

**ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCE**



**GEOELECTRICAL CONSTRAINTS FOR GROUND WATER MODELS
AROUND LEGEDADI, NORTH EAST OF ADDIS ABABA.**

By

MENGESHA SISAY

**A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL
FULFILLMENTS OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF
SCIENCE IN EXPLORATION GEOPHYSICS.**

November 2008.

Addis Ababa

**ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCE**

**GEOELECTRICAL CONSTRAINTS FOR GROUND WATER MODELS
AROUND LEGEDADI, NORTH EAST OF ADDIS ABABA**

**By
MENGESHA SISAY KASSA
FACULTY OF SCIENCE
DEPARTMENT OF EARTH SCIENCE**

Approved by board of examiners:

.....
Chairman, Department Graduate Committee **signature**

.....
Dr. Shimeles Fisseha
Principal Advisor **signature**

.....
Ato Moges Tigabe
External Examiner **signature**

.....
Dr. Tigistu Haile
Internal Examiner **signature**

Acknowledgement

First and foremost I am grateful to my advisor Dr. Shimeles Fisseha for the proper supervision, support and guidance he provided me through out my research work. His critical comments, brotherly approach and unreserved effort have given me the opportunity to explore more. I acknowledge my deep gratitude to Dr. Tigistu Haile, a very cooperative person, who most happily forwarded me important ideas.

My gratitude also goes to Water Works Design and Supervision Enterprise (WWDSE) for providing me all the necessary data.

I have no words to express my special thank to my friends Solomon Sahile, Tilahun Azagegn, Tatek Assefa and Tamrat Fantaye for provision of reading materials, softwares, data and their positive attitude towards helping me.

My appreciation and thanks is also to my father Ato Sisay Kassa, who took my earliest footsteps in the paths of knowledge and also my mother Muluaem Dejene who always wish best to her son. Special thanks are also to my elder brother Melaku Sisay for his gift of laptop to my research work and to my little daughter Mahlet Mengesha for her patience to stay alone without my treatment.

Last but not least, my deepest heart felt gratitude also goes to my beloved fiancée, Rahmet Mohamed, who is my source of respiration. Her love and encouragement has played important role through out my academic life.

TABLE OF CONTENTS

| | Page |
|---|-------------|
| Acknowledgement | i |
| Table of contents | ii |
| List of figures | iv |
| List of tables | iv |
| Abstract | vi |
| CHAPTER ONE | |
| INTRODUCTION | 1 |
| 1.1. Purpose and overview of the study..... | 1 |
| 1.2. The Location of the Study Area..... | 2 |
| 1.3. General objectives..... | 2 |
| 1.4. Previous studies..... | 4 |
| 1.5. Methodologies used..... | 8 |
| CHAPTER TWO | |
| GEOLOGICAL AND HYDROGEOLOGICAL REVIEWS | 9 |
| 2.1. Geological frame work of the area..... | 9 |
| 2.1.1. Local Geological Settings | 9 |
| 2.1.1.1 Tertiary Volcanic Rocks..... | 9 |
| 2.2. Hydrogeology of the study area..... | 12 |
| CHAPTER THREE | |
| ELECTRICAL RESISTIVITY METHODS | 14 |
| 3.1 General consideration | 14 |
| 3.2 Theoretical basis..... | 14 |
| 3.2.1. Geoelectrical method..... | 14 |
| 3.2.2. Potential distribution in the Earth..... | 15 |
| 3.2.3. Electrical Resistivities of rocks | 20 |
| 3.2.4. Apparent Resistivity..... | 21 |
| 3.3. Electrode arrangements..... | 21 |
| 3.3.1 Wenner Configuration..... | 23 |
| 3.3.2 Schlumberger Configuration..... | 23 |

| | |
|---|-----------|
| 3.3.3 Dipole-dipole configuration..... | 24 |
| 3.4 Depth of Investigation..... | 26 |
| 3.5 The Principle of Equivalence and Suppression..... | 26 |
| 3.5.1 The Principle of Equivalence..... | 26 |
| 3.5.2 Suppression..... | 27 |
| CHAPTER FOUR | |
| DATA SET PROCESSING AND INTERPRETATION..... | 28 |
| 4.1 Data set and Survey Layout..... | 28 |
| 4.2 Processing and Interpretation of Resistivity Data..... | 29 |
| 4.3 Inversion..... | 30 |
| 4.4 The Computer Program..... | 32 |
| CHAPTER FIVE | |
| RESULTS AND DISCUSSIONS..... | 34 |
| 5.1 Pseudosections..... | 34 |
| 5.1.1 Pseudosections of profile 1..... | 34 |
| 5.1.2 Pseudosections of profile 2..... | 35 |
| 5.2 Sliced-depth resistivity sections and stacked plots..... | 36 |
| 5.3 Interpretation of Individual Sounding Points..... | 39 |
| 5.3.1 Comparison of Interpreted Sounding Points Based on Water Table Depth..... | 42 |
| 5.4 Geoelectrical sections..... | 43 |
| 5.4.1 Geoelectrical section of profile 1..... | 44 |
| 5.4.2 Geoelectrical sections section of profile 2..... | 46 |
| 5.5 The Comparison of Hydrogeophysical Results..... | 49 |
| 5.6 Conclusions..... | 54 |
| 5.7 Recommendations..... | 55 |
| References | 57 |
| List of Appendices | |

List of Figures

| | Page |
|---|-------------|
| Figure.1.1 Location Map of the Ada'a-Becho Project area..... | 3 |
| Figure.2.1 Geological Map of the Study Area..... | 11 |
| Figure 3.1 Equipotential and current lines for a pair of current electrodes | 16 |
| Figure 3.2 The Wenner Configuration | 23 |
| Figure 3.3 The Schlumberger Configuration..... | 24 |
| Figure 3.4 The Dipole-dipole Configuration..... | 25 |
| Figure 4.1 Post map showing the distribution of VES point and boreholes..... | 28 |
| Figure.5.1 Apparent Resistivity Pseudosection of Profile 1..... | 35 |
| Figure.5.2 Apparent Resistivity Pseudosection of Profile 2..... | 36 |
| Figure.5.3 Lateral resistivity map at a pseudo-depth of $AB/2 = 500m$ | 37 |
| Figure.5.4 Stacked plot of sliced resistivity sections at different depth levels..... | 38 |
| Figure 5.5a Geoelectric section along profile 1..... | 44 |
| Figure 5.5b Interpreted block diagram of the subsurface along profile 1..... | 45 |
| Figure 5.6a Geoelectric section along profile 2 | 47 |
| Figure 5.6b Interpreted block diagram of the subsurface along profile 2..... | 48 |

List of Tables

| | Page |
|--|-------------|
| Table 5.1: Summery of conducted VES points with resistivity values and interpreted lithologies used for the construction of geoelectric section in this thesis work..... | 39 |
| Table5.2: Summery of conducted VES points with their resistivity values and interpreted lithologies deduced from the present study..... | 40 |

Table 5.3: Summary of conducted VES points with their resistivity values and interpreted lithologies (on report of WWDE).....41

Table 5.4: The depth of the water table on different zones of the survey area deduced from the present study.....42

Table 5.5a Interpreted results of VES-22 deduced from the present study.....49

Table 5.5b Interpreted Results of VES-22 (on report of WWDE).....50

Table 5.6a Interpreted Results of VES-21 (On this thesis work).....50

Table 5.6b Interpreted Results of VES-21 (On the report of WWDE).....51

Table 5.7: Resistivity values of the major geological formations deduced from the present study.....52

Table 5.8: Resistivity value ranges of the major geological formations (Taken from WWDSE, 2007).....53

Abstract

Geophysical surveys were carried out around Addis Ababa namely on the Ada'a plain, the Becho plain and different traverses with different orientations in the Abay plateau by Water Works Design and Supervision Enterprise (WWDSE). The methods employed were electrical resistivity sounding, electrical resistivity imaging and magnetic mapping. The study mainly focuses on the evaluation of the groundwater potential of Ada'a and Becho plains and was designed for the purpose of pressurized irrigation development.

In this thesis work, only electrical resistivity sounding method is employed and the study area is restricted along a transverse of Gohatsion-Chancho-Sululta-Lagedadi-Adaa which is located between $9^{\circ}04'78''$ & $9^{\circ}56'58''$ N and $38^{\circ}27'29''$ & $38^{\circ}54'67''$ E. The study aims to map the possible paths of fluids and to develop geoelectrical models of a given area interms of ground water studies. This includes detail reprocessing and analysis of the existing data. And to acquire practical experience in the interpretation of resistivity data.

From the pseudosection along profiles and the sliced depth section at different depth levels show the northern part is relatively resistive than southern part. This may indicate the thickness of the hard rock pledges southward or an extended conductive response of the overburden.

The interpreted result of the individual VES points and the two geoelectric sections shows, in the northern flank there is a favorable condition to aquifer shallower than the southern flank. But thick aquifer is observed on the southern flanks as compared to the northern flank. The graphs obtained from hydrodynamic data also confirm this result. And the ground water flows from north to the south direction.

The depth of investigation attained by the resistivity data was not deep enough to penetrate the lower volcanic aquifer. Therefore the use of deep probing, natural source EM geophysical methods such as controlled source or conventional Audio Magnetotelluric (CS/AMT) is recommended. Besides, the potential methods (gravity and magnetic) integrated with other techniques such as remote sensing in GIS framework are recommended to come up with full picture of the subsurface map of the survey area.

Generally results from vertical electrical soundings as obtained from the stacked graphic plot, pseudosections and geoelectric section analysis show that northern flank is relatively resistive than the southern part. Therefore, from the hydrogeological point of view the southern part deserve more interest for ground water exploration.

CHAPTER ONE

INTRODUCTION

1.1 Purpose and Overview of the Present Study

Ground water is that portion of the atmosphere precipitin, mostly rainfall, which has percolated into the earth to form under ground deposits are referred to as aquifers which is a lithologic unit or combination of a lithologic unit capable of yielding water to pumped wells or springs (Charles *et al.*, 1999). The need of more water supplies from subsurface sources is partly an out come of its quality due to the fact that some contamination may be removed by passage through the soil as a result of infiltration, absorption and exchange reactions. Thus, its Physical and chemical quality due to the natural purification processes that occur as water moves down through the earth generally result in a safer source of supply than surface water. As per the information from Addis Abeba water and sewerage authority (AAWSA) more than 30 % of Addis Abeba city municipal water supply is from ground water source; besides all industries, factories flower farms and many other activities are currently using ground water for their water consumption(Tilahun Azagegn, 2008).

Therefore, ground water is emerging as a critical issue and a reliable water supply is essential in areas surrounding Addis Ababa.Recently great efforts have been made in conceptualizing groundwater flow regime of the area surrounding Addis Ababa to verify inter-basin groundwater flow. Among the procedures are understanding of regional and local groundwater dynamics and localization i.e., spatial and depth ward variations within aquifer systems.

The uneven distribution of ground water from one geographic location to another is part of a problem in hydrology. This in turn affects the depth of ground water table on different geologic horizon and delineated area of the low resistivity due to effects associated with porosity and the pore structure of the rocks and amount of water saturation. 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 this measurement can reveal how the physical properties of the earth's interior vary vertically and laterally. Moreover,

the method helps to acquire information about the subsurface over a substantial area in a reasonable time frame and in a cost-effective manner (Flathe, 1964).

Geophysical surveys were carried out around Addis Ababa namely on the Ada'a plain, the Becho plain and different traverses with different orientations in the Abay plateau by Water Works Design and Supervision Enterprise (WWDSE). The methods employed were electrical resistivity sounding, electrical resistivity imaging and magnetic mapping. The study mainly focuses on the evaluation of the groundwater potential of Ada'a and Becho plains and was designed for the purpose of pressurized irrigation development.

In this thesis work, it is proposed to employ existing electrical sounding data in order to map the possible paths of fluids and the potential of ground water around Legedadi, north east of Addis Ababa. Further more, the thesis work is intended to contribute towards the effort to understand the ground water system of the survey area and to acquire practical experience in the interpretation of resistivity data.

1.2 The Location of the Study Area

Ada'a and Becho plains are found in the upper part of Awash River basin. They are situated in central Ethiopia, in Oromia Regional State. Ada'a plain has elevation varying between 1600 and 1900masl and is found approximately between the coordinates $38^{\circ}50'E - 39^{\circ}15'E$ and $8^{\circ}30'N - 8^{\circ}53'N$, while Becho plain is found between elevation 2040 and 2120masl and approximately bounded between coordinates $38^{\circ}08'E-38^{\circ}36'E$ and $8^{\circ}38'N - 9^{\circ}00'N$. Out of this region the study area, in this thesis work, is restricted along the transverse of Gohatsion-Chancho-Sululta-Lagedadi-Adaa, which is located between $9^{\circ}04'78''$ and $9^{\circ}56'58''N$ and $38^{\circ}27'29''$ and $38^{\circ}54'67''E$ as shown in Figure 1.1.

1.3 General Objectives

A geophysical study was carried out around Addis Ababa by WWDSE. The methods employed were electrical resistivity sounding, electrical resistivity imaging and magnetic mapping. The study mainly focuses on the evaluation of the groundwater potential of Ada'a and Becho plains and was designed for the purpose of pressurized irrigation development. As per the Terms of

Two types of electrical resistivity surveys were undertaken. The first one is that of Vertical Electrical Soundings (VES) with a maximum current electrode separation, $AB/2=1000$ meters, along three traverse lines within the two plains- Ad'aa and Becho plains. The survey traverses are:-

- i) Kachise–Becho-Adaa,
- ii) Muger–Holeta-Becho and
- iii) Goha-Tsion–Chancho – Sululta – Legedadi - Adaa.

The second one was a two-dimensional resistivity imaging survey with dipole-dipole array aiming at a maximum penetration of 200 meters.

In the present work the existing Vertical Electrical Soundings (VES) data were chosen for detailed reprocessing and analysis by targeting the following objectives:

- To map the possible paths of fluids and determine depth to the aquifer.
- To develop geoelectrical models of a given area in terms of ground water studies. This helps in determining the aquifer properties of these areas, including depth to the saturated zones, degree of weathering and fracturing of the water-bearing zone.
- Delineate the most promising areas for future ground water development by studying the kind and thickness of the overlying strata and the lithology encountered with it.
- To acquire practical experience in the interpretation of resistivity data.

1.4 Previous Studies

Among the various studies with direct relevance for the present work, few are listed below:

1. Water works design and Supervision Enterprise Currently Working extensively on the study and development activity of water resource in general and ground water investigation in particular around Addis Abeba. The study is research oriented which bases on new

conceptual model and requires generating sufficient data to prove the conceptual model. The following are some of the conceptual frameworks used for modeling.

- Ground water flows from north (Entoto) to south (Akaki) and then to south-southeast (Dukem) area.
- Ground and surface waters in Legedadi and Dukem are generated from precipitation.
- The geology of the well field is complex and single layered aquifer.

In order to verify these assumptions, different sets of geophysical investigations integrated with other methods were done around Addis Ababa namely on the Ada'a plain, the Becho plain and different traverses with different orientations on the Abay plateau. The methods employed were electrical resistivity sounding, electrical resistivity imaging and magnetic mapping. The objective of the geoelectric survey conducted in the selected traverse was to

1. Identifying geological structures, like faults and lineaments that are important for groundwater occurrences, storage and circulations.
2. Verifying the conceptual lithologic succession of Ada'a and Becho plain and the Abay plateau.
3. Identification of different lithological and hydrogeological units based on their resistivity contrasts.
4. Determining the aquifer properties of these plains, including depth to the saturated zones, degree of weathering and fracturing of the water bearing rocks, thicknesses of the overburden or confining materials.

