

DELINEATION OF POTENTIAL GOLD MINERALIZATION ZONES IN PHITSHANE
MOLOPO AREA SOUTHEAST BOTSWANA USING INDUCED POLARIZATION AND
RESISTIVITY MEASUREMENTS

by

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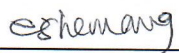
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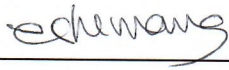
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CERTIFICATION

The undersigned certifies that he/she has read and hereby recommends for acceptance by Faculty of Science a dissertation/thesis titled:

Delineation of potential gold mineralization zones in Phitshane Molopo area southeast Botswana using induced polarization and resistivity measurements, in fulfillment of the requirements for the degree of Master of Science in Geological Sciences of the BIUST.



Prof Elisha M. Shemang

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DEDICATION

This thesis is dedicated to my beloved daughter Bella though whom I found courage to putting more effort in my study. This work is also dedicated to my whole family and colleagues who also encouraged me throughout life.

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ABSTRACT

An integrated geophysical approach (using induced polarization together with resistivity) geophysical techniques was applied in the research area (Phitshane Molopo area, Botswana) in search for potential gold mineralization from the interpreted data to delineate potential sites for mineralization. Reports on historic exploration suggest that gold mineralization is associated with quartz $\pm$ carbonate veins that cut across the banded iron formations. The 2D IP/ERI measurements were acquired along ten 300 m long profiles trending northeast southwest, with 15 m line separation and 7.5 m electrode spacing. The data were then inverted using the standard Gauss-Newton optimization method to produce 2D and 3D models. Based on a combination of IP and resistivity results, two anomalous zones are observed increasing in strength from line 1 to line 10. Possible mineralization is observed to be at shallow depths as evident from the 2D models and 3D horizontal sections. Since all of the high chargeability zones shown on the chargeability models correspond to parts which are highly resistive, then these zones exhibiting distinct anomalies can be mapped out as possible areas of disseminated sulphide mineralization hosted within quartz veins cross-cutting banded iron formations. The integrated use of IP and ERI methods was successful in delineating zones that are likely to be hosting disseminated sulphides and/or potentially gold-rich zones in the Phitshane Molopo area, Kraaipan Greenstone Belt.

KEY WORDS: Induced Polarization (IP), gold deposit, anomaly, resistivity, pole-dipole configuration

1.1 Background

a

20°E 22°E 24°E 26°E 28°E
18°S 20°S 22° 24°

Namibia

0 80 km

Kasane

Maun

Nata

Francistown

Palapye

Mahalapye

Gaborone

Lobatse

Mafikeng

Amalia-Kraaipan Greenstone Terrane

South Africa

Kalgold Mine

50 km

Botswana

b

25.2120 25.1113 25.0093 24.9063

25.7530 25.6642 25.5752 25.4862

Metlobo

Sedibeng

Phitshane Molopo

Mokatake

0 5 km 10 15

LEGEND

- Probable fault
- Possible fault
- Remnant greenstone
- Moderately mag. greenstone/normal magnetism
- Moderately magnetized greenstone/rev
- Highly magnetized intrusive
- Res. BIF
- Normal BIF
- Major dykes
- Weakly magnetized granite
- Weakly Magnetic Basement Granite/gneiss
- Non-magnetic intrusive granite
- Weakly non-magnetic greenstone
- Study area

c

KRCP037

25.0812°

25.6662°

135 m

KRCP037 KRCP036

307.5 m

KRCP038

25.6697°

KRCP045

500 m

N

1

greenstone belt highlighted in green (modified from Carney et al., 1994; Laconia Resources Limited, 2016) (b) detailed geology of the Kraaipan project area, with the dark gray rectangular marker (▪) indicating the study area, and (c) satellite image showing the layout of the 10 profiles surveyed (red lines). An insert in (a) shows the geographic location of Botswana in Africa.

The rocks in the study area are of Archean age and are known as Kraaipan greenstones and are part of the of the Archaean granite-greenstone terrane hosted in the Kaapvaal Craton, southern Africa, covered mainly by Neoarchean and Proterozoic rocks. The Kraaipan granite–greenstone associations in the area under study (Figure 1-1) comprises of metamorphosed Archean mafic volcanic units, intermediate layers of ferruginous and siliceous metamorphosed sediments (largely BIF and chert), different granitoid rocks units, together with tonalitic and trondhjemitic gneisses (TTG), granodiorites and adamellites (Walraven & Anhausser, 1999). This terrain is essentially located in northwest South Africa however extending into southern Botswana, where the rock units are mostly obscured by Tertiary to Recent Kalahari sediments (e.g. Mapeo et al., 2004; Poujol et al., 2008; Aldiss, 1985).

The Archaean granite-greenstone associations contain a number of the earliest rock units and are a home for numerous major deposits however their complicated means of their genesis together with how the oldest mainland stabilized remains not completely acknowledged (Benn et al., 2006). It is significant to understand the geology, geological structures and petrogenesis of a terrain in order to select an area for mineral potential. Geological structures occur with the features that are related to economically important mineral deposits (e.g. Mitchell, 1984). Understanding both the surface and sub-surface structures, and the genesis of mineralization of those rocks gives insights into occurrence of the valued mineral deposits (Goleby et al., 2004). Kaapvaal Craton is a particular example of a region containing Archean terrains with mineral deposits because it has many operational and economical mines generating vital quantity of gold, platinum, base-metals, (de Wit, 1992). It hosts several gold mines including Kalgold and the Kalahari Goldridge deposit within the Banded Iron Formations (BIFs) in South Africa. To date, the extension of the terrain into southeast Botswana has been reasonably studied for its mineral potential, but of all the investigations only a few included the use of geophysics in the investigations.

The results of previous exploration by exploration companies in the Phitshane Molopo area has resulted in drilling in the area. The drilling in the area intersected significant shallow gold mineralization (Laconia Resources Limited, 2016). Geochemical soil survey has also been conducted in the area by exploration companies and the outcomes also indicated several geochemical anomalous areas (Laconia Resources Limited, 2012). These anomalous zones were bench marked for follow ups and the focus of exploration process by the prospecting companies. The gold prospect of the Phitshane Molopo area has been confirmed recently by an exploration company, (Laconia Resource Limited) through drilling and the mineralization was found to be hosted in quartz-carbonate vein swarms cross-cutting banded iron formations (Laconia Resources Limited, 2016) (Figure 1-2).



Figure 1- 2: Example of banded iron formation rock units with quartz and/or carbonate veins crossing-cutting them, in Phitshane Molopo.

The gold prospectivity analysis by the Laconia Resources Limited company indicated that since the Kraaipan belt (host for Phitshane Molopo area) lies on the same terrain where the Kalgold mine (South Africa) is located, it therefore indicates that the area is highly

prospective for lode-gold mineralization. The Kalgold Mine is possessed by Harmony Gold Mining Company Ltd. It has been operational until 1996 with an approximated prior-mining minerals resource containing over four million ounces of gold (Hammond & Moore, 2006). The gold mineralization which is discovered in the extension of the belt within Botswana is markedly same as the one found at Kalgold, as both occurrences are within the quartz $\pm$ carbonate vein swarms cross-cutting the host rocks known to be banded iron formation (Figures 1-2). In the two territories, the veins rich in gold are in close association with sulphide disseminations mostly pyrite, dispersed in the middle of quartz veins (Laconia Resources Limited, 2016).

Based on field observations and direct evidence of mineralization as quartz $\pm$ carbonate veins, the selection and use of geophysical techniques in investigation of potential gold-bearing zones in Phitshane Molopo area is a rational choice to define morphological attributes such as lateral continuity, thickness and depth extent of mineralized zones (Moreira et al., 2019). Gold (Au) has one of the most anomalous intrinsic physical properties, density of 19,300 kg/m³ and electrical conductivity of 5×10^7 S/m (Salmirinne and Turunen, 2007). Even so, directly detecting gold from geophysical responses is implausible due to its minimal concentrations in ore deposits (Doyle, 1990). However, geological structures such as shear zones, faults, veins and veinlets, lithological units (e.g., BIF), minerals (e.g., pyrite) and alteration zones, that are oftentimes associated with gold can be identified and mapped using geophysical techniques (Paterson and Hallof, 1993). The use of geophysical techniques for mineral exploration is quite conventional, especially for metallic and non-metallic ores (Yusefi et al., 2017). The application of different geophysical techniques in mineral exploration have yielded mixed results, as it depends on the physical properties contrast of the target zones and host rocks (Salmirinne and Turunen, 2007; Ramizi and Mostafaie, 2013; Moreira et al., 2019). On the downside, morphological attributes or geometry and physical contrast of the targeted geological structures as thin veins embedded within or hidden under overlying deposit trivializes the use of magnetic, electromagnetic or gravity methods because the density and magnetic anomalies they produce are too subtle to be detectable using these methods (Martínez et al., 2019). These methods are more suited to searching for massive deposits (Martínez et al., 2019). Contrarily, the efficacy of induced polarization (IP) and electrical resistivity imaging (ERI) in investigating such geological structures as

mineralized veins and disseminated deposits has been proven in numerous studies (Bery et al., 2012; Moreira et al., 2012; Ferdows and Ramazi, 2015; Han et al., 2016; Hope and Andersson, 2016; Arifin et al., 2019; Gupta et al., 2019).

Figure 1-3 demonstrate the similarities linking Kalgold and Kraaipan Project in terms of genetic model and geological settings (Hammond & Moore, 2006) and the Kraaipan Project geological setting. The polygon outlines a region in Kraaipan Project holding which is near an intrusion (granitic rock) which possesses similar comparative time of Kalgold mineralization (Laconia Resource Limited, 2012).

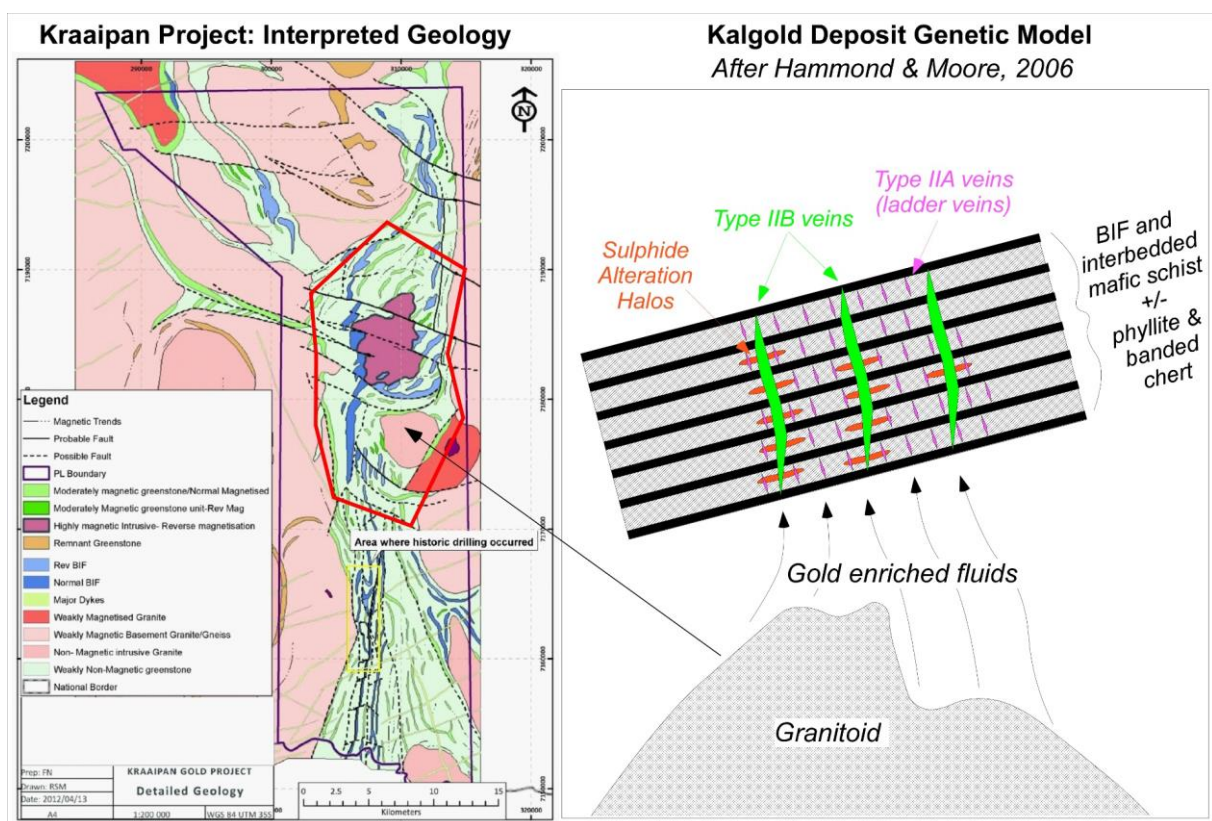


Figure 1- 3: Geological setting of the Kraaipan project by the Laconia Resources Limited in comparison with the suggested generic model of the Kalgold mineralization, South Africa (Laconia Resource Limited, 2012; Hammond & Moore, 2006).

Induced polarization (IP) and electrical resistivity methods are some of effective and widely used electrical methods for structurally controlled mineralization. Gold is highly chargeable as compared to any other geological unit (Salmirinne and Turunen, 2007), so IP can be used to map possible zones for gold mineralization and resistivity to map banded iron formation which hosts gold. An integrated use of geophysical methods was

utilized in this study to detect geological targets. The two datasets were acquired simultaneously using one equipment by IRIS to enhance interpretation of the observed data.

Inversion of these datasets assist geophysicist to obtain a snapshot of the subsurface by inverting data into images of the subsurface. Images of the subsurface are acquired by the inversion process whereby the observed induced polarization/ resistivity datasets are converted into realistic “Interpreted Depth Section” (Loke, 2000). This process allows for production of 1D, 2D and 3D distribution of electrical properties of the subsurface that gives an explanation of the observed IP/resistivity data (Loke, 2000). The inversion programs such as RES2DINV and RES3DINV by Geotomo™ softwares makes modelling process swift and reliable in producing targets (Loke, 2000).

1.2 Problem statement

The Phitshane Molopo area is reasonably studied by geological mapping (as part of Geological Survey regional mapping program) as well as by limited specialized geochronological, geochemical and petrological sampling (e.g. Aldiss, 1985; Mapeo, 1990. 1998 and Mapeo 2004) but there have been few geophysical investigations (Ramotoroko et al., 2016; Ranganai et al., 2017) aimed at assisting and mapping regional geology (since the region is mostly covered by Kalahari Sands). Potential field (gravity and magnetics) interpretation has been recently attempted by Ramotoroko et al., (2016), but a more detailed investigation is lacking. Studies done previously on the Kraaipan belt include on-ground “geological mapping, geochemistry and geophysical survey, which are mostly isolated and restricted to areas with geological outcrop” (Aldiss, 1985). It is therefore necessary to explore areas of geological cover so as to understand the geology, which will in turn assist in exploration directed at making mineral discoveries. Geophysical techniques can be used to identify target areas and redefine tectonic elements in covered terrains. Even though there is availability of some datasets (gravity and aeromagnetic) these data are of regional nature are not very useful for disseminated mineral exploration in the area. More detailed geophysical studies and interpretation should be undertaken so as to provide insights into the potential gold mineralization in the area and hence direct future gold exploration activities in the area.

Previous work undertaken by the licensed holder in the area (Laconia Resources Limited) and previous third-party works include geological mapping, geophysical mapping, geochemistry (soil sampling) and drilling intercepted significant shallow gold mineralization (Laconia Resources Limited, 2016). These findings prove that the area has potential for gold mineralization, necessitating that more work should be undertaken to develop more targets for follow ups. This work will be significant in better defining the mineralized zones which were intercepted by previous and recent drill holes in the Phitshane Molopo area. Therefore, extensive geophysical survey of area and utilization of enhance data processing techniques and interpretation will greatly assist in identify suitable sites for mineralization.

Induced polarization (IP) and resistivity are some of the most significant and widely used electrical methods for gold exploration. This advance in interpretation is strongly coupled with the improvements in instrumentation especially the switching technology and storage capabilities of recent geophysical survey instruments (Komu, 2016) which will help in directing prospecting licensed company.

The current research (work) therefore employed an integrated use of the two geophysical methods to investigate the potential gold mineralization, interpret data and to identify targets for follow-up drill targets. Potential mineralization sites delineated are shown in the 2D and 3D chargeability and resistivity subsurface sections.

1.3 Aims and objectives

Aim:

- ✓ Conduct IP and resistivity survey at Phitshane Molopo area in search for potential gold mineralization, interpret the data and delineate potential sites for mineralization.

Objectives:

- To identify and map potential sites of gold mineralization using IP and resistivity electrical methods;
- To process data with advanced processing techniques, correlate IP and resistivity models with the known geology of the area and interpret the results;

- To assess the gold resource potential of the area by combining the other geological data available with the results of the geophysical survey.

1.4 Research significance

This study will provide outputs that will assist in delineating targets for possible drilling whose results will assist to define in more details the gold resource in the Phitshane Molopo area for better estimation of the gold resource. The research will produce well-grounded results for reliable follow up targets, assist in focusing exploration activities in the study area therefore reducing drilling costs and other survey techniques such as geological mapping, geochemical studies and even other geophysical survey techniques will be able to focus on the promising areas.

Finally, the outcomes from this study will be benchmarked as a future reference for future exploration and other activities aimed at understanding the mineral potential of the Phitshane Molopo area and the Botswana part of the Kraaipan belt.

1.5 LITERATURE REVIEW

1.1.5 Gold mineralization of the Kraaipan granite-greenstone terrain

The study area is under a licensed prospective area to the Laconia Resources Limited company which covers about 50 km length of the extension of Kraaipan greenstone belt (KGB), southern Botswana. It comprises of lateral belts heading north of Archean (~3500Ma) metavolcanics and metasedimentary rock units which are isolated by granitoid rocks (Aldiss, 1985). The belt extends in the Republic of Botswana and it is understood to be particularly prospective for gold (orogenic) together with Ni-Cu-PGM sulphide mineralization because these geological units are within the same rocks as the Kalgold (which has more than four million ounces of gold) and Kalplats (over six point five million ounces of gold) gold deposits within the South African part (Laconia Resources Limited, 2016).

Previous exploration within the KGB identified gold mineralization which is noticeably similar to that found at Kalgold. The mineralization within the Botswana part is found to occur in shallow dipping ($\sim 65^\circ\text{E}$) qtz- CO_3 vein streams, inside sub-greenschist facies, magnetite-chert, BIFs (Laconia Resources Limited, 2016). In the South Africa part, the Kalgold deposit is in close association with the two class of veins (namely IIA and IIB) shallow dipping at 20° to 40°W . The group IIA veins are ladder veins favourably advanced in centimeter-scale Fe-rich mesobands (Hammond & Moore, 2006), whereas the group IIB are composed of huge quartz-carbonate veins cross-cutting the whole orebody (Hammond & Moore, 2006). The gold mineralized veins in both areas are associated with sulphide disseminations which is dominated by pyrite (Hammond & Moore, 2006).

Several studies more especially in the South Africa part have been conducted on the Kraaipan greenstone belt trying to confirm the presence of gold mineralization. Lewins et al., (2008), a conference paper about the Kalahari Platinum project which indicated that drilling defined a resource of 4.2 million ounces Pt+Pd+Au and this confirmed that indeed the belt is rich in gold.

Hammond & Morishita (2009) and Hammond & Moore (2006) conducted a study on sources of ore fluids at the Kalahari Goldridge deposit (South Africa) located on the Kraaipan belt, from this study, with proof from Strontium, Carbon and oxygen isotope signatures in carbonates. They have suggested that gold mineralization in the Kalahari Goldridge hosted inside the BIF that is flanked by a mafic schist in the footwall and hanging wall (clastic metasedimentary units). Interpretations from the isotope signatures indicated that the fluids responsible for ore-generation were most likely from mantle-derived magmatic rocks that underlie the ferruginous package in the Kraaipan greenstone belt.

In the Botswana part Ranganai et. al, 2017 conducted geophysical and hydrogeological groundwater prospectivity in the Kraaipan granite-greenstone terrain, Southeast Botswana. They found out that the area has high potential for water and mineral resources such as gold.

Ramotoroko (2016) also mapped the extension of the Kraaipan granite-greenstone terrain in southeast Botswana using regional aeromagnetic and gravity data with the aim to map the rocks at depth to understand the geology while the secondary objective was to subsequently assess the mineralization and groundwater potential in the area which. They suggested that the area has potential for mineralization necessary for detailed local investigation aiming for mineral and water investigations.

1.1.6 Induced Polarization (IP)

This technique uses the capacitance property of the subsurface to locate areas where one has clay and metalliferous ore disseminations within their host rocks (Kearey et al., 2002).

The method of Induced polarization method was first developed by Conrad Schlumberger in 1920. He observed the low-frequency polarizability of earth materials which occurs as a result of current injection (Schlumberger, 1920). Viability of the technique in subsurface exploration was first demonstrated by Bleil (1953). He revealed that polarization caused by the availability of metalliferous disseminated mineralization was quantifiable and explainable as far as physical properties are concerned.

Extensive research has been conducted successfully using IP in various fields and has ended up being the most frequently utilized geophysical technique in delineating zone of (gold) mineralization potential (Dennies, 1990; Sultan et.al., 2009 etc.)

In particular Gouet et.al., (2016) used geological, resistivity and induced polarization data for the identification of the associated gold deposits at Wadi El Beida area, South Eastern Desert, Egypt. They suggested that Au mineralization in the study area is associated with positive IP anomalies. They found out that gold and disseminated sulfides are located on an alteration shear zone which is composed of quartz–feldspathic highly ferruginated rock (gossans) occupying the eastern and central parts of the area. Additionally, Fon et.al., (2012) successfully used the IP technique to delineate structures controlling gold mineralization in East Cameroon. Gouet et.al., (2016) had positive results when using IP in conjunction with resistivity for gold mineralization in East Cameroon and suggested that the success of these methods was attributed to the high conductivity and

high chargeability of the gold mineral. Hammond & Moore (2006) successfully utilized geological studies in examining gold mineralization at the Kalahari Goldridge, South Africa.

1.1.7 Resistivity

The resistivity method was first developed in 1912 by Conrad Schlumberger and it has been widely practiced in groundwater and environmental studies since 1970 (Anhausser, 1999). It also used for mapping conductive ore bodies. Since then it has been used worldwide in conjunction with IP for mineral exploration as a supporting method to map resistive background.

1.1.8 The inverse problem

The inversion procedure converts surface induced polarization or resistivity measurements into practical interpreted depth section. This process seeks to produce 1D, 2D and 3D distribution of electrical properties that defines acquired field measurements. The inversion programs are applied iteratively to; 1) assess the outcomes with respect to what is known geologically, 2) estimate the depth of detection, and 3) decide the suitability of specific measurements (Pezzot, 2005).

This process suffers from non-uniqueness, which means that a single dataset can result into several geophysical possible models that acceptably explains it. Validation of the inverse model requires information from the geological studies of an area of interest and an experienced interpreter.

Prior to solving an inverse problem, it is essential to understand the forward problem which is a mathematical procedure of assessing data based on some physical or mathematical model depending on a given set of model parameters with some other relevant information such as geometry (Reid et al., 2014). This is basically calculating data when we know the model of the Earth and it's a simple straight forward concept because only one answer from its calculation is expected.

An inverse problem is a mathematical procedure where one estimates the numerical values and their related statistics of a set of model parameters, of a presumed model that is based on a set of observations. This is to say estimating possible models when data are available (the reverse of a forward problem). In an inverse problem, instead of generating one result to a specific model; numerous models are generated and therefore the inverse problem helps display which model best fits model results from observed data from the field (Loke, 1999). The problem of non-uniqueness from inverse modelling can be mitigated by imposing independent constraints from other geological surveys.

Several researchers have worked on algorithms to carry out inversions of IP/resistivity data and published papers. Some of these searches include; Oldenburg and Li, (1994) using DC resistivity algorithm; Carbone et al., (2006) using numerical methods for modeling potential fields observations on real datasets and Loke & Baker (1996) who developed an algorithm based on the smoothness-constrained least-squares method.

2. THE STUDY AREA

2.1 Location and Accessibility

The study area (Phitshane Molopo) is located in the south east part of Botswana near the border with Republic of South Africa. It is located within longitude 25.074°E to 25.0884°E and latitude 25.6608°S to 25.6752°S (Figure 1-1 c) in Southeast Botswana; It forms part of the Kraaipan greenstone belt (Figure 1-1 b) which extends from South Africa into Botswana. This belt is rich in gold as evident from gold operating mines in the South African part (e.g. Kalgold mine). The current study was carried out within an area of about 866 km² property owned by Laconia Resource Limited.

