GEOPHYSICAL INVESTIGATION FOR POTENTIAL GOLD MINERALISATION IN SHAKWATU AREA OF NIGER STATE, NIGERIA USING VERY LOW FREQUENCY AND ELECTRICAL RESISTIVITY METHODS

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OGU, Onyedikachi Johnson
(MTech/SPS/2017/7271)

DEPARTMENT OF PHYSICS

FEDERAL UNIVERSITY OF TECHNOLOGY MINNA,

SEPTEMBER, 2021

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL FEDERAL UNIVERSITY OF TECHNOLOGY MINNA, NIGERIA, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF TECHNOLOGY (MTech) IN PHYSICS (APPLIED GEOPHYSICS)

SEPTEMBER, 2021

ABSTRACT

Minerals serve a very important economic commodity to the growth and development of any nation, state or community. In an attempt to delineate potential zones for gold mineralisation, a geophysical investigation was carried out around Shakwatu area of Niger State, Nigeria. Mineral potential (especially gold) is evident by the extensive artisanal mining activities in the area. The Very Low Frequency Electromagnetic-VLF EM and electrical resistivity method was employed in the study. A total of six (6) profile lines (500 m in length), and 100 m inter-profile spacing were established on the study area at a sampling rate of 20 m each. The VLF-EM and the geoelectric data were qualitatively interpreted using the Karous Hjelt Fraser Filtering (KHFF) and RES2DINV Software respectively. VLF-EM data revealed a number of subsurface zones with high real component current density which define the potential subsurface structural features (fractures/ faults zones) with possible gold mineralisation. These zones were interpreted as the potential or inferred structurally controlled fracture zones with possible gold mineralisation, with profiles 1 – 6 showing significantly conductive mineralised zones at a depth of 20-80m. Results from 2D resistivity imaging show an elevated (high) resistivity zones and a variation in shape due to heterogeneous nature of mineralisation within the study area at different depths. The two results when compared show a degree of correlation. The high resistivity zones which could infer a quartz veining structure.

TABLE OF CONTENTS

LIST OF TABLES

Tables **Page**

LIST OF FIGURES

LIST OF PLATES

Plates **Page**

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Mineral development is vital to any nation's economic and technological advancement and therefore, its importance can't be over emphasized because it is one in all the sources of commercial material provide. The Nigerian Extractive Industries and Transparency Initiative, NEITI reported that there are about forty (40) different kinds of solid minerals and precious metals buried in Nigerian soil that are yet to be exploited. The commercial value of Nigeria's solid minerals has been estimated to run into hundreds of trillions of dollars, with 70 per cent of these buried in the bowels of Northern Nigeria (Vanguard Newspaper, 2018).

Mineral exploration is the initial stage of the mining cycle, the aim of which is to locate a new source of useful minerals. It is the search for mineral deposits, and it begins with identifying large areas that may show the occurrence of certain type of ore deposit that could be developed as a resource. Mineral exploration involves the process of finding commercially viable concentrations of minerals to mine. It is a much more intensive, organised and professional form of mineral prospecting. Mineral exploration which is the initial phase of the mining cycle is geared towards locating a new source of useful minerals (Idowu, 2013).

The exploitation of mineral resources has experienced prime importance in several developing countries which includes Nigeria. Mineral resources are an important channel of wealth generation for any nation but before they are exploited, they need to pass through the stages of exploration, mining and processing (Ajakaiye, 1985; Adekoya, 2003).

In recent times, mineral mining in Nigeria accounts for only 0.3% of its GDP, due to the nation's huge interest in the oil sector, domestic mining industry is underdeveloped, leading to the nation's having to import minerals that it ought to have been able to produce domestically (Idowu, 2013). Gold in Nigeria usually exists in alluvial and eluvia placers, and primary veins from several parts in the northwest and southwest of Nigeria. The most prominent of such are found in the Maru, Anka and Malele areas of Zamfara State; Tsohon Birnin Gwari and Kwaga area in Kaduna State; Gurmana area in Niger State; Bin Yauri in Kebbi State; Okolom-Dogondaji in Kogi State; and Iperindo area in Osun state. Other smaller occurrences of gold beyond these major areas include: Ajegunle-Awa area in Ogun State; Korobiri and Degeji area in Kwara State; Oban Massif area in Cross River State; and Ilasa area in Oyo State (Idowu, 2013).

In Niger State, the geological location endows it with mineral resources. The state boasts of commercial quantity of large mineral deposit such as gold, talc, kaolin, tantalite, granite, marble, copper and lead (NSEZP, 2017). According to officials of the ministry of Mining and Mineral Resources, there is no local government area in the state that does not have one or more deposits of solid minerals. The development of the solid mineral sector opens up the state to economic opportunities such as capturing the interest of foreign investors which thereafter result into job creation though the establishment of various industries and provision of social amenities, thereby improving the standard of living of her citizens. However, what is witnessed today is that most of the mineral development, especially the exploitation is done by informal and in most cases illegal miners using very crude techniques with no consideration for the environment or human health (Idowu, 2013).

The Nigerian Geophysical Survey Agency (NGSA) and private exploration/mining companies have continued to shed more light on the endowments and potentials of gold mineralisation in the country through its recent investigation.

The primary gold mineralisation is associated with veins, stringers, lenses, reefs and similar bodies of quartz, quartz feldspar and quartz-tourmaline rocks in both the supracrustal rocks and basement. The veins range in thickness from several centimeters to a few metres, often displaying lenticular or pinch and swell (boundinage) structure and invariably steeply inclined occurring as isolated body or as parallel or echelon veins system (Kankara and Darma, 2016).

Applied Geophysics tends to provide applicable investigative methods to exploring, as well as the development of the Earth's confined resources through geophysical approaches in studying and enhancing the usage of such resources for human capital development. In mineral exploration, integrated geophysical methods can be used to investigate and explore ore minerals irrespective of mode of occurrence, either massive or disseminated.

According to Unuevho *et al*. (2016), an ore body is a rock from which one or more metals can be profitably extracted. Examples of such metals include gold, silver, platinum, copper, lead, zinc and tin. Exploration Geophysical method, aims at detecting or inferring the presence and position of ore minerals, hydrocarbons, geothermal reservoirs, ground water reservoirs and other geological structures using surface methods to measure the physical properties of the earth along with the anomalies in these properties (Alisa,1990).

In the exploration for subsurface resources the methods are capable of detecting and delineating local features of potential interest that could not be discovered by any realistic drilling programme. A wide range of geophysical surveying methods exists, for each of which there is an ‘operative’ physical property to which the method is sensitive. Integrated geophysical methods have proven to be very effective in the field of exploration geophysics in recent times. Hence, geophysical methods are often used in combination.

In the recent times, integrated geophysical investigations have been found to be useful and also experienced increased application in many geological studies ranging from shallow engineering studies, groundwater and mineral deposits explorations as well as in a variety of geo-environmental studies such as investigations of contaminated sites or waste disposal areas (Olorunfemi and Mesida, 1987; Sharma, 1997; Frohlich and Parke, 1989; Steeples, 2001). The ground electromagnetic (Very low frequency- VLF) and electrical resistivity methods are part of the primary geophysical tools for investigating the subsurface for ore bodies (Kearey *et al.*, 2002).

1.1.1 VLF Electromagnetic Surveying

The Very Low Frequency (VLF) method is a passive method that utilises radiations from military communication transmitters within the frequency band (15-30 kHz). These transmitters generate plane electromagnetic waves that can induce secondary eddy currents particularly in electrically conductive elongated targets. Radio waves at VLF frequencies could be used to prospect for conductive mineral deposits. The VLF method is particularly useful for mapping steeply dipping structures such as faults, fractures and shallow areas of potential mineralisation.

The well-established very low frequency electromagnetic (VLF-EM) method is a rapid, wide coverage and cost effective technique for locating both hidden ores and the structures associated with the mineralisation, in use for over 30 years (McNeill *et al*., 1991; Ogilvy *et al.*,1991; Bayrak , 2002).

According to Paterson and Ronka (1971), the advantages of VLF-EM method include: lightweight and inexpensive equipment design, speed of field operation, ease in equipment handling, and low overall operation cost. VLF-EM method has proved to be an effective exploration tool for quick mapping of the resistivity, phase and other VLF-EM parameters (the real and imaginary components) of the vertical magnetic field which contain valuable diagnostic information and tilt angle of the near surface features using only 5 m of electric dipole (Bayrak, 2002) .

The VLF-EM method offers a relatively fast approach to delineate the fractures and this fractured zone has high conductivity which could be zones of mineralisation or water aquifer (Benson *et al*., 1997).

1.1.2 Electrical Resistivity Surveying

The electrical resistivity, which is a commonly used method, is based on the apparent resistivity measurements along the earth surface (Frohlich and Parke, 1989; Sporry, 2004).

Electrical survey is aimed at determining the subsurface resistivity distribution by taking measurements on the ground surface. The true resistivity of the subsurface can be estimated from these measurements. The ground resistivity has a relationship with various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. Electrical resistivity method has been employed for many decades in hydrogeological, mining and geotechnical investigations (Loke, 1999). More recently, it has been used for environmental surveys.

1.2 Study Area

In this section we shall be discussing the location, climate, vegetation, land use and land resources of the study area.

1.2.1 Location of the Study Area

The study area is located between *Latitudes 9° 40′ 10.1843″* to *9° 40′ 21.7524″* and *Longitudes 6° 42′02.0897″* to *6° 42′13.3764″* (Figure 1.1) and fall within the Kushaka schist belt. The survey site covers an expanse of 250,000 square-meters (m^2). The Kushaka schist belt occupies a belt of about 50 km wide and stretching from the Minna area up to the TsohonBirninGwari area of northwestern Nigeria.

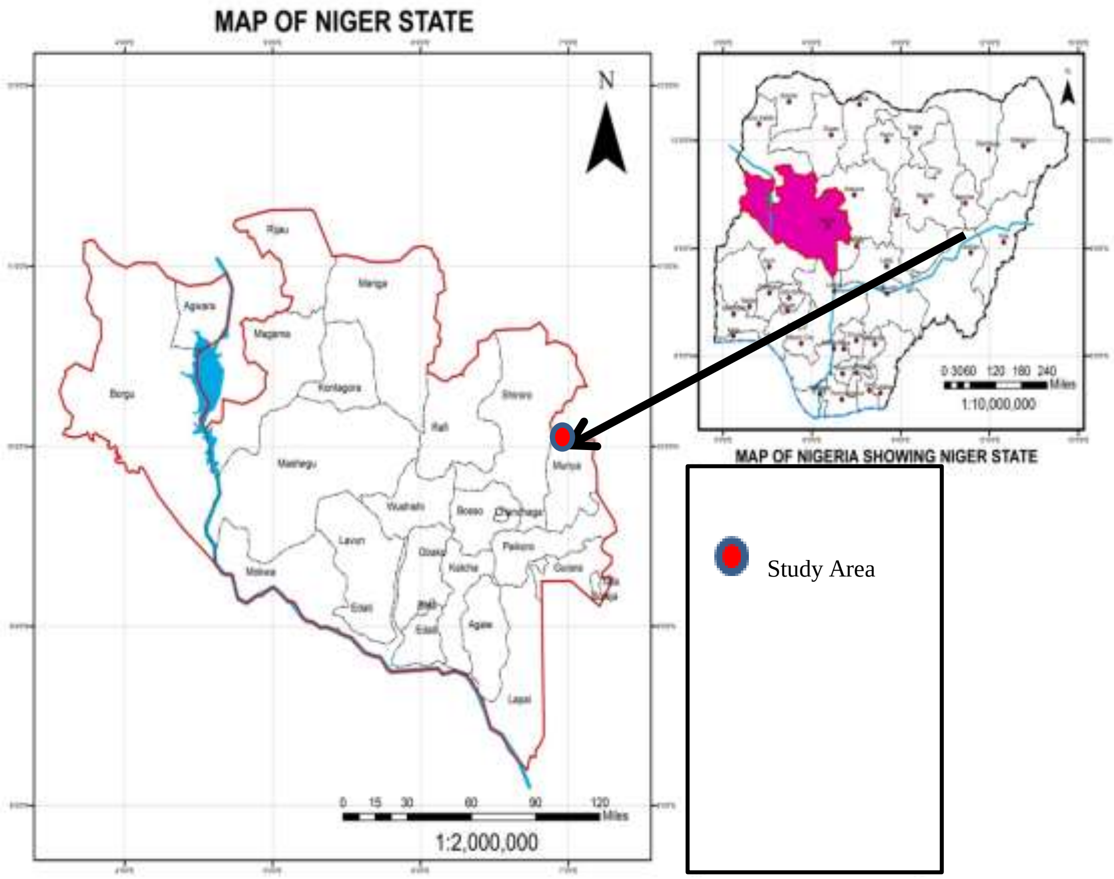

Figure 1.1: Map of Niger State Showing the Study Area

1.3 Statement of the Research Problem

The mineral sector over the years has been a potential wealth reserve. But what we experience so far is government's diversion of attention into crude oil thereby causing the mineral sector to suffer set back. The oil market today is seen to have experience some level of fluctuation in terms of market price and value. Following the invention of solar driven cars, solar powering systems which has replaced our fuel generating sets and many other upcoming technological inventions. We can therefore conclude that the oil sector will one day become a thing of the past. If nothing is done to salvage the situation, then the nation's economy will be left to suffer.

This therefore calls for government's attention to diversifying her effort towards developing the mineral sector. The development of the mineral sector will enable the government meet up with some current challenges ranging from job creation, security challenges (because a very good number of our youths will be gainfully employed), infrastructural development, basic amenities, revenue generation and many more. Niger state is said to be endowed with so many minerals of high economic value which cuts across virtually all the local government areas in the state. These minerals include: gold, talc, kaolin, tantalite, granite, marble, copper and lead, iron ore (high quality), quartzite, granite, tourmaline, topaz, tantalite, hydro carbon (oil & gas) and many more. The revenue to be generated from some of these minerals is enough to sustain not just the state but even the nation at large.

One of the major challenges bordering our mineral sector is the incessant artisan (illegal/unskilled) mining activities that has so far damaged most of our farm lands and also exposed the environment to environmental hazards. In the study area for instance, there are several mine pits that were left uncovered over time which has resulted into erosion. Most of these minerals are structurally controlled, so as these artisans (unskilled) miners engage in their activities may end up damaging these geologic structures. Minerals such as gold for instance are found in veins and pegmatite cavities, which are no larger than a few meters in diameters and due to their small size, local miners most times, miss out these mineral hosts during their mining activities.

1.4 Justification for the Study

With the dwindling of the price of crude oil in recent times, and the abundance of economic solid minerals in Northern Nigeria, it is pertinent for Nigeria to exploit, explore and harness these vast minerals for economic and sustainable development. Exploiting and harnessing these rich solid mineral deposits would open the gate for establishing small scale industries which would go a long way in curbing the unemployment and insecurity menace in the country most especially in the North.

In Shakwatu, the potential for gold mineralisation is seen by numerous artisan workings in the area, several geologic exposures (outcrops) of different rock formations, rock intrusions and many more. The area is predominantly underlain by schists which is composed of quartzite, most of which are fractured. These findings prove that the area has potential for mineralisation necessitating more work to be done to further confirm these findings. This work will be important to better define the mineralisation zones and also aid any further drilling program in the area. These therefore call for the need to carry out an intensive geophysical survey over the area and use data processing techniques that enhance interpretation in order to identify suitable drilling sites.

The harnessing of imaging techniques in geophysics becomes significant because for instance many economically viable minerals such as those in veins or pegmatite cavities are small in size (measuring up to a few meters in diameter). Due to their small size, these deposits are easily missed with conventional mining methods (such as trenching or tunneling), and most geophysical techniques which are one-dimensional methods could probe the subsurface in only one dimension, vertical or horizontal and cannot produce the resolution necessary to detect them. Such as Electrical resistivity to resolve geologic features that are as small as a fraction of a meter to a few meters in longest dimension and very shallow, within a few meters of the surface.

The very low frequency electromagnetic and electrical (2D) resistivity methods are some of the most effective geophysical methods to map this kind of mineralisation.

Both Very Low Frequency (VLF) and resistivity (2D) methods are well-known geophysical exploration techniques, due to their conceptual simplicity, low equipment cost and easy to use, the methods are routinely used in mineral exploration. They are environmentally friendly because the methods do not induce adverse effect during and after use. Results from both VLF and electrical method (2D resistivity) will be able to delineate geological structure like faults/fractures, which are possible host for mineral deposits.

1.5 Aim and Objectives of the Study

The aim of this research is to delineate potential mineralised zones in Shakwatu area of Niger State, Nigeria, using Very Low Frequency Electromagnetic (VLF-EM) and electrical method (2D resistivity). The objectives of the study are to:

(i) delineate the trend of the structures in the study area

(ii) identify and interpret anomalous (fractured) regions from the real and imaginary component of the VLF data and geoelectric pseudosection.

(iii) correlate the current density pseudosection from the VLF data and the geolectric pseudosection to delineate potential mineralisation zones.

1.6 Significance of the study

This research will serve an important endeavour in delineating potential mineral zones which will in turn help to define mineral resource in the study area. Having known the economic value of minerals, the study has the potential to attract positive economic effect to the local community.

This research will also save an investor from spending so much as it utilises effective geophysical processing techniques for better interpretation and producing reliable follow-up targets, by so doing reducing costs during the drilling phases.

Furthermore, results from this research will serve as a future reference for other researchers who may wish to embark on a similar research in the study area and also help enlighten mining investors on the mineral potential of the area.

1.7 Scope of Research

This research is constrained to survey grid set up, Electromagnetic (VLF) and electrical (2D) resistivity data acquisition, analysis and interpretation using KHFF (Karous Hjelt Fraser Filtering) software, Res2DINV software. This research seeks to delineate both geological, structural features associated with mineralisation in the area.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Electromagnetic Surveying

The electromagnetic methods have the broadest range of different instrumental systems. They can be classified as either time domain (TEM) or frequency domain (FEM) systems. The FEM uses one or more frequencies, While TEM measurements as a function of time. EM methods can be either passive, as it utilises natural ground signals (e.g. magnetotellurics) or active, where an artificial transmitter is used either in the near field (e.g. in ground conductivity meters) or in the far field (Reynolds, 2011).

The major advantage of the EM-methods is that they do not require direct contact with the ground as we can find DC electrical methods. Therefore the EM-measurements can be carried out in a faster way than the DC measurements (Reynolds, 2011).

The EM methods has a wide range of applications which include: Mineral exploration Mineral resource evaluation, Groundwater surveys, Mapping contaminant plumes, Geothermal resource investigations, Contaminated land mapping, Landfill surveys, Detection of geological and artificial cavities, Location of geological faults and so on.

2.1.1 Principles of EM surveying

Electromagnetic methods utilise the response of the ground to the propagation of incident alternating electromagnetic waves which comprises of two orthogonal vector components: an electric intensity (E) and a magnetising force (H) (Figure 2.1), in a plane perpendicular to the direction of travel (Reynolds, 2011). An electromagnetic field can be generated by passing an alternating current through either a small coil comprising many turns of wire. The frequency range of electromagnetic radiation varies from atmospheric micro-pulsations at a frequency (<10 Hz), through the radar bands (108 - 1011 Hz) up to X-rays and gamma-rays at frequencies (> 1016 Hz).

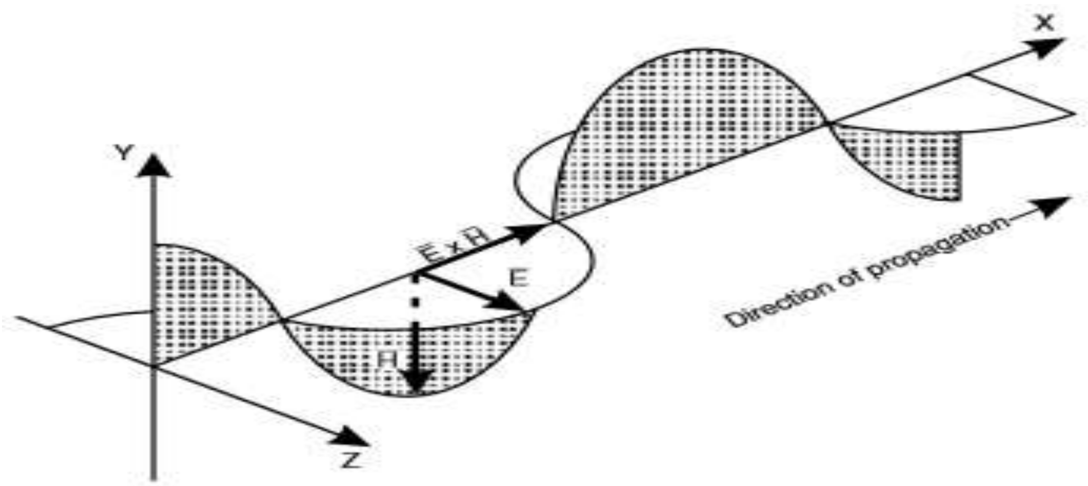

Figure 2.1: Basic elements of an electromagnetic wave, showing the two principal electric (E) and magnetic (H) components (Reynolds, 2011)

For geophysical surveys, frequencies of the primary alternating field are usually less than a few thousand hertz .The wavelength of the primary wave is of the order of 10 – 100 km compared to that of a typical source–receiver separation which is much smaller (≈4 –100+ m). However, the propagation of the primary wave and associated wave attenuation can be disregarded (Figure 2.2). In general, a transmitter coil is used to generate the primary electromagnetic field, which propagates above and below ground.