The result of the study revealed that the geologic structure in the area are normal faults, beddings, fissuring and tilting of the rock affect the various rock unit in the area. Hydrogeological section of the ground water regime associated with the volcanics, Lacustrine and alluvial sediments. The volcanic rocks in the area are highly affected by four different faults and fractures. And the information on the sub-surface configuration is outlined from the model of the individual VES points. From this survey the resistivity value of the

major formation have been epitomized as shown on table 5.8 .The VES data and drilling mapping wells enabled to draw the hydrogeological cross section. Based on these hydrogeological cross sections the spatial distributions of the aquifer on Abay plateau could be subdivided as follow:

- The central part of Abay sedimentary formation forms Syncline and volcanic unit that overly it follows the same trend.
- The Entoto ridge was found to be a fissural eruption and act as a barrier to the ground water flow through it.
- The thickness of the rhyolites trachtes and upper basalt could be very thick which makes it difficult for the VES data investigation to penetrate the lower volcanic aquifer.

While the spatial distributions of the aquifer On Becho plain are subdivided as follow:

- Upper basalt aquifer is composed of fractured and massive basalt and having 50m thickness. The ground water potential of this aquifer is not significant as compared to the lower basaltic aquifer and the water level depth increase from north to south.
- The lower basaltic aquifer is composed of Scoraceous basalt with high potential of ground water.

2. Geophysical investigation for construction material deposit in the Legedadi area (Kifle Damtaw, 1990): In this work, seismic refraction method was used for the purpose of mapping construction of material near the Legedadi dam, which is about 28 km NE of Addis Ababa. The objective of the survey was to determine the thickness and nature of the overburden material, to determine the quality and nature of the relatively fresh bedrock and estimate the thickness and volume of rock that could be used for construction materials. The result of the study revealed that relatively fresh basalt bedrock overlain by a highly weathered basaltic overburden material.
3. Hydro-geochemical characterization of aquifer systems in upper Awash and the adjacent Abay plateau using geochemical modelling and isotope hydrology (Tilahun Azagegn, 2008): This is the detailed and latest study and used as an essential reference in the present work. Some of the findings and recommendation of this work are given below.

- Hydrogeochemical investigation is recommended as an integral component of hydrogeological investigations and groundwater resource evaluations. Applications of isotope techniques are also recommended to supplement hydrogeological investigation for recharge source identification and to fully characterize the deep aquifer system in the area.
 - Further hydrogeological investigation in the area is recommended and should involve:
 - Drilling of deep test wells in the plateau, transition and rift zones be conducted in a way to characterize distinct aquifer system.
 - Detail hydrogeological and hydrogeochemical investigations are recommended in order to identify and delineate zones of economic and investment interest.
4. The geophysics of the Filwuha area (Elias Lewi, 1999): The objectives of the study is to identify the lateral and vertical dimension of the probable hot water aquifer and for the selection of a potential drilling site for the additional thermal water supplying boreholes. This could sustain adequate and reliable yields. He concluded from resistivity survey at Filwuha area that there are two low resistivity zones that were indistinguishable at shallow depth and emerged at higher depth i.e. the first zone between National Palace and Ethiopian Mapping Agency and the second stadium zone. Moreover,for further delineation of the thermal zone in the southwest direction, it was recommended to drill two test wells of large depth of 350m, even deeper if possible. It was also mentioned that, this would be useful for understanding and assessment of the thermal groundwater in the area, to know the nature and full extent of the resource.
5. Hydrology of Addis Ababa (Aynalem Ali, 1985): The main purpose of this work is to suggest for the city water resources and to Water- policy decision makers, the possibility of developing ground water research with in the surrounding in order to contribute for the best solution of some important social, economic, and industrial problems. The result of the study is that the water producing zones are fractured basalt and the coarse grained parts of the interflow sediments. And, the presence of a large number of buried electrical cable lines in Hilton compound does not allow the possibility of geophysical surveys specially by means of electrical methods.

1.5 Methodologies

The methodologies used in this thesis work involve two vital phases.

The initial phase is basically assessment of previous studies and validating the main findings. As a starting framework, background information on the geological, hydrological and hydrogeological aspects of the study area is obtained from a report entitled Evaluation of water resources of the ADA'A and BECHO plains ground water basin for irrigation development project (WWDSE, 2007). The report is composed of two volumes: Volume-I, Geology, Hydrology and Hydrogeology of Ada'a-Becho Plains and Volume-II, Evaluation of Ground water resource potential.

The second phase involves processing and interpretation of the geophysical data in light of the existing background information harvested from the initial phase. A total of 32 VES stations, along the traverse of Gohatsion-Sululita-Legedadi-Adea were used for this study.

CHAPTER TWO

GEOLOGICAL AND HYDROGEOLOGICAL REVIEWS

2.1 Geological framework of the area

The major geological formations and tectonic features of the research area were adopted from the above report (WWDSE 2007), and a thesis titled Hydrogeochemical Characterization of Aquifer systems in Upper Awash and adjacent Abay plateau using Geochemical Modelling and Isotope Hydrology (Tilahun Azagegn, 2008).

2.1.1. Local Geological Setting

The stratigraphy of the survey area is summarized as follows:

2.1.1.1 Tertiary Volcanic Rocks

Tertiary volcanic rocks which could be subdivided into Paleogene and Neogene formation age-sequences have wide distribution in the recharge area, transit zone and on the plains of the groundwater basin under study (WWDSE, 2007).

A) Paleogene Rock

The stratigraphy of the Ada'a-Becho Plains groundwater system shows a remarkable configuration. In northern part of the study area, Paleogene volcanic rocks dominate the Abay plateau. Some of the Paleogene Volcanic rocks are the following:

Blue Nile Basalts (PbnB): This unit has small distribution at the northern edge of the recharge area of the groundwater basin in Abay plateau. The formation is composed of columnar alkaline flood basalt of very low permeability. The thickness of this formation varies from 100 to 200 meters.

Abay Beds (JabB): This unit occurs in the Abay river gorge lying between the Adigrat sandstone and the Antalo limestone. It consists of alternating beds of thick sandy limestone, calcareous sandstone, gypsum and shale. The total thickness of the Abay beds reaches up to 580m.

Ashangi Basalt (PasB): This unit is exposed in the northern part of the area representing the oldest fissural flood basalt next to the Blue Nile basalt. It is strongly weathered, crushed and predominantly consisting of alkaline basalts with interbedded pyroclastics and rare rhyolites and is commonly injected by dolerite sills and dykes.

Alaji Rhyolite (PalRy): This unit has wide distribution in the northern and central part of the Abay Plateau. It is consisting of rhyolites, ignimbrites and subordinate trachytes. Obsidian bearing rhyolites are common in Segnogebeya area.

Amba Aiba Basalt (PaaB): This unit has wide distribution on the Abay Plateau on the northern part of the recharge area. The basalt is deeply weathered and favors water storage and movement. The thickness of this formation is more than 200 meters.

Tarmaber Basalt (PntbB): This unit exposed in the western and northern plateau parts and water shed divide of the Awash and Abay river basins. And covers more than 70% of the Abay Plateau and underlies under the Neogene acidic and basic volcanic rocks in the upper Awash River basin. This formation is basalt with large proportion of scoraceous lava flows. It is highly weathered, fractured and pinkish to grayish in color. The formation is highly pervious, which highly favors groundwater storage and movement.

B. Neogene Rock

Addis Ababa Basalt (NadB): This unit is fine to coarse grained basalt composed of olivine and plagioclase phenocrysts. In most part of the outcropped area it is relatively thin (20m) lava flow overlying the ignimbrite.

Addis Ababa Ignimbrite (NadI): It is outcropped in most part of the plane area around Addis Ababa and the Becho plane. It is composed of welded tuff (ignimbrite) and non welded pyroclastics fall (Ash and tuff). It is grayish to white color and when welded it exhibits fiamme textures, elongated rock fragments of various color. Around the Legedadi plane and Melkakunture area the thickness of this unit reaches up to 200m (from exploration drill data). In the Becho plane area it is covered by thin 5-7m thick residual soil developed from the same rock.

Figure 2.1 Geological map of the study area (modified from Ada'a Becho groundwater potential evaluation project, WWDSE, 2007)

2.2 Hydrogeology of the Study Area

The mode of ground water occurrence is affected by the geologic development and properties, delineation, and boundary conditions of soil and rock formations through which the water percolates. They depend also on ongoing activities and climatic and environmental conditions (Aynalem Ali, 1985).

An aquifer is a body of naturally occurring material containing water below the surface of the earth. It must have inter-connecting pores or other openings through which water can flow. Therefore an aquifer has both permeability (which is the quality of formation which controls the passage of water through it) and porosity, a measure of rocks ability to hold water (Charles, *et al.*, 1999). Depending on the material and its relation ship to overlying and underlying layers in the earths crust aquifers may be classified as follow.

1. A water table aquifer is one that does not have a layer of confining material over it.
2. A confined aquifer has a layer of relatively impermeable material over it. In some circumstances a well in a confined aquifer may overflow at surface; this may be called a flowing artesian aquifer.
3. A semi- confined or leaky artesian aquifer is a confined aquifer in which the confining layer is permeable enough to permit significant upward leakage.
4. A perched aquifer is one that rests on a relatively impermeable layer with an unsaturated zone below it.

Although, locally, ground water is obtained from precambian basement rocks and Mesozoic Sedimentary rocks, the principal sources of ground water in Ethiopia are fractured volcanic rocks largely basalts and ignimbrites as well as Quaternary sediments (Tamru Alemayehu *et al.*, 2003). And the volcanic rocks of Addis Ababa are characterized by extensive aquifer with fracture permeability and moderate productivity. Generally, the aquifer of Ethiopia based on their productivity divided into five (Tesfaye Chernet., 1985).

1. Extensive aquifer with intergranular permeability (Unconsolidated Sediments; Alluvium, Colluviums, Lacustrine, Sediments, poorly cemented sand stone).
2. Extensive Aquifer with fracture and/or caustic permeability (Consolidated sediment and metamorphosed carbonates, limestone, sandstone, evaporate marble).
3. Extensive Aquifer with fracture permeability (Volcanic rocks rhyolites, trachyte, ignimbrite).
4. Localised aquifer with fracture and interangular permeability (non carbonate metamorphic rocks granite intrusive).
5. Main Geothermal areas, common occurrence of thermal ground water in fractured volcanic rocks and subordinate unconsolidated sediment.

According to the study undertaken by (WWDSE, 2007). The Ada'a-Becho plains groundwater basins lower aquifer is part of the regional groundwater and its main recharge area is situated in Abay Plateau but its discharging area is in Awash River basin rift valley.

Regarding recharge in the Becho plain the following supporting information were shown by (WWDSE, 2007). The bedrock in this area is basalt and tuff that is distributed in the whole area with different thickness and depths. There is alluvial deposit of thickness on the bedrock, which forms the topsoil in the area and no fault is found. In the survey area the oldest and underlying sedimentary rocks are dipping in the southeast direction. The volcanic rocks resting over these sedimentary secessions have also following the dipping direction of the underlying sedimentary rocks. These volcanic rocks in the area are highly affected by four different faults and fracture systems and solution cavities below the surface facilitate flow through the aquifers. The most water bearing rocks with better yield is that of the basaltic rocks which are fractured and weathered. Moreover the scoraceous basalts particularly the Tarmaber basalt underlying either the other age group basalts or the acidic rocks is the best aquifer due to its scoraceous nature; possibly high porosity and permeability, widespread in the area and confined by the overlying lithology (WWDSE, 2007).

CHAPTER THREE

ELECTRICAL RESISTIVITY METHODS

3.1 General Considerations

Geophysics studies properties of the earth and its internal constitution from the physical phenomena associated with it by applying the principle of physics. Measurements of electrical resistivity are made with circuit in which the earth is one of the components, namely resistor. The procedure is attained by passing a measured amount of electric current through a segment of the earth and then measure the potential difference associated with the current. Using the measurement of contrasts in the physical properties of materials beneath the surface of the earth and attempt to deduce the nature and distribution of the materials or bodies with in the earth that are amenable to measurement like resistivity, density, magnetism, rigidity, compressibility, etc. The measurements can be made in a variety of ways to determine a variety of results. In the field lay out the electrodes are either expanded outward about a centre point which is Vertical Electrical Sounding (VES) or on the other hand, the field lay out moves along a profile keeping a fixed distance between the electrodes, to study the lateral changes in electrical resistivity known as profiling.

Geophysical interpretations are mostly remote inference about the observed physical property. However, when appropriate subsurface investigations are integrated with geophysical measurements, large volumes of material can be explored both accurately and cost-effectively.

3.2 Theoretical Basis

3.2.1 Geoelectrical Methods

The theory and field methods used for resistivity surveys are based on the use of direct current, because it allows greater depth of investigation than alternating current and because it avoids the complexities caused by effects of ground inductance and capacitance and resulting frequency dependence of resistivity.

An electrical method of investigation in relation to structural mapping used to determine the lithological succession and the possible water bearing horizons in terms of resistivity and depth.

3.2.2 Potential Distribution in the Earth

For a particular arrangement and spacing of electrodes an equation giving the apparent resistivity in terms of applied current, distribution of potential, and arrangement of electrodes can be arrived at through an examination of the potential distribution due to a single current electrode. The effect of an electrode pair or any other combination can be found by superposition (Flathe, 1964).

Consider a single point electrode located on the boundary of a semi-infinite, electrically homogeneous medium, which represents a fictitious homogeneous earth. Because air has infinite resistivity, no current flows upward so as to define hemispherical surface. If the electrode carries a current, I , measured in Amperes, the potential at any point in the medium or, on the boundary is given by;

$$U = \rho \frac{I}{2\pi a} \quad (3.1)$$

where U = potential, in Volts

ρ = resistivity of the medium, and

a = distance from the electrode.

Equation 3.1 is the fundamental equation in Electrical resistivity prospecting and it is possible to use it to develop more practical relationships. And the potential at a point of infinitely far away by convention is arbitrarily defined to be equal to zero. Thus, at distance r from the current electrode A , there are regions possess the same potential these surfaces are known as Equipotential surfaces. They represent imagery shells, or bowls, surrounding the current electrodes, and on any one of which the electrical potential is everywhere equal.

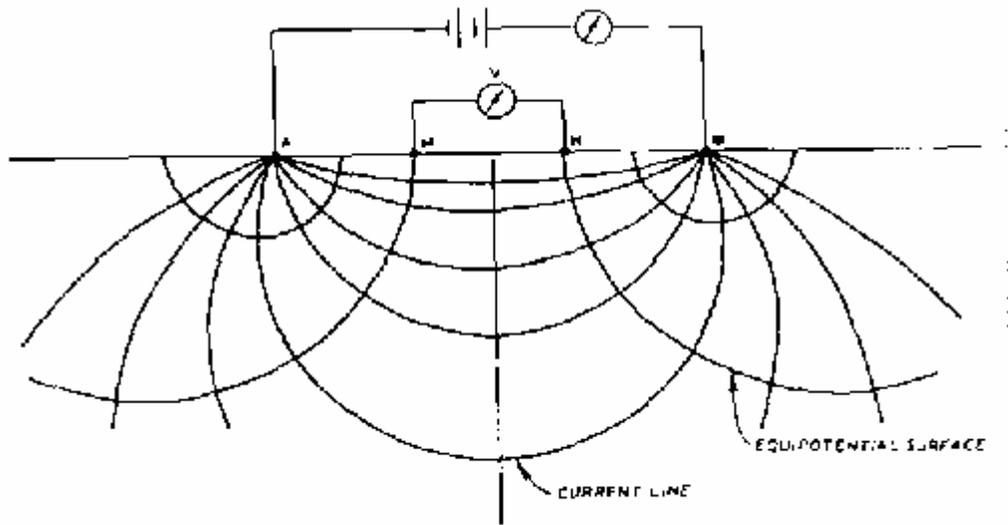


Figure 3.1. Equipotential and current lines for a pair of current electrodes A and B.

To find a practical method of determining the resistivities of the layers and the depths of the boundary planes from the potential differences that are measured at the surface of the earth, one has to know the fundamental mathematical relation between the measured quantities and the parameters that define the layer distribution in the surface (Otto, 1879).

