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INTEGRATED GEOPHYSICAL INVESTIGATIONS AT SODERE THERMAL SPRINGS, MAIN ETHIOPIAN RIFT

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GEOPHYSICAL INVESTIGATION TO CHARACTERIZE THE GEOTHERMAL RESOURCES OF SODERE THERMAL SPRINGS, MAIN ETHIOPIAN RIFT.

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Declaration

I, the undersigned, declare that this thesis is my original Work, has not been presented for degrees in any other University and all Sources of material used for thesis have been duly acknowledged.

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Dr. Tigistu Haile.

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ABSTRACT

In this thesis work two integrated geophysical surveys namely magnetic and electrical resistivity sounding have been carried out over the Sodere thermal springs area. The area is located within the Main Ethiopian Rift (MER), close to Nazareth town and is accessible on an all weather asphalt road on a detour from Nazareth-Assela main road. The Sodere thermal waters are one of the famous and relatively well-utilized centers in the country, which is being used for both recreational and healing purposes.

Total magnetic field surveys at station spacing of 25 m well distributed and covering the thermal area were carried out. About 300 magnetic data points were obtained. Further, a total of ten VES stations, distributed to lie on three convenient traverses were measured using the Schlumberger symmetrical array. Maximum current electrode separation (AB/2) of up to 500m was used for the sounding survey. The results of the magnetic survey were presented in terms of profile plots and also contour maps which were later continued upward to remove near surface effects. The resistivity survey data were used to construct apparent resistivity pseudosections and the data were further interpreted and plotted to obtain geoelectric sections.

From the magnetic anomaly map of the magnetic survey, the heat source is characterized by the lowest magnetic anomaly response interpreted as resulting from rock units that are forced to lose their magnetization due high temperature. Such areas with low magnetic anomaly and weak zones have been outlined. From the electrical survey, areas of low resistivity (typically $< 20\Omega m$) observed on the pseudo- and geoelectric sections along Profiles-1and -2 are interpreted as hydro thermally altered zone and the overall low resistivity observed along Profile-3 is interpreted as highly water saturated region of the area because of the close proximity of the profile to the Awash river and the absence of structures that act as a barriers for ground water movement.

Based on the analysis of the two geophysical methods and thermal manifestation, the area has geothermal potential for further development from central to northwest of the study area. Considering the limitations in depth of the electrical methods employed, further geophysical investigations are proposed to reinforce tl IV f the study.

CHAPTER ONE

INTRODUCTION

1.1 General Introduction

Geophysical methods play a key role in geothermal exploration since many objectives of geothermal exploration can be achieved by these methods. The geophysical surveys are directed at obtaining indirectly, from the surface or from shallow depth, the physical parameters of the geothermal systems. A geothermal system is made up of four main elements: a heat source, a reservoir, a fluid, which is the carrier that transfers the heat, and a recharge area. The heat source is generally a shallow magmatic body, usually cooling and often still partially molten. The volume of rocks from which heat can be extracted is called the geothermal reservoir, which contains hot fluids, a summary term describing hot water, vapor and gases. Colder rocks that are hydraulically connected with the reservoir usually surround a geothermal reservoir. Hence water may move from colder rocks outside the reservoir (recharge) towards the reservoir, where hot fluids move under the influence of buoyancy forces towards a discharge area.

A geothermal system generally causes in homogeneities in the physical properties of the subsurface, which can be observed to varying degrees as anomalies measurable from the surface. These physical parameters include temperature (thermal survey), electrical conductivity (electrical and electromagnetic methods), elastic properties influencing the propagation velocity of elastic waves (seismic survey), density (gravity survey), and magnetic susceptibility (magnetic survey). Most of these methods can provide valuable information on the shape, size, and depth of the deep geological structures constituting a geothermal reservoir, and sometimes of the heat source.

Detailed geophysical, geological and geochemical studies will be needed in order to identify drilling locations. The objective of the more detailed studies is to identify the existence of a productive reservoir at attractive temperatures and depths. The sequence in which geophysical methods are applied depends to a considerable extent on the specific characteristics of each prospect. It is not wise to define a particular sequence of geophysical surveys as being applicable to all potential reservoirs.

Owing to its location visa-vis the main tectonic activities and well-known plate margins of the world, Ethiopia is endowed with enormous geothermal potential. The Great East Africa Rift system, which practically divides the country into two-thirds and one-thirds on the north western and southern eastern regions respectively, forms a major morphologic feature with several implications from the geothermal resources point of view.

The section of this Rift that passes over Ethiopia is associated with a series of volcano-tectonic episodes and collapse structures that have resulted in the thinning of the crust and the swallowing of the magmatic sources. This in turn gives rise to areas of high thermal gradient and, where subsurface fluids are abundant, to thermal springs of varying discharges and temperatures. Other manifestations of this favorable high thermal gradient include steam discharges, hot grounds, hot mud, etc.

Ethiopia's geothermal resources are located in the Afar Depression and all along the Rift Valley. Some of these resources like the Aluto-Langano (Lakes District) and the Dubti-Tendaho (northern Afar) areas are being studied in detail with the view to utilizing the resource for electric power generation (Tibebu A., 2001; Gianelli G,1993 and the references therein; Tesfaye C.,1982; UN Technical Report, 1973).This potential has been estimated to be in the area of 1000 MW, larger than the electric energy generating potential of the hydropower resources developed so far. Other small area, low budget and less extensive studies have been conducted in manifestation areas of the Boku, Gergedi and Gemeto thermal springs with a view to small scale utilization of the resource for house hold, mass heating and recreational purposes (Balia R. etal, 2002; Tigistu H. etal, 2002, 2003; Tamiru A. and Venire A., 1997). A large number of similar indications, probably suitable for small-scale utilization- like supplying urban centers with hot water, recreation and thermal bath centers still need further investigation.

One such resource, albeit famous and most widely used but still less studied of these resources in the Main Ethiopian Rift is the thermal springs of the Wabeshebelle Resorts at Sodere. There is both scientific and future economic interest in studying this system of springs. Its possible relation with the geologic features of the Rift, the depth to the potential aquifers, major structures in the area need extensive work.

In this thesis work geophysical exploration methods, specifically the electrical and magnetic methods of prospecting, have been applied to investigate the thermal centers of Sodere. Owing to their proximity to Addis Ababa and the city centers of Nazareth and Assela, and lying close to the confluence of the major roads connecting the south and south eastern parts of the country, the Sodere thermal springs are one of the widely used thermal springs in Ethiopia. Their use is mainly for recreational and healing purposes although their thermal characteristics, discharge volume and extent of the springs promise their potential for wider application.

The thesis is organized in five chapters. The first chapter, the introductory chapter, discusses about the general theories and fundamental of geothermal resource and their characteristics, the location of the study area and the objectives of the study. In the second chapter theoretical background on the two methods employed on the problem area, i.e. the magnetic and electrical methods of prospecting is outlined. The third chapter gives the descriptions of data acquisition and processing. In the fourth chapter results and discussion of the data are given while the last and fifth chapter gives conclusions of the work and recommendations.

1.2 Location of the study area

The study area, Sodere is located close to Nazareth town and is accessible on an all weather asphalt road on a detour from Nazareth-Assela main road. It is one of the famous recreational centers and easily accessible area of the country. It is bounded between UTM coordinate 542000-545000 Easting and 926000-930000 Northing ($39^0$23'-$39^0$24.5' longitude and $8^0$22.7'- $8^0$24.9' latitude), which forms in part of the Main Ethiopian Rift (MER). More specifically, it is located about 130km, SE of Addis Ababa; 30Km, SE of Nazareth and 5km, East of Awash Melkasa. The study area covers 12km^2 and the maximum elevation of the area is about 1440m above sea level. Figure 1 gives the general location of the area.

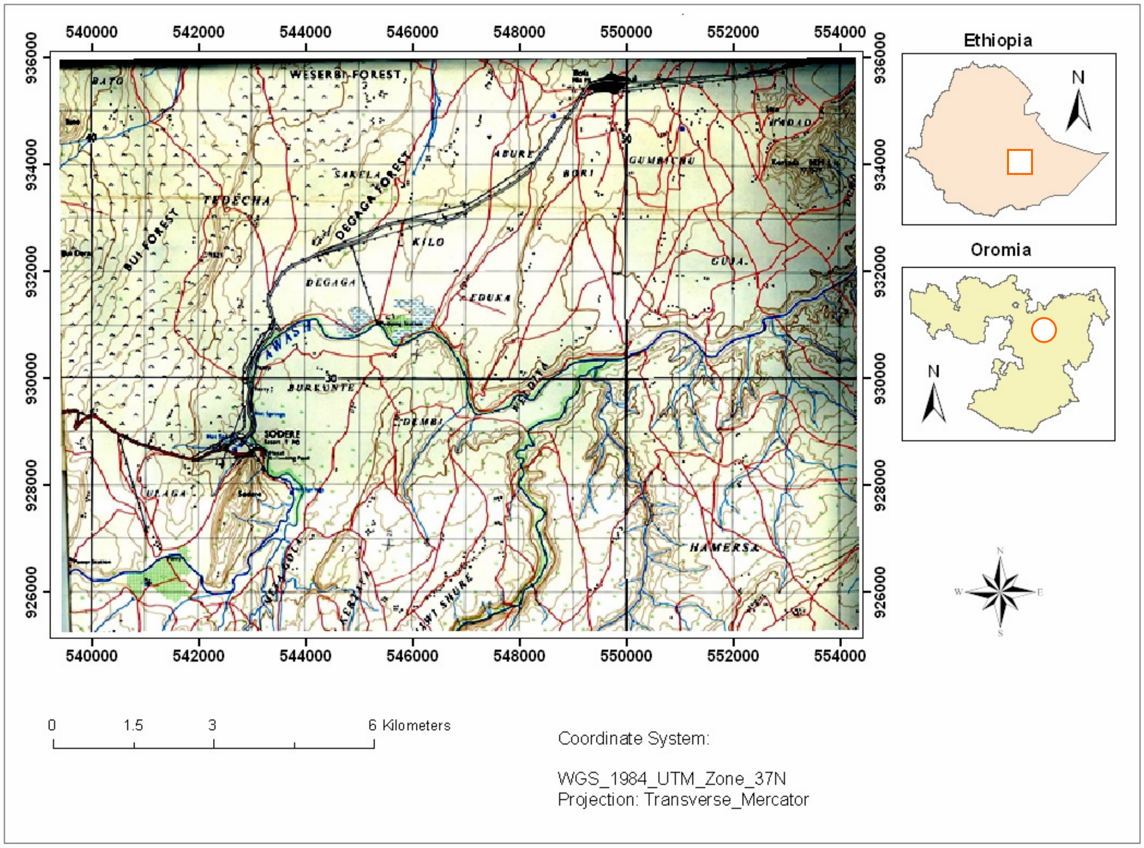

Figure1. Location map of the study area

1.3 Relevance of the Study

Considering the shortage of modern energy supplies in the country and the climate change issue due to green house emissions, there is a need to develop geothermal energy in Ethiopia to serve as a source of reliable base load power generation to increase its hydro-power generation, which relies on highly seasonal fluctuations. The diversification of energy sources is essential in order to ensure a sustainable energy supply.

There is a huge potential for the development of Sodere geothermal resource. Moreover, with the belief that this resource can become an essential part of the future development of the area and help to acquire sufficient knowledge on the springs that would be useful for their future development and utilization. Utilization of the resources will be included in the future development plans of the nearby towns and cities. It will also be useful in planning new and accessible area of exploitation of the thermal waters and establishment of infrastructures that exploit the resource.

This is important resource, which, in truth, is underutilized. It is estimated that less than 40% of the spring discharge is currently utilized for the bathing centers and the two swimming pools. Therefore there still is a huge potential for better use and future development of the resource. There is a possibility to use this resource, in addition to a possible extended use for recreational purposes, for power generation be it for small or large scale depending on the results of an elaborate study.

In summary, the relevance of the study can be two fold:

I) **Economic**

The result of the study can be used for the development of the area further as modern and attractive tourist and recreational center.

II) **Scientific**

The study will help in up grading the understanding of the characteristics of the thermal resource in Ethiopia. Moreover, it will help to enhance the knowledge on the different aspects of geothermal exploration and on the methodic exploration scheme developed on studies of the earlier and similar thermal centers of the Main Ethiopian Rift.

1.4 Objectives of the Study

The general objectives of the integrated geophysical methods around the spring is to characterize the thermal setting of the area and to provide the necessary background information for further development of the thermal resource.

Specific Objectives:

- Mapping of the major geologic structures over the area and their role as paths for rising hot water.
- Study the potential of the thermal springs for further development and delineate prospective areas for utilization of the thermal waters from shallow depth discharges.
- To acquaint oneself with the methods of geophysical data acquisition, interpretation and presentation of results.

1.5 Methodology

Although the location of a geothermal field is controlled by the regional geology, its characteristics, as recognized at the surface through the geothermal exploration techniques, are essentially hydro geological phenomena. They depend not only on suitable heat source but also on the presence of a medium (normally water) in which the heat can be transported to the surface and on a permeable path along which the medium (the fluid) can travel. In simple terms, the recipes for a geothermal system are: large source of heat, a reservoir to accumulate heat, a barrier to hold the accumulated heat and adequate supplies of water (ancient connate, magmatic waters or more recent juvenile, meteoric waters).

A good understanding of these components and their interaction is essential for better utilization and development of the resource. A successful exploration program, therefore, should be directed at studying and resolving these component parts. The geophysical methods to be used are those that would enable one to study the component parts directly or indirectly. The magnetic methods would map the major structures that are paths for the rising heat to shallow depths to interact with the down-flowing waters in the aquifer zone. Electrical sounding surveys would establish the vertical stratification of the geoelectric layers of the area. This method will also help to localize within the region where the thermal waters may be accessed from shallow depths.

1.6 Geology of the Study Area

Regional geology

The trap basalt and may be some alternating layers of ignimbrites are the oldest exposed and out-cropping formations on the edges (except in the kella horst, where the Precambrian basement and Mesozoic sediments are exposed) of the MER and tops of the plateau. These do not occur on the floor of the rift (Dipaola, 1970). Figure 2 is the general geologic map of the Nazareth-Dera region (Alula Damte, et.al. 1992) where the Sodere area is a part as depicted in Figure 3.

