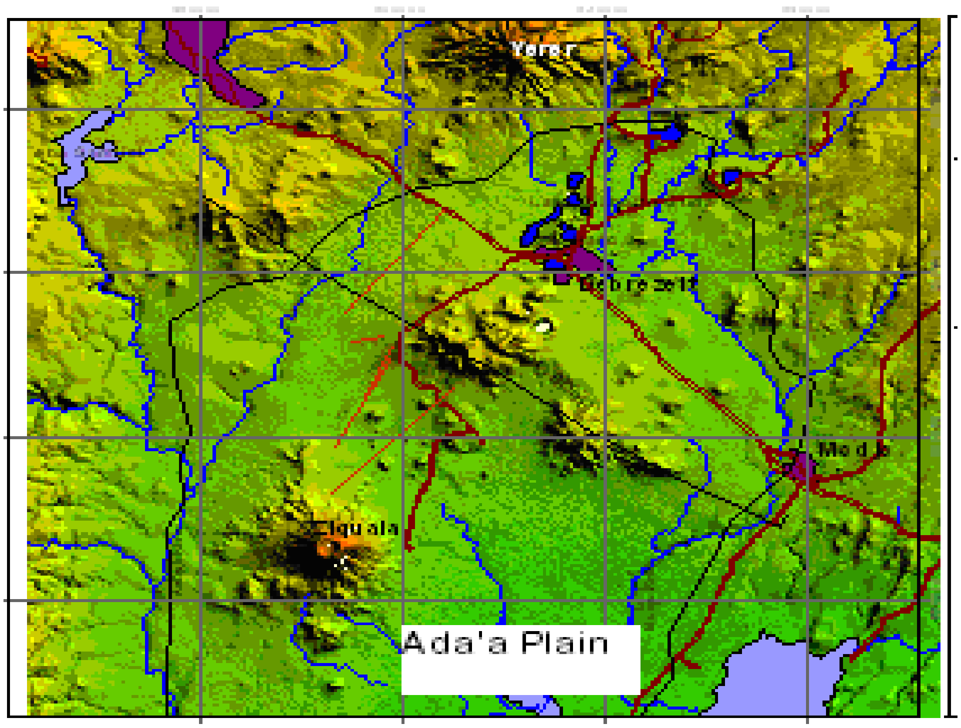
Integrated Geophysical Investigation FOR THE EVALUATION OF GROUND WATER RESOURCES AT ADA'A PLAIN NEAR DEBRE - ZEIT



A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS Ababa UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN EXPLORATION GEOPHYSICS

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ADDIS ABABA UNIVERSITY

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TABLE OF CONTENTS

CONTINUED…

List of Figures

ABSTRACT

This MSc thesis work entitled " Integrated Geophysical Investigation for the Evaluation of Ground Water Resources at "Ada'a Plain" located in Central Ethiopia, Oromiya Regional State and bounded approximately between geographic coordinates of 480000E - 540000 E and 900000N - 980000N.

Multi-disciplinary studies are currently going on at Ada'a Plain for the evaluation of groundwater potential and design of pressurized irrigation development, by the Ethiopian Ministry of Water Resources. The work is being undertaken by Water Works Design and Supervision Enterprise, on consultancy basis. Preliminary interpretation and conceptualization of the groundwater system of the plain have been made by the consultant. One of their findings reveals that the regional hydraulic gradient seams to be affected by some geologic features. One such possibility is regional scale structure(s), acting as a hydraulic barrier that impedes the movement of the groundwater.

This integrated geophysical investigation (Vertical Electrical Soundings/VES and magnetic methods), as part of a research project for MSc dissertation, was carried out to verify the inferred groundwater barrier and its possible connection to the linear geologic structures. Moreover, it also aims at establishing the hydro-Stratigraphy of the plain. The magnetic survey was found to be useful in lithologic mapping and identifying linear geologic features. On the magnetic map, NW-SE trending anomalies are in conformity with the anticipated groundwater barrier. However, the inferred groundwater barrier (the main target of the geophysical survey) was not detected and mapped by the resistivity method.

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To my wife Fantanesh Yimam, I am, as always, more deeply indebted than can be adequately expressed. Not only her devotion in typing, printing and binding of this thesis, but her moral support and encouragement have ensured my successful accomplishment.

My special thanks also goes to Ministry of Water Resources for giving me the opportunity to pursue the postgraduate study.

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Finally, I express my thanks to Water Works Design and Supervision Enterprise for providing me resistivity/VES data, borehole logs and other information which are useful for the thesis work.

ACCRONOMY

SWL	Static Water level
WWDSE	Water Works Design & Supervision Enterprise
MoWR	Ministry of Water Resources
VES	Vertical Electrical Sounding
nT	Nato-Tesla
m.a.s.l	meters above sea level
APGWB	Ada'a Plain Ground Water Basin.
MER	Main Ethiopian Rift

CHAPTER I

1. NTRODUCTION

1.1 GENERAL

Geophysical surveys have long been utilized by the mining and petroleum industries for many decades and basically used to determine, indirectly, the extent and nature of the geologic materials beneath the surface. With further development, geophysical techniques have found applications in wider areas of earth sciences addressing engineering geology, hydrogeology and environmental issues, among others.

Ideally groundwater development should be preceded by proper investigation and assessment which might be undertaken at various levels. Reconnaissance investigations, usually, are carried out in a short span of time using limited resources. This in turn requires the use of cost effective techniques in order to gain some preliminary knowledge of resources. Detailed investigations, generally, will require more time (depending on size of study area, data available, etc) and, may require the use of geophysics and some test drilling.

Regional ground water assessment programs usually carried out over relatively large areas and will provide guidelines for pinpointing the most likely areas for detailed work by providing information on the overall potential of the area available for exploitation.

This manuscript, as a research project for MSc dissertation, deals with application of geophysical techniques for regional hydro geological studies, i.e. assessing and mapping of groundwater resources and their spatial distribution.

During this study, primary and auxiliary data were collected, reviewed, analyzed and interpreted. Acquiring the auxiliary data set includes collection of maps, technical reports and other written documents related to the studied area, while the primary data collection comprises geophysical data involving resistivity [Vertical Electrical Sounding (VES)], and magnetic survey.

The thesis has been organized in Five Chapters. The First Chapter is Introduction and presents general insight on the location, objective and scope of the study. Chapter Two is overview of the study area and puts further emphasis on the physiographic, general geologic, hydrogeologic and tectonic aspects of the study area. Chapter Three discusses the basic principles of the geophysical methods with emphasis on resistivity and magnetics. Chapter Four discusses the theoretical basis of resistivity and magnetic methods. Finally Chapter Five discussions about the field work, data reduction interpretation conclusion and recommendation of the studies.

1.2 THE STUDY AREA

1.2.1 Location and Topography

The study area, Ada'a plain is situated in the upper part of Awash River Basin. Specifically, it is situated in Central Ethiopia, in Oromiya Regional State, and bounded, approximately, between geographic coordinates of 480000E - 540000 E and 900000N - 980000N . The Ada'a plain groundwater basin is found along the Addis Ababa-Djibouti highway, from 35 to 70 km of distances from Addis Ababa, and topographically varies between 1600 and 1900 m above the mean sea level (a.m.s.l).

The area is bordered by the Erere Mountain and Kesem River basin Water shed divide, in the north, and Koka reservoir in the south. The total area of Ada'a plain is more that 1500 km^2.

The mean annual rainfall of the study area is about 902 mm, and, the mean monthly temperature varies from 16 to 22^{o}C.

It is dominated by an extensive lacustrine deposit over the flat area with isolated hills and mountains like mountain Ziquala. A number of small Lakes scattered within small area, at and near by Debre Zeit town. Dukem and Mojo are the other main towns situated at the western and eastern extreme of the study area respectively.

During dry seasons, the Study area is accessible by dusty roads using four-wheel-drive vehicles. During rainy seasons, however, the soil becomes sticky and slippery, making accessibility difficult.

The location of the study area is shown in figure 1.

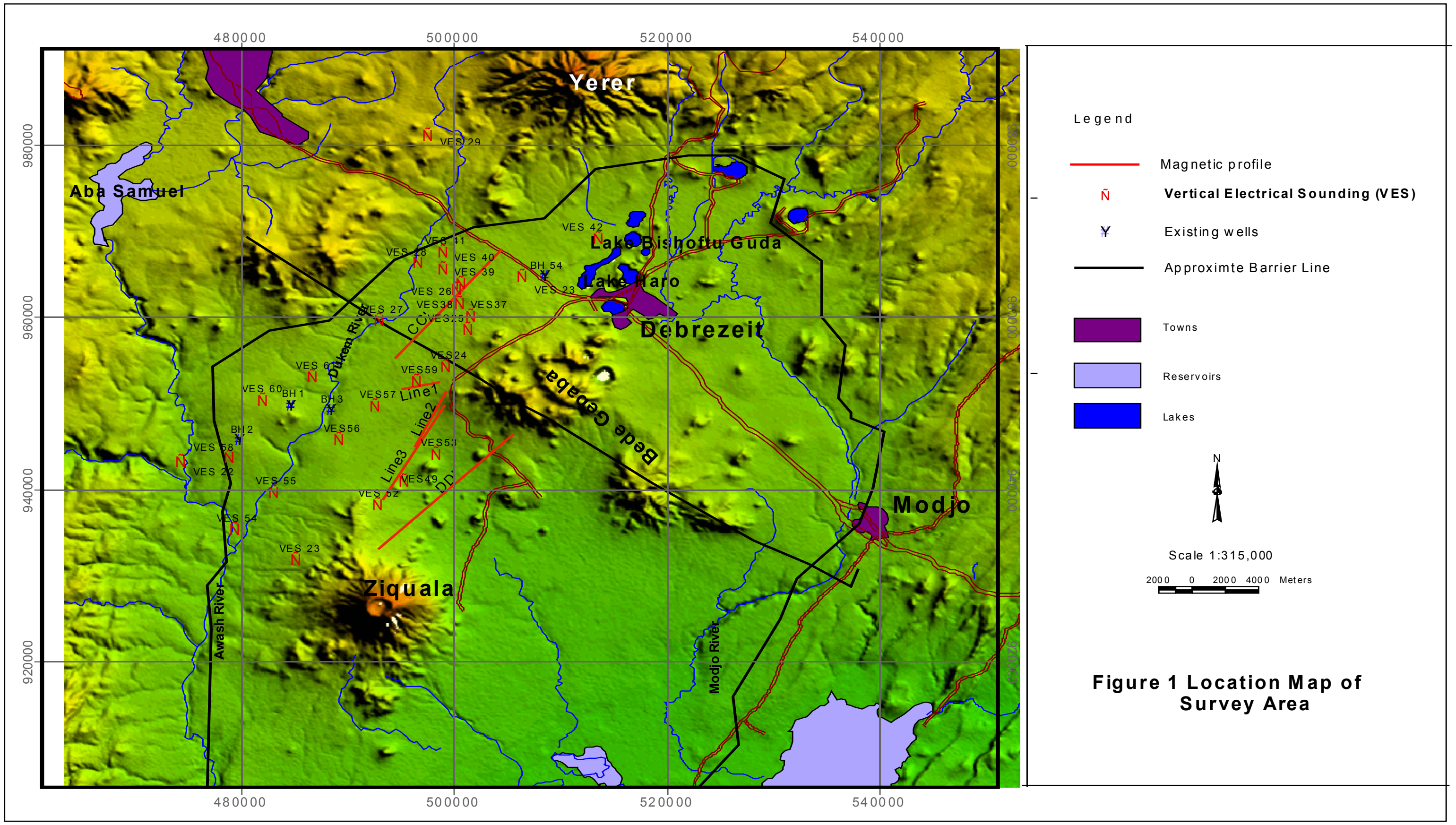


Figure 1 Location of the Study Area

1.3 OBJECTIVES AND SCOPE OF THE STUDY

Multi-disciplinary studies are currently going on at Ada'a Plain for the evaluation of groundwater potential and design of pressurized irrigation development, by the Ethiopian Ministry of Water Resources. The work is being undertaken by Water Works Design and Supervision Enterprise, on consultancy basis.

Preliminary interpretation and conceptualization of the groundwater system of the plain have been made by the consultant. Accordingly, a longitudinal profile of the Ada'a Plain, showing both the topography and potentiometric surface, reveals that the regional hydraulic gradient seams to be affected by some geologic features. One such possibility is regional scale structure(s), acting as a hydraulic barrier that impedes the movement of the groundwater. The water level contour also shows that the depth to the water table is reversed, appearing deeper at topographically low areas. Moreover, linear geologic structures, anticipated from aerial photo and Land-Sat imagery interpretations, are thought to have some connection with the regional hydro-geological regime (Figure-1).

This integrated geophysical investigation, as part of a research project for M.SC dissertation, was carried out to verify the inferred groundwater barrier and its possible connection to the linear geologic structures. Moreover, it also aims at establishing the hydro-Stratigraphy of the plain.

1.3.1 Objectives

The specific objectives of the work are:

1) Out-lining the inferred subsurface groundwater barriers.
2) Delineating other linear geologic structures that were anticipated by other techniques.
3) Mapping the saturated zone and trace the regional configuration of the water table of the project area.
4) Supplementing additional local sub surface geologic and hydro-geologic information.
5) Showing the merit of integrated geophysical investigation for evaluating the groundwater resources and its role in establishment of regional models.

Nevertheless, it is beyond the scope of this study to undertake exhaustive investigations covering the whole of Ada'a plain, owing to limited logistical and financial resources and time constraint. Thus the geophysical survey was made on the western periphery of Ada'a plain of (south west of Debre Zeyt), within the geographic coordinates (UTM), 470000E to 490000E and 95000N to 97000N.

The results, conclusions and recommendations, from this localized study area might be applied to the remaining part of the plain.

CHAPTER II

2. GENERAL OVERVIE OF THE STUDY AREA

2.1 PHYSIOGRPHY

From physiographical point of view, Ethiopia is broadly divided into three major regions:

a) The western highland, including the Ethiopian plateau and associated lowlands (WHAL),
b) The Eastern Highland and associated lowlands (EHAL) and,
c) The Rift Valley (RV), running North-South approximately, in the middle of the country and dividing the western from the eastern highlands.

The study area lies at the upper shoulder (western margin) of the Main Ethiopian Rift (MER) system, within upper Awash River basin. Quaternary tectonics, volcanism and sedimentation, played a significant role in shaping the present morphology of the Rift valley.

2.2 GEOLOGY AND TECTONIC OF THE MAIN ETHIOPIAN RIFT

2.2.1 Regional Geology

The regional geological of the area is characterized by a series of formation and events from early Tertiary to Quaternary era. The grand Afro-Arabian swell was formed in upper Eocene. Following uplift of horn of Africa, immense quantities of lavas, the Trap series, extruded from fissures and eruption centers **(Mohr, 1961).**

The trap series lavas which are mostly basaltic in composition (with some acidic flows in the upper parts) cover large areas of Mesozoic sediments and in some places; they rest directly on the Basement complex. Such uplifts, together with the extrusion of thick and extensive Trappean lava, account for the formation of the present highland region of Ethiopia.