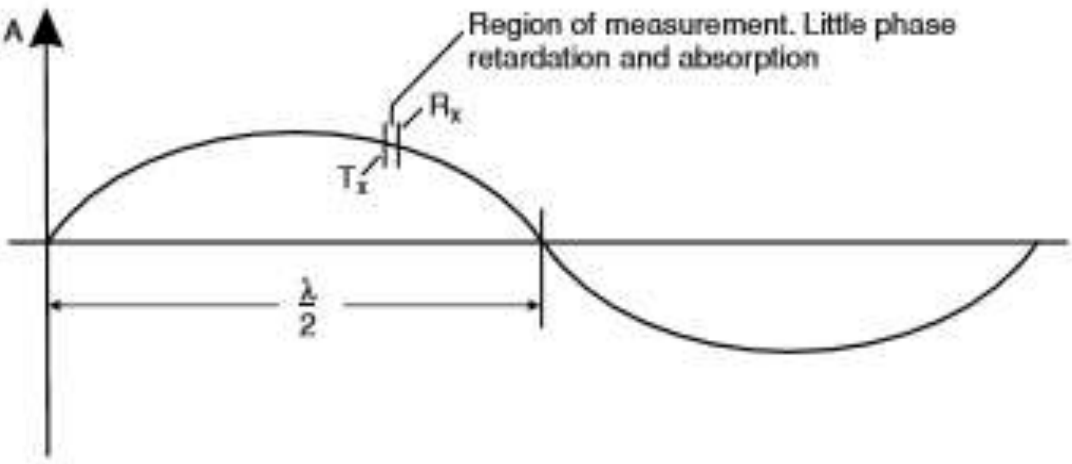

Figure 2.2: Physical Separation of the transmitter and receiver (Reynolds, 2011)

When the EM radiation travels through subsurface media it is modified slightly relative to that which travels through air. If a conductive medium is present within the ground surface, the magnetic component of the incident EM wave induces eddy currents within the conductor. This eddy current will in turn generate their own secondary EM field which is detected by a receiver (Figure 2.3).

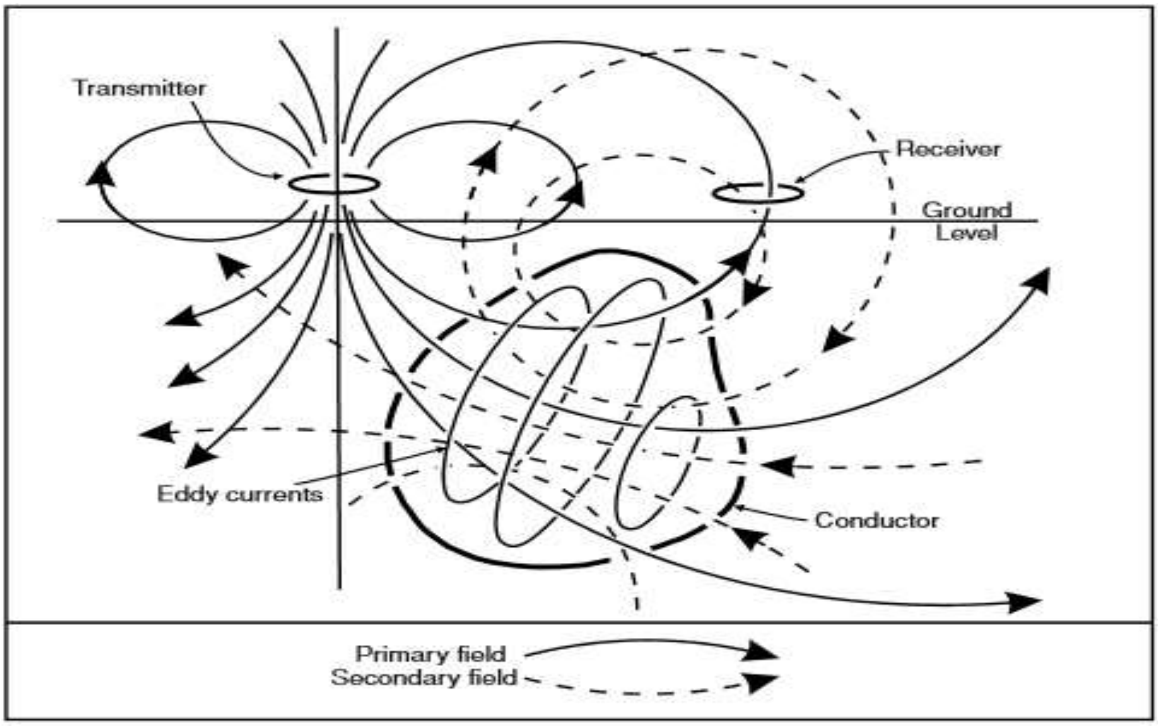

Figure 2.3: Generalised schematic of the EM surveying method (Reynolds, 2011)

The receiver further generate primary field which travels through the air. Hence the overall response of the receiver is the resultant effect of both the primary and the secondary fields. Consequently, the measured response will differ in both phase and amplitude relative to the unmodulated primary field. The degree of variation of these components reveals significant information about the geometry, size and electrical properties of any subsurface conductor.

2.1.2 Very low frequency (VLF) method

VLF technique is a far field (passive) method. The VLF method uses powerful remote radio transmitters set up in different parts of the world for military communications (Klein and Lajoie, 1980).

The source of the VLF method is electromagnetic radiation generated in the low frequency band of 15-25 kHz by the powerful radio transmitters used in long-range communication and navigational systems.

These transmitters generate plane electromagnetic waves that can induce secondary eddy currents particularly in electrically conductive elongated (2D) targets. There are around 42 global ground military communication transmitters operating at VLF frequencies of 15-30 kHz. The signals from these stations are harnessed for a variety of applications such as ground water detection, soil engineering, nuclear waste detection, and mineral exploration (Sundararajan, Babu, Prasad and Srinivas, 2006). A VLF anomaly represents a change in the attitude of the electromagnetic vector overlying conductive materials in the subsurface.

Paal (1965) observed that radio waves at VLF frequencies could be used to prospect for conductive mineral deposits. Since then, VLF transmitters at several locations around the world have been used widely as EM sources for near-surface geologic mapping. The VLF technique is especially useful for mapping steeply dipping structures such as faults, fractures and shallow areas of potential mineralisation. The depth of investigation varies from 4-5 meters in conductive soils to 40-60 meters in highly-resistive soils. VLF instruments measure two components of the magnetic field: the “tilt angle” and ellipticity. Some instruments also measure a third magnetic component and/or the electrical field. One of the advantages of the VLF method is that the field equipment is small and light and is conventionally operated by one person and more so, there is no need for a transmitter.

Such signals maybe used for surveying up to distances of several thousand kilometers fro m the transmitter.

2.1.3 Principle of operation of the VLF method

EM field is essentially planar and horizontal at large distances from the source. The radiated field from a remote VLF transmitter, propagating over a uniform or horizontally layered earth and measured on the earth's surface, consists of a vertical electric field component and a horizontal magnetic field component each perpendicular to the direction of propagation (Figure 2.4). These radio transmitters are very powerful and induce electric currents in conductive bodies thousands of kilometers away. Under normal conditions, the fields produced are relatively uniform in the far field at a large distance (hundreds of kilometers) from the transmitters. The induced currents produce secondary magnetic fields that can be detected at the surface through deviation of the normal radiated field.

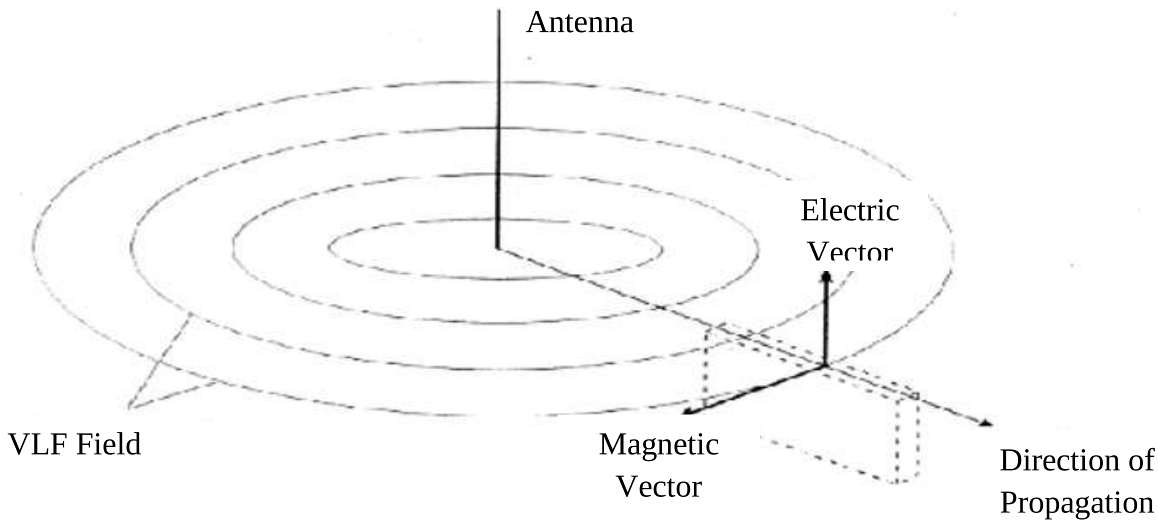

Figure 2.4: Principle of VLF method (Kearey, 2002)

The dashed lines show a tabular conductor striking towards the antenna which is cut by the magnetic vector of the EM field. The electric component E lies in a vertical plane and the magnetic component H lies at right angles to the direction of propagation in a horizontal plane. A conductor that strikes in the direction of the transmitter is cut by magnetic vector and the induced currents produced a secondary magnetic field.

Consequently, for a conductor to have a VLF anomaly, it must strike generally towards the VLF transmitter. Thus not all conductors will be detected in a VLF-EM survey with a single transmitter azimuth. High frequency of the VLF transmitters means that in more conductive environments, the exploration depth is quite shallow. In addition, the presence of conductive overburden seriously suppresses response from basement conductors, and relatively small variations in overburden conductivity or thickness can themselves generate significant VLF anomalies. This is why VLF is more effective in areas where the host rock is resistive and the overburden is thin.

VLF-EM waves travel in three modes namely: skywave, spacewave (wave-guided by the ionosphere and earth surface), and groundwave. As the groundwave is attenuated through long distances, only the skywave and spacewave are received as the primary wave (Jeng et al. 2004). The depth of penetrations of these waves is dependent on the frequencies and the electrical conductivity of the ground. This depth increases as both the frequencies and ground conductivity decreases as (Kearey and Brooks 1984).

2.1.3.1 Skin depth

This is the depth of penetration of a wave passing into a conductor in which the amplitude of the wave is attenuated to $1/e$ of its amplitude at the surface of the conductor. Mathematically, it is denoted as:

$$\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}} \cong \frac{500}{\sqrt{\sigma f}} = 500\sqrt{\frac{\rho}{f}} \qquad (2.1)$$

where;

δ = Skin depth in meters

μ_o = Magnetic permeability of free space = 4π x 10-7 Henry/m w = Angular frequency (2πf)

σ = Electrical conductivity of earth material (mho/m) (Inverse of resistivity, ρ) and

f = Signal frequency.

2.1.3.2 Effective Depth of Exploration

This defines the maximum depth a body can be buried and still produce a signal recognizable above the noise. It is denoted by Z_e and defined mathematically as:

$$Z_e = 100\sqrt{\frac{\rho}{f}} \tag{2.2}$$

2.1.4 VLF electromagnetic measurement

Very Low Frequency electromagnetic (VLF-EM) geophysical prospecting method is a passive geophysical method and an inductive exploration technique that is primarily used to map shallow subsurface structural features in which the primary electromagnetic (EM) waves induce current flow (Karous, and Hjelt, 1983). In principle, it utilises transmitters operating between 15 kHz to 25 kHz as the primary EM wave source. Onuegbuchulam *et al*. (2016) reported that ground and airborne very low frequency electromagnetic (VLF-EM) surveys have yielded success in the area of delineating electrical conductors and also to map geological contacts.

VLF survey or measurements are made utilising some special military communication transmitter which is located several kilometers away at the high powered military communication transmission stations. The signals generated can travel long distance and able to penetrate the subsurface to induce eddy current in buried conductors. The technique measures the components of very low frequency EM field which are related to the geo-electric structure of the subsurface (Saydam,1981). The electromagnetic method measures the bulk conductivity of subsurface material beneath and between the instrument transmitter and receiver coils. The readings are commonly expressed in the conductivity units of milliohms/meter (m-ohms/m) or millisiemens per meter (ms/m). EM surveys are used for locating subsurface zones of highly fractured bedrock, buried steel drums and tanks, plumes of groundwater contamination, and clay rich horizons (Onu, and Ibe, 1998). Measurements of the conductivity of the earth using the "wave-tilt" method were first done in the 1930's. However, those early measurements were carried out with a relatively high frequency and, as a result, had a shallow depth of investigation.

Paal (1965) found that radio waves at frequencies of 3-30 kHz could be used to detect shallow ore bodies. By surveying over known ore bodies in Sweden, he further discovered that the horizontal VLF magnetic field reached a maximum value over underground conductors and the modulus of the vertical magnetic field dropped to a minimum at the same location. Since 1964, commercially available ground VLF instruments have been manufactured. However, early instruments used atmospheric magnetic fields as sources. In 1967, a new approach was introduced by Collett and Becker which used VLF transmitters as the signal source. The new approach used a coherent source and made it possible to measure the phase angle between the horizontal electric and magnetic fields (McNeill and Labson, 1991). The detection of subsurface formations or anomalies is made feasible by using a portable VLF receiver recording the in phase and quadrature components of the vertical secondary magnetic field relative to the horizontal and primary field (Zhang, 2015). The VLF transmitter can be considered as a vertical electric dipole at the ground surface generating electromagnetic waves which consist of a vertical electric field component and a horizontal magnetic field component. In most cases, when measurements are made at a large distance from the transmitter, the electromagnetic wave can be viewed as plane wave propagation horizontally. When the primary electromagnetic field impinges on the surface it is both reflected back into the air and refracted into the earth (see figure 1). By measuring the shifted reflected magnetic field relative to the primary field, the subsurface structures can be constrained (McNeill and Labson, 1991).

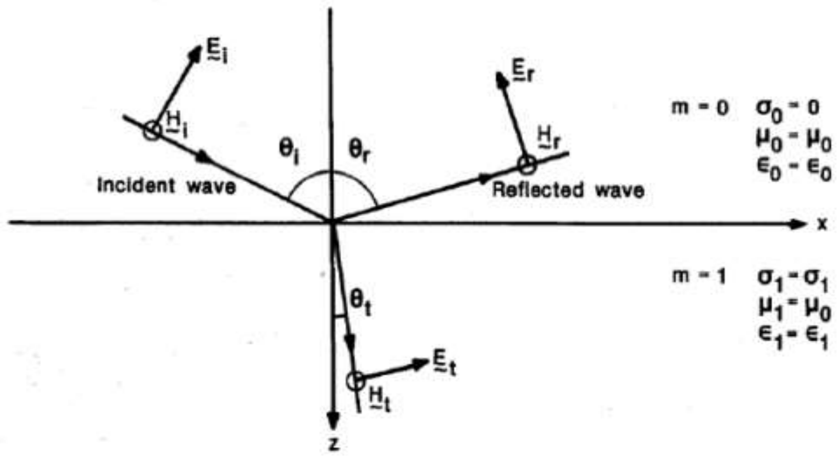

Figure 2.5: Field components near the surface of the earth (McNeill and Labson, 1991)

Where;

E and H represent the electric field and magnetic field, θ_i is the angle of incidence, σ is the conductivity, μ is the permeability, ϵ and is permittivity and index m represents different materials.

There are various factors inhibiting measured data in VLF electromagnetic prospecting. One among them is the effect of topography in the survey areas. Uneven terrain contributes significant anomalies which cause the observed VLF data to depart from the pattern which would be expected on flat ground. It is therefore important to distinguish between such topographic responses and actual subsurface anomalies (Abdul-Malik, Myers and McFarlane, 1985). Another factor inhibiting VLF measured data is the effect of water in the survey areas. Unlike moisture in the ground, surface waters such as lakes and rivers usually have a clear conductivity contrast with surrounding ground materials, therefore VLF anomalies are created when surveying. Like the topography effect, the VLF responses of surface waters need to be distinguished from those due to ground conductors.

VLF instruments are lightweight and portable, and they can be used to study large areas quite quickly (Liu *et al*., 2006). The VLF method employs the use of very low frequency radio waves (15 to 30 kHz) for exploration of fractured zones for assessing groundwater in hard rocks (Dutta *et al.*, 2006). It helps to determine the electrical characteristics of the underground and shallow rocks. There are VLF transmitting stations, for marine communication primary purposes, electromagnetic signals traveling between the ionosphere and the Earth's surface.

The signal emitted by the antennas around the world can be captured in the field by means of VLF instruments, and according to the basic electromagnetic theory, at long distances from the source, the waveform approaches a plane wave (Zlotnicki *et al*., 2006). There is a relationship between primary magnetic field (H_p) and magnetic secondary field (H_s) created by a conductive body that acts as a second source (Kaya *et al*., 2007). This means that electric currents in the conducting body (such as a fracture) is generated when radio waves (EM field) pass through it, creating another magnetic field (H_s). The resulting vector from the sum of H_p and H_s produces a time-varying elliptically polarized field. This elliptical shape has two components with the same frequency, but different amplitude and phase. The in-phase amplitude H_p is the real component, while the out of phase H_p is the imaginary component or quadrature component (Eze *et al*., 2004). The electromagnetic field equation for a conductive medium can be represented by the Helmholtz equation derived from the Maxwell equations:

$$\nabla^2 \begin{Bmatrix} \vec{E} \\ \overrightarrow{H} \end{Bmatrix} = i\sigma\omega \begin{Bmatrix} \vec{E} \\ \overrightarrow{H} \end{Bmatrix} \tag{2.3}$$

where;

E and H are respectively the electric and magnetic fields, σ is the conductivity (mS/m), μ is the permeability (Henry / m) and ω the angular frequency. In contrast, both the tilt angle (θ) and ellipticity (e) are calculated using the expression below:

$$\theta = \tan^{-1}\left(\frac{\overrightarrow{H}_S}{\overrightarrow{H}_P} \sin\alpha \cos\phi \right) \tag{2.4}$$

where H_p is the primary field, H_s is the secondary field, ∅ is the change of phase between Hp and H_s. H_s is tilting, and α represents the angle above H_p due to the coupling between the transmitter and the underground structure. Then, it is defined $H_s \sin\alpha = \Delta H_y$, thus equation (2.9) becomes:

$$\theta = \tan^{-1}\left(\frac{\Delta\overrightarrow{H}_Y}{\overrightarrow{H}_P} \cos\phi \right) \tag{2.5}$$

where $\Delta H_y \cos\emptyset$ is the real component or in-phase of the H_s field. The tangent of the tilt angle is proportional to the H_s real component, which is measured in the vertical direction. Therefore, the measurement of the tilt angle is very similar to measuring the real component (in-phase) of H_s in the vertical direction.

VLF data can be enhanced by applying filtering procedures. The filter application is essential to obtain a reasonable correlation between the anomaly and the structure. The filters are designed to decrease noise from the EM signal. The two methods widely used in VLF data processing are Fraser, as well as Karous and Hjelt filters.

Fraser filter is a low-pass function for estimating the average of tilt angle measurements produced by a subsurface conductor. In a linear sequence of tilt angle measurements say: M_1, M_2, M_3..... Mn, the Fraser filter F_1 is expressed as:

$$F_1 = (M_3 + M_4) - (M_1 + M_2) \tag{2.6}$$

The first value F_1 is located between M_2 and M_3 positions, the second value between M_3 and M_4, and so on. Karous and Hjelt (1983) developed a statistical linear filter, based on Fraser´s one, which provides a profile of current density vs. depth (H_0) and is derived from the magnitude of the vertical component of the magnetic field (H_z) in a specific position. Their technique involves filtering the same data set for various depths and gives an idea about the conductivity with depth, since high current density corresponds to good conductors. This technique has found wide popularity as it provides a simple, readily implemented scheme for semi-quantitative analysis and target visualization. The apparent current density pseudo section should provide a pictorial indication of the depths of various current concentrations and hence the spatial distribution of subsurface geologic features (Ogilvy and Lee, 1991). When we measure over conductors, the in-phase part of the equivalent current distribution has only positive values. Negative parts on both sides of the conductor can be caused either by the length of the filter or by a decrease of current density due to current gathering which is not present in 2D structures (Nabighian, 1988). In the simplest form, the Fraser filter is:

$$\frac{\Delta_z}{2\pi} I_a\left(\Delta_x/2\right) = -0.205H_{-2} + 0.323H_{-1} - 1.446H_0 + 1.446H_1 - 0.323H_2 + 0.205I_a\left(\Delta_x/2\right)$$

(2.7)

where Δ_z is the assumed thickness of the current sheet, I_a, is the current density, x is the distance between data points and also the depth to the current sheet. The H_2 through H_3

values are the normalized vertical magnetic field anomalies at each set of six points. The location of the calculated current density is assumed at the geometrical center of the six data points (Sundararajan *et al*., 2007).

In VLF-EM surveying, the two most important field measurements are the in-phase (abbreviation IP) and Quadrature (abbreviation Quad) and can be expressed as the normalized real and quadrature components of the vertical magnetic field.

$$In\ phase = \frac{real(\vec{H}_Z)}{\sqrt{\vec{H}_X^2 + \vec{H}_Y^2}}$$

(2.8)

$$Quad = \frac{imag(\vec{H}_Z)}{\sqrt{\vec{H}_X^2 + \vec{H}_Y^2}} \qquad (2.9)$$

The other two quantities are surface impedance and tilt angle, which yield useful information about the properties of the ground and can easily be calculated. Referring to the in-phase definition, tilt can also be defined as arctan(in-phase). Since in-phase tends to be small, the two diagnostics are usually very similar in shape.

$$Tilt\ angle = \arctan\left(\frac{real(H_Z)}{\sqrt{H_X^2 + H_Y^2}}\right) \qquad (2.10)$$

2.2 Electrical Resistivity Method

An electrical survey is aimed at determining the subsurface resistivity distribution by making measurements on the ground surface. The true resistivity of the subsurface can be estimated using these measurements. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. Geoelectrical resistivity surveying has shown great improvement, and also has become an important and useful tool in the field of hydrogeology, mineral prospecting and mining, as well as in environmental and engineering (Griffiths *et al*., 1990; Dahlin and Loke, 1998; Olayinka, 1999; Olayinka and Yaramanci, 1999; Amidu and Olayinka, 2006; Aizebeokhai *et al*., 2010). Electrical surveys can either be active or passive. It is passive if it uses electromagnetic (EM) fields generated by natural phenomena as a source of signal source. In contrast, active methods harness signal generators to generate the required input signal. The signal sources and receivers can be coupled to the ground through galvanic contacts such as electrodes planted into the ground or via electromagnetic (EM) induction such as coils of wire.