A thick succession of ignimbrites, unwedded tuffs, ash flows, rhyolites and trachytes from a large part of the rift floor and also out crop in the rift escarpments and on the adjacent plateau margins. The name "Nazareth series" was introduced to these formations by Meyer et al., (1975) and it was accepted replacing the word "series" by "group" by Kazmin and Seife Michael (1978) and others. In the rift the Nazareth group attains thicknesses of up to 250m and some times more, while on the rift the shoulders only a few meters of ignimbrites are generally observed. There is no doubt that the bulk of eruption was restricted to the sagging rift (Kazmine and Seife Michael, 1978). These authors have proposed also that, centeral type of eruptions have played a significant part in the formation of the Nazareth Volcanics, which has given rise to Gara Gumbi, possibly Assebot and Afdem. Age of the Nazareth group was also determined as between 9.5 and 3 to 4 my.

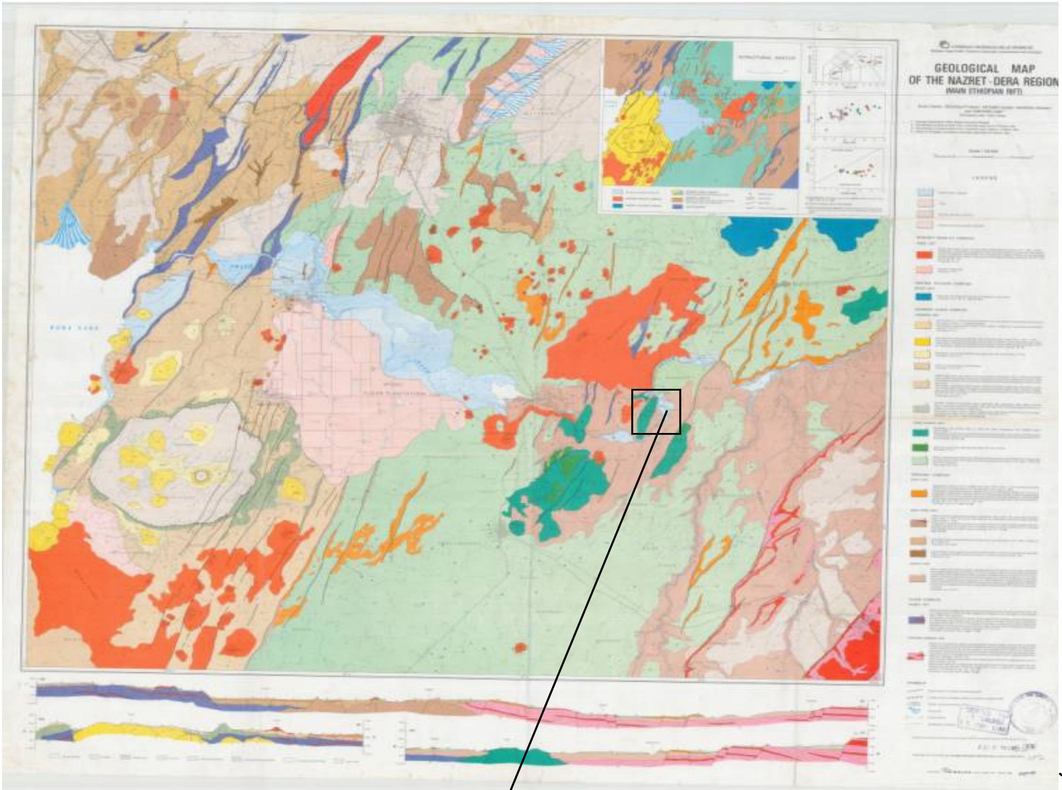

Figure 2. General geological map of the Nazareth-Dera region of which the Sodere area is a part.

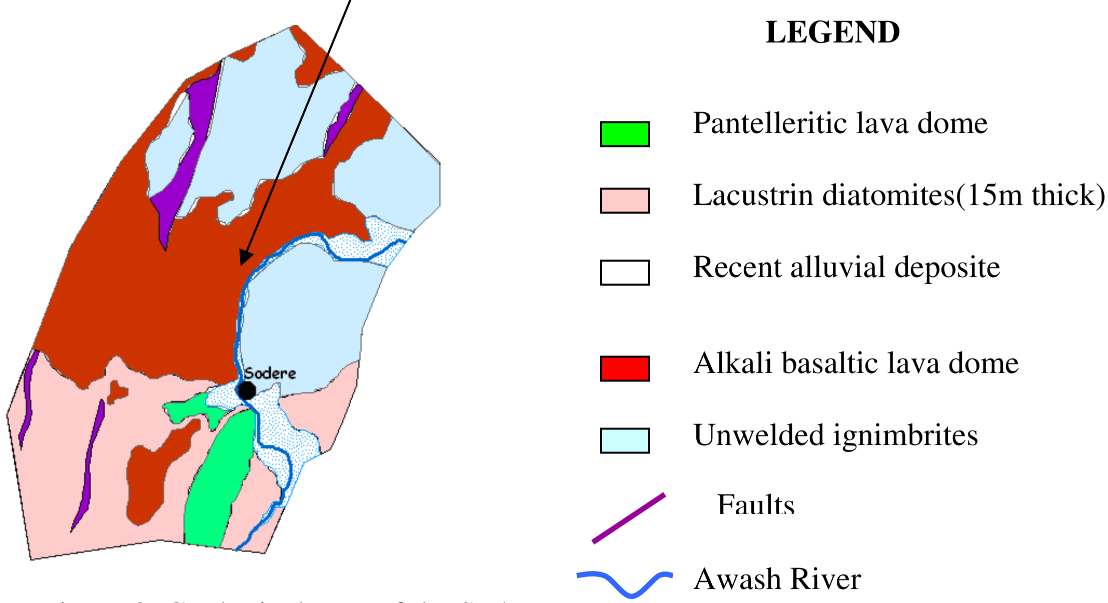

Figure 3. Geological map of the Sodere area.

The Nazareth group was accompanied by formation of the shield volcanism on the rift's eastern shoulder. The Arba Gugu shield volcano is synchronous with the early stage of Nazareth volcanism, and Chilalo and Badda with kakka, Encuolo, Wachacha and many others belong to a numerous groups of trachytic volcanoes developed in the upper Pliocene on both side of the rift.

On the top of the Nazareth group are the Bofa basalts; the name "Bofa" is after the type locality of the unit which is found south east of Nazareth. Bofa basalts were named as weleanchiti basalts, Bishoftu basalts, etc…by different authors. Age of these basalts lavas range from 3.5-1.5my (Kazmine and Seife Michael, 1978). The Bofa basalts are not restricted to the central part of the rift as younger units, but are rather evenly distributed over the rift floor. They represent an episode of fissures eruption that immediately followed a major faulting episode. Occurrence of the Bofa basalts in the deep drilling wells of Aluto Langano geothermal field, having thickness of 800m could also prove the wide and significant flow coverage of the basalts with in the rift floor.

According to Kazmin and Seife Michael (1978), the Wonji group includes all rifts volcanic formed after the last major episode of rift faulting which followed deposition of Bofa basalts. The name "Wonji series" was introduced by Meyer et al., (1975) and it was accepted by the substitution of "group" for "series". The Dino ignimbrites are the oldest dated as 1.5my (Kazmin and Seife Michael, 1978) and these are found overlying the Bofa basalt to the North-east of Nazareth. Other than Dino ignimbrite, the Wonji group consists major units of panteleritic volcanic centers are aligned en-echelon along segments of the Wonji fault belts. The main product consists of peralkaline rhyolites and trachytes with some pumices, pithstones and obsidians. Occurring mostly at late post caldera stages (Gibson, 1970; Dikine and Gibson, 1971; Thrall, 1973 and Brotzu et al., 1974-1975). The youngest flows of the recent fissure basalts are historic and have fresh flow near Metehara; while the older basalts contemporaneous with early stages of development of the pantelleritic volcanoes were fissural and the younger eruption were partly central type. Most of them being volcanic cones following fractures of the Wonji fault belts.
Along the active axis of the MER presence of the sub-historic and historic acidic edifices (obsidian) i.e. Gnaro, Jano, Aluto, Chebbi, etc. could simply presence of a shallow magm magma champers. Apart from this area that has these type of flows have usually fumaroles, altered, hot and warm

ground and hot spring around the feet of the volcanoes. Area where exist these types of volcanism are believed to have a potential of geothermal.

CHAPTER TWO

THEORETICAL BACKGROUND

2.1 MAGNETIC METHODS

2.1.1 Introduction to Magnetic Exploration

Magnetic survey is measurements of the magnetic field or its components at a series of different locations over an area of interest, usually with the objective of locating concentrations of magnetic materials or of determining depth to basement.

Unlike the gravitational observations, man has been systematically observing the earth's magnetic field for almost 500years. Sir William Gilbert published the first scientific treatise on the earth's magnetic field entitled *De magnete*. In this work, Gilbert showed that the reason compass needles point toward the earth's North Pole is because the earth itself appears to behave as a large magnet. Gilbert also showed that the earth's magnetic field is roughly equivalent to that which would be generated by a bar magnet located at the center of the earth and oriented along the earth's rotational axis. During the mid-nineteenth century, Karl Frederick Gauss confirmed Gilbert's observations and also showed that the magnetic field observed on the surface of the earth could not be caused by magnetic sources external to the earth, but rather had to be caused by sources within the earth. Geophysical exploration using measurements of the earth's magnetic field was employed earlier than another geophysical technique. Von Werde located deposits of ore by mapping variations in the magnetic field in 1843. In 1879, Thalen published the first geophysical manuscript entitled *The Examination of Iron Ore Deposits by Magnetic Measurements.* Even to this day, the magnetic methods are one of the most commonly used geophysical tools. This stems from the fact that magnetic observations are obtained relatively easily and cheaply and few corrections must be applied to the observations. Despite these obvious advantages, like the gravitational methods, interpretations of magnetic observations suffer from a lack of uniqueness.

2.1.2 Forces Associated with Magnetic poles

Charles Augustine de Coulomb, in 1785, showed that the force of attraction or repulsion between electrically charged bodies and between magnetic poles also obeys an inverse square law like that derived for gravity by Newton. To make the measurements necessary to prove this, Coulomb (independent of John Michel) invented the *torsion balance*. The mathematical expression for the magnetic force experienced between two magnetic monopoles is given by,

$$F_m = \frac{1}{\mu} \frac{p_1 p_2}{r^2} \qquad (1)$$

where μ is a constant of proportionality known as the *magnetic permeability*,

p_1 and p_2 are the strengths of the two magnetic monopoles, and

r is the distance between the two poles.

In form, this expression is identical to the gravitational force expression . There are, however, two important differences. Unlike the gravitational constant, G, the magnetic permeability, μ is a property of the material in which the two monopoles, p_1 and p_2, are located. If they are in a vacuum, μ is called the magnetic permeability of free space. Unlike m_1 and m_2, p_1 and p_2 can be either positive or negative in sign. If p_1 and p_2 have the same sign, the force between the two monopoles is repulsive. If p_1 and p_2 have opposite signs, the force between the two monopoles is attractive.

It is possible to derive the magnetic force produced by a dipole by considering the force produced by two magnetic monopoles. If a dipole simply consists of two magnetic monopoles, you might expect that the force generated by a dipole is simply the force generated by one monopole added to the force generated by a second monopole.

The force associated with this fundamental element of magnetism, the magnetic dipole, now looks more complicated than the simple force associated with gravity. The magnetic force appears to originate out of the *North Pole* (*N*) of the magnet and to terminate at the *south pole*, *S*, of the magnet.

2.1.3 Units Associated with Magnetic Poles

The units associated with magnetic poles and the magnetic field is a bit more obscure than those associated with the gravitational field. From Coulomb's expression, we know that force must be given in Newton, N, where a Newton is a $kg\ m / s^2$. Permeability μ is defined to be a unit less constant. The units of pole strength are defined such that if the force, *F*, is 1 N and the two magnetic poles are separated by 1 m, each of the poles has strength of 1 Amp-m (Ampere-meters). In this case, the poles are referred to as *unit poles*.

$$F_m = \frac{1}{\mu} \frac{p_1 p_2}{r^2} \tag{1}$$

The *magnetic field strength*, *H*, is defined as the force per unit pole strength exerted by a magnetic monopole, p_1. *H* is nothing more than Coulomb's expression divided by p_2. The magnetic field strength *H* is the magnetic analog to the gravitational acceleration, *g*.

$$H = \frac{F_m}{p_2} = \frac{p_1}{\mu r^2} \tag{2}$$

Given the units associated with force, *N*, and magnetic monopoles, *Amp-m*, the units associated with magnetic field strength are Newton per Ampere-meter, *N / (Amp- m)*. A *N / (Amp - m)* is referred to as a *tesla (T)*, named after the renowned inventor Nikola Tesla. When describing the magnetic field strength of the earth, it is more common to use units of nanoteslas (nT), where one nanotesla is 1 billionth of a tesla. The average strength of the Earth's magnetic field is about 50,000 nT. A nanotesla is also commonly referred to as a *gamma*.

2.1.4 Magnetic Induction

When a magnetic material, say iron, is placed within a magnetic field, *H*, the magnetic material will produce its own magnetization. This phenomenon is called *induced magnetization*. In practice, the induced magnetic field (that is, the one produced by the magnetic material) will look like it is being created by a series of magnetic dipoles located within the magnetic material and oriented parallel to the direction of the inducing field, *H*. The strength of the magnetic field induced by the magnetic material due to the inducing field is called the *intensity of magnetization*, *I*.

2.1.5 Magnetic Susceptibility

The intensity of magnetization, *I*, is related to the strength of the inducing Magnetic field, *H*, through a constant of proportionality, *k*, known as the Magnetic Susceptibility.

$$I = \frac{k}{H} \tag{3}$$

The magnetic susceptibility is a unit less constant that is determined by the physical properties of the magnetic material. It can take on either positive or negative values. Positive values imply that the induced magnetic field, *I*, is in the same direction as the inducing field, *H*. Negative values imply that the induced magnetic field is in the opposite direction as the inducing field.

In magnetic prospecting, the susceptibility is the fundamental material property whose spatial distribution we are attempting to determine. In this sense, magnetic susceptibility is analogous to density in gravity surveying.

2.1.6 Mechanisms for Induced Magnetization

The nature of magnetization material is in general complex, governed by atomic properties. There are three types of magnetic materials: Paramagnetic, diamagnetic, and ferromagnetic.

- *Diamagnetism* - Discovered by Michael Faraday in 1846. This form of magnetism is fundamental property of all materials and is caused by the alignment of magnetic moments associated with orbital electrons in the presence of an external magnetic field. For those elements with no unpaired electrons in their outer electron shells, this is the only form of magnetism observed. The susceptibilities of diamagnetic materials are relatively small and negative. Quartz and salt are two common diamagnetic earth materials.