In the upper Pliocene to recent, a succession of pantelleritic Rhyololites, Trachytes and Ignimbrites with subordinate intermediate and basic rocks, were erupted chiefly at the rift margins and along the seismically active Wonji fault. This trachyte-pantelleritic ignimbrite covered most of the southern Ethiopian plateau and filled the Main Ethiopian Rift. Its thickness ranges from about 300m to 500m, probably even greater on the rift floor **(Mohr 1968, Baker et al. 1972).**

2.3 TECTONICS

The Tertiary - Quaternary system, known as the East African system, is one of the largest structural features of the earth crust. They are widely believed to have been formed by diverging lithospheric plates, since early Tertiary times. It extends from Mozambique to Syria. The east African system is most typically developed in the section as the main Ethiopian Rift **(Mohr, 1964)**, which extends from lake Chamo, in the south, to Afar in the north. The main Ethiopian Rift is characterized by NE-SW, and ENE-WSW trending normal faults. According to previous studies in and around the project area, lineaments (faults) are predominantly trending NE-SW with dip towards NW and SE respectively.

2.4 GEOLOGY OF DEBRE-ZEYT

The area around Debre-Zeyt, (where Ada'a plain occupies a larger proportion) is mainly covered by volcanic and sedimentary rocks. The sedimentary rocks consist of alluvial cover and lacustrine sequences. Volcanic activity in the area has given rise to central composite volcanoes as well as to monogenic apparatea as domes, spatter cones and maars. Ignimbrites, consisting of several units, appear as wide sub-horizontal covers, while basaltic lavas are generally tabular.

From geological map of Debre Zeyt **figure2. Mazzarini, 1999)** recognize ten volcanic units that were grouped into four volcanic complexes. These were defined on the basis of field data and morpho-structural features, further they define three main structural sectors; the western rift margin, the main rift floor and an intra-rift depression (fig 2).Since upper Miocene, the Debre Zeyt area was the site of the interaction between the Main Ethiopian Rift and an E-W traverse structure (Yerer-Tullu Wellel Volcanic Lineament,YTVL) that produced the smoothing of the morphological expression of the rift margin and the onset of a secondary rift axis associated with the most recent volcanic activity **(F. Mazzarini 1999)**. A simplified geological map of Debre zeyt is shown on figure 2.

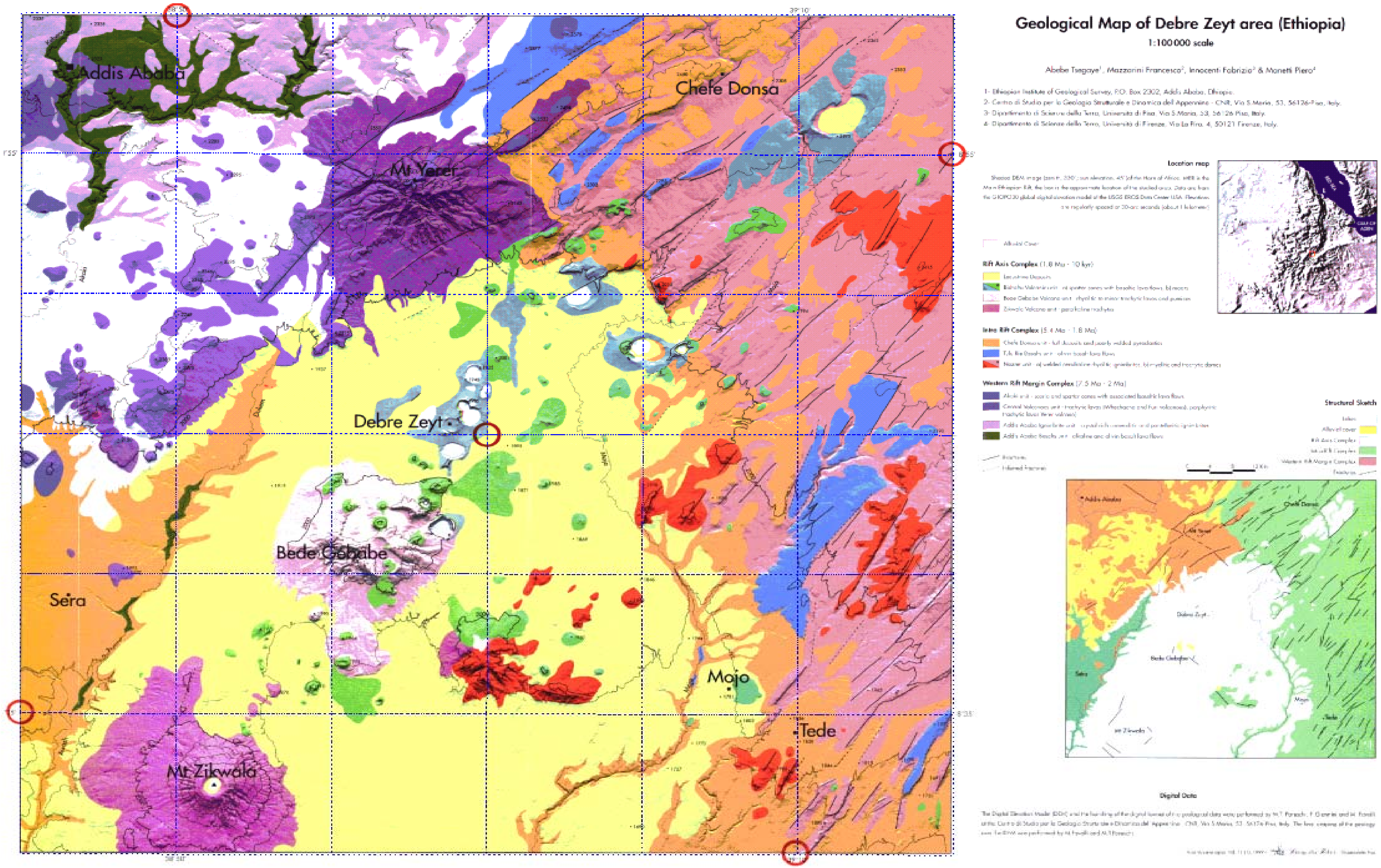


Figure 2 Geological Map of Debre Zeit Area

2.4.1 Stratigraphy

According to **(F. Mazzarini, 1999)**, three complexes were defined; based on morph-structural features and their relation with MER.

2.4.1.1 Western Rift Margin Complex

This complex exhibits age ranging from 7.5 to 2 Ma. It is dominated by four volcanic units, grouped according their age. They are:

1) **Akaki unit** - Scoria and spatter cones with associated basaltic lava flows,
2) **Central Volcanic Units-** Trachy lavas (Whechacha and Furi volcanoes), porphyritic trachy lavas (Yerer volcano)
3) **Addis Ababa Ignimbrite unit-** crystal rich comendic and pantelleritic ignimbrites, and,
4) **Addis Ababa Basalt unit**- olivine and olivine basalt lava flows.

2.4.1.2 Intra-Rift complex

In this complex upper Miocene-Quaternary products which constitute the floor of the main rift and its successive fillings are:

Chefe Dansa unit- fall deposits and poorly welded pyroclastics

Tulu Rie Basalts unit- Olivine basalt lava flows

Nazret unit- a) welded peralkaline rhyolitic ignimbrites
b) Rhyolitic and trachytic domes

2.4.1.3 Rift Axis Complex

The study area Ada'a plain stretches almost on this complex. It is made up of a Quaternary-Holocene consisting of young central volcanoes, lacustrine deposits and basaltic cinder and spatter cones; aligned NNE along the axis of the secondary rift. The stratigraphic units of the area will be discussed in detail according to their age, in increasing order.

Zikwala Volcanic unit(ZV). Zikwala is an isolated, well preserved composite cone standing 1300m above its regional base and located in the southern part of the studied area. Lavas are the dominant products with pyroclastics mainly occurring at the south-eastern foot of the volcano. Lavas are dominated by peralkaline Trachytes.

Bede-Gebabe Volcano unit (BGV). Bede-Gebabe, located in the central part of the studied area, is a volcanic complex with a quasi-circular shape, slightly elongated towards NNE and with a maximum altitude of 400m above the surrounding relief. Its morphology is dominated by the occurrence of several coalescent caldera structures. Lacustrine deposits rest above (BGV) all over its marginal portion. Furthermore, spatter cones and basaltic lava flows belonging to the younger Bishoftu Volcanics are present in the central part of the volcanic complex. The most recent products are represented by Rhyolitic obsidians, pumices and lavas show a composition ranging from Rhyolites to minor Trachytes, **(Gasparon et. al., 1993)**

Lacustrine deposits (LD). LD represent about 28% of the exposed rocks and are developed on a relative, NE elongated depression, in the central sector of the area. These fine grained deposits are generally brown-yellowish, thinly stratified and often contain abundant volcanic matrix. In the successions, volcanic layers are frequent and become predominant and coarse grained in the neighboring of the maars.

Generally, the axial sequence developed since 1.2 Ma up to Holocene is constituted by composite volcanoes, scoria cones and maars grown along a relatively narrow NNE trending depressed area .The youngest Volcanics are inter-bedded with lacustrine deposits.

2.5 HYDROGEOLOGY OF ADA'A PLAIN

The aquifers of Ada'a plain are lacustrine sediments, scoria, scoraceous basalt and vesicular basalts (volcanic aquifers).

The thickness of lacustrine sediment can reach up to 100m, underlain by scoraceous basalt.

The lacustrine sediments show a lot of differences in their permeability, those showing the highest permeability are the ones consisting of volcanic sands, water lain volcanic sands (such as those around Debre Zeyt and Metehara). On the other hand, fine grained sediments with intrbedding of massive tuffs and fine ash are also known.

The volcanic aquifers have primary porosities like vesicles, and secondary porosities like faults, fractures & fissures produced as a result of tectonic activities and weathering zones. Generally in the volcanic rocks ground water circulation, occurrence (storage) is associated with those porosities ,while in the alluvial and lacustrine aquifers, it is in the interstitial spaces in between the sediments.

In the rift floor the geological complexity, has created a highly segmented groundwater distribution although the regional groundwater flow is from the escarpments into the valley and north east wards to lake Abe. (HALCROW, 1989).

The report of Tesfaye Chernet and HLCROW indicates that there is a groundwater divide between Lake Ziway and Ada'a plain groundwater basin.

In general the main Ethiopian rift regional groundwater system have a divide between Lake Ziway and APGWB, i.e. one part from the divide flows in north east direction along the rift valley to Lake Abbe, the other part flows from the divide south west direction along the rift to lake Chew Bahir. (WWDSE, 2006,Inception Report, evaluation of water resources of Ada'a plain).

Review of the previous studies & available data shows the plain is separated by barrier condition of Bede Gebaba ridge, that can be categorized by the depth the ground water in to two zones Fig 1.

The first zone (Zone I) is N-E of Bede Gebabe volcances in this zone the groundwater depth is relatively shallow (30-40m) and all Debre - Zeite lakes are concentrated in this zone.

The main reason for shallow groundwater could be the barrier condition of the acidic volcanic rocks of Bede Gebabe. According to Seifu Kebede (1999) condcting gechemical & isotopical mass balance, the lake water outflow as groundwater was found to be very low this could be that the Bede Gebabe ridge acts as barriers for groundwater flow in S.W direction.

The second zone, which is found S.W of Bede Gebabe. The surface elevation of this zone is lower than the first. The ground water depth is deep and reaches up to 100m and at some places even deeper. (WWDSE,Inception Report, evaluation of water resources of Ada'a plain).

The most important features governing the groundwater flow and storage in volcanic rocks are, vertical permeability due to primary and secondary fractures or horizontal permeability or due to horizon containing opening due to the lava flow and gas expansion during solidification or due to occurrence of impervious horizons and dykes. In the volcanic terrain, it is possible to find potential water bearing zones intercalated with relatively impervious units. In such aquifers ground water occurs under confined conditions. Interbedding of massive units with fractured and porous media also gives rise to multi-layer aquifer systems.

2.5.1 Hydrogeological Boundaries

Geological boundaries define the volume of an aquifer and hydrological, boundaries, especially the water table, define the volume of water stored within it Commonly encountered geological boundaries are stratification of aquifers and of aquifers against aquicludes, the termination of aquifers by faults , unconformities and igneous intrusions (dykes,sills).

Not every geological boundary need function as a hydrogeological boundary: there must be a noticeable difference in either the transmissive or storage characters of the ground, or in the chemistry of the ground-water on either side of the boundary. Hydrogeological boundaries are therefore usually revealed by there being across them a change either in water levels, or in the gradient of water levels, or in water quality. The causes of the discontinuity or abrupt drops of water level on either side of the barrier is that the barrier (bedrock ridge) is virtually impermeable and impede the flow of ground water.

The contrast in physical properties, like resistivity, density and magnetic susceptibility between the barrier and the country -rock will enable us to delineate and outline a buried groundwater divide. Thus a properly planned and executed geophysical investigation (with closely spaced observation points and perpendicular to the strike of the expected divide) will give satisfactory information. However, the delineation of the structure will become difficult if the width of the barrier is narrow.

High resistivity anomalies are normally anticipated while crossing the barrier, if it is a basic volcanic intrusion acting as a ridge it will display a high magnetic response. Massive trachytic and rhyolitic mountains and their roots are usually aquifuges acting as groundwater barriers around them, since these units are acidic they exhibits a low magnetic response. The density contrast between the barrier and host-rock will make a gravity method useful. All the above techniques are effective when there is no surface evidence about the presence of the barrier, and thus detecting and recognizing its existence.

CHAPTER III

3. PRINCIPLES OF GEOPHYSICAL EXPLORATION

3.1 GENERAL

Geophysical investigations of the interior of the Earth involve taking measurements at or near the Earth's surface that are influenced by the internal distribution of physical properties. Analysis of the geophysical data reveals the distributions of physical properties at depths that reflect the subsurface geology.

Depending on the source signals, geophysical methods falls into two major groups: those that make use of natural fields of the Earth (passive methods), and those that require artificially generated energy as source signals (active methods). The passive methods utilize the Earth's natural fields which include; the gravitational, magnetic, electrical and electromagnetic fields. The active geophysical methods, in the other hand, involve detection of responses for artificially generated local source fields and waves such as: electrical, electromagnetic and seismic. In general, the aim of geophysical prospecting is searching for local perturbations in the naturally occurring or artificial fields caused by concealed geological features.

Though, almost all geophysical survey methods have wider scope of utilizations, there is always one physical property for which a particular method is exceptionally sensitive and as such determines its specific range of applications. However, a number of geophysical methods may be applied simultaneously (integrated geophysical exploration) in solving certain geological problems, and such approach, greatly reduces the problem of ambiguity, which is the inherent drawback in the interpretations of results from one method, by complementing the information gap from the additional methods. Moreover, surface and drill hole geological information are of vital importance for the successful analysis of geophysical data.

3.2 ELECTRICAL METHODS OF PROSPECTING

The electrical methods of geophysical exploration include a variety of techniques employing both natural and artificial sources, of which the latter has wider application. Within the artificial source group, in which electrical signal is injected to the subsurface, a distinction may be made between inductive and conductive methods.

The former involve the measurement of secondary magnetic fields set up by induced current in the subsurface as a result of external excitations, either in frequency or time domain. Frequency Domain Electromagnetic Method (FDEM) and Time Domain Electromagnetic Method (TDEM) can be taken as typical examples of active source EM methods, whereas, the Magneto-telluric (MT) and 'VLF' methods represent the passive source ones.

The latter, the conductive methods, make use of direct current or alternating current, injected to the ground by galvanic means, and involves measurements of the spatial configuration of subsurface electrical potential. Electrical resistivity method and Induced Polarization (IP) are the most commonly used methods in this subgroup. Spontaneous potential (SP), is also a galvanic electrical technique that employs natural sources.

