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**GEOPHYSICAL INVESTIGATION OF SULPHIDES MINERALISATION IN
MAITENGWE GREENSTONE BELT, NORTH-EAST BOTSWANA.**

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ABSTRACT

ABSTRACT

During early 1990s, the then Botswana Geological Surveys (now BGI) used geochemical, geophysical (Horizontal Loop Electromagnetic (HLEM), magnetic and gamma ray) and borehole drilling methods in the Maitengwe Greenstone Belt in order to determine the gold and base metal mineralization potential. However, these geophysical methods had limited spatial resolution, and could not adequately determine the spatial distribution mineralized zones and the geometry of sulphide-rich veins. For this reason, this study utilized aeromagnetic dataset as desktop studies and a follow up using the IP method in conjunction with electrical resistivity imaging (ERI) and Time Domain Electromagnetic (TEM) method to determine the spatial distribution and the geometry of potential mineralized zones. The findings of the study reveal that structural lineaments on the aeromagnetic data of Maitengwe area are mostly oriented NE-SW. Induced polarization and electrical resistivity methods successfully identified zones of potential mineralization in Maitengwe Greenstone Belt. High sulphide mineralization potential zones were identified in all the eight survey lines. Such zones occur beneath 100 m depths and are characterized by chargeability values of 7.4mV/V -12.8 mV/V and resistivity values of 400 Ω m-9205.0 Ω m. Such values of moderate to high resistivity and high chargeability corresponds with silicified mineralized zones. Zones of low resistivity coinciding with high chargeability values are possible alteration zones with significant metallic minerals. The inferred mineralized zones appear sub-vertical to vertical and trends in a NE-SW direction. This is consistent with the direction of the lineaments identified using the high-resolution aeromagnetic data, suggesting that these mineralized zones may be associated and controlled by these structures. The TEM results of 1D

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soundings correlate with the 2D resistivity models. The results reveal a three-layered earth in which the resistivity increases with depth.

Keywords: Sulphide mineralization, geological structures, chargeability, greenstone belt, resistivity, induced polarization, Time domain.

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LIST OF ABBREVIATIONS

IP- Induced polarisation

ERI- Electrical resistivity imaging

TDR- Tilt derivative

TDEM- Time domain electromagnetic

TMI- Total magnetic intensity

RTP- Reduced to pole

1VD- First vertical derivative

BGI-	Botswana	Geoscience	Institute
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INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Greenstone belts are economically significant repositories for mineral deposits (Kwan et al., 2019). They are richly endowed with mineral deposits of copper, nickel, iron, manganese, chromite and gold (Mukhopadhyay, 2020; Fayol et al., 2019; Kwan et al., 2019; Chen & Liu, 2018; Ghosh et al., 2015; Smelov et al., 2010; Filipa et al., 2007; Trench & Williams, 1994). Greenstone belts are zones of interlayered metamorphosed volcanic ultramafic-mafic rocks and sedimentary rocks which are surrounded by granite and gneissic bodies occurring in Archean and Proterozoic age (Smithies et al., 2018; Anhaeusser., 2014; Carney et al., 1994). Maitengwe greenstone belt forms part of the Francistown granite greenstone complex that sits on the Zimbabwean craton (Aldiss, 1991). Maitengwe, Matsitama, Tati and Vumba greenstone belts occur in part of the Zimbabwe craton exposed in north-eastern part of Botswana (McCourt et al., 2004).

Economic deposits of gold, nickel, copper which are associated with sulphides have been found and are mined in the adjacent greenstone belts of the Zimbabwean craton. Tati greenstone belt host Cu/Ni deposits in Tekwane, Selkirk and Phoenix deposits, the belt also host gold deposits namely the Map Nora, Gold Eagle, Signal Hill and Mupane Au deposits (Maier et al., 2008; Tombale, 1992; Key, 1976). The mineralised zones in these belts are localised in shear and fault zones. The mineralization in the Vumba belt has been found in shear zones and gold-bearing sulphides are disseminated in quartz bands in amphibolite.

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Significant nickel sulphides deposits namely Damba, Hunters Bay, Trojan and Shangani are mined in this craton in Zimbabwe (Hofmann & Bekker, 2014; Markwitz et al., 2009). These mineral deposits are also localized in geological structures that play a crucial role in the formation of this mineralisation in the Zimbabwe craton (Newman, 2010). Mineral deposits of economic value have not yet been discovered in Maitengwe greenstone belt, however there is a possibility of similar occurrence of economic sulphides mineralisation in the belt despite its small size.

1.2 PREVIOUS STUDIES

Geochemical and geophysical studies were conducted by Botswana Department of Geological Surveys known today as Botswana Geoscience Institute (BGI) in the Maitengwe greenstone belt. A regional geochemical survey was conducted in 1988 as an overshoot to the BGS/ BGR 'Mineral exploration of the Vumba Schist Belt'. Subsequent geochemical surveys were carried out in 1991 and 1992 respectively extending the 1988 grid and the results indicated that sulphides are strongly correlated in soils overlying the greenstones (Chatupa, 2000). A reconnaissance geological mapping took place at the same time of the geochemical sampling. Follow up by geophysical survey took place in 1992 to constrain selection of drill targets and five-drill holes were completed in 1992/93. Geophysical survey consisted of Horizontal Loop Electromagnetic and ground magnetics.

Sulphide mineralisation was intersected in four of the five drill holes and most of the mineralisation occurred in hydrothermally altered amphibolite and ultramafic rocks. Holmes et al (1993) stated that the presence of pyrite, pyrrhotite is encouraging as gold mineralisation is associated with these sulphides in the greenstone belt. Rock suites in Maitengwe

INTRODUCTION

greenstone belt show extensive alteration along contact zones and shearing in probable fault zones. Such areas coincide with high magnetic signature and enriched trace elements in soils.

Hence there is some potential for base metals and gold mineralisation to be investigated in detail in this greenstone belt (Holmes et al., 1993).

1.3 PROBLEM STATEMENT

From the drill hole information, the mineralisation in this belt occurs as disseminations also along quartz and carbonate veins. The association of this mineralization with veins and zones of possible shearing suggests that the mineralisation in this area may be structurally controlled. However, the previous methods employed had limited spatial resolution due to the large spacing used during survey and could not adequately determine the spatial distribution mineralized zones and the geometry of sulphide-rich veins.

Induced Polarization (IP) geophysical method is usually used as a follow up on targets generated by Electromagnetic and magnetic method. This has been used with proven efficacy in several studies to determine the spatial distribution of disseminated sulphides and the geometry of sulphide-rich veins/structures (e.g Wu et al., 2022;Sidiq et al., 2021;Dakir et al., 2019;Martinez et al., 2019).

Botswana Geoscience Institute brochure (2020) also mentioned that no structural interpretation was conducted in this area even though mineralisation is controlled by structures such as shear zones, faults and lithological contacts.

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1.4 AIM AND OBJECTIVES

To utilize the IP method in conjunction with electrical resistivity imaging (ERI) and Time Domain Electromagnetic (TDEM) method to determine the spatial distribution of disseminated sulphides, and the geometry of potential mineralized zones.

- Carryout a detailed structural interpretation of the area using the already available high-resolution aeromagnetic data to delineate potential zones of interest.
- Conduct a combined IP, ERI and TEM survey to investigate the presence of mineralised zones.
- Determine the geometry and distribution of potential zones of sulphides mineralisation from the survey results.

RESEARCH SIGNIFICANCE

The research is an attempt to further investigate the sulphide mineralisation in Maitengwe by studying the spatial distribution and geometry of the sulphide mineralisation.

The findings of this study would significantly contribute to future mineral exploration activities in Maitengwe greenstone belt since not much work has been done to investigate mineralisation potential of this belt.

The study will also contribute to pure scientific knowledge in Botswana.

1.5 THESIS OUTLINE

CHAPTER 1- is introductory section, it covers the background of the study, the aims and methodology involved.

CHAPTER 2- Covers the literature review, location, geology, deformational events that affected the area and drill hole information from previous studies.

CHAPTER 3- Presents the first part of the methodology; it gives a brief overview of the desktop studies using aeromagnetic data. Structural analysis and interpretation of the aeromagnetic data. The chapter describes in detail the process and filters applied to enhance the data, the consequent structural map and exploration target delineation.

CHAPTER 4- Gives the overview and principles behind induced polarisation conjunction with electrical resistivity imaging and electromagnetic geophysical method. It describes the theory behind these techniques and inversion of geophysical data.

CHAPTER 5- Presents the second part of the methodology: IP and electrical resistivity imaging and TDEM field data acquisition. It provides a description of the equipment, the field procedures and processing of the data.

Chapter 6- Is presentation of the data acquired and interpretation. It also discusses the inversion results of the geophysical data and the conclusion

CHAPTER 2

STUDY AREA

2.1 LITERATURE REVIEW

Greenstone belts are known worldwide to host economic mineral deposits. Albiti greenstone belt in Canada is by far the largest and produces significant amount of gold yearly (De souza, 2019). Greenstone belts of the Yalgarn craton in Australia are a major producer of gold and nickel deposits (Doublier et al., 2014). The Barbeton greenstone belt in South Africa is the oldest known greenstone belt and one of the oldest golds producing mines (Ward, 1995). Significant magmatic nickel sulphides deposits in Zimbabwe are hosted in Archaean greenstone belt. The mineralisation is spatially associated with crustal scale structure that seem to act as conduits for hydrothermal fluids that localise the mineral deposits (Chisambi et al., 2021). A good review on the role of geologic structures in mineral exploration is given by Morishita& Wada, (2021) who demonstrated that fracture systems influence the Skarn type mineralisation from hydrothermal activity, other studies are given by Wu et al., (2022);Sidiq et al., (2021); Dakir et al., (2019); Martinez et al., (2019).

GEOPHYSICAL TECHNIQUES IN MINERAL EXPLORATION

The increasing demand for mineral commodities has given rise to the use of geophysical techniques in the detection and delineation of mineral resources. The techniques depend on measuring the different physical properties of the subsurface (Kearey et al., 2002). The use of a single geophysical method results in poorly constrained results; hence an integrated geophysical approach gives results with prominent precision and greater consistency (Essa &Munschy, 2021). High resolution aeromagnetic data are extensively used as a base for geological interpretations to map geological structures that localise mineralisation (Chisambi

STUDY AREA

et al., 2021). Delineation of these structures is carried out on filtered and enhanced aeromagnetic data sets. The process of data enhancement can improve subtle anomalies hence otherwise make interpretation more practical (Leseane et al., 2020). Some useful mineral indicators to look out for in exploration are faults, fractures, shear zones, arched or domed strata, oxidised and hydrothermally altered areas (Ugunmola et al., 2015). These structures act as a conduit for hydrothermal fluids that carry metallic minerals and trap sites for mineral deposits. Several studies have shown the importance of aeromagnetic data in both mineral exploration and understanding the subsurface structure (Folkes et al., 2021; Leseane et al., 2020; Al Ibiari et al., 2018; Robertson et al., 2017; Rodríguez et al., 2017; Salem & Ali, 2016; Bultman, 2015; Al Kadasi, 2015; Abu El-Ata et al., 2013; Anand & Rajaram, 2006)

INDUCED POLARISATION AND ELECTRICAL RESISTIVITY IMAGING

The application of geo-electrical methods for different purposes has grown widely over the years. Induced Polarisation (IP) in conjunction with Electrical Resistivity Imaging (ERI) method are employed in mineral exploration (Elis, 2015; Scott, 2014; Moreira et al., 2012; Pardo et al., 2012; Zhdanov, 2009), geothermal, groundwater exploration, environmental investigations and several applications in hydrocarbon exploration (Burtman & Zhdanov, 2015; Burtman et al., 2014; Orozco et al., 2012; Lesmes & Morgan, 2001). IP technique measures the electrical chargeability of the ground while the ERI measures the resistivity. It was firstly used in exploration of metallic ores and sulphides ores due to strong polarisation effects increased by the presence of metallic or semi conductive material. Induced polarisation method maybe adopted as a follow up survey since the polarisation data from this technique provides insights for interpreting results of other common exploration survey methods (Trench & Williams, 1994).

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Examples of application of IP and ERI in base metal exploration is over the disseminated copper ore zone known as the Copper Mountain Orebody in Gaspé area, Quebec, Canada (Reynolds, 2011). The mineralisation was evaluated at 4% metallic mineralisation of pyrite and chalcopyrite, the orebody has been delineated from several boreholes. Dakir et al., (2019) applied resistivity and IP techniques to locate metalliferous veins in Taroucht and Tabesbaste area. In a study by Martínez et al., (2019) to locate galena veins, ERI could not give insights on the degree of mineralisation of these structures. However, IP made it possible to differentiate which are the mineralised structures, fractures gave high values of chargeability (50 mV/V).

Even though IP has had great success, the method is labour intensive and surveying large areas could be time consuming and expensive. Just like any other method geological situations are one of the factors to consider when selecting a geophysical survey technique. IP can fail in surface materials that are very resistive that is resistive overburden can negatively affect the resulting signal due to voltage and power limitations of the transmitter hardware (Marchant et al., 2013).

ELECTROMAGNETIC METHOD

Electromagnetic (EM) surveys measures variations in electrical properties of rocks particularly electrical resistivity or its inverse electrical conductivity (Rodriquez et al., 2007). Electromagnetic method has the broadest range of instrumental systems and notable range of applications (Reynolds, 2011). The Transient electromagnetic (TEM) sounding system measures in time domain as compared to frequency domain. The method has been successful in mineral, hydrogeology and environmental investigations. In mineral exploration, Law et al., (2019) demonstrated the use of TEM to delineate mineralised fracture zones. Guo et al., (2020) presented a good review on the application of electromagnetic method in mineral exploration.

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Even though geophysics has proven to be of paramount importance in exploration of mineral resources, geophysical data interpretations on the other hand can be quite challenging. Many geophysical inversion models may fit the observed data making the given interpretation nonunique (Reynolds, 2011). To reduce this problem, it is vital to integrate geophysical techniques to optimise interpretation, having prior knowledge and geological information can also be helpful in constraining the geophysical models and guide interpretations.

2.2 LOCATION

Maitengwe greenstone belt is situated in the north-eastern part of Botswana. The study area is located south of Maitengwe Village near the main tarred road to the village. It is found within the geographic coordinates -20.00025S and 27.20348E. The area is relatively flat with no or limited outcrops.

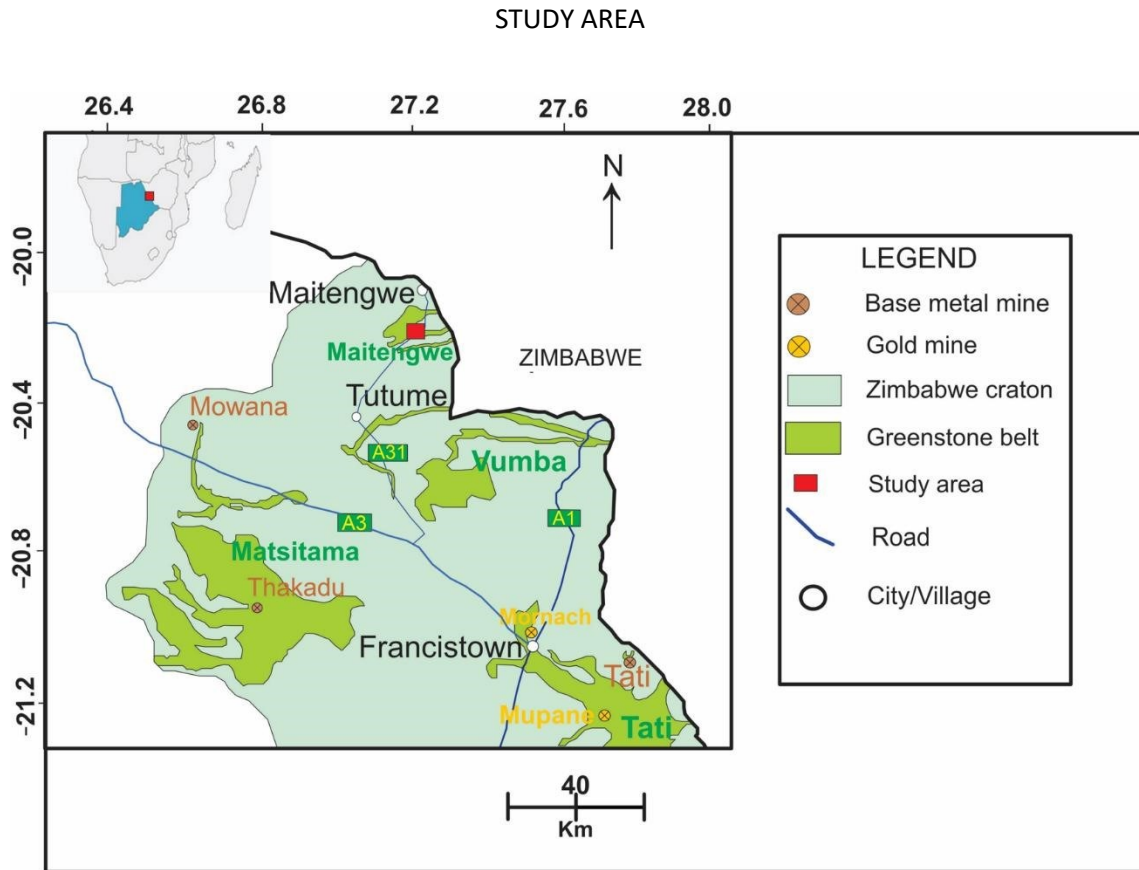


Figure 2.1: Location of the study area and the regional geology modified from (Van Waarden, 2014) Showing the greenstone belts of the Francistown granite greenstone complex found on the southwestern part of the Zimbabwean craton extending into Botswana. Various base metal and gold mines are found within the Tati greenstone belt.

2.3 REGIONAL GEOLOGY

Maitengwe greenstone belt forms part of the Francistown granite greenstone complex that sits on the south-western part of the Zimbabwe craton extending into Botswana. Archaean rocks consisting of granite and gneissic rocks together with rocks of greenstone belt forms the crystalline basement. Supracrustal rocks of the greenstones are dominated by mafic and ultramafic metavolcanic rocks. Carney et al., (1994) correlates these rock suites to the Upper Bulawayan greenstones. The granitoids of the Francistown complex consist variably foliated tonalite-trondhjemite-granite (TTG) gneisses with lesser late-kinematic granodiorite, monzonite and granites (McCourt et al., 2004). These greenstones are metamorphosed to low-grade greenschist to amphibolite facies, they are strongly sheared and deformed.

DEFORMATIONAL EVENTS OF THE ARCHAEOAN OROGENY OF ZIMBABWE CRATON

Aldiss, (1991) relates the Archaean structures in the northeast Botswana to have been caused by either three, four or five semi continuous phases of regional deformation. The sequence of events summarised here were discussed by (Litherlands, 1975). The primary deformation in this orogeny comprises of F1 and F2 deformation phases. F1 and F2 folds have the same stretching direction, these are related to compressional forces resulting in interpenetrative deformation. F1 deformational phase is of regional scale and was followed by G1 plutons and G2 migmatization. This phase gave rise to vast isoclinal folds with amplitude on a scale of hundreds of kilometres. The second phase of deformation (F2) is more prominent in the field as compared to F1 however this dominance does not mean it is of greater magnitude strain than F1. F2 (a) is regarded as F2 late-stage major shearing and cuts across existing S₂ fabric. The last phase of primary deformation accompanied M5 retrogression and related A3 gold veins, some areas also experienced K-feldspar metasomatism. F3 deformation affected the G3 granites, B3 meta dolerites and A4 vein phase. Litherlands, (1975) suggest that F3 follows closely upon G3 due to the evidence of flow folding on the granites as compared to the brittle F3 folding on the gneisses. F4 deformation causes small scale brittle shears and forms structures such as crenulation and strain slip cleavages. This deformation folds the lineation common to the previous phases. A5 veining followed F4 deformation and G4 granites marked the last event of the orogeny.