Electrical conductivity is a physical property that can be employed for a variety of problems in mineral exploration. It can be related directly to the mineralisation or be harnessed to delineate the geological structure associated with the mineralisation. The electrical resistivity method is an effective way to determine positions and depth extensions of gold-bearing quartz veins (Guo *et al.*,1999). Recently, geophysical exploration has played an important role in defining mineralised structures beneath cover (Liu *et al*., 2006).

Electrical methods of geophysical investigations are based on the resistivity (or its inverse, conductivity) contrasts of subsurface materials. The electrical resistance, R of a material is related to its physical dimension, cross-sectional area, A and length, l through the resistivity, ρ or its inverse, conductivity, σ by

$$\rho = \frac{1}{\sigma} = \frac{RA}{l} \qquad (2.11)$$

Low-frequency alternating current is introduced as source signals in the DC resistivity surveys in determining subsurface resistivity distributions. Hence, the magnetic properties of the materials can be ignored (Telford *et al*., 1990) the Maxwell's equations of electromagnetism then reduce to:

$$\nabla \cdot \vec{E} = \frac{1}{\varepsilon_0} q \qquad (2.12)$$

Resistivity measurements are normally made by injecting current into the ground through two current electrodes (C1 and C2), and measuring the resulting voltage difference at two potential electrodes (P1 and P2). From the measured current (I) and voltage (V) values, the apparent resistivity (pa) value is calculated.

$$\rho_a = K \, V/I \qquad (2.13)$$

where K is the geometric factor and it depends on the type of array that is being employed in the survey. For this research, the Wenner-Alpha array was adapted. The geometric factor "K" for a Wenner-Alpha array is given as thus:

$$K = 2\pi a \qquad (2.14)$$

where;

"a" is the inter-electrode spacing

The calculated resistivity value is usually not the true resistivity of the subsurface, but an "apparent" value which is the resistivity of a homogeneous ground that will give the same resistance value for the same electrode arrangement.

2.2.1 2-D Electrical Imaging Surveys

The application of imaging techniques in geophysics becomes necessary because for example many economically significant minerals (such as those in veins or pegmatite cavities) are no larger than a few meters in diameter (Nasir *et al*, 2018). Due to their small size, these deposits are easily missed with conventional mining methods (for instance trenching or tunneling), and most geophysical techniques which are one-dimensional methods probe the subsurface in only one dimension, vertical or horizontal cannot produce the resolution (detail) necessary to detect them. Electrical resistivity survey along the earth surface is a well-known geophysical exploration technique and due to its conceptual simplicity, low equipment cost and easy to use, the method is routinely used in mineral exploration (Sultan *et al.*, 2009; Jong-Oh *et al*., 1991). It is environmentally friendly because the method does not induce adverse effect during and after use.

One of the greatest limitations of the resistivity sounding method is its inability to take into account horizontal changes in the subsurface resistivity. Hence, a more accurate model of the subsurface is needed which is the two-dimensional (2-D) model where the resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line (Loke, 1999). In such case, it is assumed that resistivity does not change in the direction that is perpendicular to the survey line. 2-D surveys are the most practical economic compromise between obtaining very accurate results and keeping the survey costs down. A typical 1-D (VES) resistivity sounding surveys usually involve about 10 to 20 readings, while 2-D imaging surveys involve about 100 to 1000 measurements. The cost of a typical 2-D survey could be several times the cost of a 1-D (VES) sounding survey. In many geological situations, a 2-D electrical imaging surveys can give useful results that are complementary to the information obtained by other geophysical method.

2.2.2 Geology and resistivity

Usually resistivity surveys give a picture of the subsurface resistivity distribution. In order to convert the resistivity picture into a geological picture, some knowledge of typical resistivity values for different types of subsurface materials and the geology of the area surveyed, is important. Igneous and metamorphic rocks have proven to have high resistivity values. The resistivity values of these rocks are greatly tied to the degree of fracturing, and the percentage of the fractures filled with ground water (Loke, 1999). Sedimentary rocks, which usually are more porous with higher water content, normally have lower resistivity values. Wet soils and fresh ground water have even lower resistivity values. Clayey soil normally has a lower resistivity value than sandy soil. This is because of a particular rock or soil sample depends on a number of factors such as the porosity, the degree of water saturation and the concentration of dissolved salts. Hence, there exist an overlap in the resistivity values of the different classes of rocks and soils.

2.3 Description of the Study Area

This section discusses the accessibility, climate, vegetation, land use and land resources of the study area.

2.3.1 Accessibility

Shakwatu town is a sparsely populated area in Niger State, Nigeria. The proposed survey site is just 14.8km from Maitumbi round-about.

2.3.2 Climate

The area is known for its tropical climate. The summers here have a good deal of rainfall, while the winters have very little. The average annual temperature is 27^{o}C and the rainfall averages at 1229 mm. The least amount of rainfall occurs in January, most of the precipitation here falls in September. The temperature is highest on average in March at around 30.5^{o}C and August is the coldest month, with temperature averaging 25.3^{o}C.

2.3.3 Vegetation

Shakwatu happens to be an agrarian (agricultural) community. The vegetative cover in the area is rich in both wild plants and food crops. Millet, beans, maize, sweet potatoes, yam cassava, groundnut, soyabeans are grown as food and cash crops in the farmlands. Natural vegetation of scattered shrubs and grassy fields has been cleared for human economic use. Natural trees also occur for both timber and fruits.

2.3.4 Land Use and Land Resources

The land in the area is subdivided into small pieces and the major land uses include small scale farming mainly rain-fed. The main crops cultivated in this area are cash crops and tubers which are sold for commercial purposes. The rest of the land is covered with pasture for livestock and infrastructure which include human settlement, schools and access roads. Most of the locals are involved in artisanal mining which happens to be the major source of income in the area.

2.4 Geological Review of the Study Area

Niger State lies between latitudes 8°15’–11°15’ N and longitudes 4°00’–7°15’ E. It is bordered in the North by Kaduna and Kebbi states and in the South by Kogi state. It shares boundary in the West with Kwara state and Benin Republic and in the East with the Federal Capital Territory and Kaduna state. It has a total landmass of about 80,000 square kilometers. According to Obaje (2009), Niger State is underlain by the basement complex rocks while the other is occupied by the Cretaceous sedimentary rocks of the Bida Basin and part of the Sokoto (Iullemeden) Basin (Figure 2.6). According to Oyawoye (1972) and Ajibade *et al*., (1989), the basement rocks consist of a suite of Precambrian gneisses, migmatites and metasedimentary schists crosscut by granitoids. The migmatite-gneiss complex includes migmatites, gneisses, mylonites and amphibolites. The mylonites are major shear zones which mark the stratigraphic breaks between the gneissic basement complex and the cover rocks of the Birnin-Gwari Schist formation.

The study area is bordered by two rock types namely fine-grained biotite granite rocks and undifferentiated schists (Figure 2.7). The area is made up of granitic rocks underlain by schist; this is confirmed by lots of quartzite outcrops within the study area. Within the study area, we can observe a drainage channel (in form of a stream channel), this was also confirmed on the field.

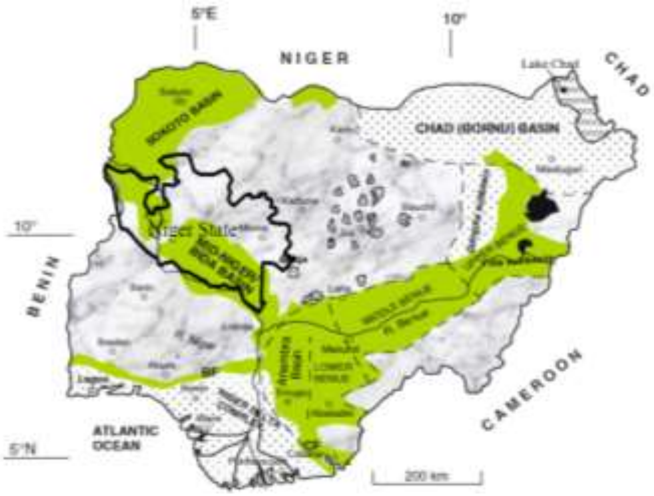

Figure 2.6: Geological map of Nigeria showing Niger State (Obaje, 2009).

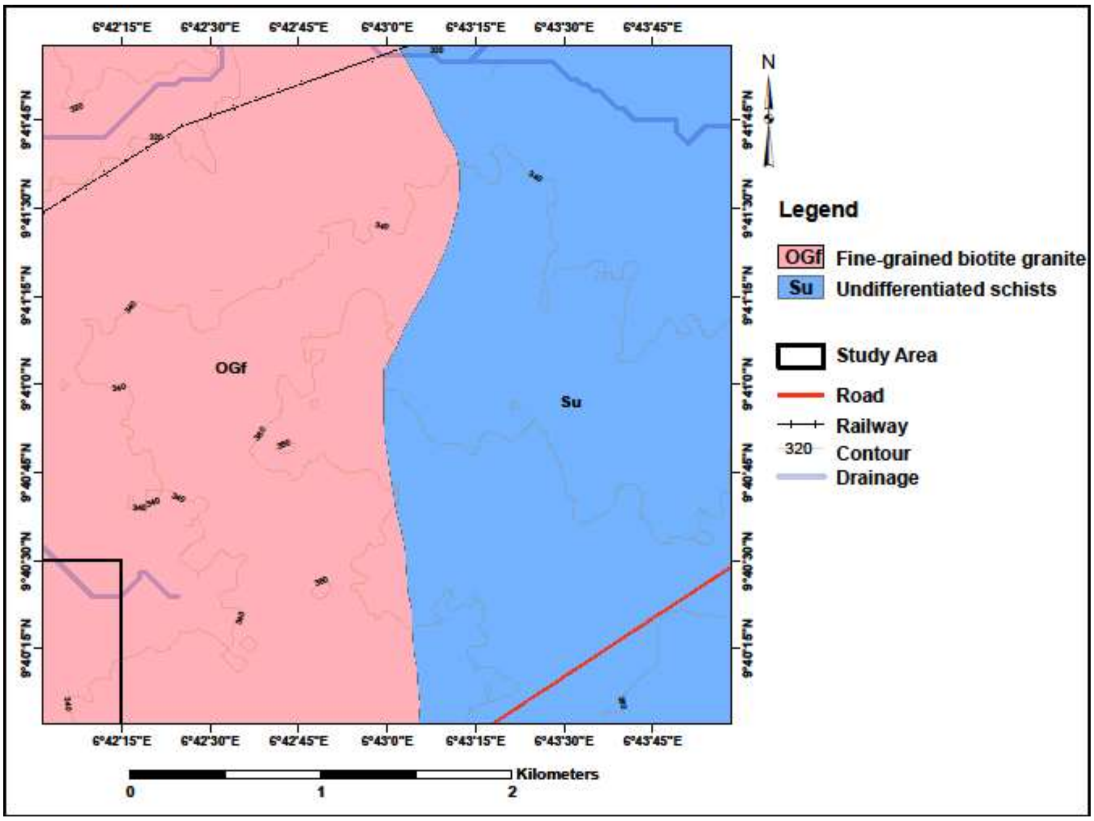

Figure 2.7: Geological map of the study area

Buser (1966) was able to note the establishment of paleo structures having activities such as tectonic movements, metamorphism, mineralisation and drainage. This was followed by aeromagnetic data interpretation across Nigeria continental mass as carried out by Ajakaiye *et al*. (1991). Their results showed that the NE-SW trending anomalies are the dominant magnetic fractures of most of these areas.

Alabi (2011) in his work, detected eight large granitic masses occurring as batholiths and continuous uninterrupted ridge in the northeast direction of about 18 Km in length, average width of 1.5 Km and an average height of 35 meters above their surrounding plains (an example is the Paiko and Minna batholiths).

Megwara and Udensi (2013) carried out trend analysis using aeromagnetic data over parts of the Southern Bida basin, Nigeria and the surrounding basement rocks. Here after, quantitative analysis of the total magnetic intensity map wa carries out. Magnetic lineaments were inferred using the Euler deconvolution and analytical signal techniques. Deductions made from the study include; The Romanche fracture zone passed through the study area and the prominent trends of lineaments are the North-South, Northeast-Southwest and the Northwest-Southeast directions.

Idris-Nda *et al.* (2015) carried out a geological study involving the determination of the various rock types and lithology in Niger state, Nigeria. The study shows that the state is basically underlain by crystalline and sedimentary rocks occurring in equal proportion. The crystalline rocks comprises mainly of granite, gneisses, migmatite and schist, while the sedimentary deposits are mostly made up of sandstone, clays and shale.

The sedimentary formations belong to the Bida Basin of deposition. The Bida Basin which is also known as the mid-Niger Basin or the Nupe Basin is a NW–SE trending intracratonic sedimentary basin which extend from Kontagora in Niger State to areas slightly beyond Lokoja in the south. Its total length is estimated at 400 km with a maximum width of about 160 km which tapers to less than 60 km at Dekina. The largest portion of the basin occurs in the southern half of Niger State.

2.5 Geophysical Review of Related Literatures

Several authors have carried out research using Geoelectric (2D resistivity) and electromagnetic (Very low frequency) method which is reviewed as thus:

Bayrak (2002) reported the integrated geophysical exploration (Very Low Frequency, induced polarisation, gravity, magnetic and self potential) for the occurrence of chrome ore in southwestern Turkey. The VLF parameters (apparent resistivity, phase, real and imaginary components of the vertical magnetic field and tilt angle of the magnetic polarisation ellipse) were acquired using 16 kHz (GBR, Rugby, England) radio signal. Mapping of the VLF-EM resistivity, phase, real component of vertical magnetic field and filters (Fraser, 1969 and Karous and Hjelt, 1983) yielded good results by differentiating conducting ore bearing fault zones within the resistive ultrabasic rocks. Low values of resistivities (<100 Ohm.m) which is obvious in the reconnaissance mapping extend in about N 25^o E direction. This direction correlated with the extension of known chrome occurrences in the field.

Geophysical and ore microscopic studies were carried out in the Wadi Sa'al area, South Sinai, Egypt in order to explore for sulphide mineralisation in the area. The study entails investigating the subsurface mineralisation in the area using an integrated geophysical technique (vertical magnetic gradient -VMG, magnetic susceptibility- MS, very low frequency- VLF and self-potential – SP). The VLF surveys identified conductive subsurface bodies, at several sites in the area, at depths ranging from 18 to 73 meters below the ground surface (Mamoun *et al.*, 2004).

Tijani *et al.* (2009) reported the application of VLF and Horizontal Electrical Resistivity Profiling (HRP) as mapping tools for detection of subsurface structural features in respect to gold mineralisation prospect around the outskirts of New-Bussa Niger State. The result shows a number of subsurface zones with high real component current density which define the potential fracture zones (possible gold mineralisation).

Gnaneshwar *et al.* (2011) reported that the VLF method was employed in the Schirmacheroasen area of East Antarctica to investigate its response, which was performed along four profiles. The preliminary results shows locations of geological boundaries and shear zones/faults, which may indicate that VLF anomalies are as result of shear zones located along contacts between different rock types.

An integrated geophysical investigation involving Very Low Frequency and VES methods was conducted at a site in Ibadan South-Western Nigeria in order to provide detailed information on the location for disposal of waste with utmost priority being prevention of groundwater pollution. VLF-EM data indicated the absence of linear features while VES showed the presence of three to four geoelectric layers namely topsoil, dry lateritic soil, clay layer, weathered/fresh bedrock with no evidence of fracture which may promote large scale groundwater pollution (Adewuyi and Oladapo 2011).

Idowu *et al.* (2013) reported a combined geophysical investigation involving very low frequency electromagnetic (VLF-EM) and electrical resistivity methods which was conducted at Ijapo Housing Estate, Akure, South-Western Nigeria, to assess its foundation integrity for future engineering construction. The VLF-EM result revealed concealed geological structures suspected to be fractures/faults and geoelectric method delineated about four major geoelectric layers namely: the top soil, lateritic layer, weathered basement and the fresh basement and series of bedrock ridges and depressions.

Michael *et al*. (2013) employed the Very low frequency electromagnetic method to carry out geophysical survey in twenty-three (23) locations of parts of the Eastern Basement Complex of Nigeria. The lengths of the profiles were between 120 meters and

650 meters. The sampling rate along each profile was 5 meters with profile lines oriented in N–S, and E–W directions. The result was analysed using KHFFILT (Karous Hjelt Fraser filtering) software. The results of the survey showed that majority of the fractures were oriented in the NE – SW direction, followed by fractures oriented in the NW – SE direction signifying that the study area is well fractured.

In the quest to investigate the location and depth of mineral rocks at Olode village, Oyo State, Nigeria, Magnetic and resistivity geophysical methods were employed. 80 magnetic data points were acquired in 10 profiles using G-816 proton precession magnetometer with 10m spacing in between each profiles and 10m stations interval. Resistivity data were obtained using Campus Tiger resistivity meter and 9 VESs were acquired using Schlumberger configuration. The results of these geophysical methods show that there are rocks with high magnetic susceptibility and conductivity values from the centre towards the eastern region of the study area and low magnetic susceptibility and conductivity values at the western region (Ojo *et al*., 2014).

In the exploration of Lead-Zinc (Pb-Zn) mineralisation over the Ishiagu area of Abakaliki Basin, Lower Benue Trough, very low frequency Electromagnetic (VLF-EM) technique was employed to determine the Pb-Zn mineralisation in the sedimentary bedrock. The conductivity contrast between the conductive mineralised veins and the host rock so generated by induction mechanism was used to delineate the potential zones of Pb-Zn mineralisation. The result shows high VLF anomalies which yielded a high conductivity contrast result and is well-suited for Pb- Zn mineralisation and the geologic information of the area. The integration of KHF filtering and VLF interpretation shows strong EM induction, probably indicating the presence of Pb-Zn deposits (Victor *et al*., 2015).

In the geophysical investigation conducted at Rufus Giwa Polytechnic, Owo, South-Western, Nigeria with the aim of evaluating the groundwater potential in the area. The Very Low Frequency Electromagnetic (VLF-EM) and Vertical Electrical Sounding (VES) was employed. The VLF-EM result reveals the presence of conductive zones. The geoelectric section revealed 3 to 5 major layers comprising the topsoil, clay, laterite, weathered layer, partly weathered layer/fractured basement, and fresh basement rock (Falowo *et al.*, 2015).

Oladejo *et al.* (2015) reported an electromagnetic survey carried out at Ibodi, village, Ilesa in Atakunmosa West Local government area with a view to determining the probable locations for groundwater exploration in the study area. The result revealed fractured zones which are suspected to be the best locations for groundwater prospects in the study area.

Onwuegbuchulam *et al.* (2016) employed the very low frequency (VLF) electromagnetic technique to investigate possible geologic features like fractured / conductive zones in Auchi and its environs in Edo state, Southwestern Nigeria. The study shows that the area is sparsely fractured, and a total of five conductive zones were observed.

Shendi *et al.* (2017) reported a survey carried out in Wadi Isbayia area, South Sinai Peninsula, in order to test for the efficiency of the VLF-EM method in the exploration of sulphide mineralisation in arid environments. The VLF-EM measurements were carried out along fifteen (15) profiles covering a quartz monzonite bedrock. The Interpretation of the VLF measurements, in conjuction with geological information, has shown that sulphide minerals in the study area extend from the ground surface to a depth of about 200 m. The structural lineaments, especially faults were responsible for the controlled distribution of the sulphide mineralisation. Some rock samples collected from the sites of the VLF-EM anomalies in the study area, have been prepared and examined by ore microscopy which confirmed the presence of pyrite and chalcopyrite as well as iron oxides, disseminated in the quartz monzonite bedrock. These results showed that the VLF-EM method is an effective tool in the exploration of sulphide minerals in the arid environments.

Dogara and Aloa (2017) reported a geophysical investigation with the aim of locating and estimating the quantity of some possible deposits of gypsum at Ikpeshi, Etsako Local Government Area of Edo State. The Wenner and Schlumberger electrical resistivity methods were employed at spread lengths of a=1m, a=3m, a=6m and a=9m across the entire area, after which a total of twelve vertical electrical sounding (VES) points were sounded at appropriate locations with a maximum spread of 100 meters. The surveyed area shows the presence of some traces/crystals of gypsum at depths of between 3m and 9mand a resistivity range of 1 to 3000Ωm spread around the investigated area.

Arifin *et al.* (2019) investigated the potential zones for gold mineralisation at the Felda Chiku 3, Gua Musang, Kelantan, East coast Malaysia. A total of twenty-one (21) geophysical survey lines were conducted at the proposed mineral exploration site using the electrical resistivity (pole – dipole) and induced polarisation arrays to get the maximum depth of 150 m with 400 m survey length. The result from the resistivity and chargeability concentration maps and the potential mineralised zones so delineated, was observed to be dominantly concentrated towards the southwest and northern part of the study area. The data showed that the potential mineralised zones are trending approximately north-south directions.

Osinowo and Falufosi (2018), reported an integrated geophysical investigation carried out around Ihale in Bunnu-Kabba area of Kogi, Northcentral Nigeria in order to probe the surface in terms of rock magnetic susceptibility and ground conductivity for the purpose of identifying mineralised pegmatite veins that could serve as host for gold and associated metallic deposits. Seven (7) zones of relatively high VLF-EM derived current density with matching high residual positive magnetic anomalies present closely correlate-able signatures with subsurface response obtained around the reference profile established where local mining activities shows evidence of gold and associated metallic mineralisation of the pegmatite vein within the study area.