In all the above cases, the measured responses reflect the distribution of electrical parameters in the Earth section under investigation.

3.3. DIRECT-CURRENT, RESISTIVITY METHOD.

In geophysical investigations programs such as groundwater exploration, ore prospecting, depth to bedrock determinations, etc., the electrical resistivity method provides a quick and economic means to obtain vital subsurface information.

The DC-resistivity method measures the potential difference resulted from the artificial excitation due to a current sent to the ground section. The diagnostic parameter, the electrical resistivity ρ, resulting from measurements at a number of electrode positions, reflects the electrical properties in the ground as a function of depth or lateral distance.

The electrical resistivity ρ of a material is defined as the resistance across a unit cross section of the material; it is a characteristic of the material and unlike the resistance does not depend on the dimensions of the sample. Its unit is ohm-m, and conductivity, which is the reciprocal or inverse of resistivity is expressed in mho/m or S/m.

3.3.1 Resistivity of Rocks

The electrical resistivity of rocks is an extremely variable property and depends on a number of factors. Electrical conduction in most rocks is mainly electrolytic because most mineral grains are insulators and conduction takes place through the interstitial fluid, which usually contains some dissolved salts. Thus the resistivity of a geologic formation depends on porosity, degree of saturation and the resistivity of the fluid that fills the pore space. In crystalline rocks with low porosities, the conduction is mainly along cracks and fissures, which facilitate circulation of electrolytic liquids through the rock formations. Hence, the degree of weathering and/or fracturing, by and large, determines the electrical resistivity of such geologic media.

3.3.2 General Principles of Resistivity Survey

The basis of the resistivity survey is that; when current is applied by conduction into the ground through a pair of electrodes, any subsurface variation in conductivity alters the current flow within the Earth and, this in turn, affects the distribution of electric potential. The degree, to which the potential is affected at the surface, depends upon the position, shape, size and conductivity of the materials at depth. It is, therefore, possible to obtain information about the subsurface distribution of the constituents from measurements of the electric potential made at the surface.

The resistivity method is based Ohm's law which, in more generalized form, states that the electric field strength at a point, in an electrically isotropic material, is proportional to the current density passing that point.

An electrically isotropic medium is the one for which the resistivity ρ, is a scalar function of the point of observation and the current density **J**, is in the same direction as the electrical field vector, **E**.

In an anisotropic medium, **J** has a directive property and, in general, is not in the direction of **E**. This calls for some modification in Ohm's law as:

$$J_x = \sigma_{xx}E_x + \sigma_{xy}E_y + \sigma_{xz}E_z$$
$$J_y = \sigma_{yx}E_x + \sigma_{yy}E_y + \sigma_{yz}E_z$$
$$J_z = \sigma_{zx}E_x + \sigma_{zy}E_y + \sigma_{zz}E_z \quad \ldots (3.3.1)$$

Now, consider a single electrode, placed on an electrically homogeneous and isotropic half space of resistivity, ρ.

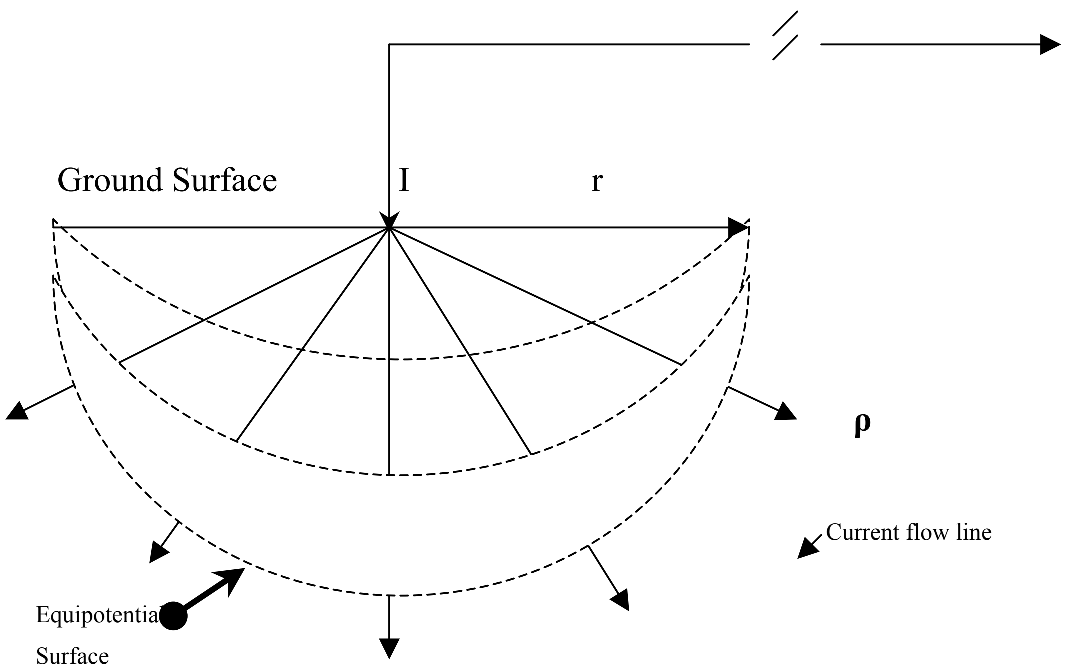


Figure 3. 1 Current Flow in a uniform half space, from a single electrode

The current density at distance r:

$$J = \frac{I}{A} = \frac{I}{2\pi r^2} \qquad \text{. . . (3.3.2)}$$

By Ohm's Law $E = \rho J \Rightarrow$

$$E = \frac{\rho I}{2\pi r^2} \qquad \text{. . . (3.3.3)}$$

For current strength, I in a hemispherical ground section of resistivity (ρ), the potential V at distance r, from the electrode is given by:

$$V = \frac{\rho I}{2\pi r}, \text{ since } V = E \cdot r \qquad \text{. . . (3.3.4)}$$

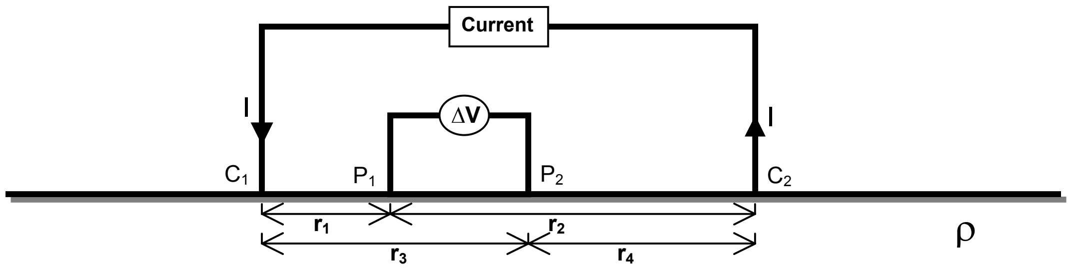


Figure 3. 2 Four-Electrode Layout

Four-Electrode Layout. C_1 and C_2 are current electrodes, while P_1 and P_2 are potential probes.

The usual practice is to pass current into the ground by means of two electrodes and to measure the potential difference between a second pair, placed in line between them (figure 3.2).

The potential measured at P_1 due to currents entering and exiting via C_1 and C_2, is:

$$V_{p1} = \frac{I\rho}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2}\right]$$

And, at P_2 is:-

$$V_{p2} = \frac{I\rho}{2\pi}\left[\frac{1}{r_3} - \frac{1}{r_4}\right]$$

In practice, a potential difference rather than a potential, is measure. Hence, the potential difference between P_1 and P_2 is given by:

$$\Delta V = V_{p1} - V_{p2} = \frac{I\rho}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right] \quad \ldots (3.3.5)$$

The resistivity of a half -space is then given by:

$$\rho = \frac{\Delta V}{I} \cdot \left[\frac{2\pi}{\left(1/r_1 - 1/r_2 - 1/r_3 + 1/r_4\right)} \right] = \frac{K\Delta V}{I} \qquad \text{. . . (3.3.6)}$$

Where, I is the current, △V is the measured potential difference and K;

$$K = \left[\frac{2\pi}{\left(1/r_1 - 1/r_2 - 1/r_3 + 1/r_4\right)} \right] \qquad \text{. . . (3.3.7)}$$

K is called the geometric factor and depends upon the positions of the electrodes in a specific array.

If the electrode configuration is altered so that K becomes different, the ratio △V/I will alter on homogeneous ground in such a way that the calculated true resistivity ρ, equation (3.3.6), will always be the same.

Over an inhomogeneous and/or anisotropic earth, the resistivity so calculated by equation (3.3.6) will vary with position and/or direction of the electrode array. Thus on inhomogeneous ground, the value of resistivity obtained from equation (3.3.6) is known as the apparent resistivity, denoted by ρ_a. In homogeneous ground this is the true ground resistivity but usually it represents weighted average of the resistivities of all the formations through which the current passes.

A measured value of apparent resistivity at a point is not necessarily a representative of the true resistivity of any element in the earth neither is a simple average of true resistivities. It does, however, vary systematically across a geologic section and can be diagnostic of both layering and of the presence of conductive or resistive inhomogeneities. We thus write the expression for the apparent resistivity as:

$$\rho_a = \frac{K\Delta V}{I} \qquad \text{. . . (3.3.8)}$$

3.3.3 Symmetrical Electrode Arrangements

The simplest method of carrying out a resistivity survey is to arrange the four electrodes in a straight line (collinear arrays) on the surface of the ground, i.e., two current electrodes (a positive one through which current enters the ground and a negative one to which it returns) and, the other two electrodes to measure the resulting potential difference.

In routine field works, the common collinear arrays namely **WENNER and SCHLUMBERGER** arrays are used. (The descriptions of routinely used electrode arrays are given in Appendix-II)

3.3.4 Probing Depth

For homogenous and isotropic earth, the depth of current penetration almost linearly depend on the current electrode separation i.e., the wider the separation, the larger depth of probing. For an inhomogeneous medium, however, the percentage of the total current that penetrates to a given depth depends not only upon the electrode separation but also upon the resistivities of the earth layers.

It is not practically possible to explicitly determine the depth of penetration, for a given electrode arrangement. Nevertheless, a general rule-of thumb can be established for depth of penetration or probing depth, in the case of inhomogeneous and anisotropic media. For example, in the case of SCHLUMBERGER array the percentage of current that penetrates to a given depth is approximated to be 1/3 of the current electrode spacing. Similar current - depth relation is established for other arrays.

3.3.5 Field Procedures

There are two basic methods of carrying out resistivity measurements and the choice mainly depends upon the particular problems under consideration.

The first one, known as Vertical Electrical Sounding (VES) /Electrical Drilling is done using an expanding electrode system. It is used to determine the vertical changes in the resistivity of the subsurface layers and the depth to the discontinuity of such horizons. The method of electrical drilling furnishes detailed information on the vertical succession of the various conducting zones in terms of their individual thicknesses and true resistivities. It is particularly valuable for investigations on horizontally or near horizontally stratified ground. The technique is based upon the fact that the fraction of the current .put into the ground, penetrating below any particular depth, increase with an increased separation of current electrodes.

For quantitative interpretation of sounding data, i.e., the determination of number of layers, thickness and resistivity, the ground is considered as being made up of approximately uniform resistivity layers, bounded from others of differing resistivity by plane interfaces. These interfaces correspond, generally, to boundaries between strata of different lithologies.

The second method, known as Electrical profiling/Electrical Trenching is also referred to as Constant Separation Traverse and is used to determine the variations of apparent resistivity in horizontal direction. It is particularly suitable when the boundaries or discontinuities are vertical rather than horizontal. The electrodes, normally in straight line, are kept a fixed distance apart and are moved as a whole along the surface in a predetermined direction. The interpretations on profiling data is mainly qualitative and is particularly applicable for locating laterally oriented high or low resistivity subsurface materials.

3.3.6 Ambiguity in Geophysical Interpretation

The ultimate aim of any geophysical investigation is to deduce some aspect of the Earth's internal structure on the basis of geophysical measurements taken at (or near to) the Earth's surface. This type of problem is known as inverse problem. Inverse problems suffer from an inherent ambiguity, or non-uniqueness, in the conclusions that can be drawn. The ambiguity arises because many different geological configurations could reproduce the observed measurements. Since a unique solution cannot, in general, be recovered from a set of field measurements, geophysical interpretation is concerned either to determine properties of the subsurface that all possible solutions shares, or to introduce assumptions to restrict the number of admissible solutions (Parker 1977).

Generally the degree of uncertainty in geophysical interpretation can often be reduced to an acceptable level by the general expedient of taking additional (and in some cases different kinds of) field measurements, by knowledge of local and general geology of the surveyed area, by recognition of the physical properties (like density, susceptibility, conductivity, etc.) of the rocks in the studied area that correct interpretations are achieved.

3.4 THE MAGNETIC METHOD

The earth's magnetic field resembles the field of a large bar magnet situated near the center of the earth. Many geological formations, by virtue of their magnetic minerals content, will behave like large buried magnets and will then have a magnetic field associated with them. These local magnetic fields will be superimposed on the magnetic field taken, in the locality of such geological formations, and show deviations from the undisturbed earth's magnetic field. These changes or anomalies could be large or small in magnitude, and could either increase or decrease the earth's main field. Their influences on the main field depend on the geometry, orientation, depth of burial and magnetic properties of the body and the direction and intensity of the inducing earth's field.

Magnetic surveys are used to locate and delineate:

- Magnetic iron ore deposits
- Metallic ore deposits which may have either magnetite or pyrrhotite associated with them.
- Geological structures like contacts, faults, dykes, etc.

Magnetic surveys are used in groundwater studies to map the depth to the magnetic basement rock and also it provide a valuable aid to lithological mapping, as the character of a magnetic anomaly is indicative of the rock. Moreover, it can also be applied in mapping structural features, which often provide a conduit for the accumulation of groundwater and, at times, act as barriers.

3.4.1 Principle of Magnetic Method

3.4.1.1 Magnetic force

The force between two poles of strength m_1, and m_2, situated a distance **r** apart is given by:-

$$F = \frac{m_1 m_2}{\mu r^2}\vec{r} \qquad \text{. . . (3.4.1)}$$

Where, $\vec{r}$ =unit vector from m_1 to m_2

μ = permeability = $\mu_r\mu_0$

μ_r = relative permeability (~ 1 for air and many rocks)

μ_0= permeability of free space =$4\pi 10^{-7}$ henry/m

r = separation between m_1 and m_2

3.4.1.2 Flux density/Magnetic induction

A magnetic field strength gives rise to a magnetic flux, just as electric field strength can give rise to an electric charge flux (current). The magnetic flux density that is the flux per unit area, also called magnetic induction, is denoted by **B,** and the field strength by **H**.