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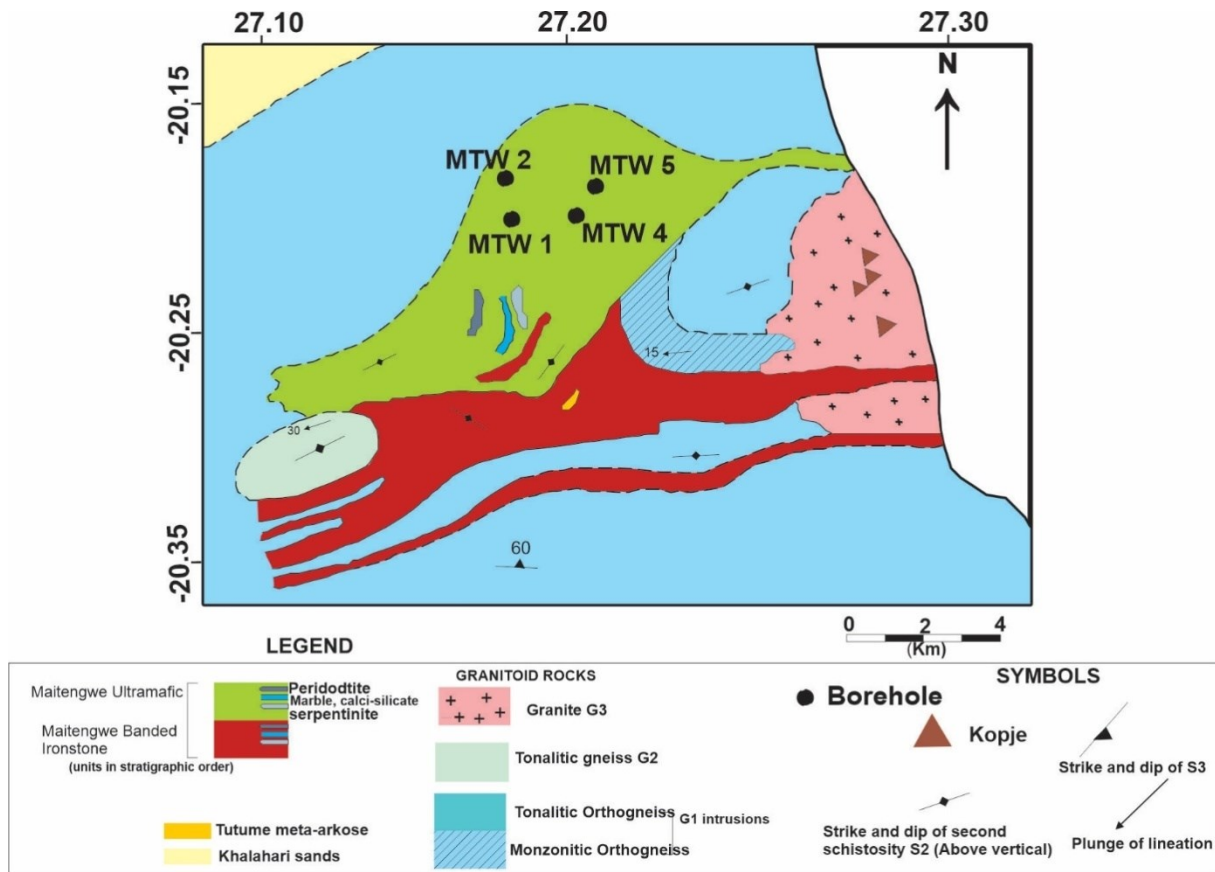


Figure 2.2: Local geology in Maitengwe greenstone belt modified from (Litherlands, 1975)

2.4 LOCAL GEOLOGY

Litherlands, (1975) divided the Maitengwe group in lower Maitengwe Banded Iron Formation (BIF) overlain by the Maitengwe Ultramafic Formation. Maitengwe greenstone belt comprises of three sequences of metasedimentary and metavolcanics namely: The Mpapho banded ironstone formation, The Mazuwe Amphibolite and The Sokwane quartz sericite schist (Chatupa, 2000).

Mpapho Banded Ironstones

These rocks are readily recognised in the aeromagnetic map because of their high magnetic response (figure 3.1). They depict minor tectonic deformation as they remain uniformly

STUDY AREA

banded over hundreds of metres along strike. The Ironstones are associated with bands of with serpentinite marble and calci-silicate, iron free chert and minor ultramafic schist. Amphibolite is more distinctively intercalated with the ironstones towards top of the formation. Lenticular rich layers of iron oxides (hematite and magnetite) also occur in this formation though with limited vertical and horizontal extent. The banded ironstones stand out as ridges whereas the amphibolite is low lying.

Mazuwe Amphibolite

These unit consist mainly of amphibolite, ultramafic schist and are interbedded with thin ironstones, calci-silicates, serpentinites and marble/carbonates. Chatupa, (2000) notes three types of amphibolites; dark grey to black weakly foliated amphibolite with sparse felsic minerals, gray-greyish green medium to coarse amphibolite with quartz/carbonate alteration and lastly extensively foliated actinolite/tremolite (ultramafic) schist. The last-mentioned amphibolite type was observed on most outcrops whilst the first two were observed from drill cores. Most of the amphibolite exposure showed evidence of S_1 and S_2 tight folding with vertical plunges. The banded ironstones in this formation have less silica content as compared to those in Mpapho Formation and they show extensive tectonic deformation demonstrated in the tight folding.

Sokwane Quartz Sericite Schist

Presence of this rock type was observed from drillholes as there were no exposures in the area Chatupa, (2000). Quartz sericite schist was observed in drill hole MTW1 and MTW2 dipping north at high angles. The base of The Sokwane formation is inferred to be intersected in drillhole MTW 2, extensive alteration is noted at this contact, this could be a possible shear contact. A conglomerate unit was intersected in MTW1 drillhole and this validate the sedimentary origin of the felsic rocks.

STUDY AREA

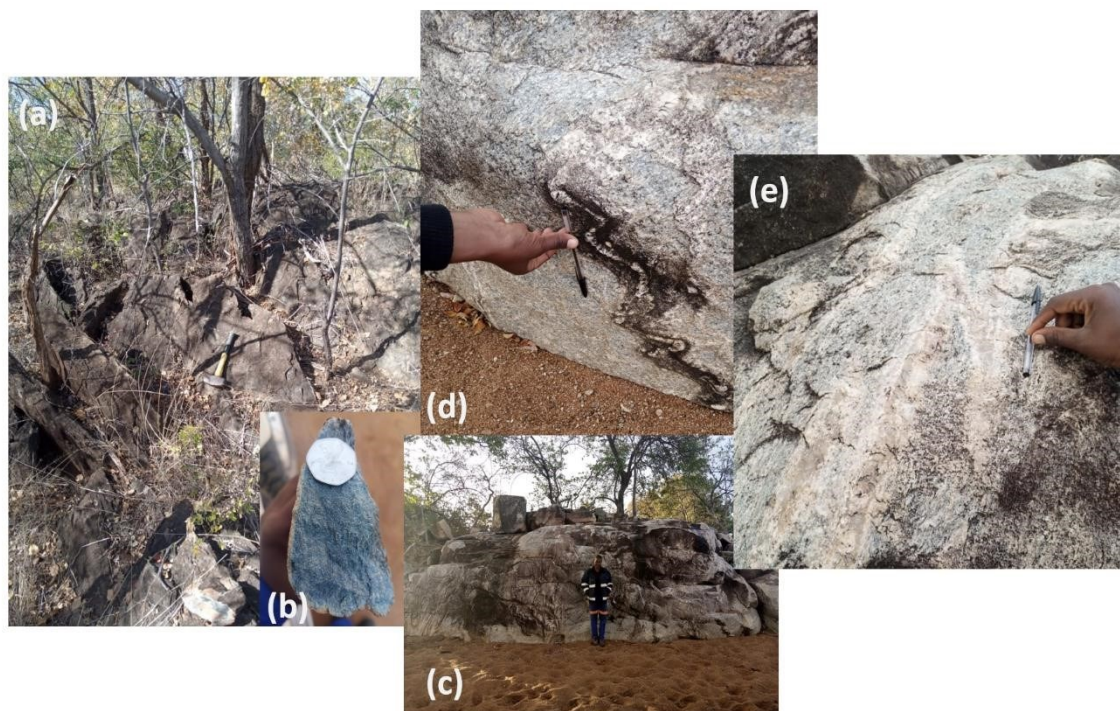


Figure 2.1: Shows local outcrops. (a) is a mafic rock outcrop dipping SW and (b) is the fresh surface of the outcrop. Exposed on river section (b), (c), (d) are granitoids showing deformation/folding of the quartz veins.

2.5 DRILLHOLE INFORMATION AND MINERALISATION

The drill program carried out by Department of Geological Survey in this area was to determine the stratigraphy of the belt and explore for gold and base metal mineralisation potential. Geochemical survey results reveal that Ni and Cr distribution are correlated with soils overlying the greenstones while anomalous values of Cu are related to the Dagwi monzonite and greenstone contact. Mineralisation is largely hosted hydrothermally altered amphibolite and ultramafic rocks. The mineralisation is confined to zones of possible shearing that facilitated passage of hydrothermal fluids. High values of gold (0.01-0.65ppm) were observed in hole MTW 1, at depth range 110-160m. Mineralisation is disseminated occurring as blebs, smears and stringers along carbonate and quartz veins. The drillholes are presented in figure 2.4 below.

STUDY AREA

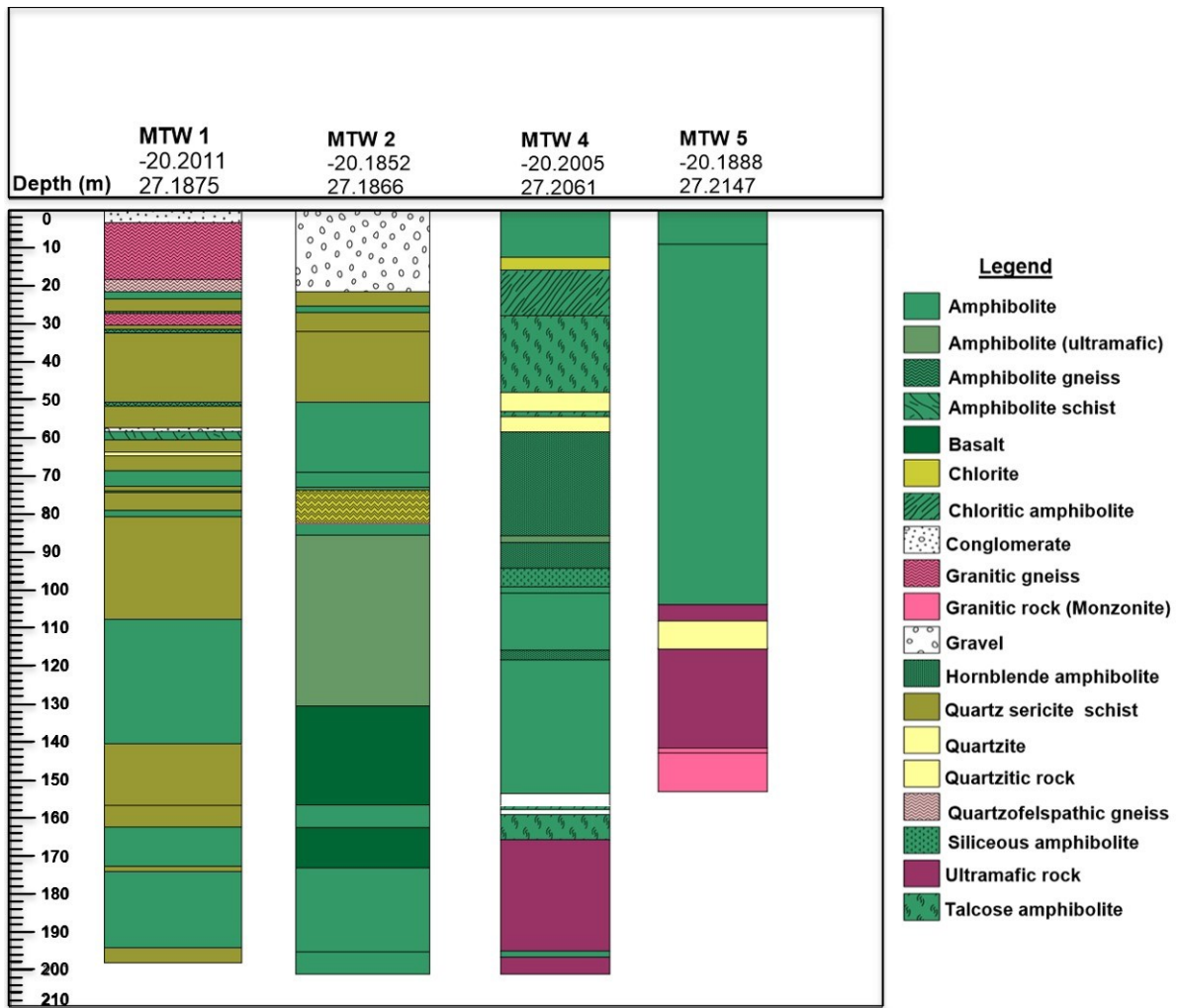


Figure 2.4: Drill borehole of the study area showing the stratigraphy in Maitengwe greenstone belt modified from Chatupa, 2000). MTW 4 is closest to the survey area and therefore used in geological interpretations

CHAPTER 3

HIGH RESOLUTION AEROMAGNETIC DATA

3.1 STRUCTURAL ANALYSIS OF STUDY AREA AEROMAGNETIC DATA

Aeromagnetic data analysis plays an important role in exploration of mineral deposits, delineation of basement structures and lithological mapping. Aeromagnetic maps are a useful aid in reconnaissance geological mapping (Kearey et al., 2002). Several studies have shown the importance of aeromagnetic data in both mineral exploration and understanding the subsurface structure (Leseane et al., 2020; Eldosouky et al., 2017; Robertson et al., 2017; Salem & Ali, 2016; Martinez & Li, 2015; Abu El-Ata et al., 2013; Anand & Rajaram, 2006). Structures such as shears zones, faults and folds affect the localization of mineral deposits by acting as conduits for hydrothermal fluids. The structures can form before or after mineralization event and in some cases formation of the structures and mineralization appear to be nearly synchronous. Mineralization in Maitengwe is confined to specific zones in the greenstones. These are zones of possible shearing where there was sufficient plumbing to facilitate mobilization of hydrothermal fluids (Chatupa, 2000). According to the Botswana Geoscience Institute brochure (2020), the mineralization is controlled by structures such as shear zones, faults and lithological contacts, however from the previous studies no structural interpretation was carried out in the area. It is suggested that further investigations should focus on high strain deformation zones, small-scale splay faults, simple shear zones and lithological contacts which are conduits for Au bearing fluids. The structural analysis of the aeromagnetic data of Maitengwe greenstone belt is conducted to delineate these structures that are targets of interest in mineral exploration.

Magnetic data is a reflection of the variation in the geomagnetic fields due to the magnetic compositions of the subsurface rocks (Innocent et al., 2019). When the earth magnetic fields interact with rocks that are magnetic (high susceptibility) they become magnetised, their fields add to that of the earth. The total magnetic field which is measured in nanoteslas is stronger over magnetic rocks (Scott, 2014). Basic igneous rocks tend to have high magnetic susceptibility due to their relatively high magnetite content as compared to sedimentary rocks which have low magnetic susceptibility. The magnetic methods therefore depend on the contrast in the magnetic susceptibility of the subsurface rocks (Oladunjoye et al., 2016). The main aim of the magnetic surveys is to detect metallic ore bodies through the delineation of the associated anomalies which are usually represented by positive and high magnetic intensity.

HIGH RESOLUTION AEROMAGNETIC DATA

The aeromagnetic data used in this study is obtained from Botswana Geoscience Institute. The surveys were conducted at different times, and sometimes with different acquisition parameters. The Northeast zone aeromagnetic survey was completed in 1997 by Compagnie Generale Geophysique (Maitengwe wellfield development and resource evaluation report., 2002). A total of 33 655 km was flown at 80m clearance over an area of 5520km² along survey lines of 200 m line spacing. Tie lines were oriented 215° SW and spaced 2000 m. The Northeast grid is based on 50m square grid cell and employed the world geodetic system of 1984 (WGS 84) coordinate system. The nation-wide grid of Total magnetic Intensity grid merged from individual magnetic surveys was subject to levelling the high-resolution surveys to the national 2010/11 Tie line Survey. The magnetic base station enabled diurnal correction using the distance-weighting scheme also prior to merging the data was inspected for level of noise, positioning and IGRF corrections (Reford et al, 2013).

3.2 BACKGROUND ON THE TRANSFORMATION FILTERS

The processing of the aeromagnetic data involves applying diverse filters and transformations to the data to enhance subtle anomalies for better qualitative interpretation. Qualitative interpretation comprises of visual inspection of the magnetic signatures, the texture, shape, orientation and subtle offset and truncation of the magnetic anomalies. The Total magnetic Intensity map is enhanced by applying the Reduce to pole (RTP), First vertical derivative (1VD) and Tilt derivative (TDR) logarithms using the Geosoft Oasis Montaj package 9.9.1 version software. Figure 3.1 shows the Total magnetic intensity map of Maitengwe greenstone belt.

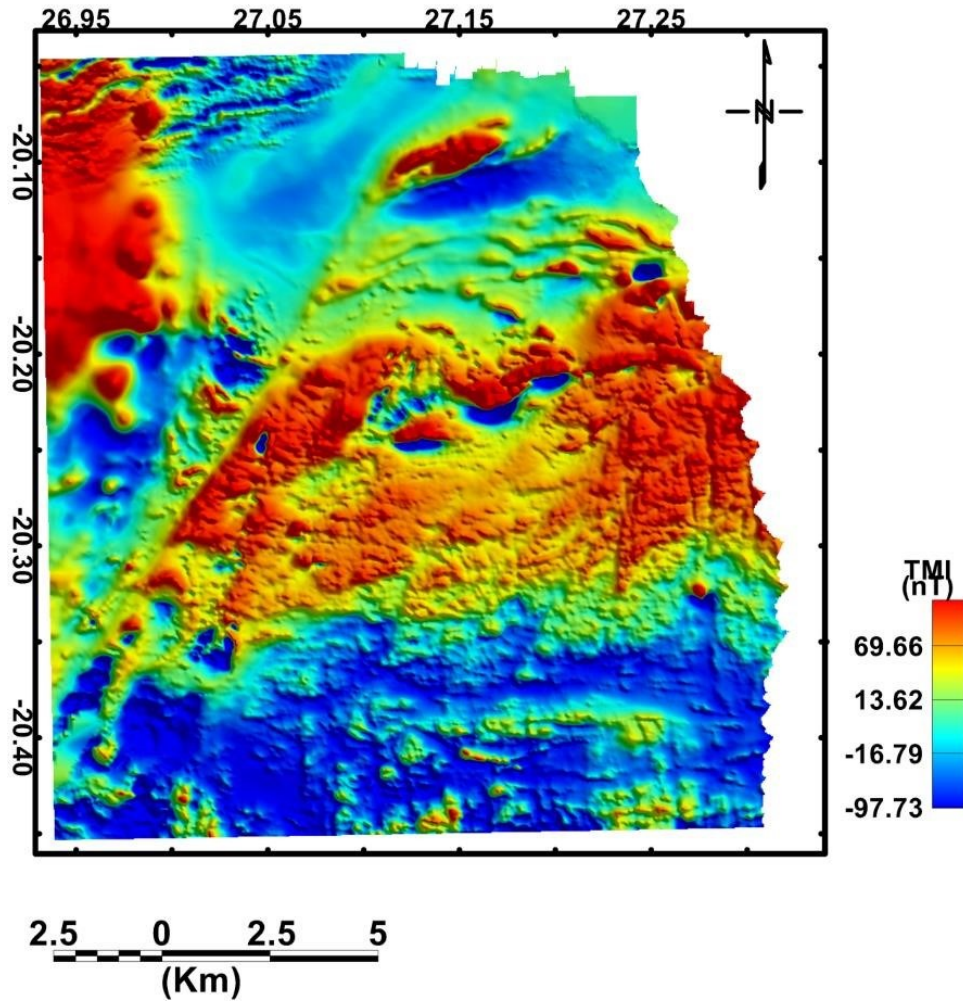


Figure 3.1: Total magnetic Intensity (TMI) map of Maitengwe greenstone belt. The broad east-west trending high magnetic intensity zone is associated with the Maitengwe greenstone belt.

3.2.1 Reduction to magnetic pole technique

The purpose of the RTP filter is to take the observed total magnetic intensity map and produce a magnetic map that would occur had the survey been carried out at the magnetic poles (Subasinghe et al., 2014). Magnetic anomalies observed elsewhere beside the magnetic poles are asymmetric even when the causative body distribution is symmetric, this is caused by the dipolar nature of the geomagnetic field (Ansari & Alamdar, 2009). Therefore, by applying RTP filter, the magnetic anomaly is changed to a symmetrical

pattern that would be observed with vertical magnetisation. The filter shifts the inclined magnetic field that occurs at the mid latitude to the vertical magnetic field at the magnetic poles (Leseane et al., 2020). This is true when the body is almost vertical, and the method is not effective if strong remanent magnetisation is present.

