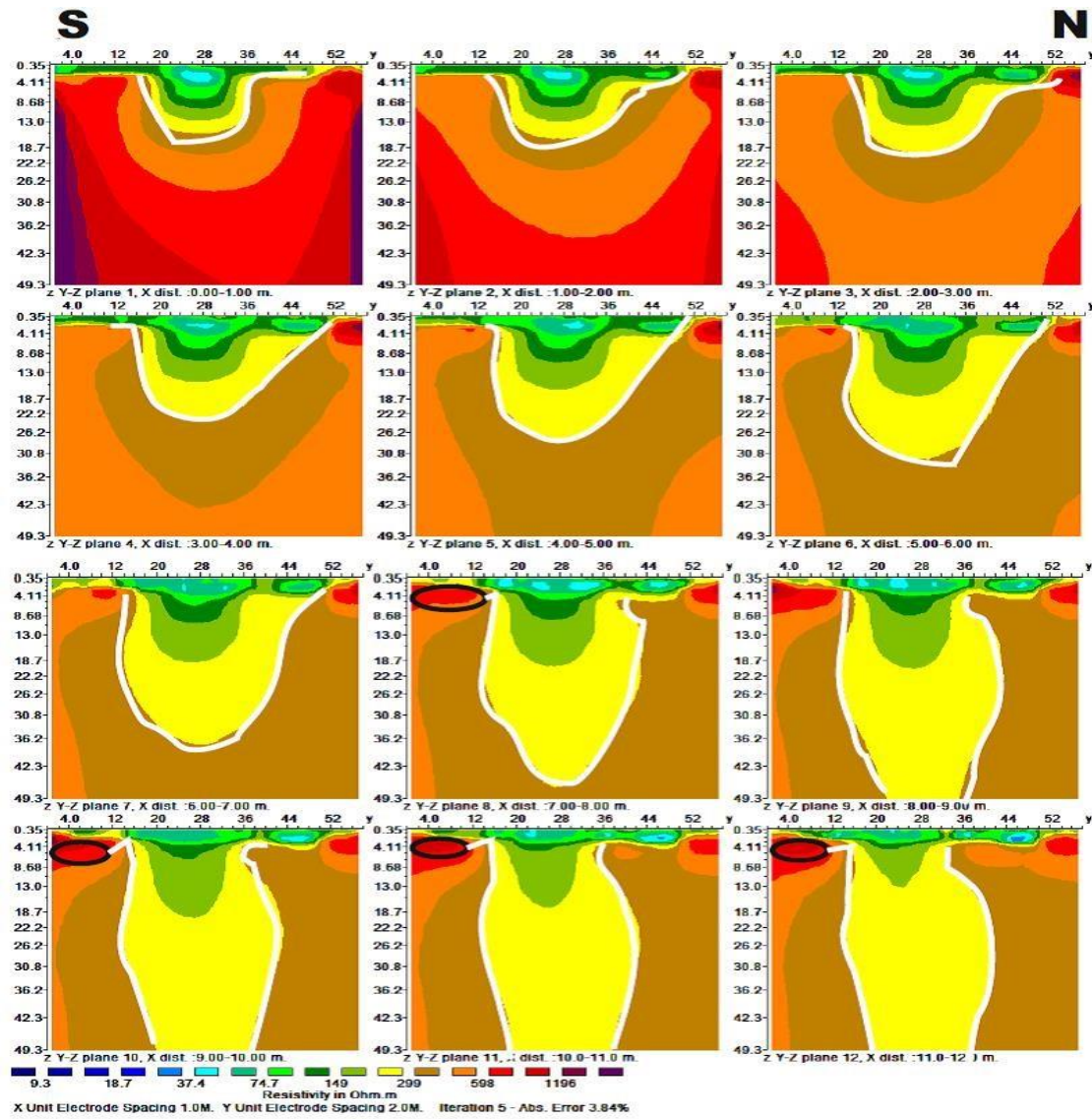


Figure 4.15: The 3-D resistivity model obtained from the inversion of the data from 0 to 58 m of the study area and displayed as vertical slices through the earth.