The magnetizing force (field strength) gives rise to the flux density, i.e. the cause of the magnetic field is the magnetizing force, thus

$$\mathbf{B} = \mu \mathbf{H} \qquad \ldots (3.4.2)$$

Where, μ the absolute permeability of the medium on which **H** is acting. In SI units, the magnetizing force or field strength (**H**) is measured in ampere per meter [Am^{-1}]. The unit of magnetic flux is volt-second (V-s), also named Weber [Wb]. Hence, the unit of flux density **B** is [Vsm^{-2}] or [Wbm^{-2}] which is also called tesla [T]. The magnetic fields that we measure in practice are flux densities. For most geophysical purposes the tesla is too large as a unit and flux densities are more conveniently expressed in nanotesla [nT =10^{-9}T]. One nT is equals the basic unit of **B**, namely gamma [γ]. The absolute permeability (μ), being equal to **B**/**H** has its dimensions from:

$$\mu = \mathbf{B}/\mathbf{H} = \frac{v.\sec}{m^2}.\frac{m}{A} = \text{ohm-}\frac{\sec}{m} = \Omega s m^{-1}$$

The absolute permeability of vacuum is denoted by μ_0, its value in SI unit is: $4\pi \times 10^{-7} \Omega s m^{-1}$, thus in vacuum the flux density due to a magnetizing force **H** will be

$$B = \mu_0 \mathbf{H}$$

For most practical purposes, the absolute permeability of air, and even most rocks, may be taken to be μ_0

3.4.1.3 The Earth's Magnetic Field

The earth's magnetic field is akin to that of a dipole situated at the center of the earth with its magnetic moment pointing towards the Earth's geographical south. The Earth's magnetic field vector **F** is completely specified at any point by its elements. Figure 3.3 shows the elements of the earth's magnetic field.

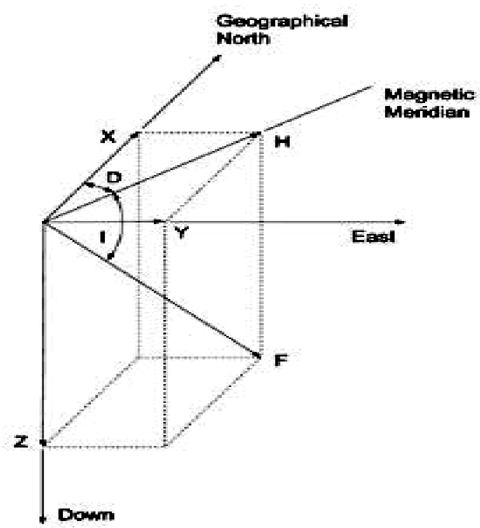


Figure 3. 3 Elements of the earth's magnetic field.

According to figure3.3, the earth's total field is **F** makes an angle I (the inclination) with the horizontal plan. It can be measured by a dip needle and is also called magnetic dip.

The angel D is the angel between geographic north and magnetic north, or the declination of **H** (here, **H** is the horizontal component of the total field vector, **F**) east or west of true north.

In the northern hemisphere the magnetic field is directed downwards towards the north magnetic pole and in the southern hemisphere it is directed up wards and away from the south magnetic pole. At the magnetic equator the magnetic field is horizontal and at the magnetic poles the field is vertical i.e., the strength of the earth's field varies from 25,000 - 30, 000 nT in the equatorial regions while 60,000 - 70,000 nT, in the polar regions.

The amplitude of total field varies more rapidly along the N-S direction as compared to the east-west. On figure3.3, **Z** is the vertical component of the total field (**F**). It is directed downwards in the northern hemisphere (+ve) and upwards (-ve) in the southern hemisphere. **H**, which is the horizontal component of **F**, is directed towards magnetic north for both the Southern and Northern hemispheres.

3.4.1.4 Relative permeability, susceptibility and magnetization

It for a medium other than vacuum we write $\mu = \mu_r \mu_0$ we get from e.q.1

$$
\begin{aligned}
\mathbf{B} &= \mu \mathbf{H} \\
&= \mu_r \mu_0 \mathbf{H} \\
&= \mu_0 \mathbf{H} + \mu_0 (\mu_r - 1) \mathbf{H} \\
&= \mu_0 \mathbf{H} + \mu_0 \kappa \mathbf{H} \qquad \ldots (3.4.3)
\end{aligned}
$$

Where, we have put, $\kappa = \mu_r - 1$, , that is $\mu_r = 1 + \kappa$.

μ_r is a ratio of the two permeabilities: ($\mu_r = \dfrac{\mu}{\mu_0}$) and therefore is a pure number.

It is called the relative permeability of the medium, and κ is called susceptibility, also is a dimensionless quantity. For a vacuum, μ_r =1 and κ = 0

From eq. 3.4.3, to obtain in vacuum a flux density equal to the density $\mu\mathbf{H}$ in the medium under consideration, we would need an additional magnetic field strength KH.

This additional field strength that may be said to be present at points of space occupied by a medium subject to a field strength H is known as intensity of magnetization M induced by H. The direct relation is given by:

$$M = KH \qquad \ldots (3.4.4)$$

Since K is a pure number M is also measured in Am^{-1}. Further B and H are vectors we can state Eq.4 more generally as magnetic induction (total field within a body) and written as:

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \qquad \ldots (3.4.5)$$

Then, for the x, y and z components of **B**, in an orthogonal coordinate system, we have

$$\left.\begin{aligned} B_x &= \mu_0(H_x + M_x) \\ B_y &= \mu_0(H_y + M_{y)}) \\ B_z &= \mu_0(H_z + M_z) \end{aligned}\right\} \qquad \ldots (3.4.6)$$

Equation (3.4.4) implies, a magnetic body placed in a magnetic field becomes magnetized by induction. The magnetization (M) is proportional to the inducing external magnetizing force. The constant of proportionality K is the magnetic susceptibility. It is a dimensionless quantity.

Magnetic susceptibility is a measure of the degree to which a material gets magnetized. The larger the susceptibility the greater the intensity of induced magnetization (M) and hence the bigger will be the anomaly produced relative to the earth's field.

The susceptibility of rocks is almost entirely controlled by the amount of ferri-magnetic minerals, their grain size, and mode of distribution and hence is highly variable.

CHAPTER IV

4. GEOPHYSICAL SURVEY AT ADA'A PLAIN

4.1 GENERAL

The choice of geophysical techniques for subsurface investigations should be made judiciously as their success depend, largely, on their suitability to the problem, among other factors. Certain problems are best solved by a particular method than other and thus, require serious consideration. However, the local terrain conditions, access and logistic difficulties, and most importantly availability of instruments and associated cost, impose further constraints on this difficult task.

In light of the above mentioned considerations, potential filed methods, namely magnetic surveys are appraised to achieve some of the objectives of the research work.

Magnetic surveys are frequently employed in mapping regional geological structures owing to their sensitivity to variations in the diagnostic physical parameters (magnetic susceptibility), which are commonly associated to areas affected by major orogenic activities and tectonic features. Cost effectiveness is yet another plus point for the preference.

The other method, found to be adequate for problems related to the principal objectives of the work, is that of electrical resistivity technique using Vertical Electrical Sounding (VES).

The effective electrical resistivity of rock materials, in general, is known to depend on such factors as porosity, fluid quantity & quality and concentrations of metallic minerals. In case of porous rocks, which are the primary targets in hydro geophysical studies, porosity, presence of pore fluids and the resistivity of the pore fluid play the most important role in shaping their response to excitations by means artificially generated electric current. Clean sands and gravels, with high porosities, for instance, make good aquifers and can easily be differentiated from lower-resistivity impermeable clays and marls, and also from solid bedrock which is usually of much higher resistivity.

In areas with major groundwater divide, the contrast in physical properties, like resistivity and magnetic susceptibility between the barrier and the country -rock will enable us to delineate and outline a buried groundwater divide. Hence, the use of combined Magnetics and electrical methods, in this work, is justifiable and is seems suitable to attain the objectives.

4.1.1 Vertical Electrical Sounding

4.1.1.1 Data acquisition

A total of twenty Sounding data were used for this thesis work, of which fifteen were obtained from Water Works Design and Supervision Enterprise (WWDSE) while, the remaining five were collected by the author (while working for WWDSE on the project area).

Since the aim of the geophysical survey is to confirm the inferred groundwater barrier and to map the hydro-Stratigraphy of the study area, the soundings were conducted in the vicinity of the anticipated subsurface divide, and along the two major zones where deep and shallow groundwater level are encountered. Generally the resistivity survey was not conducted on a regular grid thus, the spacing of the VES points were not uniform. Rather, they were dictated by the geology, topography and accessibility of the area under investigation.

The symmetrical Schlumberger electrode configuration was used for all soundings. The maximum current electrode separation, AB/2=1000m, was chosen based on the depth of interest, (the anticipated depth to the water bearing horizon) and subsurface geology.

In each case, the sounding curve, which is a log -log graph of apparent resistivity versus half the current electrodes separations, was plotted, right in the field as a measure quality control. If any error is detected during data acquisition, it was automatically corrected either by taking repeated measurements, by improving the contact resistance of the electrodes or by changing the position of the measuring electrodes.

4.1.1.2 Instrumentation

The instrument used for the survey was ABEM Terrameter SAS 1000A which is a portable integrated (transmitter and receiver in one unit) resistivity meter. It has a digital (LCD) readout, and automatically calculates the ratio, (V/I) and displays the resistance either in ohms or milliohms. With the help of automated cables the instrument is capable of making an electrical imaging survey. It is powered by 12V battery. The complete set for electrical measurements includes:

- Metal (steel) rods for current and potential electrodes.
- Isolated Steel and copper wire for power and potential circuits.
- Alligator clips and banana plugs
- And other accessories.

4.1.1.3 Data Processing and Presentation

4.1.1.3.1 Qualitative Analysis

The aim of interpreting Field VES curves is to determine the thickness and resistivities of subsurface layers in order to obtain the geological picture of the subsurface. Nevertheless, it is mandatory and beneficial to make quick qualitative assessments of the field curves before a detail quantitative interpretation.

At early stages of geophysical survey programs, such a practice provides crucial parameters, which may influence the further progress of the data acquisition process. In addition to that, this helps to impart some useful prior knowledge on the geoelectric nature of the area under investigation. On the latter (processing and interpretation) stage, the spatial distribution of electrical parameters can be depicted in the form of plan maps and depth pseudo-sections.

In the present case the smoothed field data, from spatially aligned adjacent soundings, have been plotted in the form of pseudo-sections, using the apparent resistivity (ρ_a) and pseudo depth values (AB/2). Such plots enables to geoelectrically characterize the area both in vertical and lateral directions.

4.1.1.3.2 Quantitative Analysis

The Schlumberger sounding curves, resulted from field measurements were initially analyzed through the classical procedure known as curve matching, using two layer master curves and auxiliary point charts, **(Bhattacharya and Patra, 1968)**. In this preliminary manual interpretation, the number of layers, their thicknesses and resistivities are obtained. These parameters help to develop a preliminary, conceptual multilayer earth model of the study area.

The layer parameters so obtained have been used as starting models for a computer based modeling and inversion programs. In the present case, the resistivity and thickness values, resulted from the former procedure, were entered as initial models to an iterative-least squares inversion program, RESIST **(Velen, 1988),** for further refinement and final analysis.

The inversion algorithm generates theoretical Schlumberger apparent resistivity curves of the starting models and compares it to the field curve at the given current electrode positions. In case of discrepancies between the two, the program iteratively adjusts the model, until a satisfactory fit is obtained between the observed (field curves) and computer generated theoretical sounding curves.

The program terminates based on either pre-determined error criterion (in least squared senses) or at a maximum number of iterations, as defined by the user.

However, due to the well-known problems inherent to the interpretations of VES curves, namely equivalence and suppression, the best-fit model may not necessarily agree with the geology of the area under investigation. Thus, in order to arrive at an accurate and reasonable conclusion, the VES curves were interpreted in light of the knowledge of the local geology and other apriories. Moreover, attempts have also been made to correlate and adjust the VES results with geologic log of boreholes, whenever available.

Finally, geoelectric-sections were constructed by correlating the interpreted true resistivities and thicknesses of adjacent soundings in order to depict the geoelectric stratifications of subsurface. Such sections, under favorable circumstances and judicious analysis, provide closer pictures of the subsurface geology.

4.1.2 Magnetic Method

4.1.2.1 Data Acquisition

Measurement of total magnetic intensity was made along traverse lines running perpendicular to the inferred groundwater barrier. The magnetic data were also collected on randomly distributed short profiles over the area in order to prepare the magnetic contour map which reveals the magnetic trends of geologic interest. Based on the approximate geometry, depth and trend of the anticipated geological structure/barrier, the station spacing was chosen to be 50m.

A base station, far from artificial disturbances such as power lines, railways, metallic fencing and footings, etc, is chosen for monitoring and correcting diurnal variations. For each day, readings were taken at the base station almost every two hours, apart from at the beginning and end of the survey.

4.1.2.2 Instrumentation

The magnetic data were collected with Scintrex-made MP-2 proton-precession magnetometer. The MP-2 utilizes the phenomenon of nuclear magnetic resonance to measure the intensity of the earth's magnetic field. It has a measurement resolution of 1 gamma.

4.1.2.3 Data Processing and Presentation

The observed magnetic data were corrected for diurnal variation using the base station readings taken during the survey. The resulting magnetic data have been smoothed using moving average filter in order to remove erratic features probably originating from cultural noise. The corrected and smoothed total field magnetic values were presented in the form of profile and also contoured to produce magnetic map. On the profile the positions of true anomaly peaks, maximum gradients and other characteristics are more easily determined which helps to visualize the continuous variation of anomalies along the surveyed line.

CHAPTER V

5. RESULTS AND INTERPRETATION

5.1 VERTICAL ELECTRICAL SOUNDING

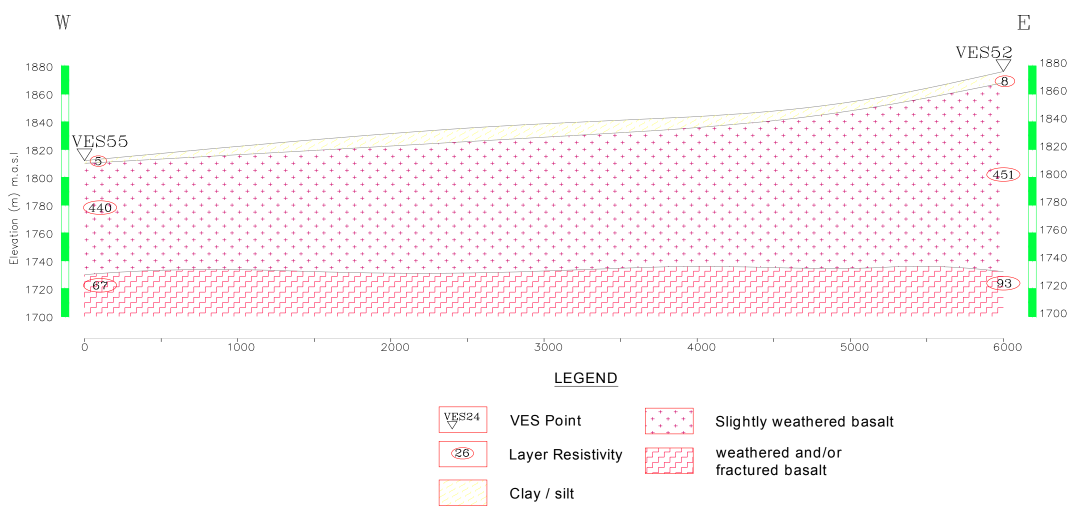


Figure 5. 1 Geo elctric Section Along VES 55-VES 52, Ada'a Plain

5.1.1. VES 55 - VES 52

Fig. 5.1 shows the geo-electric section along VE 55-VES 52, it is towards the southern periphery of the surveyed area. The geologic log and water level of BH2, found about 3km west of this traverse line are used as a control to adjust and correlate the VES results and further, the geologic log is used to give lithologic description to the inferred geo-electric layers.