2.2 Geology

2.2.1 Regional geology

The Kraaipan greenstone belt is situated in the west-central part of the Kaapvaal craton and is largely located in the North West Province of South Africa. Its western part protrudes into southern Botswana (Figure 2-1). The regional geologic units of this belt include: Late Archaean volcanic rocks of the Ventersdorp Supergroup, Kraaipan-Madibe greenstone belt, the Mmathethe granite, the Kanye and Lobatse volcanic formations, the younger Karoo sediments and Tertiary-Recent sedimentary rocks of the Kalahari Group which covers a large part of the belt (Aldiss, 1985). The regions of the Kraaipan Group have been suggested based on the BIF and chert outcrops (Aldiss, 1985). The greenstones comprise of three narrow striking belts: Stella, Kraaipan and Madibe (Walraven & Anhausser, 1999). These belts are dominated mostly by mafic metavolcanics rocks interlayered with ferruginous chert. The granitoid rocks incorporate tonalitic and trondhjemitic gneisses (TTGs), granodiorite and adamellites. The terrane (Ramotoroko et al., 2016) was the Neoarchean Gaborone Igneous Complex (which incorporates A-type-granitoids, anorthosites, rhyolites and auxiliary mafic rocks that are represented by the Mmathethe granite (Aldiss, 1985; Mapeo et al., 2004).

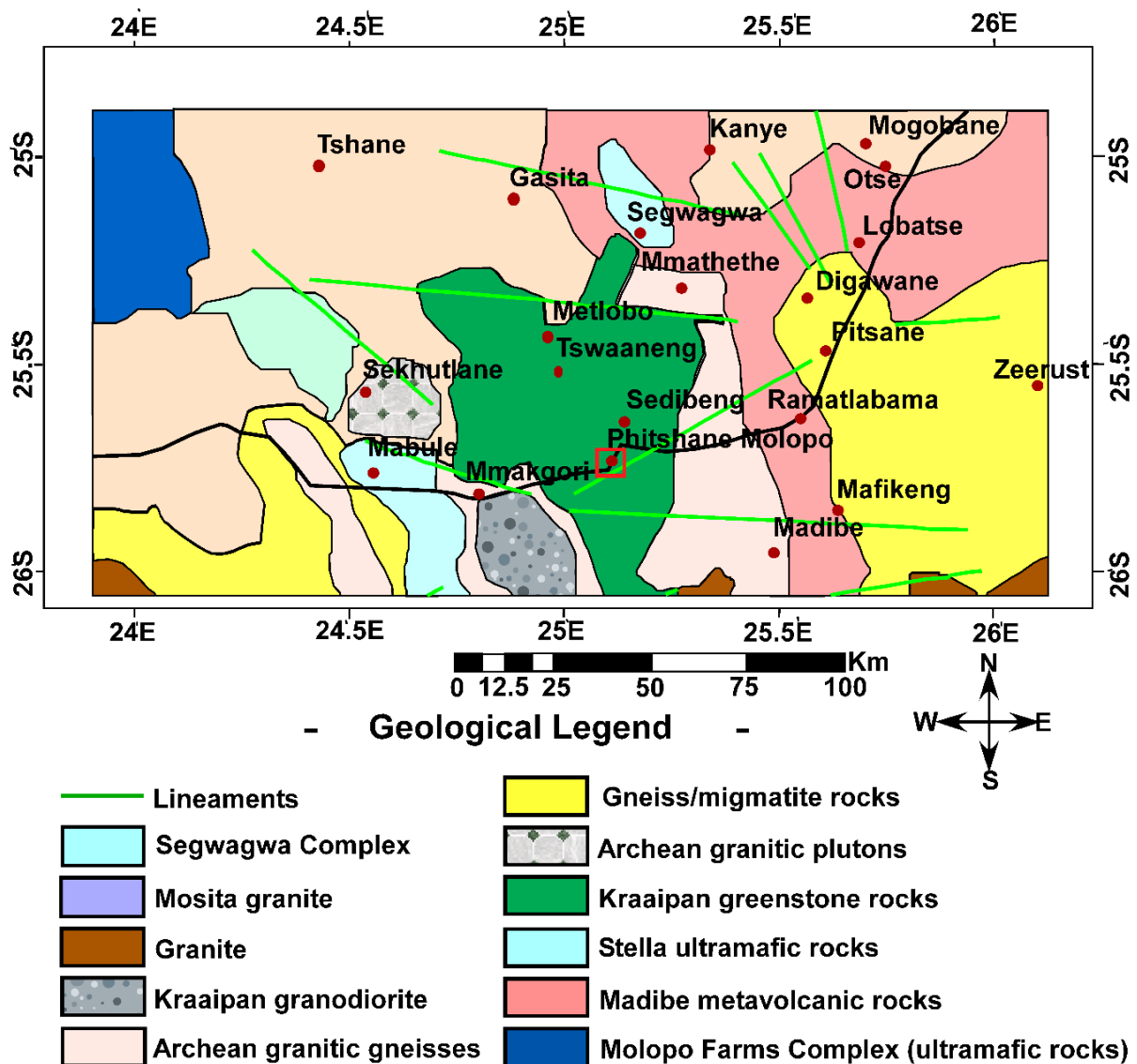


Figure 2- 1: Regional geology of the larger Phitshane Molopo area with the study area indicated with a square (Ranganai, 2017).

2.2.2 Detailed geology and Mineralization

Borehole cross sections KRP035, KRP036, KRP037, KRP038 and KRP039 (Figure 2-2) shows geology from historical drilling and borehole logs KRPC037 and KRPC038 from recent drilling by the license owner, Laconia Resource Limited (Figure 2-4 (a) and (b)).

Geologically, the area is generally covered by the undifferentiated Kalahari beds (< 5 meters thickness) and largely covered by the banded iron formations which outcrops in

the form of synclines. The historical borehole logs (Figure 2-2) which are within and in close vicinity of the study are indicate that there is an interlayered sequence of Goldridge Formation BIFs and greenstone (weathered and undifferentiated) and this might be because of the structural complexity of the whole sequence has overturned dipping 80° to 85° to the south-southwest (Laconia Resources Limited,2016).

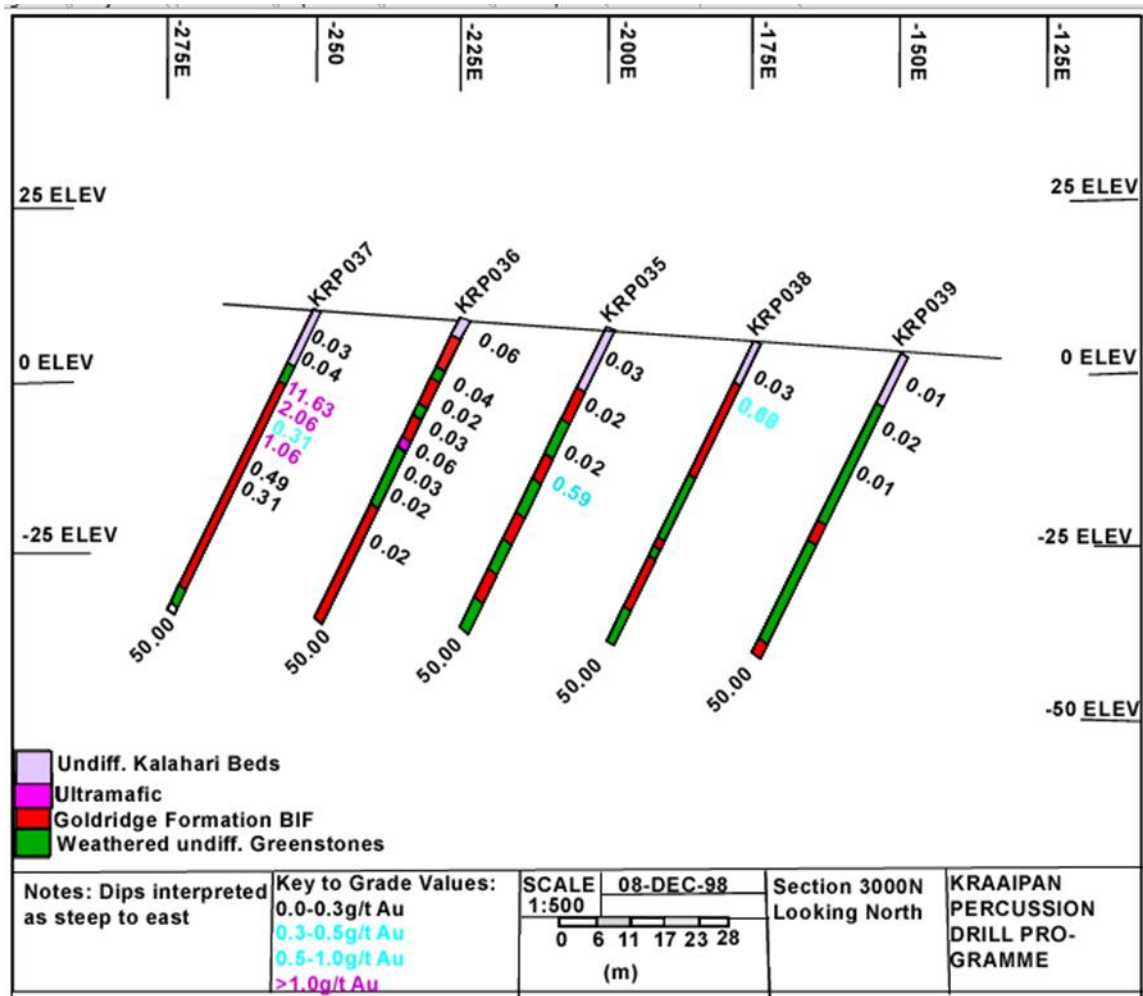


Figure 2- 2: The geological sections of boreholes in the study area with ore grades (from historical drill holes) (Laconia Resource Limited, 2012).

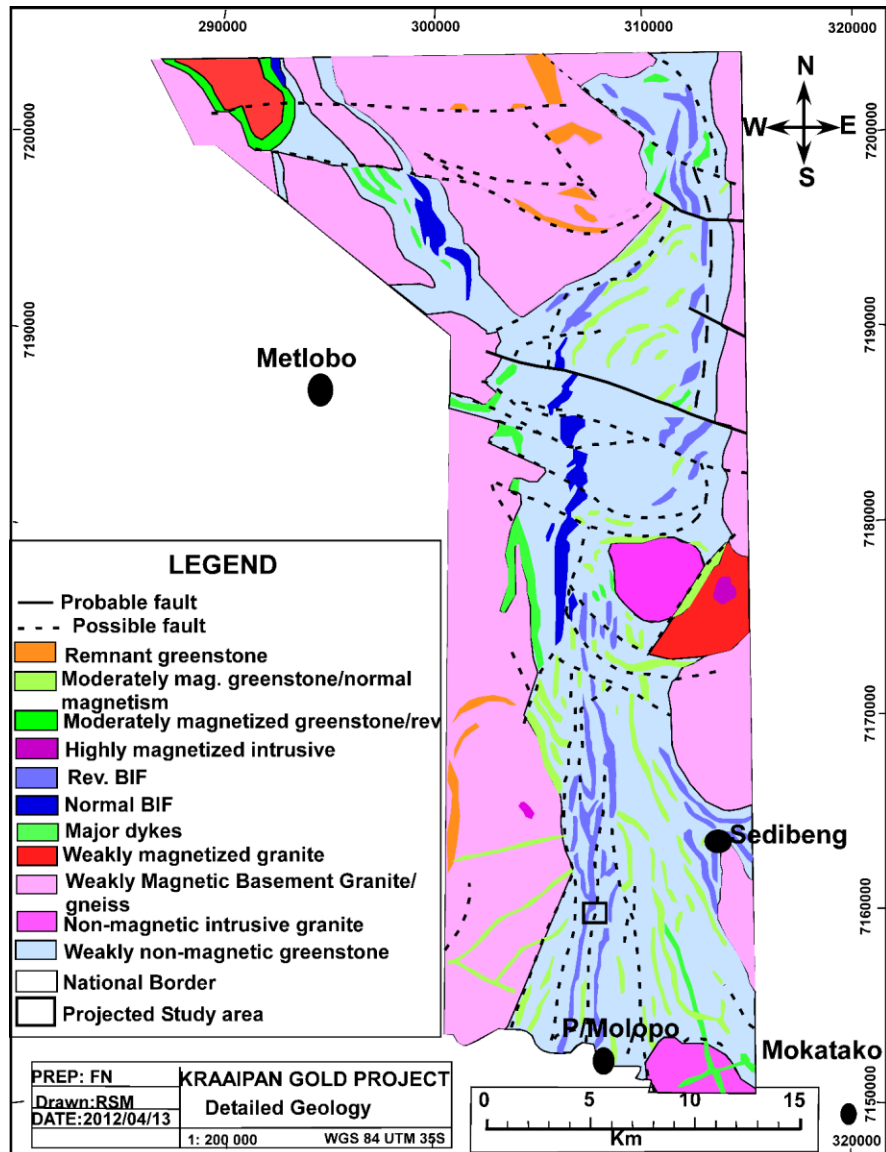


Figure 2- 3: Detailed geological map of The Laconia company licensed area. The study area is within the region marked with a square (modified after Laconia Resources Limited, 2012).

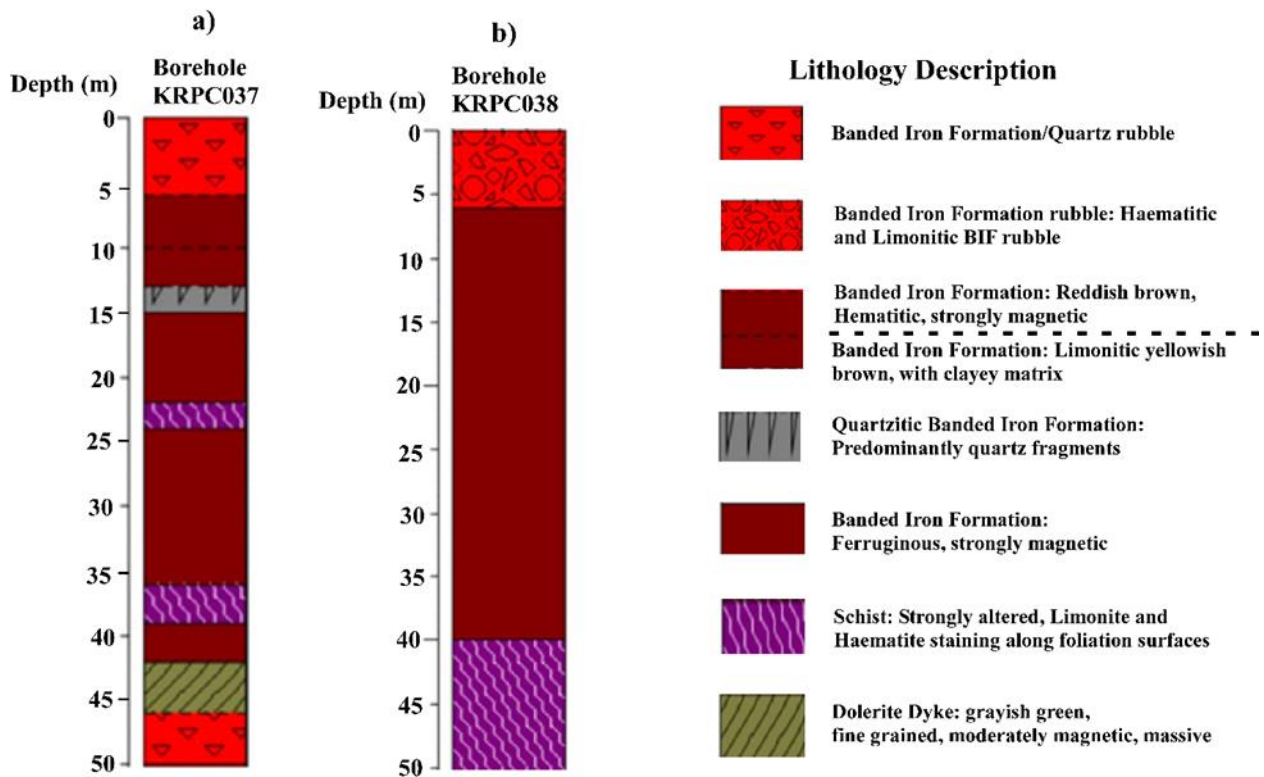


Figure 2- 4: The stratigraphic and depositional sequence of the study area, as established from (a) KRPC037 borehole and (b) KRPC038 borehole (Laconia Resources Limited, 2019).

The gold mineralization which has been recognized by an earlier exploration company within the Kraaipan greenstone belt in Botswana part is similar to the one found at the Kalgold mine in South Africa. Mineralization occurs within the quartz-carbonate veins (which are dipping by angle of $\sim 650^\circ$ E) and also found occurring in clusters within a steeply dipping, sub-greenschist, magnetite-chert, BIF rock units (Kraaipan Resource Limited, 2016). Previous drilled boreholes were designed to intercept these veins. The gold mineralized veins in the area are associated with sulphide mostly pyrite within and around quartz veins (Laconia Resources Limited, 2016). Previous exploration revealed gold mineralization in the Kraaipan Project (Laconia company licensed area (Figure 2- 3)), with the most valued rock chip samples documenting gold results ranging from 4.4g/t to as high as 36g/t Au (Laconia Resources Limited, 2016). The gold anomalous zones have also been identified from soil geochemistry as shown in Figure 2-5.

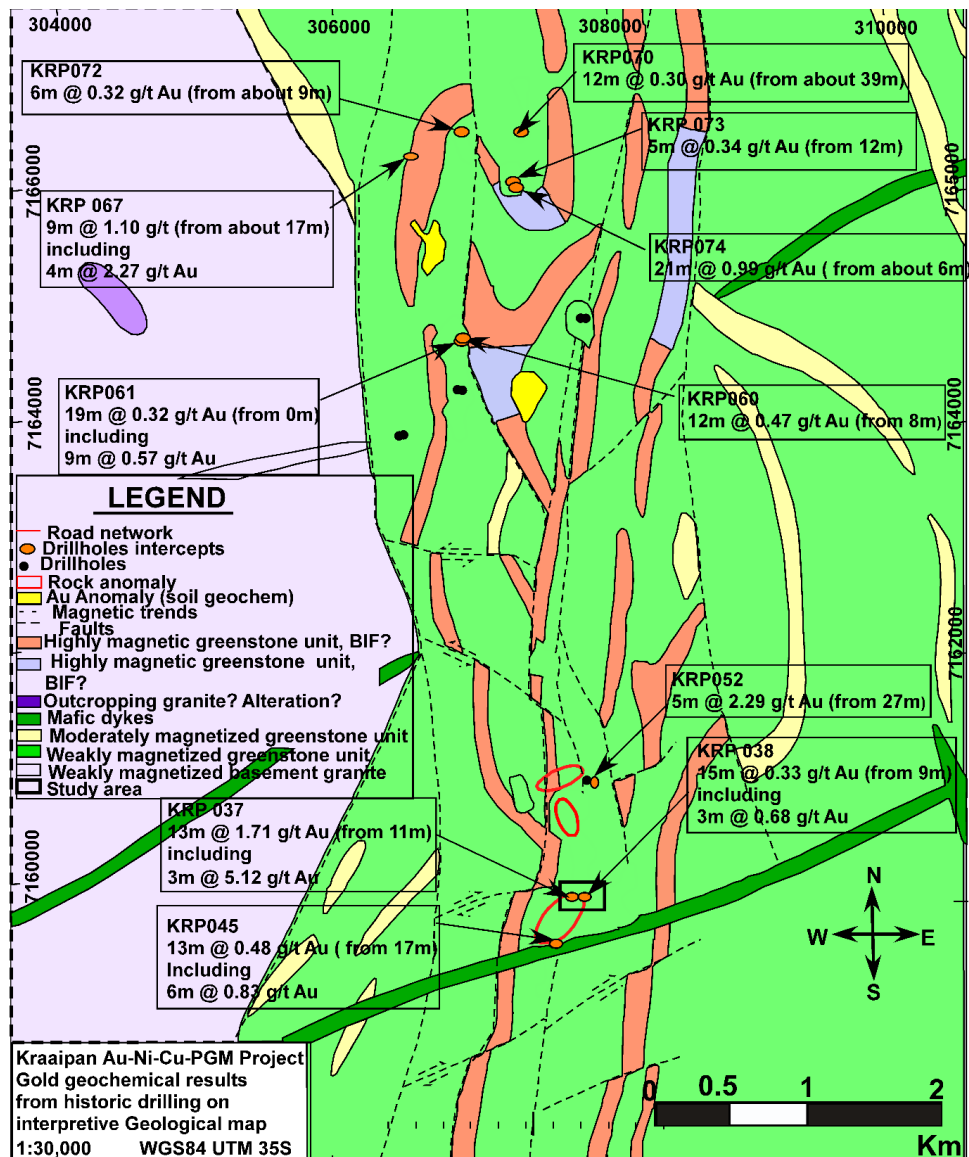


Figure 2- 5: Location of the historical Percussion Rotary Air Blast (RAB) drill holes in relation with zones of gold anomalies (from soil geochemistry) (Laconia Resource Limited, 2012).

3. BASIC PRINCIPLES

3.1 The Induced Polarization (IP) Method

The IP method was recognized in the 1950s and was referred to as over-voltage (Sumner, 1976). IP studies are relatively frequent, especially in mineral investigation studies. It can detect conductive minerals at low concentrations which may somehow be overlooked through the use of electrical resistivity (Sumner, 1976). The IP phenomena centers around the decaying potential contrasts as a function of time after the transmitter current is turned off; the voltage takes a few seconds to return to zero. IP method broadens the resistivity technique by making an extra measurement of the capacity of the ground to store electrical charge. The IP response's strength is dependent on amount of sulphide surface exposed to the pore water rather than the volume of sulphides contained in a rock (Schlumberger, 1920). Both the resistive and capacitive properties of the rock and soil are measured simultaneously in IP survey (Binley & Kenma, 2005). Practical uses in near-surface IP surveys have been inhibited by an insufficient understanding of the physical and chemical processes governing the IP response. However, Zhdanov & Keller (1994), Siegel, (1959), Sumner (1976), and Telford et al (1990) have significantly contributed to the IP effect description in the process of understanding induced polarization phenomenon.

The induced polarization phenomena are of electro-chemical origin, and depend mainly on the surface characteristics of the pore structure and the two main mechanisms responsible for the IP effect which are understood reasonably include; membrane, also known as electrolytic polarization and electrode polarization/ overvoltage (Kearey et al., 2002).

Membrane/ shale membrane Polarization (Figure 3-1 (a)): This type of polarization happens to non-metallic minerals (Kiberu, 2002). Most rock forming minerals possesses overall negative (anion) charges on external surfaces that are exposed to the pore liquid. These negative charges lure the cations to their surface (Ward, 1990; Kearey et al., 2002). The concentration of cations extends approximately up to 100 μm within the pore fluid, if the diameter of the pore throat matches this distance (100 μm), there will be an inhibition of ions activity which will result in applied voltage (Kearey et

al.,2002). Cations and anions will accumulate on either extremity of the blockage, when interrupting the applied voltage, the ions return to their former locations over a limited time giving rise to a steady decaying voltage. The phenomenon is common where we have clay minerals because the space between mineral grains are very small. The effect is inversely proportional to pore fluid salinity and the electronic path for current flow (Kearey et al., 2002).

Electrode Polarization (figure 3-1(b)): This phenomenon takes place when there is a metallic grain within a pore space. When a current is applied on either side of the pore space, the cations and anions are forced on opposite sides of the grain. Both ions centralize on either side of the metal grain that are trying whether to accept electrons conducted through the grain or release the electrons to the grain. There will be a buildup of ions on either side of the metal as the rate of electron exchange surpass that of electron conduction. The removal of impressed voltage will result in ions to slowly return to their original locations and lead to a transitory decaying voltage termed overvoltage/ electrode polarization (Kearey et al., 2002). This type of polarization occurs to good conductors like metallic sulphides, oxides and graphite (Kearey et al., 2002). Since this type of polarization is a surface phenomenon, hence inversely proportional to the size of the grain therefore suitable for exploration of disseminated ore bodies.

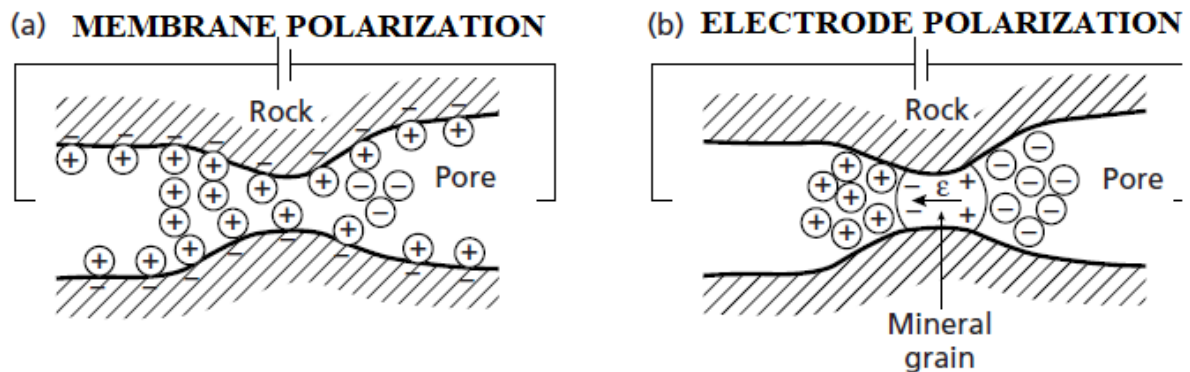


Figure 3- 1: Induced Polarization (IP) mechanisms (Kearey, 2002).