This problem can be simplified by the following assumption:

- The potential field about the vertical axis of the current source is axially symmetric and the potential is additive.
- The subsurface consists of a finite number of layers separated by horizontal boundary planes.
- The field is generated by a point source of current located at the surface.
- The deepest layer extending to infinite and each of the layers is electrically homogeneous and isotropic.

The electrical potential V for DC (direct current) satisfies the differential equation of Laplace (Otto, 1879).

$$\nabla^2 V = 0 \quad (3.2)$$

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \quad (\text{in cartesian coordinates}) \quad (3.3)$$

Since the potential field has a cylindrical symmetry about the vertical axis passing through the point delivering the current, one should preferably use Laplace equation in cylindrical coordinates;

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} + \frac{1}{r^2} \frac{\partial^2 V}{\partial \theta^2} = 0 \quad (3.4)$$

For a solution symmetrical with respect to the vertical axis, $\frac{dV}{d\theta} = 0$ and $\frac{d^2V}{d\theta^2} = 0$ so equation (3.4) becomes

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} = 0 \quad (3.5)$$

The particular solution of equation 3.5 is obtained from method of separation of variables by making the assumption that there exist solutions that have the form;

$$V(r, z) = U(r)W(z) \quad (3.6)$$

Substituting equation 3.6 into equation 3.5 yields;

$$\begin{aligned} W(z) \frac{d^2 U(r)}{dr^2} + \frac{1}{r} W(z) \frac{dU(r)}{dr} \\ + U(r) \frac{d^2 W(z)}{dz^2} = 0 \end{aligned} \quad (3.7)$$

Dividing throughout by $U(r) W(z)$ gives;

$$\begin{aligned} \frac{1}{U(r)} \frac{d^2U(r)}{dr^2} + \frac{1}{U(r)r} \frac{dU(r)}{dr} \\ + \frac{1}{W(z)} \frac{d^2W(z)}{dz^2} = 0 \end{aligned} \quad (3.8)$$

Equation (3.8) is satisfied if and only if

$$\frac{1}{U(r)} \frac{d^2U(r)}{dr^2} + \frac{1}{U(r)r} \frac{dU(r)}{dr} = -\lambda^2 \quad (3.9)$$

and

$$\frac{1}{W(z)} \frac{d^2W(z)}{dz^2} = \lambda^2 \quad (3.10)$$

where λ is an arbitrary real constant.

The solution of equation (3.10) can be written as

$$W(z) = C_2 e^{-\lambda z} \quad \text{and} \quad W(z) = C_3 e^{+\lambda z} \quad (3.11)$$

The solution of equation 3.9 is;

$$U(r) = C J_0(\lambda r) \quad (3.12)$$

where J_0 is Bessel function of order zero.

Combining equation (3.11) and (3.12) give particular solutions of a differential equation 3.5;

$$V(r, z) = C e^{-\lambda z} J_0(\lambda r) \quad \text{and}$$

$$V(r, z) = C e^{+\lambda z} J_0(\lambda r) \quad (3.13)$$

where C and λ are arbitrary constants.

However, any linear combination of solutions is also a solution of differential equation. Thus, by making λ to go through all possible values from $0 \rightarrow \infty$ and allowing the two constants C to vary independent of λ , the general solution of equation (3.5) is

$$V(r, z) = \int_0^{\infty} [\phi(\lambda)e^{-\lambda z} + \psi(\lambda)e^{+\lambda z}] J_0(\lambda r) d\lambda \quad (3.14)$$

In equation (3.14) both $\Phi(\lambda)$ and $\Psi(\lambda)$ are arbitrary function of λ .

From the basic theory of the potential generated by a point source of current of intensity I, located at a point p is given by

$$V(r, z) = \frac{I\rho}{2\pi} \left[\frac{1}{\sqrt{r^2 + z^2}} \right] \quad (3.15)$$

To write equation (3.15) can be written in Lipschitz integral formula that is;

$$\left[\frac{1}{\sqrt{r^2 + z^2}} \right] = \int_0^{\infty} e^{-\lambda z} J_0(\lambda r) d\lambda \quad (3.16)$$

So that equation (3.15) can be written in the form of

$$V(r, z) = \frac{I\rho}{2\pi} \int_0^{\infty} e^{-\lambda z} J_0(\lambda r) d\lambda \quad (3.17)$$

The general solution of differential equation (3.14) can now be written in the form

$$V(r, z) = \frac{I\rho}{2\pi} \int_0^{\infty} \left[e^{-\lambda z} + \theta(\lambda)e^{-\lambda z} + \chi(\lambda)e^{+\lambda z} \right] J_0(\lambda r) d\lambda \quad (3.18)$$

where $\theta_i(\lambda)$ and $\chi_i(\lambda)$ are arbitrary functions of λ .

The solutions of the form of equation (3.18) are valid in all layers of the subsurface. The function $\theta_i(\lambda)$ and $\chi_i(\lambda)$ may not take the same form in each of the layers in the subsurface (Otto, 1879).

In the case of a point source of current at the surface of a horizontally layered earth we must thus write separate expressions for the solution in different layers that is;

$$V_i(r, z) = \frac{I\rho_i}{2\pi} \int_0^{\infty} \left[e^{-\lambda z} + \theta_i(\lambda)e^{-\lambda z} + \chi_i(\lambda)e^{+\lambda z} \right] J_0(\lambda r) d\lambda \quad (3.19)$$

Equation (3.19) is called Stefanescu integral and the subscript “i” refers to several layers of the subsurface.

3.2.3 Electrical Properties of Rocks

Surface electrical resistivity survey is based on the distribution of electrical potential in the ground around a current-carrying electrode which depends on the electrical resistivities and distribution of the surrounding rocks and soils. This is because of the fact that all materials, including soil and rock, have an intrinsic property, called resistivity that governs the relation between the current density and the gradient of the electrical potential. The propagation of electric current in rocks and minerals may occur in three ways. These are Electronic (Ohmic), Electrolytic and dielectric conduction (William, 1997).

The first is the normal type of current flow in materials containing free electrons, such as the metals. In an electrolyte the current is carried by ions at a comparatively slow rate. Dielectric conduction takes place in poor conductors or insulators, which have very few free carriers or not at all.

Variations in the resistivity of earth materials, also called an anomalous resistivity, which may be due to discontinuity of rock formation or change in physical condition perturbs the distribution of current or potential lines compared to their pattern of a homogeneous earth and thereby reveal something about the composition, extent, and physical properties of rocks and soils in the subsurface (Flathe, 1964). Since in most rock materials the porosity and the chemical content of the water filling the pore space are more important in governing resistivity than grains of mineral which the rock it self is composed.

The resistivity of rocks is also strongly influenced by the presence of ground water, which acts as an electrolyte. Due to the good electrical conductivity of ground water the resistivity of sedimentary rock is much lower when it is water logged than in the dry state. Very roughly, igneous rocks have the highest resistivity, sediments the lowest, with metamorphic rocks intermediate; however, there is a considerable overlapping of different rocks (Telford, et al., 1976).

3.2.4. Apparent Restivity

Apparent resistivity is defined as the resistivity of an electrically homogeneous and isotropic half-space that would yield the measured relationship between the applied current and the potential difference for a particular arrangement and spacing of electrodes. The apparent resistivity is definitely not an average value and only in the case of homogeneous ground it is equal to the actual resistivity (Telford et al., 1976). That means the resistivity determined would have been true resistivity if the ground were homogenous and isotropic. However, usually, the ground constitutes various materials and there may be some variations in the lateral or vertical dimensions and that is why we call an apparent resistivity. Its magnitude depends not only on the nature of the geologic system but also on the geometric dispositions of the electrodes used for the measurement (William, 1997).

3.3. Electrode Arrangements

The general formula measured by a four electrodes method is simpler for some special geometers of the current and potential electrodes. The most commonly used configurations are the Wenner, Schlumberger and Polar Dipole- Dipole arrangements. In each configuration the four electrodes

are collinear but their geometers and spacing are different. If a symmetrical array, such as the Schlumberger or Wenner array, is used, the resistivity value obtained is associated with the location of the center of the array (William, 1997).

Consider an arrangement consisting of a pair of current electrodes A and B act as source and sink respectively and a pair of potential electrodes M and N to measure the potential difference between two detection points. As shown in Figure 3.1, at the detection electrode M the potential due to the source A is; $\rho I/2\pi r_{MA}$ while the potential due to the sink at B is; $-\rho I/2\pi r_{MB}$.

The potential difference measured by voltmeter connected between M and N can be obtained by determining the potential at one potential electrode M and subtracting from it the potential at N.

$$V = \frac{\rho I}{2\pi r_A} - \frac{\rho I}{2\pi r_B} = \frac{\rho I}{2\pi} \left[\frac{1}{r_A} - \frac{1}{r_B} \right] \quad (3.20)$$

where r_A and r_B are distance from the point to electrode A and B respecevely hat means;

$$V = U_M - U_N = \frac{\rho I}{2\pi} \left[\frac{1}{AM} - \frac{1}{BM} + \frac{1}{BN} - \frac{1}{AN} \right] \quad (3.21)$$

where U_M and U_N are potential at M and N respectively.

AM= distance between electrode A and M, etc.

$$V = \frac{\rho I}{2\pi} \frac{1}{K} \quad (3.22)$$

where K is a geometric factor.

From equation (3.22) ρ can be obtained as

$$\rho = 2\pi K \frac{V}{I} \quad (3.23)$$

3.3.1. Wenner Configuration

The Wenner array consists of four electrodes in line separated by equal intervals denoted ‘a’ as shown in the Figure.3.1. Applying equation (3.23) the geometric factor K is equal to “a”, so the apparent resistivity is given by;

$$\rho_a = 2\pi a \frac{V}{I} \quad (3.24)$$

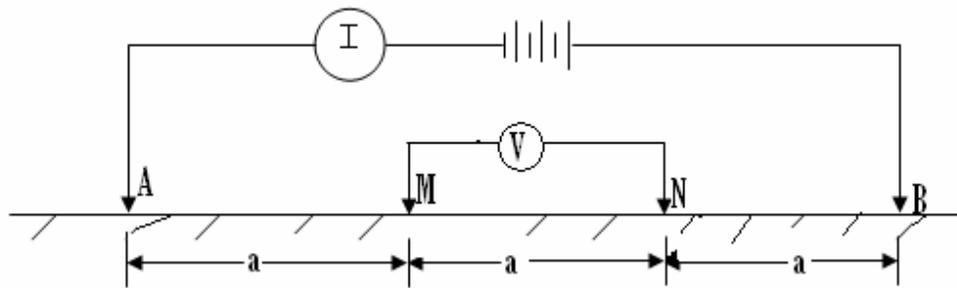


Figure 3.2. The Wenner configuration.

Horizontal profiling, means moving the array along a line of traverse, although horizontal variations may also be investigated by individual measurements made at the points of a grid. Electrode arrays with constant spacing is used to investigate lateral changes in apparent resistivity reflecting lateral geologic variability or localized anomalous features and for the investigation of aerial geology are also made with a fixed electrode spacing(Otto, 1879).

3.3.2. Schlumberger Configuration

In the Schlumberger configuration the current and potential pairs of electrode have a common mid point, but the distance between adjust electrodes differ. As shown in figure.3.3. In this configuration the operator expands electrode spacing by increasing the distance between current electrodes or between potential electrodes, but one at a time during a course of measurement. And the whole set of electrodes must be moved between stations.

$$\rho_a = \pi \left[\frac{s^2}{a} - \frac{a}{4} \right] \frac{V}{I} = \pi a \left[\left(\frac{s}{a} \right)^2 - \frac{1}{4} \right] \frac{V}{I} \quad (3.25)$$

In the Schlumberger array, changing the spacing of the potential electrodes may produce an offset in the apparent resistivity curve as a result of lateral inhomogeneity. Such an offset may occur as an overall shift of the curve without much change in its shape. Under such conditions, the cause of the offset can often be determined by repeating portions of the sounding with different potential electrode spacing (Zohdy, 1989).

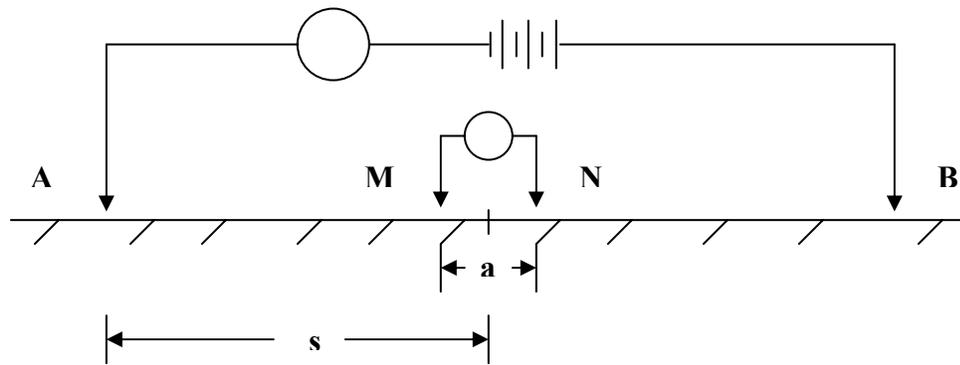


Figure 3.3. The Schlumberger configuration.

In the survey with varying electrode spacing, field operations with the Schlumberger array are faster, because all four electrodes of the Wenner array are moved between successive observations, but with the Schlumberger array, only the outer ones need to be moved. The Schlumberger array also is said to be superior in distinguishing lateral from vertical variations in resistivity (Orellana, *et al* 1966).

3.3.3. The Dipole- dipole Configuration

The dipole-dipole array is another class of resistivity array of current and potential electrodes. The polar dipole-dipole array shown in Figure 3.4. This array used to delineate subsurface

geology through geoelectrical method is that electrical resistivity is a function of length taken either in vertical or horizontal direction.

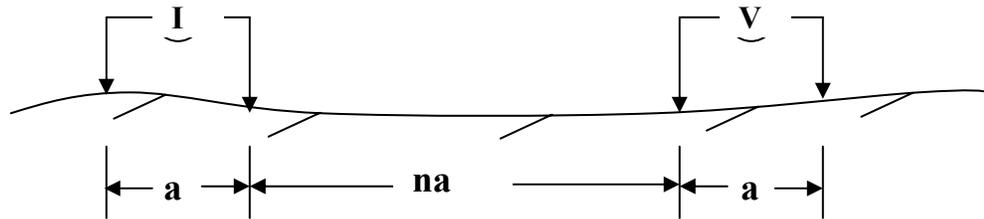


Figure 3.4. The dipole-dipole configuration.

In the field lay out the electrodes are either expanded outward about a center point which is Vertical Electrical Sounding (VES) or on the other hand, the field lay out moves along a profile keeping a fixed distance between the electrodes, to study the lateral changes in electrical resistivity known as profiling.

$$\rho_a = \pi a n(n+1)(n+2) \frac{V}{I} \quad (3.26)$$

where V = potential, in Volt

ρ = resistivity of the medium

a = distance between the electrodes

a (n+1) = restricted separation between the centres of the dipoles.

Occasionally, a combination of vertical and horizontal methods may be used. Where mapping of the depth to bedrock is desired, a vertical sounding may be done at each of a set of grid points. However, before a commitment is made to a comprehensive survey of this type, the results of resistivity surveys at a few stations should be compared with the drill hole data.

In general the selection of a particular electrode array for resistivity survey is controlled by many variables perhaps the most important being the strength of the anomalous response of the arrays

over the type of target which is being sought, the purpose of the project, the speed of coverage the terrain, the ground current level, the easy of interpretation of the data, and the number of personnel involved in the operation.

3.4. Depth of Investigation

Depth of investigation is a depth that contributes most to the total signal measured on the ground surface it does not mean that the entire measured signal originated at that depth alone. The contributions for the measured signal may come from all depths, but the contributions from the depth of investigation are the largest. In that case, our depth of investigation is synonymous with the depth of the maximum contributions to signal (Telford, *et al.*, 1976). Therefore the depth of investigation is an important physical concept in any method of geophysical prospecting.