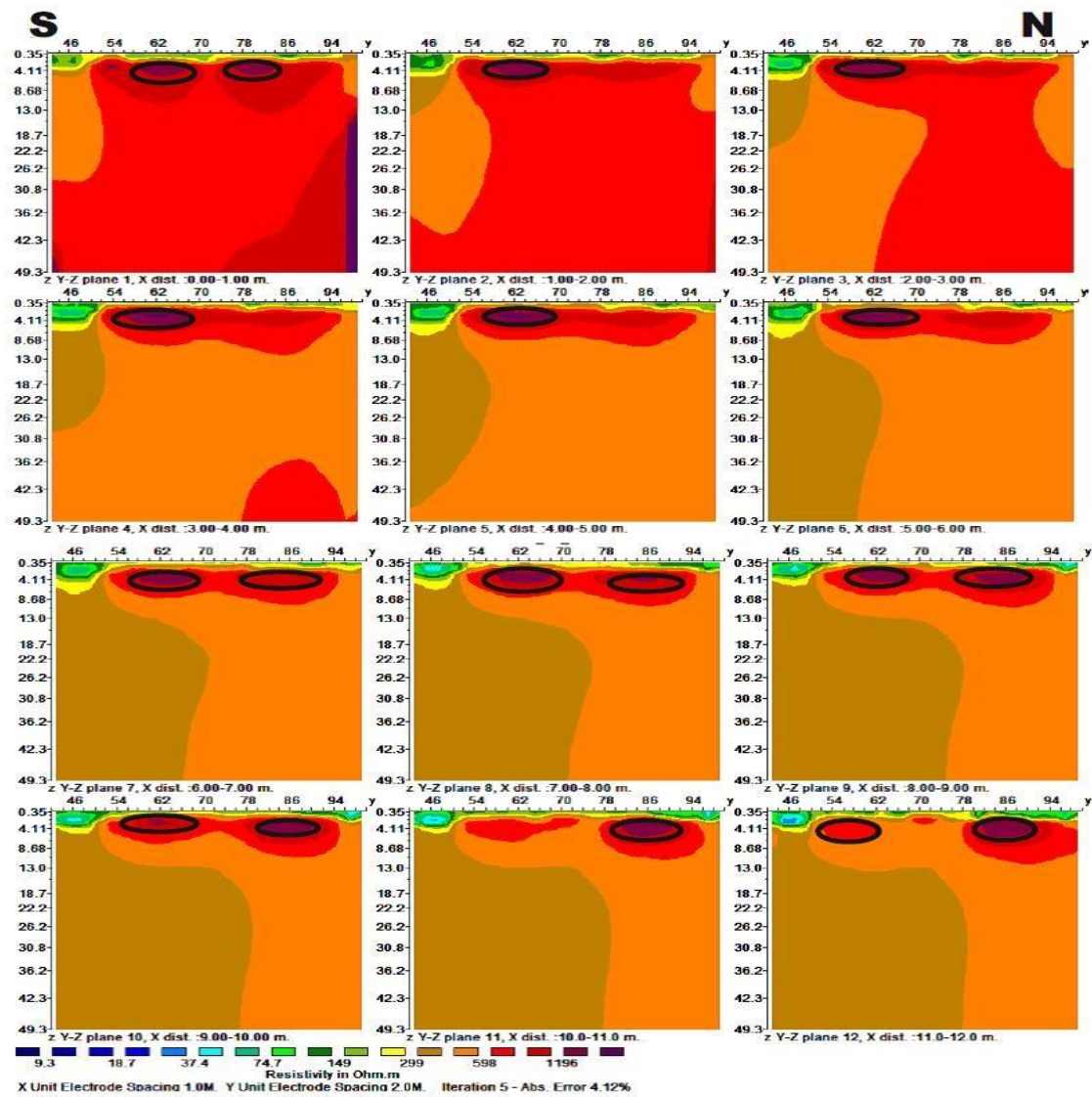


Figure 4.16: The 3-D resistivity model obtained from the inversion of the data from 42 to 100 m of the study area and displayed as vertical slices through the earth.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Generally, a disturbed near subsurface was observed with some portions of it having resistivities ranging between 37.4 and 299 Ωm which might be caused by the mixture of topsoil and gravel as a result of digging and refilling activities. This was observed within overburden thicknesses ranging between 1.5 and 4 m (Figs. 4.1 to 4.10). Resistivity varied both horizontally and vertically in all profiles but not at the same rate.

The survey results also indicated low to high resistivity anomalies at a number of locations in the study area. Judging from their rectangular shapes, alignments, dimensions and resistivity contrast with the background materials, some of these anomalies were identified to be possible graves, fractures or cracks, natural cavities, dykes and bedrock materials. These anomalies, whether less, moderately or highly resistive, indicated materials with compositions slightly or largely different from their background materials. This might have resulted from grave infilling material in the case of anomalies suspected to be graves. Some graves might have been built and others not and located at different depths with varying dimensions. In addition to the observation that some burials could have been done with coffins and others without coffins, the orientation of the anomalies (S-N and E-W) suggests that different burial styles were possibly used. Most of the anomalies resided within the first 5 m of the subsurface.

Viewing the subsurface from different positions: from the surface of the earth downwards (figures 4.11 and 4.12), assuming a position inside the earth and observing it from east to west (Figs. 4.13 and 4.14) and from south to north (Figs. 4.15 and 4.16), confirmed the presence of the aforementioned anomalous zones in the study area. A low resistivity zone was also observed between 26 and 58 m of the study area in the S-N direction and between 30 m and 70 m in the E-W direction of the study area. This zone may not be well consolidated and thus may not support infrastructural development. It

should therefore be noted if the study area is ever considered for the building of structures. However, the rest of the study area may be suitable for constructional works since the tomb-like structures and such possible subsurface features as cracks or fractures, voids etc. are sparsely populated and can easily be taken care of. The underlying bedrock of granite may also be helpful in this direction.

The electrical resistivity method was thus successful in delineating grave or tomb-like and other subsurface features. The study area could have been a cemetery since tomb-like features were detected.

5.2 Recommendations

It is recommended that:

- some of the tomb-like anomalies be excavated to confirm the results.
- alternative geophysical methods be used to study the area to also confirm the results.
- being a vast piece of land, the remaining area should also be surveyed to determine the extent of the cemetery.

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