The IP measurements in the field are typically carried out using a four-electrode arrangement; two (A and B) for introducing electric current into the ground and two (M

and N) as potential difference receptors (Figure 3-2). When there is occurrence of IP effects, a voltage declining curve, $V_s(t)$ is observed at the M and N receptors in the course of current interruptions (off-current) between each slot (Gouet et al., 2016). There is monitoring of the decaying voltage after the applied current is interrupted (Figure 3-3) when performing IP measurements under time-domain and the parameter of interest is termed chargeability, **M**, (Siegel, 1959; Kiberu, 2002). The parameter estimates the material's capability to maintain charges after an impressed current is switched off. It is measured over set out time interval some seconds after the current is switched off (Kearey et al., 2002). To better define the decay curve, several chargeability windows are measured. Two types of voltages observed in time domain IP are the primary voltage (that vanishes immediately after current stoppage) and the secondary voltage which decreases with time following switching off the current source (Figure 3-3) (Kearey et al., 2002). Chargeability is characterized as the area, **A**, under the decay curve over a certain time interval (t_1 - t_2) standardized by a consistent voltage contrasts, ΔV_c , shown in equation 3-1 Siegel, 1959).

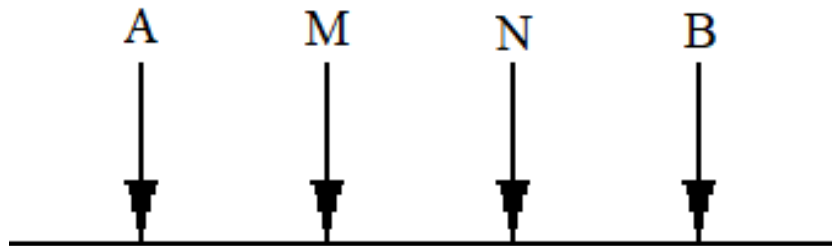


Figure 3- 2: A standard four electrode IP and resistivity array (AB= current injection and MN = potential reception electrodes) (Loke, 1999).

Overvoltage measurement is difficult as the time current is stopped due to electromagnetic effect which, on switching, produces temporary disruption (Kearey et al., 2002). Consequently, there is a time delay between current termination and start of a measurement. Following current termination, voltage decay is measured in various time windows then integrated to give the apparent chargeability (M_a) which is given in milliseconds (ms) or millivolts per volt (mV/V) (Telford et al., 1990).

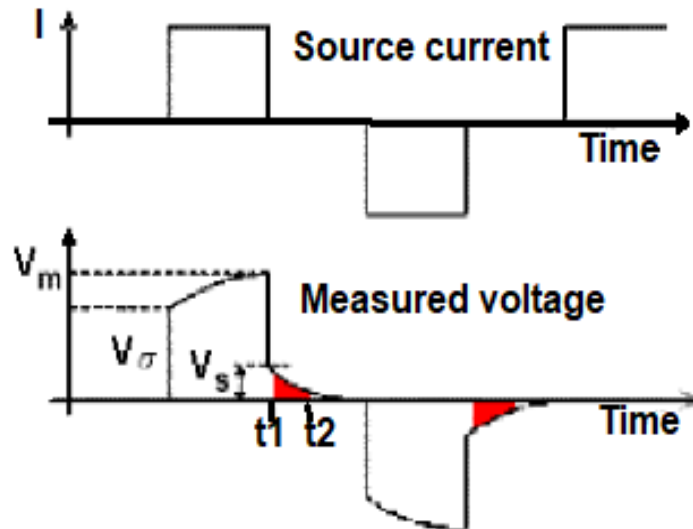


Figure 3- 3: A coordinated decay voltage utilized as a measure of chargeability, M, and chargeability equation. Source (Seigel, 1959; Kearey,2002; Haldar, 2018)

$$m_a = \frac{1}{V_p} \int_{t_1}^{t_2} V_{s(t)} dt \quad \dots\dots\dots(3-1)$$

The units millivolt per volt (mV/V) are utilized because the residual voltage (V_s) is much smaller than the steady voltage and chargeability is measured in milliseconds when the residual voltage have the same units as the steady voltage (V_p). IP is mostly and widely used and suitable for sulphide metal ores due to their strong IP effect and is mostly suited to be used in conjuncture with resistivity method rather than using a standard resistivity. It is not easy to detect disseminated metal ores using a standard resistivity method because of the frequently low resistivity contrast of their disseminated nature (Telford et al.,1990). Clay is also a common source for strong IP effect so it is very critical to have more geological knowledge of the site to accurately ascertain the source of the effect.

IP measurements can also be made in frequency domain where quantification of apparent resistivity is made at two (low and high) frequencies generally below 10Hz (Kearey et al., 2002). Parameters measured are Percentage Frequency Effect (PFE), and the Metal Factor. PFE is normally explained as the ratio of the difference between resistivity measured at Direct Current (DC) or at low alternating current frequency (0.05-

0.5 Hz), ρ_f and apparent resistivity measured at very high AC frequency (0.1-10 Hz) given in equation 3-2 while the metal factor is defined in equation 3-3 (Kearey et al.,2002).

$$PFE = 100 \frac{(\rho_{0.1} - \rho_{10})}{\rho_{10}} \dots\dots\dots (3-2)$$

$$MF = 2\pi \times 10^5 \frac{(\rho_{0.1} - \rho_{10})}{\rho_{0.1}\rho_{10}} \dots\dots\dots (3-3)$$

The metal factor normalizes the Percentage Frequency Effect with respect to lower frequency resistivity, and subsequently eliminates to a limited degree, the variety of IP effect with the viable host rock resistivity.

3.1.1 General Chargeability values for different earth materials (Telford et al.,1976).

From the Telford et al., 1976 guides, it is observed that field measurements tend to vary from laboratory values because in field measurements, large volumes of mixed materials are involved making it difficult to use the guide values in field measurements to infer the IP effects (Telford et al.,1976).

The examples given in Tables 3-1 to 3-3 list the chargeability of different minerals at 1% volume concentration (Telford et al., 1976). Square wave current duration was 3 seconds while the decay was integrated over 1 second. The values seem to be high with reference to the standard field measurements because it is not conventional to use a long timing cycle nor to integrate the total decay curve. Nonetheless, they demonstrate the discrepancy among IP sources. (Telford et al.,1976).

Table 3- 1: Chargeability values of 1% mineral concentration. (Komu, 2016; Telford et al.,1976).

Mineral	Chargeability (milliseconds)
Pyrite	13.4
Chalcocite	13.2
Copper	12.3
Graphite	11.2
Chalcopyrite	9.4
Bonite	6.3
Galena	3.7
Magnetite	2.2
Malachite	0.2
Hematite	0.0

Table 3- 2: Values of chargeability for various earth materials. The charging time was 3s and the integration time from 0.02 to 1 s of the decay curve. (Komu, 2016; Telford et al.,1976).

Material	Chargeability (milliseconds)
Groundwater	0
Alluvium	1-4
Gravels	3-9
Precambrian volcanics	8-20
Precambrian gneisses	6-30
Schist	5-20
Sandstones	3-12
Argillites	3-10
Quartzites	5-12

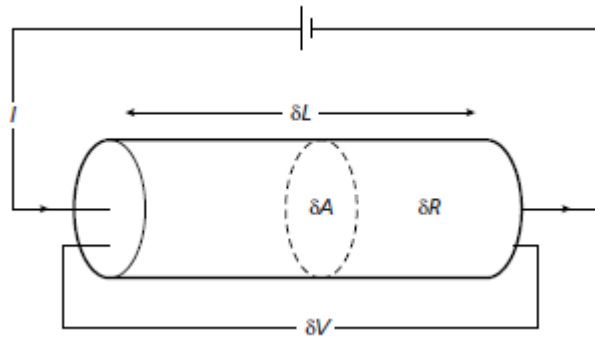
Table 3- 3: Chargeability values of a variety of mineralized and barren rocks. The ON-time was ~1 minute and the decay curve were integrated (except the prime transient and final noise) (Komu, 2016; Telford et al.,1976).

Material	Chargeability (milliseconds)
20% Sulphides	2,000-3,000
8-20% sulphides	1,000-2,000
2-8% sulphides	500-1,000
Volcanic tuffs	300-800
Sandstone, siltstone	100-500
Dense volcanic rocks	50-500
Shale	50-100
Granite, granodiorite	10-50
Limestone, dolomite	10-20

3.2 RESISTIVITY

This is an active geophysical technique which uses an artificial source introduced into the ground via two current rods and measuring the induced potential between two potential rods (Figure 3-2). It makes use of DC or low frequency AC currents in investigating electrical resistivity of the subsurface. Resistivity technique is widely utilized in conjunction with the induced polarization method because the IP instrumentation is capable of collecting the two datasets simultaneously and are utilized in the studies involving both horizontal and vertical discontinuities in the electrical (resistivity) properties of the ground (Sarma, 2014). Electrical resistivity is the impedance (in ohms) among the opposite faces of a unit cube of a material (Kearey et.al., 2002). Apparent resistivity, ρ_a , is calculated making use of the potential difference for interpretation. This apparent resistivity is equal to the real resistivity only when the material is uniform.

A conducting cylinder (Figure 3-4) with resistance δR , length δ and a cross-section area δA its resistivity ρ is given by equation 3-4;



$$\rho = \frac{\delta R \delta A}{\delta L} \dots\dots\dots (3-4)$$

Figure 3- 4: Parameters for defining resistivity and the equation for calculating it (Kearey *et al.*, 2002).

SI units for resistivity is ohm-meter (Ωm) with the reciprocal of it being conductivity and it's given in siemens (S) per meter (S/m).

The calculated resistivity is pseudo value (apparent resistivity) of the ground, it is the resistivity of a comparable ground. To determine the true resistivity of the ground one perform inversion of the measured apparent resistivity, ρ_a , utilizing inversion software. Ohm's law (equation 3-5 for current flow in continuous medium) is the physical law which governs the resistivity surveys.

$$J = \sigma \bar{E} \dots\dots\dots (3-5)$$

where σ is the electrical conductivity, $\mathbf{J}$ is the current density and $\mathbf{E}$ is the electric field intensity, respectively. In practice, we measure electric field potential. Below is the connection between the electric potential and field intensity;

$$E = -\nabla \phi \dots\dots\dots (3-6)$$

Merging equations (3-5) and (3-6),

$$J = -\sigma \nabla \phi \dots\dots\dots (3-7)$$

In the case of point current sources (for almost every survey) over an elemental volume ΔV surrounding a current source, I , located at (x_s) , (y_s) and (z_s) , the relationship between the current and current density (Dey & Morrison 1979; Loke, 2004) is given;

$$\nabla \cdot \mathbf{J} = \left(\frac{I}{\Delta V} \right) \delta(x - x_s) \delta(y - y_s) \delta(z - z_s) \dots\dots\dots (3-8)$$

where δ = the Dirac delta function. Equation (3-8) can then be rewritten as;

$$-\nabla \cdot [\sigma(x, y, z)] = \left(\frac{I}{\Delta V} \right) \delta(x - x_s) \delta(y - y_s) \delta(z - z_s) \dots\dots\dots (3-9)$$

Equation 3-9 gives the potential distribution due to a point current. More techniques have been established in solving the equation (Loke, 1996 - 2004) and this is termed the forward modelling problem. This is where the potential that would be observed over a given sub-surface structure is determined. Fully analytical methods are used for easy demonstrations, like a sphere during a homogenous medium, or a vertical fault in between two areas with a continuing resistivity (Dobrin, 1960).

For a random resistivity distribution, numerical techniques are frequently utilized. In 1D demonstration where the sub-surface is confined to a variety of horizontal layers, a method called linear filter is frequently utilized (Koefoed, 1979; Loke, 1996 - 2004). For cases involving 2D and 3D, the finite-difference or finite element methods are the foremost adaptable.

For a homogenous and isotropic subsurface with one current source (Figure 3-5); current flows away from the source radially and the potential differs inversely with distance from the source (Dobrin, 1960; Loke, 1996 - 2004). The surfaces with equal potential have a hemisphere shape and the current flow perpendicular to the equipotential surface. Below is the equation for this case;

$$V = \frac{\rho I}{2\pi r} \dots\dots\dots (3-10)$$

where r is the distance of a point in the medium from the electrode.

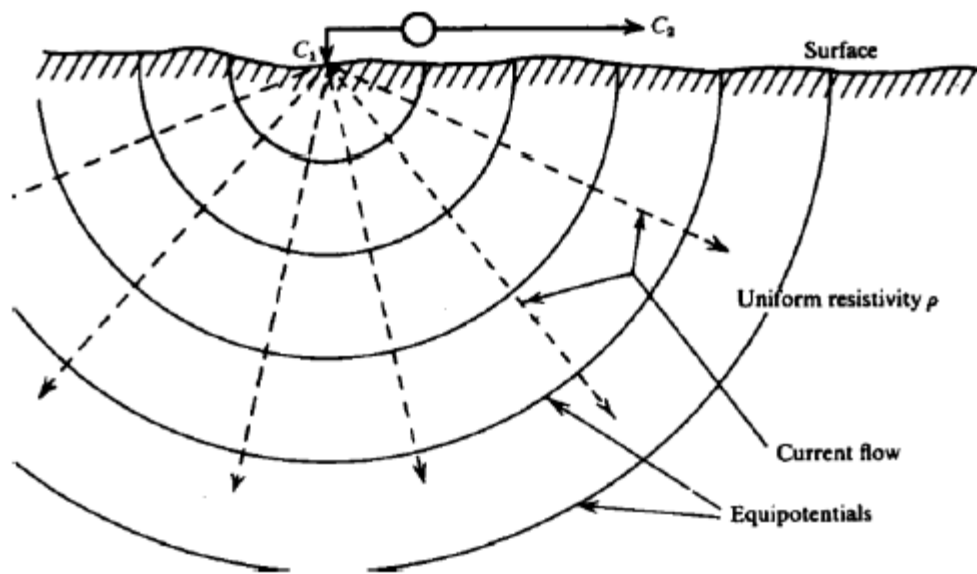


Figure 3- 5: Electrical current flow for a single surface electrode and the resulting potential distribution (Loke, 2004).

For practical purposes, at least two current (a positive and a negative) electrode are used and the potential distribution is shown in Figure 3-6. The potential values have a uniform pattern about the vertical plane at the mid-point between the 2 electrodes (Loke,1996-2004).

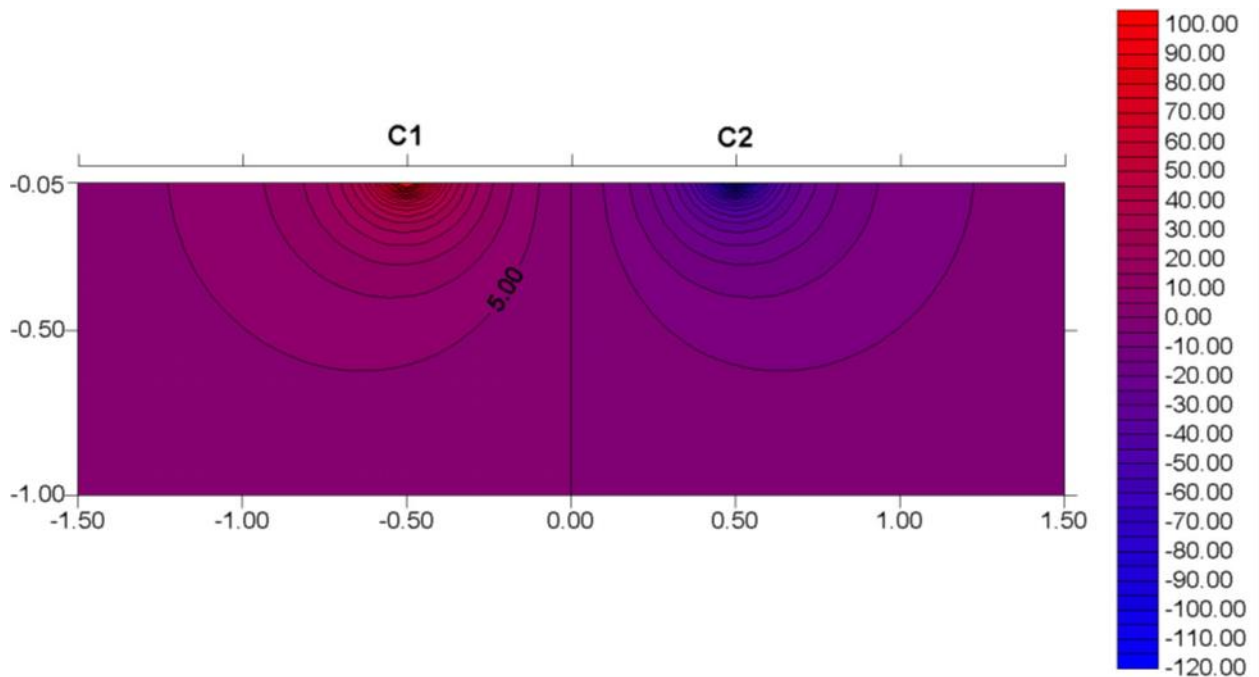


Figure 3- 6: The distribution of voltage for a pair of current rods (1 m apart) with 1 amp current injected and a homogenous half space with resistivity of 1 ohm-meter (Loke, 2004).

The potential value within the medium from such a pair is given by;

$$V = \frac{\rho I}{2\pi} \left(\frac{1}{r_{c1}} - \frac{1}{r_{c2}} \right) \dots\dots\dots (3-11)$$

r_{c1} and r_{c2} are distances of the point from the first and second current electrodes (Loke,1996 - 2004).

Practically, in all surveys, electric potential between two points (usually on the surface of the ground) is measured. The potential difference for an arrangement with 4 electrodes (Figure 3-7) is given by

$$\Delta V = \frac{\rho I}{2\pi} \left(\frac{1}{r_{C1P1}} - \frac{1}{r_{C2P1}} - \frac{1}{r_{C1P2}} + \frac{1}{r_{C2P2}} \right) \dots\dots\dots (3 - 12)$$

Actual field measurements are always conducted over a varied medium where subsurface resistivity has a 3D distribution (Loke,1996 - 2004). Current is injected into the ground through 2 electrodes termed C1 and C2 (Figure 3-7) and the resulting potential difference is measured at 2 potential electrodes (P1 and P2).

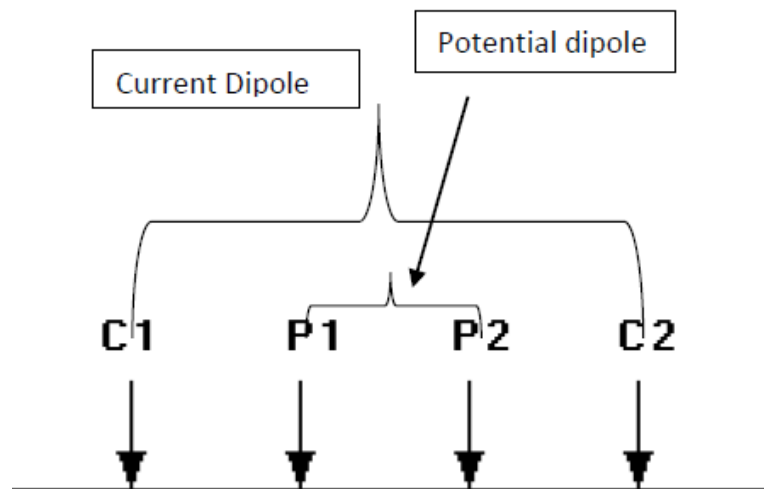


Figure 3- 7: A standard four electrode array to measure IP and resistivity (Loke, 2004).

The calculated resistivity is an “apparent” value (not the true resistivity of the subsurface) of a homogenous ground and it will give the same resistance value for the same electrode configuration (Loke,1994 - 2004). The “apparent” and “true” resistivities have a complex relationship and determining the true resistivity from the apparent resistivity values is the “inversion” problem (Loke,1994 - 2004). Apparent resistivity, ρ_a , is calculated from the current, I , and potential values, $\Delta\phi$, respectively.

$$\rho_a = k \frac{\Delta\phi}{I} \dots\dots\dots (3-13)$$

where,

$$k = \frac{2\pi}{\left(\frac{1}{r_{C1P1}} - \frac{1}{r_{C2P1}} - \frac{1}{r_{C1P2}} + \frac{1}{r_{C2P2}}\right)} \dots\dots\dots (3-14)$$

Geometric factor, k , is dependent on the electrode arrangements. Resistivity instruments usually give a resistance value, $R = \Delta\phi/I$, so practically the ρ_a is given by;

$$\rho_a = kR \dots\dots\dots (3-15)$$

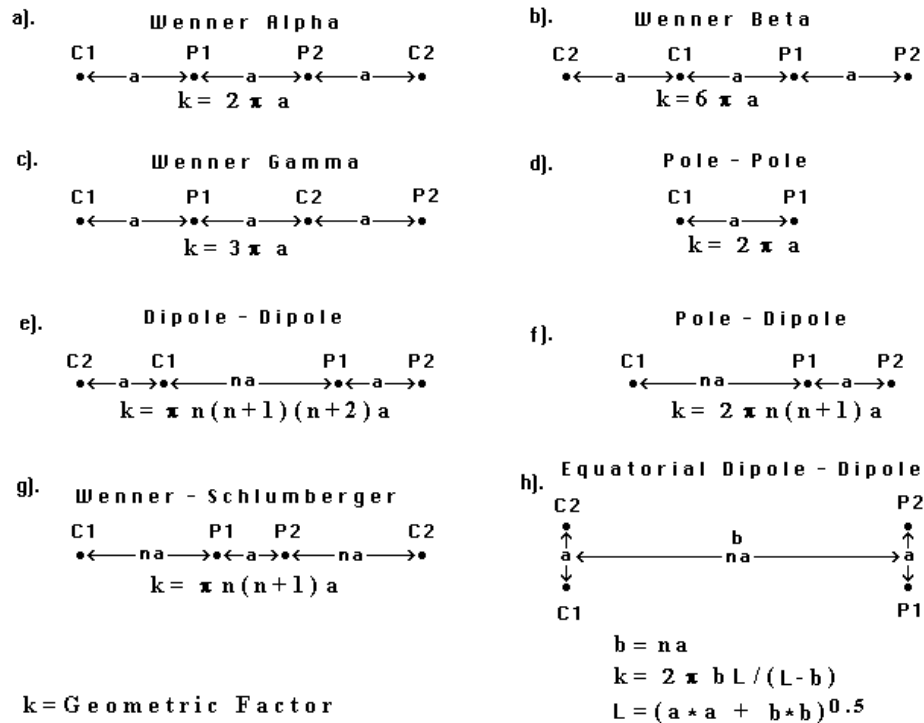


Figure 3- 8: Commonly used electrode arrays in resistivity survey and their k (geometric factors) (Loke,2004).

3.2.1 Resistivity values for rocks, soils and ore types

According to Loke (2004), igneous and metamorphic rocks tend to possess high values of resistivity and these values are dependent on the degree of fracturing, the percentage of the fractures that are filled with fluid and the composition of that fluid. This is to say, a given rock type can have an outside resistivity range) from approximately 1,000 to 10 million ohm-meter) depending on its water content. On the other hand, the more porous and higher water content sedimentary rocks normally have lower resistivities in comparison with other rock types.

Porosity and clay content affect the resistivity of rocks. Soil rich in clay is usually less resistive as compared to sandy soil, however, there is an overlap in the values of various rocks and soils (Gomez-Ortiz et al., 2007). This is because resistivity of a rock or soil is affected by many factors (e.g. porosity, the degree of water saturation and dissolved salts concentration).

Resistivity ranges of different ore types are also shown in table 3-9. Metallic sulphides (e.g. pyrrhotite, galena, pyrite) are usually conductive. The nature of the ore body (massive or disseminated) affect resistivity (Loke,1996-2004). For instance, graphitic slate has low resistivity which is the same as that of sulphides and this can cause challenges in mineral exploration. Oxides such as hematite have high resistivity values and an exception is magnetite (which have low resistivity value) (Loke,1996-2004).