In the geophysical investigation for delineation of gold mineralisation in Bugai town, Birnin Gwari, Kaduna, North Western Nigeria, electrical resistivity method using the dipole-dipole array was employed and ten (10) parallel 2D profile data were collected manually each of length one hundred meters (100 m,) separated by ten meters (10 m) and with minimum electrode spacing of three meters (3m). The 2-D data were processed using RES2DINV computer inversion software for effective and accurate interpretation of the location for the gold deposit. Results from 2D resistivity models show a variation in shape due to heterogeneous nature of mineralisation within the study area at different depths (Nasir *et al.*, 2018).

CHAPTER THREE

3.0 MATERIALS AND METHOD

3.1 Materials

The following materials were used during the course of the research work:

i) Scintrex Envi meter

ii) Data recording sheet

iii) Existing topographical, geologic map of the area

iv) Global Positioning System (GPS)

v) Digital satellite image of the study area

vi) Compass clinometer

vii) Hammer, reel tape, ruler, pencil and pen

viii) Resistivity meter (Geotron- G42)

ix) Twenty-one (21) set of electrodes

x) Cables

xi) Pegs for profiling

xii) KHFF (Karous Hjelt Fraser Filter) Application

xiii) RES2DINV Software

xiv) A Laptop

3.2 Method

The research design that summarises the methodology employed in this research is presented as thus;

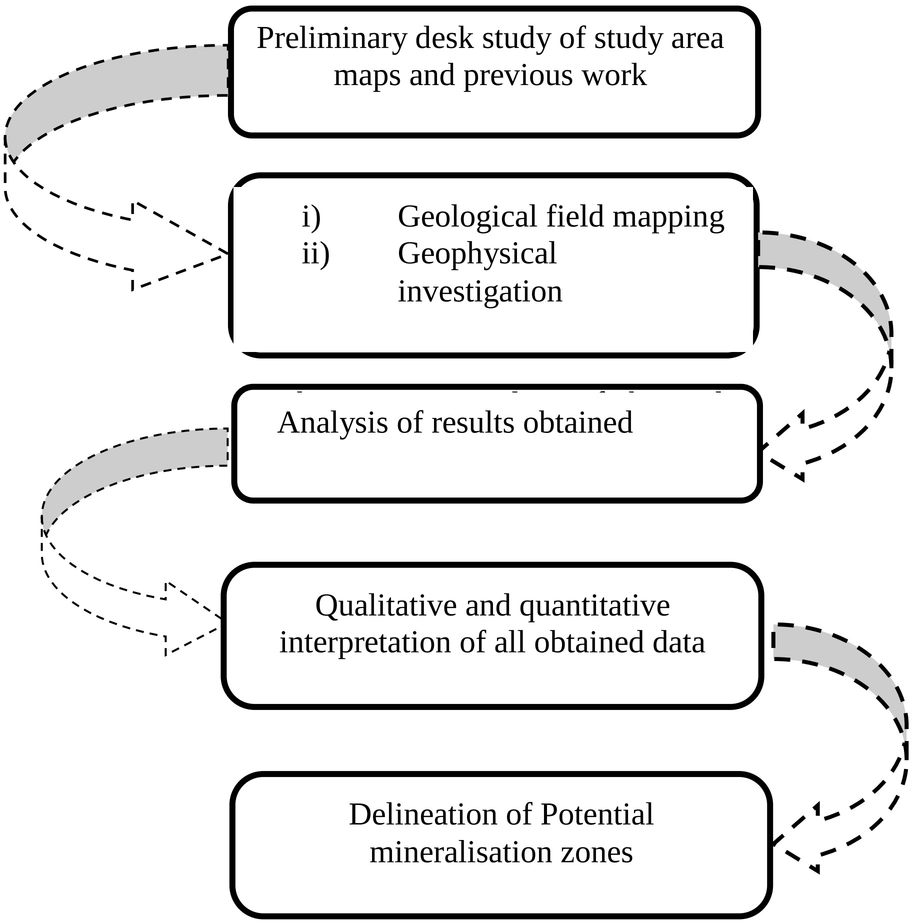

Figure 3.1: Research Methodology Design

3.2.1 Preliminary desk study

Prior to the field work, a desktop study was carried out. These include reconnaissance survey (identifying outcrops and major geological features), review of related literatures, and study of the geology map of the area and other relevant geological information.

3.2.2 Geological field mapping

This involves taking the joint directions of most outcrops within the study area in order to establish the structural trend of the structures in the study area. This was done using a compass clinometer.

3.2.3 Geophysical data collection

In this research, two different geophysical investigation methods (Very Low Frequency and Electric resistivity method) were employed in order to probe the subsurface so as to delineate regions of the subsurface having mineralisation potential. The geophysical parameters which were employed in this study to characterise the subsurface are the electrical properties of the earth (conductivity and resistivity).

3.2.3.1 Very Low frequency electromagnetic method

Electromagnetic method on the other hand measure ground conductivity or resistivity its inverse and due to the relative ease of electrical conduction across a mineralised vein is able to map occurrence of mineralised veins in the subsurface (Eze *et al*., 2004; Osinowo *et al*., 2018). Electrical resistivity on the other hand, determines the subsurface resistivity distribution by making measurements on the ground surface (Loke, 1999). Electrical methods of geophysical investigations are based on the resistivity (or its inverse, conductivity) contrasts of subsurface materials.

Measurement of ground conductivity to delineate mineralised veins, which often presents significantly higher conductivity value than the rocks that host them, was undertaken using Scintrex Envi VLF-EM meter. The meter is capable of measuring terrain conductivity by determining the ratio of the real (Re) to the imaginary (Im) components of the propagating time varying low frequency (15–25 KHz) primary (H_p) (originating from far distant transmitting station) EM field and secondary (H_s) EM field generated when eddy current flow in subsurface conductor or conducting zone. The measured difference in field intensity and phase lag between the primary and the secondary EM field is related to the ground conductivity where a phase lag of the secondary EM field relative to the primary EM field of about half a period (180°)

indicate a conducting ground, while a resistive ground (poor conductor) will cause the secondary EM field to lags the primary EM field by 90° (Ogilvy and Lee, 1991).

Plate 3.1: Field operation of VLF survey

Plate 3.1 shows the field operation of a VLF-EM survey. VLF-EM data were collected along profiles and measurements were made with a station separation of 20 m using the Scintrex Envi meter in the VLF-EM mode. The Scintrex Envi meter harnesses the magnetic component of the electromagnetic field generated by military radio transmitters that makes use of the VLF (Very Low Frequency) band (15 to 30 KHz) commonly used for short distance communication. The Scintrex Envi meter measures this field strength and phase displacement around a fractured zone or any conductive body in the rocks. It detects the ratio (in percentage) between the vertical and the horizontal components. The two parts of the vertical component is the in-phase and quadrature. The in-phase is a good representation of the tilt. After turning on the equipment, we did a frequency scan, at the end of the scanning process; the equipment displays three different signals. The scanning was done orthogonal to the strike. The frequency with the best signal strength was selected as the source for the entire VLF survey because it provided a field which is approximately perpendicular to the direction of the strike of the envisaged geological structure beneath the ground surface. The study area covers a total of 500 m^2 area of landmass. The profile runs in the East-West (E-W) and West-East (W-E) direction, which is perpendicular to the principal joint direction. The lengths of the profiles are 500 m with a 100 m inter-profile spacing and a sampling rate of 20m on each profile. The in-phase (real) and quadrature (imaginary) data were recorded for each profile.

3.2.3.2 Electrical resistivity (2D) method

In this research work, the Wenner-alpha array in electrical resistivity survey was adopted. The basic field equipment for this study is the Geotron Resistivity meter (G-42), which displays apparent resistivity values digitally as computed from ohm's law. It is powered by a 12 Volt (V) Direct Current (DC) power source. Other accessories to the resistivity meter include twenty-one (21) metal electrodes, cables for current and potential electrodes, harmers (four), measuring tapes, writing pads. In field configuration, the electrodes are positioned symmetrically along a straight line, the current electrodes on the outside and the potential electrodes on the inside. Both the current and potential electrode positions are aligned using constant electrode "a" spacing. To change the depth range of the measurements, the current electrodes and the potential electrodes are displaced outward together. During the field work, the Geotron

Resistivity meter performs automatic recording of both voltage and current, stacks the results, computes the resistance in real time and digitally displays it. The Geotron resistivity meter was configured in a mode that it displays apparent resistivity.

3.2.3.3 Electrical resistivity (2D) imaging

There are several arrays most commonly used which include Wenner (alpha), Schlumberger, dipole-dipole, pole-pole and pole-dipole arrays. The choice of employing a particular array against another depends on a number of factors namely: the geological structures to be delineated, heterogeneities of the subsurface, noise level, sensitivity of the resistivity meter, the background and electromagnetic coupling, depth of investigation, the sensitivity of the array to vertical and lateral variations in the resistivity of the subsurface and the horizontal data coverage and signal strength of the array (Aizebeokhai, 2010). The Wenner (alpha) array was employed in this research. The 2d resistivity survey was taken along a low conductivity target region at 100m spread. This owes to the assumption that mineralization within zones of elevated resistivity on the geoelectric pseudosection and low conductivity on the VLF pseudosection comprises of quartz veining structures (Nasir et al., 2018). A total of twenty-one (21) electrodes were used for the survey. Figure 3.2 shows a possible sequence of measurements for the Wenner electrode array for a system with 21 electrodes (that is numbers 1-21). The spacing between adjacent electrodes is “a”, it is varied for 5 m, 10 m, 15 m, 20 m, 25 m and 30 m. The asterisk represents datum points, and there are a total of Sixty-three (63) datum points which is used to build up apparent resistivity pseudo section. For the first measurement, electrodes number 1, 2, 3 and 4 are used. In this case, electrode 1 is used as the first current electrode C1, electrode 2 as the first potential electrode P1, electrode 3 as the second potential electrode P2 and electrode 4 as the second current electrode C2 as shown in Figure 3.4. For the second measurement, electrodes number 2, 3, 4 and 5 are used for C1, P1, P2 and C2 respectively. This is repeated down the line of electrodes until electrodes 17, 18, 19 and 20 are used for the last measurement with “a = 5 m” spacing. The resistivity value was recorded for each datum points. This process is done for a= 10 m, 15 m,   20 m, 25 m and 30 m respectively. The recorded result is thereafter processed using the RES2DINV software to generate the 2D pseudo section.

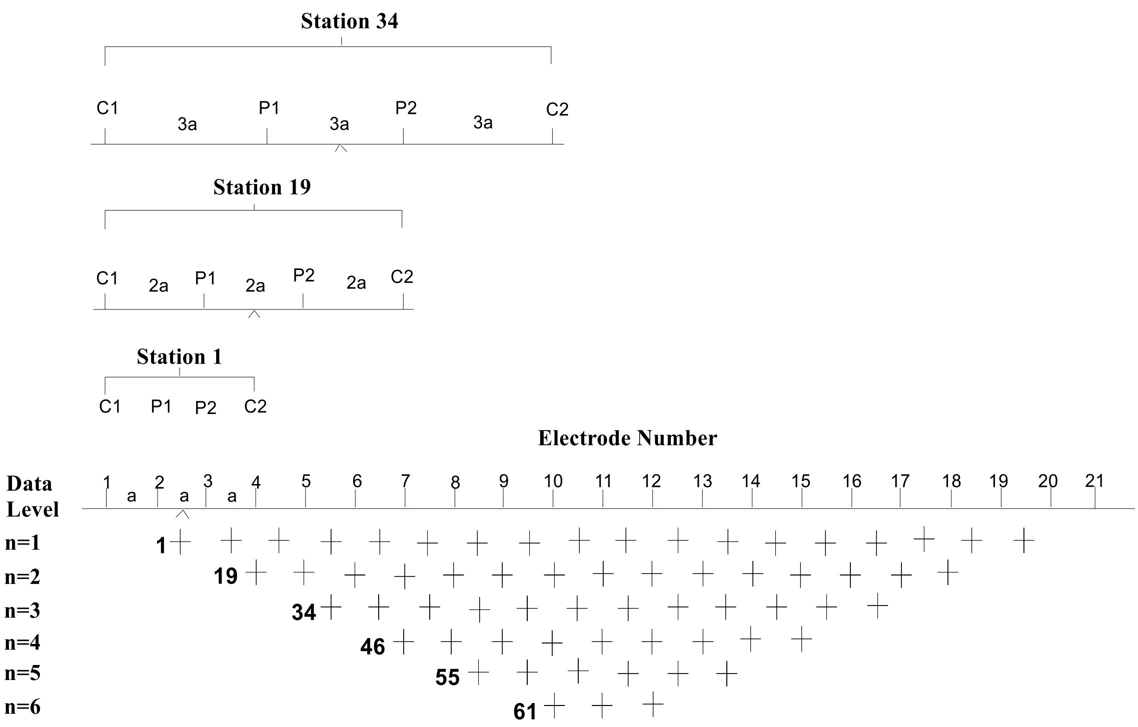

Figure 3.2: Arrangement of electrodes for 2D resistivity Survey

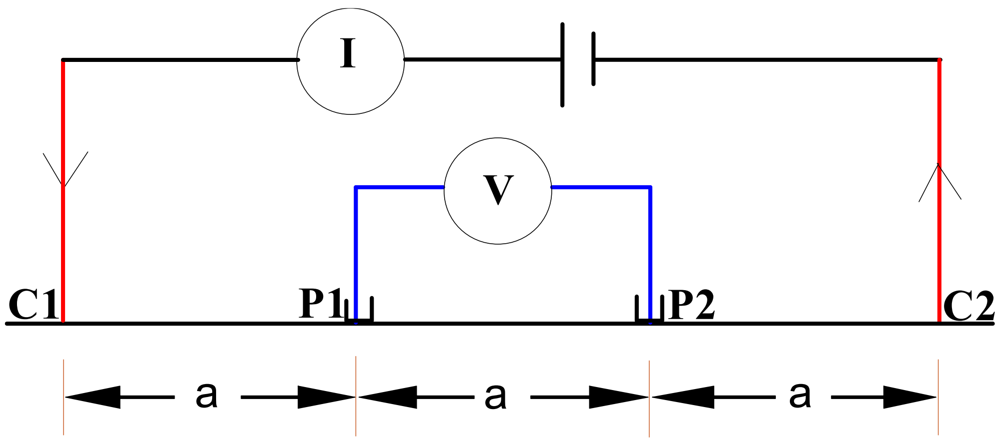

Figure 3.3: A Typical Wenner Alpha Electrode Configuration

3.2.4 Analysis of results

The field data collected were and analysed using the various geophysical applications as the case may be.

3.2.4.1 Structural trend analysis

The joint directions of most outcrops in the study area was noted and recorded with the help of a compass clinometer. A total of One hundred and sixteen joint directions were taken. This data was thereafter used to plot the Rosette diagram of the study area using an application called ROCKWORKS, which shows the principal joint directions of the study area.

Plate 3.2: Outcrop Showing Various Joints

3.2.4.2 Analysis of very low frequency electromagnetic

In order to locate the anomalies, measured data were processed using KHFFILT application. Anomalies of the raw VLF-EM profiles are usually complicated and this calls for data processing so as to improve the resolution of local anomalies and limit the possible interpretational error (Victor *et al*. 2015).

The acquired data were thereafter subjected to Fraser (1973) filtering to generate the filtered equivalent of the raw real and the imaginary components whose anomaly peaks directly overlie the causative sources and the anomaly amplitude directly relate to the causative conductors (McNeill and Labson, 1991). The reason for this is to remove the noise commonly associated with power line harmonic radiations, Global System Mobile (GSM) telecommunication transmitters and global lightening by so doing, enhancing the data so generated. The filtered data were subjected to Karous and Hjelt (1983) filtering. This filter is based on the concept that VLF-EM anomalies are caused by galvanic current response from conductive targets within the earth, transformed the measured in-phase component of the EM field into current densities at constant depths (McNeill and Labson, 1991).

The KHFFILT program was also used to perform Karous-Hjelt and Fraser filtering on the raw field data. Lower values of relative current density correspond to higher values of resistivity (low conductivity), while higher values of relative current density correspond to lower values of resistivity (high conductivity). The conductive targets were denoted with positive Fraser and Karous-Hjelt anomalies. The European convention rule of using red colour for conductive targets and the blue for resistive (non-conductive) targets employed in the current density pseudo section plot (Pirttijarvi, 2004).

3.2.4.3 Analysis of electrical resistivity data

The acquired field electrical resistivity data was analysed using RES2DINV software and the result produced an inverse model resistivity section of the subsurface.

3.2.5 Qualitative and quantitative interpretation of results

The field data results were analysed and interpreted in order to establish the structural trend of the structure, anomalous zones and contact points in the area on each profile and establish the overburden thickness and the depth to basement rock in the area.

CHAPTER FOUR

4.0 RESULT AND DISCUSSION

In this chapter we shall be discussing the results obtained from analysis of the raw data obtained from both VLF and electric resistivity methods.

4.1 Structural Trend Analysis of the Study Area

Figure 4.1 shows the structural trend of the structures in the study area. The surrounding outcrop within the vicinity of the investigated site display high fracture intensity which makes them suitable for potential mineralisation zone. The joint directions of the outcrops determined on the field are predominantly NS, with the principal joint direction indicating NE to SW direction as indicated on the Rose diagram (Figure 4.1)

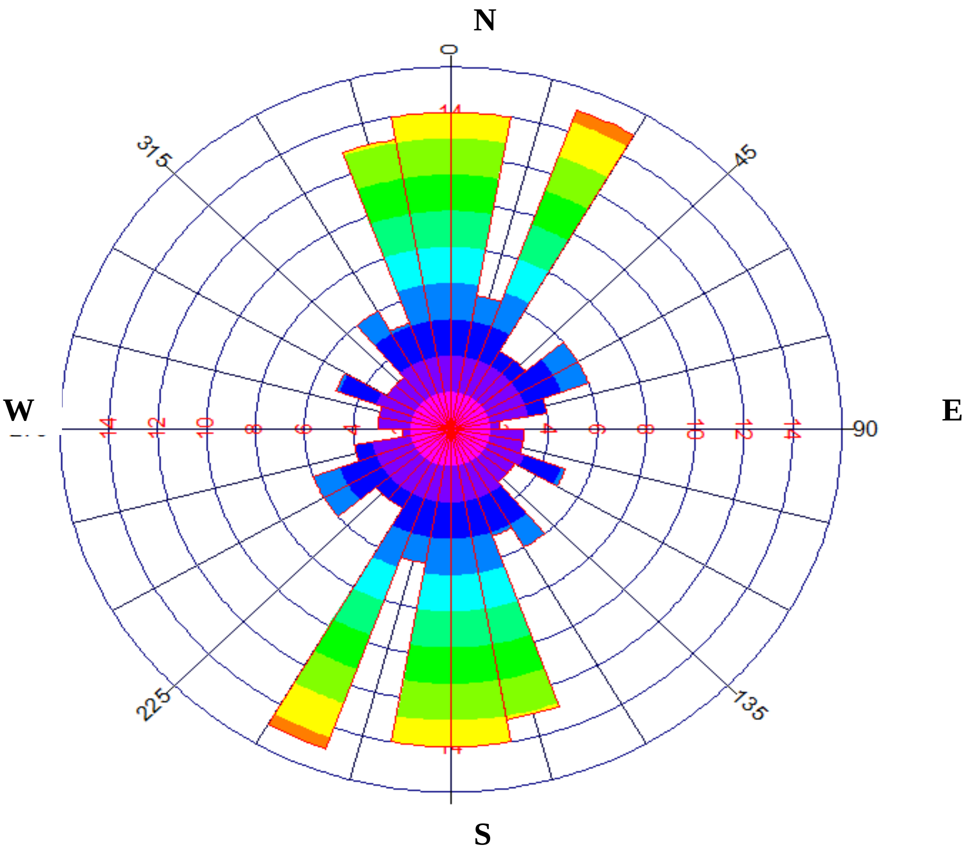

Figure 4.1: Rose Diagram showing principal joint direction of the study area

4.2 VLF Results Discussion

Interpretations were done normally by considering the high amplitude signal, which is diagnostic of anomalous (fractured) zones. For each sample point, a plot of the raw field data, the Fraser filtered data and the Karous-Hjelt pseudo sections are displayed (Figure 4.3a-Figure 4.8c). The pseudo section is a measure of conductivity of the subsurface as a function of depth. The conductivity is shown as colour codes with conductivity increasing from negative to positive.

4.2.1 VLF Interpretation for profile 1

Figures 4.3a, 4.3b and 4.3c represent the unfiltered (raw) in-phase, filtered in-phase plot and current density pseudo section of in-phase data for profile 1 respectively. As a result of noise and other electromagnetic effects, the VLF measurement (Figure 4.3a) has been filtered for better interpretation and to enhance the signal. At Profile 1 with traverse oriented in the E-W direction, a plot of filtered data shows prominent positive response (peaks) at a distance of 300-440 m and a negative response at a distance of 30-80 m and 200-290 m respectively (Figure 4.3b). Positive response results into probable fracture zones (Michael *et al*., 2013; Oluwafemi and Oladunjoye, 2013). Both the positive and negative response of the filtered in-phase plot in Figure 4.2b corresponds to the current density pseudo section (Figure 4.3c). This positive response corresponds to conductive zones on the current density pseudo section at a depth extending from 20-75 m and oriented at NS-NE and NS respectively (Figure 4.3c). The negative response results in non-fractured zone on the current density pseudo section at a depth of 20-50 m and 20-80 m respectively and oriented at NS and NW-SE respectively.