3.2.2 First vertical derivative

In order to enhance and define the edges of the magnetic anomalies, the RTP map was subject to derivatives techniques. One of these is the first vertical derivative, it is the rate of change of the magnetic field in the vertical direction. Applying this filter attenuates the effects of long wavelength anomalies and significantly improves the short wavelengths anomalies that are due to shallow causative bodies (Salem & Ali, 2016). Ibraheem et al., (2019) mentioned that the zero value of the vertical derivative of the RTP magnetic field coincides with the edges of the magnetic anomalies (geological boundaries). The first order derivative is formulated as follows.

$$VDR = \left(\frac{\partial M}{\partial z} \right)^2 \quad 3.1$$

3.2.3 Tilt derivative also known as Local phase

This is the arctangent of the ratio of vertical derivative to the total horizontal derivative and ranges between $-\pi/2$ and $+\pi/2$ (Pal et al., 2017). The half distance between $\pm \pi/4$ gives the source depth whilst the zero contours determine the source boundaries of a vertical source (Oruç& Selim, 2011). The zero contours determine the horizontal location of sudden lateral changes in susceptibility. TDR crosses zero at near or the contact of a vertical source and is negative outside the source hence this is efficient in enabling the anomaly to be traced out along strike. One of the advantages of this edge detection filter is that it can suppress strong

signals at the same time enhancing weaker signals, enabling the study of both signals appreciated (Mousa & Al-Rahim, 2016). The formula for TDR is expressed as follows.

$$TDR = \frac{VDR}{HTDR} \quad 3.2 \quad \text{given} \quad THDR = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2} \quad 3.3$$

3.3 RESULTS AND INTERPRETATION OF STRUCTURAL ANALYSIS

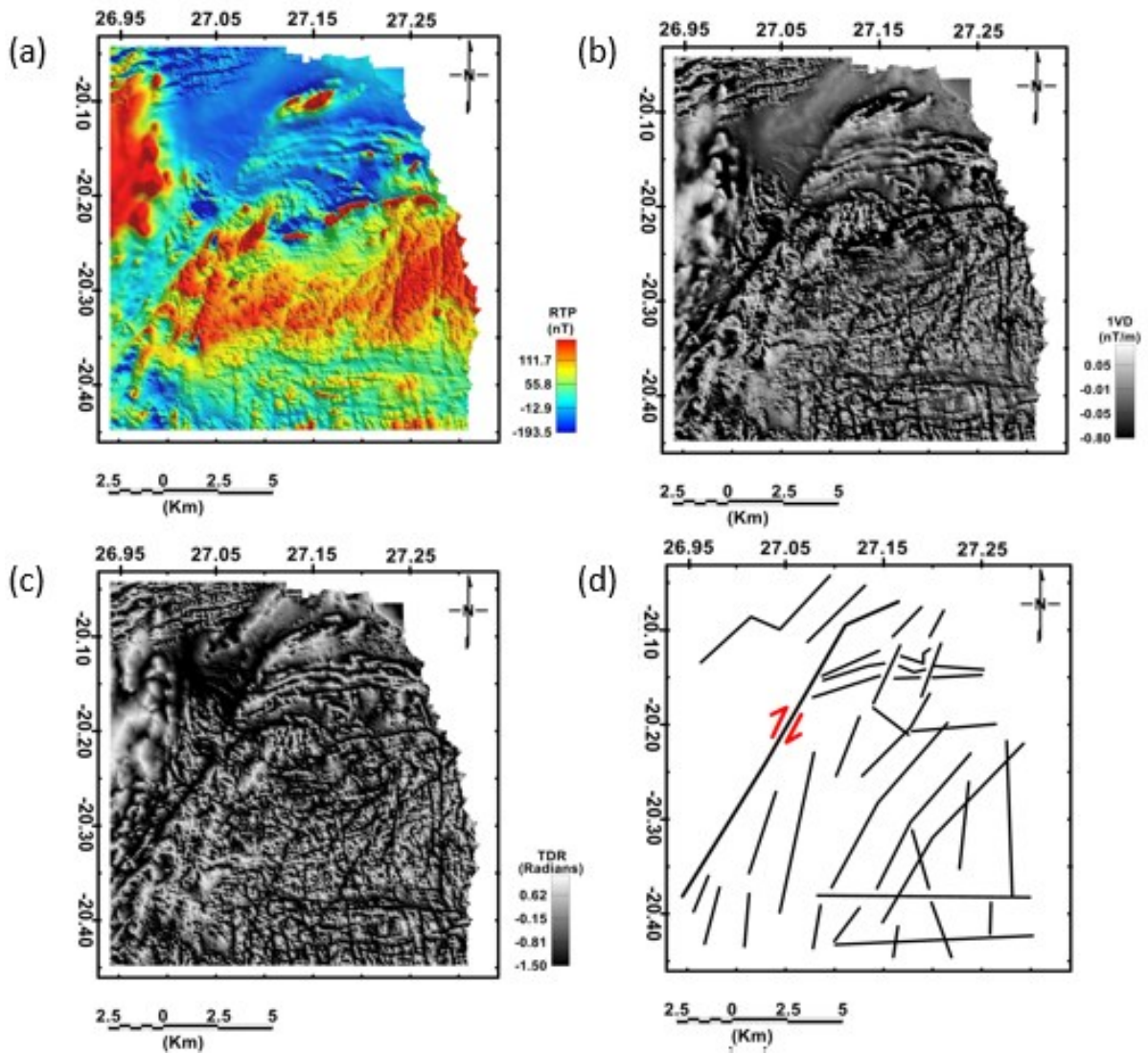


Figure 3.2: Shows the enhanced aeromagnetic maps after applying the various filters. (a) Reduce to pole (RTP), (b) first vertical derivative of (RTP), (c) Tilt derivative of (RTP) and (d) is the delineated lineaments (major shear fault indicated by red arrows showing shear sense).

The aeromagnetic survey area lies between magnetic latitude of -60° and inclination of -10° .

A general look at the RTP map shows a shift in the position of the inherited magnetic anomalies (Figure 3.2(a)). The inclination and declination of the magnetic field has been eliminated, subsequently the anomalies have been placed directly over their respective causative bodies. Textural variation in the RTP map shows major division of basement geology. The map shows a broad magnetic high response at central part of the map represented by reddish orange colours (55.9 nT -112.0 nT). The high magnetic is due to Banded ironstones and the ultramafic rocks in the belt. Low magnetic region represented by the blue colours (-193.9 nT to -12.8 nT) are usually due to sedimentary cover which give a smooth non-magnetic texture. This signature is related to young Khalahari sands and subdues the amplitude of linear magnetic anomalies trending E-W. The north-western part of the map also shows a high magnetic intensity associated with Stormberg lava basalt cover. The southern portion of the map is characterised by a stipple texture that is attributed to the granitoids surrounding the Maitengwe greenstone belt.

Lineament analysis was carried out in the enhanced RTP map using the first vertical derivative and tilt derivative algorithms. Extraction of lineaments was done from both the 1VD and TDR grids displayed in grey scale (figure 3.2 (b) and (c)) which provides better visualization of these structures. Deformational features such as faults, joints, folds are associated with abrupt discontinuity of magnetic anomalies, offsets or truncation in similar magnetic units (Olasunkanmi et al., 2020). Faults can either be magnetic or non-magnetic based on the geologic processes that change the magnetic response along the fault (Leseane et al., 2020).

Linear magnetic anomalies can be attributed to magnetic dykes (figure 3.2(a)). Narrow linear features are visible on both the first vertical derivative and tilt derivative maps (figure 3.2 (b) and (c) respectively). The linear features represented by light colours represent dolerite dykes and dark linear features are related to faulting, shears zone and fractures. The maps depict that the major trend of the structural lineaments is predominately in, NE-SW, followed by NS and minor trend in E-W direction. A major shear fault (figure 3.2 (a)) can be delineated trending in an NE-SW direction, the high magnetic regions terminate in this zone (Maitengwe wellfield development and resource evaluation report, 2002). The linear magnetic lineaments on the north of the maps (figure 3.2 (a), (b) and (c)) also terminate in this zone bound to the right side of the structure. From the visual observations, this could be a shear fault showing a dextral (right lateral) movement. The NE trending non-magnetic lineaments (faults or fractures) parallel this major shear and cut through Maitengwe greenstone belt. These lineaments are quite prominent from the RTP map having no magnetic signature but depicted by the abrupt truncation of the high magnetic units. These structures can serve as conduits for hydrothermal fluids that deposit economic minerals. The broad high amplitude curvilinear or linear anomalies represent the iron stones and the circular high amplitude anomalies are attributed to basic and ultrabasic igneous rocks (Maitengwe wellfield development and resource evaluation, 2002).

After delineating the lineaments, they were digitized using the map tool extension in Oasis montaj software. The resultant map of the delineated lineaments is figure 3.2 (d) and from this exploration target was selected as illustrated in figure 3.3.

PART 1: METHODOLOGY

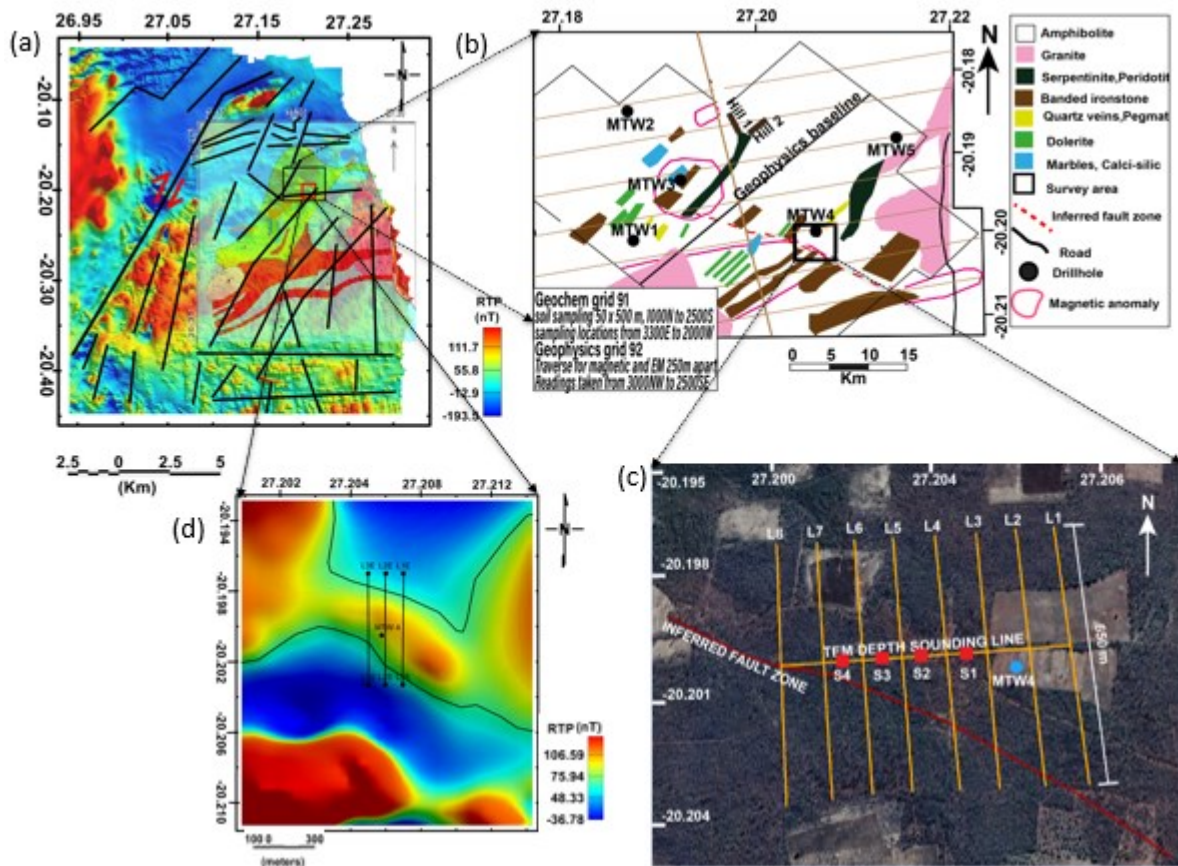


Figure 3.3: Illustrates the selected survey area from the previous geophysical survey anomalies and aeromagnetic data. Figure 3.3 (a) is reduced to pole aeromagnetic map, the insert inside the map is the geologic map of Maitengwe group (Maitengwe banded iron formation in red and Maitengwe ultramafic Formation in green), the black rectangle is the area of previous geological survey, and the selected survey area of the current study is depicted by the red rectangle. Previous geological, geophysical and geochemical survey grid are shown in (b). Inside the figure are drillhole indicated by the black circular dots (Drillhole MTW4 is shown inside the selected survey area) and the magnetic anomalies shown as pink circles. The survey design is depicted in (C), the IP-ERI survey lines run in SSE to NNW direction. Cutting across these line is the TEM depth sounding line, sounding points are represented by the red rectangles. Aeromagnetic signature of the survey area (d) shows the extent of the potential mineralized ultramafic unit, outlines by the black lines, the first three line and borehole MTW 4 are also included for reference

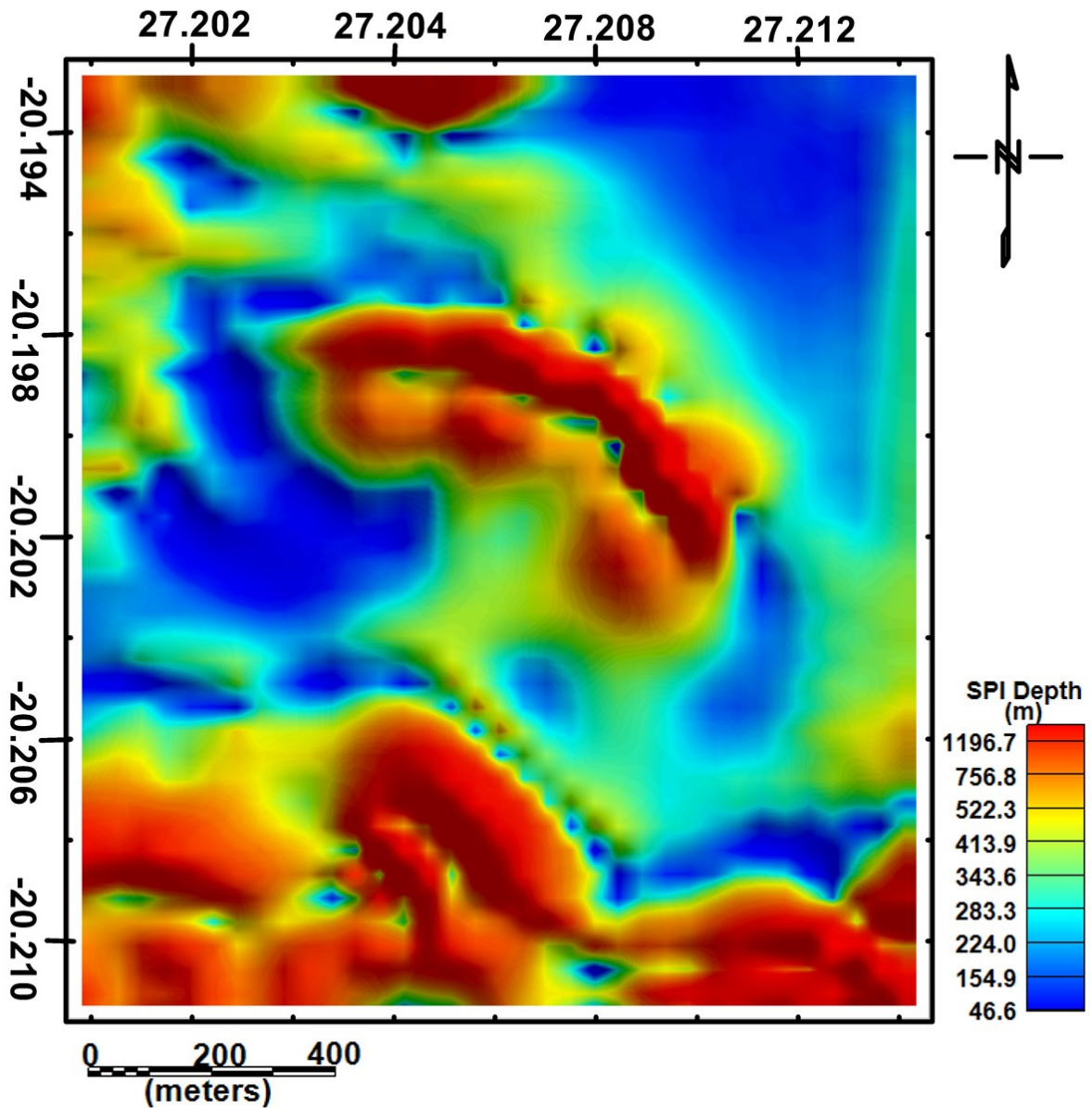


Figure 3.4: Shows the Source Parameter Imaging (SPI) map. SPI method calculates the depth to magnetic sources. It can be noted that the anomaly associated with the mineralized ultramafic rock unit outlined in (Fig.3.3(d)) is located at deeper depth of 1196.7 m. The orange to red colors on the map legend shows deep sources whilst the blue colors indicate shallower depth.

CHAPTER 4

THEORY: BASIC PRINCIPLES OF METHODS

4.1 DIRECT CURRENT RESISTIVITY

This is a surface geophysical technique in which electrical current is injected into the ground through two electrodes and the resulting potential difference (voltage) is measured. Electric current flows through earth materials in two ways that is: Electronic conduction and electrolytic conduction. The resistivity is determined from Ohms Law using the potential difference between two electrodes for a known current (Okpoli, 2013; Loke, 1999). The current electrodes configuration (A, B) denoted by C1 and C2 respectively in the figure 4.1 below is known as the transmitting dipole. The potential electrode pair (M, N) denoted by P1 and P2 respectively in the figure below are the measurement dipole.

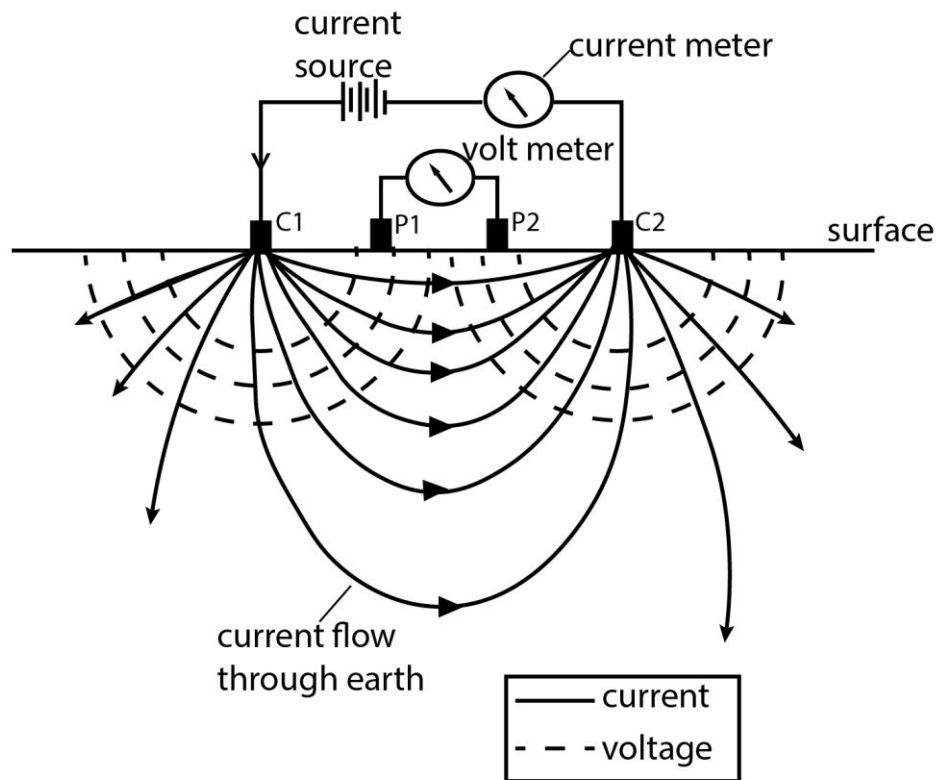


Figure 4.1: Basic concept of DC resistivity measurements (ASTM International guide, 2010)

4.1.1 Measurement Principle

Considering an electronically uniform cylinder with length (L) in meters(m) and constant cross section (A) in m^2 , through which current (I) in Amperes (A) is passing, the material of the cylinder will resist the conduction of the electrical current through it, resulting in a potential drop in Volts (V) between the opposite faces (Reynolds, 2011).

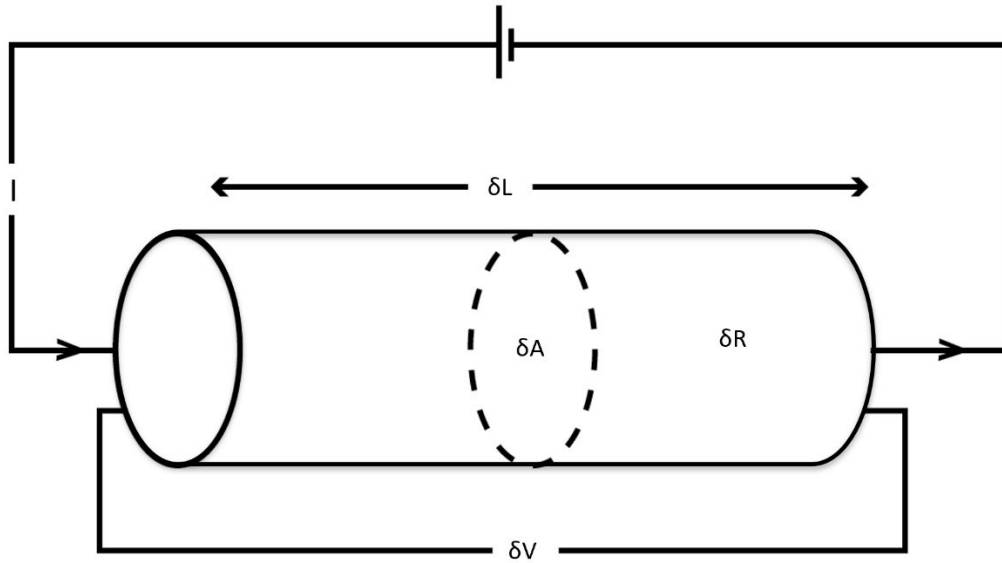


Figure 4.2: Demonstrates current flow through a conductor (Kearey et al., 2002)

The resistance is the constant of proportionality given by

$$R = \frac{\Delta V}{I} \text{ Eq.(4.1) with units of Ohms } (\Omega)$$

We also know that for a material the resistance is directly proportional to its length and inversely proportional to its cross-sectional area so that

$$R = \frac{\rho L}{A} \text{ (4.2) OR } \rho = \frac{RA}{L} \text{ (4.3)}$$

Resistivity (ρ) is given as Ohm-metre, Ωm . Electrical resistivity is how a material resist a steady electrical current flow.

The inverse of resistivity, $\frac{1}{\rho}$ is the conductivity (σ) which has units of Siemens/meter

(S/m), equivalent to $\Omega^{-1}m^{-1}$. It is a bulk property that describes how well a material allows current to flow through it. Electrical resistivity surveys are founded on Ohms Law which controls the current flow in the ground and can be represented in vector form (Okpoli, 2013; Loke, 1999) as follows:

$$J = (4.4)$$

Where;

J is the current density (A/m^2),

σ is the electrical conductivity in (S/m), or $\Omega^{-1}m^{-1}$

E is the electrical field intensity in V/m

Apparent resistivity and geometric factor

The field measurements of current and voltages are converted to apparent resistivity, which is a weighted average of the resistance of earth materials to current flow. The earth is not homogenous, hence the measurements we get are an average resistivity of the earth below the measuring site within a certain depth range. Geometric factor (k) depends on the geometric spreads of the electrodes and contributes a term that has unit length (m). The term is defined by the following expression;

$$K = 2\pi \left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB} \right]^{-1} \quad (4.5)$$

Where the ground is not homogenous, the resistivity calculated is known as apparent resistivity (ρ_a) (Reynolds, 2011). The measured voltage with injected current is converted to apparent resistivity by a geometric factor that considers the air-earth interface as defined by the equation below

$$\rho_a = k \frac{\Delta V}{I} \quad (4.6)$$

Where ρ_a is *apparent resistivity*, ΔV , I is the induced current and k is the geometric factor (depends on electrode array configuration)

4.1.2 Resistivity value for rocks, soils and ore types

Resistivity of a rock or soil is dependent on factors such as porosity, nature of pore electrolyte, saturation degree, connectivity of pores etc. Sandy soils are more resistive than clay rich soils.