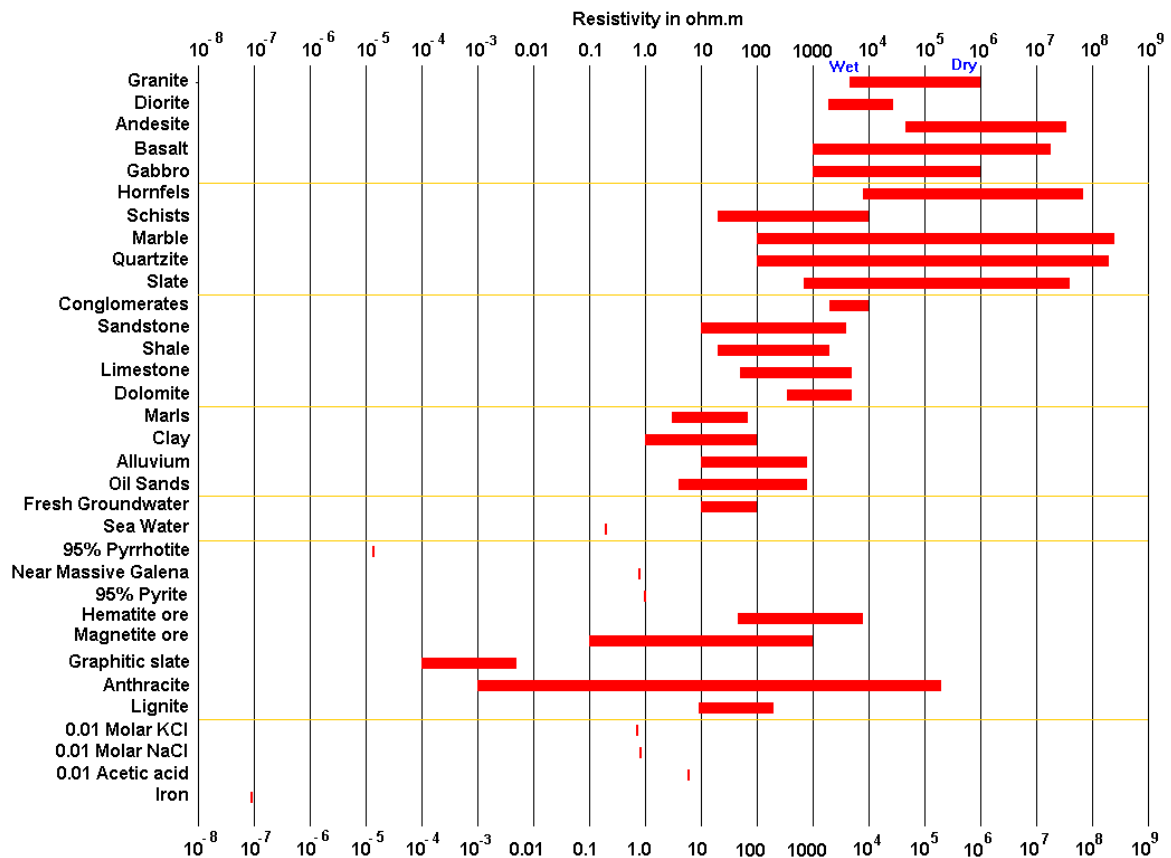


Figure 3- 9: Resistivities for some rocks, soils and minerals. (Loke,2004)

3.3 Inversion (Loke, 1996-2004)

This is the application of mathematical problems in science to transform a set of observed data to reconstruct a model (Loke, 1996-2004). An attempt to seek a model that provides a response that is almost the same as the actual measured values is made in geophysical inversions. Model is defined as “an idealized mathematical representation of a section of the earth” (Loke, 2001). There are set of parameters in a model which are defined as physical quantities we would like to predict from the observed data. All inversion methods plan to determine a subsurface model whose response agrees with the measured data subject to specific limitations.

The RES2DINV and RES3DINV programs uses a cell-based method whereby the model parameters are represented by resistivity values, and the measured apparent resistivity values are the field data. The finite-difference or finite-element methods (Dey & Morrison;

Silvester & Ferrari, 1990) give a link among the model parameters and response for both the 2D and 3D resistivity models. The subsurface is partitioned into small rectangular cells in RES2DINV and RES3DINV program, (Loke, 1999). In optimization methods altogether, iteration modifies the initial model to minimize the contrast between the model response and the observed data.

The set of observed data are often written as column vector, **y**, given by

$$\mathbf{y} = \text{col}(y_1, y_2 \dots y_m) \dots \dots \dots (3-16)$$

m represents the number of measurements. Model response, **f**, can be written in the same form as;

$$\mathbf{f} = \text{col}(f_1, f_2 \dots f_m) \dots \dots \dots (3-17)$$

For the resistivity routine, it is a standard practice to utilize the logarithm of the apparent resistivities for the observed data and model response and therefore the logarithm of the model as the model parameters.

$$\mathbf{q} = \text{col}(q_1, q_2 \dots q_n) \dots \dots \dots (3-18)$$

n represent the number of model parameters. The discrepancy vector, **g**, gives the difference between the observed data and model response and it's given by

$$\mathbf{g} = \mathbf{y} - \mathbf{f} \dots \dots \dots (3-19)$$

In the least square optimization method, the initial model is modified in such a way that the sum of squares error, **E**, of the difference between the model response and the observed data values is reduced.

$$\mathbf{E} = \mathbf{g}^T \mathbf{g} = \sum_{i=1}^n \mathbf{g}_i^2 \dots \dots \dots (3-20)$$

In an attempt to reduce **E** above we use the Gauss-Newton equation below in determining the change in model parameters that would reduce the sum of squares error (Lines and Treitel 1984; Loke, 2004).

$$\mathbf{J}^T \mathbf{J} \Delta \mathbf{q}_i = \mathbf{J}^T \mathbf{g} \dots\dots\dots (3-21)$$

Δq is the model parameter change vector while **J** is the Jacobian matrix of size **m** by **n** of partial derivatives and its elements are given by

$$J_{ij} = \frac{\partial f_i}{\partial q_j} \dots\dots\dots (3-22)$$

That is the change within the *i*th model response anticipated by a change in the *j*th model parameter. A new model will then be attained by

$$\mathbf{q}_{k+1} = \mathbf{q}_k + \Delta \mathbf{q}_k \dots\dots\dots (3-23)$$

In practice, a straightforward least square equation (3-21) is never employed by itself in geophysical inversion. In some cases, the matrix product **J^TJ** could be singular, and thus the equation of the least square does not have an answer for **Δq**. Furthermore, the matrix product **J^TJ** is almost singular and this usually happens when a poor initial model which is dissimilar from optimum model is employed. Marquardt-Levenberg modification (Lines & Treitel, 1984; Loke, 2004) to the Gauss-Newton equation is used to avoid such problems and it is given by;

$$(\mathbf{J}^T + \lambda \mathbf{I}) \Delta \mathbf{q}_k = \mathbf{J}^T \mathbf{g} \dots\dots\dots (3-24)$$

I is the identity matrix. The factor **I** is named the Marquardt or damping factor and this method is additionally referred to as the ridge regression method (Inman, 1975); (Loke, 2004). The range of values that the components of parameter change vector, **Δq**, can take, are effectively constrained by the damping factor. Whereas the Gauss-Newton method in equation 3-21 attempts to scale back the sum of squares of the discrepancy vector only. The Marquardt-Levenberg modification method also lowers a mixture of the

magnitude of the discrepancy vector and therefore the parameter change vector. The method has been utilized successfully in the inversion of resistivity sounding datasets where the model contains a small number of layers.

Nonetheless, when the amount of model parameters is massive like in 2D and 3D inversion model which has sizable number of small cells, the resultant model by this method can have varying resistivity distribution with delusive high/low resistivity zones (Constable et al., 1987; Loke, 2004). This problem is controlled by further modifying the Gauss-Newton least squares equation so as to reduce the spatial variations within the model parameters. That is, the model resistivity values change in a smooth manner and this smoothness-constrained least squares method (Ellis & Oldenburg 1994; Loke, 2004) is given by;

$$(J^T \lambda F) \Delta q_k = J^T g - \lambda F q_k \dots \dots \dots (3-25) \quad \text{where,}$$

$$F = \alpha_x C_x^T C_x + \alpha_y C_y^T C_y + \alpha_z C_z^T C_z$$

And C_x , C_y and C_z being the smoothing matrices within being the x-, y- and z-direction respectively. α_x , α_y , and α_z being the relative weights given to the smoothness filters in the x-, y- and z-directions.

Equation 3-25 also attempts to reduce the square of the roughness of the model resistivity values and it is actually termed an L2 norm smoothness-constrained optimization method, which tends to produce a model with a smooth variation of resistivity values. This approach is suitable if the particular subsurface resistivity varies in a smooth and gradational manner (Loke, 1996-2004).

4. MATERIALS, METHODS AND DATA PROCESSING

4.1 Material

Prior to the commencement of field, desktop studies were conducted whereby relevant literature pertaining to the proposed topic were obtained and were reviewed. This included review of the regional geology map of the Kraaipan belt from Ramotoroko et.al., (2016) and Ranganai (2017), geology of Phitshane Molopo area by Aldiss (1985), reports from Laconia Resource Limited website and other journal articles from South Africa researchers such as (Hammond & Moore, 2006; Poujol et.al., 2002; Anhaeusser & Walraeven, 1999) and other researches related to the topic of research. Information obtained from literature review assisted in designing the sampling grid and sampling stations. The sampling grid and stations were mapped in UTM coordinates and this information were then used to layout the field data collection plan. Figure 4-1 shows equipment used for data collection.

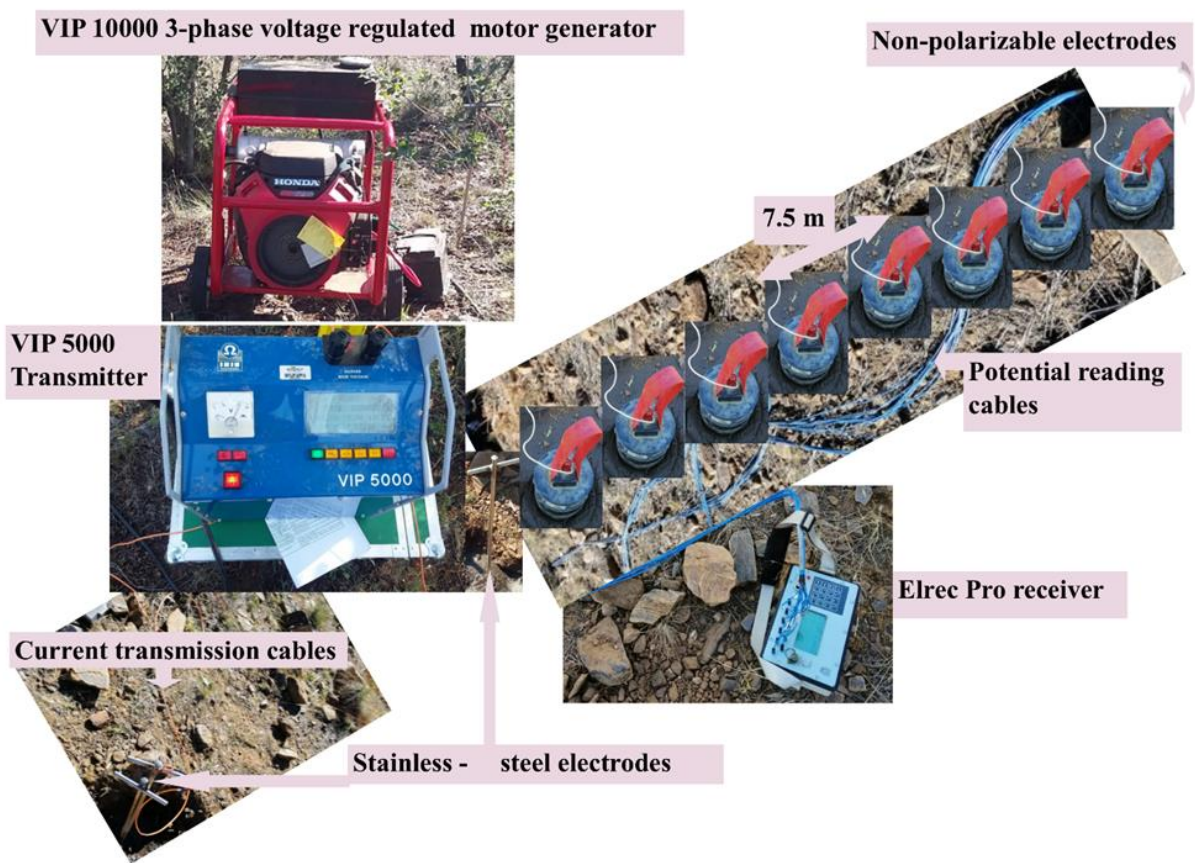


Figure 4- 1: Images showing the data acquisition setup consisting of the Elrec Pro unit, potential measuring and current transmission cables laid on the ground, a pair of stainless-steel electrodes planted into the ground and an array of non-polarizable potential electrodes connected to the potential measuring cables.

For communication during the survey, the Kenwood walkie-talkie with a two-way communication was used.

4.2 Methods and data acquisition

VIP 5,000 transmitter which was powered by the VIP 5, 000 generator was used to transmit DC current pulses into the ground through stainless steel rods. The pulses were set to 2 seconds ON and OFF duration. Stainless steel rods were utilized throughout the survey for current injection hammered into the ground. Clay was added in each depression and watered with salt water for easy conduction (Figure 4-1) because the survey was directly on top of the BIF outcrop so this helped in minimizing contact resistance and enabled more current to be injected into the ground.

ELREC Pro receiver measures potential in potential dipole (MN) during current transmission (the “ON-time”). The apparent resistivity value for this measurement is automatically determined and this is based on the injected current (I) strength, the primary voltage (V_p) (measured during current transmission) and the array. The potential decay is also measured by the receiver during current interruptions (“OFF-time”) and this potential difference is termed secondary voltage (V_s) or residual voltage. The two voltages (V_p and V_s) are used by the instrument to automatically calculate chargeability value which is the ratio between the induced polarization measured during the OFF-time and the one measured during the current interruption (“ON-time”).

Measurement of the voltage was realized through 11 porous pots (10 channels) along a NE-SW direction with 307.5 m total length per line, using a line having line spacing of 15 m and 7.5 m electrode spacing in a grid of 307.5 m by 135 m. The station was located based on the location of borehole logs which intercepted significant amount of gold mineralization. The spacing was based on the fact that mineralization is documented to be of disseminated nature and one should not design large spacing to avoid missing the

target. The 7.5 m electrode spacing was filled with saturated copper sulphate (making sure that the copper coil inside the non-polarizable electrode was completely covered by the solution). The porous pots are put into a shallow depression moistened with water (with clay added in the depression to enhance contact between the porous pot and the rocky ground are also essential to cancel out the self-potential and its polarization with the current switching). The receiver then measures contact resistivity for each dipole and if it's very high more wet clay is added into the electrode pit until there is a reduction in the contact resistance value (until we have a value less than 1 K Ω).

IP and resistivity survey were carried out along 10 profiles (Figure 4-2) with 307.5 m total length per line having line spacing of 15 m in a grid of 307.5 m by 135 m. Connection between the receiver and the receiver electrodes was through a multi-electrode potential cable which was created by putting together a number of single cables bundled together by a cable-tie ("snake cable") with female connectors exposed where the electrodes are connected to the "snake" (7.5 m). This mechanism allowed for simultaneous measurement and increased productivity there by reducing time spent in the field.

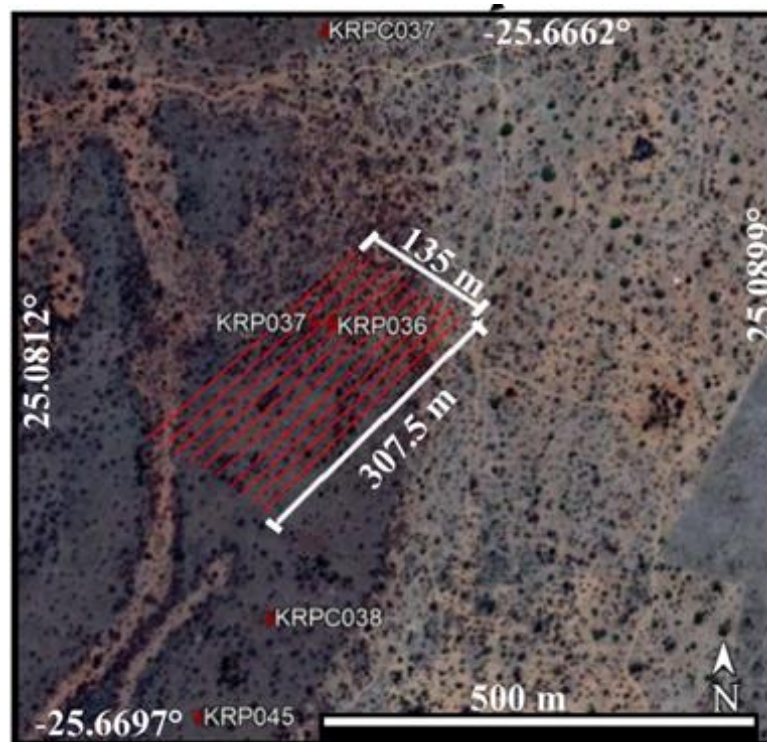


Figure 4- 2: Satellite image showing the layout of the 10 profiles surveyed (red lines).

Anomalously high chargeability values usually correspond to areas enriched with disseminated sulphides (which typically occurs with gold mineralization) and these are marked as primary targets. Coordinates are given in decimal degrees.

Anomalously high apparent resistivity values are generally associated with quartz-veins or BIFs. A combination of high apparent resistivity and high chargeability is typical for a sulphide-bearing quartz vein.

The ELREC pro receiver was used for measuring induced polarization and resistivity in the time domain window. The receiver has ten simultaneous dipole readings and all the channels were utilized giving a total of ten measurement levels. Before the acquisition the receiver measures the contact resistances of the receiver electrodes and the improvement on the resistance and ground contact was made by adding clay and fresh water around the receiver pots thereby reducing high values of the contact resistance because of the highly resistive banded iron formation encountered on the surface of the surveyed area.

4.3 Quality assurance

IP receiver has its own quality assurance parameters, which are employed to make sure that the produced IP/resistivity datasets are of acceptable quality and they include;

- Standard deviation- which defines data quality of the chargeability and apparent resistivity and it was set to at 3%.
- Root Mean Square Deviation (RMS) which qualifies the “goodness” of the fit between the measured decay curve and the “best fit” master curve. All data with RMS error of more than 3% was discarded and re-measured.
- Stacking- the quadrupoles were measured 3-6 times and an averaged value recorded (enhance signal-to-noise ratio).

- Potential electrodes always had a constant saturated salt throughout and we made sure that it covers the copper coil inside the porous-pot so as there is no potential gradient created.
- Good insulation of cables both for current transmission and potential reception to avoid electrical leakages.

Since a pole-dipole is an asymmetrical array to eliminate this asymmetry the measurements were repeated with the electrodes arranged in the reverse manner and both the forward and reverse measurements were combined so as to remove any bias in the model due to asymmetrical nature of the array.

Main challenge encountered during data acquisition;

- Noise from a highly resistive BIF

The survey was carried out directly on top of a BIF outcrop. The IP and resistivity are galvanic methods whereby one has to plant electrodes into the ground but this was very difficult due to the outcrop. One has to introduce as much current into the ground as possible so given a highly resistive layer it was challenging. Also, contact resistance between the ground and the porous pots was high. An attempt to try by all means to reduce the contact resistance was done by introducing wet mud into small depressions which were made for porous pots and mud was also added around the current electrodes watered with salt water. All these caused delays and sometimes it took two days to complete on survey line.

4.4 Data Processing

Every day after field work data was transferred into a computer in text format so as to enable interrogation of the data to ensure that mistakes made during entries manually in the field (e.g. wrong station number and incorrect current values) were corrected and data edited using a Notepad ++ text editor. After successful editing and correction of data to satisfaction, the data was then saved in a *.dat* file format readable by the RES2DINV software. The data was then read into the RES2DINV software. This software is capable of detecting spurious data points which were then removed through

a method called apparent resistivity and chargeability statistics. This was done so as to eliminate single data points because we are not interested in single data point, but rather trends (Loke, 2015).

This process of removal of single data points was performed in RES2DINV (and RES3DINV) programs with minimal input from the user. Additionally, editing of the datasets was carried out by performing preliminary inversion and the distribution of the Root Mean Square errors (RMS) were displayed in the form of bar charts for both apparent resistivity and chargeability datasets (Figure 4-3). From these bar charts bad data are recognized by their relatively large RMS errors and small heights of the bars and were removed prior to performing the post inversion process. Bad datasets are caused mostly by poor ground-electrode contact which might have been the case in this study as it was performed directly on top of a BIF hill. As a rule of thumb, data points with errors of 100% (Loke, 1996 - 2015) and more are referred to as bad data points and removed by moving the vertical line to the left of the bars to 100% error bar. Only those points with apparent chargeability and resistivity percentage errors of 50% and below were utilized in this study.

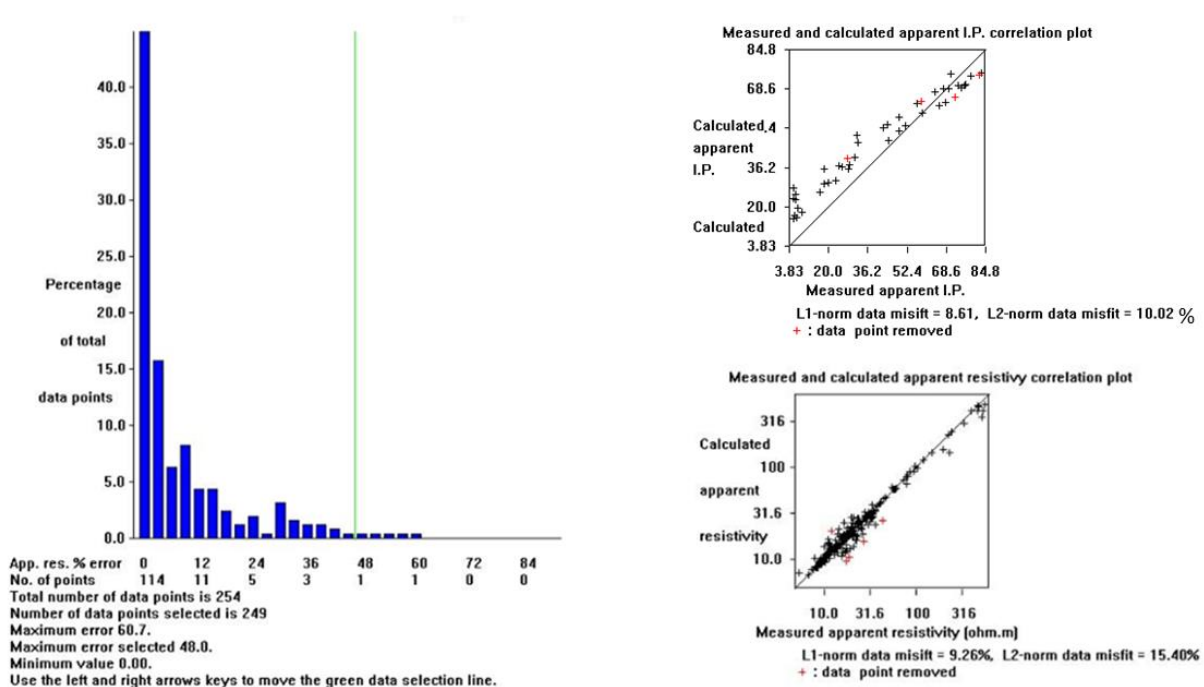


Figure 4- 3: Error distribution bar charts demonstrating resistivity and chargeability percentage errors with their correlation plots on the right side

The inversion routine employed by the RES2DINV™ program is predicted on the smoothness-constrained method by DeGroot & Constable (1990) (Loke, 2003). The inversion program subdivides the subsurface automatically into a variety of small rectangular blocks, and attempts to work out the true resistivity values by decreasing the difference calculated and measured apparent resistivities (Loke, 2009). A standard Gauss-Newton method which “uses a direct method to solve the least-square equations” was utilized in this study. A standard least-squares model constraint method that tries to minimize the square of the difference (L2 norm) among the observed and calculated apparent resistivities and tends to generate better models in cases where model changes in a smooth manner was utilized (Claerbout & Muir, 19973; Loke, 2003). Root Mean Square (RMS) error gives a measure of the discrepancy between the measured and calculated resistivity values. In this study, a convergence limit of 1% change between two consecutive iterations (Root Mean Square) was utilized. The program stops when the RMS fitting error is below limit set. In all the 2D and 3D models it was achieved within five to seven iterations. The final inversion resistivity sections generated have L1-norm data misfit of less than 10%.

There are generally two approaches to calculate induced polarization effect from mathematical models (Loke, 2015): the non-linear complex and linear perturbation methods. The perturbation method was utilized in this study and it regards the chargeability model as a tiny perturbation of the base resistivity model.

IP inversion was described by Li & Oldenberg (1994) as a two-step process; 1) carry out an inversion with only resistivity dataset which produce a model that is independent of the measured data; 2) use the resistivity model as a base and calculate the apparent chargeability values using the equation of chargeability. While keeping the resistivity model constant or fixed, the apparent chargeability data is then inverted to get a chargeability model of the subsurface.