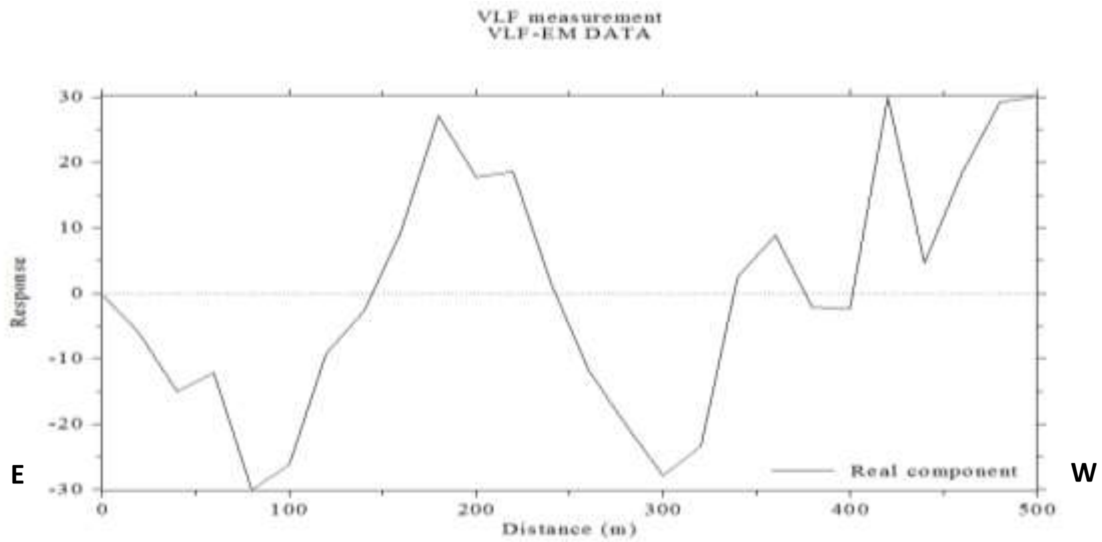

Figure 4.2a: Plot of unfiltered (raw) in-phase data against distance at profile 1

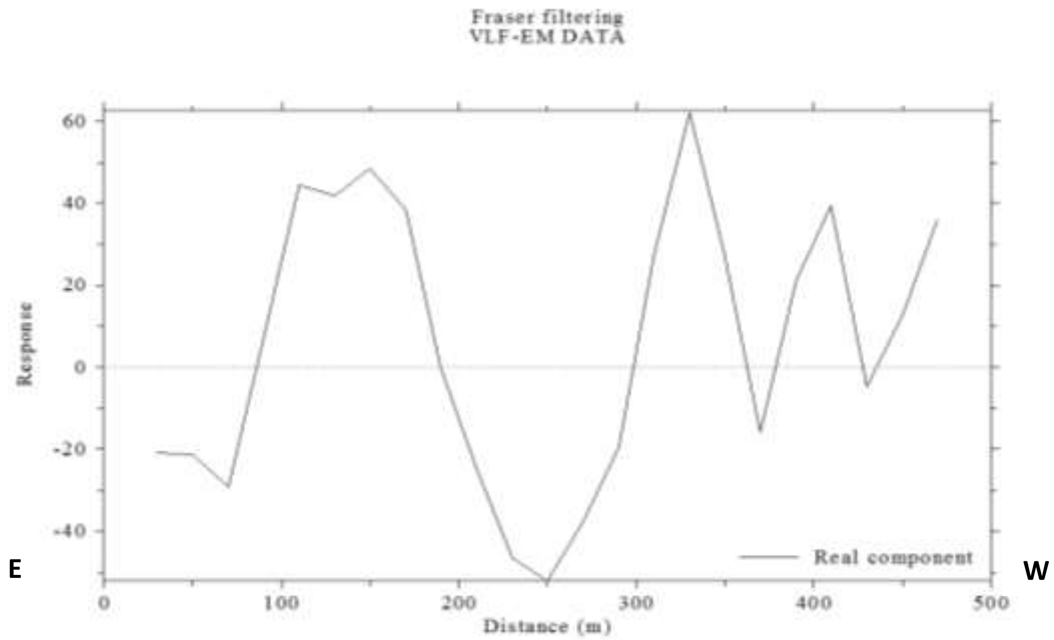

Figure 4.2b: Plot of filtered in-phase data against distance at profile 1

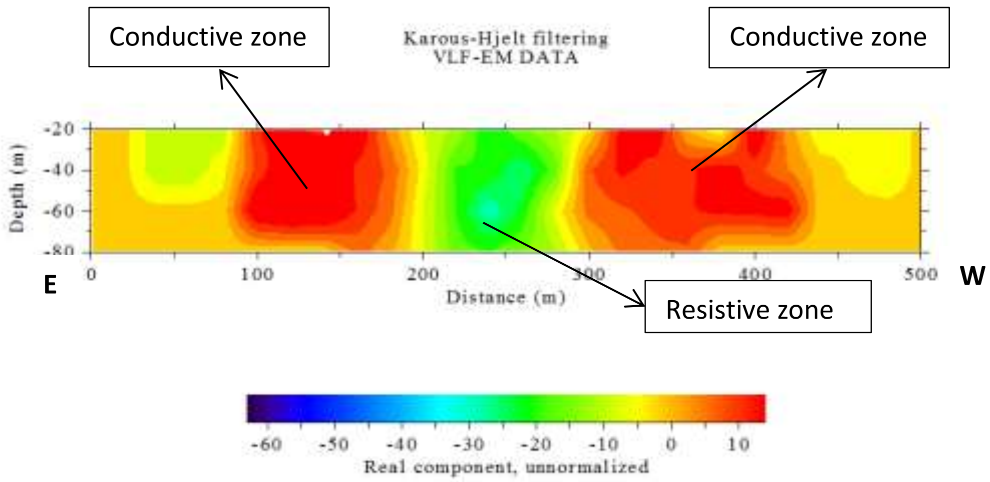

Figure 4.2c: Current density pseudo section of in-phase data against distance at profile 1

4.2.2 VLF Interpretation for profile 2

The unfiltered in-phase plot, filtered in-phase plot and the current density pseudo section for profile 2 is represented by figure 4.4a, 4.4b and 4.4c respectively. At profile 2 with traverse oriented in the W-E, two positive responses were identified at a profile distance of 80-230 m and 340-420 m respectively (Figure 4.4b). Similarly, three negative responses were also identified at a profile distance of 20-70 m, 220-330 m and 440-460 m respectively. The positive response results to probable but not well fractured zones and this agrees with the current density pseudo section which is characterised by high conductive zones at a depth of 20-80 m and oriented at NS-SE and SE direction respectively (Figure 4.4c). The negative response which results into non-fractured zones corresponds to low conductive (resistive) zones on the current density pseudo section at a depth extending from 20-50 m and 20-80 m respectively and oriented at NS direction.

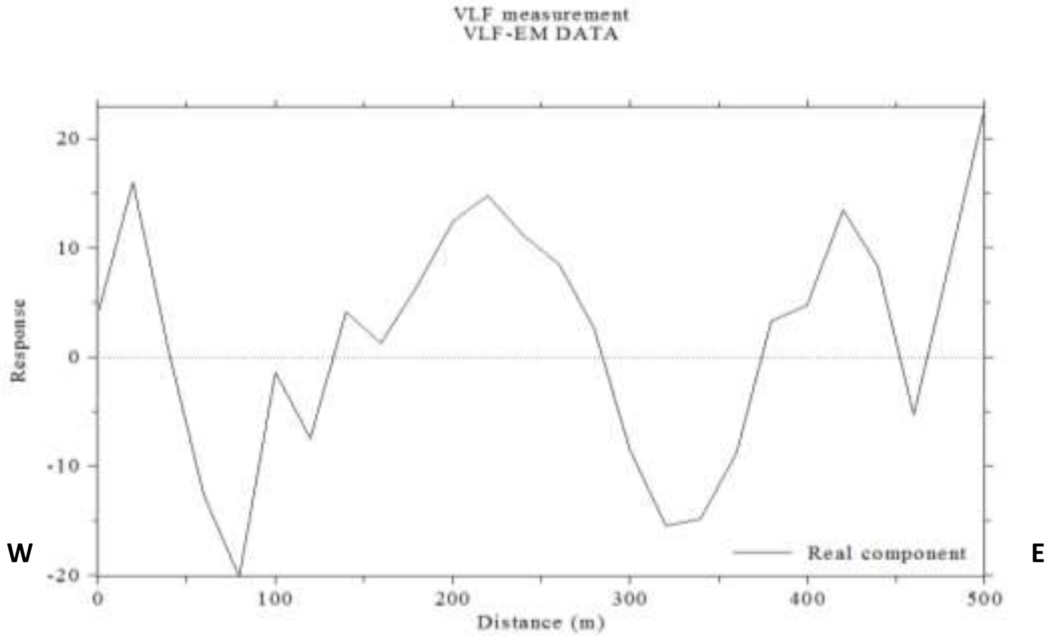

Figure 4.3a: Plot of unfiltered (raw) in-phase data against distance at profile 2

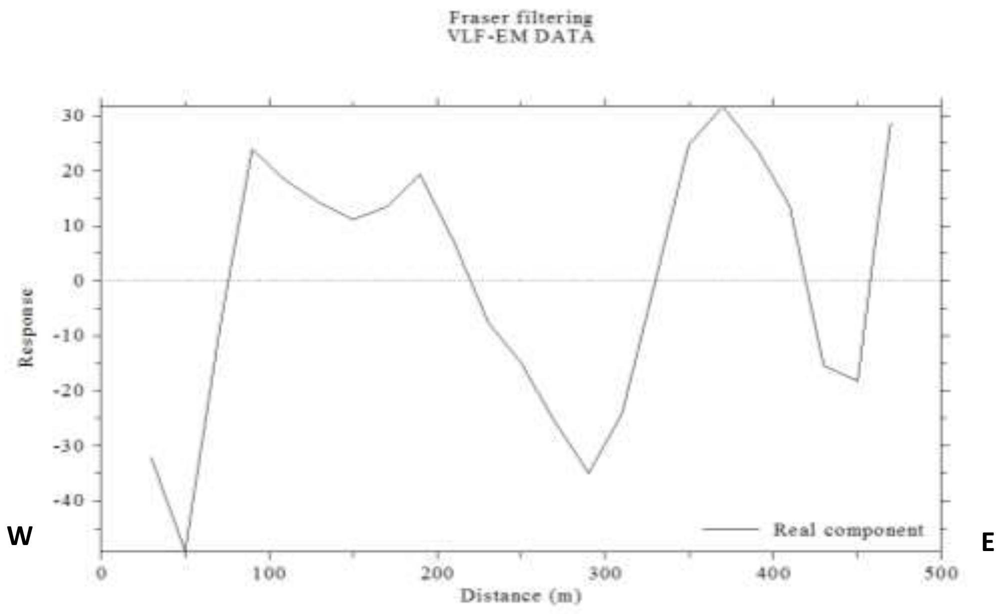

Figure 4.3b: Plot of filtered in-phase data against distance at profile 2

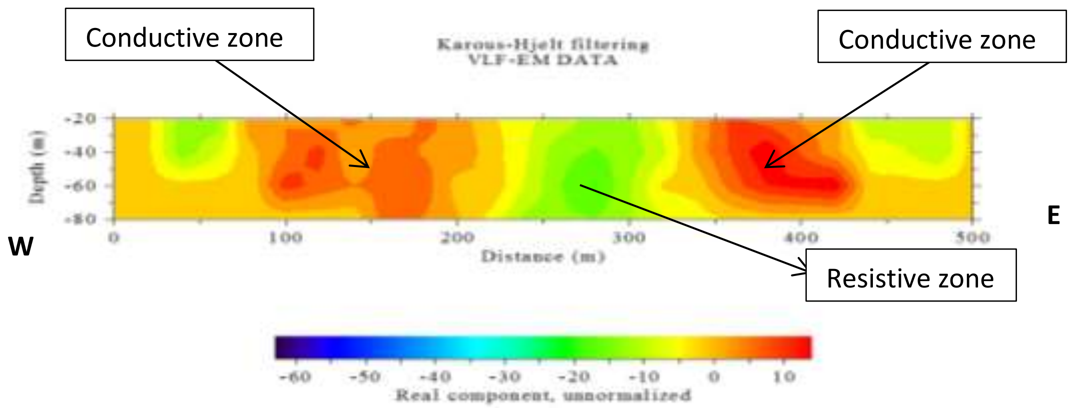

Figure 4.3c: Current density pseudo section of in-phase data against distance at profile 2

4.2.3 VLF Interpretation for profile 3

At profile 3 both the unfiltered in-phase plot (Figure 4.5a), filtered in-phase plot (Figure 4.5b) and the current density pseudo section (Figure 4.5c) for profile 3 respectively. From profile 3, with traverse oriented in the E-W direction, two positive responses were identified at a profile distance of 25-130 m and 280-320 m respectively

(Figure 4.5b). Also, a prominent negative response was observed at a profile distance of 140-270 m (Figure 4.5c). The positive responses result into fractured zones, which corresponds to high conductive zones on the current density pseudo section at depths extending from 20-60 m and oriented at NW-SE direction (Figure 4.5c). On the other hand, the negative response results into a non-fractured zone, which corresponds to a low conductive (resistive) zone on the current density pseudo section at depths extending from 20-80 m and oriented at NE direction.

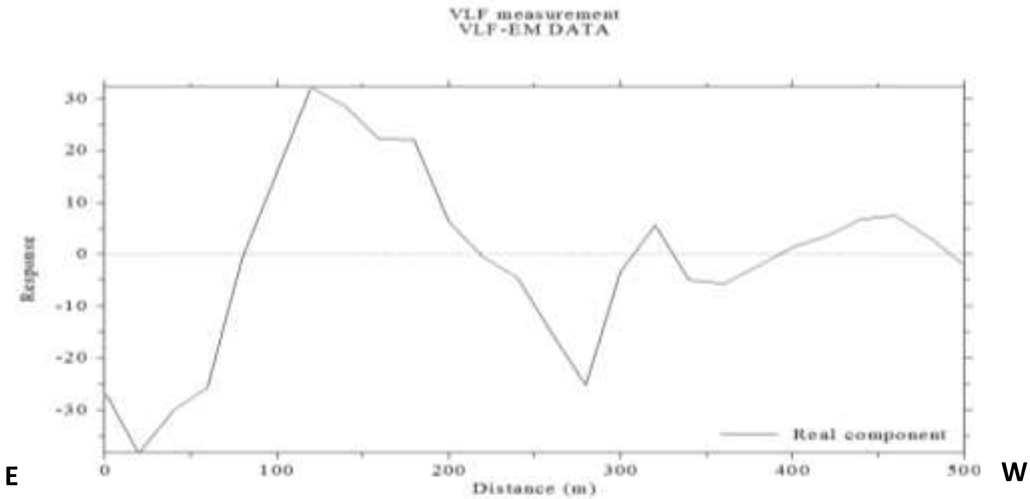

Figure 4.4a**:** Plot of unfiltered (raw) in-phase data against distance at profile 3

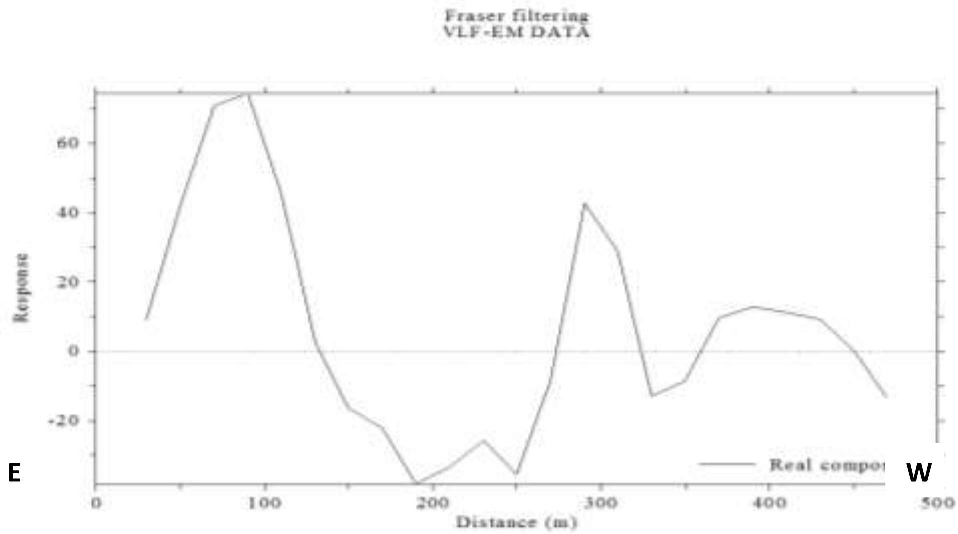

Figure 4.4b**:** Plot of filtered in-phase data against distance at profile 3

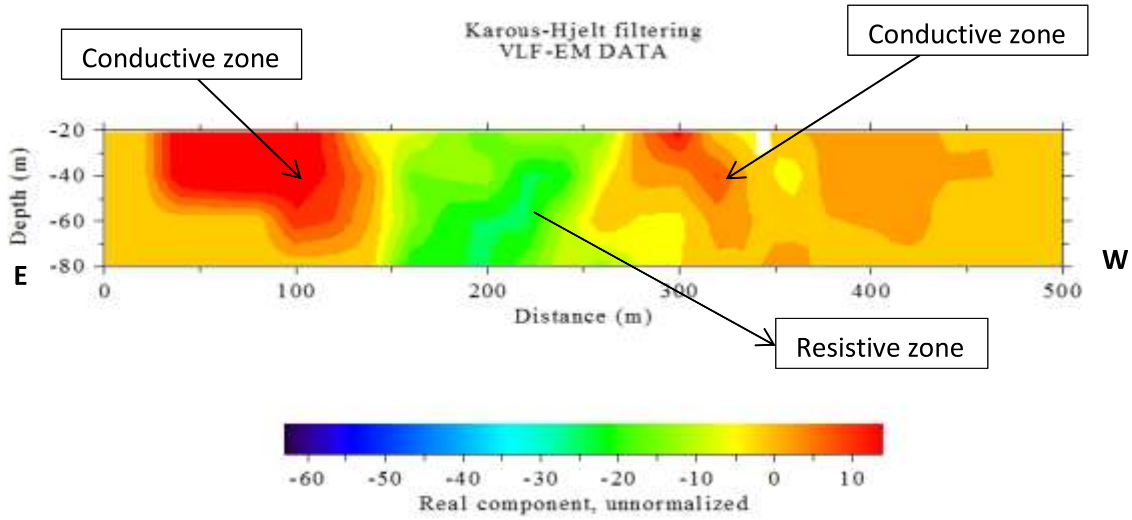

Figure 4.4c**:** Current density pseudo section of in-phase data against distance at profile 3

4.2.4 VLF Interpretation for profile 4

The raw VLF data Figure 4.6a and filtered VLF data (Figure 4.6b) collected along profile 4 were plotted. From Profile 4 oriented in the W-E direction, there exist two prominent positive responses identified at a profile distance of 80-130 m and 340-420 m respectively (Figure 4.6b). Similarly, a prominent negative response was identified at a profile distance of 280-340 m (Figure 4.6b). The positive response results into fractured zones which correspond to high conductive zones on the current density pseudo section at a depth extending from 20-80 m and oriented at NS and SE direction respectively (Figure 4.6c). The negative response which results into a non-fractured (resistive zone) corresponded with a low conductive zone on the current density pseudo section with depth extending from 20-80 m and oriented at NE-SW direction.