There is no simple relationship between the electrodes spacing at which curve has been reached features of the apparent resistivity curve are located and the depths to the interfaces between layers. The depth of investigation will always be less than the electrode spacing. Typically, maximum electrode spacing of three or more times the depth of interest is necessary to assure that sufficient data have been obtained. This governs the effective depth of investigation (Flathe, 1964).

3.5. The Principles of Equivalence and Suppression

3.5.5. The Principles of Equivalence

Equivalence refers to the condition in which different combinations of layer resistivities and thickness may lead to an apparent resistivity curves which are within the accuracy of observations indistinguishable although not identical. The Equivalence Problem may occur due to too low or too high values of the transverse resistance (T) or longitudinal conductance (S) caused by difference in the content of aquifer (Orellana and Mooney, 1966). Equivalence is controlled by the nature of the current flow for example for the VES method:

- Current flow perpendicular to thin resistive layer.
- Current flow parallel to thin conductive layer.

There is interplay between thickness and resistivity; there may be anisotropy of resistivity in some strata; large differences in geoelectrical section, particularly at depth, produce small differences in apparent resistivity; and accuracy of field measurements is limited by the natural variability of surface soil and rock and by instrument capabilities. As a result, different sections may be electrically equivalent within the practical accuracy limits of the field.

3.5.2 Suppression

Suppressions happen when the effect from the thickness of an intermediate layer is very small as compared to its depth. The test of geological reasonableness should be applied in particular; interpreted thin beds with unreasonably high resistivity contrasts are likely to be artifacts of interpretation than the real features (Telford, *et al.*, 1976).

Adjustments to the interpreted values may be made on the basis of the computed VES curves and checked by computing the new curves. Because of the accuracy limitations caused by instrumental and geological factors, effort should not be wasted on excessive refinement of the interpretation.

CHAPTER FOUR

DATA SET, PROCESSING AND INTERPRETATION

4.1 Data Set and Survey Layout

Figure 4.1 shows the positions of VES points and borehole sites, used for this thesis work. The 32 soundings are indicated by the ‘▼’ symbol. Four VES points located close to the boreholes, ‘●’; at Sululta, Chancho, Legedadi and Segnogebeya, are labeled as 18, 19, 32 and 22 respectively. Moreover two profile lines, defines by alignments of VESes are indicated by the broken lines ‘---’, and are used to examine variations of geo-electrical parameters in two orthogonal directions.

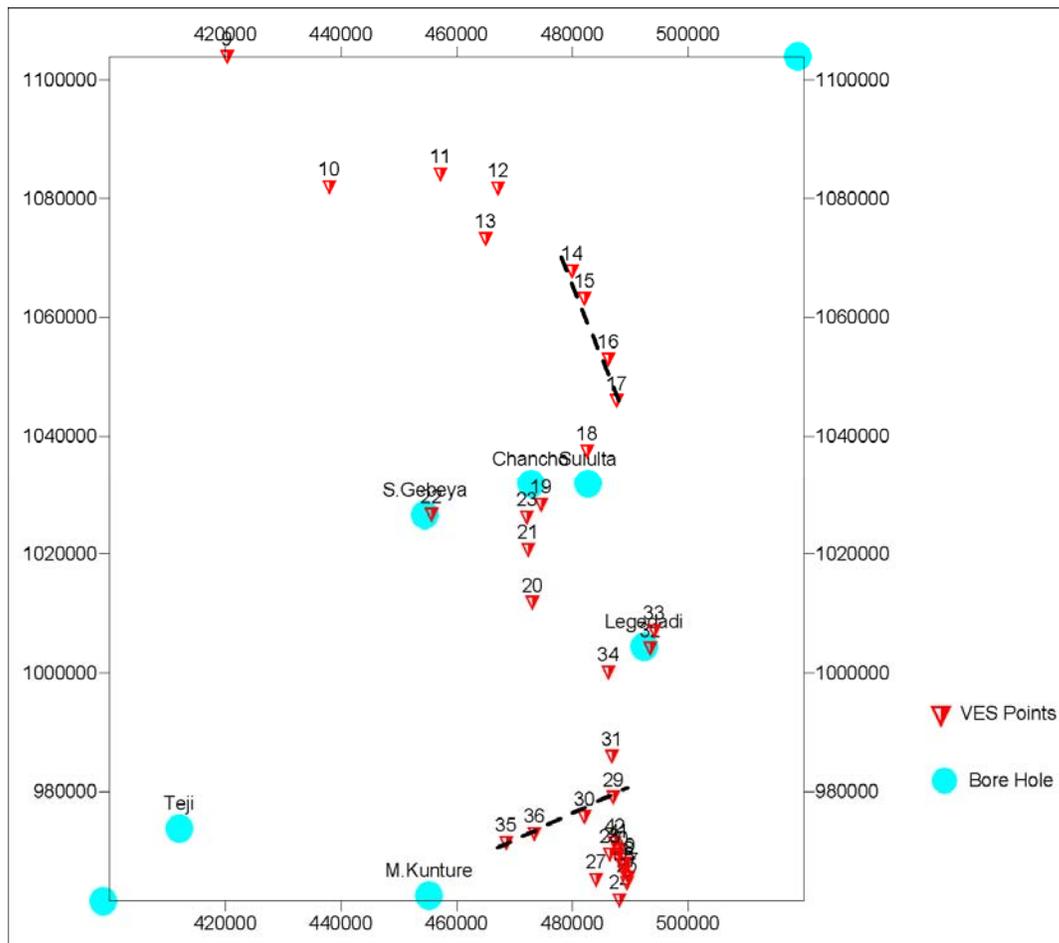


Figure 4.1, Post map showing the distribution of VES point and boreholes.

4.2. Processing and Interpretation of resistivity data

Data processing, the steps of preparing the field data for geophysical interpretation, often includes judgments and observations based on the experience of the processor. Interpretation of the data, as well as the planning of the survey, must be guided by the available knowledge of the local geology. The interpreter normally knows what he is looking for in terms of geological features. Interpretation is a continuous process throughout geophysical investigations and its adequacy is crucial to achieve the objectives (Zohdy, 1989).

The first step of the data processing is the transformation of the instrument responses, the source current strength and the potential difference, to apparent resistivity values using the relation;

$$\rho = \frac{K\Delta V}{I} \quad (4.1)$$

where ΔV = potential, in Volt

K = geometric factor

ρ = resistivity of the medium, and

The main objective of quantitative interpretation of resistivity sounding data is to determine the thickness and resistivity of different horizon, from the measured field curves and use these parameters to obtain the geo-electric stratification of the area under investigation. Quantitative interpretation in resistivity work usually involves the use of direct and inverse modeling. From a given set of layer parameters, it is always possible to compute the apparent resistivity as a function of the separation of current electrodes.

Preparation of geophysical models always assumes the following:

- (I) Earth materials have distinct subsurface boundaries.
- (II) A material is homogeneous (having the same properties throughout).
- (III) The unit is isotropic (properties are independent of direction).

In this research work three interpretation procedures were applied, namely: two layer curves matching with master curves and auxiliary point charts. Direct correlation with available borehole data and computer matching technique by an iterative least squares inversion program Win-resist (Win-resist Version 5.1, 1981-2001).

Before the availability of personal computers, the curve matching process was done graphically by plotting the field data plotted on transparent log-log graph paper at the same scale of catalogs of two-and three-layer standard curves. The use of standard curves requires an identification of the curve type followed by a comparison with standard curves of that type to obtain the best match, Auxiliary Point Method, which requires the use of small set of auxiliary curves and some constructions. This method is very important, in that it can be used to interpret, in principle, any number of layers by alternate use of two layer master curves, which is done by matching the initial branch of the field curve with an appropriate two layer master curve and a family of auxiliary point curves that correspond to the field curve type. Therefore, rough estimation based on segment by segment matching will be the best that can be done. The process is controlled by using those auxiliary curves to define allowable positions of the origin of the two-layer curve being fitted to the latter segments of the field curve. The first approximations of the layer parameters were thus obtained through the above method (Zohdy, 1989).

The inversion of VES data is non linear inversion and hence the determination of the model parameters involves iterative procedures which employ an approach of modifying the parameters of an initial guessed model which are used to compute a new model response and the observation values is monitored. The model response can be either a linear or non linear function of the model parameters. The plot of apparent resistivity versus spacing is always a smooth curve where it is governed only by vertical variation in resistivity.

4.3 Inversion

Geophysical inversion involves the estimation of the parameters the postulated earth model from a set of observations Inverse theory is an organised set of mathematical techniques for reducing data based on inferences drawn from observations. The role of inverse theory is to provide information about the model parameters starting with data and general principle that means

inversion implies that a cause was inferred from an effect (Orellana and Mooney, 1966). We use an inverse solution to obtain a model that best fits a data in a least square sense. The basic statement of an inverse problem is that the model parameters and the data are in some way related and that relation ship is known as the model.

On the other hand, forward solutions proceed from cause to effect and are unique determinations. They are often preliminary evaluations to predict amplitudes and relations from possible physical conditions. The forward solutions may be used to field surveys to assess hypothesis variants among geologic alternatives.

Because the theoretical curves are always smooth, the field curves should be smoothed before their interpretation is begun, to remove obvious observational errors and effects of lateral variability. Isolated one-point spikes also called an out liar in resistivity are removed rather than interpolated. The curves should be inspected for apparent distortion due to effects of lateral variations. Comparison with theoretical multilayer curves is helpful in detecting such distortion. The site conditions should be considered; excessive dip of subsurface strata along the survey line (more than about 10 percent), unfavorable topography, or known high lateral variability in soil or rock properties may be reasons to reject field data as unsuitable for interpretation in terms of simple vertical variation of resistivity.

The simplest way to interpret multilayer case is that of a single layer of finite thickness overlying a homogeneous half space of different resistivity. The VES curves for this case vary in a relatively simple way, and a complete set of reference curves can be plotted on a single sheet of paper (Zohdy, 1989).

Standard two-layer curves for the Schlumberger array. The curves are plotted on a logarithmic scale, both horizontally and vertically, and are normalized by plotting the ratio of apparent resistivity to the first layer resistivity ρ_a / ρ_1 against the ratio of electrode spacing to the first layer thickness $\frac{AB/2}{h_1}$.

Where three or more strata of contrasting resistivity are present, the VES curves are more complex than the two-layer curves. For three layers, there are four possible types of VES curves,

depending on the nature of the successive resistivity contrasts. The classification of these curves is as H, K, A, and Q type. These symbols correspond respectively to bowl-type curves, which occur with an intermediate layer of lower resistivity than layers 1 or 3; bell-type curves, where the intermediate layer is of higher resistivity; ascending curves, where resistivities successively increase; and descending curves, where resistivities successively decrease with depth.

4.4 The computer program

The transfer of raw data to computer is important to do the process of reduction, inversion and analysis. Then the determination of the final model parameters will be done by using the computer program, Win-resist (Win-resist Version 5.1, 1981-2001). What is actually going on the program is briefly outlined below:

1. First array type used in the data collection is specified and the field data for each sounding station is loaded along with the current electrode spacing. Thus, a measured resistivity values are displayed with error bars indicating the estimated accuracy. This is done for all sounding stations.
2. A skilled guess of layer parameters (which is based on a geological concept or obtained by curve matching) are fed to the computer as input into the computer. When choosing the model entering option, the program enquires for the number of layers, resistivity, and thickness assumed for the initial guess. The program requires the values to be given in order and starting from the first layer.-after the required inputs as specified above is supplied. The program displays the graph of the field curve with the model given in step above.
3. The apparent resistivity curve for the input model of step 2 is computed, using a forward calculation. This makes the program ready for comparison of the theoretical curve and the field curve.
4. Trial-and-error adjustments of the layer parameters are made until the theoretical computed curve agrees with the measured curve. And this iteration process continues as commanded by the user until the calculated error is with in the prescribed error limit.

By these process the resistivity and depth values of each VES is quantitavily determined. These parameters are used for construction of geoelectric sections which indicate the electrical stratification of the studied area.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

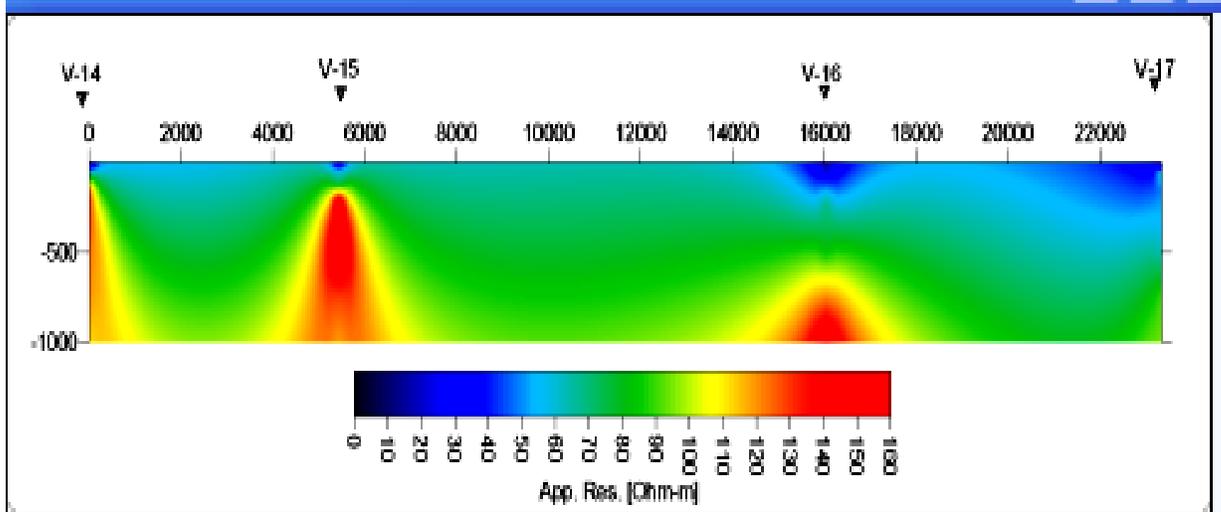
5.1 Pseudosections

One way of presenting the measured apparent resistivity values is in the form of pseudosections along a profile. The field data obtained from each sounding is grided and displayed as regular contour maps or image maps, displaying areas of anomalously high or low value. So, pseudosections are basically meant for qualitative interpretation and show the lateral and vertical variations of electrical properties within the sub-surface (Ewnetu Gashawbeza, 1998). In this thesis work, the pseudosections are constructed using mapping software called Surfer 8 (Surfer Version 8.01, 2002).

5.1.1 The pseudosection of Profile 1

This line represents the northern part of the study area and runs, nearly, in north-south direction. It comprises four resistivity sounding points namely, VES-14, -15, -16 and -17. They are positioned at a horizontal distance of 0m, 5435m, 16050m, and 23347m, respectively, from the northern tip of the line. And the elevation for VES-14 and -15 is almost the same (2625masl), VES-16 rises to 2658m but VES-17 is 2572masl.

The pseudosection generated from the apparent resistivity data for this line is given in Figure 5.1. The inter-station separation, shown in the preceding paragraph, are quite large and any interpretation, based on such plot, appears unpractical. Nevertheless, it is employed in this study in the hope of obtaining some insight about the broader geo-electric variation along the profile direction and probably serves to infer a localized vertical view beneath the sounding points. Keeping this in mind, the overall resistivity picture of this profile may be characterized as having a resistive bottom, of values in excess of $120\Omega\text{m}$, overlain by intermediate to conductive overburden; ranging $10\text{-}70\Omega\text{m}$. Around the north side of this profile (VES 14 & 15) the pseudosection plot shows an increase in resistivity response at shallow depth. Further south, the high resistivity portion appears deeper, especially at a localized portion beneath VES-15 and at the extreme end of VES-16.