- *Para magnetism* - This is a form of magnetism associated with elements that have an odd number of electrons in their outer electron shells. Paramagnetism is associated with the alignment of electron spin directions in the presence of an external magnetic field. It can only be observed at relatively low temperatures. The temperature above which paramagnetism is no longer observed is called the *Curie temperature*. The susceptibilities of paramagnetic substances are small and positive.

- *Ferromagnetism* - This is a special case of paramagnetism in which there is an almost perfect alignment of electron spin directions within large portions of the material referred to as *domains*. Like paramagnetism, ferromagnetism is observed only at temperatures below the Curie temperature. There are three varieties of ferromagnetism.

    - *Pure Ferromagnetism* - The directions of electron spin alignment within each domain are almost all parallel to the direction of the external inducing field. Pure ferromagnetic substances have large positive susceptibilities. Ferromagnetic minerals do not exist, but iron, cobalt, and nickel are examples of common ferromagnetic elements.

    - *Antiferromagnetism* - The directions of electron alignment within adjacent domains are opposite and the relative abundance of domains with each spin direction is approximately equal. The observed magnetic intensity for the material is almost zero. Thus, the susceptibilities of antiferromagnetic materials are almost zero. Hematite is an antiferromagnetic material

    - *Ferromagnetism* - Like antiferromagnetic materials, adjacent domains produce magnetic intensities in opposite directions. The intensities associated with domains polarized in a direction opposite that of the external field, however, are weaker. The observed magnetic intensity for the entire material is in the direction of the inducing field but is much weaker than that observed for pure ferromagnetic materials. Thus, the susceptibilities for ferromagnetic materials are small and positive. The most important magnetic minerals are ferromagnetic and include magnetite, titanomagnetite, ilmenite, and pyrrhotite.

2.1.7 Susceptibilities of Rocks and Minerals

Although the mechanisms by which induced magnetization can arise are rather complex, the field generated by these mechanisms can be quantified by a single, simple parameter known as the susceptibility, *k*. As we will show below, the determination of a material type through knowledge of its susceptibility is an extremely difficult proposition, even more than by determining a material type through knowledge of its density.

The susceptibilities of various rocks and minerals are shown below.

Table1. The susceptibilities of various rocks and minerals.

Material	susceptibility
Air	~0
Quartz	-0.01
Rock salt	-0.01
Calcite	-0.001-0.01
Sphalerite	0.4
Pyrite	0.05-5
Hematite	0.5-35
Illmenite	300-3,500
Magnetite	1,200-19,200
Limestone	0-3
Sandstone	0-20
Shales	0.01-15
Schist	0.3-3
Gneiss	0.1-25
slate	0-35
Granite	0-50

Gabbro	1-90
Basalt	0.2-175
perodotite	90-200

Unlike density, notice the large range of susceptibilities not only between varying rocks and minerals but also within rocks of the same type. It is not uncommon to see variations in susceptibility of several orders of magnitude for different igneous rock samples. In addition, like density, there is considerable overlap in the measured susceptibilities. Hence, knowledge of susceptibility alone will not be sufficient to determine rock type, and, alternately, knowledge of rock type is often not sufficient to estimate the expected susceptibility. This wide range in susceptibilities implies that spatial variations in the observed magnetic field may be readily related to geologic structure. Because variations within any given rock types are also large, however, it will be difficult to construct corrections to our observed magnetic field on assumed susceptibilities.

2.1.8 Remanent Magnetization

If we have a magnetic material and place it in an external magnetic field (one that we've called the inducing field), we can make the magnetic material produce its own magnetic field. If we were to measure the total magnetic field near the material, that field would be the sum of the external or inducing field, and the induced field produced in the material. By measuring spatial variations in the total magnetic field and by knowing what the inducing field looks like, we can, in principle; map spatial variations in the induced field and from this determine spatial variations in the magnetic susceptibility of the subsurface. Although this situation is a bit more complex than the gravitational situation, it's still manageable. There is, however, one more complication in nature concerning material magnetism that we need to consider. The induced magnetic field is a direct consequence of a magnetic material being surrounded by an inducing magnetic field. If you turn off the inducing magnetic field, the induced magnetization disappears. If the magnetic material has relatively large susceptibilities, or if the inducing field is strong, the magnetic material will retain a portion of its induced magnetization even after the induced field disappears. This remaining magnetization is called *Remanent Magnetization*. Remanent Magnetization is the component of the material's magnetization that solid-earth geophysicists use to map the motion of continents and ocean basins resulting from plate tectonics. Rocks can acquire a remanent magnetization through a variety of processes. As a volcanic rock cools, its temperature decreases past the Curie temperature. At the Curie temperature, the rock, being magnetic, begins to produce an induced magnetic field. In this case, the inducing field is the Earth's magnetic field. As the Earth's magnetic field changes with time, a portion of the induced field in the rock does not change but remains fixed in a direction and strength reflective of the Earth's magnetic field at the time the rock cooled through its Curie temperature. This is the remanent magnetization of the rock that recorded magnetic field of the Earth at the time the rock cooled past its Curie temperature. The only way you can measure the remanent magnetic component of a rock is to take a sample of the rock back to the laboratory for analysis. This is time consuming and expensive. As a result, in exploration geophysics, we typically assume there is no remanent magnetic component in the observed magnetic field. Clearly, however, this assumption is wrong and could possibly bias our interpretations.

2.1.9 Magnetic Field Nomenclature

Because the magnetic field does not act along any easily definable direction, earth scientists have developed a nomenclature to describe the magnetic field at any point on the Earth's surface.

- *Declination* - The angle between north and the horizontal projection of F. This value is measured positive through east and varies from 0 to 360 degrees.
- *Inclination* - The angle between the surface of the earth and F. Positive inclination indicate F is pointed downward, negative inclinations indicate F is pointed upward. Inclination varies from -90 to 90 degrees.

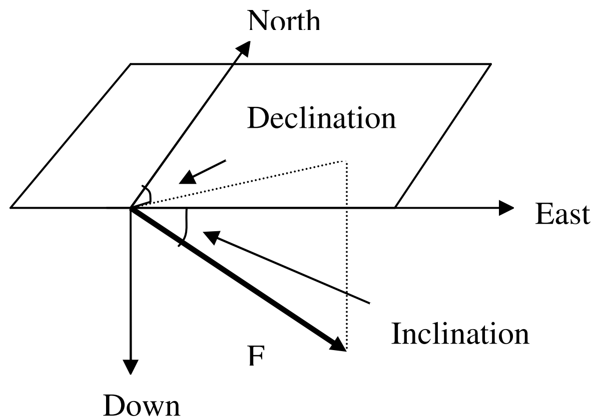

Figure 4. Magnetic field nomenclature

- *Magnetic Equator* - The location around the surface of the Earth where the Earth's magnetic field has an inclination of zero (the magnetic field vector *F* is horizontal). This location *does not* correspond to the Earth's rotational equator.
- *Magnetic Poles* - The locations on the surface of the Earth where the Earth's magnetic field has an inclination of either plus or minus 90 degrees (the magnetic field vector *F* is vertical). These locations *do not* correspond to the Earth's north and south poles.

The *main* magnetic field refers to that portion of the Earth's magnetic field that is believed to be generated within the Earth's core. It constitutes the largest portion of the magnetic field and is the field that acts to induce magnetization in crustal rocks that we are interested in for exploration applications.

2.1.10 The Earth's Magnetic Field

Ninety percent of the Earth's magnetic field looks like a magnetic field that would be generated from a dipolar magnetic source located at the center of the Earth and aligned with the Earth's rotational axis. Sir William Gilbert first gave this first order description of the Earth’s magnetic field in 1600. The strength of the magnetic field at the poles is about 60,000 nT. If this dipolar description of the field were complete, then the magnetic equator would correspond to the Earth's equator and the magnetic poles would correspond to the geographic poles. as we've come to expect from magnetism, such a simple description is not sufficient for analysis of the Earth's magnetic field. The remaining

10% of the magnetic field cannot be explained in terms of simple dipolar sources. Complex models of the Earth's magnetic field have been developed and are available.

If the Earth's field were simply dipolar with the axis of the dipole oriented along the Earth's rotational axis, all declinations would be 0 degrees (the field would always point toward the north). As can be seen, the observed declinations are quite complex.

As observed on the surface of the earth, the magnetic field can be broken into three separate components.

- *Main Field* - This is the largest component of the magnetic field and is believed to be caused by electrical currents in the Earth's fluid outer core. For exploration work, this field acts as the inducing magnetic field.

- *External Magnetic Field* - This is a relatively small portion of the observed magnetic field that is generated from magnetic sources external to the earth. This field is believed to be produced by interactions of the Earth's ionosphere with the solar wind. Hence, temporal variations associated with the external magnetic field are correlated to solar activity.

- *Crustal Field* - This is the portion of the magnetic field associated with the magnetism of crustal rocks. This portion of the field contains both magnetism caused by induction from the Earth's main magnetic field and from remanent magnetization.

2.1.11 Magnetics and Geology

What are we actually going to observe, and how is this related to geology? The portion of the magnetic field that we have described as the main magnetic field is believed to be generated in the Earth's core. There are a variety of reasons why geophysicists believe that the main field is being generated in the Earth's core, but these are not important for our discussion. In addition to these core sources of magnetism, rocks exist near the Earth's surface that are below their Curie temperature and as such can exhibit induced as well as remanent magnetization.

Therefore, if we were to measure the magnetic field along the surface of the earth, we would record magnetization due to both the main and induced fields. The induced field is the one of interest to us because it relates to the existence of rocks of high or low magnetic susceptibility near our instrument. If our measurements are taken near rocks of high magnetic susceptibility, we will, in general, record magnetic field strengths that are larger than if our measurements were taken at a great distance from rocks of high magnetic susceptibility. Hence, like gravity, we can potentially locate subsurface rocks having high magnetic susceptibilities by mapping variations in the strength of the magnetic field at the Earth's surface.

2.1.12 Temporal Variations of the Earth's Magnetic Field

Like the gravitational field, the magnetic field varies with time. When describing temporal variations of the magnetic field, it is useful to classify these variations into one of three types depending on their rate of occurrence and source. Please note explicitly that the temporal variations in the magnetic field that we will be discussing are those that have been observed directly during human history. As such, the most well-known temporal variation, magnetic polarity reversals, while important in the study of earth history, will not be considered in this discussion. We will, however, consider the following three temporal variations:

- *Secular Variations* - These are long-term (changes in the field that occur over years) variations in the main magnetic field that are presumably caused by fluid motion in the Earth's Outer Core. Because these variations occur slowly with respect to the time of completion of a typical exploration magnetic survey, these variations will not complicate data reduction efforts. Solid earth geophysicists are very interested in studying these secular variations, because they can be used to understand the dynamics of the Earth's core. To understand these temporal variations and to quantify the rate of variability over time, standard reference models are constructed from magnetic observatory observations about every five years. One commonly used set of reference models is known as the *International Geomagnetic Reference Field*. Based on these models, it is possible to predict the portion of the observed magnetic field associated with the Earth's main magnetic field at any point on the Earth's surface, both now and for several decades in the past. Because the main magnetic field as described by these secular variations changes slowly with respect to the time it takes us to complete our exploration magnetic survey, this type of temporal variation is of little importance to us.

- *Diurnal Variations* - These are variations in the magnetic field that occur over the course of a day and are related to variations in the Earth's external magnetic field. This variation can be on the order of 20 to 30 nT per day and should be accounted for when conducting exploration magnetic surveys. Diurnal variations are believed to be caused by electric currents induced in the Earth from an external source. In this case, the external source is believed to be electric currents in the upper atmosphere, or the ionosphere. These electric currents in the ionosphere are in turn driven by solar activity. Given the size of these variations, the size of the magnetic anomalies we would expect in a typical geophysical survey, and the fact that surveys could take several days or weeks to complete, it is clear that we must account for diurnal variations when interpreting our magnetic data.

- *Magnetic Storms* - Occasionally, magnetic activity in the ionosphere will abruptly increase. The occurrence of such storms correlates with enhanced sunspot activity. The magnetic field observed during such times is highly irregular and unpredictable, having amplitudes as large as 1000 nT. Exploration magnetic surveys should not be conducted during magnetic storms.

2.1.13 Measuring the Earth's Magnetic Field

Instruments for measuring aspects of the Earth's magnetic field are among some of the oldest scientific instruments in existence. Magnetic instruments can be classified into two types.

- *Mechanical Instruments* - These are instruments that are mechanical in nature that usually measure the attitude (its direction or a component of its direction) of the magnetic field. The most common example of this type of instrument is the simple compass. The compass consists of nothing more than a small test magnet that is free to rotate in the horizontal plane. Because the positive pole of the test magnet is attracted to the Earth's negative magnetic pole and the negative pole of the test magnet is attracted to the Earth's positive magnetic pole, the test magnet will align itself along the horizontal direction of the Earth's magnetic field. Thus, it provides measurements of the declination of the magnetic field. The earliest known compass was invented by the Chinese no later than the first century A.D., and more likely as early as the second century B.C.

Although compasses are the most common type of mechanical device used to measure the horizontal attitude of the magnetic field, other devices have been devised to measure other components of the magnetic field. Most common among these are the *dip needle* and the *torsion magnetometer*. The dip needle, as its name implies, is used to measure the inclination of the magnetic field. The torsion magnetometer is a devise that can measure, through mechanical means, the strength of the vertical component of the magnetic field.

- *Magnetometers* - Magnetometers are instruments, usually operating non-mechanically, that are capable of measuring the strength, or a component of the strength, of the magnetic field. The first advances in designing these instruments were made during WWII when Fluxgate Magnetometers were developed for use in submarine detection. Since that time, several other magnetometer designs have been developed that include the Proton Precession and Alkali-Vapor magnetometers.

2.1.14 Total Field Measurements

Given the ease of use of the proton precession magnetometer, most exploration geophysical surveys employ this instrument and thus measure only the magnitude of the total magnetic field as a function of position. Surveys conducted using the proton precession magnetometer do not have the ability to determine the direction of the total field as a function of location.