Generally, metallic sulphides such as pyrite, galena and magnetite are conductive. Hematite and sphalerite when pure have high resistivities (insulators) but when combined with impurities they tend to be good conductors (Reynolds, 2011). The nature of the ore body (massive or disseminated) affects the resistivity. Igneous and metamorphic rocks tend to have the highest resistivities, sedimentary rocks have the highest conductivity due to their high pore fluid content and metamorphic rocks have intermediate but overlapping resistivities.

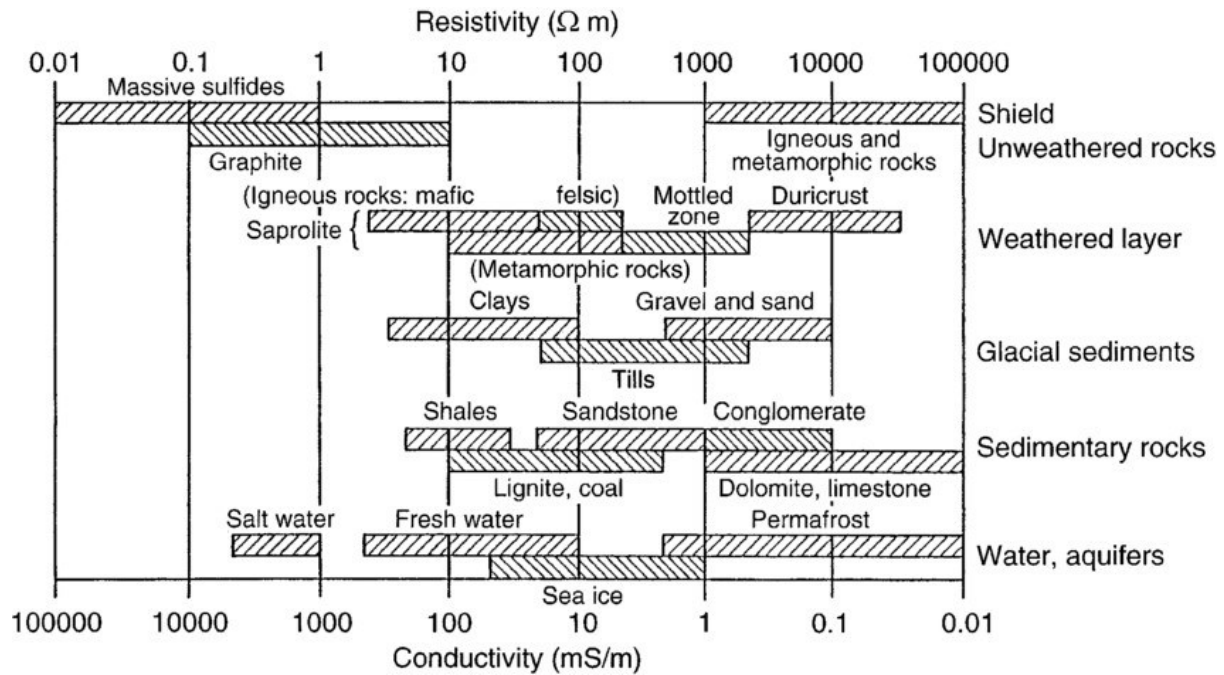


Figure 4.3: Different resistivities of the earth materials (Kafri et al., 1997)

4.2 INDUCED POLARISATION METHOD

IP technique determines the electrical chargeability of the ground, the method is based on electrically charging the ground to detect those materials that can store electrical charges for some time (Martinez et al., 2019). This ability of a material to store a charge is called chargeability (measured in mV/V). Minerals such as pyrite, pyrrhotite, chalcopyrite, Sphalerite, graphite, galena, bornite, magnetite exhibits a strong IP effect. This geophysical method is widely used for exploration for ore bodies principally disseminated sulphides (Orozco et al., 2012; Langore et al., 1989)

When a current is injected into the ground, the ground charges up that is polarises and acts as a capacitor. Once the current is switched off, the induced charge takes some time before it dissipates (Kearey et al., 2002). The amount of charge retained and the time it takes for the charge to be acquired and diffused is characteristic to a particular material in the ground. The

rate of decay of the induced polarisation potential is dependent on the lithological properties of the rock, pore geometry and water saturation (Lesmes and Frye, 2001). Induced polarisation surveys always include resistivity measurements because the same potentials used to acquire apparent resistivity also measure chargeability.

For IP to occur, the presence of fluid filled pores in a material is essential. Most rock forming minerals are poor conductors of electricity therefore electric current in unmineralized rocks is carried by water in fractures and pore spaces (Sumner, 2012). The absence of pores and electrolyte will result in no appreciable IP effect and very high resistivity of the medium. Electric charge transfer in a porous medium occurs in two pathways: electrolytic conduction and surface conduction (Kemna et al., 2004). Even though IP phenomena are still unclear, two mechanisms of electrochemical processes namely, Membrane and Electrode polarisation are generally accepted mechanisms that explains the IP effect at frequencies below 1kHz (Sogade et al., 2006).

4.2.1 Membrane polarisation

It is due to variations in the mobility of ions in the pore fluids, also referred to as ‘normal’ IP effect (figure 4.4 (a)). Non-metallic minerals, most importantly clay minerals are the source of this IP effect. They have a negative surface charge and when in the presence of an electrolyte e.g water attract cations and forms an electrical double layer on the particle surface. This causes a build-up of positive ions (cation cloud) which may extend 1mm into the pore fluid. When the size of the pore diameter is less than 1mm, and a voltage is applied then the negative ions will accumulate on one side of the pore and leave the other (Titov et al., 2010; Kemna et al., 2004). Once the voltage is cut off the ions return to their equilibrium position resulting in a voltage decay. Membrane polarisation is greater when the rock contains clay

scattered throughout the matrix and when the pore fluid is saline (Kemna et al., 2004; Telford et al., 1990).

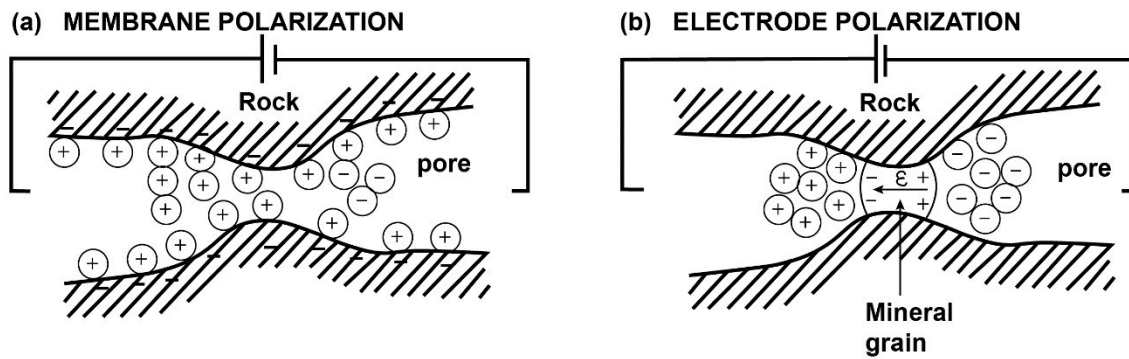


Figure 4.4: Induced polarisation (IP) mechanisms (Kearey et al., 2002).

4.2.2 Electrode polarisation

This occurs at the transition between electrolytic and electronic conduction at the interfaces between pore fluids and metallic minerals (figure 4.4 (b)). It is larger than the ‘normal’ IP effect (membrane polarisation). The presence of metallic minerals in the rock, provide an alternative electronic path for current flow. The metallic mineral blocks or are next to a pore fluid path and current is applied to the rock, an electrochemical potential (Overvoltage) build up between the electron conducting mineral and the pore electrolyte (Sogade et al., 2006). These electrochemical forces that oppose the flow of current are described as polarising the interface. The increase in voltage required to drive the current through the interface is known as Overvoltage (Sumner, 2012). When targeting metallic ores though, the interest is obviously in overvoltage effect.

Table 4.1: Table showing chargeability values of different earth materials measured in a lab (Defourney et al., 2020)

Material Type	Chargeability (mV/V)	Material Type	Chargeability (mV/V)
Pyrrhotite	~10	20% Sulphides	2000–3000
Pentlandite	~10	8%–20% Sulphides	1000–2000
Pyrite	13.4	2%–8% Sulphides	500–1000
Copper	12.3	Volcanic tuffs	300–800
Graphite	11.2	Sandstone, Siltstone	100–500
Chalcopyrite	9.4	Dense volcanic rocks	100–500
Magnetite	2.2	Shale	50–100
Galena	3.7	Granite, Granodiorite	10–50
Hematite	0.0	Limestone, Dolomite	10–20

4.2.3 INDUCED POLARISATION MEASUREMENTS

General

IP measurements can be made in either time domain (*pulse transient measurements*) or frequency domain (*frequency variations*) (Sumner, 2012). In Time domain what is measured is the decay of voltage between two potential electrodes after current cut-off. Whereas Frequency domain determines apparent resistivity of the ground by applying various frequencies of the applied current (Kearey et al, 2002). The choice of the measuring method is a matter of desired sensitivity and availability of equipment. Time domain measurements are usually favoured due to their rapidity as compared to other measurements (Ahmed et al., 2020).

Time domain induced polarisation

It measures the decay of voltage between two potential electrodes after transmitted positive and negative current has been switched off to get apparent chargeability (M_a) which is the measure of strength of IP effect (Ali et al., 2020). M_a is given by the ratio;

$$M = \frac{V_S}{V_P} \quad (4.7)$$

Where V_P is the ON-time measured voltage (primary voltage) and V_S is the OFF-time voltage (Secondary voltage) (Sumner, 2012). It is not easy to measure voltage at instant turn off due to large transient caused by breaking the current circuit (Reynolds, 2011), so it is measured at specific times after cut-off. On the other hand, secondary voltage must be measured before residual has decayed to noise level. The measured parameter in time domain is the area under the decay curve of Voltage V_t which is corresponding to the time interval (t_1, t_2) as illustrated in figure 4.5. Another way of defining the curve is the integration of these values with respect to time which gives the area under the curve. Dividing the integral with V_P gives chargeability which has units of time (milliseconds) (Ali et al., 2020).

It is expressed as:

$$M = \frac{1}{V_P} \int_{t_1}^{t_2} V_t dt = \frac{A}{V_P} \quad (4.8)$$

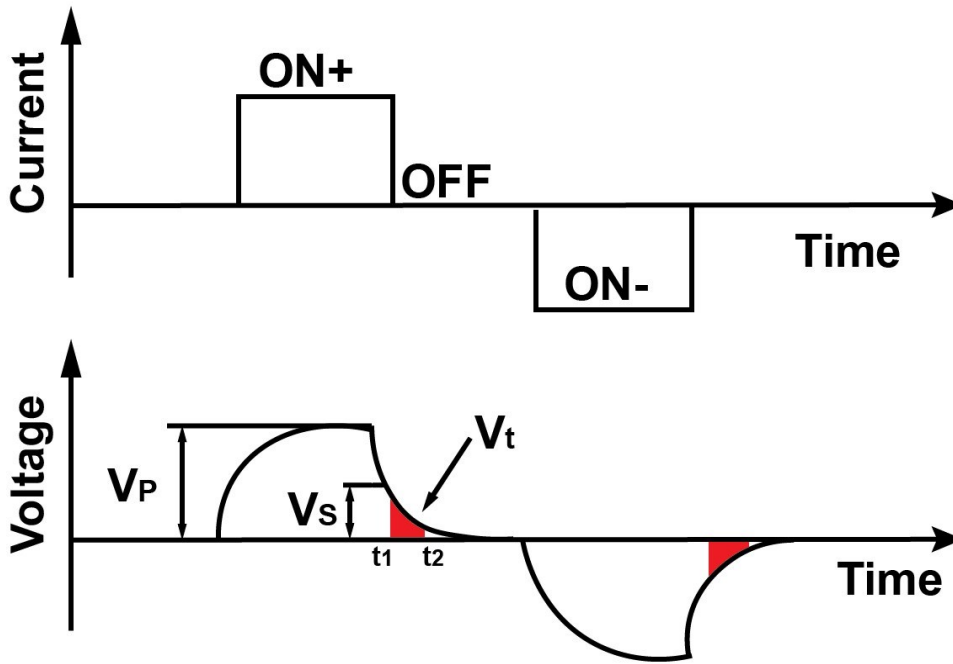


Figure 4.5: Time domain waveform (Ali et al., 2020)

Frequency domain induced polarisation

Measurements in frequency domain can be made at two or more frequencies less than 10Hz for instance (0.1 and 5Hz) using similar electrode array and resistivity measurements as in time domain. The measured parameter is the steady state response after filtering and the derived parameter is the **Frequency effect (FE)** expressed as

$$FE = \frac{V_L - V_H}{V_H} \quad (4.9) \quad \text{or} \quad FE = \frac{\rho_{aL} \rho_{aH}}{\rho_{aH}} \quad (4.10)$$

In eq. 4.9 and 4.10, V_L and V_H are the steady state voltage at low and high frequencies respectively. Equation 4.11, represent the respective apparent resistivities, ρ_{aL} and ρ_{aH} at low and high frequencies respectively. The apparent resistivity at low frequencies is greater than the apparent resistivity at higher frequencies due to resistivity of the rocks decreasing as the

alternating current is increased (Reynolds, 2011). For a weakly polarisable material in which the FE is less than 1, the frequency effect is equal to the chargeability in the time domain. The two frequencies used in the FE can also be expressed as the Percent frequency factor (PFE) as follows:

$$PFE = \frac{\rho_{aL}\rho_{aH}}{\rho_{aH}} * 100 \quad (4.11)$$

The frequency effect equation was revised by (Marshall and Madden., 1959), to give the *Metal Conduction Factor (MF)*. The metal factor parameter is believed to be effective in delineating the disseminated sulphides ores as compared to the Frequency effect data. Metal factor is used to compensate for the variations in effective resistivity of the host rock, as well as changes in the pore fluid and size, temperature that are not related to the capacitive effect of the metal content (Telford et al., 1990). It is derived from the FE equation and written as:

$$MF = A \frac{FE}{\rho_{aL}} \text{ or } MF = A * FE * \sigma_{aL} \quad (4.12)$$

Where ρ_{aL} is the apparent resistivity at low frequency, σ_a is the apparent conductivity

($\rho_{aL} > \rho_{aH}$ and $\sigma_{aL} < \sigma_{aH}$) at lower frequency, $A = 2\pi * 10^5$ and FE is the frequency effect.

The units of Metal factor are $\Omega^{-1} \text{ m}^{-1}$.

4.2.4 SOURCES OF NOISE

The IP measurements obtained in the field are a result of many sources including the desired ground response of the current injection. These sources include Telluric currents, capacitive coupling, self -potential background drift, spikes, harmonic noise and electromagnetic coupling effect etc (Olsson et al., 2016). Other sources of noise are powerlines, fences,

railway lines and pipelines. Fortunately, noises from man-made electrical instruments rarely operate in the IP frequency range of interest. The use of filters to eliminate unwanted noise is an appropriate way of improving signal to noise ratio of the IP receiver. Low band filtering can be used to reject frequencies from powerlines and radio interferences at threshold of 10Hz. Self-potential noises are usually from electrochemical reactions in the ground within the vicinity of the profile. They usually have low amplitude with unstable frequencies. In case of polarisation by electrode, one way of reducing this problem is to switch the polarity of the current (Ali et al., 2020). The use of non-polarising electrodes also offers greater stability in measurements especially when current is being injected for longer period (Martinez et al., 2019).

According to Telford et al., (1990) there are four irrelevant signals of which three being Telluric noise, self-potentials, current electrode variations that are seen as noise in IP measurements. The other, electromagnetic inductive coupling occurs at higher frequencies and must be measured and eliminated.

Telluric noise

These currents continuously flow through the earth and are caused by either natural or human activity. Telluric currents cause similar anomalous effects to those met in resistivity survey; their direction may differ, but they are usually parallel to the subsurface. Their effect is removed using alternating current. At each direction change of current, the telluric current alternately increase or decrease the measured voltage by similar magnitude, adding the output over various cycles provides the true potential difference effect (Kearey et al., 2002).

Capacitive coupling

Refers to current leaks from high potential surfaces or conductors to low potential surface or conductors. Capacitive coupling is a voltage variation due to electrical leakages from current and voltage electrodes and wires. It is normally small enough to be negligible unless the wires insulation is defective. In borehole logging where the wires are very close to each other, its necessary to use shielded wires. In order to reduce the effects of capacitive coupling, it is necessary to distance the receiver and transmitter and for this reason the double dipole array is usually preferred since the transmitter and receiver have large distance between them (Telford et al., 1990).

Electromagnetic Inductive coupling

This is the most challenging effect in IP measurements, occurs mostly in deep surveys that uses long wires and large electrode interval and higher frequencies also pronounced in conductive environments. It can be removed theoretically from the field data hence improving the quality and interpretability of the data (Hallof, 1974). When current cables lie close to or parallel to voltage cables, current is induced in latter, as a results spurious voltage will be measured. It is best to keep current cables from voltage cables as far as possible from each other usually 10m apart (Keary et al., 2002) or cross them at right angles. Electrode array such as Double dipole and Pole- Dipole are usually employed to minimise the effect of EM coupling (Brown, 1985) and the frequencies usually kept below 10Hz.

4.2.5 ELECTRODE CONFIGURATIONS

Electrode configuration in electrical survey consist of electrode combinations of A-M-N-B with gradual increasing distances among them for consequent combinations. There are several ways to position electrodes in order to inject current and measure the potential difference. The

choice of an array depends on depth of investigation, sensitivity, resolution and signal-noise ratio amongst others. The value of the apparent resistivity is affected by the geometry of the array used as defined by the geometric factor (k). In each array, the four electrodes used are colinear, the difference is in their spacing and geometries. Resistivity surveys are carried out either in soundings or profiling. Vertical electrical soundings (VES) detect lateral changes in resistivity whereas lateral profiling aim to detect lateral changes with resistivity (Abraham et al., 2013). By increasing the separation of current electrodes this increases the depth of penetration.

The following electrode arrays are usually employed in geo-electrical surveys:

Wenner Array

This array was first initiated for geophysical prospecting by Wenner (1916) (Zohdy et al., 1974) and most of the early 2D surveys were carried out with this survey. The four electrodes are arranged linearly on the ground surface such that the spacing between them is: $AM = MN = NB = a$ as illustrated by in figure 4.6 (a). The Wenner array has almost horizontal contours beneath the center of the array making it more sensitive to vertical changes (Horizontal structures) in ground resistivity below the midpoint of the array. On the other hand, it is weak in delineating horizontal changes that is narrow vertical structures. The array has moderate depth of investigation, the median depth of investigation is 0.5 times the 'a' spacing (Loke, 1999). Wenner array has strong signal strength, and this is useful in areas with high background noise.

Schlumberger Array

It is widely used in electrical prospecting; the electrodes are placed the same way as in the Wenner array but with $AM \geq 5MN$ (Abraham, 2013; Zohdy et al., 1974) refer to figure 4.6 (b). The potential electrodes are at the center of the array with smaller spacing typically less than

one fifth of the current dipole separation. The current electrode spacing is progressively increased whereas the potential electrodes dipole remains the same until measured voltage becomes negligible (too small to detect). Schlumberger array is less time consuming when it comes to field set up, has greater depth of investigation and better resolution as compared to Wenner array. On the downside it requires longer current carrying cables and the recording instrument has to be sensitive.

Dipole-Dipole Array

It is mostly employed in resistivity/ IP surveys because of low EM coupling between the current and potential circuits. In this array, the current electrode is next to each other at spacing 'a', the potential electrodes are also placed besides each other at spacing 'a', the current and potential dipoles are separated by distance 'na' (Loke, 1999) as shown in figure 4.6 (d). The contour patterns are almost vertical as n is increased therefore this array is most sensitive to resistivity variation beneath the electrodes in each dipole pair and is also sensitive horizontal variations in resistivity. The method is weak detecting vertical changes hence poor in mapping structures such as sills and sedimentary layers. The depth of investigation depends on the both the current dipole spacing and the separation between the dipoles and is generally shallower than that of the Wenner array (Okpoli, 2013).