On the geo-electric section, fig.5.1 the interpretation highlights three different resistivity layers.

The uppermost layer, resistivities ranges between 5-18 ohm-m with an average thickness of 5m. This layer may possibly represents the black cotton soil (clay) that cover the farm lands.

The second layer thickness beneath VES 55 is 83m and is getting progressively thicker (145m) towards VES 52.

The computed true resistivities of this horizon ranges between 440-451 ohm-m. This resistive layer is related to a slightly weathered basalt.

The bottom electrical substratum is marked by a moderate resistivities (67-93 ohm-m). It lies at a depth of 89m in the vicinity of VES 55, beneath VES 52 it is relatively deeper (151m). This moderately resistive strata presumably represent the potential aquifer of the area (moderately weathered and/or fractured basalt.)

5.1.2 VES 52-VES 49. VES 53

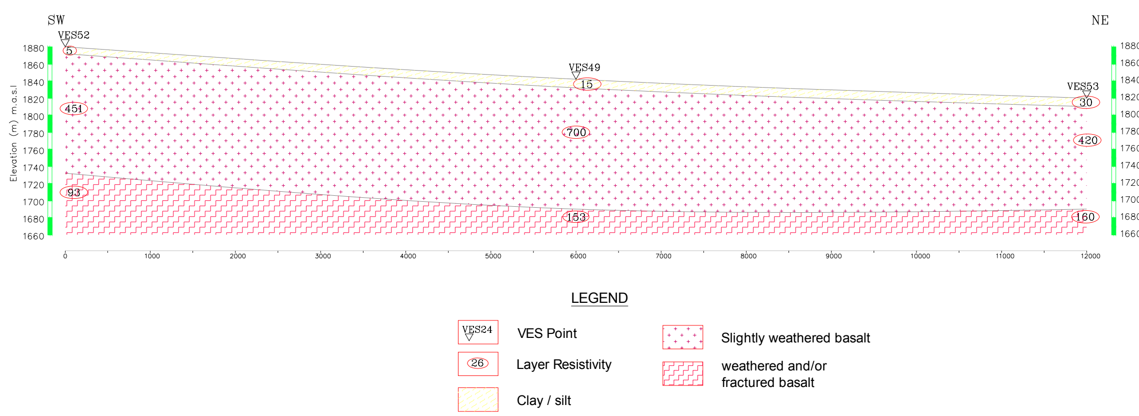


Figure 5. 2 Geo electric Section along VES 52-VES 49-VES 53, Ada'a Plain

Figure 5.2, shows the geo-electric section constructed by correlating the resistivities and thicknesses of the adjacent soundings, that were laid along NE-SW running traverse line located south of the surveyed area.

The geo-electric section fig.5.2 reveals the presence of three distinct resistivity layers. The topmost layer is characterized by lower resistivity values (5-30 ohm.-

m) and having an average thickness of 5m, it may represent loose and fine unconsolidated material possibly clay and silt.

The underlying second layer resistivity ranges between 420-700 ohm-m and it has an average thickness of 140m. This layer could be related to fresh to slightly weathered basalt. The variation in resistivity along this horizon can be associated to the variation in degree of weathering and intensity of fracturing. The central portion of the layer being fresh basalt (700 ohm-m) bounded by slightly weathered basalt (420-441 ohm-m).

The third geo-electric layer marked by a moderate resistivity values (93-160 ohm-m) is interpreted as representing the water bearing strata (moderately weathered and or/fractured basalt).

The depth to the top of the inferred aquifer is relatively deeper (145m) below VES 52 and VES 49, beneath VES 53 it lies at a depth of 120m. The lateral variation of the resistivity along the saturated horizon is insignificant, the slight decrease in resistivities towards VES 52 (93 ohm-m) might have been caused by a progressive increase in the electrical conductivity (EC) of the groundwater or to a variation in weathering and fracturing of the water bearing basaltic strata.

5.1.3 VES 25-37-38-39

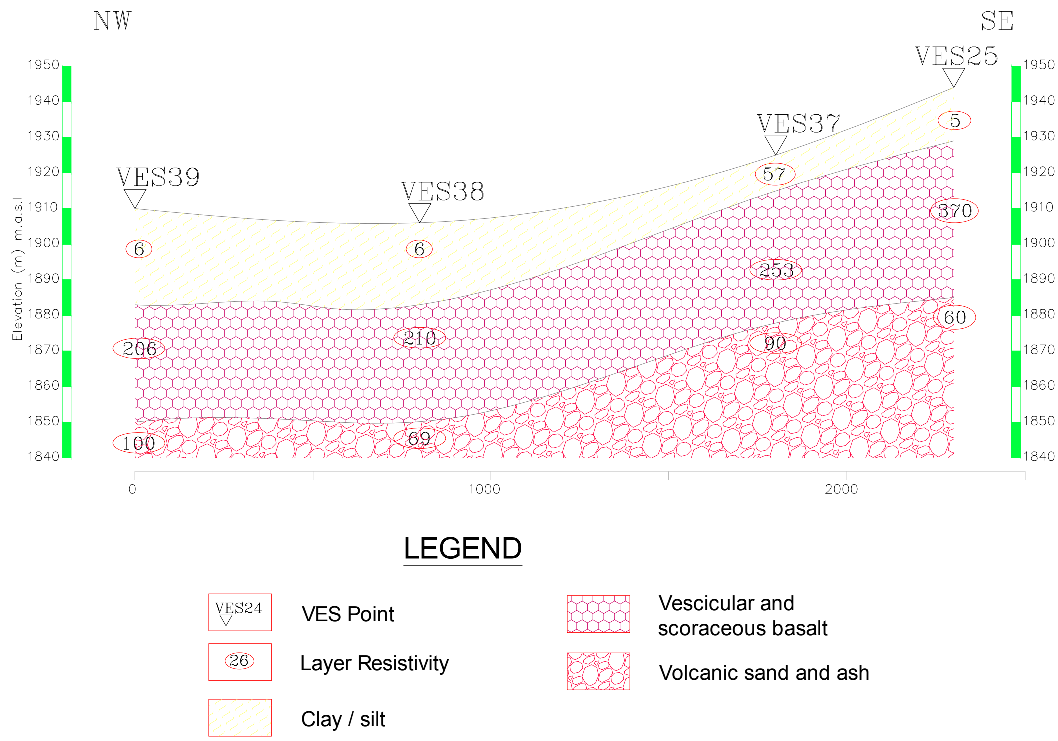


Figure 5. 3 Geo Electric Section along VES 39-VES 38-VES 37-VES 25, Ada'a Plain

Fig.5.3 shows the geo-electric section that was constructed along the inferred barrier, the most important target of the geophysical survey.

Four VESs (VES 25, VES 38, VES 38 and VES 39) were carried out following the strike of the inferred groundwater barrier. Fig.5.3 shows the constructed geo-electric section along the anticipated geologic structure (barrier), which is the most important target of the geophysical survey.

Three major resistivity layers were clearly delineated, i.e. the model highlights three layer cases. The first layer is characterized by a uniform resistivity (5-6 ohm-m). The thickness of this horizon varies from 14m (VES 25, VES 37) to 23m beneath VES 38 and VES 39. It possibly represent the top lacustrine sediment of the arable lands. The uniform resistivity (6 ohm-m) is an indication that the sediment has a uniform grain size, moisture content and degree of packing.

The second layer exhibits higher resistivities (206-370 ohm-m) with an average thicknesses of 45m. The high resistivities are interpreted as a response of vesicular and scoraceious basalts. Which are found in the depth range of 56m, as recorded on geologic log of BH5), used for calibration of the geo-electric parameter, resistivities and thicknesses.

The configuration of this layer is such that it is slightly dipping NW, between VES 25 and VES 38, and gets flat beyond VES 38, (towards VES 39). Generally this vescicular-scoraceious basalt tends to follow the general shape of the topography.

The bottom substratum lies at an average depth of 65m, with resistivity varying between 60-100 ohm-m. From the available subsurface geological information (BH5) this moderately resistive layer is related to a saturated volcanic sand, and pumice.

The static water level (62m) and the stratigraphic succession of the borehole (BH5) indicate that the volcanic ash and sand comprise the ground water resources of the area around BH4.

5.1.4 VES 24-VES 25-VES 43

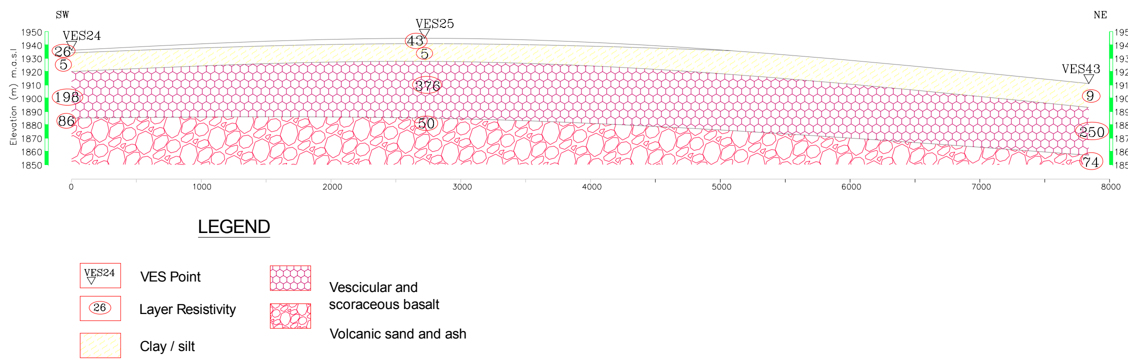


Figure 5. 4 Geo Electric Section along VES 24-VES 25- VES 43

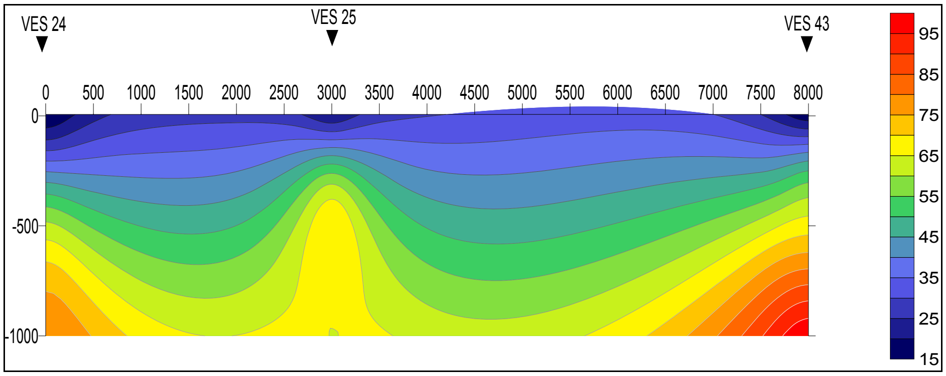
Three soundings namely VES 24, VES 25, and VES 43 were conducted along a traverse line orienting NE-SW crossing the inferred groundwater barrier perpendicularly.

Fig.5.4 shows the constructed geo-electric section along VES 24, VES 25 and VES 43.

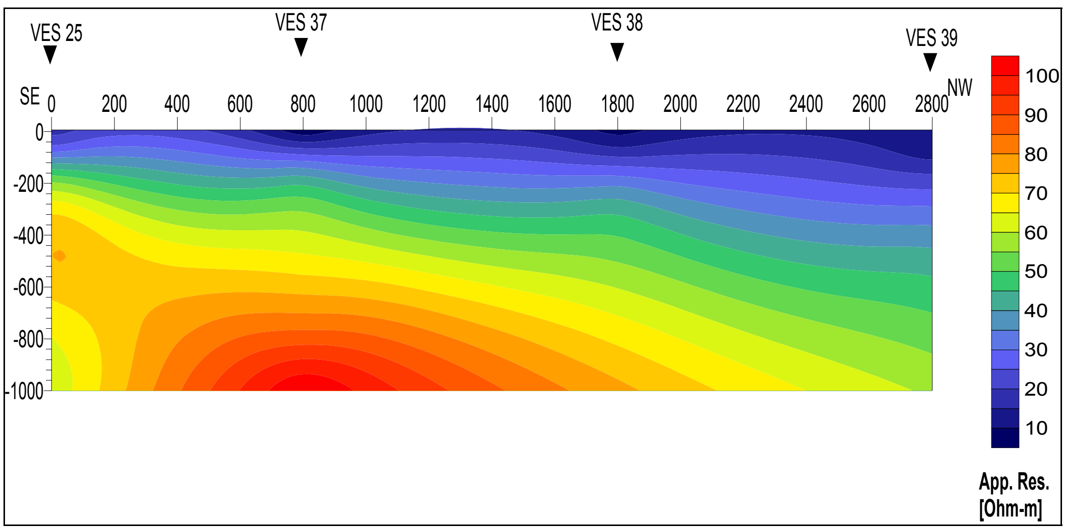
On the geo-electric section three resistivity layers were distinguished, more or less with a similar layer parameters (resistivity and thicknesses) as that obtained along VES 39 - VES 25, (in the direction of the anticipated barrier).

The first 15-20 meter of the subsurface material exhibits low resistivities 5-9 ohm-m, it possibly represent the upper clayey or silty topsoil. The second layer is characterized by a high resistivity values (198-376 ohm-m) and thickness varying from 31m to 46m. It is relatively thicker (56m) and resistive (376 ohm-m) beneath VES 25, this horizon is associated to vesicular and scoracious basalt. The third layer displays moderate resistivity (59 - 86 ohm-m) and interpreted as representing the water bearing strata (aquifer). the average depth to the top of the saturated zone is 61m. The material of the aquifer being volcanic sand and pumice.

5.1.5. Apparent Resistivity Section (pseudo-sections)



(a)



(b)

Figure 5. 5 pseudo-sections (a) Along VES 24,25,43 (b) Along VES 25, 31, 38,39

On both pseudo-sections fig.5.5 a & b, the shallower depth level are dominated by a low resistivity values, interpreted as a response of overburden materials which is mainly composed clay and silt. Continuous and uniformly increasing resistivity values dominate the deeper level on both figures. This is possibly due to the response of the volcanic lithologies (scoracious and vesicular basalts). The absence of abrupt termination or patchy and localized anomaly features on both pseudo sections is a clear indication of the uniform and similar nature of the subsurface lithologies on both sections.