5. INVERSION MODELS AND INTERPRETATION

5.1 2D Resistivity and chargeability models

The geophysical surveys were carried out along 10 profiles labeled L1 to L10 (Figure 4-6) and were processed using the RES2DINV software to produce 2D inverse chargeability and resistivity of the subsurface which were then correlated with the stratigraphy log of KRPC037 (Figure 2-4 (a)). The historical borehole logs KRP035, KRO036, KRP037, KRP038 and KRP039 (Figures 2-2) are projected on the sections which are in close proximity with them and indicate the ore grade found in them. The results of the profiles (L1 to L10) are shown in Figures 5-1 to 5-10. 3D horizontal (X-Y plane) resistivity and chargeability models was produced by combining the 10 2D profiles and processed using the RES3DINV program and the results are shown in Figures 5-11 and 5-12. The isosurfaces for both resistivity and chargeability generated by a 3D display software called Slicer Dicer are displayed in Figures 5-13 and 5-14 respectively.

The pole-dipole inverted resistivity and chargeability 2D sections (Figures 5-1 to 5-10) represent the resistivity and chargeability of the subsurface underneath L1 to L10. The deep colors purple-red-orange represent zones of high resistivity and high chargeability zones while blue represent zones of low resistivity and chargeability. Each figure contains two models; (one is the resistivity model (a) whilst the other one is the chargeability model (b)).

L1: Resistivity and chargeability inversion models and interpretations

Figure 5-1 displays the variation of resistivity (a) and chargeability (b) with depth beneath Profile L1. Depth of investigation for each profile is approximately 34.2 meters. This depth is dependent on the number of channels utilized and, in this case, 11 channels were used (10 dipoles) which is the maximum for the instrument used (IP equipment).

The resistivity values for Profile L1 ranges from 3.34 Ωm to 1,290 Ωm . The geoelectric section in figure 5-1(a) shows alternating resistive fields (with $\text{Rho} > 100 \Omega\cdot\text{m}$) highly resistive on the surface followed by a conductive layer ($<18.3 \Omega\cdot\text{m}$) and a slightly resistive layer ($18.3 < \text{Rho} > 100 \Omega\text{m}$) at the bottom of the model. Highly resistive layer is attributable

to the Kraaipan greenstone rocks (Figure 2-1) (banded iron formation) which forms the cover of the study area. Beneath the BIFs there is a conductive layer (which is attributed to the strongly altered schist) (Figure 2-3(a)) and at the base of the model in Figure 5-1(a) the resistivities can be attributed to the intercalated sequence of BIF and altered mafic schist respectively.

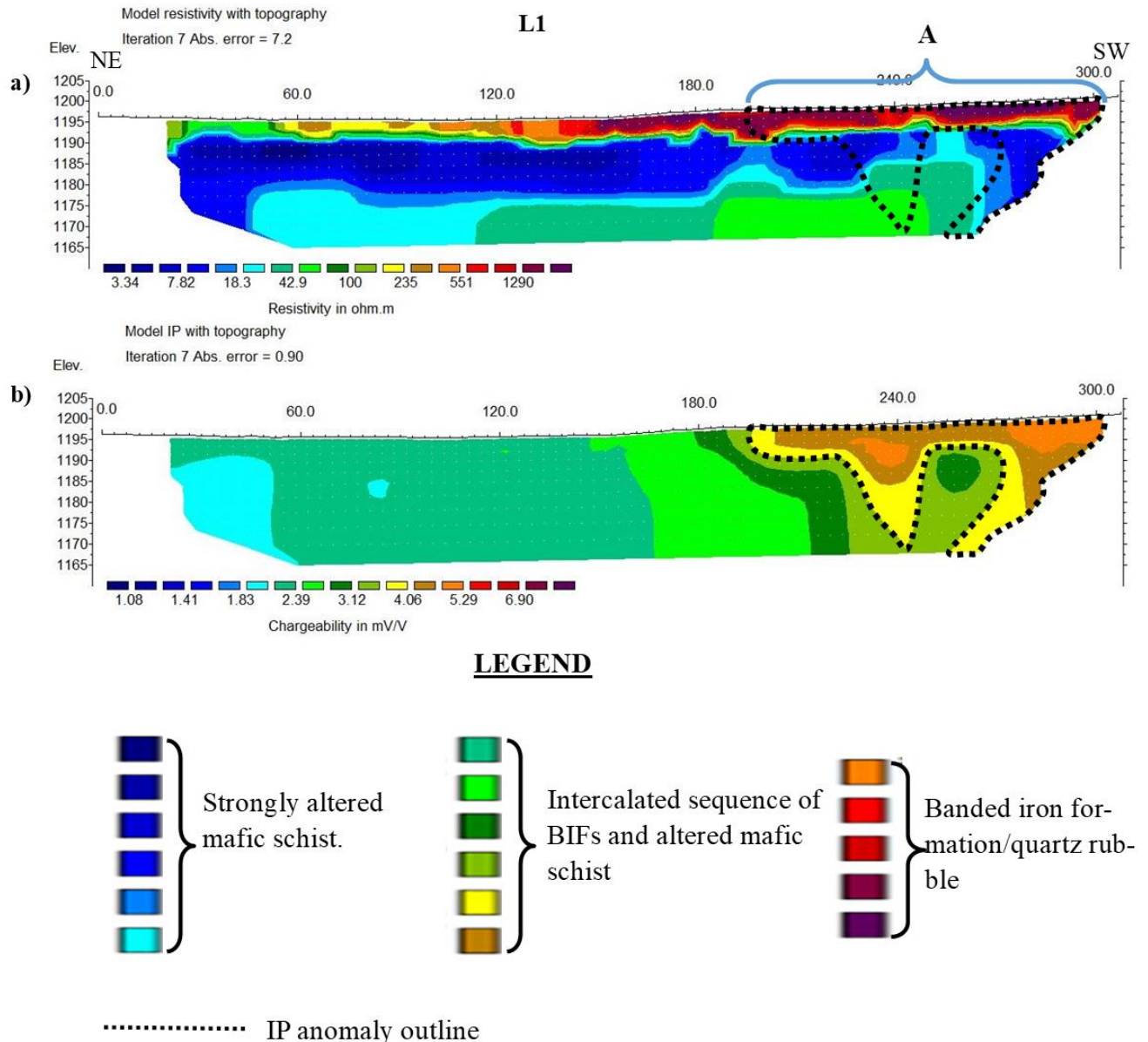


Figure 5- 1: Electrical resistivity (a) and chargeability (b) inversion models for Profile L1.

The chargeability values in Figure 5-1(b) ranges from 1.06 mV/V (non- conductor) to 6.90 mV/V (conductor). Outside a polygon labeled A, there are geologic units which are non-

chargeable and they can be attributable to barren rocks because the only time when there is a strong IP anomaly is when there is a presence of metalliferous disseminations. At a distance between 195 meters and 300 meters extending from the surface to the base of the model in both the models (a) and (b) there are prominent IP anomalies depicted by a polygon labeled **A**. In model b, polygon **A** has high resistivity and chargeability values compared to any other zone in the model. This IP anomaly is hosted in the highly resistive banded iron formations and this is an indication that there is the presence of a conductive body (metalliferous disseminations) within a highly resistive BIF (Figures 2-2 and 2-4) that is why the IP anomaly given in figure 5-1(b). Anomalously high chargeability values typically correspond to zones enriched with disseminated sulphides (which sometimes occurs with gold) and these areas are the possible primary targets for primary exploration. Anomalously high apparent resistivity values are often associated with quartz veins or rubbles or banded iron formation layers. So, a typical IP “signature” of a sulphide-bearing quartz vein is, therefore, a superposition of high apparent resistivity and high chargeability (Komu, 2016).

L2: Resistivity and chargeability inversion models and interpretations.

Figure 5-2 shows the variation of resistivity and chargeability values underneath Profile L2. The resistivity values from the model labeled (a) range from 2.41 Ωm to around 1,269 Ωm . The geoelectric section in Figure 5-2(a) shows alternating resistive fields (with $\text{Rho} > 212 \Omega\cdot\text{m}$) highly resistive on the surface followed by a conductive layer ($<14.4\Omega\cdot\text{m}$) and two slightly resistive layers ($14.4 < \text{Rho} < 212 \Omega\cdot\text{m}$) which seem to protrude from underneath the model from the deepest settings separated by a conductive layer at the base of the model. These features look like intrusions. As can be observed from the detailed local geology map, there are dyke swarms (figure 2-3) these signatures can be attributed to them. The dolerite dykes can also be observed on the borehole log KRPC037 (Figure 2-4(a)). Most greenstone belts (Kraaipan belt included) consist of volcanic and sedimentary rocks in various formations. Almost all of them have been influenced by “subsequent geotectonic factors such as the mafic and ultramafic intrusion complexes, giving rise to deformation, metamorphism and mineralization” (Hammond & Moore, 2006; Laconia Resources Limited, 2017). The resistive layer can be attributed to the banded

iron formation followed by highly altered mafic schist and dolerite dykes as can be seen in geologic log in Figure 2-4 (a).

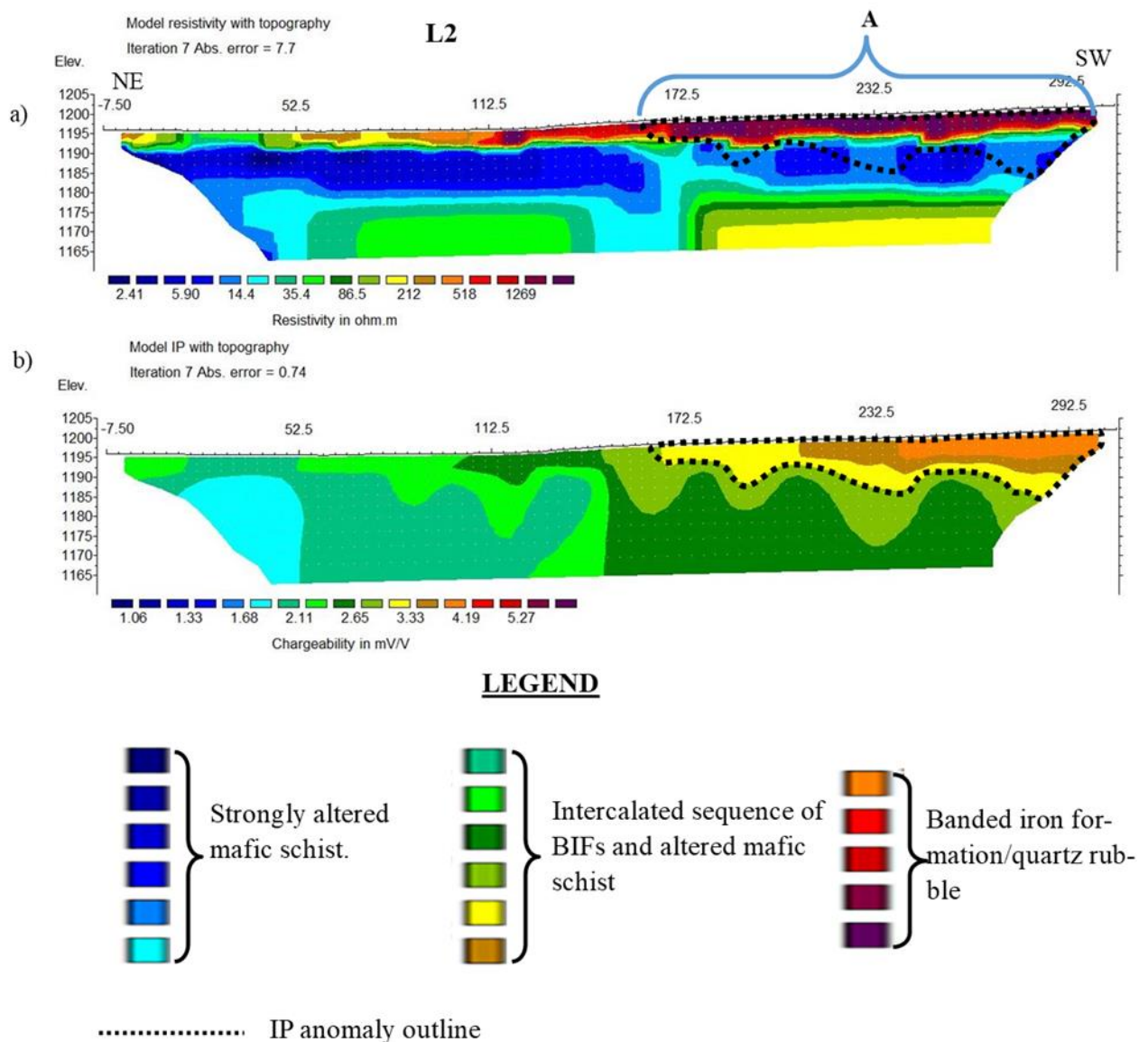


Figure 5- 2: Electrical resistivity (a) and chargeability (b) inversion models for Profile L2.

The geoelectrical section shown in Figure 5-2(b) shows chargeability anomalies along Profile L2. The chargeability values from model (b) range from approximately 1.06 mV/V to 5.27 mV/V. High chargeability values (>3.33 mV/V) are usually associated with the presence of metallic conductors (mostly sulphides) while area with less chargeability values (<3.33 mV/V) are associated with barren rocks. An area between 165 meters and

300 meters along the traverse is characterized by high chargeability values (3.33 mV/V to more than 5.27 mV/V) within a highly resistive BIF (Figure 5-2(a)).

This zone is attributable to a strong polarization of geological structures, herein interpreted as a zone of high metal assemblage (e.g. sulphides) mineral disseminations in banded iron formations and quartz veins/ rubbles. This anomaly is depicted by a polygon labeled **A**, which is believed to be the same anomaly extending from L1.

L3: resistivity and chargeability inversion models and interpretation

Figure 5-3 displays the variation of resistivity and chargeability values beneath Profile L3. Resistivity values in model (a) range from approximately 0.655 Ωm to 1,310 Ωm . The geoelectric section in Figure 5-3(a) shows alternating resistive fields (with $\text{Rho} > 149 \Omega\cdot\text{m}$) highly resistive on the surface of the model followed by a conductive layer ($< 17.0 \Omega\cdot\text{m}$) and two slightly resistive layers ($17.0 < \text{Rho} < 149 \Omega\cdot\text{m}$) which seems to protrude from underneath the model separated by a conductive layer at the base of the model. Here the two intrusion-like features described in Profile L2 are more noticeable and they are herein interpreted as the dolerite dykes (as can be seen in Figures 2-4(a)) and in between them we have a conductive mafic schist (strongly altered).

The chargeability values from model (b) ranges from around 1.05 mV/V to 4.54 mV/V. High chargeability values ($> 2.99 \text{ mV/V}$) are usually associated with the presence of metallic conductors (mostly sulphides) while area with less chargeability values ($< 3.33 \text{ mV/V}$) are associated with barren rocks (figure 5-3(b)). Two localized IP anomalies are depicted on Profile L3 occurring at zones labeled (A) and (B). Zone (A) seems to be the same anomalous zone extending from Profile L1 and L2. The chargeability values for the anomalous zones A and B range from 2.99 mV/V to 4.54 mV/V herein regarded as high IP anomalies.

The anomaly (A) extends from the top of the model to a depth approximately 7 meters at a distance of about 230 m to 300m along the profile while the anomaly (B) runs from the top of the model to the base. Both the anomalies fall largely on the highly resistive zones herein interpreted to be a zone of BIF (as seen in borehole number KRP039; Figure 2-

4(a)). These anomalies can then be interpreted as metalliferous disseminations (e.g. sulphides) within quartz veins cross-cutting banded iron formation (Figures 2-4(a) and (b))

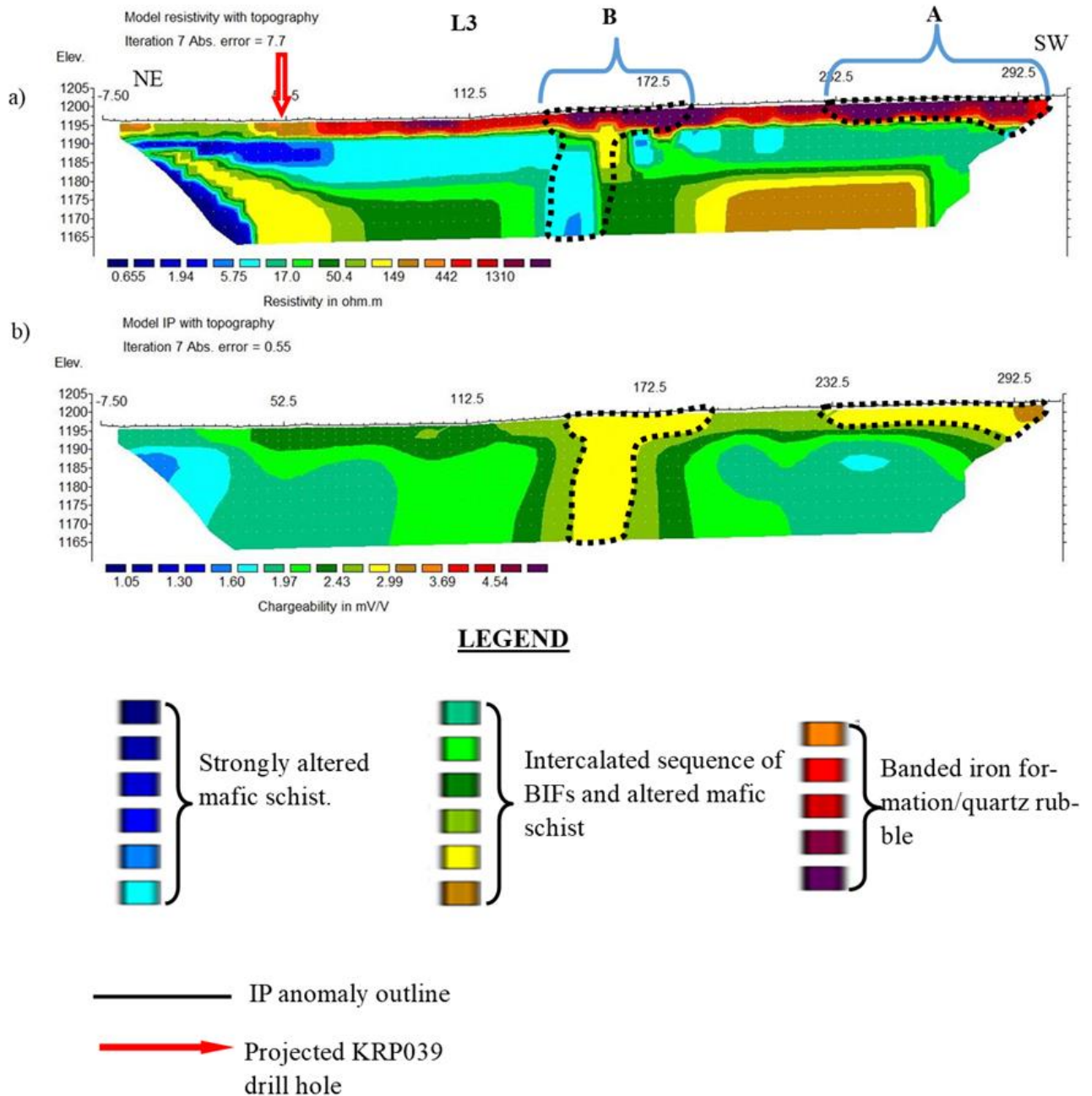


Figure 5- 3: Electrical resistivity (a) and chargeability (b) inversion models for profile 3.

The red arrow on the resistivity model depict a projected historical drill hole number KRP039 which occurs in close proximity to Profile L3 and occurs not far from the anomalous zones.

L4: resistivity and chargeability inversion models and interpretation

Figure 5-4 displays the variation of resistivity and chargeability values beneath L4. The resistivity values in the resistivity model (a) range from 1.76 Ωm to around 3,141 Ωm . The geoelectric section in Figure 5-4(a) shows a highly resistive (with $\text{Rho} > 127 \Omega\cdot\text{m}$) unit mostly preserved on the surface of the model; there is also a slightly resistive zones ($43.6 < \text{Rho} < 127 \Omega\text{m}$) shown in green color and a conductive zone ($< 43.6 \Omega\text{m}$) which is observed on the left side of the model. By using a projected borehole log indicated by the red arrow, a highly resistive layer can be attributed to be BIF, a conductive zone being the highly altered mafic schist and the semiconductor being the intercalated sequence of BIF and the altered mafic schist.

The chargeability values from chargeability model (b) in Figure 5-4 range from 0.200 mV/V to approximately 4.83 mV/V.

A small IP anomaly occurring as a pocket is observed towards the end of the profile (around 250 m). The anomaly zone labeled A has chargeability values ranging from approximately 3.94 mV/V to 4.83 mV/V. This anomaly enlarges to approximately 10 meters depth and it is believed to be the same anomaly labeled A in the previously interpreted profiles. This possible prospecting area is also observed occurring within the highly resistive banded iron formation.

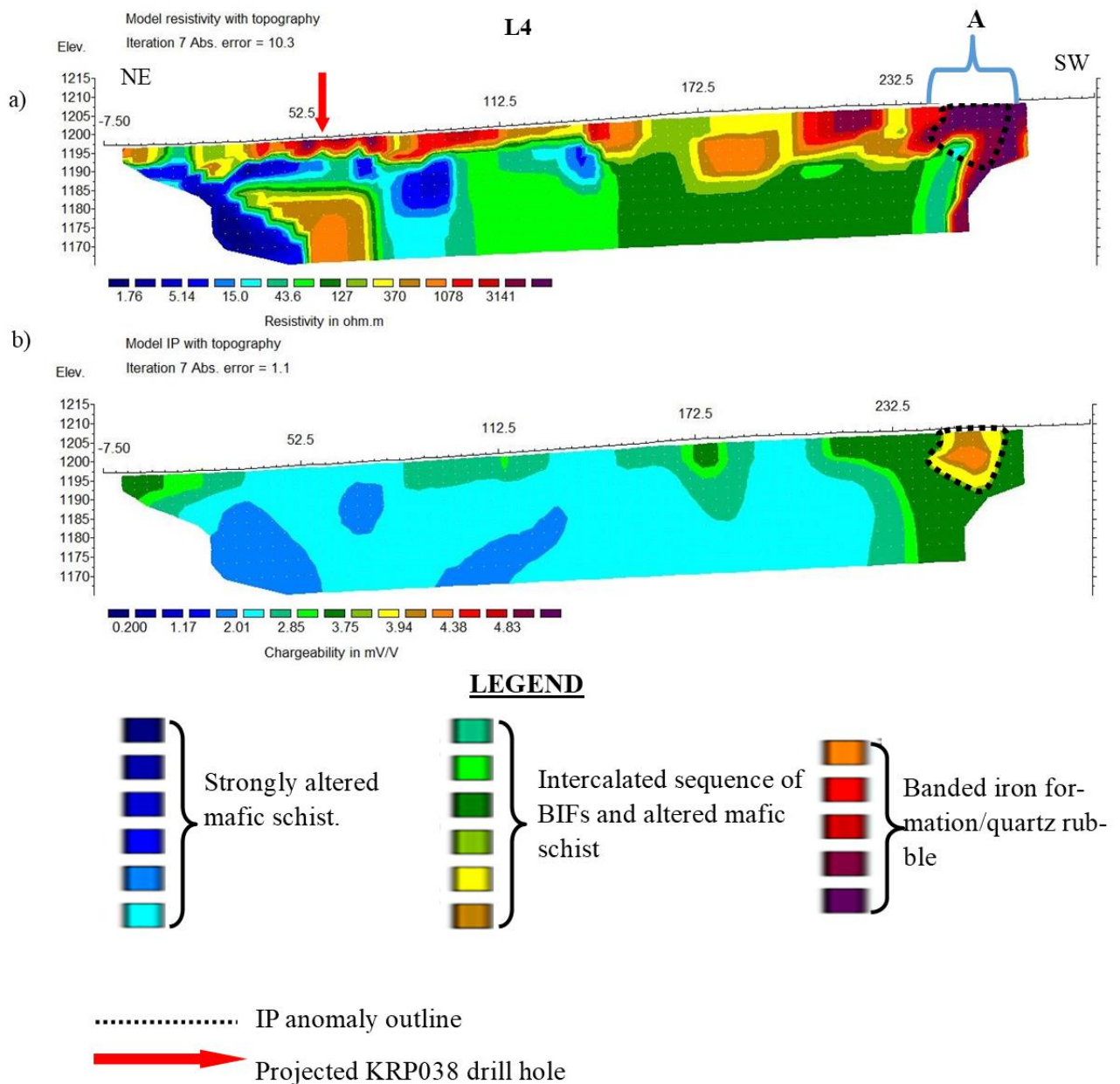


Figure 5- 4: Electrical resistivity (a) and chargeability (b) inversion models for Profile L4.