Scale; Horizontally: 1:160000

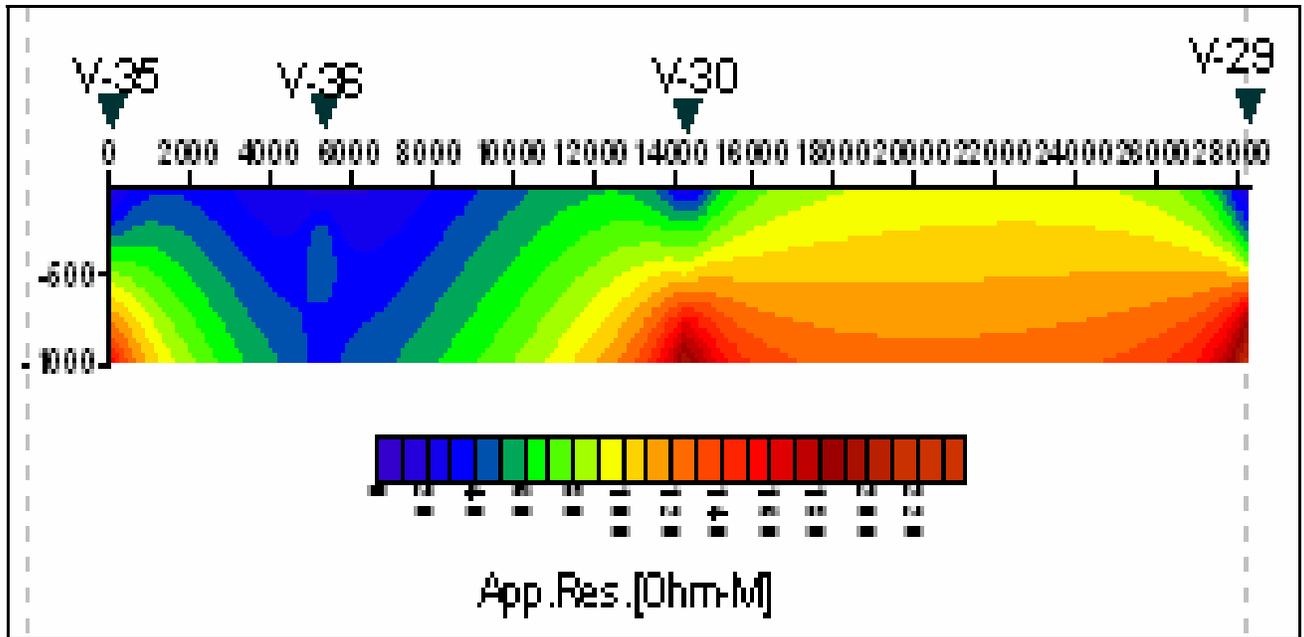
Vertically: 1:50000

Figure.5.1. Apparent Resistivity Pseudosection of Profile 1.

That means, to the right of VES 15 (to south direction), the resistivity value shows gradual decrement, i.e., an extended conductive response of the overburden thickening towards VES 17. This may indicate that the thickness of the sediment increases as one go from north (VES 14) to the south (VES 17) direction. Therefore the possible flow direction of the ground water appears from north to the south.

5.1.2 The pseudosection of Profile 2

This line runs over the southern part of the study area and crosses over in the direction of WSW - ENE. There are four resistivity soundings which are positioned at a distance of 0m, 5302m, 14390m, and 28362m for VES 35, 36, 30 and 29 respectively, from the western end. Apparent resistivity pseudosection for this line is given in Figure.5.2 Three distinct geoelectric zones are apparent; the first is between 0 and 10,000m (beneath VES 35 and 36), the second is in between (10,000-18,000m) beneath (VES 30), and the third one is beyond 18,000m profile distance comprising the region covered by VES 29.



Scale; Horizontally: 1:200000

Vertically: 1:72000

Figure.5.2. Apparent Resistivity Pseudosection of Profile 2.

The first zone is characterized by medium to low resistivity responses under VES - 36 there is a funnel shaped region with lower range of resistivity. The resistivity value gets a little bit higher to the deeper section and narrower resistive patches at the left bottom of this section.

The second zone is characterized by all range of resistivity. At the extreme top (near VES - 30) has low resistive and shows an increment to the deeper section. The third zone has a vast portion which is covered by medium resistivity except lower value at the extreme top of VES - 29.

5.2 Sliced-depth Resistivity Sections and Stacked Plots

The knowledge on the lateral distribution of the electrical resistivity at the subsurface sheds additional light towards a complete understanding of the geological frame work of the area under investigation. Sliced depth sections when presented in a form of stacked plots, in particular, provide ample visualization of the overall picture of the subsurface electrical parameters and their variation both in lateral and vertical directions. Moreover, it greatly facilitates our

interpretations of discontinuities in terms of geological structure, which are of great interest, for hydro-geophysical analysis.

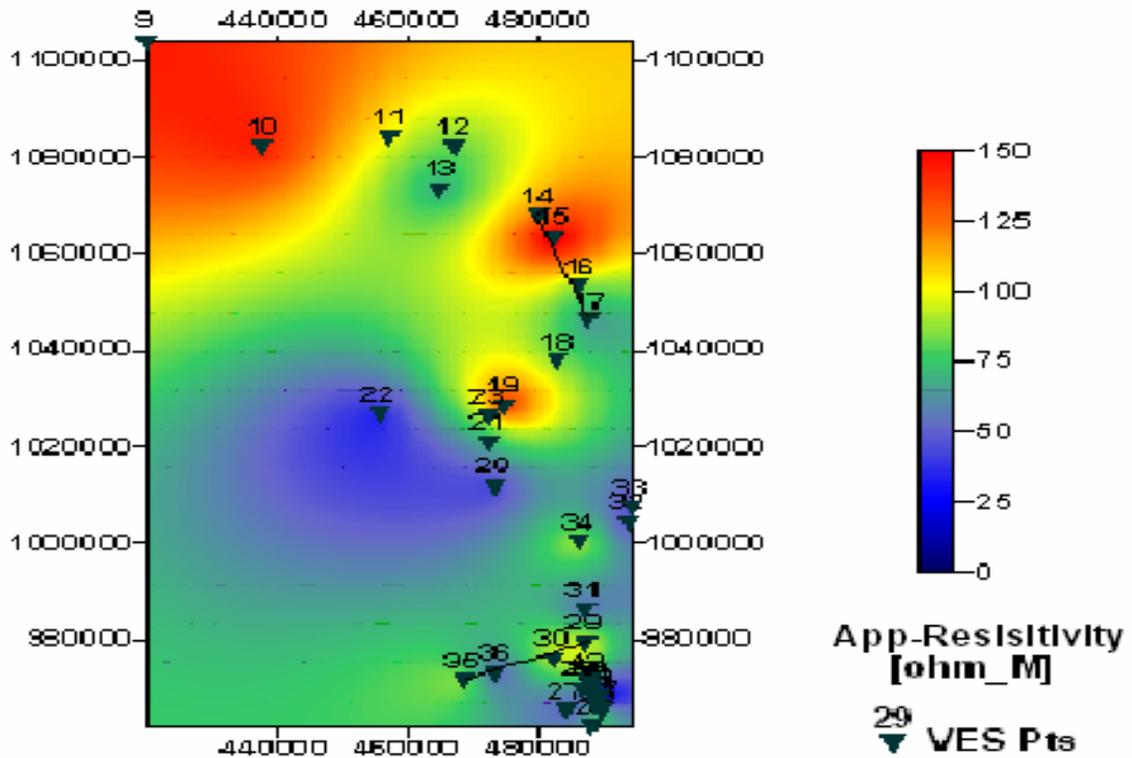


Figure.5.3. Lateral resistivity map at a pseudo-depth of $AB/2 = 500\text{m}$

Figure.5.3 depicts the lateral variation in apparent resistivity at the virtual depth, mapped at the half-current electrode separation ($AB/2$) of 500m. This figure shows that a horizon of high resistivity ($>125\Omega\text{m}$), occupies northwestern corner of the map region. And it gets slightly lower than this value ($75\Omega\text{m} - 125\Omega\text{m}$) and extends down ward until it fades out, at the middle portion of the map region. At the border of the north and the south zone (around the middle part of the map) low resistivity ($<25\Omega\text{m}$) horizon, which is supposed to be good aquifer of the region. Most portion of the southern region have a moderate resistivity range ($50-75\Omega\text{m}$) except the smaller features at the southeastern which has a higher resistivity ($>90\Omega\text{m}$). Thus, generally the northern part is more resistive than the southern part. This less resistivity may be an indication to the aquifer region.

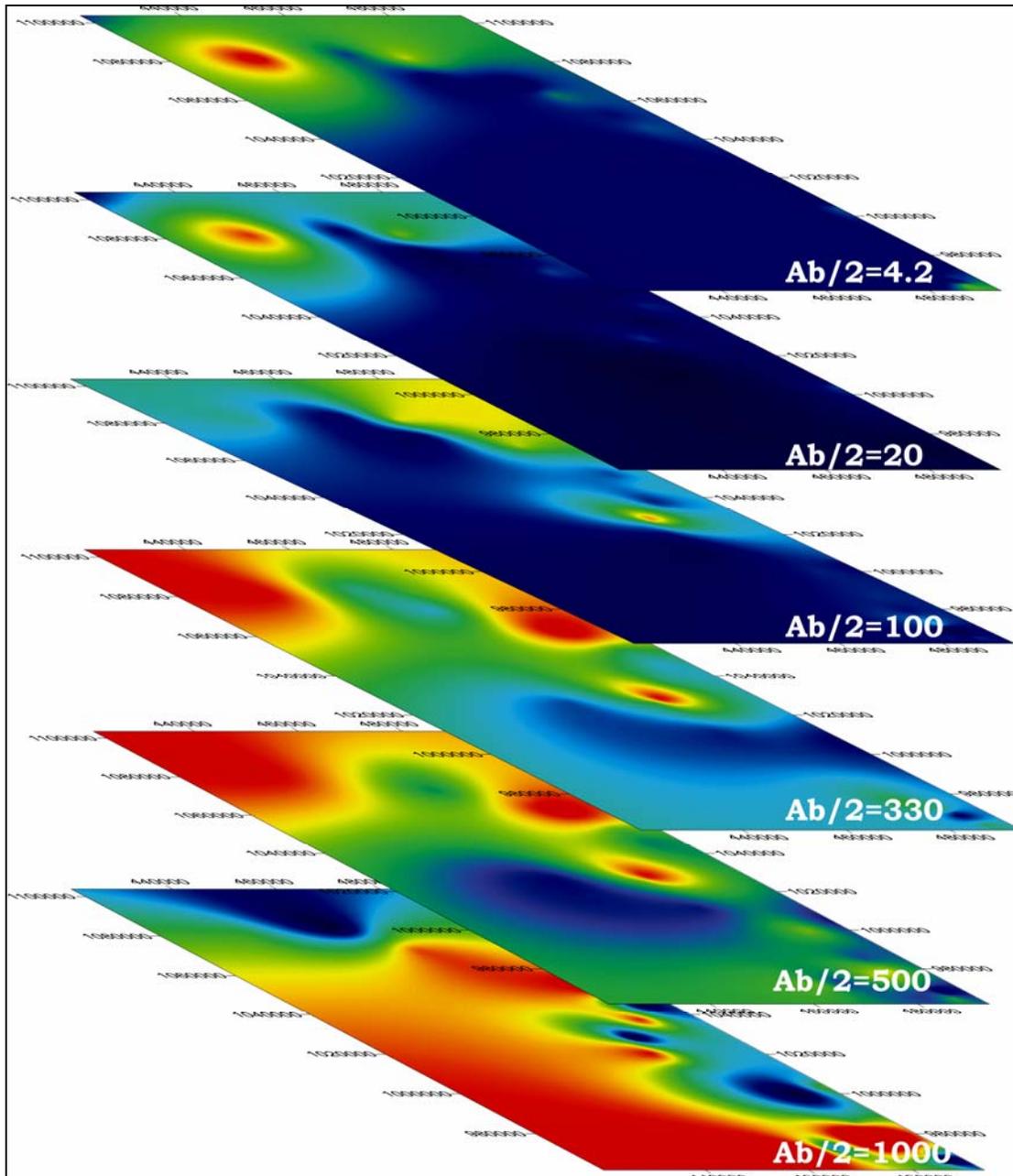


Figure.5.4. Stacked plot of sliced resistivity sections at different depth levels

Referring to figure.5.4, the general picture reveals heterogeneous subsurface with resistivity variations both in vertical and lateral senses. The broader conductive horizon which dominates the upper-two slice of the southern zone progressively narrows with depth and on the contrary the broader resistive horizon which dominates on the lower-two slice. Therefore this result also

Confirms the result obtained from the pseudo-sections. That is northern part is relatively resistive than the southern part which shows the thickness of the sediment increases to the south direction. Therefore the possible flow direction of the ground water is from north to the south.

5.3 Interpretation of Individual Sounding Points

Table 5.1: Summary of conducted VES points with resistivity values and interpreted lithologies used for the construction of geoelectric section in this thesis work.

| VES INDEX | UTM EAST | UTM North | Elevation (m) | Layer | Resistivity (Ω -m) | Thick (m) | Inferred Lithologies |
|-----------|----------|-----------|---------------|-------|----------------------------|-----------|--|
| 14 | 479916 | 1067715 | 2626 | 1 | 1.2-38 | 3 | Sandy clay |
| | | | | 2 | 848 | 35 | Fresh & dry basalt |
| | | | | 3 | 55 | 86 | Fractured basalt |
| | | | | 4 | 104 | - | Highly weathered basalt |
| 15 | 482102 | 1063111 | 2625 | 1 | 10 - 38 | 5.7 | Sandy clay |
| | | | | 2 | 63 | 57 | Highly weathered rhyolites |
| | | | | 3 | 556 | 111 | Fresh & dry basalt |
| | | | | 4 | 55 | - | Highly weathered fractured basalt |
| 16 | 486191 | 1052919 | 2659 | 1 | 6.2-25 | 16 | Sandy clay |
| | | | | 2 | 5.8 | 0.7 | unconsolidated sediment |
| | | | | 3 | 95 | 130 | Fractured basalt |
| | | | | 4 | 206 | - | moderately weathered basalt |
| 17 | 487667 | 1045826 | 2573 | 1 | 5.6 | 11 | clay soil |
| | | | | 2 | 47-93 | 29 | Highly weathered rhyolites |
| | | | | 3 | 35 | 137 | Highly weathered basalt |
| | | | | 4 | 125 | - | weathered and fractured basalt |
| 35 | 468517 | 971290 | — | 1 | 2 -14 | 4.5 | clay soil |
| | | | | 2 | 17.4 | 5.4 | unconsolidated sediment |
| | | | | 3 | 41 | 126 | unconsolidated sediment |
| | | | | 4 | 550 | - | Fresh & dry basalt |
| 36 | 473443 | 972893 | — | 1 | 2.5 - 21 | 6.8 | clay soil |
| | | | | 2 | 26 | 29 | fine grained sediment |
| | | | | 3 | 118 | 171 | Weathered and fractured ignimbrite and rhyolites |
| | | | | 4 | 15 | - | weathered and fractured |
| 30 | 482115 | 975705 | — | 1 | 2.7 - 5.6 | 6.8 | clay soil |
| | | | | 2 | 251 | 57 | moderately weathered tuff |
| | | | | 3 | 53 | 65 | highly weathered tuff |
| | | | | 4 | 431 | - | slightly fractured basalt |
| 29 | 487085 | 978957 | — | 1 | 1.2 - 5 | 5.6 | clay soil |
| | | | | 2 | 13.6 | 14 | fine grained sediment |
| | | | | 3 | 90.5 | 109 | moderately weathered basalt |
| | | | | 4 | 1019 | - | fresh basalt |

From table 5.1, it is seen that the first two or three interpreted layers on the sounding curves are mostly thin but from hydrogeological point of view detailed information on these small thicknesses superficial sediment are not important in light of the regional nature of the survey. Therefore, these layers were lumped together and represent as one unit. Thus the sounding data are interpreted into four layers model parameter.

The first layers has resistivity (1-38 Ω m), interpreted as the top soil dominantly clay or sandy clay composition. These layers are underlain by two layers of basalt and Unconsolidated sediment with varying resistivity depending on different degree of weathering and fracturing. Moreover the resistive value of these layers is suggestive of a good potential for ground water resource. The forth layer has very high resistive value and interpreted as fresh and dry basalt bed rock.