5.2. MAGNETIC MAP

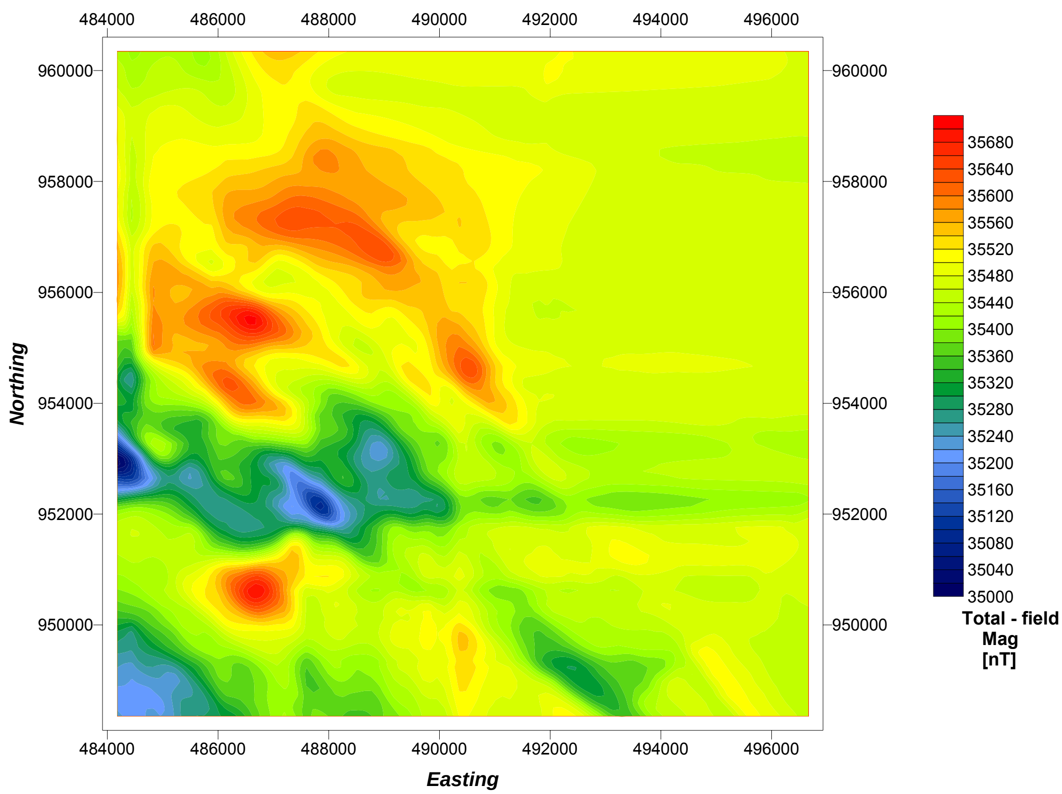


Figure 5. 6 Total Magnetic Field Contour Map

The total field magnetic map of the study area is presented in figure 5.6.

The map shows that the northern part of the surveyed area is dominated by high magnetic values and with steep gradients. This sharp gradient trending in the NW-SE direction may be the effect of shallow concealed structural features. The southern area also depicts elongated and patchy linear high magnetic features trending also in NE-SE, with alternating moderate and low values.

The central part (952000N-954000N) is characterized by a lower magnitude and smooth magnetic relief. The eastern part of the area has rather moderate magnetic responses, which may be correlated to the acidic lithologies extruded from Bede Gebabe, or may be due to the thick overburden material, resulted in the relative decrease in magnetic amplitude.

The NW-SE trending anomalies mapped both at the south and northern limit of the study area are in the general direction of the inferred barrier. Such alignment may confirm the existence of linear shallow features to be correlated with the anticipated groundwater divide.

5.3. MAGNETIC PROFILE

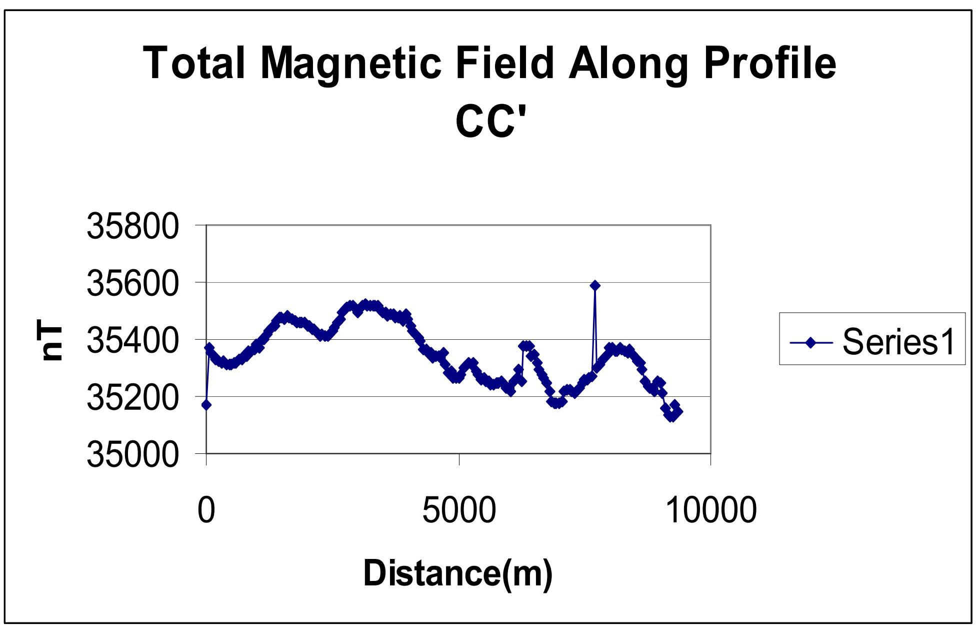


Figure 5. 7 Magnetic Profile Along Line CC'

At both ends of the profile, fig 5.7, double-peaked magnetic high are observed. The contrast in character between these two anomalies may suggest either a difference in magnetic properties of the rock producing the anomalies or a variation in depth of burial of the causative body.

The first anomaly (towards SW) is characterized by higher magnetic intensity and uniform pattern. High magnetic variation may reflect the presence of a volcanic unit (relatively basic) within a few meters of the surface, i.e. the closer the level of observation to a magnetic body, the steeper the magnetic gradients and the smaller the extent of major features on the anomaly.

On the anomaly located towards the north-eastern end of the profile, the strength of the magnetic field relatively declines with high magnetic gradient, which may be an indication of the existence of a geologic contact between volcanic units, between the more magnetic and thus more basic lithology (basalt) occurring towards south-western end of the profile and less magnetic vescicular and scoracious basalt.

5.4 CONCLUSIONS AND RECOMMENDATION

The electrical (VES) investigations conducted in the western periphery of Ada'a plain were able to delineate the water bearing horizons lying at a different depths over the surveyed area.

It is found to be deeper (145m) over zone II (south of the inferred structure) and relatively shallow (61m) at zone I, the material of the deeper aquifer (zone II) is lithologically interpreted as moderately weathered an/or fractured basalt, towards the northern limit of the surveyed area(zone I) is associated to volcanic ash and pumice.

The geo-electric sections of zone II indicates that the surveyed area is underlain dominantly by a succession of low- high and moderate resistivity layers, which may be correlated to a stratigraphy of clay, slightly weathered basalt and moderately weathered and/or fractured basalt (inferred aquifer), similar low-high and moderate resistivity layers are mapped at zone I, lithologically interpreted as silty/clayey first layer, the second and third layers being related to vescicular/scoracious basalts and volcanic ash and pumic respectively.

The variation in resistivity values along the first layer (zone I, and zone II) could possibly be related to the moisture content of the sediments, even though they are collectively categorized as a response of fine materials, clayey and silty.

The thickness of the sediments varies considerably over the entire area, the asymmetry in thickness may be attributed to asymmetry in subsurface elevation of the bed rock or due to the variations in rates of erosion.

The decrease or increase in resistivity values along the volcanic strata could be attributed to a variation in degree of weathering and intensity of fracturing.

The nearly horizontal and uniform resistivity layer on all sections indicate that no structural features (faults) affects the underlying volcanic complex.

The lithologic description given to the geo-electric layers may not be expected to represent exactly the actual sub surface geology.This might arise from unreliability of the borehole logs (when logged by inexperienced hydrogeologist or driller) which are used for calibrating layer parameters. Or due to the inherent nature of equivalence in geophysical interpretation. Thus minor inaccuracies may normally be anticipated.

The inferred groundwater barrier (the main target of the geophysical survey) was not detected and mapped to exist along the electrically/VES investigated areas. Had there been a barrier which exhibit high resistivity relative to surrounding host-rocks it would have been mapped along the geo-electric section of VES 24-VES 43 as a very resistive and shallow features at the center, flanked by moderate low resistivity layers. The identical layer in thickness and resistivity obtained along two mutually perpendicular traverse lines (along and across the inferred barrier) is diagnostic to the non-existence of geologic boundary that impede groundwater flows.

The undetectablity of the barrier by resistivity survey might be due to the fact that the VESs were not concentrated in the vicinity of the inferred structure, as compared to the magnetic profile(CC') which crosses the barrier.

The magnetic survey was found to be useful in lithologic mapping and identifying linear geologic features. The magnetic data over the shallow and/or relatively basic rocks is characterized by an enhanced values, anomaly peak. On the magnetic map the smooth and moderate responses were obtained over the area underlain by the acidic rocks. On the map, the NW-SE trending anomalies are in conformity with the anticipated groundwater barrier. Thus further detail magnetic and gravity survey are required to establish the probable relationship between the anomalies and also to outline and map the geologic boundary that may impede the flow of groundwater.

The anomaly obtained on the profile plot (towards the beginning /SW end) should be followed by extending the profile further to the SW, and conducting both magnetic and gravity surveys might give some indication (if any) about the inferred barrier.

Resistivity imaging technique revealing both lateral and vertical variation in resistivity of the subsurface will provide a reliable information about the concealed structures if conducted together with magnetics and gravity in north - south or NE-SW direction (nearly perpendicular to the strike of the anticipated barrier) to obtain the required resistivity contrast between the barrier and host-rock. Finally closely spaced soundings (VESs) and electrical profiling using at least two depth level if conducted in the vicinity of the inferred structure will supplement the results of the above mentioned geophysical methods.

5.5. REFERENCES

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DECLATATION

I, the undersigned, hereby declare that this thesis my original work and has not been presented for a degree in other university. Sources of relevant materials taken from books and articles have been duly acknowledged.

Name:
Signature:

This thesis has been submitted for examination with my approval as University Advisor.

ANNEXES

ANNEX I: THEORETICAL FOUNDATION AND INTERPRITATION OF RESISTIVITY SOUNDINGS

A.1. POTENTIAL DISTRIBUTION AT THE SURFACE OF A HORIZONTALLY STRATIFIED EARTH

In order to solve the problem of determining the layer resistivities and thicknesses, it is necessary to determine the potential on the surface of a layered earth due to a point source of direct current. Considering a point source enables one to use the axial symmetry of the potential field about the vertical line through the current sources, the other advantage being that the potential is additive.

The model considered is an n -layer layer horizontal earth. Each of the layers is assumed to be homogeneous and isotropic, separated by horizontal interfaces. The deepest n^{th} layer is the substratum and extends to infinite depth, the other layers have finite thicknesses.

Z= 0 ____ Surface

h_1 ____ ρ_1 ______ $K_1 = \frac{\rho_2 - \rho_1}{\rho_2 - \rho_1}$

h_2 ____ ρ_2 ______ K_2

h_3 ____ ρ_3 ______ K_3

h n-1 ____ ρ n-1 _ K_{n-1}

h n

↓

:

Fig A.1 A Multilayer Earth Model

The potential V for direct current satisfies laplaces's equation except at the point electrode. The Laplace's equation in cylindrical coordinate system where there is a circular symmetry with respect to the vertical line through the current source can be written as:

$$\nabla^2 v = \frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} + \frac{\partial^2 v}{\partial z^2} + \frac{1}{r^2}\frac{\partial^2 v}{\partial \theta^2} = 0 \qquad \text{... A1.1}$$

for a solution symmetrical with respect to the vertical axis

$$\frac{dv}{d\theta} = \frac{d^2 v}{d\theta^2} = 0$$

Thus eq-1 reduced to

$$\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} + \frac{\partial^2 v}{\partial z^2} = 0 \qquad \text{...A1.2}$$

The particular solution of the above differential equation (A1.2) can be obtained by the method of separation of variables and then the general solution is obtained as a liner combination of the particular is obtained as a linear combination of the particular solutions. Particular solutions of eq.A1.2, may be obtained by making the assumption that there exist solutions that have the form:-

$$V(r, z) = U(r)\, W(z) \qquad \text{... A1.3}$$

Substituting eq.A1.3 into eq.A1.2 and dividing all terms by U(r) W(z) we obtain.

$$\frac{1}{u(r)}\frac{d^2u(r)}{dr^2} + \frac{1}{r\,u(r)}\frac{d\,u(r)}{d\,r} + \frac{1}{W(z)}\frac{d^2\,W(z)}{dz^2} = 0 \qquad \text{... A1.4}$$

This equation is satisfied if :-

$$\frac{1}{u}\frac{d^2\,u}{dr^2} + \frac{1}{ur}\frac{du}{dr} = -\lambda^2 \qquad \text{... A1.5}$$

and

$$\frac{1}{W}\frac{d^2\,W}{dz^2} = \lambda^2 \qquad \text{...A1.6}$$

Where λ is an arbitrary real constant.

The solutions of eq.A1.4 are well known. They are :-

$$W = c\,e^{-\lambda z} \text{ and } W = C\,e^{+\lambda z} \qquad \text{.... A1.7}$$

The solution of eq.6 can be written as:-

$$U = C\,J_o(\lambda r) \qquad \text{.... A1.8}$$

In this equation J_o is the "Bessel function of order zero"

Combining eqs.A!.7 and A1.8, we obtain as particular solutions of the differential equation (eq.A1.2).

$V = C e^{-\lambda z} J_o(\lambda r)$ and $V = C\ e^{+\lambda z} Jo(\lambda r)$ A1.9

Where C and λ are arbitrary constants.

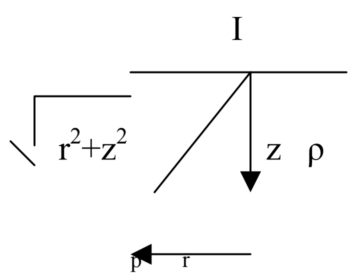
Any linear combination of solutions is also a solution of the differential equation. Thus by making λ go through all possible values from zero to infinity and allowing the two constants C to vary in dependence of λ, the general solution of eq.3 can be written as:-

$$V(r, z) = \int_{o}^{:} [\Phi(\lambda)\ e^{-\lambda z} + \psi(\lambda)\ e^{+\lambda z}]\ J_o(\lambda r)\ d\lambda \quad .... \ A1.10$$

In this equation both $\Phi(\lambda)$ and $\psi(\lambda)$ are arbitrary functions of λ,

Now, the potential at p generated by a single point source of current of intensity I located at the surface of an electrically homogeneous earth is given by :-

$$V = \frac{I\rho}{\lambda \Pi} \frac{1}{\sqrt{r2 + z^2}}$$



Where ρ is the resistivity of the homogeneous earth and I the current intensity.

Eq. 12 can be written in a form similar to that of eq.11 owing to a well-known equation from the theory of Bessel functions known as the Lipschitz integral. This equation is:-

$$\int_{o}^{\infty} e^{-\lambda z} J_o(\lambda r) d\lambda = \frac{1}{\sqrt{r^2 + z^2}} \qquad \text{.... A1.11}$$

Hence, eq.A1.10 becomes

$$V = \frac{\rho I}{2\Pi} \int_{o}^{\infty} e^{-\lambda z} J_o(\lambda r)\, d\lambda \qquad \text{...A1.12}$$

Eq. a1.12 is also a solution of A1.2

Therefore, the combined solution will be a solution of the eq.A1.2 i.e.

$$V = \frac{\rho I}{2\Pi} \int_{0}^{\infty} [e^{-\lambda z} + \theta(\lambda) e^{-\lambda z} + \psi(\lambda) e^{+\lambda z}]\ J_o(\lambda r)\, d\lambda \qquad \text{.... A1.13}$$

where $\theta(\lambda)$ and $\psi(\lambda)$ are arbitrary functions of λ.