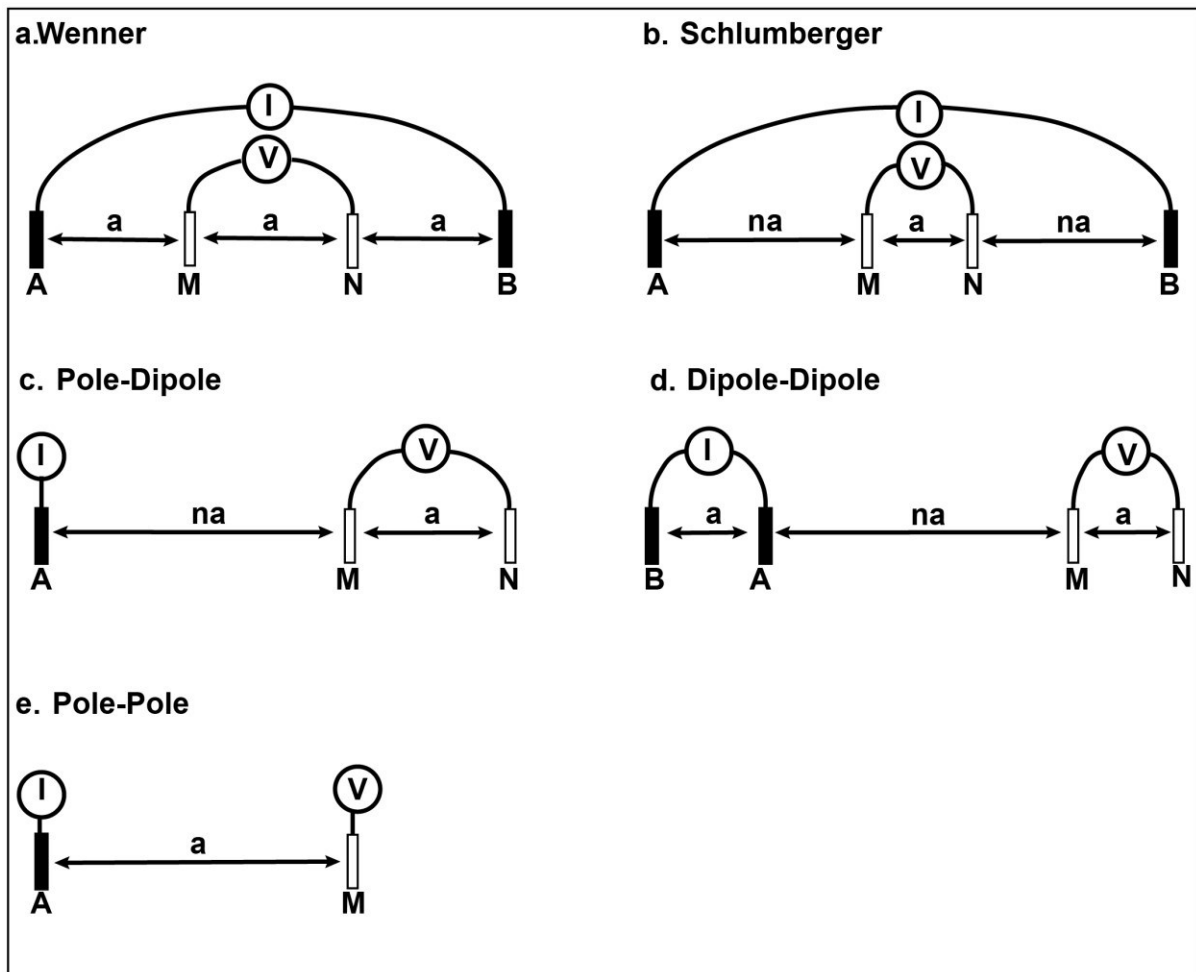


Figure 4.6: Some of the commonly used electrode configurations (Thibaut, 2017)

Dipole-pole array

The electrode configuration is similar to the Double dipole except one current pole is placed far away. The distance between the potential dipole is 'a', the distance between the closest current electrode and the potential is 'na' as illustrated in figure 4.6 (c). The effect of the current electrode placed at infinity is negligible, and the electric field of the closest current pole resembles that of a point source rather than the field dipole. The best sensitive values lie below the potential electrodes. The configuration is asymmetrical and over symmetrical structures the resistivity anomaly pseudo-sections are asymmetrical. In order to remove the asymmetry effects, measurements from forward and reverse pole-dipole array. This array has good horizontal coverage, deeper depth of investigation, has higher signal strength, and less

sensitive to telluric noise and has low EM coupling compared to double dipole (Okpoli, 2013). On the other hand, the method is time consuming and labour intensive.

4.3 ELECTROMAGNETIC METHOD

This geophysical method measures the response of the ground to the propagation of electromagnetic fields consisting of alternating electric intensity and magnetising force (Kearey et al., 2002). The primary or inducing field is generated by passing an alternating current in a loop or wire but natural sources can be utilised (energy from thunderstorms). EM surveys are employed in the exploration for sulphides ores, since these are good conductors, they can be delineated in contrast to their host rock. One advantage of EM surveys is that the acquisition is much faster, because no physical contact is required with the ground compared to electrical methods.

Principle of Electromagnetic waves

EM waves have two orthogonal components namely electric intensity (E) and magnetising force (H) in a plane perpendicular to direction of travel (Reynolds, 2011). Maxwell's equations are the mathematical formulation of laws that describes the behaviour of electromagnetic fields, they comprise of two vector equations and two scalar equations (Zhadnov, 2009). Equation 4.15 and 4.16 explain how the EM can propagate on its own. A changing electric field produces a changing magnetic field, and the produced magnetic field produces a changing electric field (Erkan, 2008). This cycle goes on enabling the EM waves to move through space. The following are Maxwell's equations

PART 2: METHODOLOGY

1. Gauss Law; Electrical field mapping is equal to charge density divided by permittivity of free space. Relates electric field to electric charge.

$$\nabla \cdot E = \frac{\rho}{\epsilon_0} (4.13)$$

2. Gauss Law for Magnetism; The net magnetic flux out of any closed surface is zero, magnetic monopole doesn't exist.

$$\nabla \cdot B = 0 (4.14)$$

3. Faraday's Law; A changing magnetic field produces an electric field

$$\nabla \times E = -\frac{\partial B}{\partial t} (4.15)$$

4. Ampere's Law; A changing electric field produces a magnetic field

$$\nabla \times B = \mu_0 J + \mu_0 \epsilon_0 \frac{\partial E}{\partial t} (4.16)$$

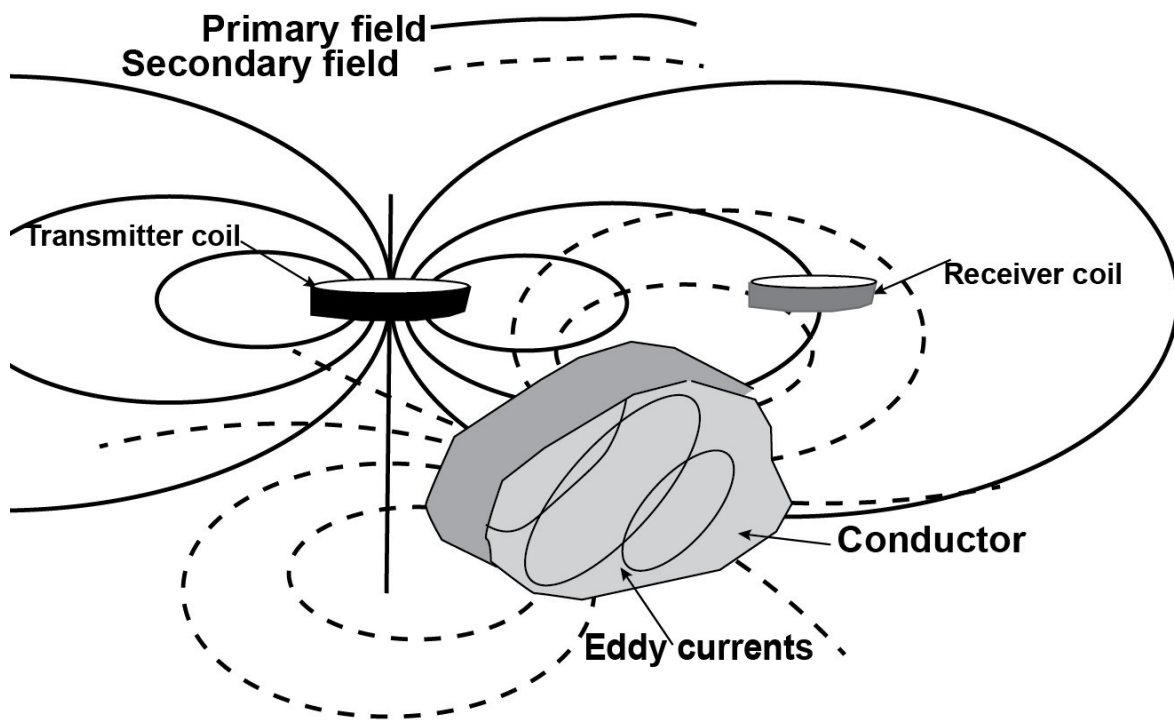


Figure 4.7: shows the basic principle of EM geophysical method (Cunningham, 2013)

Figure 4.7 above portrays how induced electromagnetic wave propagate in the subsurface. In a homogenous earth there is no difference in fields propagating above the surface and in the ground except for a slight reduce in the field propagating in the ground compared to those above. In heterogenous earth, where a conductive body is present, eddy currents are induced in the conducting body (Cunningham, 2013). The magnetic component of the primary field propagating in the ground induces alternating currents termed ‘eddy currents’ to flow in the conductor (Faraday’s Law). The eddy currents produce a secondary magnetic field that is captured by the receiver coil (Ampere’s Law). At the receiver the arriving primary and secondary field differ in phase and direction from the primary field alone, it is this difference that reveal the presence of a conductor (Kearey et al., 2002). The degree to which

these components differ gives valuable information about the geometry, size and electrical properties of the subsurface conductor.

4.3.1 TIME DOMAIN ELECTROMAGNETIC SYSTEM

EM methods can either be passive or active. Passive methods make use of naturally occurring ground signals whereas active methods utilise artificially induced current signals either in the near field or far field (Reynolds, 2011). TDEM also known as transient electromagnetic method measures the decay of electromagnetic field in the subsurface with time after current is cut off. The current is induced in a loop making it act as a magnetic coil. The transmitter current is abruptly interrupted resulting in decay of the magnetic field (Bucker et al., 2017). The signal is transmitted in pulses and measurements are made in between each pulse (Law et al., 2019). The decaying secondary field diffuses like a smoke ring (Bucker et al., 2017). They propagate deeper into the subsurface as time increases. The observation time ranges from microseconds to several milliseconds and decay of the eddy current is directly related to the subsurface conductivity. Depth of exploration ranges from few meters to hundreds of meters depending on the factors such as the set-up configuration, subsurface properties and background noise (Goncalves et al., 2017).

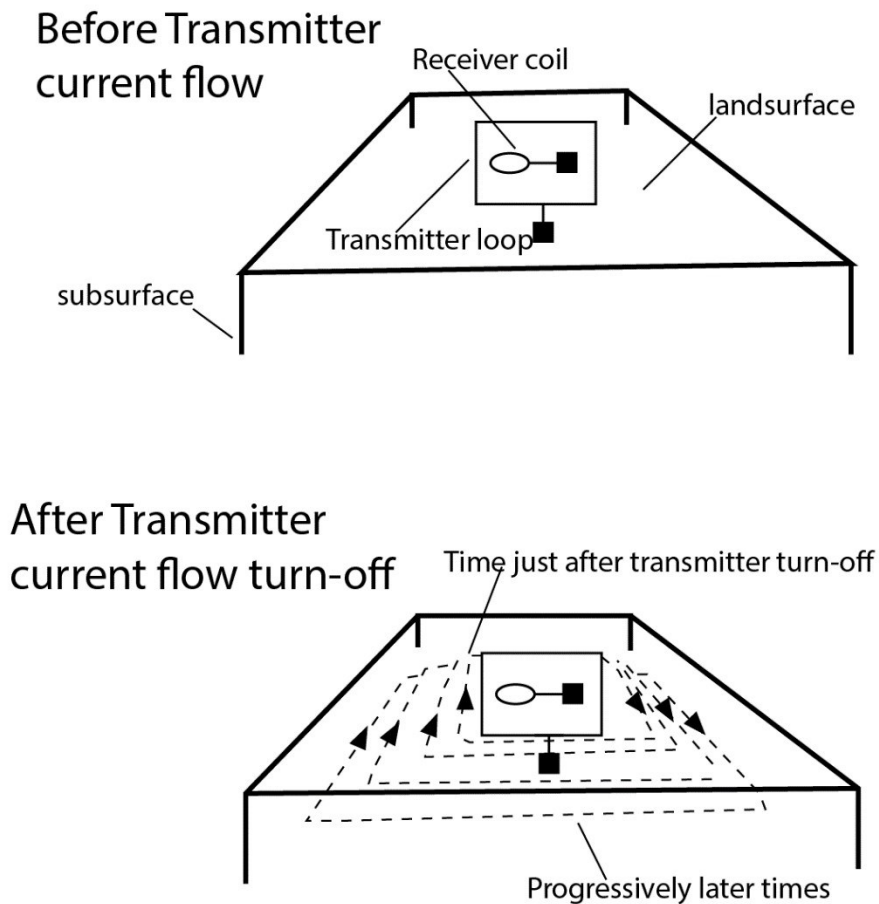


Figure 4.8: Schematic diagram of transient electromagnetic method (www.usgs.gov)

Depth of penetration of electromagnetic waves

The depth of penetration of an EM wave depends on the frequency and conductivity of the medium in which it is passing through. Electromagnetic fields attenuate gradually with depth. The depth of penetration also known as the skin depth, can be described as the depth d , at which the amplitude of a plane wave has reduced to 37% or $1/e$ of its original amplitude (Reynold, 2011). Depth of penetration is inversely proportional to frequency and conductivity of the ground. Keary et al., (2002) expressed Skin depth d as follows;

$$d = \frac{503.8}{\sqrt{\sigma f}} \quad (14.7)$$

4.4 INVERSION

Inversion intends to recover subsurface distribution of a physical property from measured field data (Liu and Xiong, 2018). Inversion recovers a physical property model which fits the observed data and is also geologically reasonable. The computer program (Res2DINV™ or Res3DINV™) determines a model that could be a representation of the actual measured values (Loke, 2003). The model is constrained by model parameters, and these are physical quantities we seek to estimate from the observed data. The model denoted by **(m)** and the dataset denoted by **(d)** are related by a function **G** forward operator, such that;

$$G(m) = d \quad (4.18)$$

The observed data however contain some amount of noise from instruments reading and numerical round off (Li and Xiong, 2018; Oldenburg and Li, 2014). The dataset can then be represented as observation from field measurements, **d_{true}** contaminated by a noise factor **η**, such that

$$d = d_{\text{true}} + \eta = G(m_{\text{true}}) + \eta \quad (4.19)$$

In the above expression **m_{true}** is the true model that satisfies the expression **G(m_{true}) = d_{true}**, that is the real distribution of the physical parameter (resistivity /chargeability) on the subsurface. There are an infinite number of models that exist that matches equation (4.1), this is called non-uniqueness of data inversion. The forward operator is based on finite difference of finite difference scheme that would reproduce the observations **d** given an estimated model **m**. This operation is called forward modelling whereas finding **m** given **d** is

the inverse problem (Astere et al., 2018; Liu and Xiong, 2018; Parker, 2014; Yanovskaya, 2003) expressed as;

$$\mathbf{m} = \mathbf{G}^{-1}(\mathbf{d}) \quad (4.20)$$

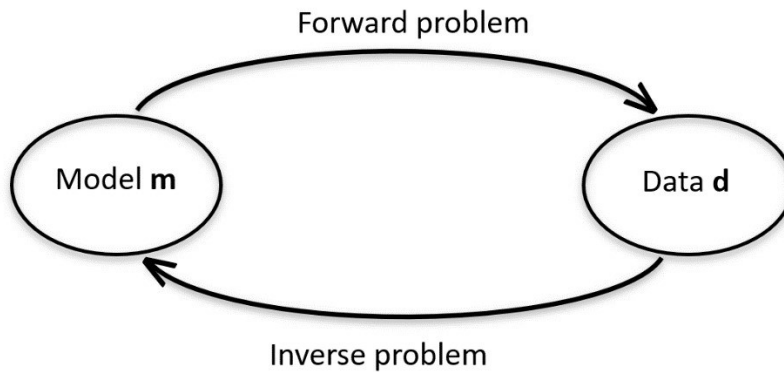


Figure 4.9: Diagram portraying forward and inverse problem (Li and Xiong, 2018)

Res2DINV and Res3DINV softwares uses a cell-based method in which the model parameters are the resistivity values of the model cells whereas the data is the measured apparent resistivity values rectangular blocks in the inversion software's (Loke, 2003). The finite difference and finite-element method provide a mathematical link between the model parameters and the model response. Optimization methods work by iteration process to reduce the difference between the model response and the observed data values (Oldenburg and Li, 2014; Loke, 2003)

There are three questions that arise from the solution of any inverse problem (Liu and Xiong, 2018; Zhadnov, 2009)

- 1) Does the solution exist?
- 2) Is it non-unique?

3) Is it stable?

The method of solution can be based on linear or nonlinear inversion techniques as well as various approaches such as least square and gradient-type methods (Zhadnov, 2002). The inversion problem is said to be ill-posed if it does not meet one of the following requirements: The solution should exist over the entire data space, the solution should be unique and lastly it should be stable (Aster et al., 2018; Zhadnov, 2002).

EXISTENCE OF THE SOLUTION

Liu and Xiong (2018) noted that it should not be expected to always find an exact physical model that matches the observed data. The solution to inverse problem is usually a class that simplifies the model. The problem must be a quasi-solution that is a solution that best fit the observed data from a selected model class (Zhadnov, 2002). The solution to an inverse program exists when there is m_δ such that;

$$\|d_\delta - (m_\delta)\| \leq \delta \quad (4.21)$$

Where δ denotes the measurement error and m_δ denotes some measure of difference between the predicted data $A(m_\delta)$ and the measured data d_δ .

NON-UNIQUENESS OF THE SOLUTION

Even for a number of infinite data points an exact solution may exist however it may be non unique, this is common in potential fields (Aster et al., 2018). Two types of inversion problems are to be distinguished when analysing inversion problems namely inversion model (Inverse scattering) problem and the inversion source problem (Liu and Xiong, 2018).

According to Blok and Oristaglio, (1995) one importance of inverse model problem is that the different location of sources can be chosen to illuminate the medium being investigated.

Inversion source problem on the other hand is more ambiguous due to the distribution that produces zero external fields. A detailed analysis on this type of non radiation source is given by Bleistein and Cohen (1977).

STABILITY OF THE SOLUTION

Computing inversion problems can be unstable, that is a small change in measurements for example in noise component (η) can bring about significant changes in the estimated model (Aster et al., 2018). This condition is referred to as ill-posed in case of continuous systems and ill-conditioned in case of discrete linear systems. Regularization is an important aspect that results in a usable solution to an otherwise ill-posed or ill-conditioned inversion problem (Zhadnov, 2002; Aster et al., 2018)

CHAPTER 5

DATA ACQUISITION AND PROCESSING

5.1 IP-RESISTIVITY SURVEY EQUIPMENT AND PARAMETERS



Figure 5.1: IP-ERI geophysical equipment employed in the survey.

The survey was conducted over 8 profiles, each with 700 m length. Line spacing between survey lines was 100 m and electrode spacing at 50 m. The profiles were oriented in NNWSSE direction, acquisition begun at the south towards the north of the survey lines (figure 3.3 (c)). The current electrode was offset by -50 m from the first potential electrode placed at 0 m on the profile. The receiver electrodes (porous pots) were connected to the

Elrec Pro receiver through multi- electrode potential cable. The receiver has 10 channels and the Dipole- pole array was selected for deeper depth of investigation which was at 200m.

5.1.1 FIELD OPERATIONS

The 3-phase generator powered the transmitter (figure 5.1). Direct current pulses were injected into the ground from the VIP 5000 transmitter through the current steel electrodes. Current in amperes transmitted depended on the load of the transmitter. The pulses were set at 4 seconds ON and OFF time duration. The potential electrode contained a saturated Copper II sulphate solution that covered the copper coil inside the porous pots. The resistance of the ground around the receiving pots was kept below 1 Kilo-Ohms, wet muddy soil was used to achieve this. At the current electrode, the resistance of the ground was kept at minimal by adding salt water to ground around the electrode when current transmission was off.

During ON time, the Elrec pro receiver measures the potential difference at the potential dipole (MN). The receiver then automatically calculates the apparent resistivity of the ground based on the injected current (I) strength, primary voltage (V_p) and the dipole-pole array configuration. Voltage decay (residual/secondary voltage) was measured during the period when there was no current transmission (OFF-TIME). The receiver automatically calculates the apparent chargeability using the ratio between the primary and the secondary voltage (V_s).

Quality of the data was achieved by setting the Quality assurance parameters in the Elrec pro receiver. The data was stacked and the standard deviation of the apparent chargeability and resistivity data set at 3%. The solution in the porous pots was checked adequately and kept at constant, the cables were also insulated to avoid current leakages. The challenge encountered

during the survey was the high contact resistance of the infinity pole. A tie line across the profiles was not achieved because of the high resistance of the pole that would not reduce despite all attempts. The survey was also conducted in an area of arable fields and during the planting season, so we had to shift some of the lines to avoid these fields and where possible we had permission to access the fields.

5.1.2 RESISTIVITY AND IP DATA INVERSION

After data acquisition the data was transferred from the receiver instrument to a computer for processing. Prosys II software was utilised to eliminate bad data points (outliers). Once the data quality was satisfactory, the data was exported in a .DAT format which is readable in the inversion software. The inversion of the data into models was carried out by the RES2DINVTM software. Preliminary inversion of the data enabled further data editing. The Root Mean Square errors (RMS) were displayed as bar charts and moving the line on the chart selected data points to be eliminated. Data points that are removed are ones further away from the line of best fit of the apparent resistivity and chargeability. The software uses a smoothness constrained least square method for the inversion routine (Loke, 2003). For a 2D model, the program divides the subsurface into rectangular blocks and appoints resistivity values that agree with the actual measurements to produce pseudo-sections. The Gauss-Newton optimization method used here minimizes the difference between the calculated and measured apparent resistivity by adjusting the resistivity of the blocks (Loke, 2003). A measure of the difference is called the RMS error and in this case the models the selected models were ones with less than 10% RMS errors. Figure 17 below shows the RMS error analysis for profile 5.