Table5.2: Summery of conducted VES points with their resistivity values and interpreted lithologies deduced from the present study.

| VES INDEX | UTM EAST | UTM North | Elevation (m) | Layer | Resistivity (Ω -m) | Thickness (m) | Inferred Lithologies |
|-----------|----------|-----------|---------------|-------|----------------------------|---------------|-----------------------------------|
| 18 | 482526 | 1037378 | 2599 | 1 | 8.4 | 11 | Top Clay soil |
| | | | | 2 | 24.5 | 30 | Sandy Clay |
| | | | | 3 | 70 | 28.6 | Highly weathered rhyolites |
| | | | | 4 | 130 | 62.6 | Highly weathered Fractured basalt |
| | | | | 5 | 177 | - | Highly weathered Fractured basalt |
| 21 | 472331 | 1020653 | 2556 | 1 | 5.3 | 12.2 | Top Clay soil |
| | | | | 2 | 97 | 37 | Weathered basalt |
| | | | | 3 | 49 | 115 | Highly weathered basalt |
| | | | | 4 | 245 | - | Massive basalt |
| 22 | 455620 | 1026514 | 2607 | 1 | 4.3 | 4.1 | Top Clay soil |
| | | | | 2 | 1.9 | 2.1 | Top Clay soil |
| | | | | 3 | 126 | 51 | Fractured basalt |
| | | | | 4 | 15.7 | 145 | Highly weathered basalt |
| | | | | 5 | 1204 | - | Dry and Fresh Basalt |
| 31 | 486821 | 985830 | - | 1 | 3 | 35 | Top Clay Soil |
| | | | | 2 | 108 | 20 | Highly weathered ignimbrite |
| | | | | 3 | 20 | 56 | Highly weathered Tuff |
| | | | | 4 | 40.5 | | Highly weathered Tuff |
| 32 | 493506 | 1007044 | 2461 | 1 | 10.5 | 2.1 | Top Clay soil |
| | | | | 2 | 46 | 33 | Highly weathered rhyolites |
| | | | | 3 | 12 | 96 | Clay |
| | | | | 4 | 35 | 50 | Highly weathered rhyolites |
| | | | | 5 | 628 | - | Dry and Fresh Basalt |

Table 5.3: Summary of conducted VES points with their resistivity values and interpreted lithologies (on report of WWDE)

| VES INDEX | UTM EAST | UTM North | Elevation (m) | Layer | Resistivity (Ω -m) | Thickness (m) | Inferred Lithologies |
|-----------|----------|-----------|---------------|-------|----------------------------|---------------|-------------------------------------|
| 31 | 486821 | 985830 | - | 1 | 3 | 35 | Top clay soil |
| | | | | 2 | 108 | 20 | Highly Weathered ignimbrite |
| | | | | 3 | 20 | 56 | Highly Weathered Tuff |
| | | | | 4 | 40 | - | Highly Weathered Tuff |
| 21 | 472331 | 1020653 | 2556 | 1 | 5.3 | 12.2 | Top Clay Soil |
| | | | | 2 | 97 | 37 | Weathered Basalt |
| | | | | 3 | 49 | 115 | Highly Weathered Basalt |
| | | | | 4 | 245 | - | Massive Basalt |
| 22 | 455620 | 1026514 | 2607 | 1 | 4.3 | 4.1 | Top Clay Soil |
| | | | | 2 | 1.9 | 2.1 | Top Clay Soil |
| | | | | 3 | 126 | 51 | Fractured Basalt |
| | | | | 4 | 15.7 | 145 | Highly Weathered Basalt |
| | | | | 5 | - | - | Fresh and dry Basalt |
| 23 | 472183 | 1026035 | 2558 | 1 | 33.2 | 0.6 | Unconsolidated sediment |
| | | | | 2 | 1.6 | 0.7 | Clay |
| | | | | 3 | 19.7 | 6.6 | Clay intercalated with silt |
| | | | | 4 | 81.5 | 147.7 | Unconsolidated sediment |
| | | | | 5 | 96.7 | - | ignimbrite rhyolites trachyte |
| 24 | 488166 | 961713 | - | 1 | 28 | 1.4 | Unconsolidated sediment |
| | | | | 2 | 16.6 | 2.5 | Clay |
| | | | | 3 | 3 | 5.8 | clay |
| | | | | 4 | 36.1 | 85.3 | Unconsolidated sediment |
| | | | | 5 | 113 | - | ignimbrite rhyolites trachyte |
| 26 | 488786 | 967458 | - | 1 | 12 | 12 | Clay intercalated with silt |
| | | | | 2 | 122 | 111 | ignimbrite rhyolites trachyte |
| | | | | 3 | 21 | - | Highly weathered basalt |
| 27 | 484140 | 965146 | - | 1 | 2.9 | 1.8 | Clay |
| | | | | 2 | 6.3 | 5.4 | clay |
| | | | | 3 | 87.5 | 6.8 | Unconsolidated sediment |
| | | | | 4 | 64.6 | - | Unconsolidated sediment silt gravel |
| 28 | 486498 | 969461 | - | 1 | 5.5 | 1.2 | Clay |
| | | | | 2 | 17.6 | 2.9 | Clay intercalated with silt |
| | | | | 3 | 4.9 | 44.9 | Clay |
| | | | | 4 | 886.5 | - | Fresh and dry Basalt |
| 29 | 487085 | 978957 | - | 1 | 3.9 | 1.3 | Clay |
| | | | | 2 | 2.2 | 4.9 | clay |
| | | | | 3 | 45.5 | 90.4 | Unconsolidated sediment |
| | | | | 4 | 1503.4 | - | Fresh and dry Basalt |
| 30 | 482165 | 975705 | - | 1 | 3.9 | 1.5 | Clay |
| | | | | 2 | 3.5 | 6.2 | Clay |
| | | | | 3 | 114.6 | 61.9 | ignimbrite rhyolites and trachyte |
| | | | | 4 | 274.8 | - | Fresh and dry Basalt |

5.3.1 Comparison of Interpreted Sounding Points Based on Water Table Depth

The northern, the central and the southern part of the survey area are compared with respect to the water table depth. This water table depth was inferred from the interpreted result of individual sounding points. These points are allocated to north, central and south zones based on their spatial distribution shown on the post map (in figure 4.1). Summary of comparison results are presented in table 5.4.

Table 5.4: The depth of the water table on different zones of the survey area deduced from the present study.

| No | Location | VES INDEX | Inferred depth of water table(m) |
|----|--------------|-----------|----------------------------------|
| 1 | North-zone | 14 | 2.1 |
| | | 15 | 4.4 |
| | | 16 | 8.2 |
| | | 17 | 11 |
| | | 18 | 11 |
| 2 | Central-zone | 21 | 12 |
| | | 18 | 11 |
| 3 | South-zone | 29 | 128 |
| | | 30 | 129 |
| | | 31 | 35 |
| | | 35 | 100 |

From table 5.4 one can observe that the depth of the water table increase from north to south. This shows that in the northern flank there is a favorable condition to act as an aquifer, shallower than the southern flank. Moreover, the ground water flows from the north to the south direction. Since ground water always moves in the direction of the down ward slope of the water table above it (Charles et al., 1999). Considering the thickness and lithologic unit of two zones below their water table depth. The northern aquifers have small aerial extent and composed of silty clay sediment which are occasionally water bearing. On the other hand, the southern aquifers indicate water-bearing rocks. The response may arise from weathered and fractured volcanic rocks saturated with water such as rhyolites, ignimbrite and trachyte. Therefore, from the hydrogeological point of view the southern flank is more significant to be used as potential of ground water resource.

5.4 Geoelectric Sections

The separation between the VES points employed in this thesis work are quite large and constructions of routine geoelectric sections for sound quantitative assessment may seem unpractical. However, maximum effort has been made to make site-to-site correlations and come up with descriptive pictures of the subsurface along two profile lines. Added to this, one of the main objectives, imparting a practical knowledge in the art of geoelectrical data processing, encourages such attempt.

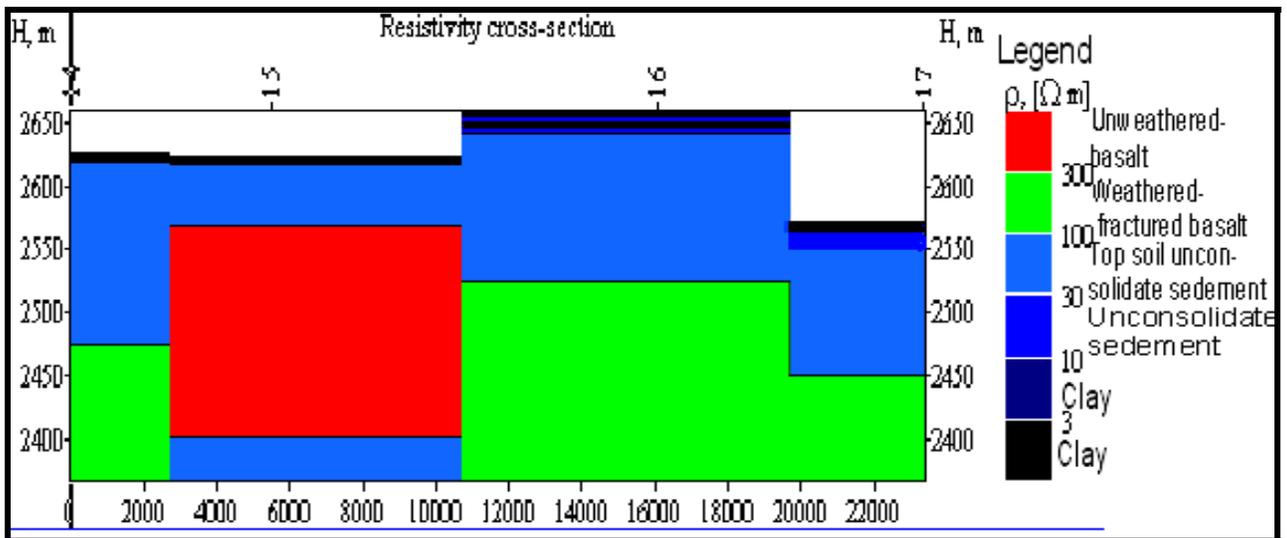
There are two types of geoelectric section presented in this work. The first type is a mere resistivity layer stratification presented on a plain Auto-cad sketch. In these sketches, thin top layers have been lumped up for visual clarity and the resistivities shown are a kind of average. Such sections are used to present the results of quantitative data appraisal from widely spaced VES points. On these sketches, question marks are used to allow the far distance between the VES points.

The second and final block model, for the profile lines, was constructed using software package called IPI2win-1D (Alexe *et al.*, 1990-2002).from the interpreted data of the individual soundings resulted from inversion package called Win-Resist (Win-Resist Version 5.1, 1981-2001).

IPI2win-1D is a package for interpretation of VES along a profile. The inputs for the program are the layer parameters, the half spacing between the current electrodes ($AB/2$), the spacing between the potential electrodes (MN), the name of VES stations and elevation of the VES points. The program is advantageous since it is suitable for interactive manual interpretation of VES curves and can handle different electrode arrays such as Schlumberger, Wenner and dipole-dipole. The model parameters could be converted into common worksheet file and the resulting Plot of the model would be produced by drag-and-drop the part of resistivity cross-section. These plots are employed for compilation of quantitative results and final analysis.

Moreover, one can observe that in the northern flank there is a favorable condition to act as an aquifer, shallower than the southern flank. The graph obtained from the analysis of collected hydrodynamic data (bottom of water wells and ground water levels versus ground surface elevations) made on the aquifer to visualize the ground water depth variations with topography also confirm this finding. The graphs show similar relation between topography and ground water level implying that, in the study area ground water flows generally to south. However, the ground water level drops deeper at low lands and shallower at the highland plateau.

The geoelectric response of the third layer has two distinct zones. In the northern side, the formation resistivity is quite high, (556-848 Ω m). Under VES-14, the depth to the bottom of this layer is 43m and drops down to 75m, beneath VES 15. This seems to be the response of recent basalt, which is most likely, fresh and dry. The southern flank, VES 16 and VES 17, on the other hand, has a resistive range of (93 - 95 Ω m) and may indicate water-bearing rocks. The response is not sufficiently discriminative and may arise from basic volcanic such as rhyolites, ignimbrite or trachyte or weathered and fractured acidic rocks saturated with water. A possible geologic structure can also be inferred between these two geo-electrically distinct subsurface zones.



Scale; Horizontally: 1:200000

Vertically: 1:6000

Figure 5.5b. Interpreted block diagram of the subsurface along profile 1.

The fourth layer appears of moderate resistivity, $55\Omega\text{m}$, beneath the very resistive third layer in the northern flank. Underneath VES-16 and VES-17 (southern flank), this layer is characterized by resistive range of 125 to $205\Omega\text{m}$, and appears at an average depth of 152m. This is interpreted to be likely response of rhyolites, ignimbrite and trachyte, weathered, fractured and possibly saturated. From Hydrogeological point of view the southern flank is the most probable aquifer as their lies a less compact permeable layer of relatively lower resistivity above it.

Under VES-14, there is a local formation whose resistivity is about $104\Omega\text{m}$, and appears as a fifth layer. The top of this layer come into picture at depth of 103m. This geoelectric substratum may be affected by high degree of weathering and fracturing.

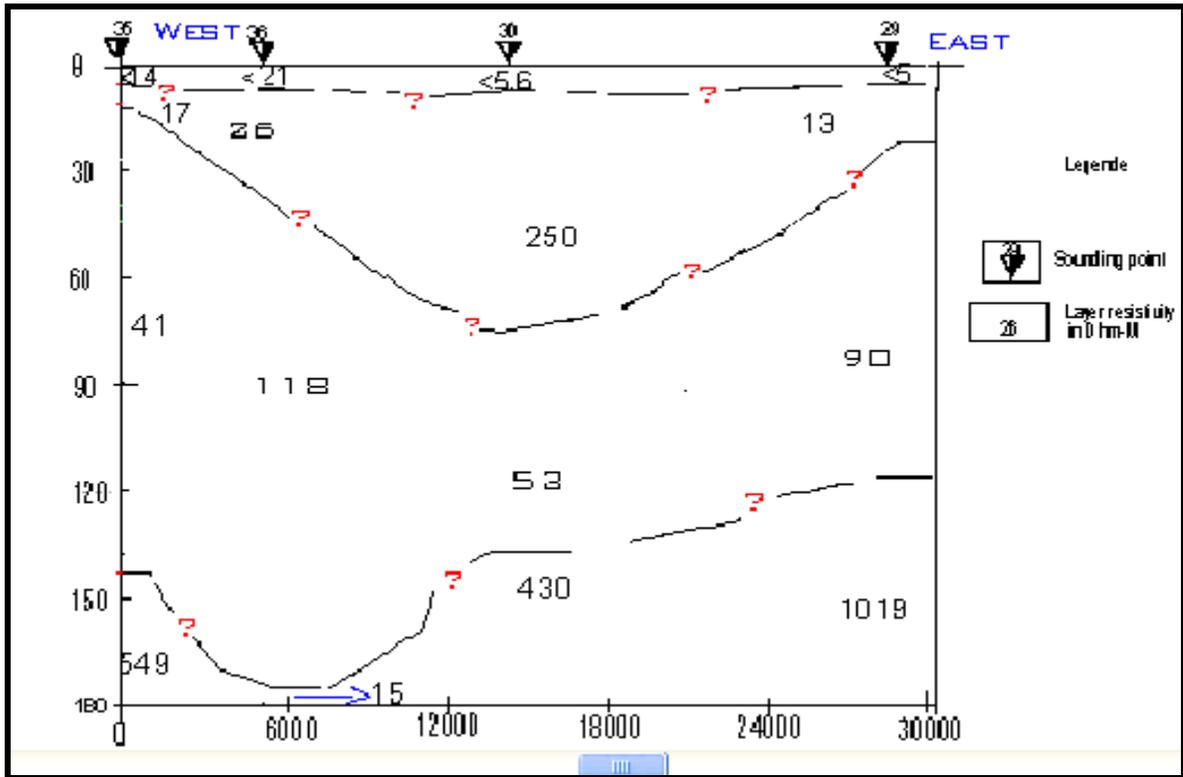
5.4.2. Geoelectric Section of profile 2

The geoelectric section of the subsurface beneath profile 2 has four geoelectric layers. The top most layers appear shallower, 5.3m underneath VES-29 and deepen to 7.35m beneath VESes -36 & 30. The maximum resistivity value is about $21\Omega\text{m}$. This layer can be interpreted as a clay soil formation with varying clay proportion.