Solution of the form of eq. A1.13 are valid in all the layers in the subsurface, but the functions $\theta(\lambda)$ and $\psi(\lambda)$ are not necessarily the same in the different layers of the subsurface. Therefore the potential due to a point source at the surface of horizontally layered earths must be written in separates expressions for the solution in the different layers, i.e.

$$V_i = \frac{\rho I}{2\Pi} \int_{o}^{:} \left[e^{-\lambda z} + \theta_i(\lambda) e^{-\lambda z} + \psi_i(\lambda) e^{+\lambda z} \right] J_o(\lambda r)\, d\lambda \quad \text{.... A1.14}$$

where the subscript is refers to the several layers in the subsurface.

Eq.A1.14 is called STEFANESCU INTEGRAL

The following boundary condition must be satisfied to get the solution of the differential equation (eq. A1.2).

1). The electrical potential must be continuous at each of the boundary planes

2) Normal component of current density is continuous across the interface

3). At the surface, the vertical component of the current density, and hence that of the electrical field intensity, must be zero

4). Near the current source the potential must approach infinity as

$$V = \frac{I\rho}{2\Pi} \sqrt{\frac{1}{r^2 + z^2}}$$

5). At infinite depth the potential must approximate to zero.

The solution to eq.3 satisfying the boundary conditions is due to STEFANESCU et al., (1930)

Thus the expression for the potential at the surface of the earth satisfying the above boundary conditions is:-

$$V = \frac{\rho I}{2\Pi} \int_{o}^{:} [1 + 2\,\theta 1\,(\lambda)]\; J_o(\lambda r)\, d\lambda \qquad \text{....A1.15}$$

where

v = potential at a surface point

I = the current intensity emitted by the current source

ρI = resistivity of the first layer

λ = a variable of integration

r = the distance from current source to the measures point

Jo = Bessel function of zero order

$\theta(\lambda)$ = Is a function often referred to as a kernel function which is controlled by the resistivity of the layers ρi, and by the depths of the boundary planes, hi.

If we define a function, $k(\lambda)$ from eg. ----- as $k(\lambda) = 1 + 2\theta 1 (\lambda)$

So that the expression for the potential becomes

$$V = \frac{\rho I}{2\Pi} \int_{o}^{:} K(\lambda) \; J_o(\lambda r) \, d\lambda \qquad \text{... A1.16}$$

where $K(\lambda)$ is a Slichter's Kernel function and $\theta 1 (\lambda)$ a Stefanescu Kernel function according to Koefoed.

The Slichter's Kernel function can be obtained by the Pekeris recurrence relation given by:-

$$Ki = \left[Ki+1 + \rho i \tan h(\lambda ti) \right] / \left[\rho i + ki + 1 \tan h(\lambda ti) \right] \qquad \ldots$$

A1.17

By eq.3 it is possible to determine the Slichter's Kernel function in the subsurface layer when the parameters of the layer distribution are known.

finally by recurrent application of eq.A1.17, we can arrive at k1, the Slichter's Kernel function.

4.2.1 Resistivity Transform

To obtain the layer distribution from the apparent resistivity curve, Koefoed (1968) introduced the concept of resistivity transform.

Eq.a1.16 can be rewritten as

$$V = \frac{I}{2\Pi} \int_{o}^{:} \rho_1 k(\lambda) \; J_o(\lambda r)\, d\lambda \qquad \text{....A1.18}$$

or

$$V = \frac{I}{2\Pi} \int_{o}^{:} T(\lambda) \; J_o(\lambda r)\, d\lambda \qquad \text{... A1.19}$$

where $T(\lambda) = \rho_1 k(\lambda) = \{1 + 2\,\theta 1\,(\lambda\}$ is known as resistivity ransform.

A simple recurrence relation (Koefoed, 1976) helps in computing the resistivity transform for any number of layers.

$$T_{i-1} = \frac{T_i + \rho_i\text{-}1 \tan h\,(\lambda\, d_{i-1})}{1 + T_i \tan h\,(\lambda\, d_{i-1}) / \rho_i\text{-}1} \qquad \text{... A1.20}$$

where $i = n_1\ n\text{-}1, \ldots$

T_i = resistivity transform over the i^{th} layer

d_i = thickness of the i^{th} layer, and

ρ_i = resistivity of the i^{th} layer

for the substratum, $T_n = \rho_n$

4.2.2. Apparent Resistivity and Resistivity Transform.

The apparent resistivity over a horizontally layered earth model can be expressed interms of the resistivity transform function.

For Schlumberger electrode configuration the apparent resistivity is readily derived by (Koefoed, 1970) as

$$\rho_a(L) = L^2 \int_o^{:} T(\lambda)\ J_1(\lambda L)\ \lambda d\lambda \qquad \ldots\ldots \quad A1.21$$

where L is half the current electrode spacing and the resistivity transform $T(\lambda)$is calculated recursively.

Eq. A1.21 can easily be evaluated by convolution using digital filters (e.g., Ghosh, 1971; Johansen, 1975) on a computer. The problem is recast in the form:-

$$\rho_a = \sum_{K = K_{min}}^{K_{max}} T(\lambda)\, f_k \qquad ..... \text{A1.22}$$

where the coefficients of a moving average filter are represented by f_k.

Obviously eq.A1.21 and eq.a1.22 are used to compute apparent resistivity model curves for schlumberger array. Similarly the apparent resistivity due to four electrodes on an n-layered earth can be obtained.

A.2 INTERPRETATION

A.2.1 Inversion

For many years the interpretation of sounding curves was performed by matching observed curves with theoretical curves found in catalogues (Mooney and Wetzel, 1956; La campagnie G'ene'rae de G'eophysique, 1963). Today, virtually all sounding is performed by "inversion" of the field data. In this process of interpretation, a computer program is developed (by convolution using digital filter eq A1.22) yielding theoretical apparent resistivity values/curves for a given layered earth model. Nowadays there are a variety of different inversion programs which are provided by the resistivity instrument manufacturers or some of which can be freely down loaded from internet, avoiding the need for developing a program. The general working principle of the inversion program is as follows:-

1. The observed apparent resistivity data will be inputed into the computer program.
2. A conceptual layered earth model, including the number of layers, their thickness and their true resistivity is developed. An initial guess of the layer parameters can be made by using manual curve matching techniques, which has recently fallen into disuse because of inversion.
3. These layer parameters are then inputed into the computer program, which in turn generate theoretical apparent resistivity valves.
4. The theoretical values are compared with the observed apparent resistivity data.

5. The conceptual layered model is continuously changed and modified until an acceptable match is achieved between the observed resistivity data and the computer generated theoretical apparent resistivity valves.

In practice what is commonly done today is to perform a least-squares fit between observed valves of apparent resistivity and valves calculated from eq.A1.22 A weighted least -squares sum S may be written.

$$S = \sum_{i=1}^{m} \left[\rho_a^{OBS}(x_i) - \rho_a^{CAL}(x_i, P) \right]^2 / \ \mathrm{Var}\left[\rho_a^{OBS}(x_i)\right] \qquad \text{... A1.23}$$

where ρ_a^{OBS} (x_i) is the observed apparent resistivity at location x_i , $\rho_a^{CAL}(x_i, P)$ is the calculated apparent resistivity at location x_i, due to the model defined by the parameters P, and Var $[\rho_a^{OBS}(x_i)]$, is the statistical variance of $\rho_a^{OBS}(x_i)$. The n-dimensional vector P is defined by the layer thicknesses t_i and the layer resistivites ρ_i. Equation. . The parameter vector P is varied through numerical automation until equation A1.23 is minimized. In practice there is a least-squares residual **€** left after minimization of equation A1.23,which results from too much noise in the observations, or by a lack of model fit caused when the parameters P determined by minimization of equation A1.23 do not exactly represent the earth which generated the data. If there is noise in the observed data, the best-fit calculated curve will follow a regression line through the scattered data points and **€**may be large. If on the other hand, the earth is not one-dimensional (1-D), **€** can also be expected to be large. Two-or three-dimensional inversion then becomes necessary. It may well be preferable to refer to this technique as automatic curve matching insofar as a large number of forward curves are compared with the field curve, automatically.

Resist 87, (Vander Vepen B.P.A, ITC/DELFT-Netherlands) was used for processing the resistivity sounding data. **Resist** supports the **Wenner, Schlumberger** and **Dipole-Dipole arrays**.

Given all the input required, i.e, both the observed apparent resistivity and initial model parameters(resistivities thicknesses and number of layers)it provides a graphic display of the observed apparent resistivity curve together with a theoretically computed curve, then the inversion process undergoes a number of iterations, to obtain more accurate models that give best fit in the sense of least squares .

ANNEX II: COMPARISION OF SCHLUMBERGER AND WENNER ARRAY

Comparison of Schlumberger and Wenner arrays

The Schlumberger and Wenner electrode arrays are the two most widely used arrays in resistivity prospecting . There are two essential differences between these arrays.

(1) In Schlumberger array the distance between the potential electrodes **MN** is small and is always kept equal to ,or smaller than, one-fifth the distance between the current electrodes **AB** , that is, **AB ≥5MN.** In the Winner array **AB** is always equal to **3MN**

(2) In Schlumberger sounding, the potential electrodes are moved only occasionally, whereas in a Wenner sounding they and the current electrodes are moved after each measurement.

(3) The manpower and time required for making Schlumberger soundings are less than that required for making Wenner soundings

(4) Stray currents in industrial areas and telluric currents that are measured with long spreads affect measurements made with the Winner array more readily than those made with the Schlumberger array.

(5) The effects of near-surface, lateral inhomogeneties are less apt to affect Schlumberger measurements than Wenner measurements. Furthermore, the effect of lateral variations in resistivity are recognized and corrected more easily on a Schlumberger curve than on a Wenner curve.

(6) A Schlumberger sounding curve, as opposed to a theoretical curve, is generally discontinuous. The discontinuities result from enlarging the potential electrode spacing after several measurements. This type of discontinuity on the Schlumberger sounding field curve is considered as another advantage over Wenner sounding curves, because if the theoretical assumption of a horizontally stratified laterally homogeneous and isotropic Earth is valid in the field, then the discontinuities should occur in a theoretically prescribed manner.

The advantages of the Wenner array are limited to the following

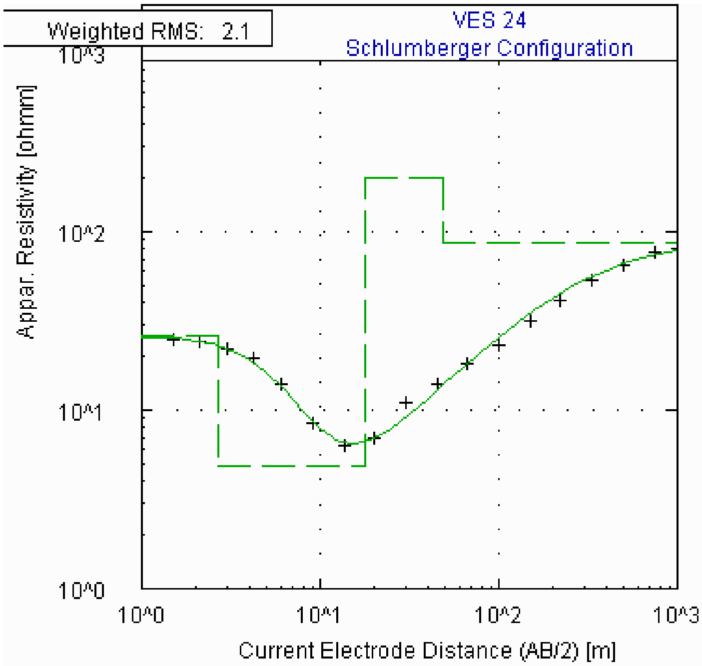
(1) The relative simplicity of the apparent resistivity formula

(2) The relatively small current values necessary to produce measurable potential differences.

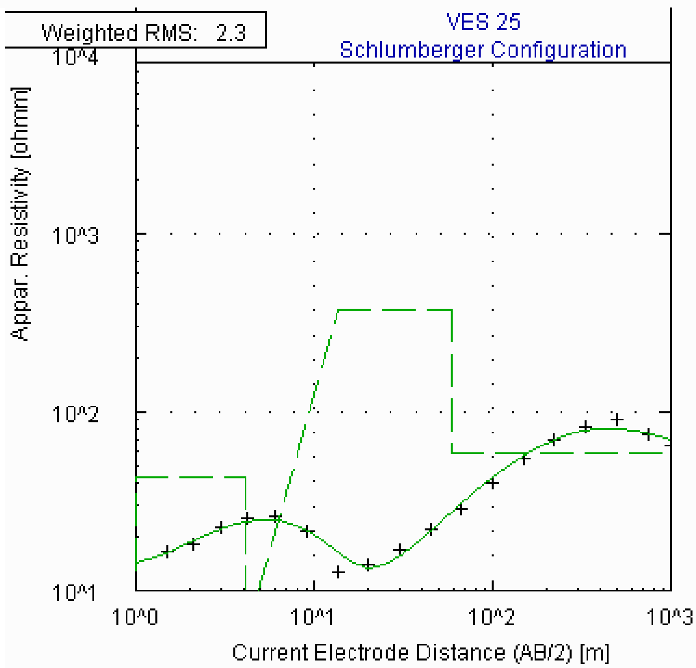
The above comparison indicates that it is advantageous to use Sclumberger array rather than the Wenner array for making electrical resistivity soundings also the interpretation techniques are diversified for Schlumberger sounding curves than Wenner sounding curves.

All the above notes are taken from Zohdy,1976, Techniques of water resources investigations ,published by the U.S Geological survey.