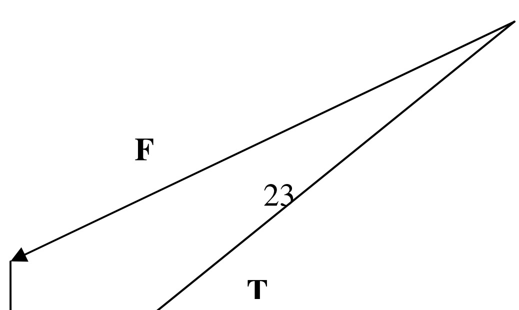

Figure 5. The total magnetic field

where **F -** is the earths' main magnetic field

A - is the anomalous field (induced and remanent magnetization), and

T - is total magnetic field (T= F+A)

Ignoring for the moment the temporally varying contribution to the recorded magnetic field caused by the external magnetic field, the magnetic field we record with our proton precession magnetometer has two components:

- The main magnetic field, or that part of the Earth's magnetic field generated by deep (outer core) sources. The vector labeled F in the figure represents the direction and size of this component of the magnetic field at some point on he Earth's surface.

- The anomalous magnetic field, or that part of the Earth's magnetic field caused by magnetic induction of crustal rocks or remanent magnetization of crustal rocks. The vector labeled A in the figure represents the direction and size of this component of the magnetic field.

- The total magnetic field we record, labeled T in the figure, is nothing more than the sum of F and A. Typically, F is much larger than A, as is shown in the figure (50,000 nT versus 100 nT). If F is much larger than A, then T will point almost in the same direction as F regardless of the direction of A. That is because the anomalous field, A, is so much smaller than the main field, F, that the total field, T, will be almost parallel to the main field.

2.1.15 Magnetic Cleanliness and Interference

When making total field measurements from which estimates of the subsurface distribution of magnetic susceptibility or the presence of subsurface magnetized bodies are made, it is imperative that factors affecting the recorded field other than these be eliminated or isolated so that they can be removed. We have already discussed several of these added complications, including spatial variations of the Earth's main magnetic field and temporal variations mostly associated with the external magnetic field. In addition to these factors, which we cannot control, there are other sources of noise that we can control.

Because any ferromagnetic substance can produce an induced magnetic field in the presence of the Earth's main field and because modern magnetometers are very sensitive (0.1 nT), the field crew running the magnetic survey must divest itself of all ferrous objects. This includes, but is not limited to, belt buckles, knives, wire-rimmed glasses, etc. As a result of this, proton precession magnetometers are typically placed on two to three meter poles to remove them from potential noise sources worn by the operators.

In addition to noise sources carried by the operators, many sources of magnetic noise may be found in the environment. These can include any ferrous objects such as houses, fences, railroad rails, cars, rebar in concrete foundations, etc. Finally, when using a proton precession magnetometer, reliable readings will be difficult to obtain near sources of AC power such as utility lines and transformers.

2.1.16 Strategies for Dealing with Temporal Variations

Like our gravity observations, magnetic readings taken at the same location at different times will not yield the same results. There are temporal variations in both the Earth's magnetic and gravitational fields.

In acquiring gravity observations, we accounted for this temporal variability by periodically reoccupying a base station and using the variations in this reading to account for instrument drift and temporal variations of the field. We could use the same strategy in acquiring magnetic observations by recording the times at which each magnetic station readings are made and subtracting the magnetic field strength at the base station recorded at that same time, temporal variations in the magnetic field can be eliminated. The resulting field then represents relative values of the variation in total field strength with respect to the magnetic base station.

2.1.17 Spatially Varying Corrections

When reducing gravity observations, there was a host of spatially varying corrections that were applied to the data. These included latitude corrections, elevation corrections, slab corrections, and topography corrections. In principle, all of these corrections could be applied to magnetic observations also. In practice, the only corrections routinely made for are spatial variations in the Earth's main magnetic field, which would be equivalent to latitude corrections applied to gravity observations. Why aren't the other corrections applied?

Variations in total field strength as a function of elevation are less than 0.015 nT per meter. This variation is generally considered small enough to ignore. Variations in total field strength caused by excess magnetic material (i.e., a slab correction) and topography could, on the other hand, be quite significant. The problem is the large variation in susceptibilities associated with earth materials even when those materials are of the same rock type.

In applying the slab and elevation corrections to our gravitational observations, we had to assume an average density for the rocks making up the corrections. Rock densities do not vary much from rock type to rock type. Density variations of 0.5 gm/cm^3 are large. Variations among different samples of the same rock type vary by even less. Therefore, we can assume an average density for the correction and feel fairly confident that our assumption is reasonable.

Magnetic susceptibilities vary by orders of magnitude even among samples of the same rock type. So, how can we choose an *average* susceptibility on which to base our correction? The answer is we can't. Therefore, instead of applying a set of corrections that we know will be wrong, we apply no correction at all to attempt to account for excess material and topography.

2.1.18 Correcting for Main Field Variations

Corrections for spatial variations in the strength of the Earth's main magnetic field are referred to as *geomagnetic corrections*. One commonly used method of accounting for these variations is to use one of the many models of the Earth's main magnetic field that are available. One such set of commonly used models of the main field is referred to as the International Geomagnetic Reference Field (IGRF).

2.2 DIRECT CURRENT RESISTIVITY METHOD

2.2.1 Fundamental Principles

DC Resistivity is an active method that employs measurements of electrical potential associated with subsurface electrical current flow generated by a DC, or slowly varying AC source. Factors that affect the measured potential, and thus can be mapped using this method, include the presence and quality of pore fluids and clays. Resistivity technique is superior, at least theoretically, to all the other electrical methods, because quantitative results are obtained by using a control source of specific dimensions. Practically, as in other geophysical methods the maximum potentialities of the resistivity are never realized. The chief drawbacks are its high sensitivity to minor variations in conductivity near surface and the practical difficulty involved in dragging several electrodes and long wires through rough wooden terrain.

In 1827, George Ohm defined an empirical relationship between the current flowing through a wire and the voltage potential required to drive that current.

$$V = I\ R \tag{4}$$

Ohm found that the current, *I*, was proportional to the voltage, *V*, for a broad class of materials that we now refer to as *ohmic* materials. The constant of proportionality is called the *resistance* of the material and has the units of voltage (volts) over current (amperes), or *ohms*.

In principle, it is relatively simple to measure the resistance of a strand of wire. Connect a battery to a wire of known voltage and then measure the current flowing through the wire. The voltage divided by the current yields the resistance of the wire. In essence, this is how your multimeter measures resistance. In making this measurement, however, we must ask two crucial questions.

- How is the measured resistance related to some fundamental property of the material from which the wire is made?
- How can we apply this relatively simple experiment to determine electrical properties of earth materials?

The problem with using resistance as a measurement is that it depends not only on the material from which the wire is made, but also the geometry of the wire. If we were to increase the length of wire, for example, the measured resistance would increase. Also, if we were to decrease the diameter of the wire, the measured resistance would increase. We want to define a property that describes a material's ability to transmit electrical current that is independent of the geometrical factors.

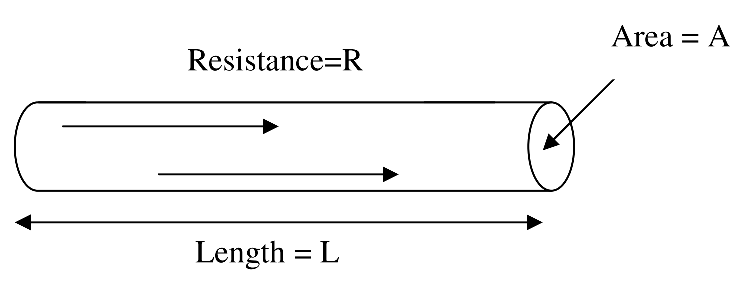

Figure 6. Definition of resistivity.

The geometrically-independent quantity that is used is called *resistivity* and is usually indicated by the Greek symbol ρ .

$$\rho = \frac{R\,A}{L} \tag{5}$$

where ρ is the resistivity

In the case of a wire, resistivity is defined as the resistance in the wire, times the cross-sectional area of the wire, divided by the length of the wire. The units associated with resistivity are thus, ohm - m (ohm -meters). Resistivity is a fundamental parameter of the material making up the wire that describes how easily the wire can transmit an electrical current. High values of resistivity imply that the material making up the wire is very resistant to the flow of electricity. Low values of resistivity imply that the material making up the wire transmits electrical current very easily.

2.2.2 Resistivity of Earth Materials

Although some native metals and graphite conduct electricity, most rock-forming minerals are electrical insulators. Measured resistivities in Earth materials are primarily controlled by the movement of charged ions in pore fluids. Although water itself is not a good conductor of electricity, ground water generally contains dissolved compounds that greatly enhance its ability to conduct electricity. Hence, porosity and fluid saturation tend to dominate electrical resistivity measurements. In addition to pores, fractures within crystalline rock can lead to low resistivities if they are filled with fluids.

The resistivities of various earth materials are shown in Table 2. Like susceptibilities, there is a large range of resistivities, not only between varying rocks and minerals but also within rocks of the same type. This range of resistivities, as described above, is primarily a function of fluid content. Thus, a common target for electrical surveys is the identification of fluid saturated zones.

2.2.3 Potentials in homogenous media

Consider a continuous current flowing in an isotropic homogenous media. (This analysis will also apply AC if the frequency is low enough that displacement current is insignificant). If V is the volume of the media, S is the surface area, Q is the charge enclosed by the volume, I is the current through the media and J the current density in amperes per square meters. The flow of current through the volume is given by

$$I = -\frac{\partial Q}{\partial t} \qquad (6)$$

Table 2. The resistivities of various earth materials

Material	Resistivity(ohm-m)
Air	∞
Pyrite	$3x10^{-1}$
Galena	$2x10^{-3}$
Quartz	$4x10^{10}$-$2x10^{14}$
Calcite	$1x10^{12}$- $1x10^{13}$
Rock salt	30 – $1x10^{13}$
Mica	$9x10^{12}$-$1x10^{14}$
Granite	100- $1x10^{6}$
Gabbros	$1x10^{3}$- $1x10^{6}$
Basalt	10- $1x10^{7}$
Limestone	50- $1x10^{7}$
Sandstones	1- $1x10^{8}$
Shales	20- $2x10^{3}$
Dolomite	100-10,000
Sand	1- 1,000
Clay	1-100
Ground water	0.5-300
Sea water	0.2

In terms of charge density q and current density J, I and Q are given by,

$$(I)_s = \oint J \cdot \partial s \tag{7}$$

and

$$Q = \int_V q \cdot \partial v \tag{8}$$

where **V** is the volume enclosed by **s**.

Substituting equation (7) and equation (8) in to equation (6)

$$\oint_s J \cdot \partial s = -\frac{\partial}{\partial t} \int_V q \cdot \partial v \tag{9}$$

Using the divergence theorem,

$$\oint_S J \cdot \partial s = \int_V (\nabla \cdot J) \partial v$$

So that equation (9),

$$\int_V (\nabla \cdot J)\, \partial v = -\int_V \left(\frac{\partial q}{\partial t} \right) \partial v$$

$$\int_V \left[(\nabla \cdot J) + \frac{\partial q}{\partial t} \right] \partial v = 0 \tag{10}$$

Since equation (10) is for any volume,

$$\nabla \cdot J + \frac{\partial q}{\partial t} = 0 \tag{11}$$

Equation (11) is the law of conservation of charges in differential form. It is known as continuity equation.

For Direct Current (DC), the stationary field is conservative and hence the electric field intensity (E) is related the scalar function **V** as,

$$E = \nabla \cdot V \tag{12}$$

where **V** is the potential measured in volts.

Current density **J** and electric field **E** are related by Ohm's Law as

$$J = -\delta E \qquad (13)$$

where δ is the conductivity

Since resistivity is the reciprocal of conductivity (σ=1/ρ)

$$J = \frac{1}{\rho} E \qquad (14)$$

or

$$J = -\frac{1}{\rho}(gradv) \qquad (15)$$

From equation 7 and 10, we have,

$$Div\ (-\frac{1}{\rho} gradv) = 0$$

$$grad \frac{1}{\rho} grad\ V + \frac{1}{\rho}(div\ grad\ V) = 0 \qquad (16)$$

Equation (16) is the fundamental equation for electrical prospecting with direct current.

For homogenous media ρ is independent of coordinates (since div grad V =0) so that equation (16) reduces to

$$\nabla^2 V = 0 \qquad (17)$$

2.2.4: A practical way of measuring resistivity

Using an experimental configuration where the two current electrodes are placed relatively close to one another and using two potential electrodes placed between the two current electrodes, we can estimate the resistivity of our homogeneous earth. The configuration of the four electrodes for this experiment is shown below. Let the distances between the four electrodes be given by R_1, R_2, R_3, and R_4, as shown in Figure 7.

The voltage recorded by the voltmeter (ΔV) is relatively small. That is, the difference in the potential at the locations of the two potential electrodes is small. We could increase the size of the voltage recorded by the voltmeter by moving the two potential electrodes outward, closer to the two current electrodes. For a variety of reasons, some related to the reduction of noise and some related to maximizing the depth over which our measurements are sensitive, we will typically not move the potential and current electrodes close together. Thus, a very sensitive voltmeter must be used. In addition to having large impedance, voltmeters need to be able to record voltage differences down to mV (10^{-3} volts). If the potential electrodes were moved closer to the two current electrodes, larger voltages would be recorded. For a variety of reasons, however, we will typically not do this in the field.

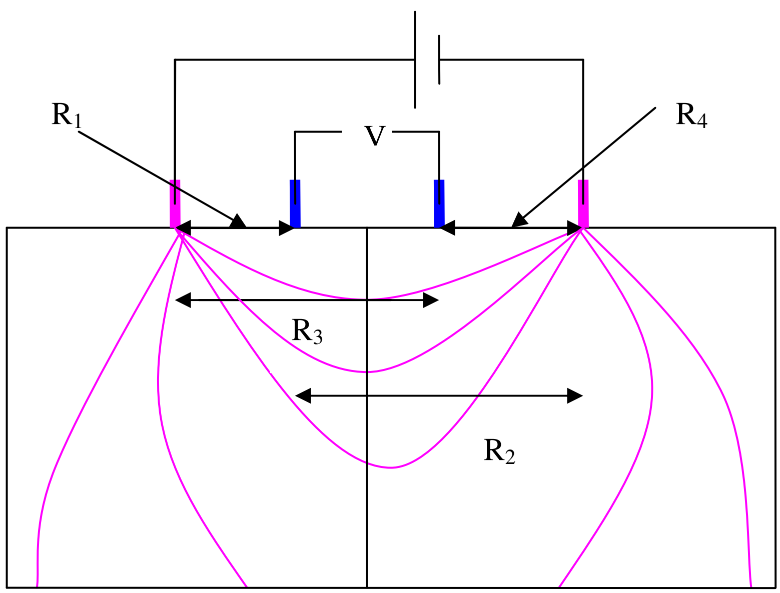

Figure 7. Practical way of measuring resistivity

Knowing the locations of the four electrodes, and by measuring the amount of current input into the ground, i and the voltage difference between the two potential electrodes, ΔV, we can compute the resistivity of the medium, ρ_a, using the following equation.

$$\rho_a = \frac{2\pi \Delta V}{i}\left[\frac{1}{\frac{1}{R_1} - \frac{1}{R_2} - \frac{1}{R_3} + \frac{1}{R_4}}\right] \tag{18}$$

In this particular case, regardless of the location of the four electrodes, ρ_a will be exactly equal to the resistivity of the medium. The resistivity computed using the equation given above is referred to as the *apparent resistivity*. We call it the apparent resistivity for the following reason. We can always compute ρ_a, and we only need to know the locations of the electrodes and measure the current and voltage. If, however, the Earth does not have a constant resistivity (that is, if the resistivity varies with depth or horizontally), the resistivity computed by the above equation will not represent the true resistivity of the earth. Thus, we refer to it as an apparent resistivity.