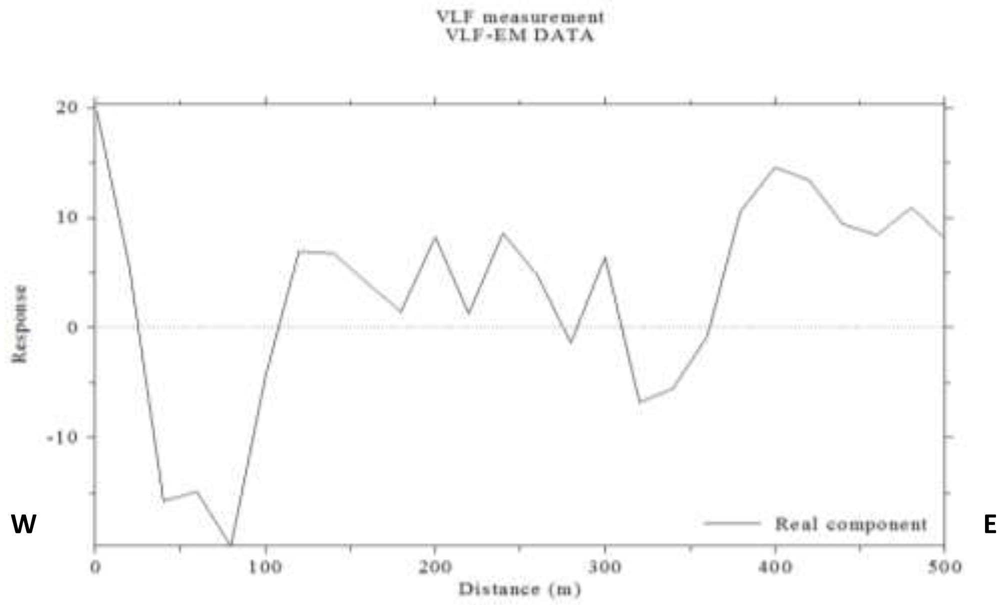

Figure 4.5a**:** Plot of unfiltered (raw) in-phase data against distance at profile 4

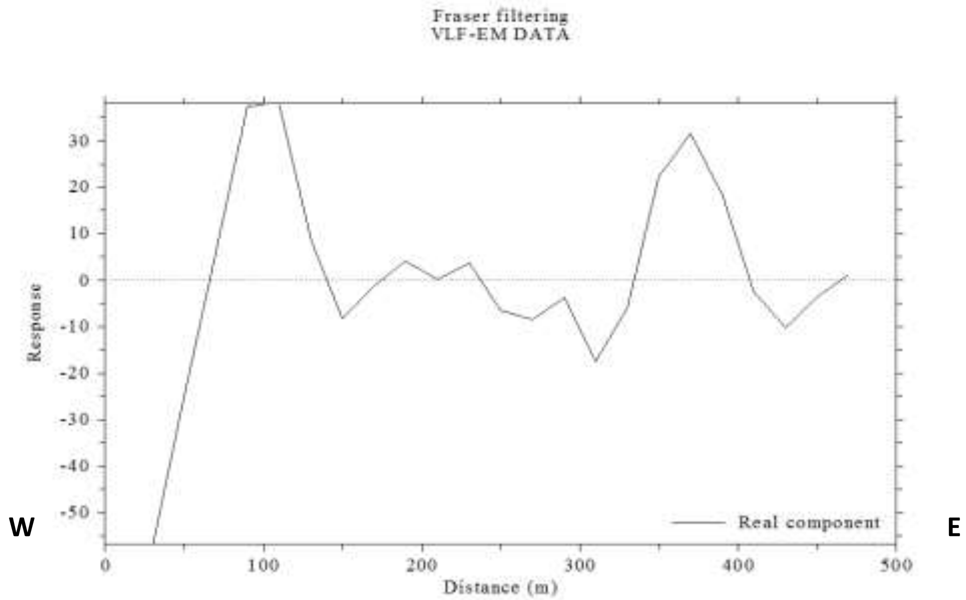

Figure 4.5b**:** Plot of filtered in-phase data against distance at profile 4

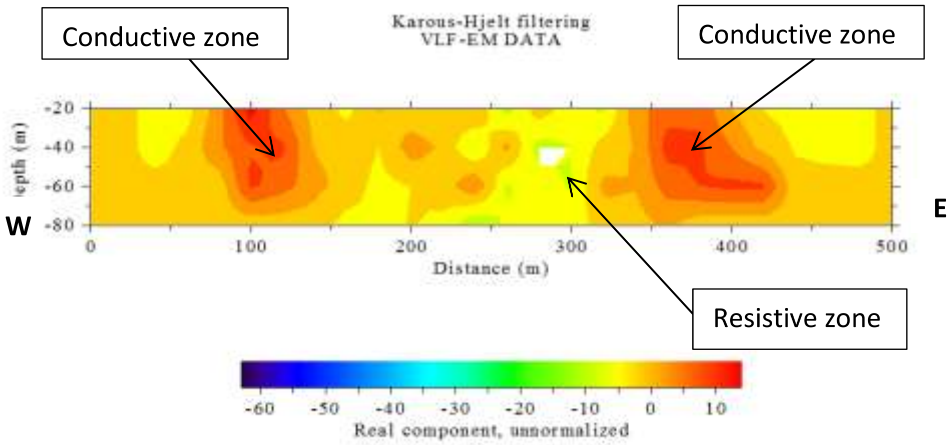

Figure 4.5c**:** Current density pseudo section of in-phase data against distance at profile 4

4.2.5 VLF Interpretation for profile 5

At profile 5, Figure 4.7a represents the unfiltered in-phase plot, Figure 4.7b represents filtered in-phase plot and Figure 4.7c shows the current density pseudo section. At Profile 5 oriented E-W direction, one very prominent positive response and one fairly prominent response was identified at profile distances of 90-120 m and 160-350 m respectively. Similarly, two prominent negative responses were identified, both at profile distances of 50-80 m and 130-250 m respectively (Figure 4.7b). Both the positive and negative responses of Figure 4.7b corresponds to the current density pseudo section (Figure 4.7c). The positive response results into a fractured zone which corresponds to high conductivity on the current density pseudo section both at depths extending from 20-40 m and 20-80 m oriented at NS and NE-SW respectively (Figure 4.7c). The negative response results into a non-fractured zone which corresponds to low conductivity (resistive zone) on the current density pseudo section, both at depths extending from 20-40 m and 20-80 m oriented at NS direction respectively.

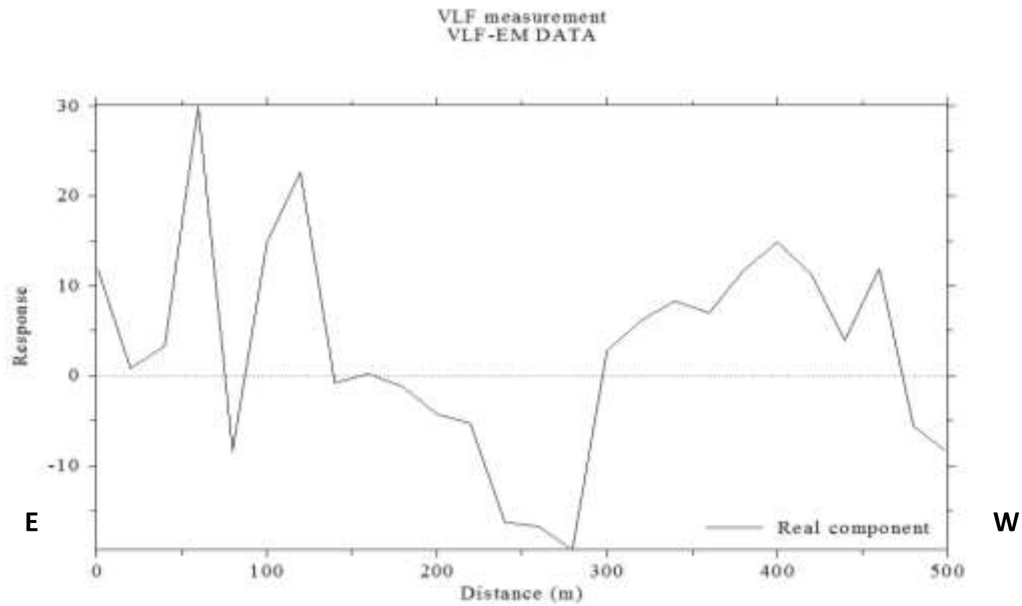

Figure 4.6a**:** Plot of unfiltered (raw) in-phase data against distance at profile 5

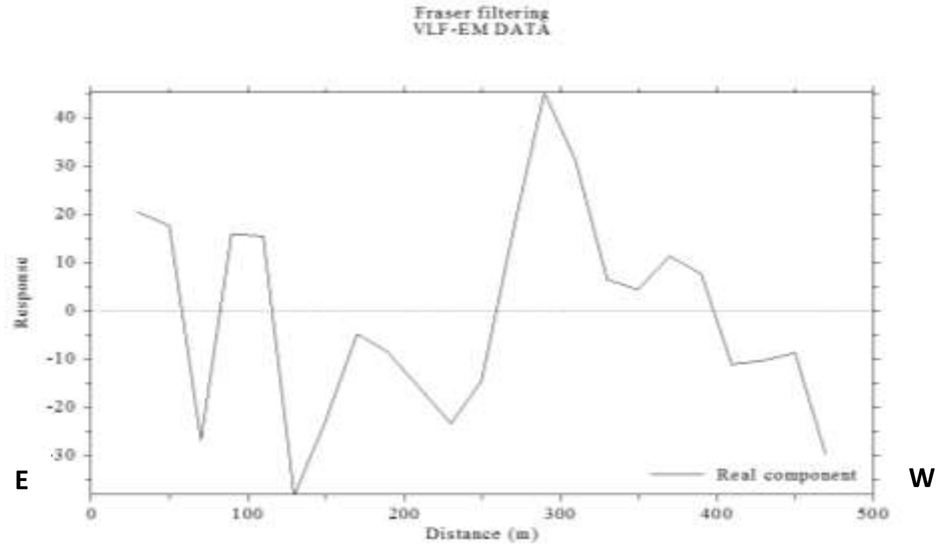

Figure 4.6b**:** Plot of filtered in-phase data against distance at profile 5

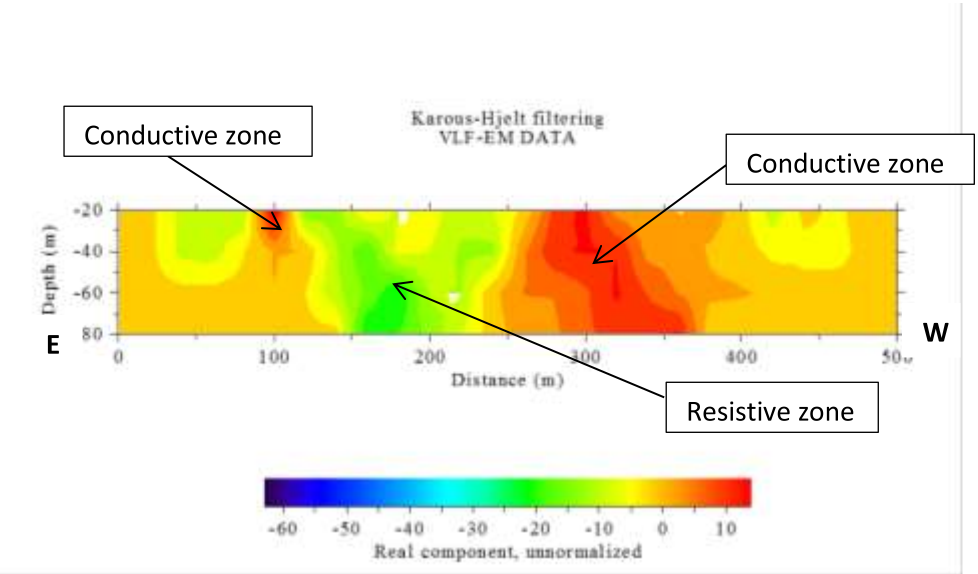

Figure 4.6c**:** Current density pseudo section of in-phase data against distance at profile 5

4.2.6 VLF Interpretation for profile 6

Figure 4.8a and 4.8b show a plot of both the unfiltered in-phase plot and filtered in-phase plot respectively against distance along profile 6. From Profile 6 oriented in the W-E direction, two prominent positive responses were identified at profile distances of 100-150 m and 350-400 m respectively. Similarly, one prominent negative response was identified at profile distance of 280-350m (Figure 4.8b). Both the positive and negative responses conform to the current density pseudo section (Figure 4.8c). The positive responses result into probable fractured zone which corresponds to high conductivity on the current density pseudo section (Figure 4.8b), both depths extending from 20-70 m and 20-75 m oriented at NW-NE and NW-SE direction respectively (Figure 4.8b). The negative response result into probable non-fractured zone which corresponds to low conductivity (resistive zone) on the current density pseudo section with depths extending from 20-80 m oriented in NE-SW direction.

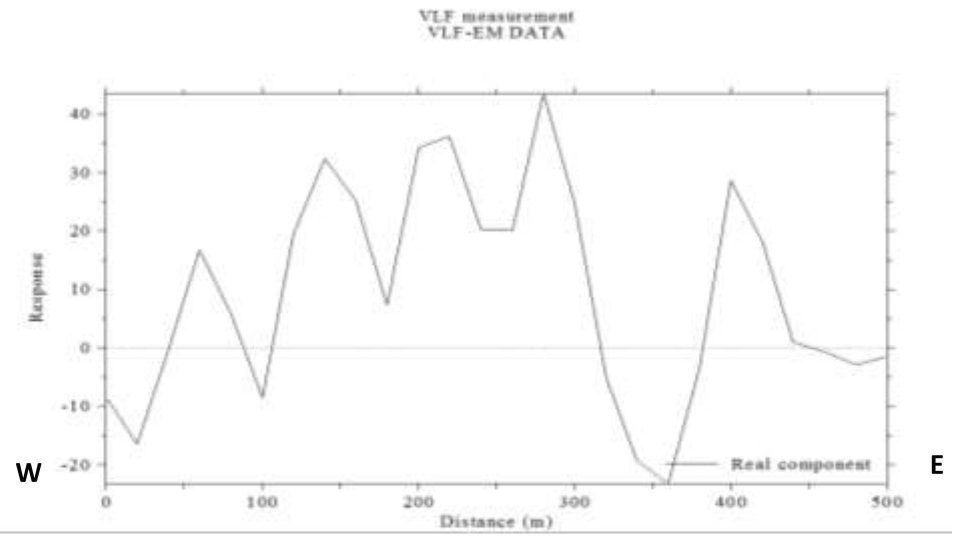

Figure 4.7a**:** Plot of unfiltered (raw) in-phase data against distance at profile 6

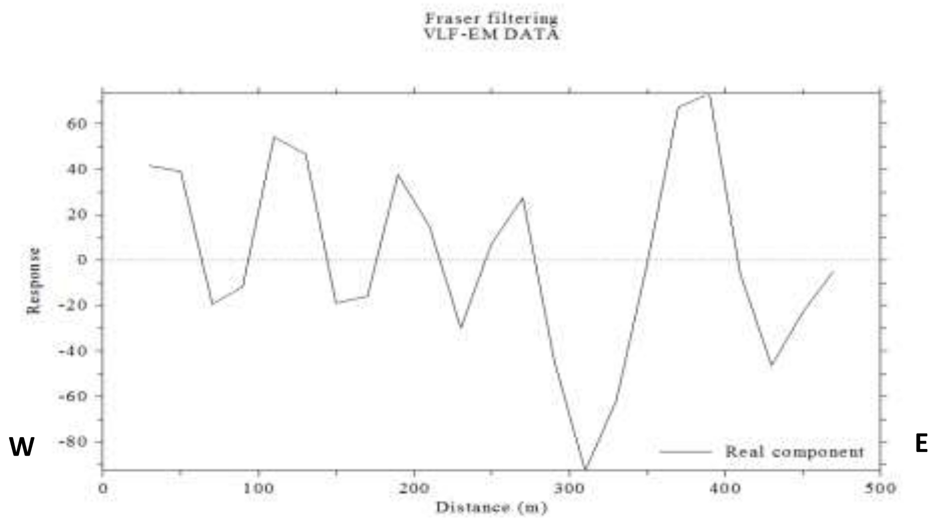

Figure 4.7b**:** Plot of filtered in-phase data against distance at profile 6

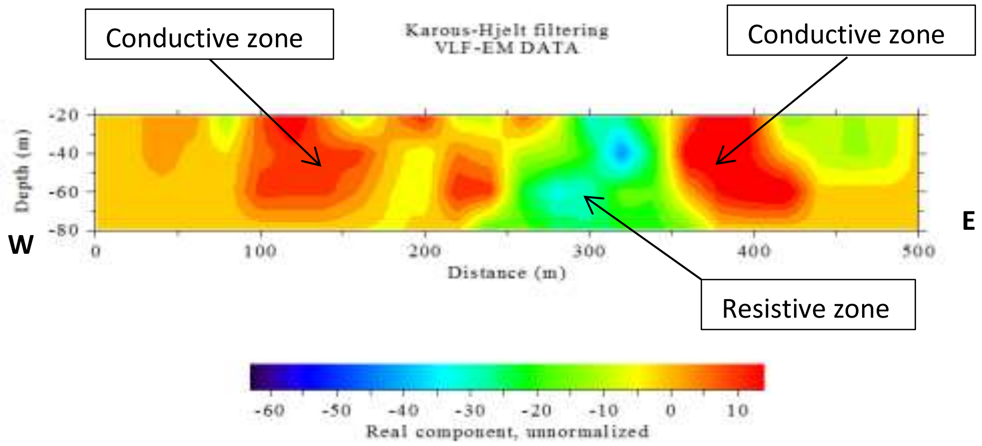

Figure 4.7c**:** Current density pseudo section of in-phase data against distance at profile 6

4.3 Electrical Resistivity (2D) Pseudo sections

The electrical resistivity (2D) pseudo sections shall be discussed for each single profile under this section.

4.3.1 2D Resistivity pseudo section interpretation for profile 1

The measured apparent resistivity pseudosection and the calculated apparent resistivity pseudosection appear to be similar along a distance of around 60-70m (Figure 4.9).

The inverted model resistivity section gives a better resolution. From the inverted model resistivity section for profile 1; it shows intermediate resistivity value range of 14 Ωm to 51 Ωm from the surface of the profile line to the depth of about 4 m. The profile is characterised by a high resistive zone with resistivity range of 98 Ωm to over 200 Ωm from the depth of 4 m to 16 m at the profile surface length of 10m to 60m. The high resistivity zone might be attributed to the presence of quartzite which serves as a potential host of some potential minerals in a basement terrain. On the profile length of 65 m to 75 m there exists a major fracture which seems to be saturated with water indicating a resistivity range of 2 Ωm to 8 Ωm, this might also be indicative of potential mineral zone as most potential minerals in the basement terrain are associated with fractured and weathered zone. The section show that depth of anomalies generally begins from a few meters and continues to more than

15 m.

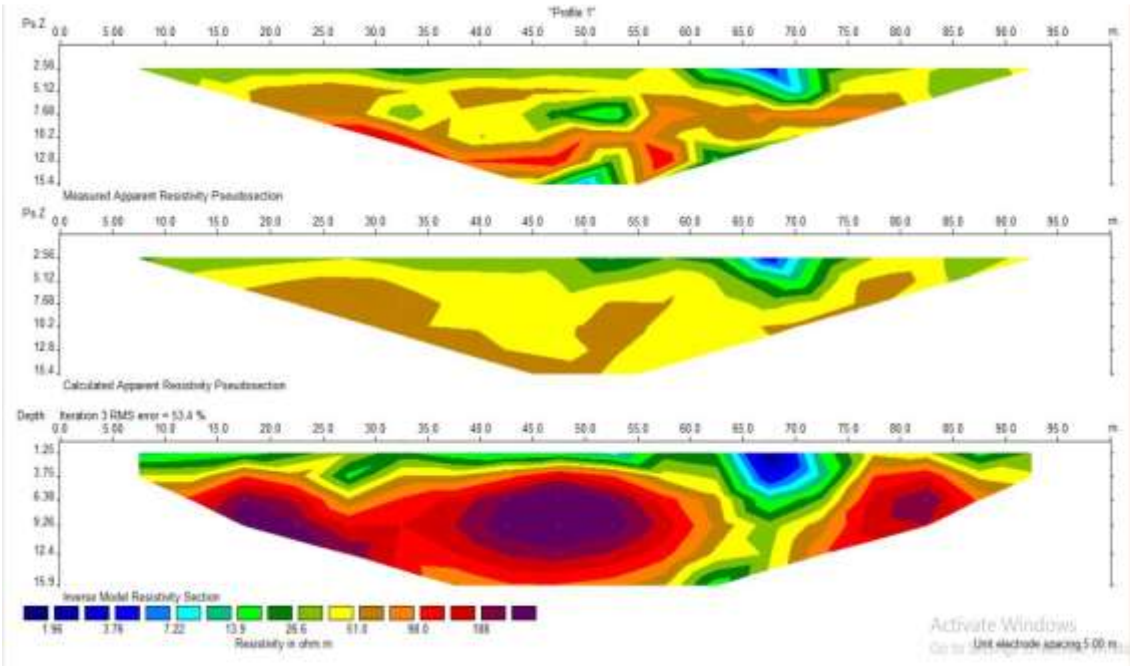

Figure 4.8: 2D Section along Profile 1

4.3.2 2D Resistivity pseudo section interpretation for profile 2

Along a distance range of about 10-45 m, the measured aparent resistivity and calculated apparent resistivity pseudosection show some similarity (Figure 4.10). From the inverted model resistivity section for profile 2 (Figure 4.10), A region with low resistivities, corresponding to clay and saturated regolith, is visible in the near surface portion of the section with depth reaching about 5m on the profile line from 10 m to 50 m. On the profile line distance of 55 m to 90 m the depth of the low resistivity materials extent to the depth of about 10m. A high resistive bottom layer at the profile distance of 10 m to 55 m is evident , with resistivity range of 838 Ωm to over 4000 Ωm typical of basement rock characterised by quarzite. This area serves as a potential mineralised zone as indicated on the inverse model. An intermediate zone between the clay and saturated regolith and the quarzite has resistivities of 150 Ωm to 355 Ωm indicative of highly weathered zone which has the potentials to host economic minerals.

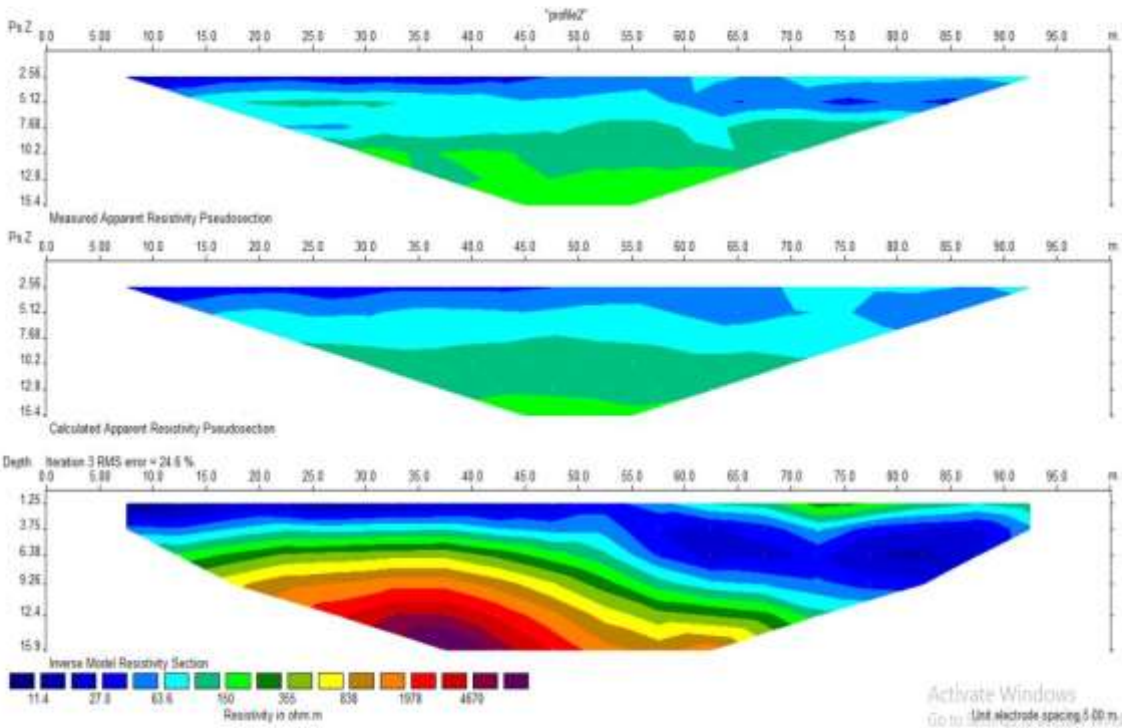

Figure 4.9: 2D Section along Profile 2

4.3.3 2D Resistivity pseudo section interpretation for profile 3

Figure 4.11 represents the measured apparent resistivity pseudosection, calculated pseudosection and inverted model resistivity section for profile 3. In order to determine the anomalous zone, the profile 3 was almost perpendicular to the main principle joint direction of the study area as indicated on the geological rosette diagram.