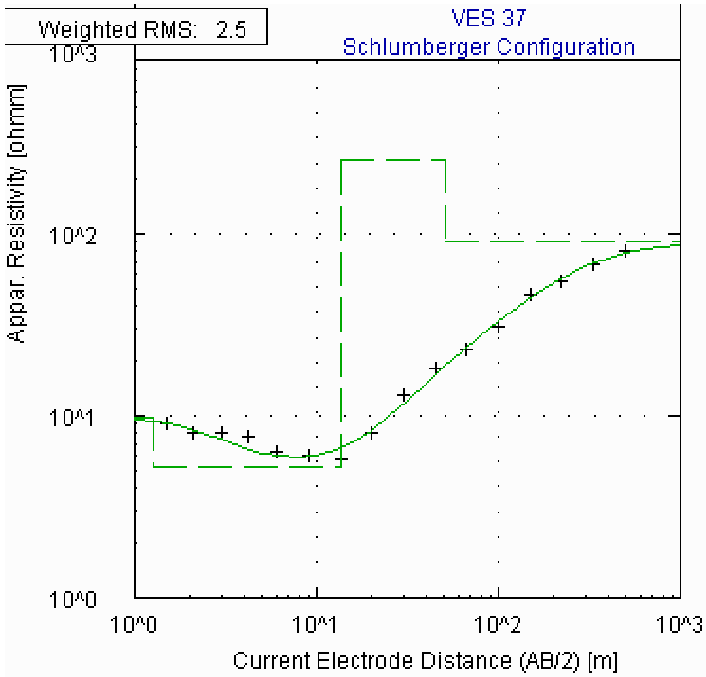
ANNEX III: SMOOTHED AND INTERPRATED VES CURVES



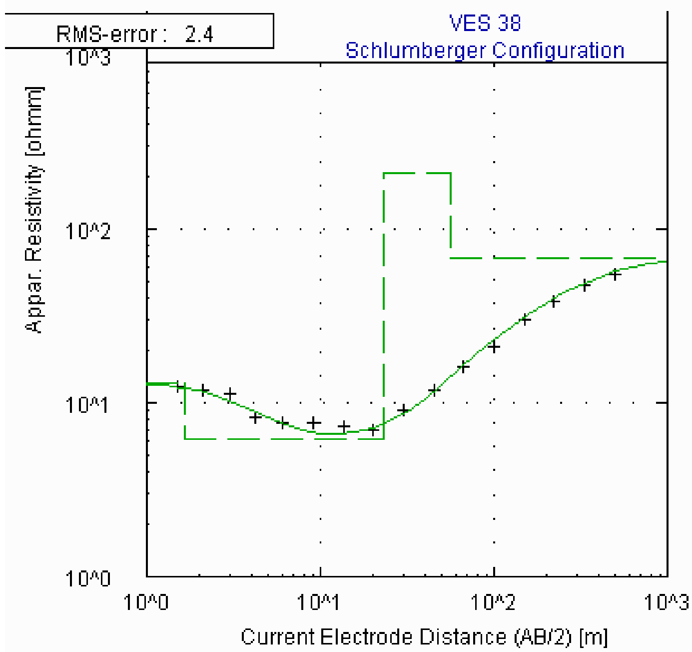
No	Res	Thick	Depth
1	25.9	2.7	2.7
2	4.8	15.2	17.9
3	198.3	30.8	48.7
4	86.4	-.-	-.-



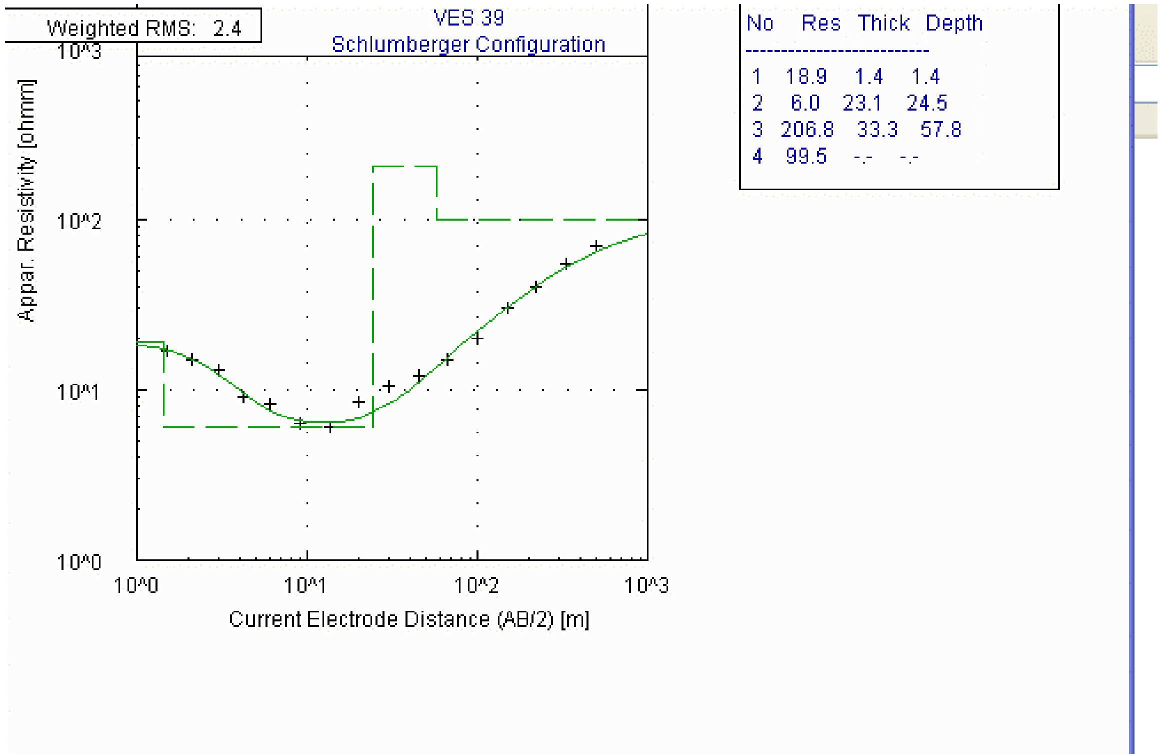
No	Res	Thick	Depth
1	13.1	1.0	1.0
2	42.9	3.1	4.1
3	5.3	9.5	13.6
4	376.3	45.7	59.3
5	59.3	-.-	-.-

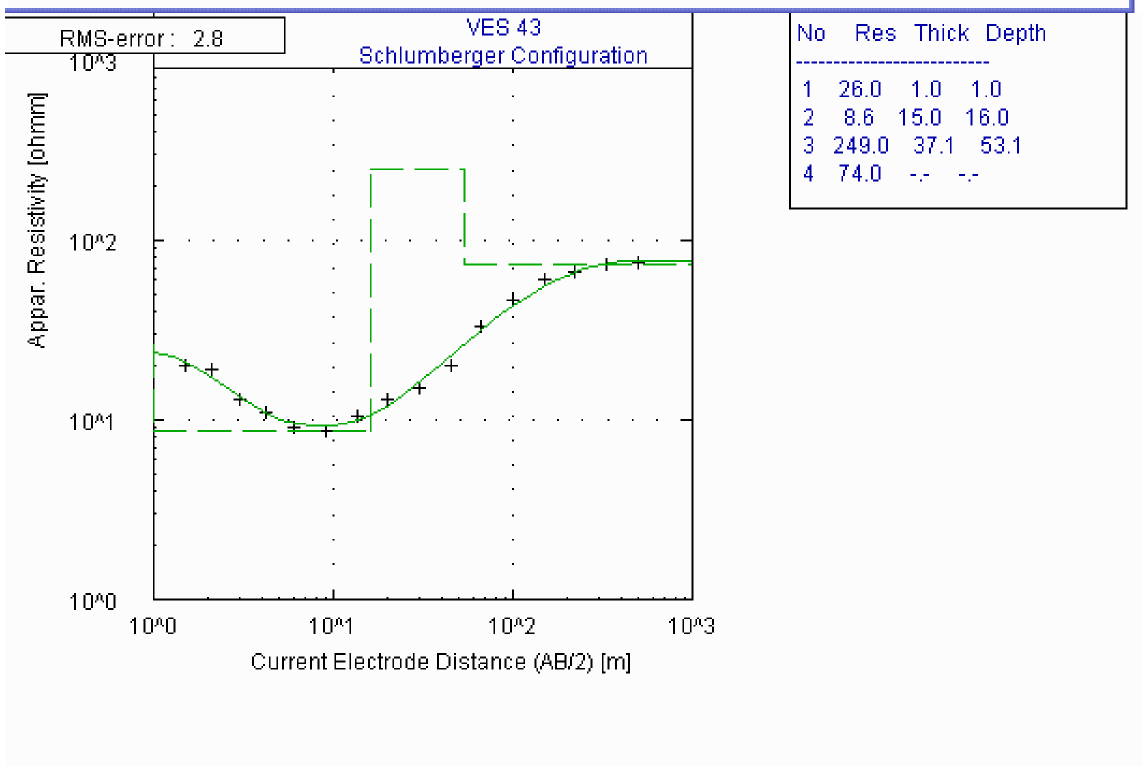


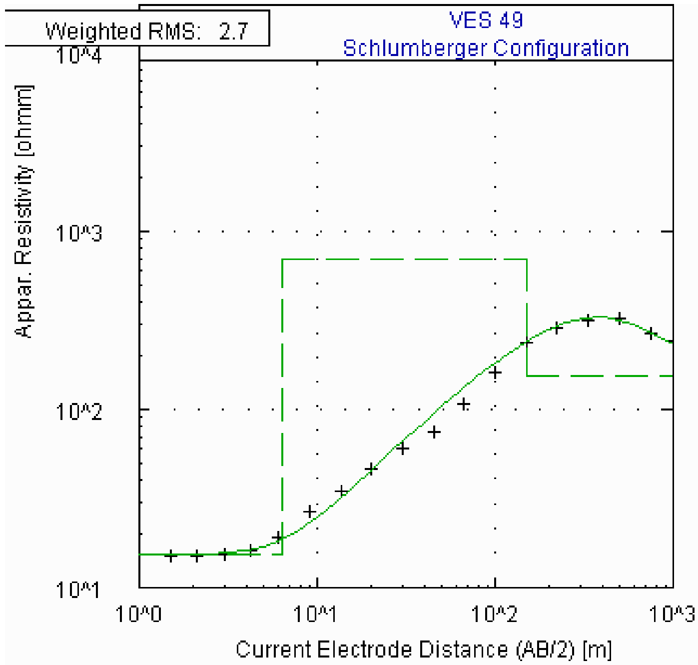
No	Res	Thick	Depth
1	9.9	1.3	1.3
2	5.3	12.4	13.7
3	252.8	36.9	50.6
4	90.2	-.-	-.-



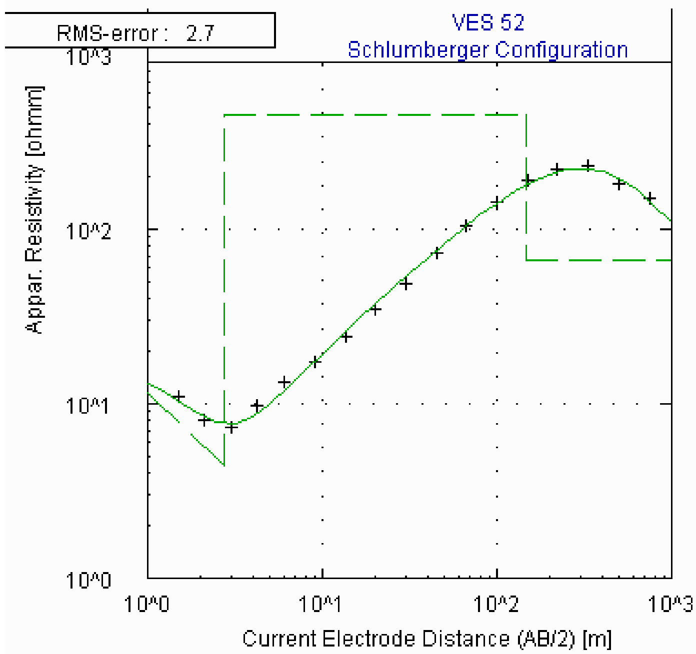
No	Res	Thick	Depth
1	13.0	1.6	1.6
2	6.1	21.7	23.3
3	209.6	32.9	56.2
4	68.5	-.-	-.-


Weighted RMS: 2.4
VES 39
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 18.9 1.4 1.4
2 6.0 23.1 24.5
3 206.8 33.3 57.8
4 99.5 -.- -.-

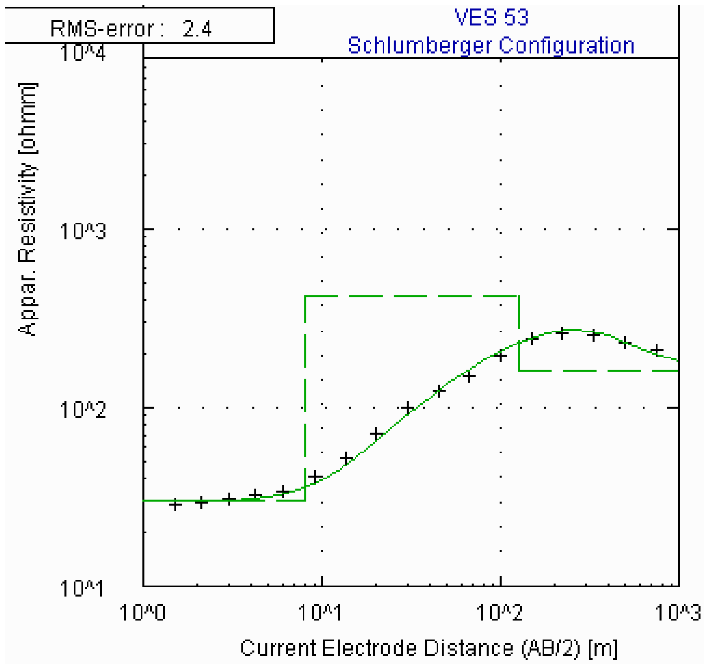

RMS-error : 2.8
VES 43
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 26.0 1.0 1.0
2 8.6 15.0 16.0
3 249.0 37.1 53.1
4 74.0 -.- -.-



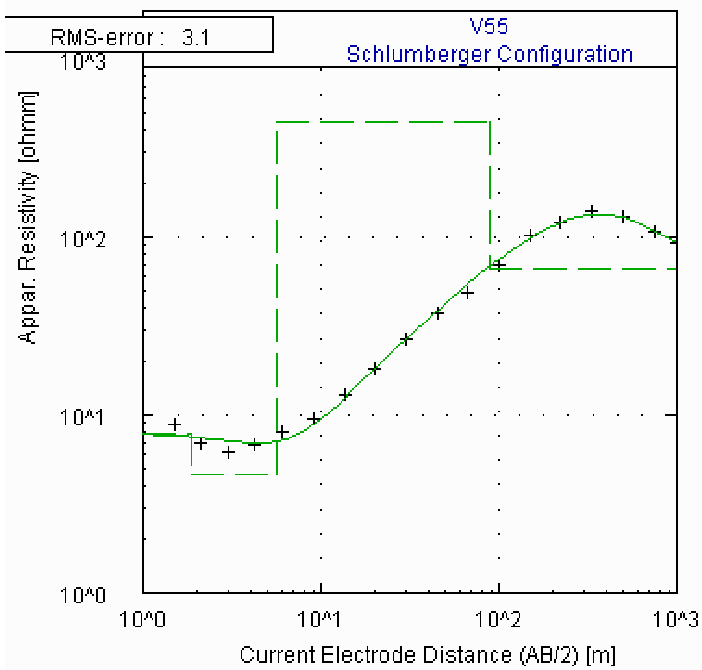
No	Res	Thick	Depth
1	15.3	6.3	6.3
2	697.2	144.7	151.0
3	153.0	-.-	-.-



No	Res	Thick	Depth
1	15.4	0.8	0.8
2	4.5	2.0	2.8
3	451.4	145.3	148.0
4	67.2	-.-	-.-



No	Res	Thick	Depth
1	30.0	8.0	8.0
2	420.0	120.0	128.0
3	160.0	-.-	-.-



No	Res	Thick	Depth
1	7.8	1.9	1.9
2	4.7	3.8	5.7
3	438.8	83.0	88.6
4	66.5	-.-	-.-

ANNEX IV: GEOLOGICAL LOG OF THE BORE HOLES, BH2 & BH5

GEOLOGIC LOG OF BH2

475705E

956271N

ELEVATION 1906m

TOTAL WELL DEPTH 220m

SWL 104m

Lithology	Depth
Clay	0-30m
Slightly fractured vesicular basalt	30-48m
Highly fractured scoraceous basalt	48-90m
Basalt with clay	90-108m
Slightly fractured basalt	108-120m
Fresh basalt	120-150m
Fractured and weathered baslt	150-200m

GEOLOGIC LOG OF BH5

493179E

968613N

ELEVATION 1919m

TOTAL DEPTH 108m

SWL 62

Lithology	Depth(m)
Clay	0-12m
Vesicular basalt	12-20m
Scoraceous basalt	20-24m
Fractured basalt	24-28m
Scoraceous and vesicular basalt	28-56m
Volcanic sand	56-80m
Pumice and sand	80-108m