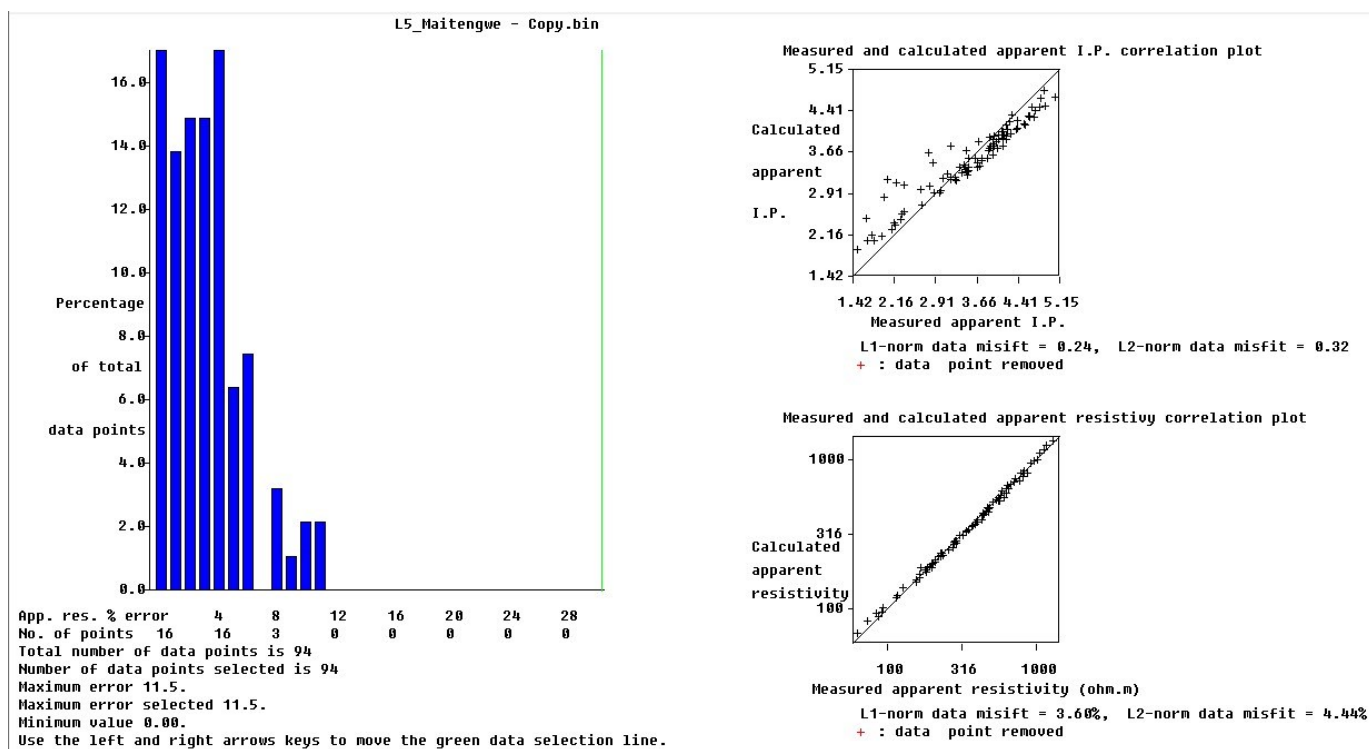


Figure 5.2: Root mean square error analysis of profile 5.

5.2 TIME DOMAIN ELECTROMAGNETIC SURVEY EQUIPMENT AND PARAMETERS



Figure 5.3: TEM data acquisition equipment employed in the survey

The TEM data was collected at four depth sounding points and with a single square- loop size of 100 m by 100 m side length. The pulse current in the transmitting loop was set at 3 Amperes with integration time of 15s. The induced voltage was measured using the high frequency -receiver coil (In-loop configuration) and the turn off time was set at 10s.

5.2.1 FIELD OPERATIONS

The measurements were carried out using a loop of wire placed on the ground surface. An alternating current is injected in transmitter coil (Tx) from the TEM47 transmitter which then induces a primary magnetic field into the ground. When the primary electromagnetic fields interact with the subsurface materials where conductors are presents, this induces eddy

currents. This electrical current would then produce a secondary electromagnetic field which contains information regarding the subsurface electrical properties. This field is detected at the surface by the receiver coil (Rx) connected to the Protem-D receiver that measures the rate of decay of the EM field. The rate of decrease is then converted to resistivity by the Protem-D receiver (Lévesque et al., 2021).

5.2.2 TEM DATA PROCESSING AND INVERSION

After acquisition, the data was transferred to a computer over a standard RS-232 port. The data was processed and converted into 1D resistivity-depth models using the WingLinkTM software. Firstly, the raw data from the receiver is converted into a readable extension through the TemMerge program. The bad/inconsistent data points were masked before inversion took place to have high quality data. The amplitude of the measured data reduces over time with the time representing the Pseudo-depth. The variation of the induced voltage (dB/dt) increases significantly and becomes unreliable when the noise level increases and the signal becomes discontinues (Lévesque et al., 2021). For this reason, it is important to remove bad data points. The 1D inversion command in the program enabled the inversion of the selected sounding. After calculating a smooth model, a layered model can be guessed from it by editing the inversion settings. The process involves entering the desired number of layers, layer thickness and resistivities to constrain the model. The inversion process was run with 5 iterations and RMS fitting of less 10%. The inverted 1D sounding models were then exported as images.

CHAPTER 6

RESULTS INTERPRETATION AND DISCUSSION

6.1 2D RESISTIVITY AND CHARGEABILITY INVERSION MODELS

The borehole log (MTW4) closest to the survey lines was used to constrain inversion of the 2D DC/IP models and guide interpretation. Information from the borehole such as the different types of lithology, number of lithological layers and depth guided the input of the model parameters in the inversion software. The inversion results from the Res2DINVTM software were visualised using Oasis Montaj software. The maximum depth of investigation for the inversion models is 210 m. The different colors in the inversion models represent the different resistivity and chargeability values indicated by the color scales below the models (figure 6.1). In the resistivity scale, the lowest values are represented by purple and deep blues, moderate resistivity range between sky blue and the greens, lastly the highest values coincide with the orange. The highest values in the chargeability scale are represented by red and pink colour, moderate values coincide with deep green and yellow, lastly the blue colour is the lowest values of chargeability.

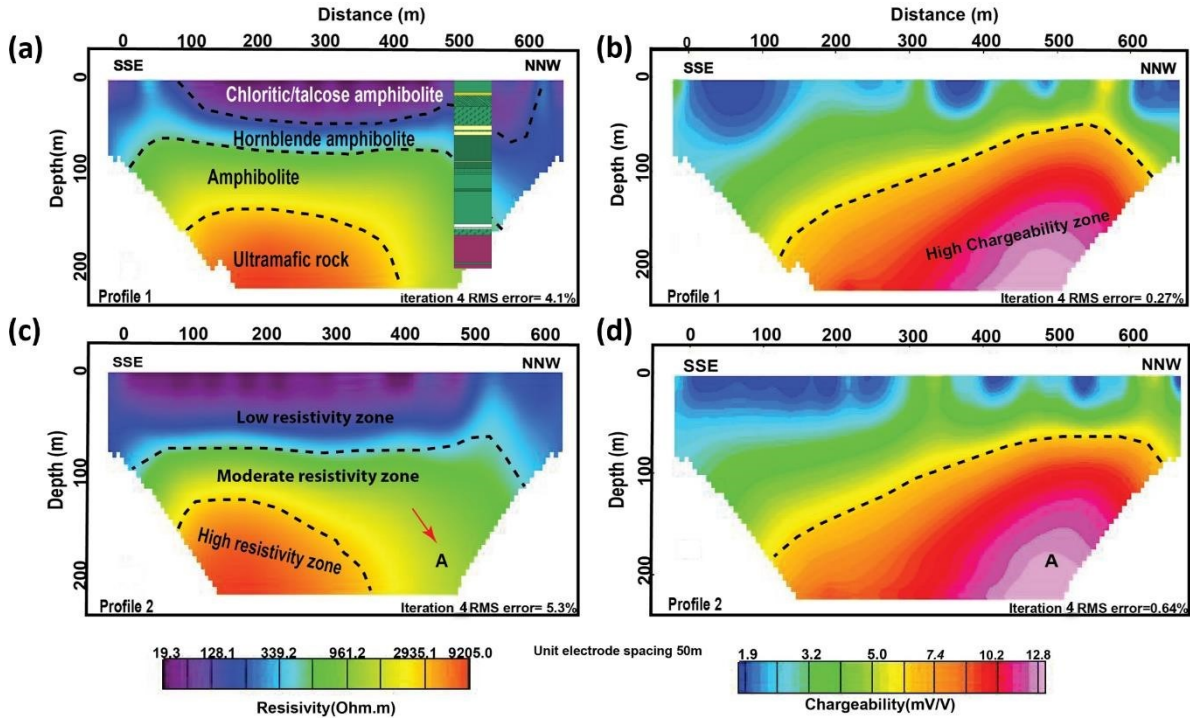


Figure 6.1: Dipole-pole 2D inversion models; (a), (c) are inverted resistivity models and (b), (d) are chargeability models for profile 1-2 respectively. Borehole MTW 4 insert is displayed in (a) to relate the resistivity values of the ERI models to the drilled borehole information. The horizontal axis (0-600 m) is the distance along the profile and the vertical axis represent depth. The black dotted lines on (a) and (c) represent the different resistivity values associated with different lithologies whilst on (b) and (d) these lines outline high chargeability zones which is a zone of interest.

Profile 1 and 2: Resistivity and chargeability inversion models

Fig. 6.1(a) and (c) are 2D inverse resistivity models for line 1 and 2 showing variable resistivity values which tend to increase with depth and extends laterally. The upper part of the models from depth 0- 40 m is characterized by very low resistivity values (19.3 Ohm.m – 128.1 Ohm.m) however these resistivity values slightly extend to deeper part that is around distance 70 m at the far end of the profiles. This layer of resistivity is attributed to chloritic/ talcose amphibolite from the borehole data. Beneath this very low resistivity follows a layer represented by shades of blue color of resistivity values between 128.1 Ohm.m – 339.2 Ohm.m. It is interpreted to be hornblende amphibolite and it extends to

approximate depth of 160 m at the far-right end of the model. The layer also appears at the top-most part of the resistivity model of line 2 at the end of the profile. Moderate resistivity values are attributed to amphibolite, it tends to be shallower at the start of the models in both Profile 1 and 2 and goes to greater depths reaching the bottom of the model toward end of the profiles. The highest resistivity which is also at the bottom end of the models for both Fig. 6.1(a) and (c) is interpreted as ultramafic rock from the borehole data. This high resistive zone does not extend laterally to the end of the profile however, it seems to extend from the beginning of the profile to distance 400m along the profile.

Figure 6.1(b) and (d) are chargeability models for profile 1 and 2 respectively. The chargeability seems to increase with depth. At the top-most part of the model is low chargeability values represented by the blue colours (1.9- 3.2 mV/V). These values reach a depth of 110m at the beginning of the profile and progressively get shallower towards the end of the profile line. The moderate chargeability values follow this least chargeability zone, it is characterised by values 3.2- 6.0 mV/V. This chargeability also extends to the top-most part of the model at distance (300- 700 m). The highest values of chargeability (7.4 - 12.8 mV/V) represented by orange to pink colours, is taken to be the IP anomaly. It starts at depth 100 m to the bottom end of the models; this extends sub-vertically towards the far end of the profile. The anomaly is more prominent at distance 200m until the end of the profile.

The area marked by dotted lines and labelled A in the figure 6.1(b) and (d) corresponds to the zones of high chargeability in the IP models which is considered anomalous. The red arrow on the resistivity model is coincident with this anomaly. Therefore, the zone marked by letter A correspond to moderate resistivity and high chargeability values. This IP anomaly is associated with possible disseminated sulphides mineralisation. Areas with moderate to high

resistivity and high chargeability values corresponds with silicified mineralised zones (Han et al., 2016; Jones et al., 1982)

Profile 3 and 4: Resistivity and chargeability inversion models

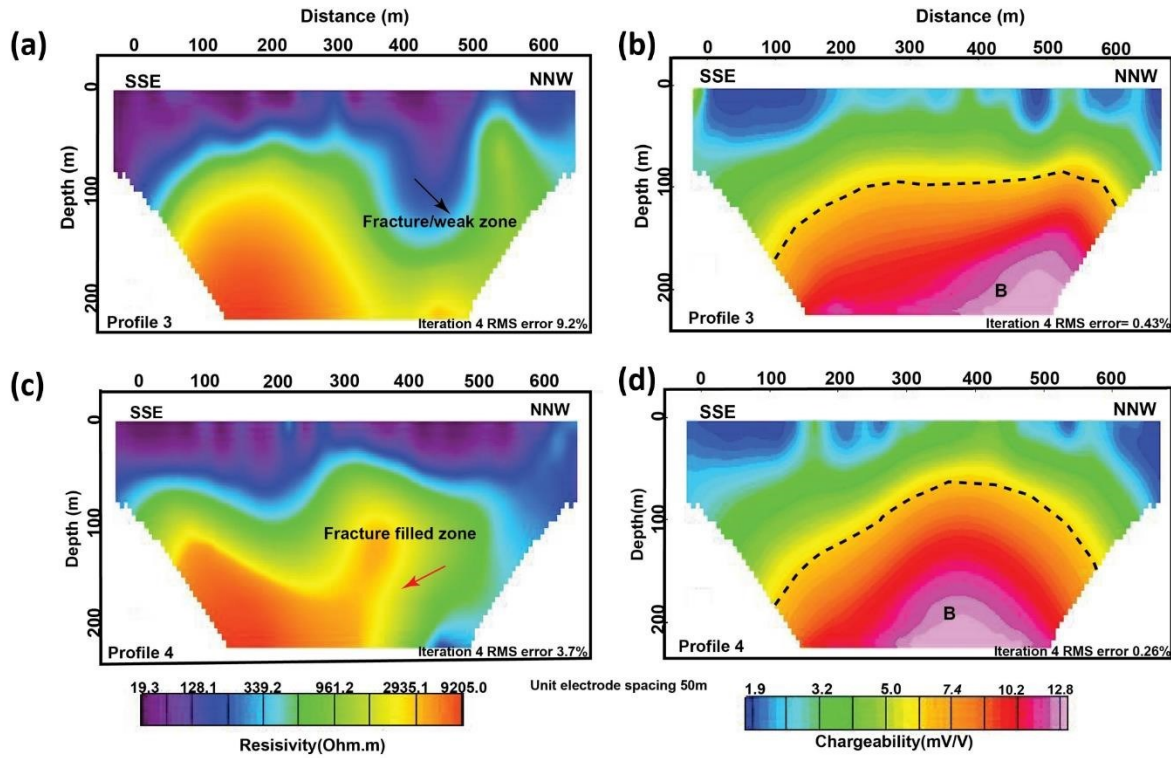


Figure 6.2: Profile 3 and 4 resistivity and chargeability 2D models. The black arrow in (a) indicate a fracture /weak zone and (b) is associated with a fracture filled zone

Figures 6.2(a) and (b) represent the resistivity and chargeability of survey line 3. Figure 6.2(c) and (d) represent survey line 4 resistivity and chargeability respectively. The model in figure 6.1(a) start with a highly conductive zone (low resistivity) but this extends to greater depth around distance 350-500m. The resistivity increases with depth. The high resistivity anomaly seems to be discontinuous at distance 400m in addition the resistivity layers are not laterally extensive as in the Profile 1 and 2. On profile 3 resistivity model at distance 400 m500 m and around depth 100m, it can be observed that the high resistivity anomaly has

significantly reduced and replaced by a vertical low resistivity zone (denoted by the black arrow). This occurrence is related to an extensively altered zone/folding of a sheared zone noted on Borehole MTW4 at depth 150 m. The resistivity model of profile 4 (Fig. 6.2(c)) however shows a linear vertical high resistivity zone at the distance 300-400 m. This zone depicted by the red arrow is probably the occurrence of a fracture-filled vein zone.

The chargeability model in Figure 6.2(b) shows a broad anomalous zone below depth of 100m. The dotted line outlines the high chargeability (anomalous zone) in both profile 3 and 4 chargeability models. In profile 4 chargeability model (figure 6.2(d)) however, the anomaly extends quite vertically at distance 300 m- 400 m compared to figure 6.2(b). Both the anomalies in these figures extend beyond the maximum depth of investigation and beyond the end of the profiles.

It can be observed that unlike the previous resistivity models in figure 6.1 (a) and (c), these figures show some possible fracture/alteration zone and fracture filled zone denoted by the red and black arrows respectively. The borehole information MTW 4 (Fig. 2.4) shows extensive alteration and indication of a shear zone between depth 118m-155m in the amphibolite. In addition, possible fracture/fault is noted at depth 156 m in the weathered talcose amphibolite.

Holmes et al., 1993 noted that the drillhole information in Maitengwe greenstone indicated hydrothermal alteration which they associated with shear zones. The shape of the anomalies in figure 6.2 (a), (c) and (d) which are vertical could be influenced by the presence and orientation of these structures. The high chargeability zone marked B which can be associated with disseminated sulphide mineralisation (high concentration of metallic minerals) is coincident with this zone of possible discontinuation and alteration in the resistivity models.

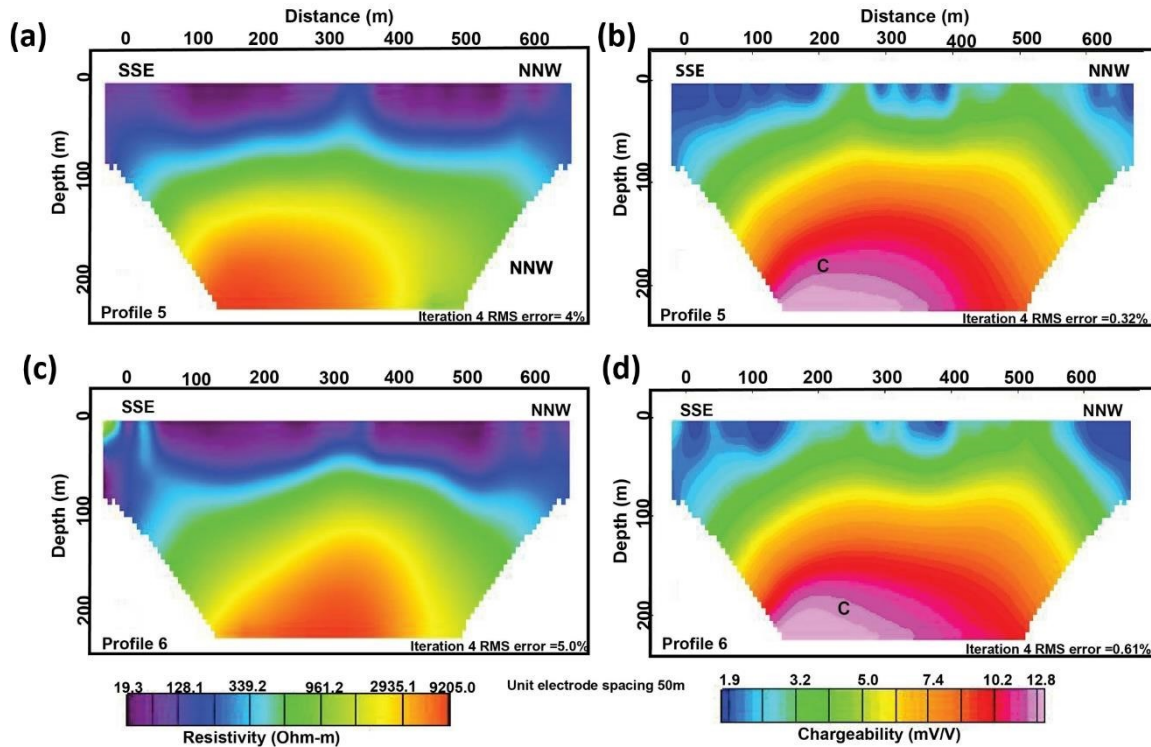
Profile 5 and 6: Resistivity and chargeability inversion models

Figure 6.3: Profile 5 and 6 resistivity and chargeability 2D models. Zone marked **D** is where chargeability values are high hence regarded as anomalous.

Figure 6.3 above represent inversion models for profile 5 and 6 respectively. A very low resistivity zone represented by the purple color (19.3-28.1 ohm.m) marks the upper part of the resistivity models to a depth of around 50m. The high conductivity of this layer could be due to weathering at shallow ground surface. Slight discontinuities are also observed on this zone. From the borehole information this was interpreted to be chloritic/talcosse amphibolite. A moderate resistivity characterises by the green colour start at depth around 110m, this resistivity is shallow at the start of the survey line but extend to greater depth toward the end of the survey lines. On both the resistivity models at depth of 150m, a high resistivity anomaly exists characterised by resistivity values of 9205.0 ohm. m. Unlike other resistivities that seem to be laterally extensive, this anomaly seems to terminate at distance 400 m from

the start of the profile. From the borehole log information this anomaly is attributed to be an ultramafic rock. In figure 6.3(c) this high resistivity zone exhibits an upright elongate shape.

In the IP models, figure 6.3(b) and (d) the chargeability increases with depth. The low - moderate chargeability coincides with low resistivities values in the resistivity models. The highly chargeable zone (7.4 -12.8 mV/V) marked by **C** is broad and laterally extensive in both figure 6.3 (b) and (d). Due to this wide anomaly, it is considered that the possible ore veins in profile 5 and 6 could be laterally developed unlike in the previous models. This IP anomaly is significant at depth 100m and goes beyond the maximum depth of investigation. In Zone **C**, the chargeability anomaly coincides directly with the high resistivity region (Ultramafic rock) in Fig 6.3 (a) and (c) in addition the resistivity models here do not show any discontinuities. It should be noted that there is a shift in the chargeability anomaly from distances 300-700 m in profile 1-4 to distances 0 – 400 m extending beyond the start of profiles 5-6. Such conditions of moderate to high resistivity and high chargeability values are most likely related to silicified mineralized zones (Jones et al., 1982; Han et al., 2016). Similar results were observed in a study conducted by Mashhadi and Ramazi (2018) to identify skarn alteration haloes. The mineralization was found in high resistivity zones associated with Skarn units and observed high IP anomalies were considered to have high sulphide mineralization. In another study by Goldie (2002) and Thompson (2010) large selfpotential anomalies has been observed in silica rocks. The widespread silicification in the silica rocks of the Yanacocha gold deposits gave rise to high apparent resistivity values.