As a final caveat, as written above, the difference between the apparent and the true resistivity of the medium is not a function of any noise that might be associated with the measurements we are attempting to record. The difference, rather, comes from the fact that our measurement, in some sense, averages the true resistivities of some region of the earth, yielding an apparent resistivity that may or may not represent the true resistivity at some point within the earth.

2.2.5 Sources of Noise

There are a number of sources of noise that can affect our measurements of voltage and current from which we will compute apparent resistivities.

- *Electrode Polarization* - A metallic electrode, like a copper or steel rod, in contact with an electrolyte other than a saturated solution of one of its own salts, like ground water, will generate a measurable contact potential. In applications such as SP, these contact potentials can be larger than the natural potential that you are trying to record. Even for the DC methods described here, these potentials can be a significant fraction of the total potential measured.

For DC work, there are two possible solutions.

1. Use no polarizing electrodes. These are electrodes that contain a metallic conducting rod in contact with a saturated solution of its own salt. Copper and copper sulfate

solutions are commonly used. The rod and solution are placed in a porous ceramic container that allows the saturated solution to slowly leak out and make contact with the ground. Because these solutions are rather environmentally unfriendly, and because the method described below is easy to employ, these so-called *porous pot* electrodes are rarely used in DC work. They are, however, commonly used in SP and IP surveys.

2. A simple method to avoid the influence of these contact potentials is to periodically reverse the current flow in the current electrodes or use a slowly varying, a few cycles per second, AC current. As the current reverses, the polarizations at each electrode break down and begin to reverse. By measuring over several cycles, robust current and voltage measurements can be made with negligible polarization effects.

- *Telluric Currents* - Naturally existing currents flow within the earth. These currents are referred to as telluric currents. The existence of these currents can generate a measurable voltage across the potential electrodes even when no current is flowing through the current electrodes. By periodically reversing the current from the current electrodes, or by employing a slowly varying AC current, the effects of telluric currents on the measured voltage can be cancelled.
- *Presence of Nearby Conductors* -Electrical surveys cannot be performed around conductors that make contact with the ground. For example, the presence of buried pipes or chain-linked fences will act as current sinks. Because of their low resistivity, current will preferentially flow along these structures rather than flowing through the earth. The presence of these nearby conductors essentially acts as electrical shorts in the system.
- *Low Resistivity at the Near Surface* -Just as nearby conductors can act as current sinks that short out an electrical resistivity experiment, if the very near surface has a low resistivity; it is difficult to get current to flow more deeply within the earth. Thus, a highly conductive* near-surface layer such as a perched water table can prevent current from flowing more deeply within the earth.
- *Near-Electrode Geology and Topography* - Any variations in geology or water content localized around an electrode that produce near-surface variations in resistivity could greatly

influence resistivity measurements. In addition, rugged topography will act to concentrate current flow in valleys and disperse current flow on hills.

- *Current Induction in Measurement Cables* - Current flowing through the cables connecting the current source to the current electrodes can produce an induced current in the cables connecting the voltmeter to the voltage electrodes, thereby generating a spurious voltage reading. Keeping the current cables physically away from, a meter or two, the voltage cables can minimize this source of noise.

2.2.6 DC Resistivity Equipment

Compared to the equipment required for gravity surveying and magnetic surveying that required for DC resistivity surveying is much less exotic. In fact, it is rather mundane consisting of nothing more than a source of electrical current, an ammeter, a voltmeter, some cable, and electrodes. Given the nature of the measurements that we are making, however, there are some considerations that must be taken into account given the equipment used to perform the measurements.

- *Current Source* - A source of DC current is required. In general, batteries are not capable of producing the DC currents required, so that if a pure DC source is used, it has to be produced by a portable electric generator. If, as is commonly done to eliminate the effects of electrode potentials and telluric currents, a slowly varying AC current is used, portable, battery driven sources can be employed for DC resistivity surveys commonly used in engineering and environmental applications.
- *Ammeter* - A simple ammeter (a device for measuring electrical current) can be used. The only constraint is that the meter be capable of measuring amperage from a few mile Amperes to about 0.5 Amperes. Many of the modern instruments are regulated such that the user determines the amperage input into the ground and the instrument attempts to deliver it. If the instrument can not deliver the specified amperage, either because the subsurface is too resistive or the electrodes are too far apart, the instrument warns the user.

- *Voltmeter* - A simple voltmeter can also be used. To avoid problems with contact potential, a voltmeter with very high impedance, above 500,000 Ohms, should be used. The voltmeter must also be capable of measuring voltages from a few millivolts to a few volts.

- *Electrodes* - To avoid problems associated with electrode potentials sophisticated electrodes known as porous pots can be used. But, because spurious electrode potentials can be mitigated through the use of a slowly varying AC source, these electrodes are not commonly used for DC resistivity measurements. If the conditions in the survey are extremely dry and contact between the electrode and the ground can not be maintained, one might consider using porous pots. For DC resistivity surveys, the most commonly used electrodes are nothing more than aluminum, copper, or steel rods about two feet in length. These rods are driven into the ground and connected with cables to the current source or the voltmeter. Under dry conditions, contact between the rod and wetting the ground surrounding the electrode can enhance the ground.

- *Cables* - To connect the electrodes to the various electrical components, cables must be employed. These cables are typically nothing more than insulated wires with stranded, copper-cored conductors. Although long cable lengths may need to be employed, given the high resistivity of the ground, resistance in the cables is typically negligible. A more significant problem is current induction in the cables used to make the voltage measurement from the current flowing in the cables going to the current electrodes. This source of noise is easily avoidable by simply keeping the voltage cables at a distance (a few feet) from the current cables. For easy deployment, cables are usually stored on reels.

2.2.7 Survey Types: Soundings and Profiles

Thus far we have begun to see how geologically relevant structure can affect electrical current flow and measurements of voltage at the Earth's surface. We've described how depth variations in resistivity can be detected by increasing current electrode spacing by estimating apparent resistivities for various current electrode spacing. We have not, however, described the specific field procedures used in resistivity surveying. Before describing these procedures, there is an important point to note about the geologic structures considered thus far. Notice that the resistivity method represents the first method that we have described which can detect depth variations in a geologically relevant parameter. For example, if we conducted gravity or magnetic surveys atop structures that varied in density or magnetic susceptibility *only* with depth, we would observe no spatial variation in the Earth's gravity or magnetic fields. Thus, these methods are insensitive to changes in density and magnetic susceptibility that occur *solely* with depth.

- *Resistivity Soundings* - As we've already shown, the resistivity method can detect variations in resistivity that occurs solely with depth. In fact, this method is most commonly applied to look for variations in resistivity with depth. Surveys that are designed to determine resistivity variations with depth above some fixed surface location are referred to as *resistivity soundings*. An example of a problem for which one might employ resistivity soundings is the determination of depth to the water table. When doing resistivity-sounding surveys, one of two survey types is most commonly used. For both of these survey types, electrodes are distributed along a line, centered about a midpoint that is considered the location of the sounding. The simplest in terms of the geometry of electrode placement is referred to as a *Wenner* survey. The most time effective in terms of fieldwork is referred to as a *Schlumberger* survey.

  For a Wenner survey, the two current electrodes and the two potential electrodes are placed in line with each other, equidistant from one another, and centered on some location as shown below.

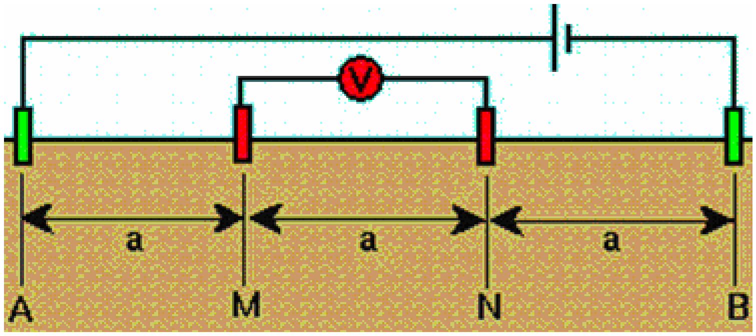

Figure 8. The arrangment of Wenner array

$$\rho_a = 2\pi a \frac{\Delta V}{i} \tag{19}$$

The apparent resistivity computed from measurements of voltage, ΔV, and current, i, is given by the relatively simple equation shown above. This equation is nothing more than the apparent resistivity expression shown previously with the electrode distances fixed to a. To generate a plot of apparent resistivity versus electrode spacing, from which we could interpret the resistivity variation with depth, we would have to compute apparent resistivity for a variety of electrode spacing, a. That is, after making a measurement we would have to move all four electrodes to new positions.

For a Schlumberger survey, the two current electrodes and the two potential electrodes are still placed in line with one another and centered on some location, but the potential and current electrodes are not placed equidistant from one another.

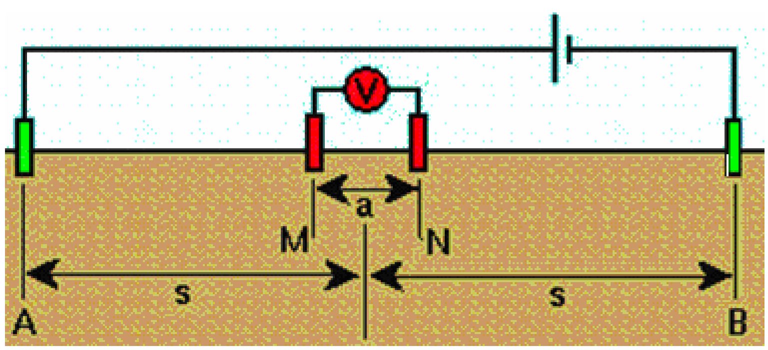

Figure 9. The arrangement of Schlumberger array

The apparent resistivity computed from the measurement of voltage , Δ V ,and the current ,*i*, is given by simple equation shown below.

$$\rho_a = \frac{\pi\left(s^2 - a^2/4\right)}{a}\frac{\Delta V}{i} \qquad (20)$$

- *Resistivity Profiles* - Like the gravity and magnetic methods, resistivity surveys can also be employed to detect lateral variations in resistivity. Unlike soundings, profiles employ fixed electrode spacing, and the center of the electrode spread is moved for each reading. These experiments thus provide estimates of the spatial variation in resistivity at some fixed electrode spacing. Surveys that are designed to locate lateral variations in resistivity are referred to as *resistivity profiles*. An example of a problem for which one might employ resistivity profiles is the location of a vertical fault.

2.2.8 The Principle of Equivalence and Suppression

In actual application of various interpretation methods to a particular field problem, limitations are set by maximum distance from the current source to which the electric field due to surface inhomogeneties. Furthermore, all measurements have finite accuracy. On account of all this causes, widely different resistivity distribution may lead to apparent resistivity curves, which, although they are not identical, cannot be distinguished in practice. This introduces ambiguity in the interpretation.

Mathematical formulation of two simple types of equivalence can be easily obtained. If we consider, for example, a relatively thin layer sandwiched between two layers whose resistivities are much larger than the sandwiched layer. Then the current flow in the earth will then tend to concentrate into the middle layer. The resistance of the elementary block of length, l and cross section, h & m to which a current flow is

$$R = \frac{\rho}{h}\left(\frac{\Delta l}{\Delta m}\right) \qquad (21)$$

and this will be unaltered if we have increase ρ and at the same time increase in the same proportion. Thus all such middle layers for which the ratio h/ρ is the same are electrically equivalent.

On the other hand, if the resistivity of the middle layer is much larger than that of the layers on either side of the middle layer, the electric current will tend to avoid it and take the shortest rout to the lower layer. The lines of the current flow will be almost perpendicular to the layer. The resistance of the elementary block will be

$$R = \rho\left(\frac{h}{\Delta A}\right) \qquad (22)$$

where, A is the cross section. In this case, all layers for the product hρ are the same are electrically equivalent, so that, h and ρ can not determined uniquely.

CHAPTER THREE

DATA ACQUISITION AND PROCESSING

3.1 Resitivity Survey

3.1.1 Instrument used and Field procedure

The instruments used for Schlumberger resistivity sounding survey are PASI 16GL Earth Resistivity Meter and the PASI P-100 Energizer along with cables reels and other accessories. A steel wire is used to connect the two ends of stainless steel current electrodes (A and B) to the transmitter output terminals and the potential electrodes (M and N) to the receiver input terminals of the instrument.

The Schlumberger electrode configuration with maximum current electrode separation (AB/2) of 500m was used for the sounding survey. Current is injected into the ground using two current electrodes, A and B, placed a distance L (AB) apart; and the potential drop that occurs between two other electrodes, M and N placed near the center of the current electrodes is measured. The current electrode separation, L, is progressively increased in steps to increase the depth of investigation, and at each step the measured current and potential reading are used to obtain the apparent resistivity of the ground.

The sounding curve which is a log-log plot of the apparent resistivity versus half the distance between the current electrodes (AB/2) is readily plotted in the field so that any erroneous measurements could be detected and taken care of.

3.1.2 Data acquisition and processing

A total of ten VES stations are made using Schlumberger field array along three profiles as shown in figure 10. Profile-1 is found inside Sodere the resort compounds and consists of four VES stations (VES-1, VES-2, VES-3 and VES-4) oriented nearly along NW to SE direction. The station separation between VES-1 and VES-2 is about 200m, between VES-2 and VES-3 is 200m, between VES-3 and VES-4 is approximately about 300m. VES-4 is found on island bounded by Awash River and is farther from VES-3 as compared to the others.