From the inverse model resistivity pseudosection, the direction of expecting anomaly is simply visible in 2D resistivity section of profile 3 (Figure 4.11) at the bottom part from 9 m to about 16 m. High presence of potential mineralisation zones are indicated in high electrical resistance quarzitic rocks as indicated on the inverse resistivity model.

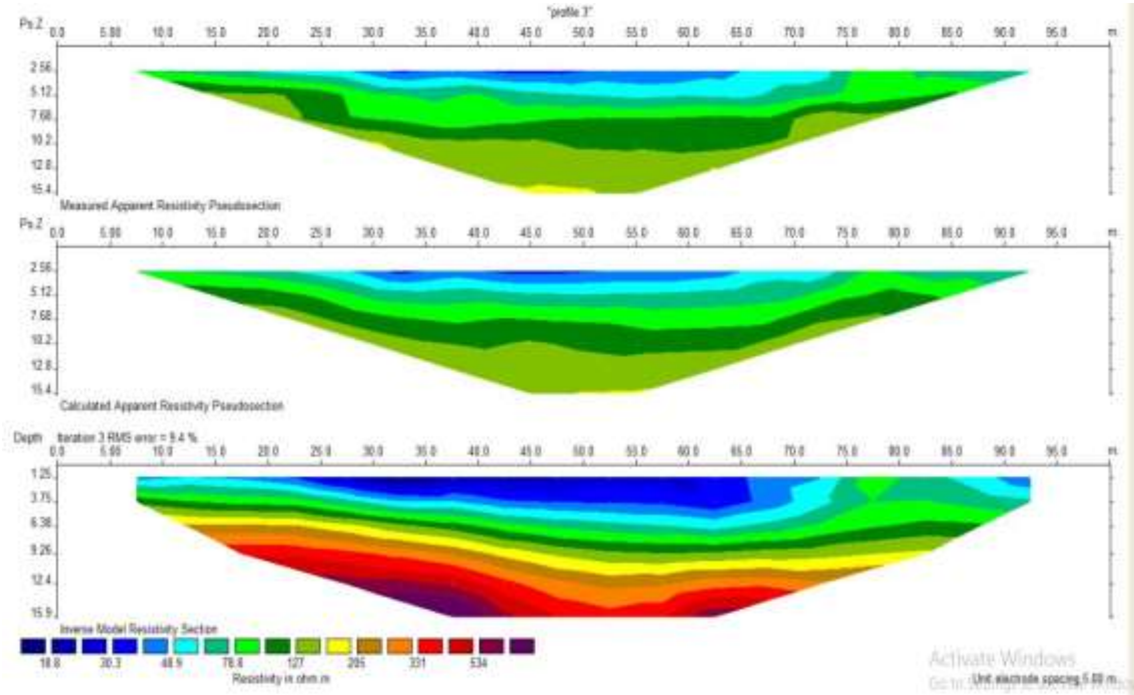

Figure 4.10: 2D Section along Profile 3

4.3.4 2D Resistivity pseudo section interpretation for profile 4

Along distance of about 10-40 m, 60-65 and 85-90, the measured apparent resistivity pseudosection and calculated apparent resistivity pseudosection show a very low resistivity value (Figure 4.12). From the inverted model resistivity section for profile 4 (Figure 4.12), there exist a low resistivity region (corresponding to clay and regolith), which is visible at the near surface with a depth to about 6 m on the profile line from 10 m to 90 m and an intermediate resistivity values from 16 Ωm to 70 Ωm (Figure 4.12). A high resistive bottom layer is observed on the profile at a distance of 15 m to 55 m, with resistivity range of 140 Ωm to over 2600 Ωm typical of basement rock characterised by quarzite. This elevation in resistivity is indicative of an anomalous zone (host rock for potential mineralisation) which could be a quartz vein for gold mineralisation.

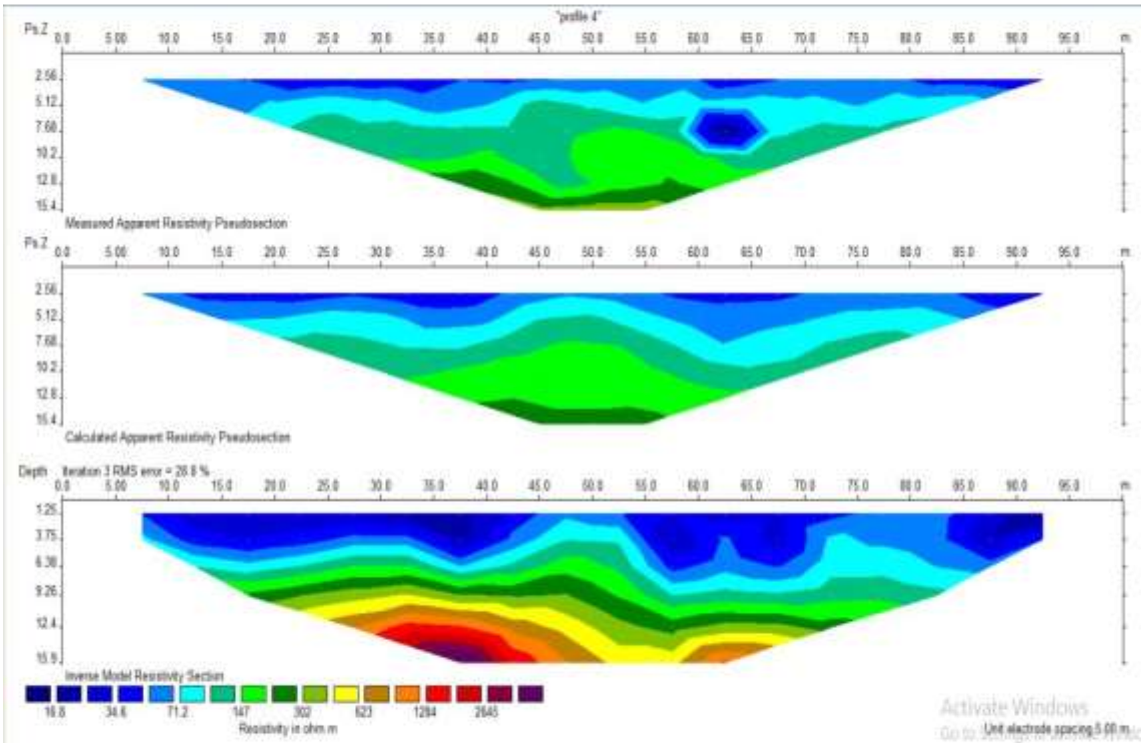

Figure 4.11: 2D Section along Profile 4

4.3.5 2D Resistivity pseudo section interpretation for profile 5

From Figure 4.13, the measured apparent resistivity pseudosection and calculated apparent resistivity pseudosection along a distance of around 20-25 m and above 85 m show a low resistivity value. Figure 4.13 is the inverted model resistivity section for profile 5. A lateral effect caused by the strong variation in surface resistivity is visible in the inverse model resistivity section of profile 5 (Figure 4.13). There is no clear evident resistivity difference between the geological materials underlying the profile line. At 60 m to 85 m of the profile, there exist a highly resistive zone at the shallow depth of less than 3m indicative of a highly resistive basement rock. The incoherent subsurface section as indicated in the profile might be attributed to the high degree of fracturing which may be due to the heterogenous nature of anomalous zone of mineralisation along the profile.

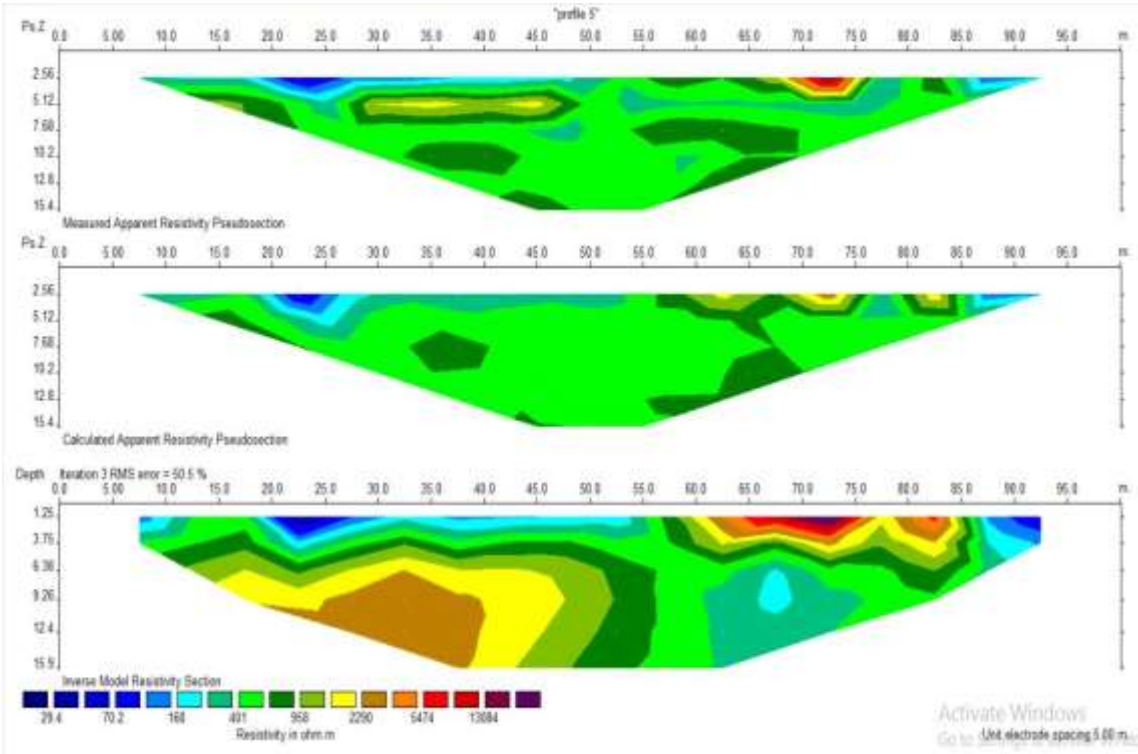

Figure 4.12: 2D Section along Profile 5

4.3.6 2D Resistivity pseudo section interpretation for profile 6

Along a distance of around 10-15 m a low resistivity value is observed from the measured resistivity and calculated resistivity pseudosection (Figure 4.14). From the inverted model resistivity section for profile 6 (Figure 4.14), a low resistivity region is observed from 10 m to 15m and also from 50 m to 90 m along the profile line on the near surface at a depth of around 3m (Figure 4.14). Also, a high resistive bottom layer at the profile distance of 35 m to 85 m is evident , with resistivity range of 683 Ωm to over 4500 Ωm typical of basement rock characterised by quarzite. This area will serve as a potential zone for mineralisation. An intermediate zone with resistivity values of 190 Ωm to 360 Ωm indicative of highly weathered zone which has the potentials to host economic minerals.

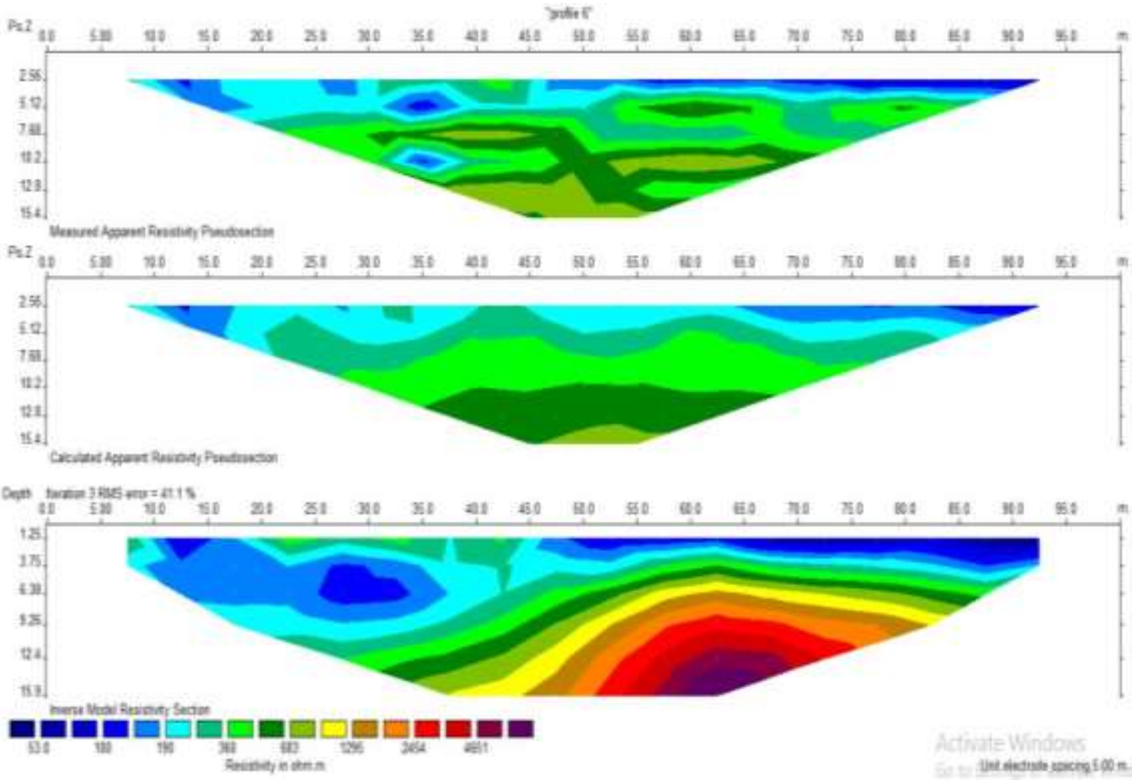

Figure 4.13: 2D Section along Profile 6

4.4 CORRELATION OF VLF PSEUDOSECTION AND GEOLECTRIC PSEUDOSECTION

4.4.1a Stacking of VLF Pseudosection and geoelectric pseudosection for profile 1

Figure 4.15 represents the stacking of both the geoelectric pseudosection and the current density pseudosection of VLF. The 2D electrical resistivity survey was taken from profile length of 200-300 m (a 100 m spread). This result show a clear correlation between both methods. A high resistivity equals a low conductivity and vice-versa. This agrees quite well. As it is conformed from the result that a resistive zone on the geolectric pseudosection conforms to a low conductive zone on the VLF pseudosection. This elevated (high) resistive zone could be a quartz veining structure which serves as a host rock for mineral such as gold.

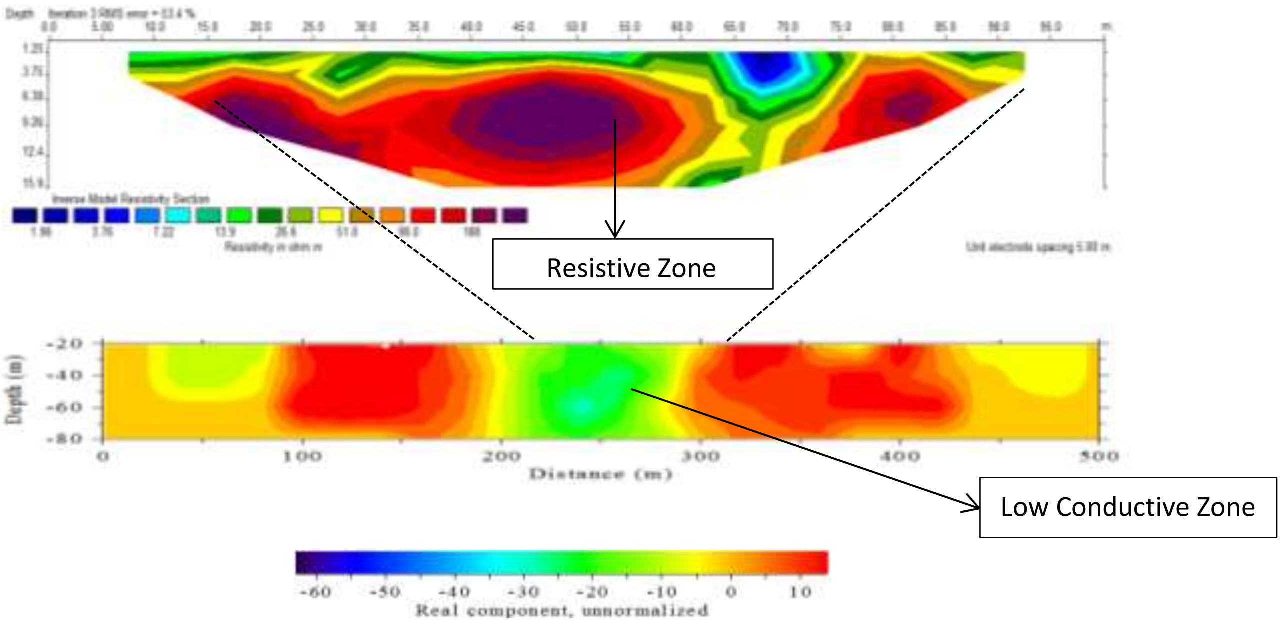

Figure 4.14: Correlation of VLF pseudosection and geolectric pseudosection for profile 1

4.4.1b Stacking of VLF pseudosection and geoelectric pseudosection for profile 2

Figure 4.16 represents the stacking of both the geoelectric pseudosection and the current density pseudosection of VLF. Both results show some degree of correlation. The variation in shape from the geolectric pseudosection is due to heterogeneous nature of mineralization within the study area at different depths. The mineralization within zones of elevated (high) resistivity on the geoelectric pseudosection and low conductivity on the VLF pseudosection comprises of quartz veining structures. High resistivity anomalies at depth greater than five meters, (5 m) are related to the mineralization of gold bearing quartz veins (Nasir *et al*., 2018).

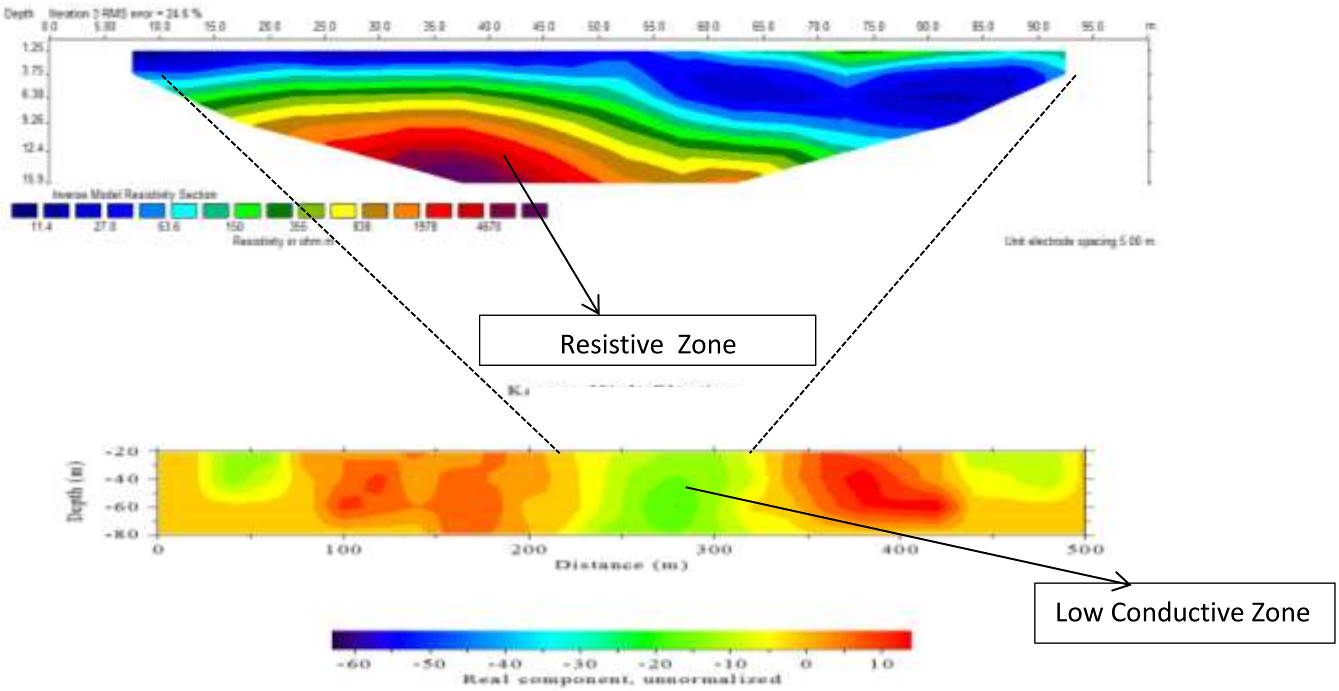

Figure 4.15: Correlation of VLF pseudosection and geolectric pseudosection for Profile 2

4.4.1c Stacking of VLF pseudosection and geoelectric pseudosection for profile 3

Figure 4.17 represents the stacking of both the geoelectric pseudosection and the current density pseudosection of VLF. Both results show some degree of correlation. The mineralization within zones of elevated (high) resistivity on the geoelectric pseudosection and low conductivity on the VLF pseudosection comprises of quartz veining structures. high resistivity anomalies at depth greater than five meters, (5 m) are related to the mineralization of gold bearing quartz veins (Nasir et al., 2018). In this case, the resistivity anomaly extends to a depth of 15.9 m, this shows a good potential zone for gold mineralisation.