L5: resistivity and chargeability inversion models and interpretation

Figure 5-5 shows the inverse resistivity (a) and chargeability (b) models of the subsurface underneath Profile L5. The resistivity values range from 3.84 Ωm to 8,388 Ωm . The geoelectric section in figure 5-5(a) shows a highly resistive (with $\text{Rho} > 311 \Omega\cdot\text{m}$) unit mostly preserved on the surface of the model; there is also a slightly resistant zones

($104 < \rho > 311 \, \Omega\text{m}$) and a conductive zone ($< 104 \, \Omega\text{m}$) which is found at the left side of the model. A highly resistant unit is attributed to BIF; a semi-conductive one is attributed to an intercalated sequence of BIF and a highly altered mafic schist while the conductive zone is interpreted to be highly altered mafic schist (as can be seen in borehole log shown in Figure 2-4(a))

The chargeability values in Figure 5-5(b) range from 1.11 mV/V to 14.0 mV/V from the surface to a depth of approximately 34.2 m. The anomaly **A** (extending from the previously interpreted profiles in Figures 5-1 to 5-4) has now increased in intensity and size. It extends from the surface to the base of the model (at the end of the profile) with chargeability values extending from 6.77 mV/V to 14.0 mV/V. Its extension reduces with depth and this might be due to the transition between a highly chargeable unit (high concentration of metalliferous disseminations) to a less or non-chargeable unit (no presence of a conductive body). There is a historical drill hole (red arrow) not far from the IP anomaly. From the borehole log less than 5 m of the Kalahari beds (Figure 2-4(a)) which is found underlined by the Goldridge banded iron formations. It is within the BIF where gold mineralization is found and this is documented in several searches (Hammond & Moore, 2006; Adomako-Ansah et al., 2017; Hammond & Morishita, 2009; Adomako-Ansah et al., 2012 etc.).

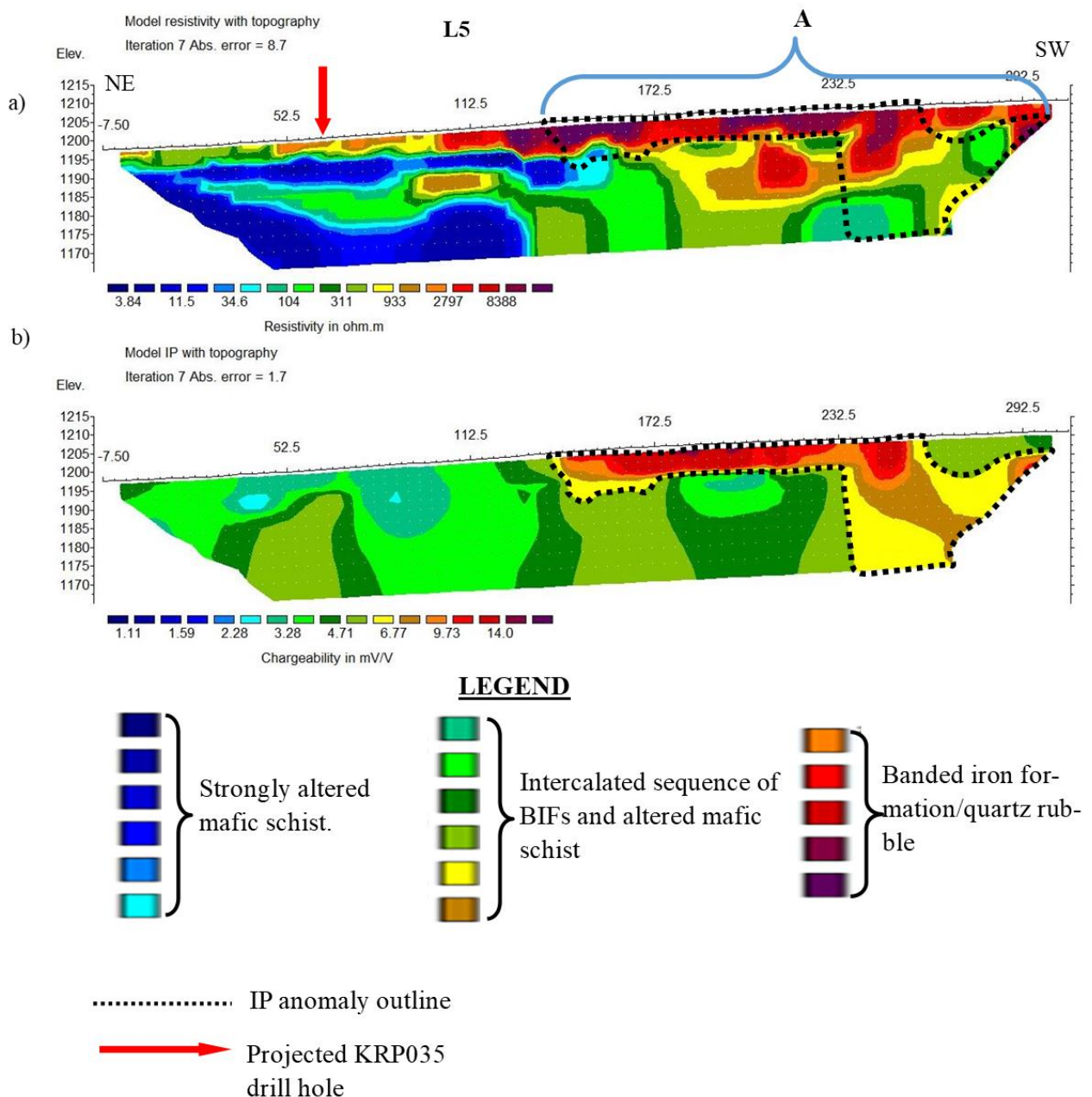


Figure 5- 5: Electrical resistivity (a) and chargeability (b) inverse models of the subsurface beneath surveyed Profile L5.

L6: resistivity and chargeability inversion models and interpretation

Figure 5-6 represent resistivity (a) and chargeability (b) inverse model underneath Profile L6. The resistivity values observed in the resistivity model range from 3.34 Ωm to about 10,170 Ωm . A highly resistive ($> 327 \Omega\text{m}$) geologic unit is observed occurring mostly on the right side of the model, followed by a dominant green-colored slightly resistive

($104 < \rho < 327$) unit and lastly a conductive ($< 104 \Omega m$) zone depicted by the blue color. An adjacent KRP036 borehole log was used to interpolate the results of Profile L6. The highly resistive layer is interpreted to be the banded iron formation which forms the base of the survey area; the semi-conductive layer being a mixture of BIF and the highly altered mafic schist while the conductive layer denotes the highly altered mafic schist.

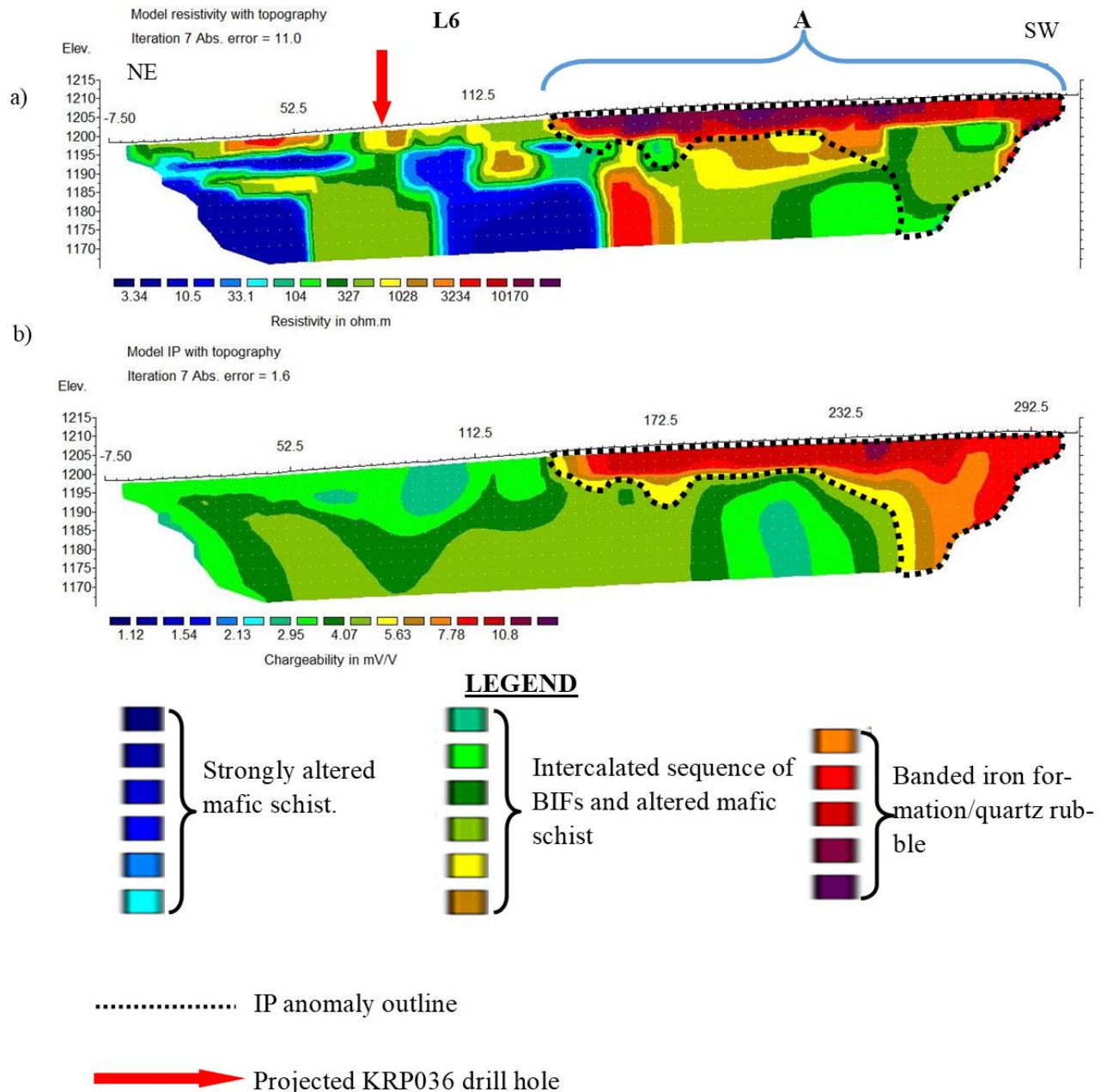


Figure 5- 6: Electrical resistivity (a) and chargeability (b) inverse models of the subsurface beneath surveyed Profile L6.

The chargeability values observed from model (b) range from around 1.12 mV/V (non-conductor) to 10.8 mV/V (conductor). A strong IP anomaly marked **A** is also observed occurring within the highly resistive BIF (Figure 5-6(a)). The anomaly is strong and seems to be the same zone extending from L5 (Figure 5-5). It extends from around 140 m to the 300 m surveyed profile. Gold mineralization in the Kraaipan belt is documented to be along the quartz vein swarms which cross-cut the banded iron formation (Hammond & Moore, 2006). These quartz veins are indicated on the resistivity model (a) by their non-conductive nature as compared to surrounding rock units. The only time where there is the presence of an IP anomaly in the resistive zone is when there is a presence of a conductor (metalliferous disseminations). There is KRP036 historical drill hole less than 100 m from the zone marked **A** which intercepted gold mineralization within the quartz veins/ rubbles hosted in the Goldridge banded iron formation (seen in Figure 2-4(a)).

L7: resistivity and chargeability inversion models and interpretation

Figure 5-7 shows the inverse resistivity (a) and chargeability (b) models of the subsurface below Profile L7. The resistivity values from model labeled **a** range from 7.05 Ωm to 8,826 Ωm . The geoelectric section in Figure 5-7(a) shows a highly resistive (with $\text{Rho} > 415 \Omega\cdot\text{m}$) unit mostly preserved on the surface of the model; there is also a slightly resistive zone ($150 < \text{Rho} < 415 \Omega\text{m}$) beneath a highly resistive unit and a conductive zone ($< 150 \Omega\text{m}$) which is mostly preserved on the left side of the model. The top-most zone which is highly resistive is herein interpreted to be a Goldridge BIF layer followed by an intercalated sequence of BIF and a mafic schist while the conductive unit is attributed to be an altered mafic schist.

The chargeability values from model (b) range from 1.17 mV/V to around 15.1 mV/V from the surface to a depth of approximately 34.2 m below the surface. It is within a highly resistive banded iron formation find two strong IP anomalies are observed occurring at the end of the profile (zone marked **A**) and a smaller one at a zone marked **B**. These two profiles seem to be the same extension of zone in L6 but here they seem to be separated by an intrusion-like semi-conductive unit which can be interpreted as dolerite dyke (seen in Figures 2-4).

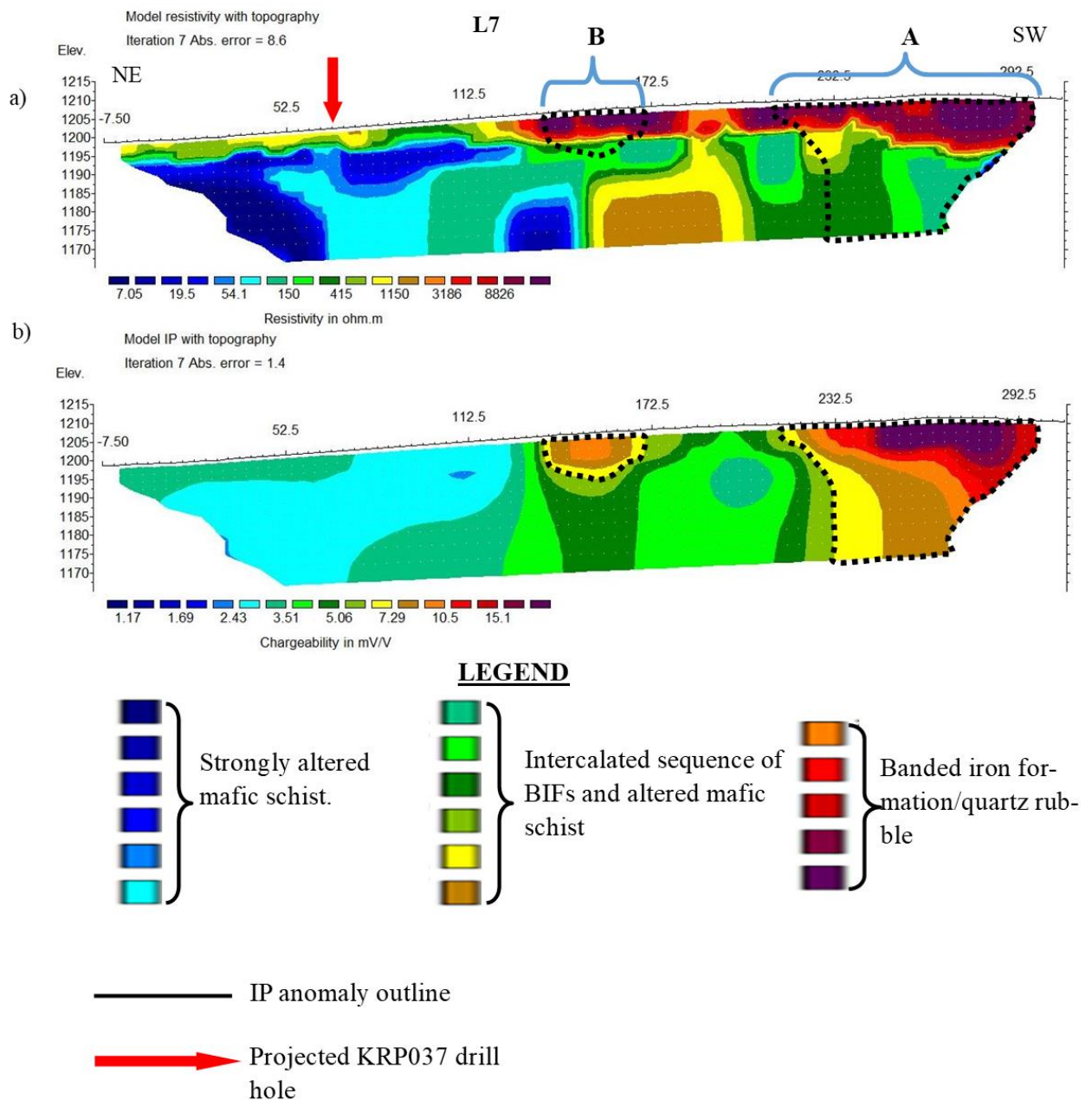


Figure 5- 7: Electrical resistivity (a) and chargeability (b) inverse models of the subsurface beneath surveyed Profile L7.

L8: resistivity and chargeability inversion models and interpretation

Figure 5-8 shows the inverse resistivity (a) and chargeability (b) models of the subsurface below Profile L8. The resistivity values from model (a) range from 7.68 Ωm to 11,519 Ωm . The geoelectric section in Figure 5-8 (a) shows a highly resistant (with $\text{Rho} > 501 \Omega\text{m}$) unit mostly preserved on the surface of the model towards the right side; there is also a

slightly resistive zones ($176 < \rho < 501 \, \Omega\text{m}$) and a conductive zone ($< 176 \, \Omega\text{m}$) which is mostly preserved at the left side of the model. The top-most zone which is highly resistive is herein interpreted to be a Goldridge BIF layer followed by an intercalated sequence of BIF and a mafic schist while the conductive unit is attributed to be an altered mafic schist.

The chargeability values range from 1.13 mV/V to approximately 18.8 mV/V from the surface to a depth of around 34.2 m along the profile. A strong IP anomaly is observed at a zone marked **A** highlighted by a dotted polygon at the end of the profile. It has chargeability values ranging from 8.42 mV/V to around 18.8 mV/V. Zone **A** could be the same anomalous zones extending from the previous profiles (also labeled **A**) hosted within a highly resistive banded iron formation.

L9: resistivity and chargeability inversion models and interpretation.

Figure 5-9 displays the inverse resistivity (a) and chargeability (b) models of the subsurface below profile 9. The resistivity values from model (a) range from 8.98 Ωm to 14,405 Ωm while chargeability values range from 1.09 mV/V to approximately 13.6 mV/V from the surface to a depth of about 34.2 m below the surface. A highly resistive ($\rho > 609 \, \Omega\text{m}$) unit at the far-right side is observed occurring on the top of the model and through field observations and borehole logs (Figures 2-4(a) and 2-4(b)) this zone is interpreted to be a BIF. Adjacent to this layer, there occurs a slightly resistive ($212 < \rho < 609$) unit interpreted to be a highly altered mafic schist. Conductive ($\rho < 212$) zones are seen occurring beneath a semi-conduct at the base of the resistivity model. The conductive zones are herein attributed to be highly altered mafic schists.

An extensive IP anomaly depicted by a black dotted polygon **A** within a highly resistive BIF (Figure 5-9(a)) is observed at the far right of the profile extending from the surface to the base of the model. It ranges from around 165 m 300 m along the profile. The chargeability values for this zone (labeled **A**) observed in the chargeability model (b) range from 6.61 mV/V to 13.6 mV/V. This anomaly is attributed to the presence of a metalliferous (e.g. sulphides) within a highly resistive banded iron formation.

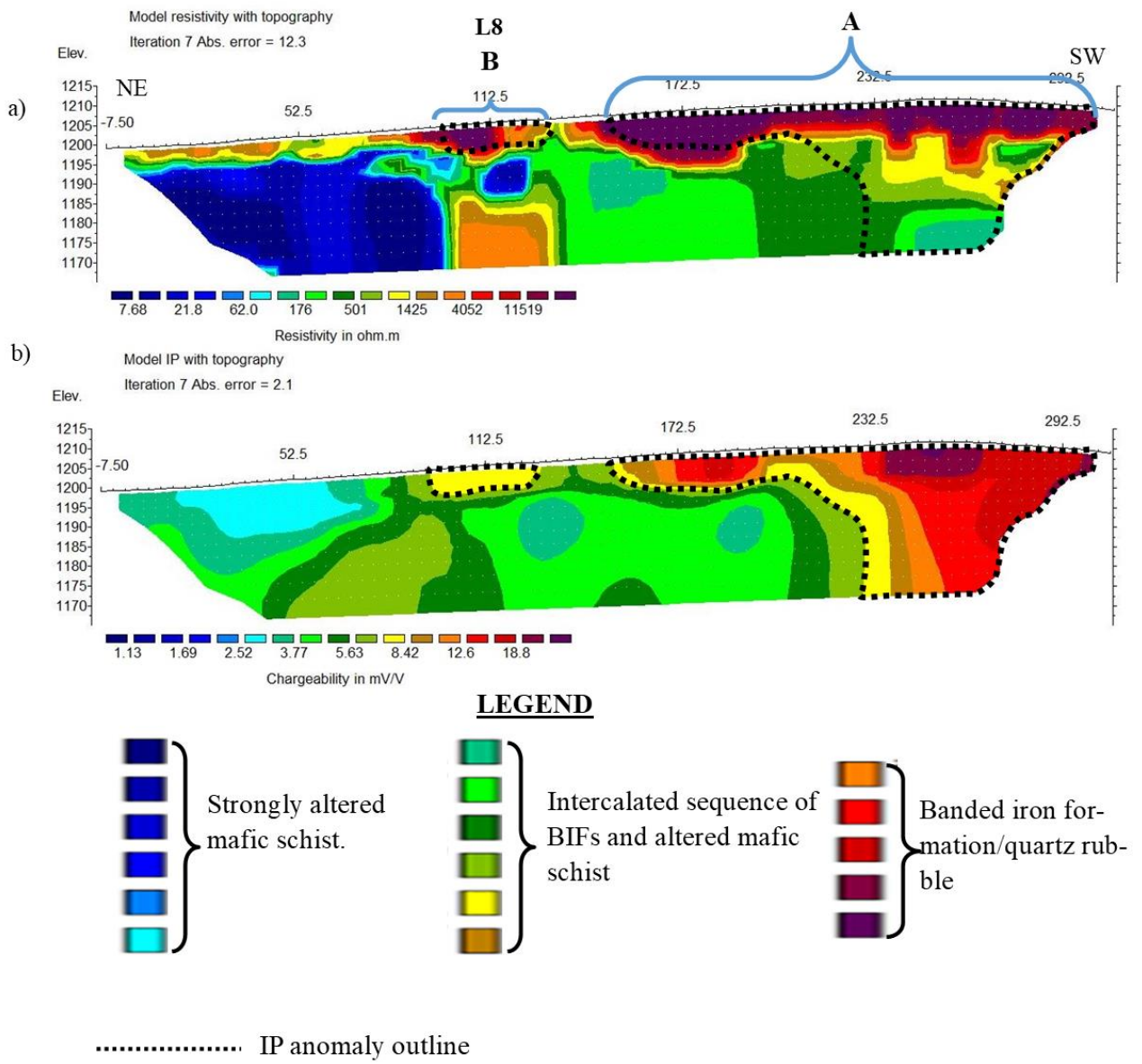


Figure 5- 8: Electrical resistivity (a) and chargeability (b) inverse models of the subsurface beneath surveyed Profile L8.

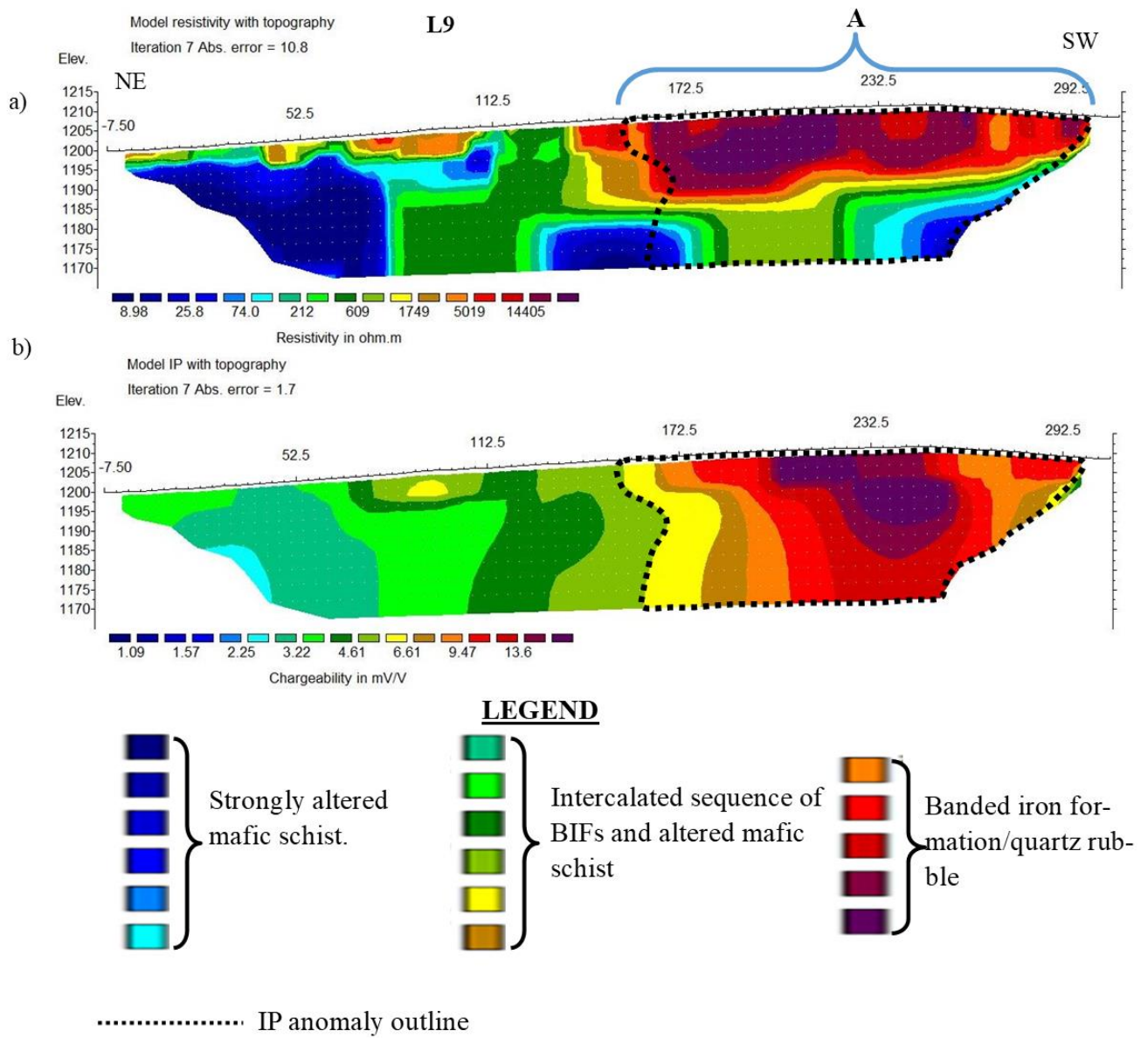


Figure 5- 9: Electrical resistivity (a) and chargeability (b) inverse models of the subsurface beneath surveyed Profile L9.