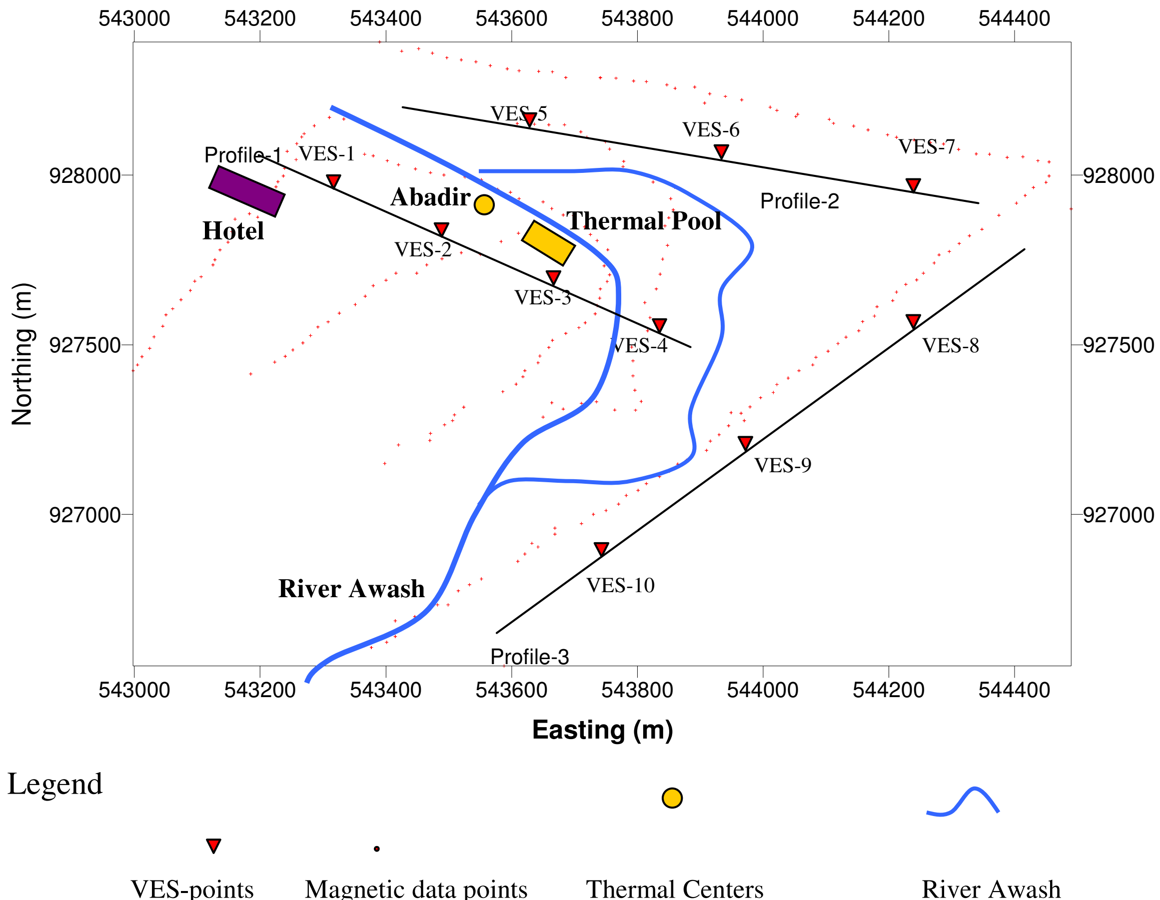

Figure 10. Survey Traverses

Profile-2 is found outside Sodere resort complex, on the other side of Awash River. It consists of three VES stations (VES-5, VES-6 and VES-7). The line runs along NW to SE direction nearly parallel to and approximately 1 km away from Profile-1 except that it is on the other side of the river. The VES station separation along profile two is uniform, at about 200m.

Profile-3 is also found outside Sodere resort hotel compounds and approximately perpendicular to Profiles -1 and -2. It consists of three VES stations (VES-8, VES-9 and VES-10) directed in the NE to SW direction. The station separation between VES-8 and VES-9 is about 300m and between VES-9 and VES-10 is approximately about 200m.

The six points per decade half-current electrode separation (AB/2) used are: 1.5m, 2.1m, 3m, 4.2m, 6m, 9m, 13.5m, 20m, 30m, 45m, 66m, 100m, 150m, 220m, 330m and 500m.The overlap readings are taken at 20m and 30m, and then at 150m and 220m. Table 3 gives the GPS locations of each VES points.

The Schlumberger sounding curves collected in the field were interpreted by using two layer master curves and auxiliary point charts to obtain the initial model parameters. This procedure is known as the technique of partial curve matching as a result of which layer parameters (layer resistivity and thicknesses) of the multilayer earth are obtained.

The layer parameters so obtained have been used as starting models in an interactive inversion program "RESIXIP", which provides the user with the tools for interpreting DC resistivity sounding data in terms of layered earth models, is used to analyze the VES data. The program utilizes a ridge regression inversion approach to fit to a suitable subsurface model to the field data through an iterative process in a least square sense and provides layer parameters (resistivity and thickness) beneath each sounding point. The program allows flexibility in data interpretation and also incorporates analysis to examine the problems of equivalence and suppression. Equivalent solution of best fit model are also generated by using certain parameters of the model depending on the type of equivalent of the many possibilities, the models which agree well with the assumed geological conditions are used to construct geoelectric sections. A geoelectric section shows both lateral and vertical variations of resistivity.

Table 3. GPS location of the sounding points

Traverse	VES No	UTM Coordinates	
		Easting	Northing
Line-1	1	543599	927945
	2	543334	928120
	3	543563	927984
	4	543817	927760
Line-2	5	543938	928244
	6	544195	928128

	7	544362	928047
Line-3	8	544279	927788
	9	544032	927369
	10	544520	928118

The smoothed field data have been plotted along each profile line to get pseudo sections using the apparent resistivity and pseudo depth values (AB/2) and depict the overall resistivity picture on a vertical section. Additional transversal lines have also been chosen along which pseudo sections have been constructed to get a generalized picture of the sub surface of the area and check for the consistency of the results. The pseudosections along the profiles from the apparent resistivity values are constructed using mapping soft ware" surfer 7".

3.2 Magnetic Survey

3.2.1 Instruments used and field procedure

The instrument used in magnetic survey is the Scintrex Integrated Geophysical System (IGS-2) geophysical equipment, which is a proton precision magnetometer. The IGS-2 system, which normally could work in various data acquisition modes, is adjusted, for this survey to measure the total magnetic field intensity and a digital display of value, with options for automatic and manual recording of the data. The magnetic data were collected along seven lines. In order to account for the diurnal variation of the earth's magnetic field, base station reading were taken at the beginning and end of each survey. A station spacing of 25m was used in all lines.

3.2.2 Data acquisition and processing

The field observed magnetic data were corrected for diurnal variation using the base station reading taken at the beginning and end of each survey. The maximum diurnal variation applied to the data amount to about 33nT. The main magnetic field at the survey area is obtained from international geomagnetic reference field (IGRF) and it is subtracted from diurnal corrected total field, then the anomalous field values are grided, hanned and contoured using the geosoft software package

(Geosoft Mapping system, 1994, Toronto, Canada.) The contoured anomalous magnetic field map is presented in Figure17.

In addition to the magnetic anomaly map, data enhancement techniques were applied to produce other maps, which may help to recognize more features. These are done by using the geosoft software package program called MAGMAP. By wave filtering method a long wave length and short wave length parts of the spectra were separated which may enable to see the nature of the data at different depth levels. Upward continuation was done to suppress shallow features and get smooth data. The apparent susceptibility maps at different depth levels are shown in Figures 19 and 20.

CHAPTER FOUR

RESULTS, DISCUSSION AND INTERPRETATION

4.1 Resistivity Survey

The resistivity data were presented interms of apparent resistivity pseudo section and geoelectric section. For this purpose, the sounding points that lie along a given line/traverse are used to draw the profiles.

4.1.1 Profile-1

This profile is found inside Sodere resort complex and is oriented along SE to NW direction. It consists of four VES points i.e. VES-1, VES-2, VES-3 and VES-4. The first three VES points run nearly parallel to Awash River while VES-4 is on an island where the river bifurcates on the upstream side before meeting again just at the Abadir bathing area.

a) Resistivity pseudosection along Profile-1

Figure 11 shows the general electrical picture of the ground section beneath Profile-1. According to the figure, high resistivity zones are observed at the bottom of VES-1 and at the top of VES-4. Low resistive zones, <20 Ω m from deeper horizon and extermly low resistivity from the left come together and tend to rise up on the surface around VES-2 and VES-3.

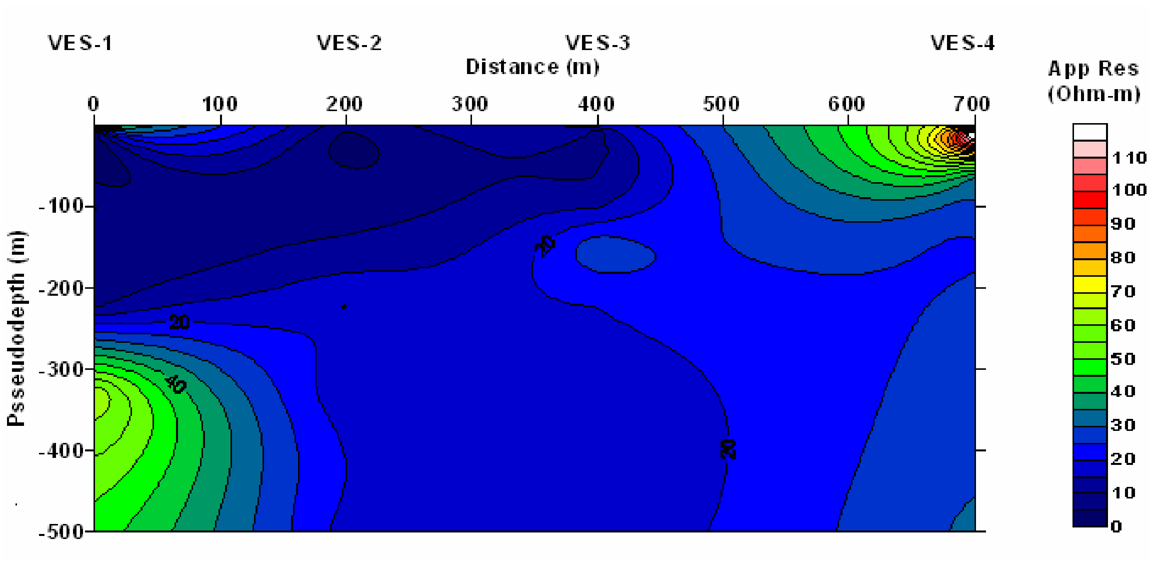

Figure 11. Apparent resistivity pseudosection along Profile-1

b) Geoelectric section along Profile-1

The interpreted geo electrical parameters from VES-1 through VES-4, along Profile-1 are presented in the form of a geoelectric section on Figure 12. The section depicts five geoelectric layers of varying thickness and resistivity response below VES-1, VES-3 and VES-4 while below VES-2, the section consists of four geoelectric layers.

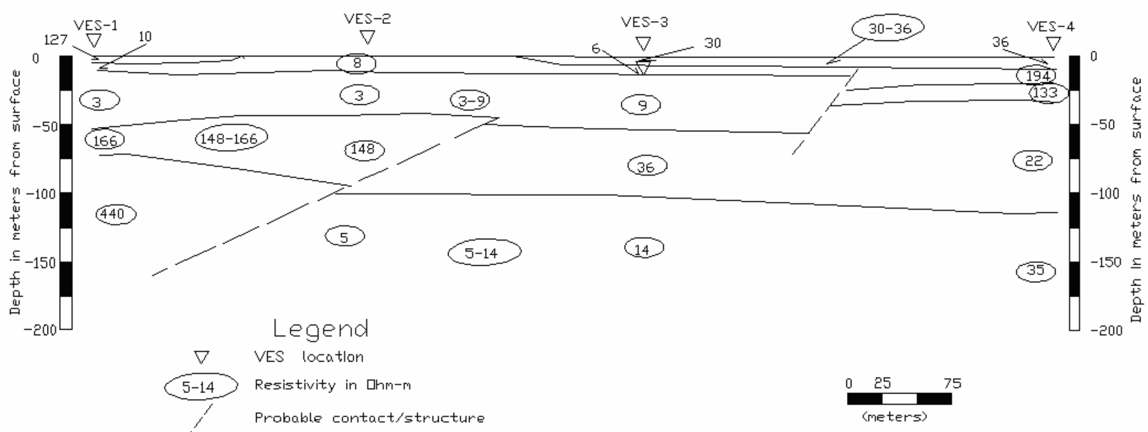

Figure 12. Geoelectric section along Profile-1

The top most layers shows resistivity ranges from 30 Ω m to 36 Ω m beneath VES-3 andVES-4 and relatively high resistivity (127 Ω m) values beneath VES-1, while low resistivity top layer is exhibited around VES-2.The resistivity variation of this layer may be result of varying degree of moisture content of recent alluvial deposit in the area. Over all, the thickness of this layer is from 1m to 2m.

The underlying very conductive second layer below VES-1, VES-2 and VES-3 is described by range of resistivity from 6 Ω m to 10 Ω m. The depth of this layer extends up to 3m from the surface. This range of resistivity layer is disappeared below VES-4. The second layer below VES-4 has resistivity of 194 Ω m and thickness about 6m.

The third, about 43meter thick layer of resistivity ranges from 3 Ω m to 9 Ω m exists below VES-1, VES-2 and VES-3.This ranges of resistivity layer is disappeared below VES-4.The third layer below VES-4 has resistivity of 133 Ω m which is slightly higher than the overlying layer.

The fourth thick layer of resistivity rages from 22 Ω m to 36 Ω m appeared below VES-3 and VES-4 and it is thicker below VES-4 than VES-3. Its depth ranges from 95m to 121m from the surface and can be interpreted as fractured, water saturated horizon. This range of resistivity layer is missed below VES-1 and VES-2. The fourth layer below VES-1 and VES-2 has resistivity ranges from 148 Ω m to 166 Ω m which is lower than the underlying layer of slightly higher resistvity.The high Resistivity layers at lower stratum below VES-1 may be due to the presence of pantelleric lava domes in the area. Two structures or contacts are identified at shallow depth between VES-3 and VES-4, deeper horizon below VES- 1 and VES-2.

Hydro thermally altered zone of low resistivity ranges from $5\,\Omega\,\text{m}$ to $14\,\Omega\,\text{m}$ is observed as a fifth layer below VES-2, VES-3 and VES-4. Two structures or contacts are identified at shallow depth between VES-3 and VES-4, deeper horizon below VES- 1 and VES-2 along north-east to south-west direction. The shallow structure may act as a conduit for cold water to recharge the hot aquifer from Awash River while the deeper structure may act as a conduit for hydrothermal water from deeper horizon.