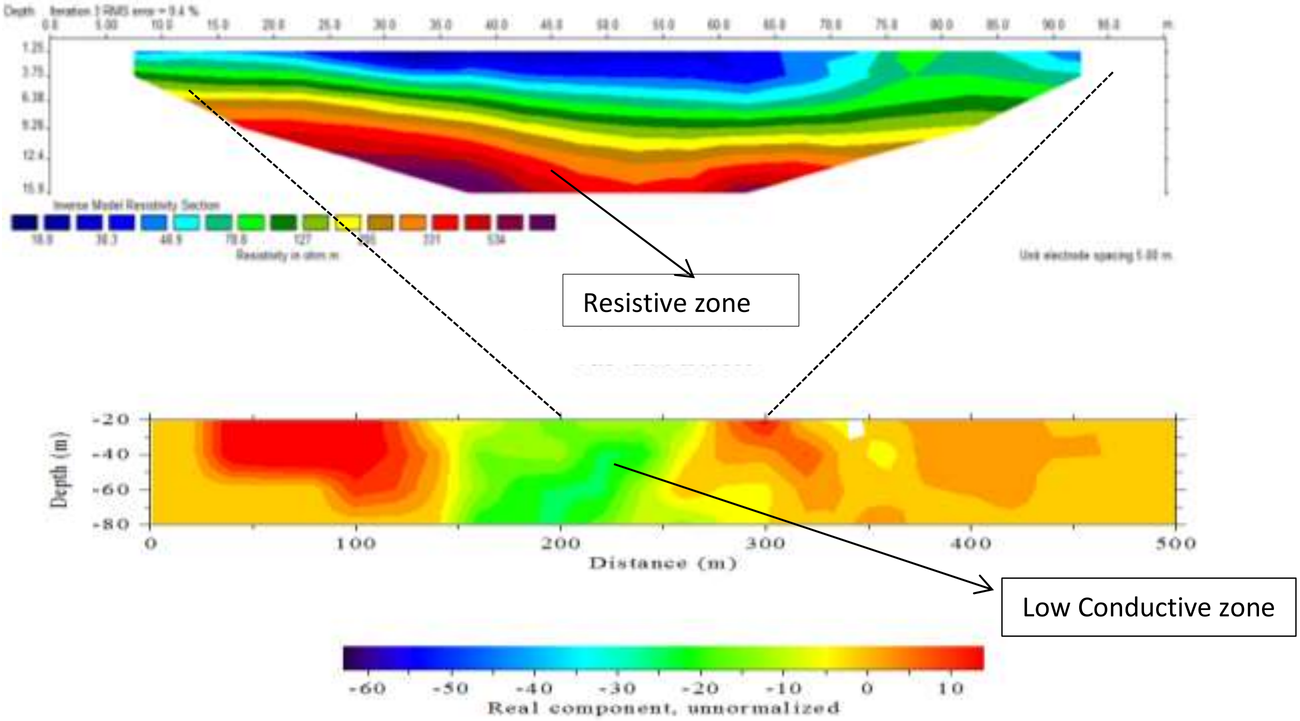

Figure 4.16: Correlation of VLF pseudosection and geolectric pseudosection for Profile 3

4.4.1d Stacking of VLF pseudosection and geoelectric pseudosection for profile 4

Figure 4.18 represents the stacking of both the geoelectric pseudosection and the current density pseudosection of VLF. Both results show some degree of correlation. Although the the anomally detected by the VLF could not properly delineate much structure (low resolution). The mineralization within zones of elevated (high) resistivity on the geoelectric pseudosection and low conductivity on the VLF pseudosection could suggest a quartz vein.

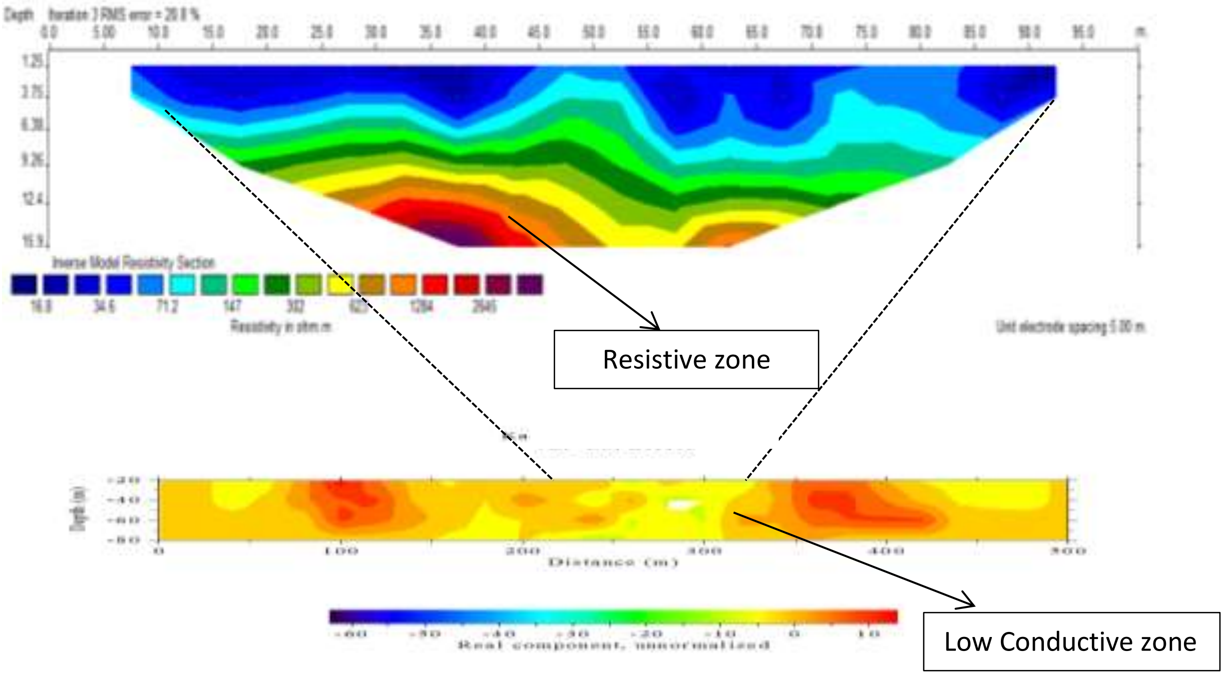

Figure 4.17: Correlation of VLF pseudosection and geolectric pseudosection for Profile 4

4.4.1e Stacking of VLF pseudosection and geoelectric pseudosection for profile 5

Figure 4.19 represents the stacking of both the geoelectric pseudosection and the current density pseudosection of VLF. Both results show some degree of correlation. There exist a contact point on the current density pseudosection along a profile length of around 240 m, which also corresponds on the geolelectric pseudosection. Many quartz veins and other hard rock gold deposits occur in zones along faults or at the contact of two different types or rock (Kankara and Darma, 2016). This shows that a high mineralisation acivitity occurs in the on this profile. The mineralization within zones of high resistivity on the geoelectric pseudosection and low conductivity on the VLF pseudosection could infer quartz veining structures. High resistivity anomalies at depth greater than five meters, (5 m) are related to the mineralization of gold bearing quartz veins (Nasir *et al*., 2018).

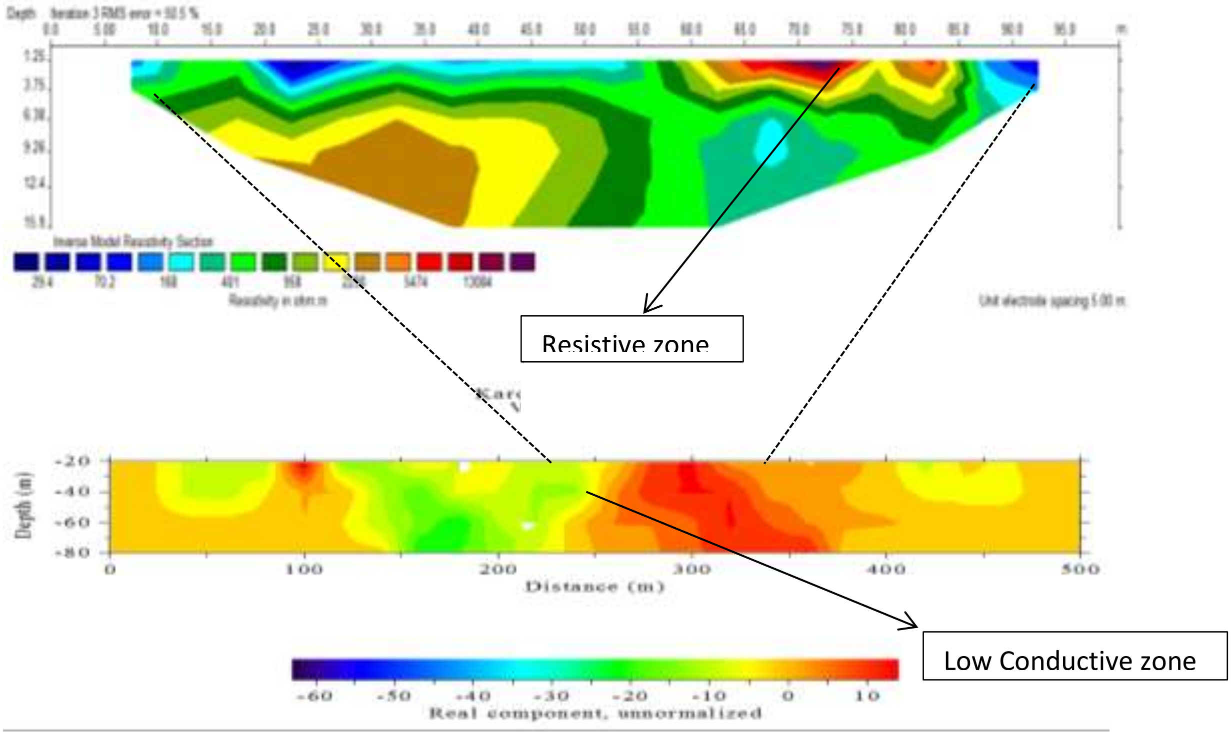

Figure 4.18: Correlation of VLF pseudosection and geolectric pseudosection for Profile 5

4.4.1f Stacking of VLF pseudosection and geoelectric pseudosection for profile 6

Figure 4.20 represents the stacking of both the geoelectric pseudosection and the current density pseudosection of VLF. Both results show some degree of correlation. The resistive zones on the geoelectric pseudosection corresponds to a low conductive zone on the current density pseudosection of the VLF. The mineralization within zones of high resistivity on the geoelectric pseudosection and low conductivity on the VLF pseudosection could infer quartz veining structures.

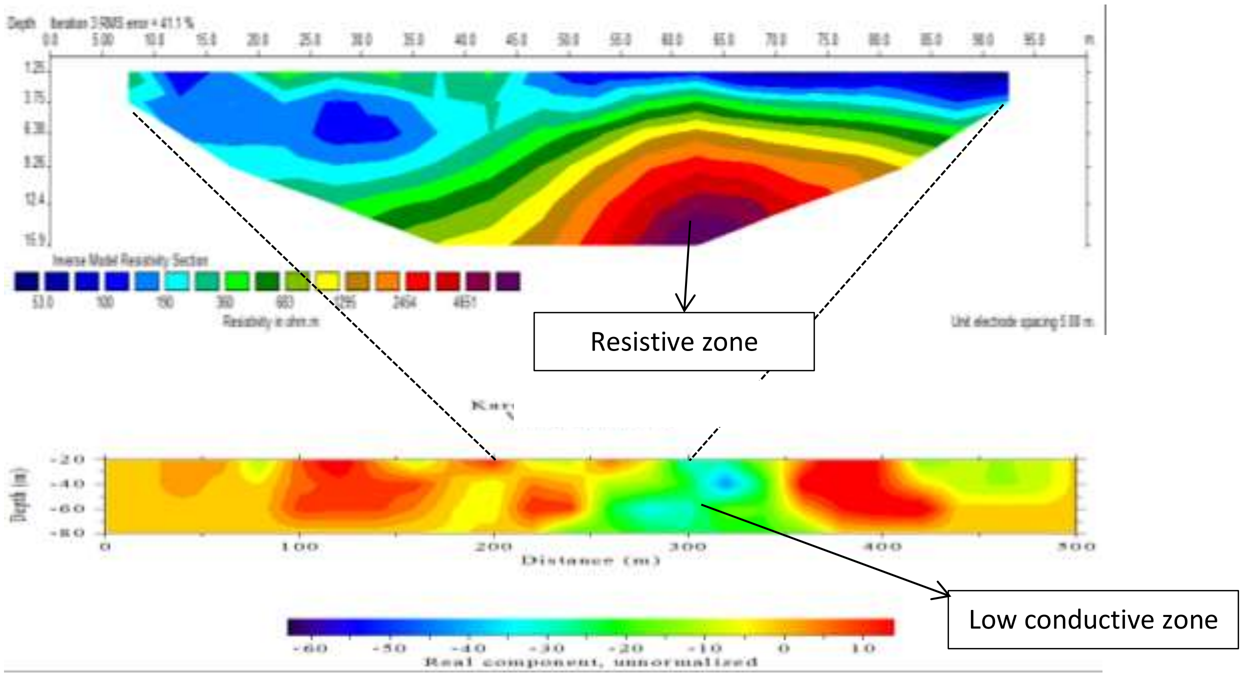

Figure 4.19: Correlation of VLF pseudosection and geolectric pseudosection for Profile 6

4.5 CONDUCTIVITY DISTRIBUTION OF THE STUDY AREA

Figure 4.2 depicts the conductivity distribution in the study area, with the deep blue representing a very low conductivity (or high resistivity) value, while the pink colouration represents high conductivity (low resistivity) value. The conductivity value ranges from a value of -100 to 74.9 Ω-1m-1. From the conductivity distribution map, we could observe some structural intrusion and discontinuities.

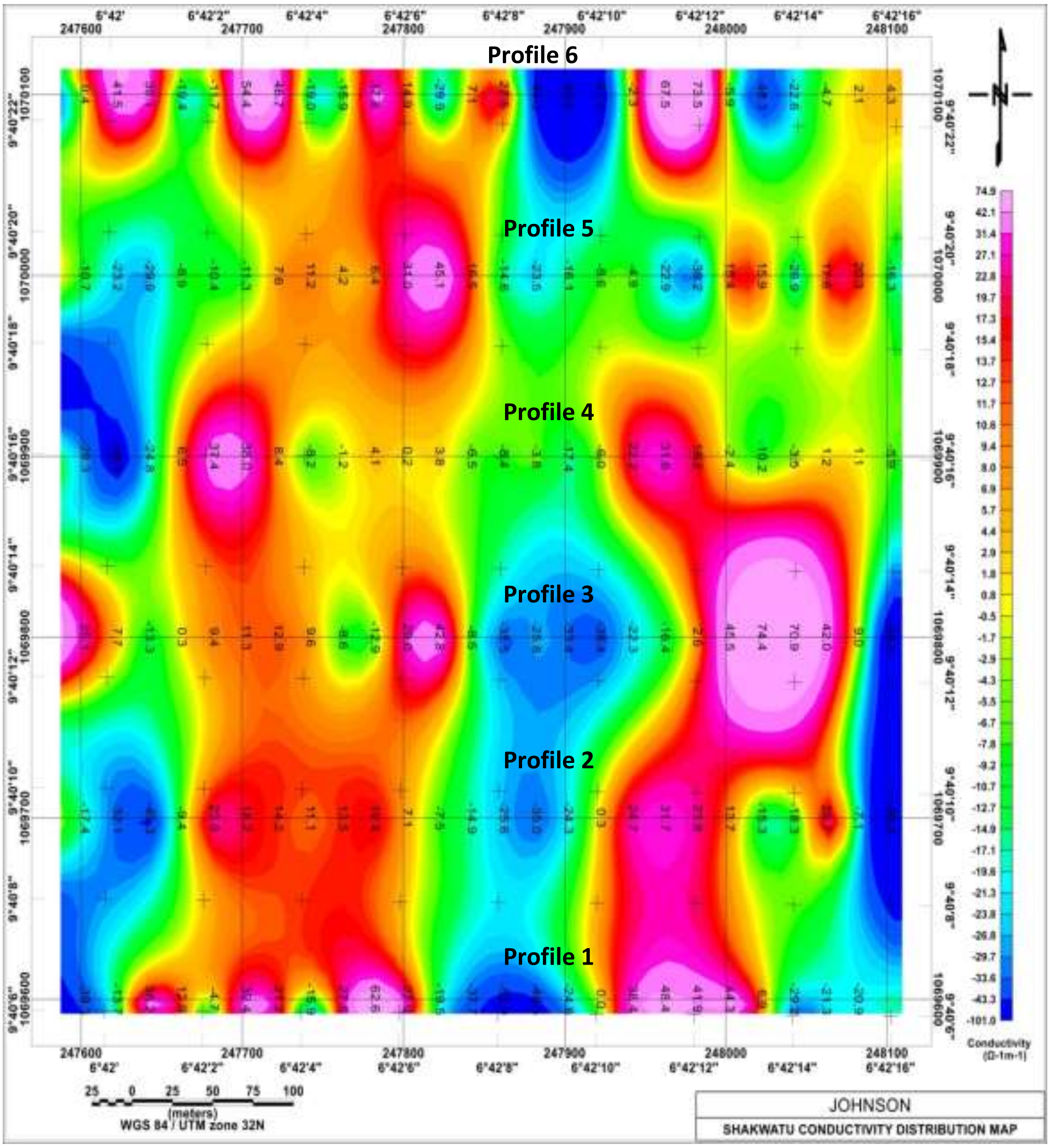

Figure 4.20: Conductivity map of the study area

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A geophysical investigation was carried out in Shakwatu town of Niger State to delineate potential gold mineralisation zones in the area. Electromagnetic (Very Low Frequency-VLF) and electrical resistivity (2D) were employed in this study.

From the structural trend analysis, the principal joint orientation was found to be in the NE and SW direction. It therefore means that the structures in the study are in line with the principal joint direction. Hence, mineralisation in the area is structurally controlled.

The conductivity map of the study area shows regions of both high and low conductivity with value ranging from -100 to 74.9 $\Omega^{-1}m^{-1}$ and the structure trending along NE-SW direction. The high conductive zones could be as a result of fracture we can serve as a potential for either water or mineral exploration.

The high VLF anomalies delineated from Shakwatu area, in Niger State yielded a high conductivity contrast. This elevated conductivity contrast may be as a result of fracture well-suited for potential mineralization and the geologic information of the area. Similarly, regions with very low conductivity results from basement rock (quartzite), this could also serve as potential mineralisation zones. This hold to the fact that a quartz veining structure shows very low conductivity contrast.

The 2D sections of the VLF identified some regions of low and high current density values, with high values delineating regions of relatively high conductivity that could be attributed to occurrence of fractured zones, with profiles 1- 6 showing very visible contrast with relative high current density values. The fractured zones are normally zones of high conductivity due to their ability to host water or metallic deposits (Osinowo and Falufosi, 2018).

On the other hand, the region with low current density values could indicate resistive zones within the basement rocks having little or no fractures. This resistive zones is visible on Profiles 1, 2, 3, 5, and 6 and exists between two rocks of varying conductivity. This low conductive (elevated resistivity) zones be a quartz vein owing to their high resistivity signature. One among many of the geologic features has it that many quartz veins and other hard rock gold deposits occur in zones along faults or at the contact of two different rock types (Kankara and Darma, 2016).

In conclusion, VLF-EM data revealed a number of subsurface zones with high real component current density which define the potential subsurface structural features (fractures/ faults zones) with possible gold mineralization. These zones were interpreted as the potential or inferred structurally controlled fracture zones with possible gold mineralization.

On the other hand, results from the geoelectric imaging models reveal a heterogeneous nature of mineralisation within zone of high resistivity (low conductivity) that may represent gold bearing quartzite vein. Quartz veins signatures are identified by high resistivity (>600 ohm-m) anomalies both at shallow and greater depths (Nasir et al., 2018). These high resistive zones will serve as target zones for further mineral exploration for gold.

Results from both VLF and geoelectric survey carried out in the study area shows some degree of correlation, which makes the area suitable for further geophysical exploration activities.

5.1 Recommendations

Based on the above conclusion, the following recommendations have been put forward:

(i) A detailed geochemical surveys should be carried out, in order to identify possible targets and geochemical patterns associated with the mineralised zones, body model and resource estimation.

(ii) A follow up geophysical method such as IP (Induced Polarisation) method could also be employed in order to determine the spatial variation in lithology and grain surface chemistry.

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APPENDIX

S/No.	Joint Angles (in degrees)
1.	340
2.	42
3.	40
4.	26
5.	286
6.	26
7.	110
8.	29
9.	356
10.	10
11.	354
12.	356
13.	200
14.	340
15.	180
16.	358
17.	10
18.	372
19.	350
20.	228
21.	260
22.	356
23.	292

24.	180
25.	212
26.	358
27.	280
28.	180
29.	340
30.	18
31.	350
32.	180
33.	20
34.	180
35.	08
36.	352
37.	276
38.	66
39.	350
40.	10
41.	348
42.	08
43.	344
44.	180
45.	340
46.	20
47.	348
48.	330

49.	54
50.	328
51.	340
52.	30
53.	210
54.	328
55.	346
56.	330
57.	66
58.	136
59.	334
60.	52
61.	172
62.	340
63.	180
64.	308
65.	270
66.	352
67.	58
68.	344
69.	20
70.	76
71.	80
72.	114
73.	150

74.	200
75.	300
76.	180
77.	320
78.	240
79.	28
80.	320
81.	72
82.	26
83.	130
84.	234
85.	02
86.	72
87.	68
88.	88
89.	20
90.	192
91.	44
92.	326
93.	352
94.	324
95.	332
96.	292
97.	110
98.	272

99.	346
100.	38
101.	258
102.	20
103.	56
104.	348
105.	06
106.	04
107.	20
108.	356
109.	200
110.	60
112.	350
113.	312
114.	302
115.	280
116.	230

Table 1.0: Joint angles of various outcrops in the study area