L10: resistivity and chargeability inversion models and interpretation.

Figure 5-10 displays the inverse resistivity and chargeability models of the subsurface below profile 10. The resistivity values from model (a) range from 1.82 Ωm to 8,635 Ωm while chargeability values from a model (b) range from 0.220 mV/V to approximately 14.1 mV/V from the surface to a depth of about 34.2 m below the surface.

A highly resistive ($\rho > 769 \Omega\text{m}$) unit at the far-right side is observed and through field observations and borehole logs (Figure 2-4(a) and 2-4(b)) this zone is interpreted to be a Goldridge banded iron formation. Adjacent to this layer, there occurs a slightly resistive ($230 < \rho < 769$) unit represented by the green color. This unit interpreted to be a highly altered mafic schist. Conductive ($\rho < 230$) zones are seen occurring beneath a semiconductor at the base of the resistivity model. The conductive zones are herein attributed to be highly altered mafic schists.

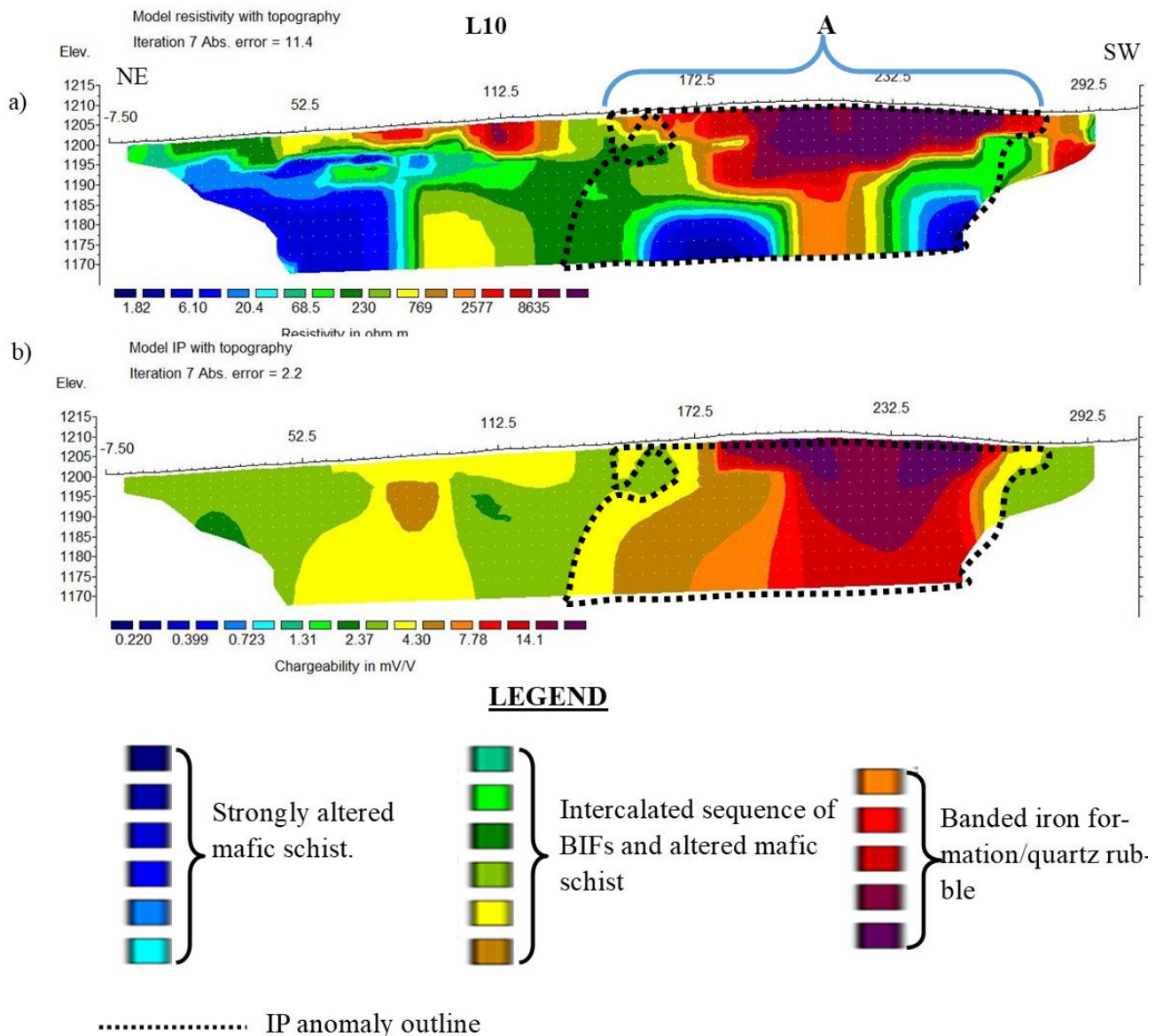


Figure 5- 10: Electrical resistivity (a) and chargeability (b) inverse models of the subsurface beneath surveyed Profile L10.

An anomalous zone marked by **A** seems to be the same zone as seen from previous profiles and it is also observed occurring within a highly resistive BIF. Chargeability values for this zone ranges from 4.30 mV/V to around 14.1 mV/V and these zones are herein interpreted to indicate the presence of a metalliferous (e.g. sulphides) disseminations since they expected to have high chargeability values compared to any other geologic units in the survey area due to their electric conducting nature.

The following figures shows clustered resistivity (Figure 5-11 a and b) and chargeability (Figure 5-12 a and b) for correlation of all the sections for all the lines and to visualize the area synoptically. The low resistivity and chargeability zones are denoted with I and A; intermediate with II and B and finally III and C for high resistivity and chargeability zones respectively. Their interpretations are summarized in table 5-1.

It can be observed in figures 5-11 and 5-12 that the anomalies descried above extends from one survey profile to the other. The highly chargeable units mostly occur towards the end of surveyed profiles.

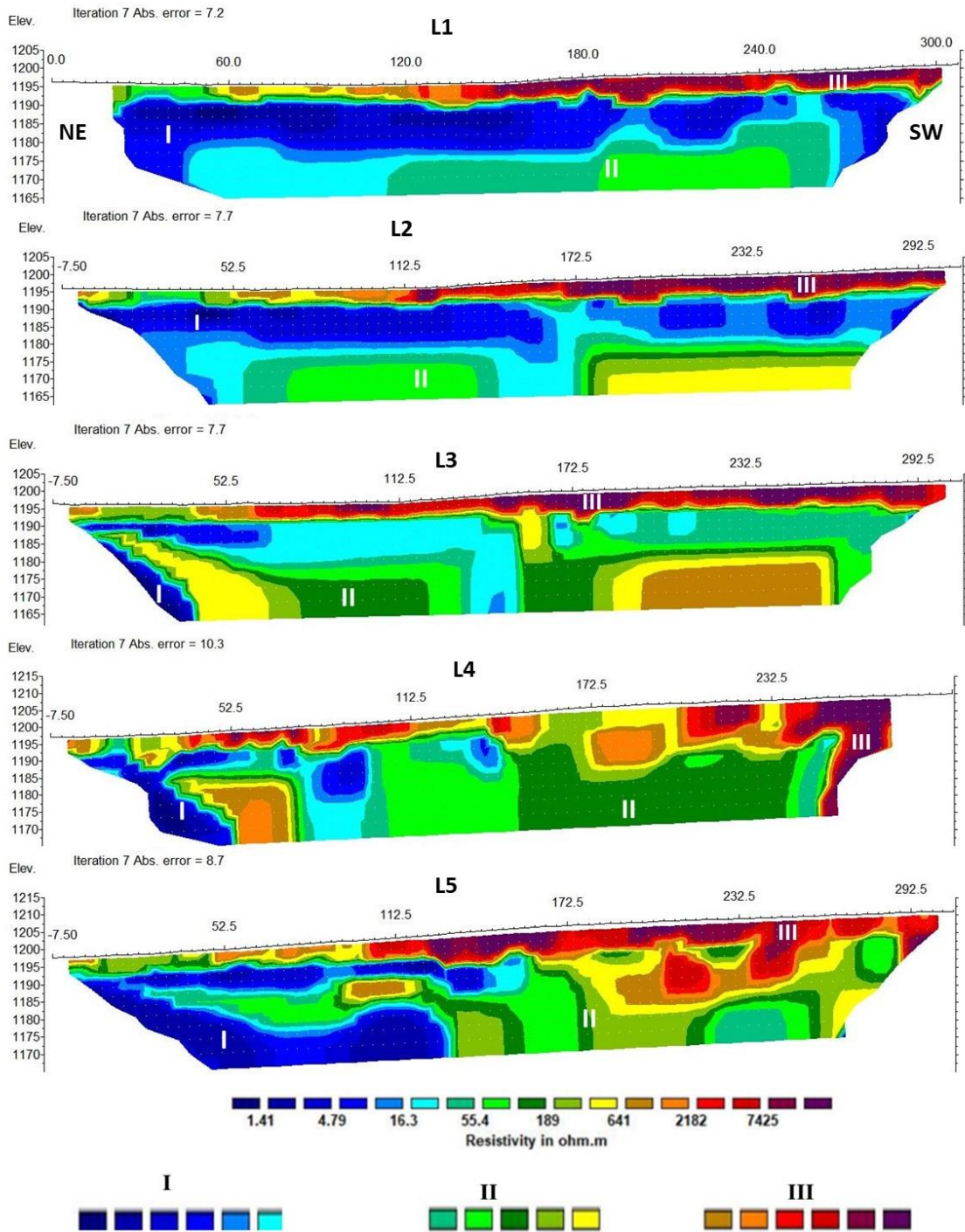


Figure 5-11 (a): The inverse resistivity models of Profile L1 to L5. The vertical axis represents the elevation and the x-axis represents the distance along the profiles, in meters. The RMS errors are given above each profile model and letters I to III represent different lithological units.

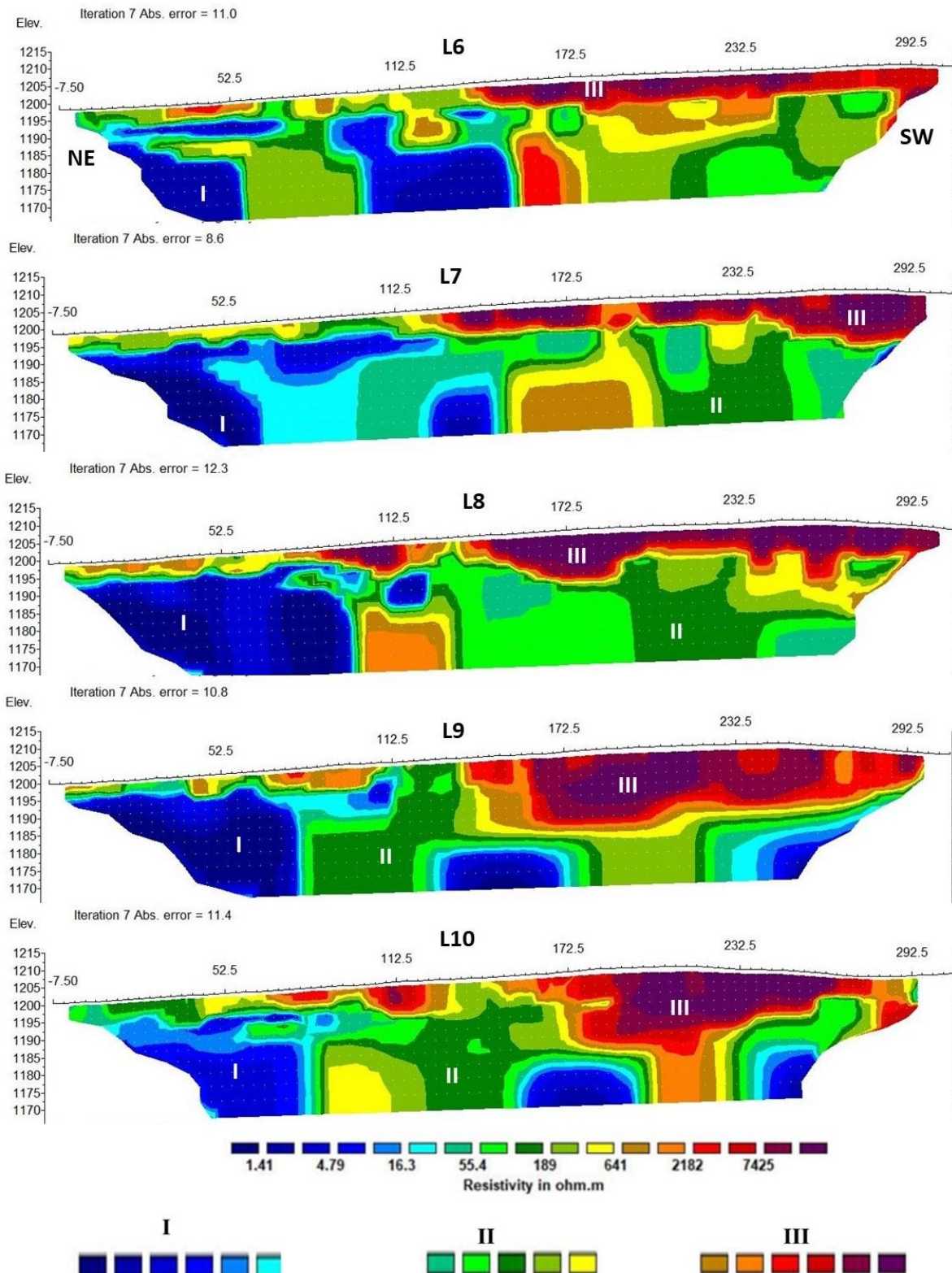


Figure 5-11 (b): The inverse resistivity models of Profile L6 to L10. The vertical axis represents the elevation and the x-axis represents the distance along the profiles, in meters. The RMS errors are given above each profile model and letters I to III represent different lithological units.

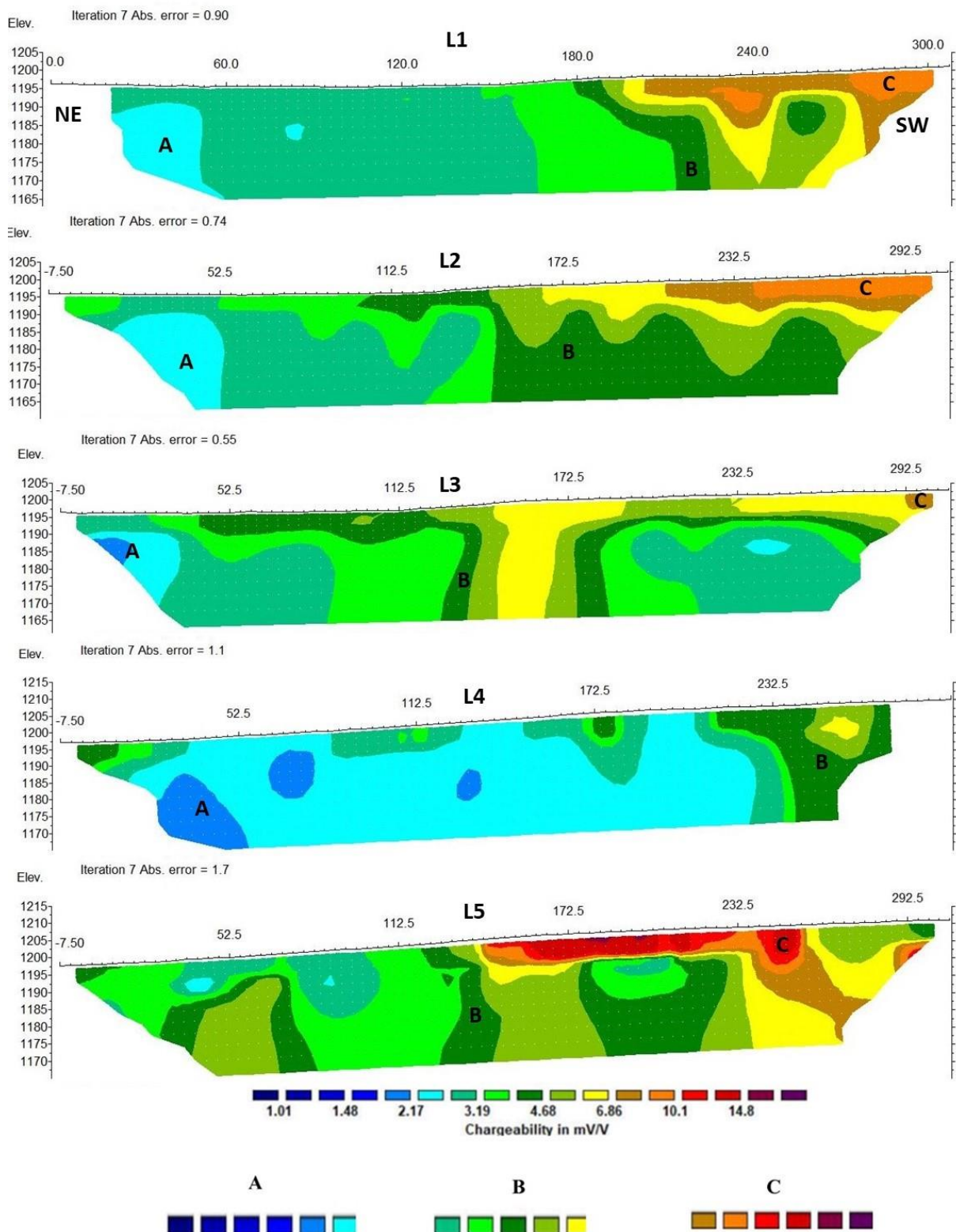


Figure 5-12 (a): The chargeability models of Profile L1 to L5. The vertical axis represents the elevation and the x-axis represents the distance along the profiles, in meters. The RMS errors are given above each profile model, and letters A to C represent different lithological units.

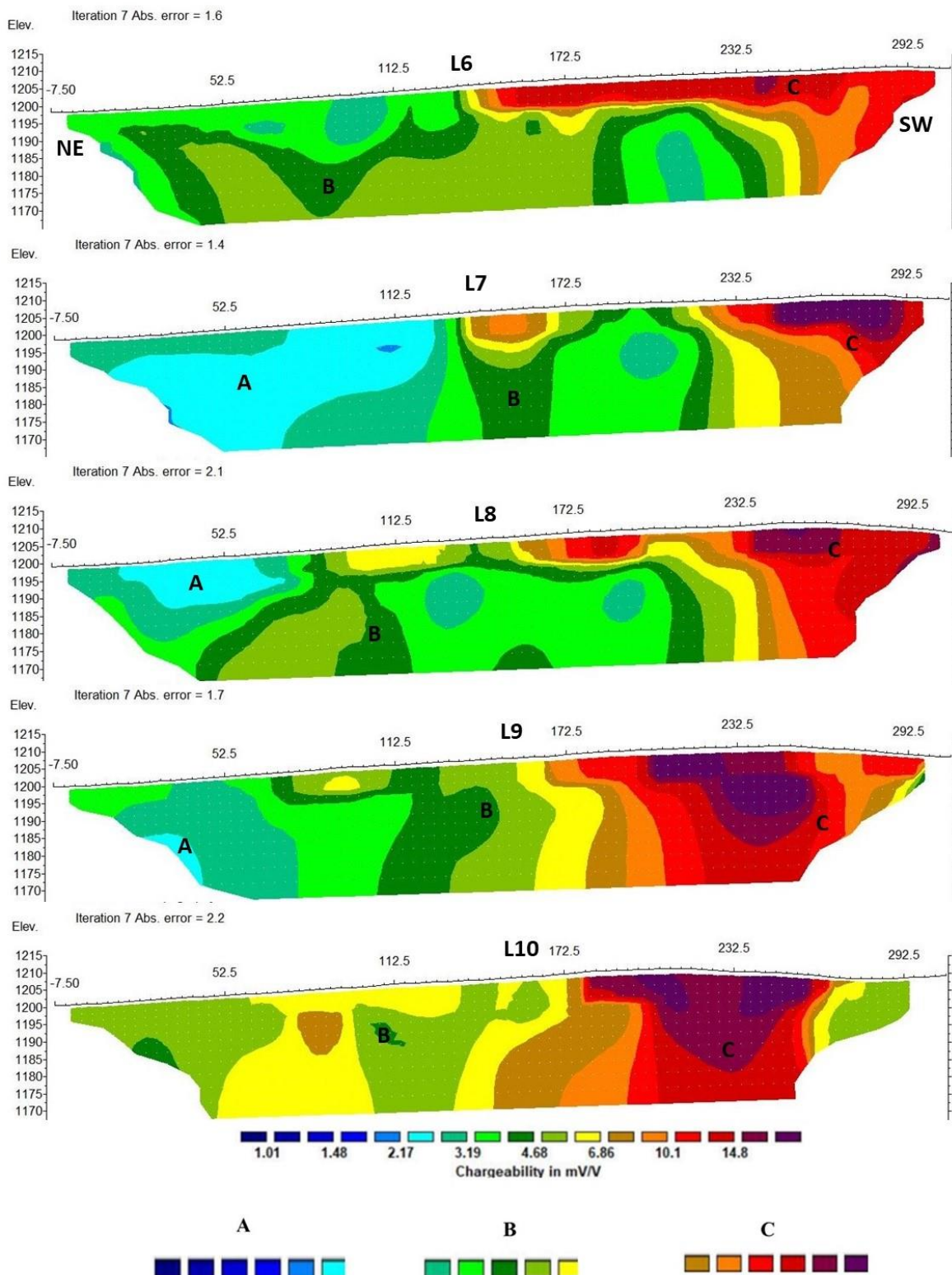


Figure 5-12 (b): The chargeability models of Profile L5 to L10. The vertical axis represents the elevation and the x-axis represents the distance along the profiles, in meters. The RMS errors are given above each profile model, and letters A to C represent different lithological units.

Table 5- 1: Three distinct geological units determined by combining the adopted chargeability and resistivity ranges.