It is also evident that resistivity models can delineate structures and lithological layers as compared to chargeability models. In a study experiment conducted by Revil et al., (2022), it showed that electrical conductivity was not sensitive enough to show the position of pyrite cubes placed in sandbox while IP method showed exactly where the pyrite cubes were located. This is because electrical conductivity depends on the quantity and degree of

connection between mineral grains or veins in the relevant host rock (Dusabemariya et al., 2020). The presence of sulphides as blebs, smears and stringers in fracture zones enriched with quartz veins give rise to a mineral ore with high resistivity and high chargeability response because IP mechanism thrives in dissemination nature of the mineralisation. These zones are targets of interest as they are potential zones of mineralisation.

Profile 7 and 8: Resistivity and chargeability inversion models

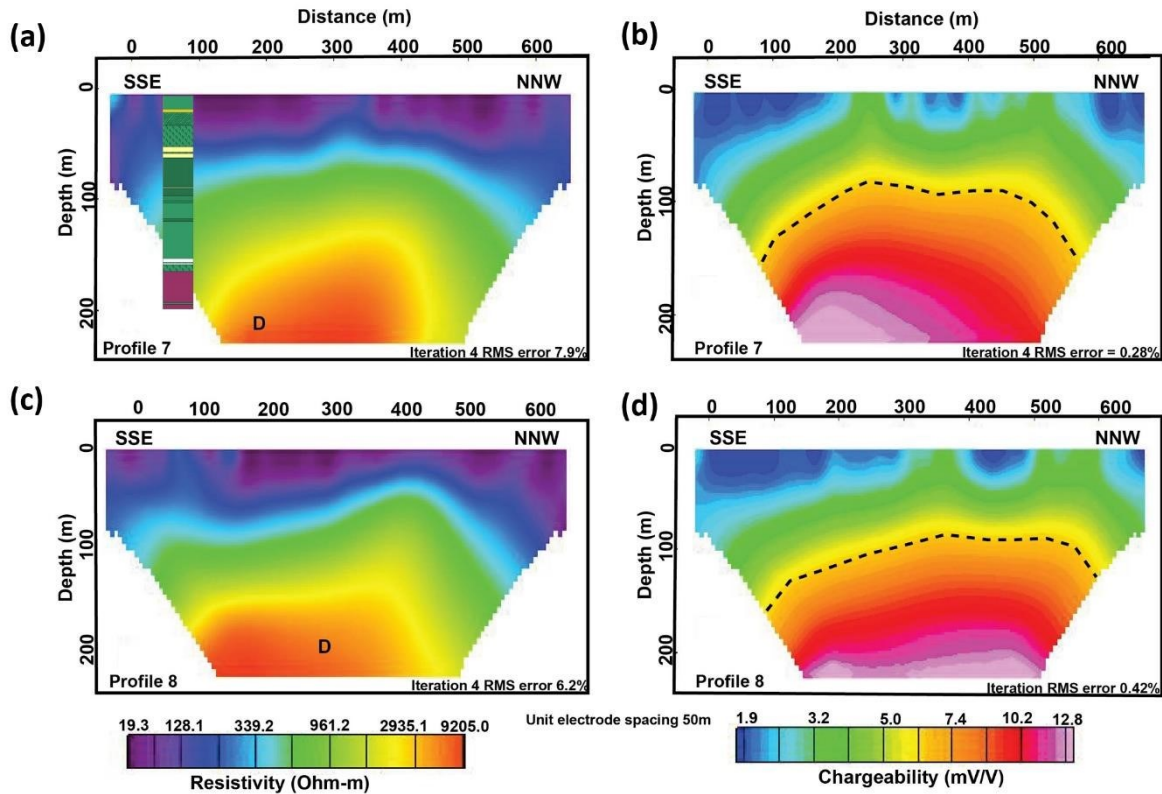


Figure 6.4: Profile 7 and 8 resistivity and chargeability 2D models. A borehole insert of MTW4 is included in (a) to relate the borehole data to the observed resistivity. Area marked **D** has high resistivity and coincides with high chargeability outline by the black dotted lines in (b) and (d).

Figure 6.4(a) and (c) are resistivity models for survey line 7 and 8 respectively. The model resistivities distribution is not different from the previous figures. The resistivity increases with depth and the top-most zone is conductive (19.3-128.1 Ohm.m). The moderate resistivity zone (green colour) starts at 110m however the zone goes to shallower depth around 400m distance along profile 8. The highest resistivity represented by the orange- pink colour marks the deeper part of the model. In figure 6.4(a) the high resistivity zone portrays a dome shape whereas in figure 6.4(c) it shows a tabular shape. This geometry could be because of the influence of geological structures in the subsurface.

The chargeability distribution for line 7 and 8 does not differ from the previous models. The figures 6.4(b) and (d) shows an increasing chargeability with depth. It can be observed that low to moderate chargeability coincides with low to moderate resistivities. High chargeability associated with disseminated sulphides mineralisation manifest below depth of 100m. In figure 6.4(c), the anomaly marked **D** is broad and laterally extensive. The anomaly coincides with a high resistivity typical of quartz veins. Even though alteration could be zones of mineralisation (Oktaviani et al., 2021; Ombiro et al., 2021; Yang et al., 2021), they also result in silicification and quartz veins that would give rise to high resistivities in figure 6.4(a) and (c).

6.2 3D RESISTIVITY AND CHARGEABILITY INVERSION MODELS

The resistivity and chargeability data set of Line 1, 2 and 3 were merged in a single dataset to produce the 3D model since the lines had the same start and end position unlike other profiles. The data was processed using Res3DINVTM software and visualised with Oasis montaj software for better picture quality. Three-dimensional (3D) visualisation is important because the real earth structure is 3D, this would make interpretations more accurate as compared to the 1D or 2D models (Yi et al., 2001). 3D models can give insights into the

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geometry, continuity and size of the ore deposits. The 3D model generated here is based on the 2D inversion results, the program interpolates data in zones where the data was not collected. Hence the visualisation of the interpolated zones where the data was collected is relatively distorted compared to zones where there was data collection (Han et al., 2016).

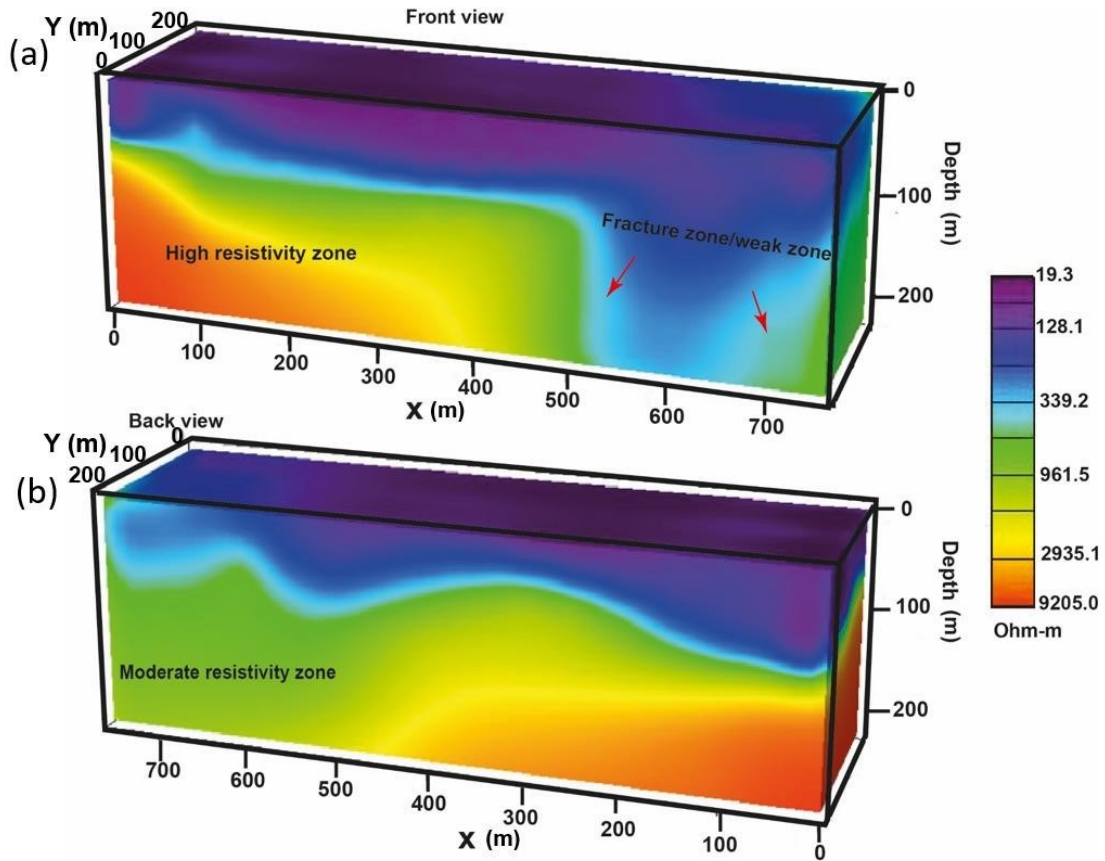


Figure 6.5: 3D resistivity model of L1-3. 3D model collated with L1-3 because they have the same start and end position. The red arrows in (a) indicate a low resistivity zone attributed to a fracture or weak zone.

Figure 6.5 (a) is the front view of the model (profile 1) and figure 6.5(b) is the back view of the model (profile 3). The resistivity increases as depth increases. The top-most zone of the model starts with a conductive layer (resistivity 19.3-128.1 Ohm.m). This zone starts from depth 0-50m however it gets shallower toward the north of the profile. The conductive zone is interpreted as chloritic/ talcose amphibolite, and the conductivity may be due to the clay

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content caused by weathering. The slightly moderate resistivity (128.1- 339.2 Ohm.m) represented by the blue colours start at approximately 50 m, the layer is thin at the beginning of the profile (S direction) and goes to greater depth at distance 500 m -700 m going beyond the maximum depth of investigation. However, at the same distance on the back view model the resistivity is moderate. This could be an indication that the possible structure here is dipping towards the northeast (towards Line 1) The moderate resistivity represented by the green colour is associated with amphibolite, this zone seems to terminate at distance 500m and shows a sharp linear contact. The red arrows indicate a possible fracture/weak zone. The region indicated by the red arrow can be associated with an altered alteration zone/shear zone. The low resistivity in this region could be a result of high concentration of metallic minerals that would greatly reduce the bulk resistivity. This is indeed a target of interest since the structure and alteration associated with it are usually associated with mineralisation. The last zone displays the highest resistivity (2935.1-9205.0 Ohm.m) in the model, the zone is interpreted as an ultramafic rock.

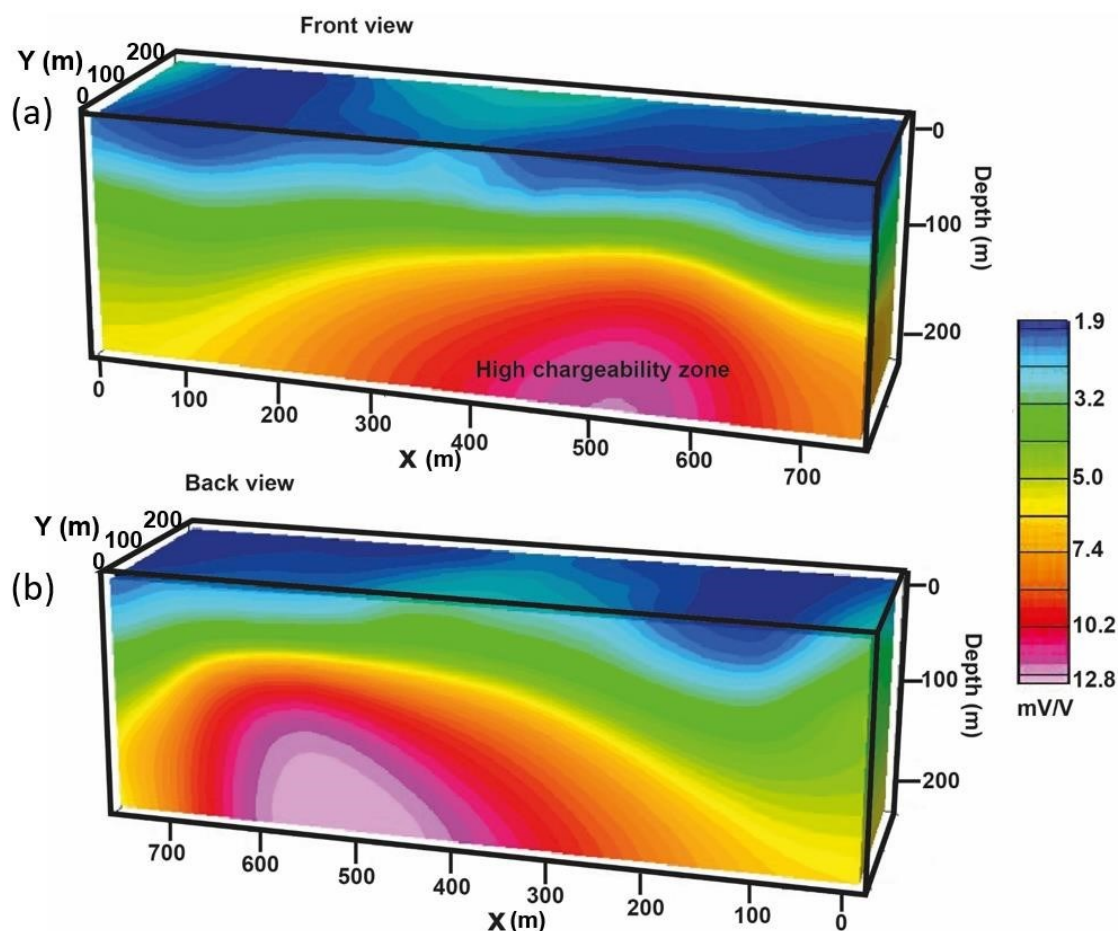


Figure 6.6: 3D chargeability model of L1-3. The position of high chargeability zone in (a) is shallower in depth than in (b) indicating a possible dipping chargeability anomaly.

Figure 6.6 represents the 3D chargeability model made by merging L1, 2 and 3 of 2D inversion models. The chargeability increases with depth. The upper most part characterised by the blue colour is the low chargeability zone. The highest resistivity zone (7.4-12.8 mV/V) associated with possible sulphide mineralisation start at depth 100m and goes beyond maximum depth of investigation. The anomaly is located at distance 300m- 700m. From the 2D inversion models the IP anomaly extend beyond the end of survey lines but here in the 3D model the boundary of the anomaly is well distinguished. The anomaly orientation (subvertical) is more prominent toward L3 (Back view model). The high chargeability zone

coincides with the low to moderate resistivity, and this is indeed a target zone of interest. From the borehole information, there is a possible fracture/fault (156 m) and the amphibolite has experienced extensive alteration and indication of folding of a shear zone (118 - 153 m). Drill-hole log, MTW 4 shows high sulphide content of +5% at depth 99.1m depth. Disseminated sulphides mineralisation starts at depth 70 m and occurs along fractures filled with quartz and carbonate veins. Geophysical results from previous studies indicate sub vertical thin causative bodies (Holmes et al., 1993) and the orientation of the anomaly (3D chargeability) from these results shows similar occurrence.

Disseminated/ isolate sulphide grains within a large body of rock usually give high IP response. Normally, areas with low resistivity and high chargeability are associated with mineralised zones since the concentration of highly conductive minerals greatly reduces the bulk resistivity, (Côrtes et al., 2016; Moreira et al., 2012). However, areas with moderate to high resistivity and high chargeability values corresponds with silicified mineralised zones (Han et al., 2016; Jones et al., 1982). Quartz and carbonates veins hosting sulphides acts as good electrical insulators in addition if the mineral grains are disseminated, they are not good electrical conductors (Dusabemariya et al., 2020). The moderate resistivity can be an indicative of higher concentrations of the mineralisation hence the reduction in resistivity compared to other anomalies corresponding to high resistivity values.

6.3 HORIZONTAL DEPTH SLICES OF 3D RESISTIVITY AND CHARGEABILITY INVERSION MODELS

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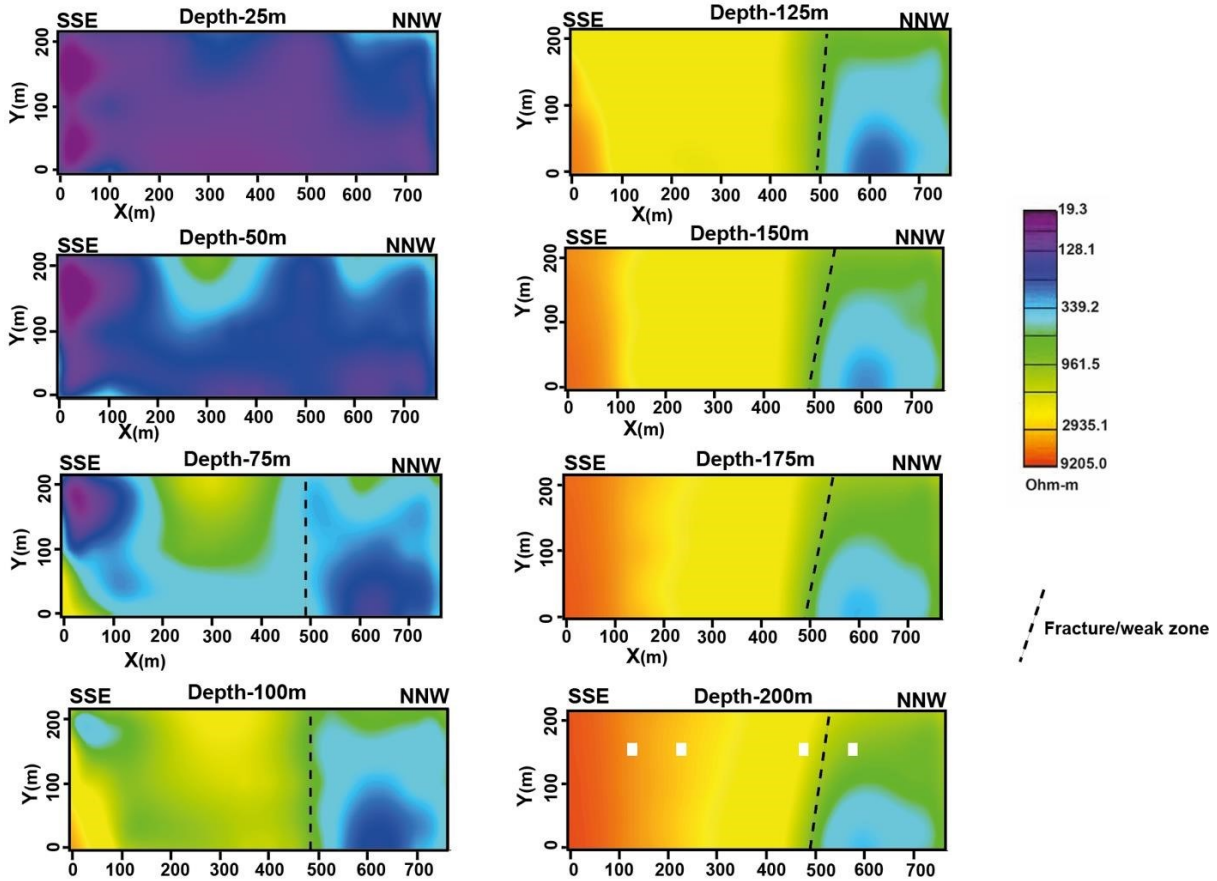


Figure 6.7: Horizontal depth slices generated from 3D resistivity model (L1-3). The depth of each horizontal slice is given in metres above the images. The dotted lines represent the boundary of the fracture/weak zone coinciding with low resistivity values.

Horizontal slices in figures 6.7 and 6.8 were generated from the 3D resistivity model using the Oasis montaj Software. The horizontal slice of 25 m depth is characterized by a very low resistivity material (<128.1 ohm.m) related to Chloritic/talcose amphibolite. A low resistivity zone is noted at depth 50 m and a scanty spot of moderate resistivity is visible at distance 300 m. As the depth increases, the low resistivity decreases at depth 75 m. Moderate resistivity material attributed to Amphibolite appears to broaden on the right side of the slices however, at distance 500 m there is a sharp abrupt change to low resistivity. From this distance (500 m-700 m) is a low resistivity zone which has been associated with fracture/weak zone. This could be a possible hydrothermal alteration zone rich in sulphide deposits. The interpreted

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fracture or weak zone appears to diminish as depth increases indicating that this zone might be localized between 100 m-200 m depth. A resistive material (2935.1 Ohm.m - 9205.0 Ohm.m) broadens on the right side of the slices as the depth increases from depth 125 m-200 m.