4.1.2 Profile-2

This profile is found outside Sodere resort complex, on the other side of Awash River. It consists of three VES stations (VES-5, VES-6 and VES-7) and the profile line runs nearly parallel to the River.

a) Resistivity pseudo section along Profile-2

Figure 13 shows the general electrical picture of the ground section beneath Profile-2. According to the figure relatively high resistivity thin zone is observed at the top between VES-6 and VES-7. A horizontal dome like low resistive zones ($<15\,\Omega\,\text{m}$), started from the left and become sharp as one goes to the center of the section, is observed. Since VES-5 is near to Abadier where the hydrothermal water is used for bathing, the low resistivity zones below VES-5 may have a connection with the lower resistivity zones below VES-2 and VES-3 of Profile-1 and slightly higher resistvity is observed at the top between VES-6 and VES-7.

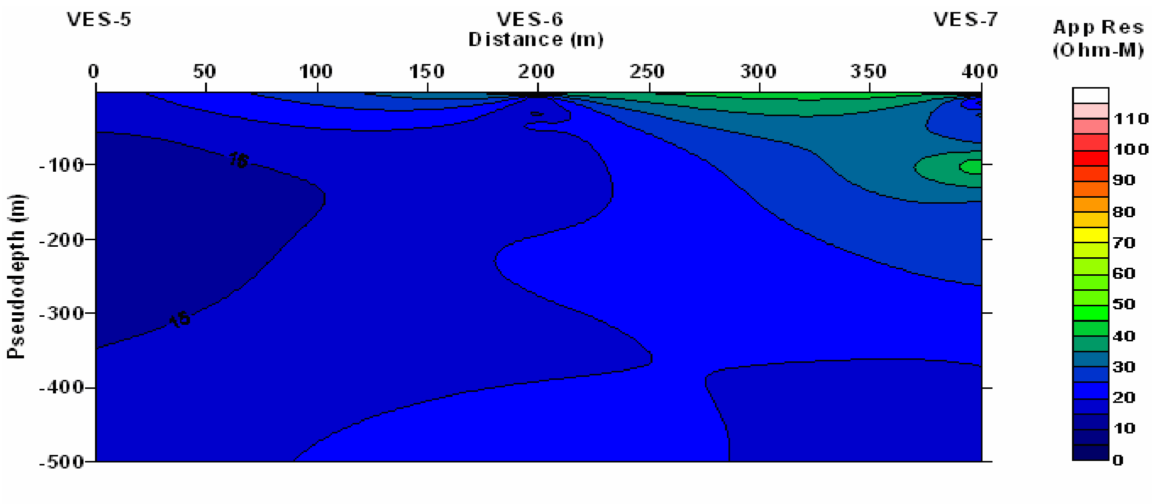

Figure 13. Apparent resistivity pseudo section along profile-2

b) Geoelectric section along Profile-2

The interpreted geoelectrical parameters from VES-5 through VES-7, along profile-2, are used to construct the geoelectric section given on Figure 14. The top thin layer of thickness about 1m to 2.5m has resistivity ranges from 54 Ω m to 78 Ω m beneath VES-6 and VES-7 which is the indication of dry alluvial deposit. The top layer is followed by 2m to 5m thick layer of resistivity ranges from 19 Ω m to 28 Ω m. The third layer of resistivity ranges from 69 Ω m to 78 Ω m is observed underlying the second layer of low resistivity. The thickest portion of this layer reaches a depth of about 20m. The varing degree of resistivity on the upper layers may due to the water content on the pore spaces of the rock unit found in the area.

The high resistivity of the third layer is followed by relatively low resistivity (7 Ω m-14 Ω m) layer. This layer coincides with the low resistvity of hydro thermally altered zone observed on the pseudo section. The thickest portion of the layer reaches a depth of 114m.

The fifth layer of resistivity ranges from 15 Ω m to 26 Ω m is found at the bottom stratum below 96m from the surface of the earth beneath VES-5 and VES-6 but it exist below 114m beneath VES-7.

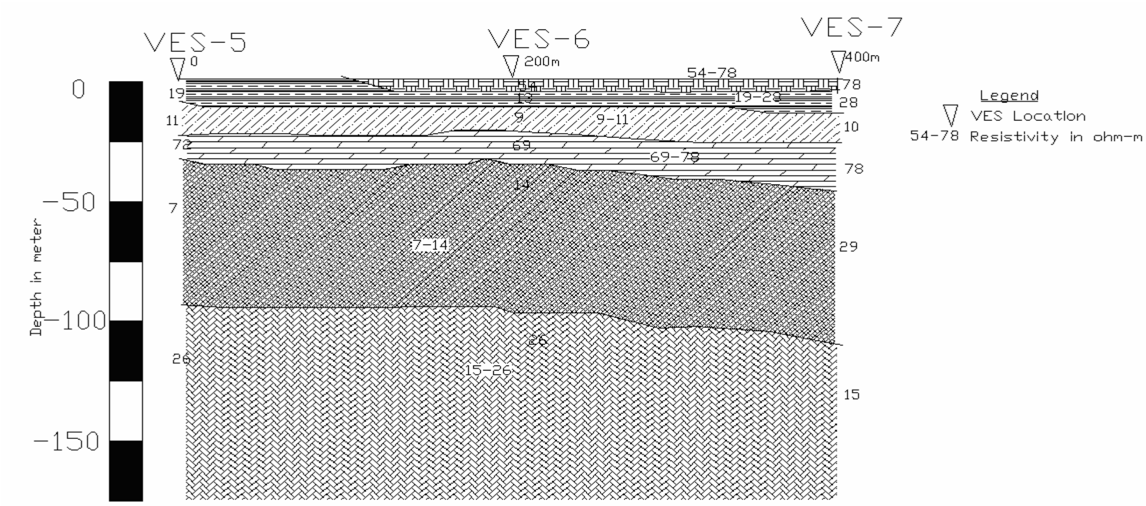

Figure 14. Geoelectric section along profile-2

4.1.3 Profile-3

This profile is also found outside Sodere resort compound and consists of three VES stations(VES-8, VES-9 and VES-10). The profile line runs nearly perpendicular to profile-1 and -2.

a) Resistivity pseudo section along Profile-3

Figure 15 shows the general electrical picture of the ground section beneath Profile-3. According to the figure, relatively high resistive zones are displayed on the upper and lower portion of the section below VES-9 which is bounded by a relatively low resistivity zones on both sides of the sounding point. The distribution of resistivity below VES-10 and VES-8 are generally low. The resistivity values observed are generally of low to moderate value indicating the possibility of a fluid saturated or moisture rich area. This may be the case because of the proximity of the area/profile to the Awash River and the presence of abundant fluids to saturate the subsurface horizons.

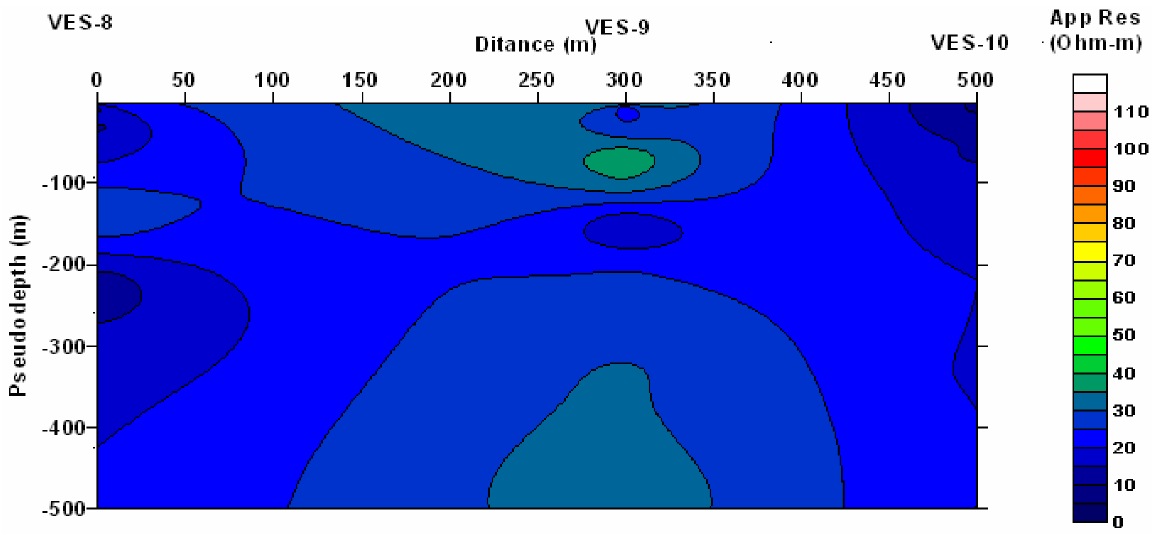

Figure 15. Apparent resistivity pseudo section along Profile-3

b) Geoelectric section along Profile-3

The sounding points VES-8, VES-9 and VES-10 are so aligned to enable one to construct a geoelectric section along Profile-3. The geoelectric section constructed from the interpreted layer parameters of the sounding points from VES-8 through VES-10 is given in Figure 16.

The section depicts five geoelectric layers of varying thickness and resistivity response. The top thinnest layer (approximately of 2-3m thickness over the section) has resistivity ranges from 37 Ω m to 46 Ω m below VES-8 and VES-9, with the layer becoming slightly thicker and conductive towards VES 10. This is the top dry soil layer and the variation in resistivity is the response of varying degrees of dryness/moisture content.

The second layer has resistivity ranges from 13 Ω m to 22 Ω m throughout the section. The thickness of this layer is nearly uniform, generally between 8m and 10 m, over the section. The low resistivity values obtained along the section are representative of a moisture/water saturated horizon.

The third layer has slightly higher resistivity response relative to the second layer and the resistivity values range from 20 Ω m to 40 Ω m. The thickest portion of this layer exists below VES-8 and the layer become thinner as one goes from VES-8 to VES-10.

The fourth layer has resistivity ranges from 9 Ω m to 19 Ω m. The resistivity values obtained are again representative of a water-saturated horizon. The source of the abundant water in the layers is definitely the Awash River and the proximity of the traverse line and the absence of any major barrier/structure for the movement of groundwater is expected to be responsible for its saturation. This layer is the thickest of the upper three layers. The middle portion is slightly bulged towards the surface than at the two ends of the layer. A slightly resistive, nearly homogenous layer, whose resistivities range from 25 Ω m to 36 Ω m, underlies the fourth layer below depths of about 100 m. This thick layer forms the substratum for the depth of investigation reached by the survey. In general, the geolectrical layers mapped along this profile are with near flat interfaces and show varying degrees of water saturation probably as a result of varying degrees of weathering and fracturing of the rock units.

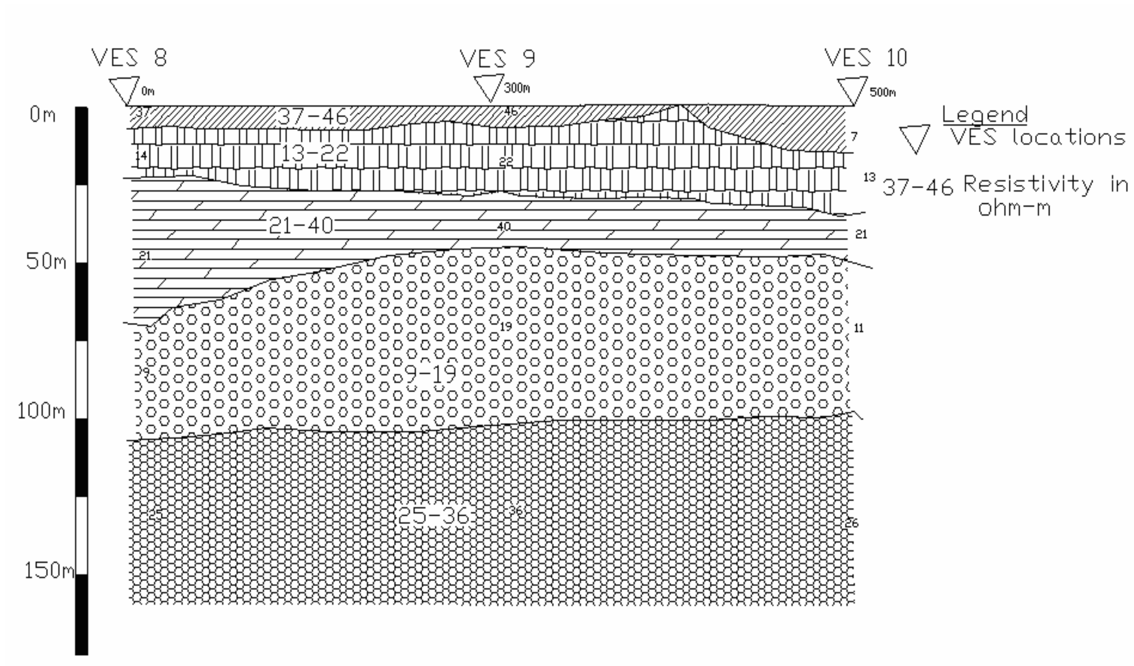

Figure 16. Geo electric section along Profile-3.

4.2 Magnetic Survey

The magnetic field of the earth is of a complex nature because of its dipolarity. The inducing magnetic field has a dip angle that varies from place to place over the surface of the earth, and this feature introduces a complexity in to the patterns of anomalies that are recorded.

The magnetic field observation made at or above the surface of the earth, the magnetization at the top of the magnetic part of the crust is characterized by relatively short spatial wave lengths, while the magnetic field from the demagnetization at the cure point in depth will be characterized by longer wave length and lower amplitude magnetic anomalies. This difference in frequency characteristics between the magnetic effect from the top and bottom of the magnetized layer in the crust can be used to separate magnetic effects at the two depths. Contour maps which are useful for interpretations were prepared by applying a variety of filtering techniques in order to enhance anomalies of interest.

The magnetic anomaly map on Figure-17 depicts low anomalies in north-south, upper central, north-west and isolated low magnetic anomaly is observed at south west of the study area. The intermediate magnetic anomaly over study area encloses the low magnetic anomaly and High magnetic anomaly is observed at the bottom of the map.