The second geoelectric layer of this profile has variable thickness and broader range of resistive signature ($13 - 250\Omega\text{m}$). To the western end, beneath VESes-35 & 36, has lower resistivity ($17 - 26\Omega\text{m}$). The bottom of this layer extends to a depth of 11.6m under VES-35 and increase to 35m around VES-36. At the mid section, this layer attains its maximum depth 74m beneath VES-30 and the resistivity jumps to $250\Omega\text{m}$. Eastward, the layer gradually thins out and the resistive response drops to $13\Omega\text{m}$. This may represent a thick alluvial deposit of variable lithology. The low resistive ($13 - 26\Omega\text{m}$) responses on both flanks may indicate fine-grained conductive sediments, silt and clay. The mid-section may indicate coarser materials, sand and gravel of early deposition owing to the depression.

The third geoelectric layer has relatively narrower resistivity range ($41 - 118\Omega\text{m}$) and variable thickness. ($63 - 132\text{m}$). Moderate resistive ($41\Omega\text{m}$) under the location of VES-35 (western end) to a depth of 144m, this may indicate the presence of unconsolidated sediment of sand, silt and

gravel which occasionally water are bearing. While a layer of relatively high resistive ($118\Omega\text{m}$) with thickness of 102m under VES-36 and 54m under VES-30 is mapped.

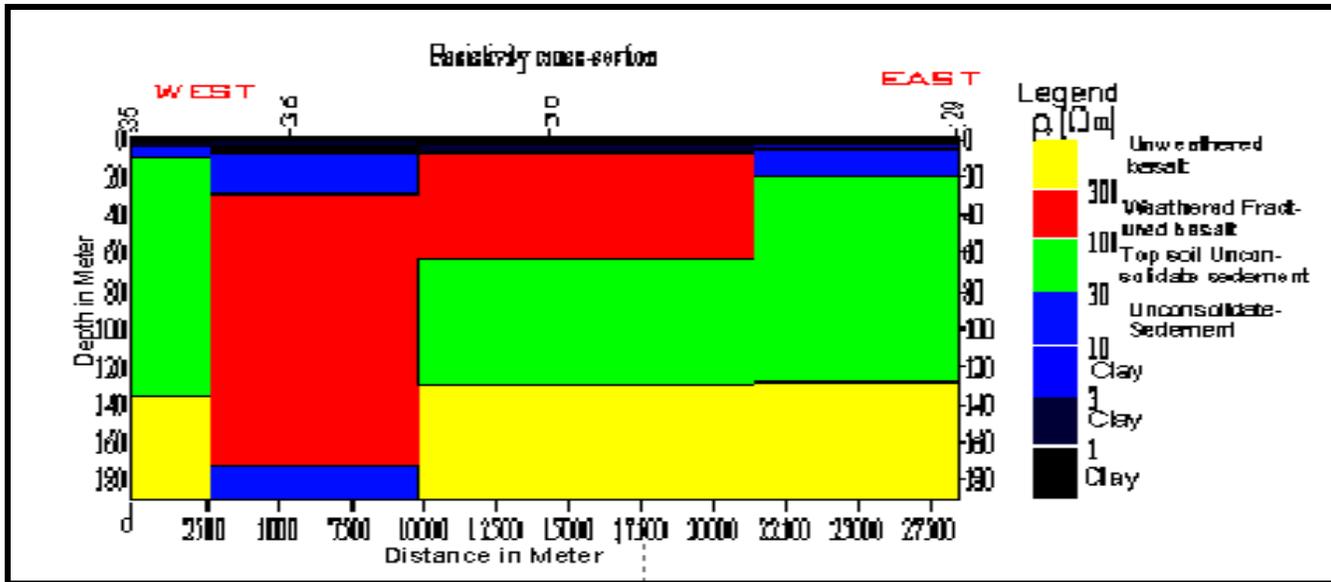


Scale; Horizontally: 1:135000

Vertically: 1:800

Figure 5.6a. Geoelectric section along profile 2.

Which is likely the response of, rhyolites, ignimbrite and trachyte weathered and fractured saturated and water bearing. To the eastern end under VES-30 & VES-29 moderate resistive (53-90 Ωm) with average thickness of 63m. This is likely, the response of moderately weathered basalt which are occasionally water bearing.



Scale; Horizontally: 1:250000

Vertically: 1:4000

Figure 5.6b. Interpreted block diagram of the subsurface along profile 2.

The fourth geoelectric layer has vast portion, which is highly resistive. At the extreme end of west (Under VES 35) and the eastern flank, the formation resistivity is quite high (430-1019Ωm). Under VES-29, the depth to the top of this layer is about 116m and drops down to 137m, beneath VES 30. This is likely to be the response of basalt, which is mostly fresh and unweathered dry to slightly water bearing bedrock. But narrow low resistive patch (15Ωm) under VES-36, where the response from the top clay formation appears, this may be due to the effect of high degree of weathering or fracturing of unconsolidated sediment of sand, silt and gravel.

5.5 The Comparison of Hydrogeophysical Results

Hydrogeophysical results as interpreted on the report of WWDE and on this thesis work are compared with respect to range of resistivity, depth of water table and some character of aquifers. The summary of the comparison result presented as follows:

- To compare some of interpreted VES points let consider VES-22 and VES-21.

Table 5.5a Interpreted results of VES-22 deduced from the present study.

| VES Index | UTM E | UTM N | Elevation (m) | Layers | Resistivity (Ohm-m) | Thick (m) | Inferred Lithologies |
|-----------|--------|---------|---------------|--------|---------------------|-----------|------------------------------------|
| 22 | 455620 | 1026514 | 2607 | First | 4.3 | 4.1 | Top soil |
| | | | | Second | 1.9 | 2.1 | Top soil |
| | | | | Third | 126 | 50.8 | Rhyolites Ignimbrite and trachyte |
| | | | | Fourth | 15.7 | 145 | Highly weathered Scoraceous Basalt |
| | | | | Fifth | 1204 | - | Fresh and dry basalt |

VES-22 is calibrated with lithological logs of the nearby boreholes at Segno Gebeya and interpreted as a geoelectric section of having five layers as shown on the table 5.5a. The first two layers have low resistivity (1.9-4.3 Ω m) and interpreted as top soil, dominantly clay or silty clay composition. The third layer with 126 Ω m resistivity and having 51m thickness is related to a rhyolites ignimbrite and trachyte and thick aquifer is expected on this layer. Further it is underlain by 15.7 Ω m with thickness of 145m this is considered to be highly weathered scoraceous basalt. The bottom layer with 1204 Ω m resistivity is considered as fresh and dry basalt.

Table 5.5b Interpreted Results of VES-22 (on report WWDE)

| VES Index | UTM E | UTM N | Elevation (m) | Layers | Resistivity (Ohm-m) | Thick (m) | Inferred Lithologies |
|-----------|--------|---------|---------------|--------|---------------------|-----------|-----------------------------------|
| 22 | 455620 | 1026514 | 2607 | First | 5.1 | 1.3 | Clay |
| | | | | Second | 1.5 | 0.6 | Clay |
| | | | | Third | 5.8 | 7.8 | Clay |
| | | | | Fourth | 117.7 | 56.2 | Rhyolites Ignimbrite and trachyte |
| | | | | Fifth | 14.3 | 127.6 | Fracture Basalt |
| | | | | Sixth | 874.2 | - | Fresh and dry basalt |

VES-22 is interpreted as a geoelectric section of having six layers as shown on the table 5.5b. The first three layers have low resistivity (1.5-5.8 Ω m) and interpreted as topsoil, dominantly clay or silty clay composition. The fourth layer with 117.7 Ω m resistivity and having 56m thickness is related to a rhyolites ignimbrite and trachyte and thick aquifer is expected on this layer. Further it is underlain by a 14.3 Ω m and 127.6m thick unit considered to be fractured basalt. The bottom layer with 874.2 Ω m resistivity is considered to be fresh and dry basalt.

Comparison of the geoelectric section of VES-22 as interpreted on this thesis work (as five layers model) as shown on the table 5.5a and as interpreted by WWDE (as a six layer model) as shown on the table 5.5b. The two different models have the following in common: a thin low resistivity (1.9-5.8 Ω m) form the top layer. And followed by a resistivity of (117-126 Ω m) nearly the same thickness (50m). The bottom layer (with infinite thickness) is high resistivity (870-1200 Ω m). Hence it can be seen that the two models have a similar general structure and that the only part difference occurs is on the number of layers and to some extent on the layer parameters. This may arise due to the problem of equivalence and suppression.

Table 5.6a Interpreted Results of VES-21 (On this thesis work)

| VES Index | UTM E | UTM N | Elevation (m) | Layers | Resistivity (Ohm-m) | Thick (m) | Inferred Lithologies |
|-----------|--------|---------|---------------|--------|---------------------|-----------|-------------------------|
| 21 | 472331 | 1020653 | 2556 | 1 | 5.3 | 12.2 | Top clay soil |
| | | | | 2 | 97 | 37 | Weathered basalt |
| | | | | 3 | 49 | 115 | Highly Weathered basalt |
| | | | | 4 | 245 | - | Massive basalt |

VES-21 is calibrated with lithological logs of the nearby boreholes at Chanco. This VES has four layer earth structures as shown on table 5.6a. The top layer has low resistivity (5.3Ωm) with thickness of 12.2m and interpreted as a top clay soil.

The second layer has a resistivity of (97Ωm) and thickness of 37m which is likely to be saturated weathered basalt.

The third layer appears as highly weathered basalt of low resistivity (49Ωm) and inferred to be the aquifer zone. This layer is followed by a bottom layer of relatively higher resistivity (245Ωm) which is inferred to be massive basalt.

Table 5.6b Interpreted Results of VES-21 (On the report WWDE)

| VES Index | UTM E | UTM N | Elevation (m) | Layers | Resistivity (Ohm-m) | Thick (m) | Inferred Lithologies |
|-----------|--------|---------|---------------|--------|---------------------|-----------|-----------------------------------|
| 21 | 472331 | 1020653 | 2556 | 1 | 5.9 | 1.1 | Clay |
| | | | | 2 | 2 | 0.6 | Clay |
| | | | | 3 | 7.9 | 18.5 | Clay |
| | | | | 4 | 132 | - | Rhyolites Ignimbrite and trachyte |

Table 5.6b shows VES-21 as interpreted on report WWDE. The top three layers have low resistivity (2-7.9Ωm) and extends to a depth of 20m. These layers are generally interpreted as a top clay soil.

The fourth layer has relatively higher resistivity (132Ωm) and interpreted as rhyolites ignimbrite and trachyte which is inferred to be the aquifer zone.

Comparing the interpretation result of VES-21 as interpreted by this thesis work and by WWDE as shown on table 5.6a and 5.6b respectively. On the interpretation of this thesis work the basaltic layers are resolved well by considering different degree of weathering and fracturing. Where as on the interpretation result of WWDE unable to resolve the basaltic layer and mapped as one lithologic unit without taking into consideration the variation arise from different degree of weathering and fracturing underlying the overburden black top soil.

- Generally there is no significant variation observed in the resistivity values of the major geological formation deduced from the present study and that of the WWDE. Although there are minor differences on some of lithological units and associated resistivity range this might be due to the use of difference model parameters while the top thin layers are lumped. From surveys conducted on this thesis work and on the WWDE the resistivity value of the major geological formation have been epitomized as shown on the table 5.7 and table 5.8 respectively.

Table 5.7: Resistivity values of the major geological formations deduced from the present study.

| No | Estimated resistivity range (Ω-m) | Main geological formation | Description | Remarks |
|-----------|--|----------------------------------|---|---|
| 1 | 1 - 40 | Clay & sandy clay | Top clay soil & sandy clay which is intercalated with silt, sand & gravel at places | This unit is occasionally water bearing |
| 2 | 40 – 100 | Volcanic rocks | Highly weathered rhyolite, moderately weathered basalt & volcanic ash | Water bearing |
| 3 | 100 – 200 | Fractured & weathered basalt | Highly weathered , fractured basalt | This unit is saturated and Water bearing. |
| 4 | 200 - 250 | Weathered basalt | weathered tuff | Dry to slightly water bearing |
| 5 | > 250 | Fresh basalt | Slightly fractured dry & fresh basalt | dry |

Table 5.8: Resistivity value ranges of the major geological formations (Taken from WWDSE, 2007).

| No. | Estimated resistivity range (Ω -m) | Main Geological formation | Description | Remarks |
|-----|--|--------------------------------------|---|---|
| 1 | 2-20 | Clay | some times wet and weathered and intercalated with silt | |
| 2 | 20-90 | Top soil and unconsolidated sediment | The unconsolidated sediment is comprised of sand, silt and gravel at places | This unit is occasionally water bearing |
| 3 | 100-150 | Acidic rock | Rhyolites, ignimbrite and trachyte weathered and fractured at places | Saturated and water bearing at places |
| 4 | 150-250 | Basic rock | Basalt which is fractured and weathered and sometimes Scoraceous | Water bearing when it is fractured |
| 5 | 250-500 | Basic rock | Basalt which is mostly fresh and un weathered | Dry to slightly water bearing |

- There is no significant variation observed on the determination of aquifer properties. To mention some of these similarities between the two studies:
 - ✚ On the upper basalt aquifer the ground water depth increase from north to south but the potential of this aquifer is not significant as compared to the lower basalt aquifer.

- ✚ The depth of investigation was not deep enough to penetrate the main aquifer (the lower volcanic aquifer).

Therefore it is possible to generalize that although there are minor variations of resistivity and associated lithological unit which could be anticipated as there is no a general correlation between the value of resistivity and associated lithological unit (Eyasu Bunaro, 1998).

- As per the report on the WWDE, a further survey using TDEM method of exploration is recommended to study the lower volcanic aquifer. Where as in this study this is not advisable. Specially on the southern flank of the study area where there exist a lower resistive response of the overburden would have a limited skin depth owing to the screening effect.

5.6 Conclusions

The hydro-geologic situation of the area has been inferred by comparison of the resistivity data with the available geological and borehole information. Based on the recent findings and existing ones, it was possible to make the following concluding remarks.

From the pseudosection along profiles and the sliced depth section at different depth levels show the northern part is relatively resistive than southern part. This may indicate the thickness of the hard rock pledges southward or an extended conductive response of the overburden.

The interpreted result of the individual VES points and the two geoelectric sections, incorporating with the geological information of the boreholes show that in the northern flank there is a favorable condition to aquifer shallower than the southern flank. But thicker aquifer is observed on the southern flanks as compared to the northern flank. The graphs obtained from hydrodynamic data also confirm this result. And the main water bearing horizons in the area are fractured and weathered volcanic rocks (Volcanic sands, basalts, ignimbrites and tuffs), lacustrine and alluvial sediments.

Although the resistivity method used for depth determination of lower volcanic aquifer region has met with only limited success owing to the depth of investigation attained by the resistivity

survey was not deep enough to penetrate the lower volcanic aquifer. In general, the results of vertical electrical soundings, as obtained from the stacked graphic plots, pseudo-depth section, the interpreted result of the individual VES points and geo-electric section analysis show that northern flank is relatively resistive than the southern part. Further more, possible geologic structure can be inferred. In particular the geoelectric response of profile one has a layer of two distinct zones. Between these two geo-electrically distinct subsurface zones a possible geologic structure can also be inferred between these two geo-electrically distinct subsurface zones. And the ground water flows from the northern direction to the southern. Therefore, from the hydrogeological point of view the southern part deserve more interest for ground water development.