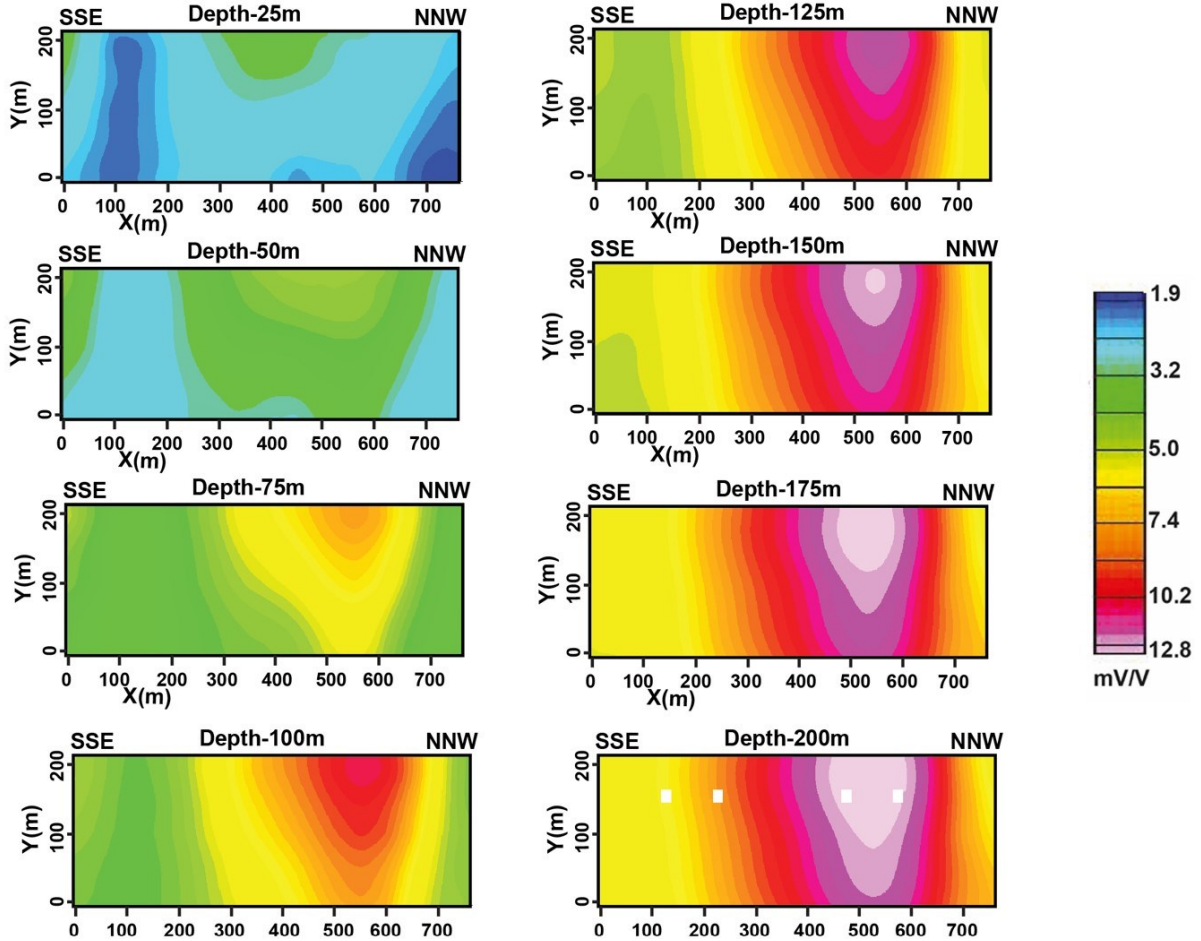


Figure 6.8: Horizontal depth slices generated from 3D chargeability model (LI-3). The depth of each horizontal slice is given in metres above the images.

In figure 6.8, chargeability values are low at depth 25 m and 50 m. This zone is characterised by blue colors and green colors intervening at depth 50 m (1.9 mV/V – 5 mV/V). The chargeability moderately increases at depth 75 m, even higher values are distinguished at distance 400 m -600 m. Chargeability values greater than 5 mV/V can be observed at depth

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100 m from distance 200 m- 700m. Highest chargeability are evident at depth 125 m-200 m which extend on the entire profiles (175 m -200 m). This zone of highest chargeability is considered to be anomalous and is associated with a mineralised zone. It is noteworthy to observe that the high chargeability zone that start appearing at depth 75 m coincides with the fracture/weak zone delineated in figure 6.7 at depth 75 m. This anomalous zone also trends in a northeast direction consistent with the fracture/ weak zone and also the lineaments delineated in the aeromagnetic data. It is evident that the chargeability extends beyond the maximum depth of investigation.

6.4 RESISTIVITY AND CHARGEABILITY ISOSURFACES

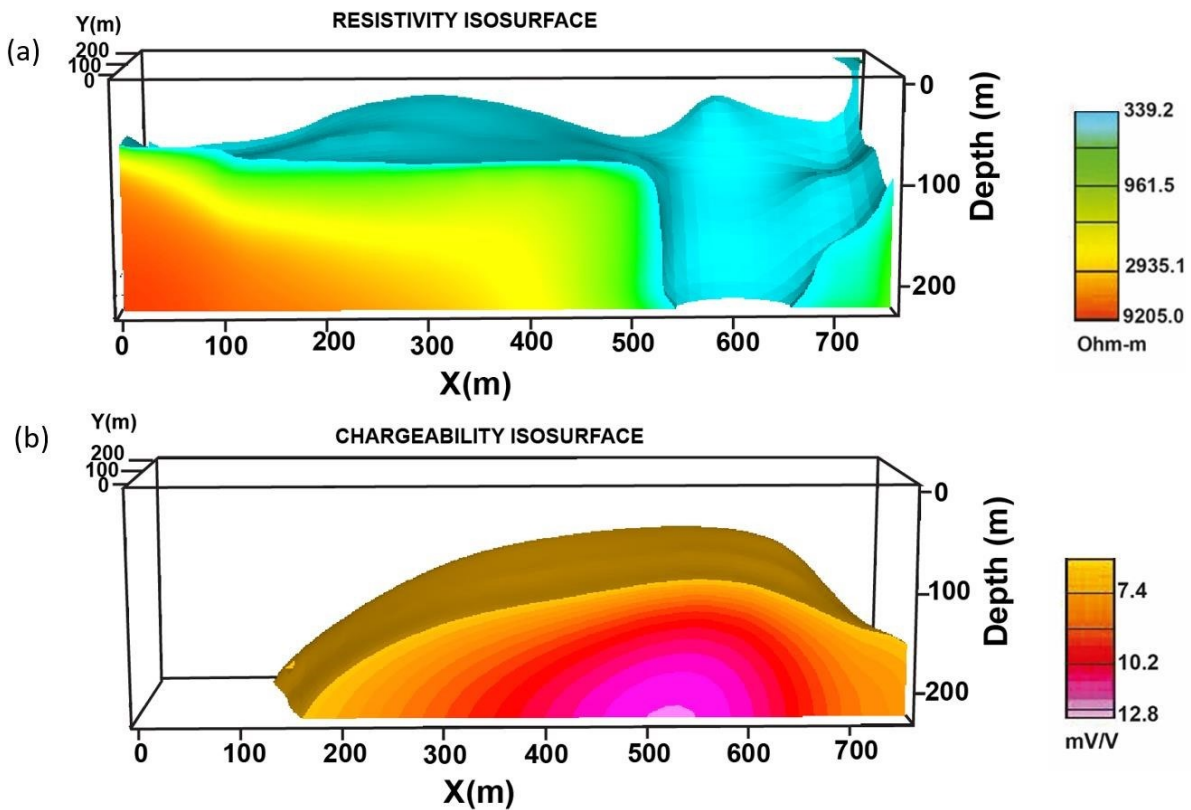
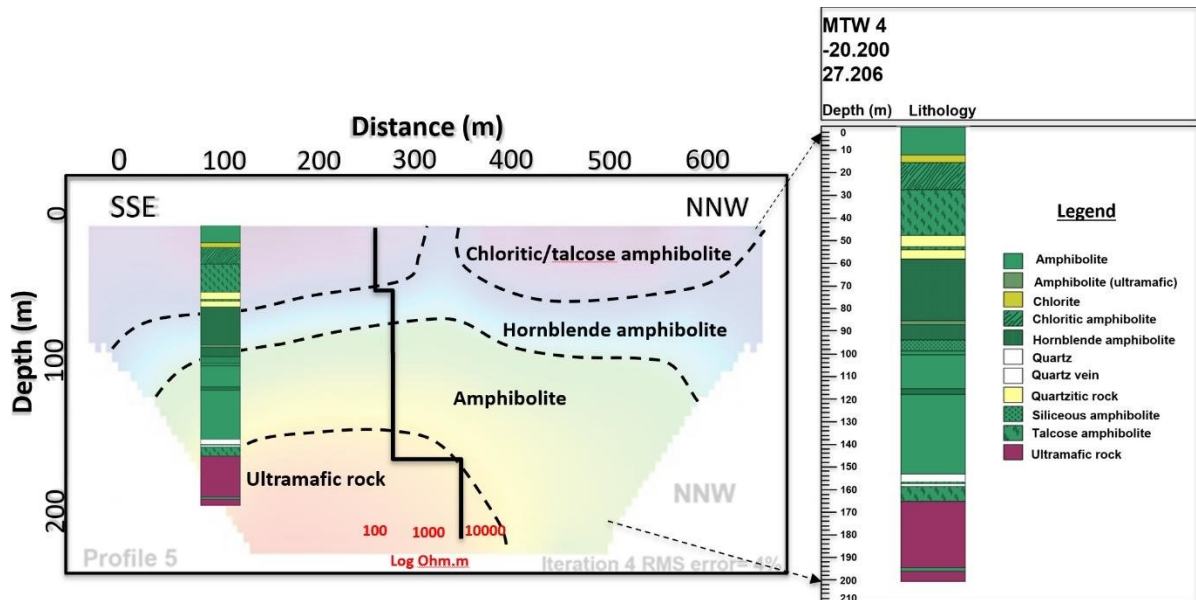


Figure 6.9: Resistivity isosurface and chargeability isosurface

The visualisation of the chargeability and resistivity isosurfaces is to give insights into the geometry and distribution of the anomalous zones. These are the potential zones of mineralisation and therefore targets of interest. The models were made by Oasis montaj using the voxel extension. The resistivity isosurface model indicates the distribution of the high resistivity zone represented by orange and red colors (2953.1- 9205.0 Ohm.m). This resistivity anomaly associated with an ultramafic rock shows a broad tabular shape geometry. It terminates abruptly at distance 500m, and the termination zone is interpreted as a fracture/weak zone (figure 6.9 (a)). The zone/structure at this point trend in a northeast direction and from the isosurface also dips in that direction. The resistivity reduces significantly at this location and high chargeability values are observed at this zone in figure 6.9(b). The high chargeability zone (7.4- 12.8 mV/V) which is considered as the IP anomaly is associated with sulphides mineralisation. In this 3D isosurface, the chargeability coincides with low-moderate values of resistivity. The orientation of this high chargeability zone trends in a northeast- southwest direction, the typical of the direction observed on the aeromagnetic lineaments in Maitengwe greenstone belt. The anomaly also appears to have vertical/subvertical orientation as indicated by the 3D chargeability model. The geometry and distribution of this chargeable zone indicate that the mineralisation is probably structurally controlled and is associated with the orientation of lineaments delineated in the aeromagnetic data.

6.5 TRANSIENT ELECTROMAGNETIC 1D INVERSION SOUNDING

(a)



(b)

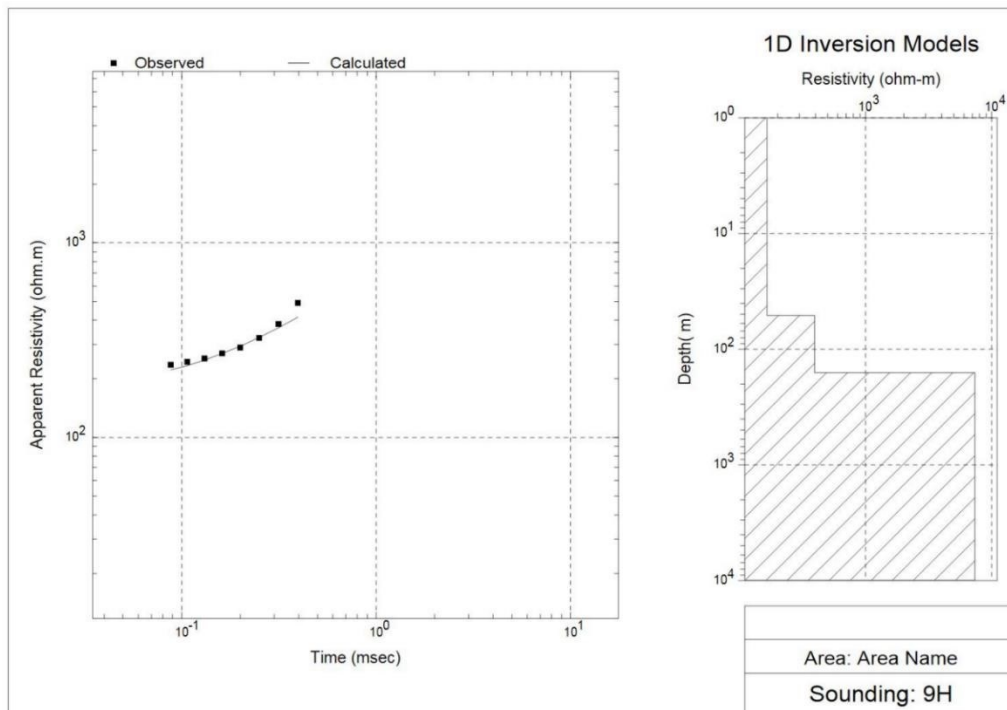


Figure 6.10: 1D TEM sounding of soundingpoint 2 (S2). On the left of the figure is the inversion results showing observed and calculated resistivity with time, on the right is the change in resistivity with depth.

1D TEM SOUNDING OF POINT 2 (Frequency 25Hz)

In figure 6.10(a), the 1D TEM sounding of sounding Point 2, is overlaid on the resistivity model of Profile 5 to correlate the lithological layering. The 1D depth sounding which shows a 3 layered earth is presented in a linear depth scale and a log resistivity scale. The thickness of this

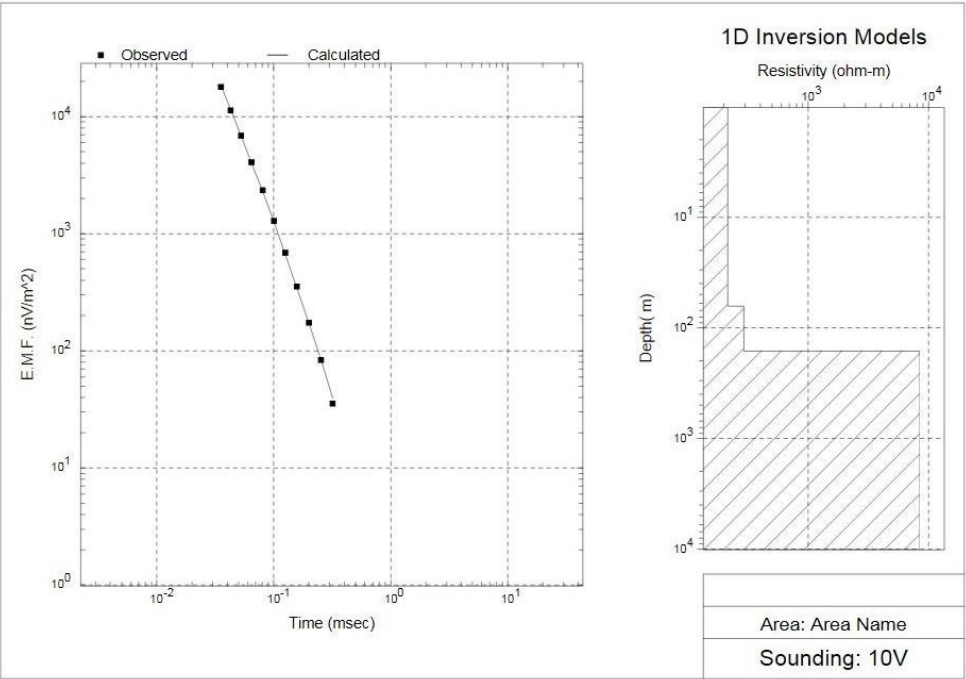
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first layer is approximately 50 m with resistivity values of approximately 1 - 160 Ohm.m. The second layer on the 1D sounding start approximately at depth 120 m with resistivity values at between 160 - 400 Ohm.m. The very low resistivity layer (chloritic/talcose amphibolite) on the 2D correlates to the low resistivity first layer on the 1D sounding. The second layer on the TEM sounding correlates to resistivity values of the layers interpreted as Hornblende amphibolite and amphibolite. The last layer that goes to infinity has resistivity values of 400 - 7000 m Ohm.m and coincides with the last layer in the 2D model interpreted as Ultramafic rock. The ERI resistivity values show a slight difference in apparent resistivities compared to TEM results. This could be attributed to difference in inversion algorithms; however, this is more likely due to the nature of the type of the geophysical method (Fotheringham, 2013). Electrical resistivity imaging is a contact geophysical method while Transient electromagnetic method is a non-contact geophysical method hence their response differs to various lithologies. The results of this study show some correlation however with respect to the lithological layering noted on the borehole log and the closeness of the resistivity values.

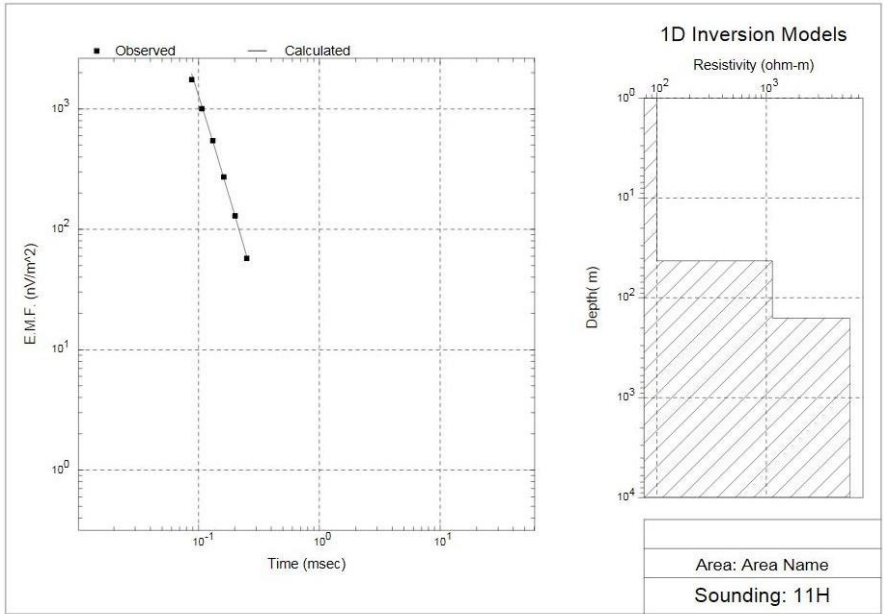
1D TEM SOUNDING OF POINT 3 (Frequency 62.5Hz)

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(a)



(b)



1D TEM
SOUNDING OF
POINT 4 (Frequency
25Hz)

Figure 6.11: 1D inversion TEM sounding of point 3 (a) and point 4 (b) from the survey design.

The results of the 1D TEM sounding of sounding point 3 and 4 are shown in figure 6.11(a) and (b) above respectively. The soundings also reveal a 3 layered earth. Figure 6.11 (a) was acquired at frequency 62.5Hz, the graph on the left shows the amplitude decay of the secondary field with time. The calculated model fits perfectly with the observed data after inversion to give the 1D inversion model on the left. The first layer in this model has thickness of 60 m and resistivity that begins at 1 - 210 Ohm.m. The second layer has thickness of approximately 110 m and resistivity values of 210 - 300 Ohm.m. The infinity layer has resistivity values starting at 300 - 9000 Ohm-m. In model in figure 6.11(b) was acquired at frequency 25 Hz, the first layer has thickness of approximately 40 m and has resistivity values of 1 - 100 Ohm.m. The second layer has resistivity starting at 100 - 1100 Ohm.m and thickness of 130m and the infinity layer has resistivity 1100 - 8000 Ohm.m. The first layer in all these sounding models is related to the very low resistivity zone on the 2D sections interpreted as Chloritic/talcose amphibolite. The second layer and third layer (Hornblende amphibolite and amphibolite) on the 2D models make up the second layer on the 1D sounding. The layer interpreted as ultramafic rock is the infinity layer on the 1D sounding and shows high resistivity values also observed on the ERI models. The variation of the amphibolite and the presence of sulphides mineralisation in this lithologies could be the reason why the TEM results reveal these rocks as a single layer. The 1D sounding resistivity values also varies because the geological conditions vary from point to point on the subsurface.

CONCLUSION

6.6 CONCLUSION

The aim of the study was to utilize the IP method in conjunction with electrical resistivity imaging (ERI) and Time Domain Electromagnetic (TEM) method to determine the spatial distribution of disseminated sulphides, and the geometry of potential mineralized zones. The findings show that structural lineaments on the aeromagnetic data of Maitengwe area are mostly oriented NE-SW. Our results reveal zones with high sulphide mineralisation potential in all the survey lines. Such zones occur beneath 100 m depths and are characterised by chargeability values of ≥ 7.4 mV/V and resistivity values of $\geq 400 \Omega\text{m}$. Zones with moderate to high resistivity and high chargeability values corresponds with silicified mineralised zones. Zones of low resistivity coinciding with high chargeability values are possible alteration zones with significant metallic minerals. These potential zones of mineralisation are correlated and validated by the drill hole information and occur at depth that coincides with the 2D inversion models. The presence of possible linear features associated with a mineralized altered fracture zone are verified in horizontal depth slices of 3D model. This inferred mineralized zone appear sub-vertical to vertical and trends in a NE-SW direction. This is consistent with the direction of the lineaments identified using the high-resolution aeromagnetic data, suggesting that these mineralized zones may be associated and controlled by these structures.

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