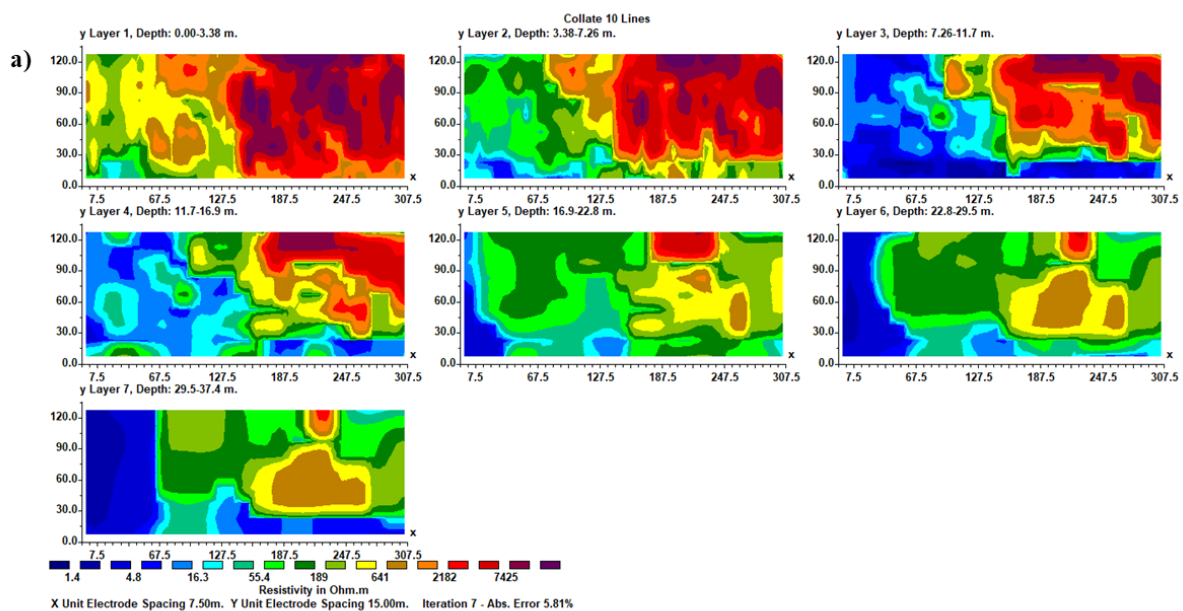
Chargeability	Resistivity	Description	Zones
Low	Low to intermediate	Limonitic BIF with clayey matrix and admixed with highly altered schist	A, I-II
Intermediate	Intermediate to high	Intensely silicified Banded iron formation/Quartz rubble, Haematitic and limonitic BIF rubble	B, II-III
High	Intermediate to high	Intensely silicified BIF with disseminated sulfides, and/or BIF hosting gold bearing quartz $\pm$ carbonate veins	C, II-III

5.2 Resistivity and chargeability horizontal (X-Y) slices

Figure 5-13 shows the horizontal (X-Y) slices showing the distribution of electrical resistivity (Figure 5-13 (a)) and chargeability (Figure 5-13 (b)) of the subsurface which were generated by collating 10 2D surveyed profiles datasets. The depth parameter is presented in numerical form above each horizontal slice and these slices indicate lateral variation in resistivity and chargeability at different depth levels starting from the surface going downwards to the base of the models.

In resistivity slices (Figure 5-13 (a)) values ranging from 641 Ω m to 7425 Ω m (high values) are evidently dominant in all layers (depth: 0.00 m-37.4 m) and occupies most of the slices with those resistivity values ranging from 1.4 Ω m to 189 Ω m occupying the least portion on the left side of the slices for the deep to deeper layers (slices 3 to 7). The high resistivity layer is attributable to banded iron formations inferred from borehole log number KRPC037 which is in close vicinity with most of the surveyed profiles while the conductive layer is attributable to highly altered mafic schist.

Figure 5-13 (b) shows distribution of electrical chargeability of the subsurface for the surveyed grid. High chargeability zones are observed throughout the slices from the surface (slice 1 surface to 3.38 m depth) all the way to the base slice (Z= 29.0 m – 37.4 m). The chargeability values for this zone ranges from 6.9 mV/V to 14.8 mV/V. This anomaly is mostly preserved on north-eastern part of the slices and can be interpreted to be the highly metalliferous disseminations zone. This is evident from the 2D profiles where there are highly chargeable zones occurring mostly towards the end of the profiles. This highly chargeable zones are mostly preserved in the BIFs and/ or quartz veins/ rubbles and this shows that there is the presence of a conductor (indicated by high IP effect) within the highly resistive (shown in the resistivity sections) and to a lesser extent on a conductive zone. The zone is herein inferred to be the probable metalliferous (e.g. sulphides which sometimes occurs with gold) disseminations that requires follow up investigations.



LEGEND

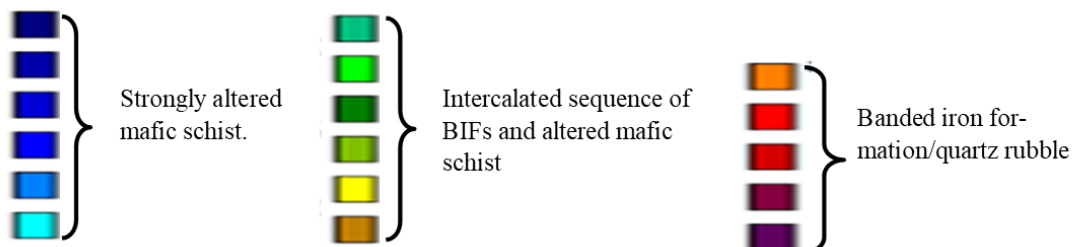
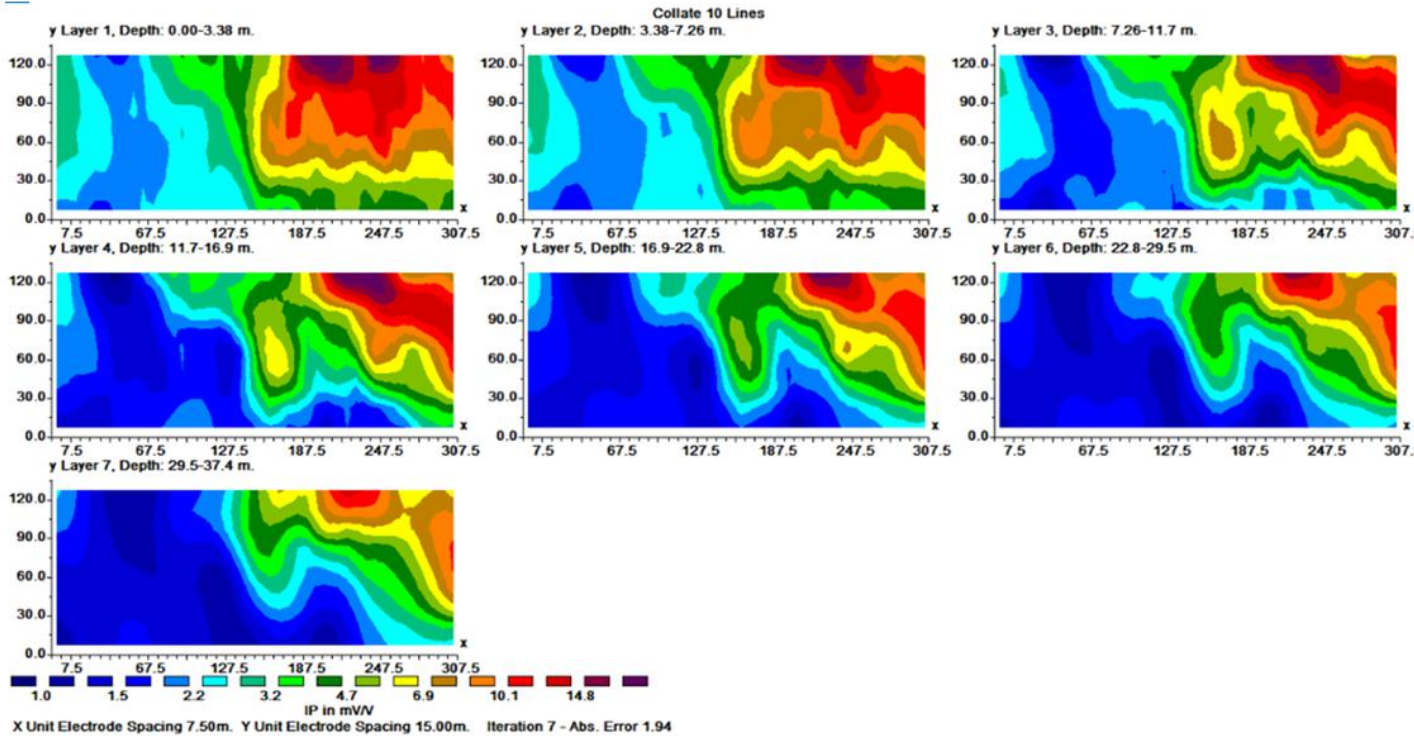


Figure 5-13 (a): The 3D horizontal (X-Y) slices demonstrating the distribution of subsurface electrical resistivity which were created by collating 10 2D surveyed profiles datasets.

b)



LEGEND

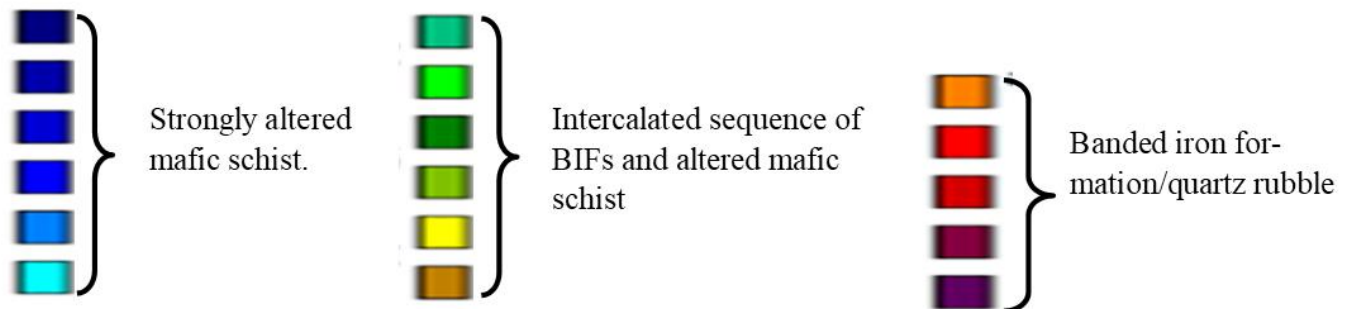


Figure 5-13 (b): The 3D horizontal (X-Y) slices demonstrating the distribution of subsurface chargeability which were created by collating 10 2D surveyed profiles datasets

5.3 Resistivity and chargeability isosurfaces

Visualization of the data has been performed by grouping the processed data according to the resistivity and chargeability values (high values) of interest thereby giving an insight for architecture and structural trends geometry analysis. This was performed by generating resistivity and chargeability isosurfaces using the processed 3D models for electrical resistivity and chargeability respectively. A 3D displaying program called Slicer Dicer software was utilized in displaying these isosurfaces (Figure 5-14) that represent the probable sites for potential mineralization which are important targets for follow ups.

The resistivity isosurfaces (Figure 5-12 (a)) show the distribution of highly resistive ($\sim 641 \Omega\text{m}$ to around $7425 \Omega\text{m}$) banded iron formations represented by red color which are the primary hosts for metalliferous disseminations in the study (evident from borehole logs in Figures 2-4 (a) and (b) and also in Figure 2-6 (mineralization map)). They occur in a tabular manner and are slightly elongated and clustered between x-axes 180 m and approximately 307.5 m and y-axes 0 m to around 135 m. These clusters are observed occurring at shallow depths range from close to the surface to depths of around 30 m on the south eastern corner of the Figures 5-14 (a).

Figure 5-14 (b) displays distribution of highly chargeable ($\sim 6.9 \text{ mV/V}$ to around 14.8 mV/V) zone represented by colors yellow-red which is believed to be the probable location of gold mineralization herein interpreted as a zone of high metal assemblage (e.g. sulphides) mineral disseminations in banded iron formations and quartz veins/ rubbles which occurs with gold. The same location and pattern are observed also in the chargeability isosurfaces (Figure 5-14 (b)) and this are the probable indications of gold mineralization and are the important targets for follow up surveys.

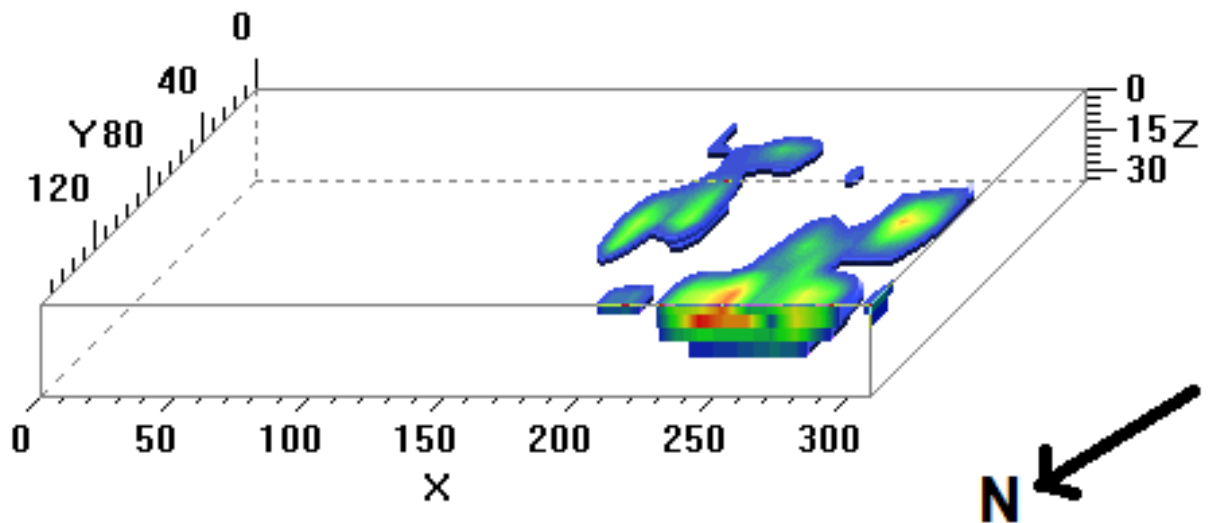


Figure 5-14 (a): The 3D resistivity isosurfaces from the Slicer Dicer™ program indicating areas of anomalously high resistivity (with values ranging from 641 Ωm to approximately 7425 Ωm).

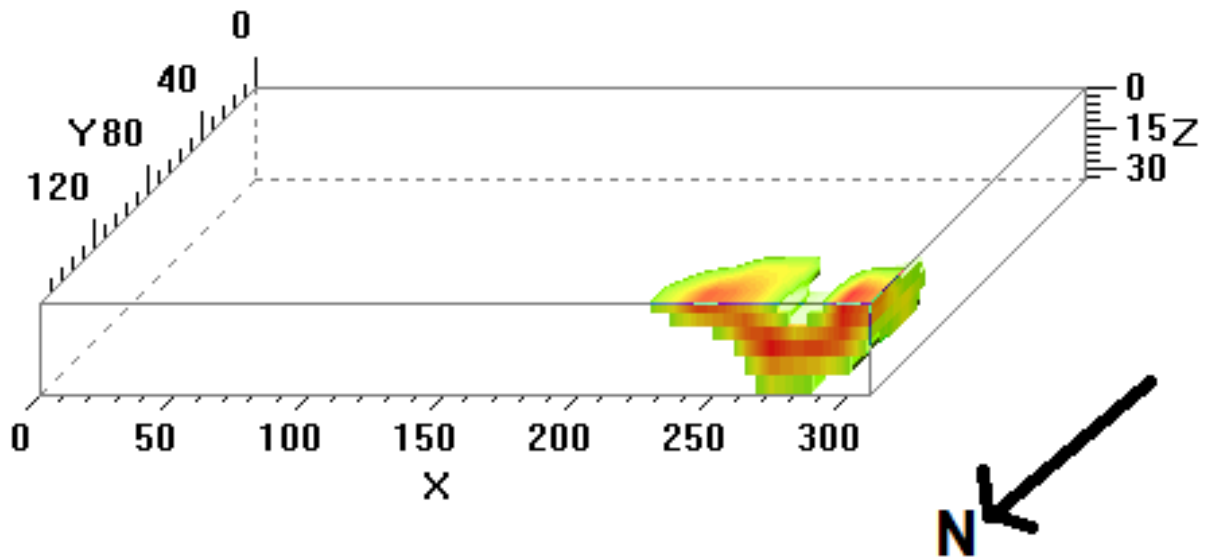


Figure 5-14 (b): The 3D chargeability isosurfaces from the Slicer Dicer™ program showing anomalously high chargeability (with values ranging from 6.9 mV/V to approximately 14.8 mV/V).

6. DISCUSSION AND CONCLUSION

6.1 Discussion

The objective of this research is to utilize a combined geoelectrical approach involving resistivity and induced polarization measurements to delineate potential gold mineralized zones in Phitshane Molopo area in the Southeast Botswana. The results obtained from the interpreted Figures 5-1 to 5-10 helped to depict highly resistive and highly mineralized zones of NE-SW trend. The results from inverse model resistivity sections indicate that high resistivity anomalies are located on the shallow depths and this is also observed from the IP results and some extend to the base of the models (Figures 5-1, 5-3, 5-5 to 5-10). The high chargeability anomalies are shown by dotted polygons labelled **A** and **B** which fall on the highly resistive zones of the resistivity models. The results suggest that metalliferous disseminations (from IP models) are hosted within the highly resistive host rock (from resistivity models). The highlighted possible mineralized zones are quite extensive and continuous as they extend from one 2D survey profile to the next (Figures 5-1 to 5-10).

The high chargeability anomalies are mostly associated with deformational zones, shearing, or the presence of metalliferous minerals or disseminated sulfides in association with quartz $\pm$ carbonate veins (Gupta et al., 2019). Although metalliferous minerals (e.g., sulfides) may be conductive, ore-grade deposits of these minerals may manifest as less conductive bodies in electrical resistivity measurements (Palacky, 1987) due to chemical and/or thermal alteration processes that can convert conductive metallic minerals into oxides or other forms that are less conductive compared to the original minerals. One such process is the silicification (Doyle, 1990; Moreira et al., 2019), that may occur due to phenomena such as recrystallization and hydrothermal fluid migration within veins that cut across porous rocks, thereby yielding highly resistive zones (Gupta et al., 2019). With these factors being considered, zones denoted A and B (high chargeability and high resistivity) are attributable to intensely silicified banded iron formation (BIF) hosting disseminated sulfides and/or BIF hosting auriferous quartz $\pm$ carbonate veins.

Most of the gold mineralization identified by exploration in the study area occur in quartz $\pm$ carbonate veins and in association with sulfides (e.g., pyrite, chalcopyrite and arsenopyrite), found in clusters or swarms that obliquely cross-cut the banded iron formation rock units (Laconia Resources Limited, 2016), analogous to the mineralization found at the well-known South African Kalgold. Beside the silicification, mechanisms such as wall rock sulfidation, adsorption-reduction and replacement of ferric ion by auric ions (Gupta et al., 2019) may have contributed to the formation of these zones, with a strong probability of forming gold mineralization. It is common that the most promising areas for occurrence of mineralization of economic potential be characterized by high chargeability and low resistivity (usually engendered by the presence of sulfides, graphite or salty overburden; Doyle, 1990) based on comparative pattern of contrast in electrical properties (Moreira et al., 2019). However, such a combination of properties is not observed in both the 2D (Figures 5-1 to 5-10) and 3D (Figures 5-13 and 5-14) inverted model sections. These kinds of results are not unexpected in IP/resistivity measurements conducted in geological settings analogous to our study area, which is situated within the Kraaipan greenstone belt. Evaluation of gold deposits in similar geological settings by other researchers (e.g., Allis, 1990; Irvine and Smith, 1990; Locke et al., 1999; Han et al., 2016) suggest changes of electrical properties in those deposits emanating from hydrothermal alteration, with an increase of the resistivity caused by intense silicification and an increase in chargeability resulting from the presence of disseminated sulfides. Leading to the discovery of the Broulan-Porcupine prospect in Ontario (Kelly, 1957), the orebodies were found in the silicified zones beneath the high resistivity anomalies.

In a study by Goldie (2002), a combination of self-potential (SP) and resistivity methods were utilized to characterize a high sulfide Yanacocha gold deposit in Peru. He delineated potential gold-bearing zones with SP values ranging from -5 to -10 V and resistivity values ranging from 1000 to 10000 Ω m. Goldie (2002) identified large silica bodies associated with high-sulfidation oxide gold deposit and deduced that the observed high resistivity and large negative SP values resulted from silicification in quartz matrix hosting auriferous minerals. His findings are similar to previous results based on induced polarization and electrical resistivity survey, which suggested that the silica units at the Yanacocha are typically highly resistive and, because of the oxidation of sulfides, exhibited poor IP responses in Peru.

In the case of Amalia gold deposit (Adomako-Ansah et al., 2017), geochemistry data have recorded gold concentration peaks in sulfidized BIF that surround the cross-cutting quartz $\pm$ carbonate veins, but there are no gold indications in the non-sulfidized BIF (e.g., Adomako-Ansah et al., 2012). Despite the absence of similar documented results in the present study area, one posits that zones displaying a combination of high chargeability (denoted A and B in 2D sections (Figures 5-1 to 5-10)) and high resistivity are likely to be representing sulfidized zones with gold mineralization in the study area.

In Misra et al., (2016), a quartz vein hosting disseminated sulfides and auriferous mineralization is poorly differentiated with resistivity measurements but can be distinguished in most of the inverted IP model sections. Similarly, the high chargeability anomaly patterns, particularly in the pseudo-3D IP model sections (Figures 5-14), are more extensively developed with clear trends compared to resistivity zones (Figure 5-13). Further, the high chargeability zones appear to be confined to the northeast end of the study area coexisting with the high resistivity zone from the surface to a depth of about 16.9 m. The wide distribution of high chargeability values at the shallow parts of the models is likely to be indicating the presence of disseminated sulfides within the intensely silicified BIF unit, whereas the linear trend observed in the underlying layers may be suggestive of structurally controlled gold mineralization hosted in east-west trending quartz $\pm$ carbonate veins that obliquely cross-cut the BIF units. From these observations, we postulate that high resistivity anomalies are related to silicification and that chargeability highs are indicative of the potential gold mineralization zones. If indeed hydrothermal alteration contributed in engendering the mineralization in the study area, distribution of chargeability and resistivity highs suggests that such mechanism was mostly confined to the southwestern end of the studied area.

The gold mineralization in Kraaipan belt is documented to be hosted within the quartz-carbonate veins cross-cutting the banded iron formation rock units (Adomako-Ansah et al., 2017; Adomako-Ansah et al., 2012; Hammond & Morishita, 2009; Hamond & Moore, 2006 etc.). These BIF rock units are highlighted by the resistivity measurements and are the highly resistive rock units compared to any other geologic unit in the study area. This is supported by the fact that these rock units were exposed on the surface in the surveyed

area (Figure 1-2). On the other hand, the results from IP measurements highlight the presence of metalliferous disseminations (mostly sulphides which sometimes occur with gold mineralization) which have high chargeability compared to any other geological unit in the area (Figures 5-1 to 5-10).

These mineralization zones are characterized by high IP (possible sulphides e.g. pyrite which occur closely in association with gold) and high resistivity features (possible quartz vein swarms hosted within the banded iron formations). The viability of the possible mineralized zones is supported by the historical drill holes which intercepted significant gold mineralization within the banded iron formations with grades up to 5.1 g/t gold (Laconia Resources Limited, 2012).

These results build on existing evidence of the mining reconnaissance works by both historic and present prospecting companies in the area (Laconia Resources Limited, 2017) and several reports (Adomako-Ansah et al., 2017; Adomako-Ansah et al., 2012; Hammond & Morishita, 2009; Hamond & Moore, 2006 etc.) which have associated gold mineralization in the study area to the quartz vein swarms cross-cutting banded iron formations.

6.2 Conclusion

The aim of this study was to use IP and resistivity measurements in search for possible gold mineralization in Phitshane Molopo area. Ten survey profiles (307.5 m each) with a spacing of 7.5 m were conducted. The pole-dipole electrode arrangement was used for the survey. The instrument used was the Elrec Pro receiver developed by Iris Instruments with pole-dipole array were conducted to try and reveal IP and resistivity anomaly zones. The data was inverted and interpreted and most potential targets recommended for follow-up shown in Figures 5-1 to 5-10. From all the 10 2D profiles two possible mineralized zones (marked **A** and **B** on Figures 5-1 to 5-10) were identified as potential mineralization zones from the interpretations.

Possible mineralization is observed to be of shallow depth as evident from the 2D models and 3D horizontal slices. The resistivity measurements successfully delineated the

banded iron formations which are the primary hosts for metalliferous disseminations in the area while the IP measurements highlighted the high chargeability zones which indicate the presence of gold mineralization. The findings in this study are supported by mining reconnaissance study by the license holder and other authors who have characterized the gold in the area to be hosted in the quartz veins/rubbles. It can be observed from the orientation of the boreholes (Figure 4-6) areas which were interpreted as the mineralized zones are situated within the same anomalies interpreted in this study. Under ideal situation when using only resistivity measurements, very low resistivity values would be an indication of the presence of metallic minerals, but deformational processes can alter rock properties (including electrical properties of mineralized zones). Thus, results from the present study support effectiveness of the combination of IP and DC geoelectrical methods as a good approach to the mapping of metalliferous dissemination bodies in the study area.

Recommendations

- Drilling is recommended over the anomalous zones found in this study more specifically from Profile L5 to L10 as they give the best indication for metalliferous mineral disseminations.
- There is a need to extend the surveyed profiles further at the end of the profiles in this study identify/map more anomalous zones to check for more anomalous zones and their extensions. The survey should preferably be on the NE direction and beyond Profiles L5 to L10 and in the regions (possibly after the validation of the result of this work through drilling).
- Geochemical studies of representative samples are recommended for determination of elemental compositions, description of alteration and ore mineralogy.

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