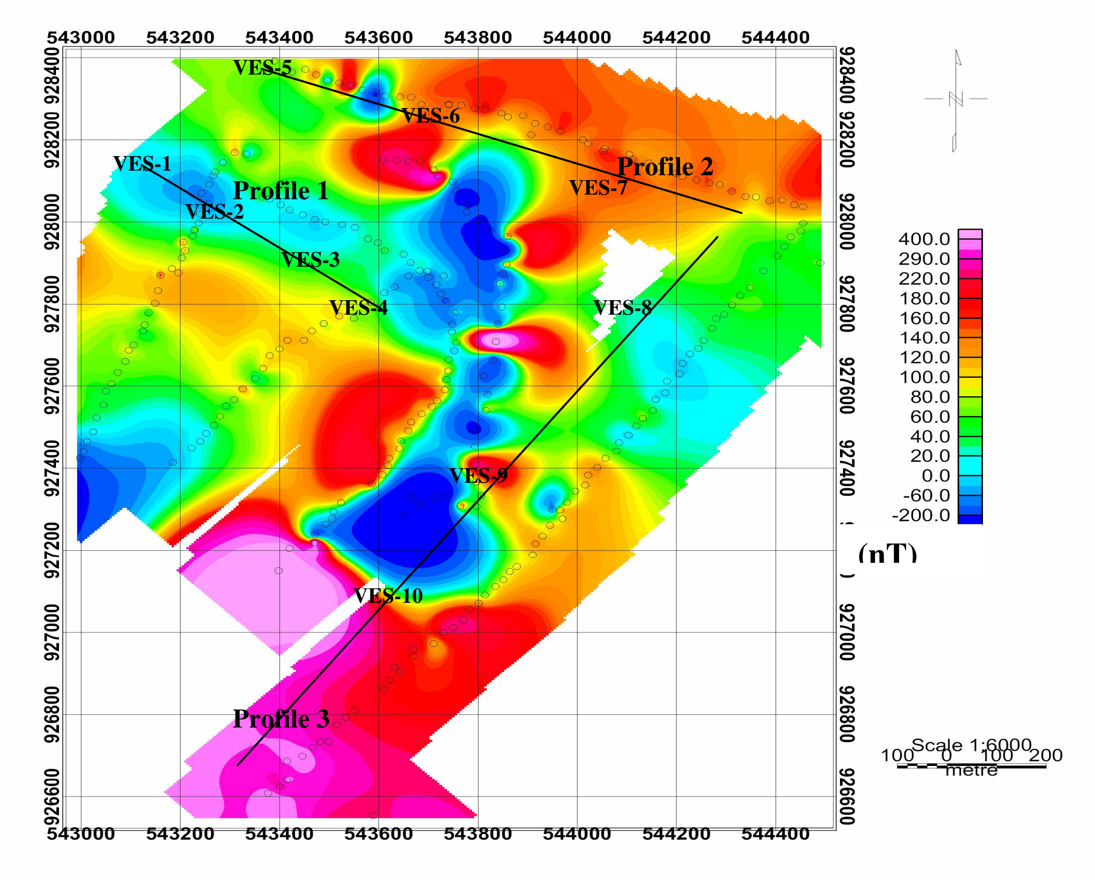

Figure 17. Magnetic anomaly contour map, Sodere Thermal Area

The upward continued map (up to 100m) is shown on Figure 18.The difference between the two maps (figure17 and figure 18) are the irregular anomaly features that have been displayed on residual magnetic anomaly map become smoothed and magnetic responses from shallow depth are removed.

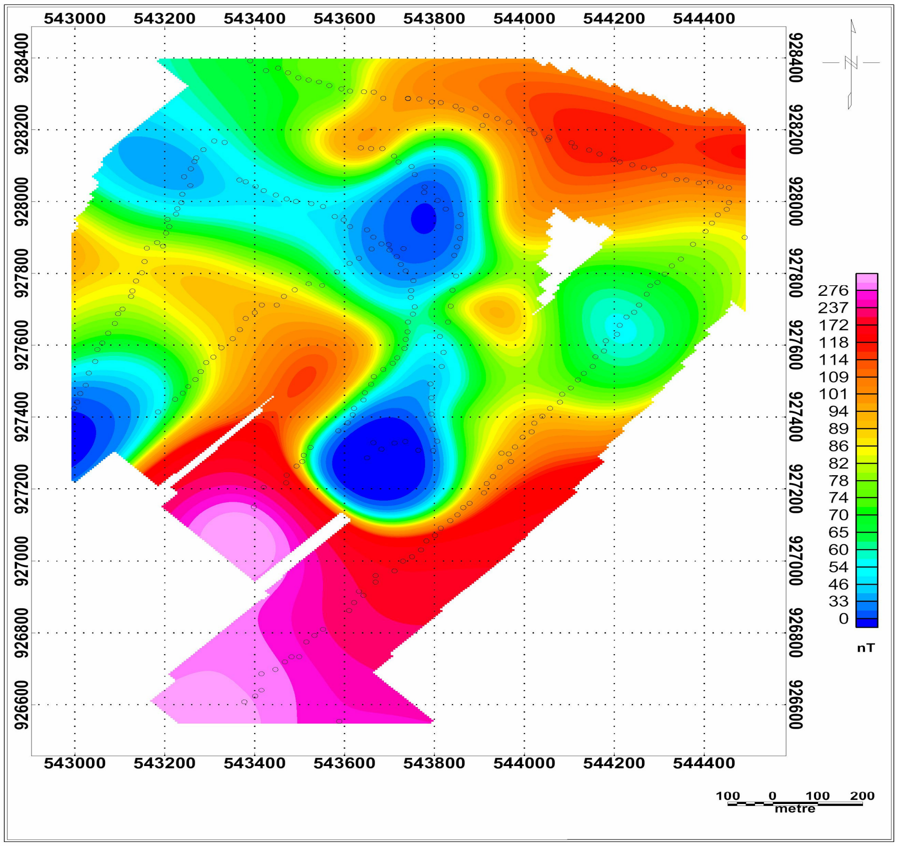

Figure 18. Upward continued (upto 100m) map of residual magnetic anomaly,
Sodere Thermal Area.

On the upward continued map (up to 200m) displayed on figure 19, the low magnetic anomaly that has been observed on the south west of the residual magnetic anomaly map is disappeared , the low magnetic anomaly that has been displayed at the bottom of the central region of the residual magnetic anomaly map become small in size. Voluminous low magnetic response from deeper horizon is observed at upper centeral and north west direction of the study area. In summary, the low residual magnetic anomalies displayed

at south west and lower central are the magnetic responses of the rock unit at shallow depth ,The low magnetic anomaly at upper central and north west of the survey area are coincide with the low resistvity region that has been observed on pseudosection and geoelectric section of profile-1and-2. Therefore, the response of low magnetic anomaly is an indication of hydro thermally altered zone of the study area. In addition, a structure that separate the two low magnetic anomalies at upper central and north west of the study area is identified along north east to south west. This structure is also identified by resistivity survey.

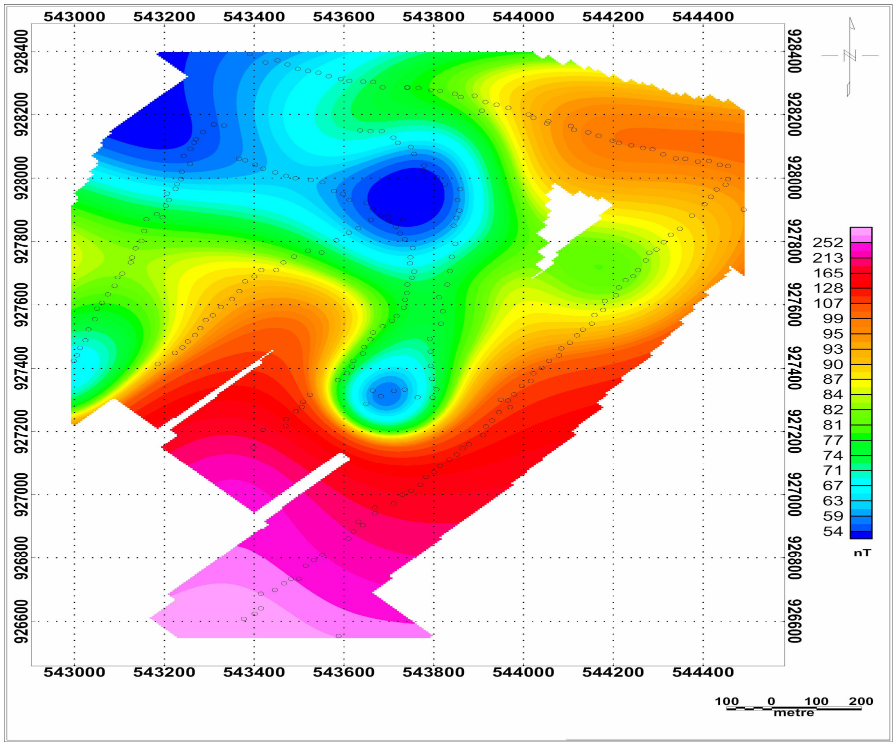

Figure 19. Upward continued (upto 200m) map of residual magnetic anomaly, Sodere thermal Area.

To illustrate more, the total magnetic field data of the magnetic survey that are on same traverse with resistvity survey are plotted as shown on Figures 19, 20 and 21.

Figure-20 shows the total magnetic field plotted along profile-1 of the resistivity survey. According to the graph, the central low total magnetic field region has strong agreement with the low resistivity that has been observed below VES-2 and VES-3.

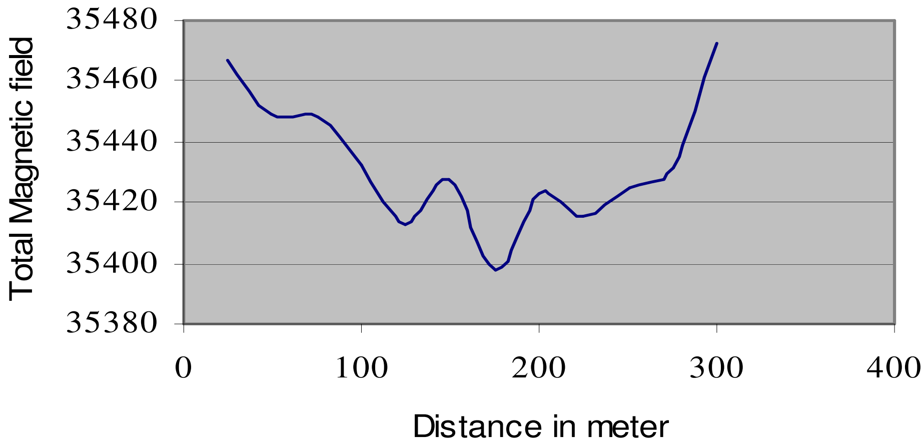

Fig-20. The total magnetic field along profile-1

Figure 21 Shows the total magnetic field plotted along profile-2. Since the traverse direction of the magnetic survey along this profile is in opposite to that of the resistivity survey. The low magnetic field at one end of the graph coincides with the low resistvity that has been observed below VES-5.

Figure 21. Total magnetic field plot along Profile-2

Figure22 shows the total magnetic field plotted along Profile-3 of the resistivity survey.

The high and the low value of the total magnetic field along this profile have no positive correlation with high and low values of resistivity survey. This in turn implies that the overall low values of resistivity along this profile may not indicate the presence of hydrothermal altered zone.

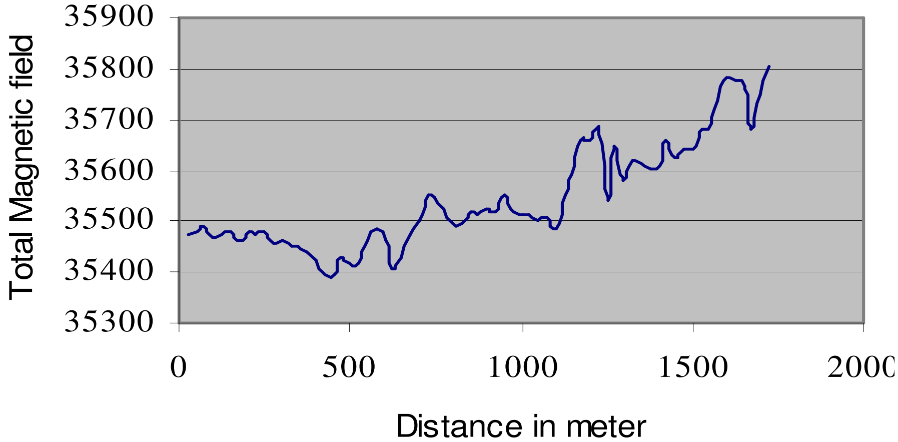

Figure 22. Total magnetic field along Profile-3

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the electrical survey, areas of low resistivity (typically $< 20\,\Omega m$) observed on the pseudo- and geoelectric sections along Profiles-1and -2 are interpreted as hydro thermally altered zone and the overall low resistivity observed along Profile-3 is interpreted as highly water saturated region of the area because of the close proximity of the profile to the Awash river and the absence of structures that act as a barriers for ground water movement.

Based on the joint analysis of these geophysical methods and thermal manifestation, the area has geothermal potential for further development from central to northwest of the study area.
Even though integrated geophysical methods, hydrogeology, geochemistry and heat flow model are very important to reinforce the outcome of the study and to come up with some conclusion, the preliminary result of the implemented geophysical methods in the study area leads to the following conclusions:

- Areas of low resistivity that coincide with low magnetic anomaly (with surface manifestations and alterations) are mapped.
- It has also been possible to map the presence of weak zones/ fractures in the subsurface which could act as conduits for the circulation of fluids in the area
- Lowering of resistivity and magnetic susceptibility could suggest the circulation of hot ground water through the fractures/faults to result in hydrothermal alteration.
- The heat source seems to be localized due to the sealing effect of fine grained, unwedded ignimbrites found in the area.
- The result of the two geophysical methods, thus, indicated that the study area has geothermal potential for further development and utilization of the thermal waters from shallow depths.

5.2 Recommendations

- Due to presence of infrastructure (buildings, power lines, etc…and rugged topography around the study area, it is inconvenient to carry out magnetic surveys long-traverse vertical electrical sounding. Therefore, the transient time domain electromagnetic (TEM) and magneto-telluric

(MT) methods are recommended for Sodere geothermal spring, for their potential to probe large depths and enhanced capacity in delineating subsurface horizons of anomalous heat and/or fluid.

- Gravity methods are recommended

  - to investigate the depth to heat source/ hot aquifer,

  - to identify the regional and local geological structures of the area that affect the hydrothermal resource of Sodere, and

  - to monitor sub surface characteristics of the groundwater.

- Integrating the geophysical results to hydro geological, geochemistry and heat flow model is helpful before qualifying the area for large-scale usage of geothermal resource.

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