5.7 Recommendations

Based on the main findings of this study, the following recommendations are given:

1. In the survey area the information obtained from the borehole data for the depth highly productive lower volcanic aquifer at Chanco, Sululta and Legedadi is beyond 300m. But the depth of investigation attained by the resistivity survey, which is less than 200m, was not deep enough to penetrate this lower volcanic aquifer region. Therefore the use of deep probing, natural source EM geophysical methods such as controlled source or conventional Audio Magnetotelluric (CS/AMT) is recommended.
2. The adjust plateau on either side of the rift affected by tectonism. This causes for the formation of different geological structures such as lineament, fault, joints, and contacts. Therefore to map such regional geologic structures, which act as hydraulic barriers that impede large scale ground water movement the potential methods (both gravity and magnetic) methods are recommended to be carried out along north-south direction which is perpendicular to the probable barrier structure (the strike of a geological anomalous body).
3. Integration of other techniques such as remote sensing in GIS framework and a land satellite thematic mapper (TM) which has greater spatial resolution allows smaller geologic features to be recognized well. Moreover, on the hostile and

inaccessible part of the region, like Abay plateau, applying technique of remote sensing is more effective to come up with full picture of the subsurface condition.

4. On the northwest of the study area there is a limitation of the drill boreholes (figure4.1). Thus drilling of deep mapping wells is recommended so as to conduct additional VES survey.
5. Since the survey area is near to Addis Ababa, the earth science department especially the exploration Geophysics stream is recommended to use this area as a teaching model area for further investigation by using different method of geophysical exploration.

REFERENCES

Alexe A.Bobachev, Igor. N. Modin, Vladimir A. Shevnin, 1990-2002. IPI2 Win V.2.1

Aynalem Ali (1985). Hydrology of Addis Ababa.Unpublished M.Sc. Thesis Addis Ababa University, Ethiopia.

Charles C.P., David Mc.G., Diane H.C., (1999). Physical geology. Eighth edition. McGraw-Hill, United state of America: 55-58; 258-278; 368-379.

Elias Lewi., (1999).The geophysics of the Filwuha area.Hydrology report Addis Ababa, Ethiopia.

Ewnetu Gashawbeza., (1998). Application of electrical resistivity and electromagnetic prospecting methods for ground water studies around Dembi, near Debrezeit.Unpublished M.Sc. Thesis Addis Ababa University, Ethiopia.

Eyasu Bunaro., (1998).Application of resistivity methods for ground water exploration around Chuko, southern region of Ethiopia. Unpublished M.Sc. Thesis Addis Ababa University, Ethiopia.

Flathe, H., (1964). New ways for interpretation of geoelectric resistivity measurements in the search for and delineation of aquifers: Internat. Assn. of Sci. Hydrology Bull., 9th year, 1, 52.

Kaufman, A.A., and Keller, G.V. (1983). Frequency & Transient soundings.

Kifle Damtaw., (1990). Geophysical investigation for construction material deposit in the Legedadi area. Hydrogeology journal Ethiopian Institute of Geological Survey (EIGS).

Orellana, E. and Mooney, H.M. (1966). Master tables and curves for Vertical Electrical Sounding over layered structures. Interciencia, Madrid.

Otto K.(1879). Geosounding principles, 1: Resistivity sounding measurements. Elsevier, Amsterdam.

Surfer Version 8.01(May 9, 2002).Golden Software, inc.

Telford, W.M., Geldart, L.P., and Sheriff, R.E.(1976). Applied Geophysics. First edition Cambridge: 442-457; 468-472.

Tesfaye Chernet., (1985). Hydrogeology of the lakes region. Ethiopian mapping agency, Addis Ababa.

Tamiru Alemayehu. Solomon Waltenigus. And Yirga Tadese., (2003). Surface and ground water pollution status in Addis Ababa.

Tilahun Azagegn., (2008). Hydrogeochemical characterization of aquifer systems in Upper Awash and adjacent Abay plateau using Geochemical modelling and Isotope Hydrology. Unpublished M.Sc. Thesis Addis Ababa University, Ethiopia.

Wiliam, L., (1997). Fundamentals of geophysics. First edition Cambridge.

Win-Resist Version 5.1(1981-2001) Microsoft corporation.

WWDSE, (2007). Evaluation of water resources of the ADA'and BECHO plains ground water basin for irrigation development project. (Phase-I report), Addis Ababa, Ethiopia.

Zohdy, A.A.R. (1989). A new method for the automatic interpretation of Schlumberger and Wenner Sounding curves.

APPENDIX

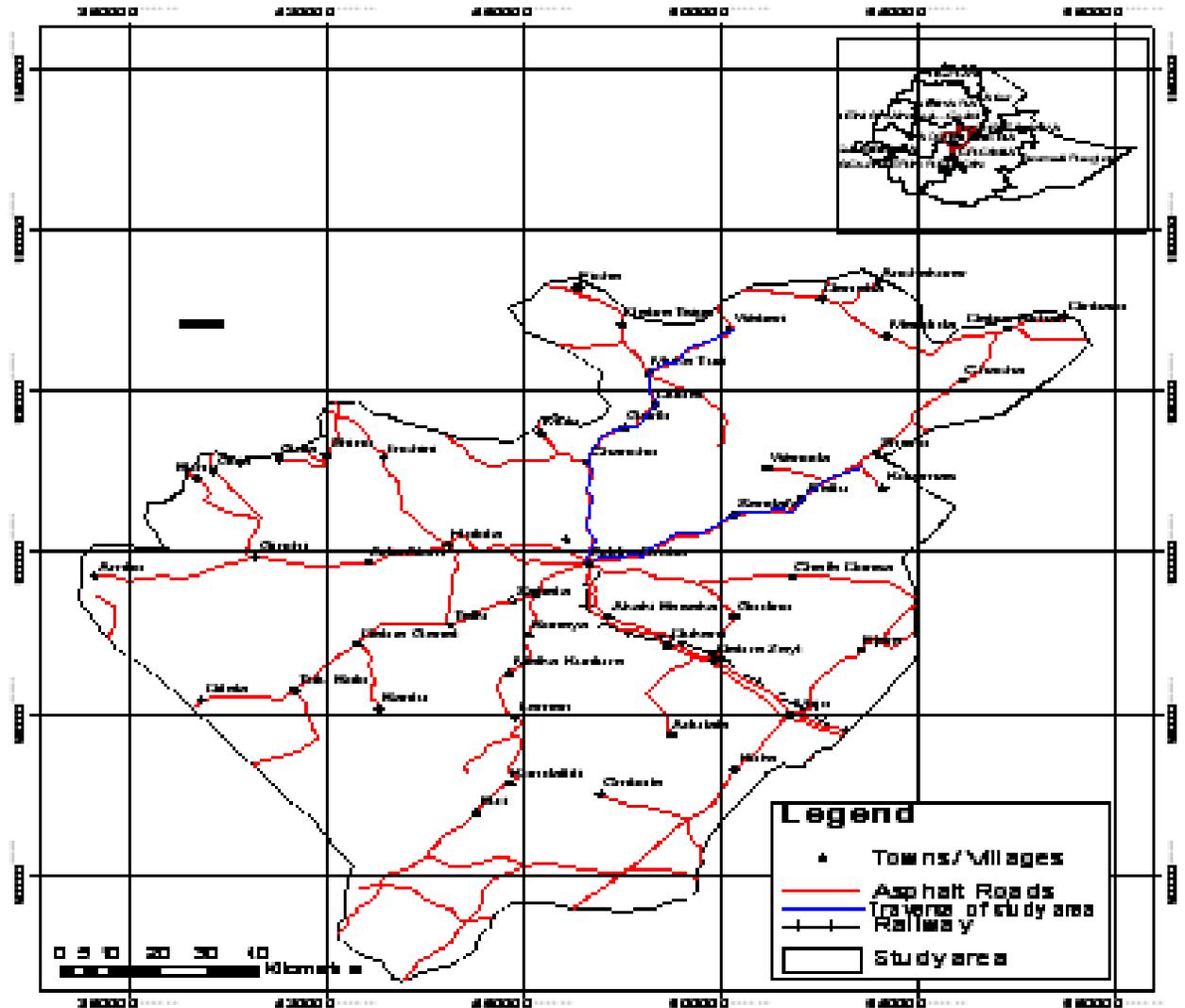


Figure.A.1 Location map for the traverse of study area (Modified from Tilahun, A., 2008)

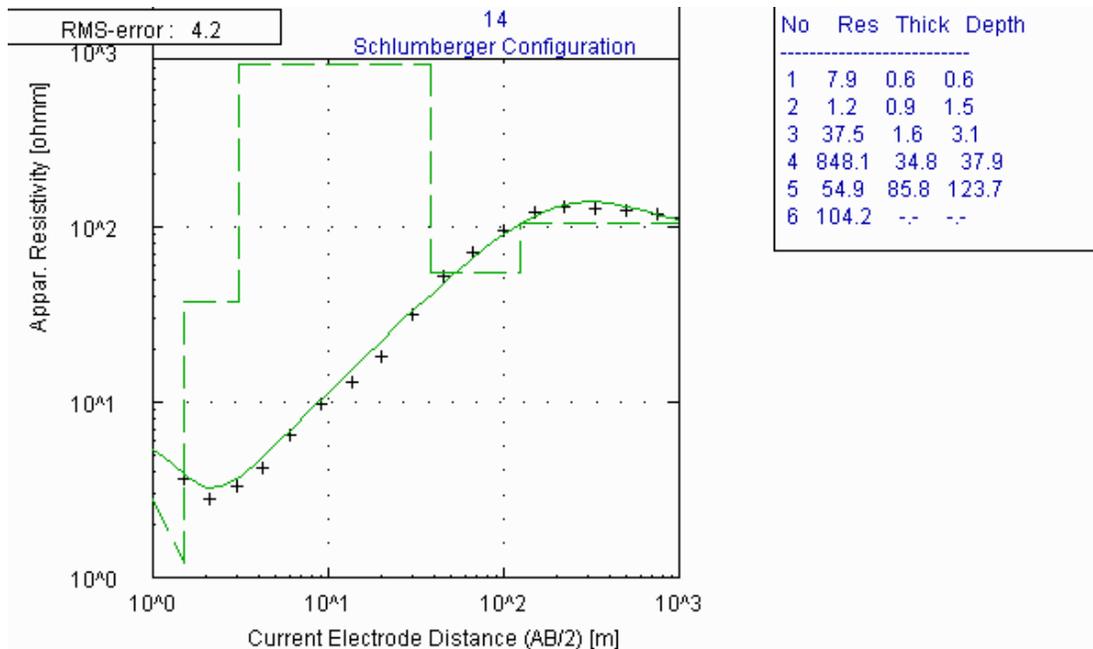


Fig.A.2.Interpretation result of V_{14}

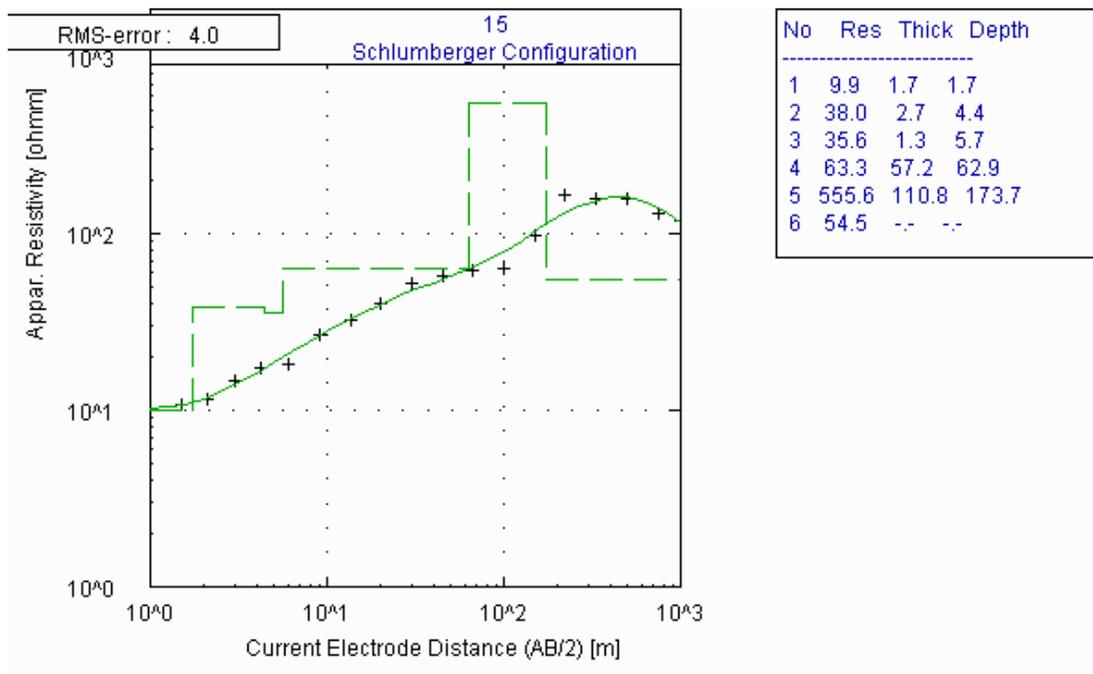


Fig.A.3.Interpretation result of V_{15}

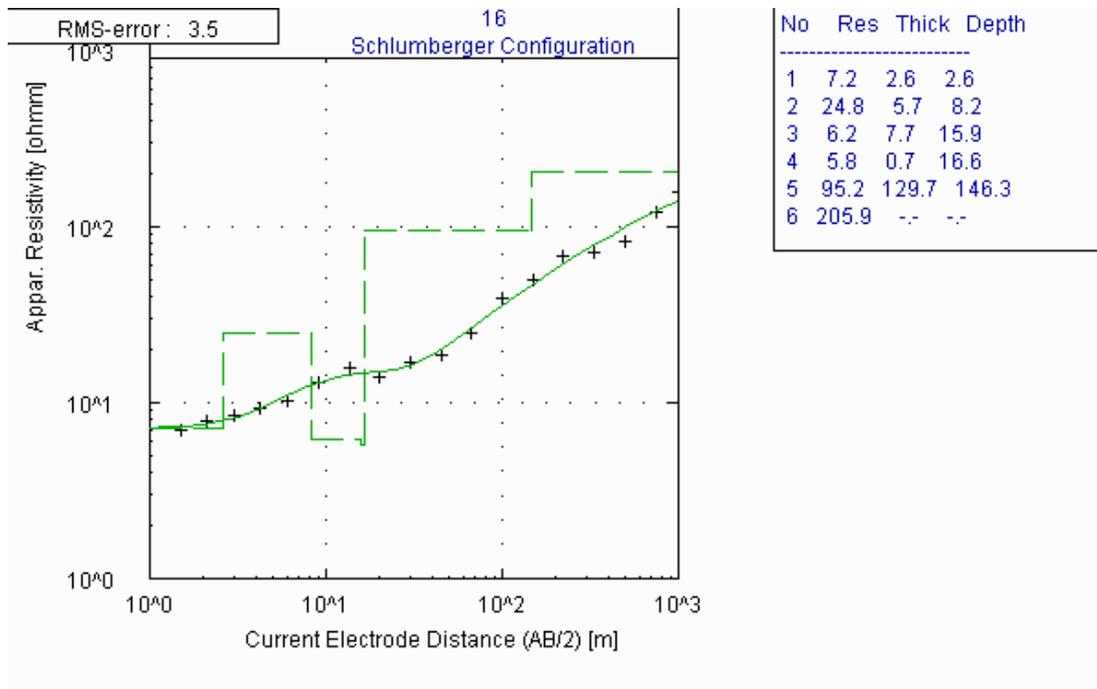


Fig.A.4.Interpretation result of V₁₆

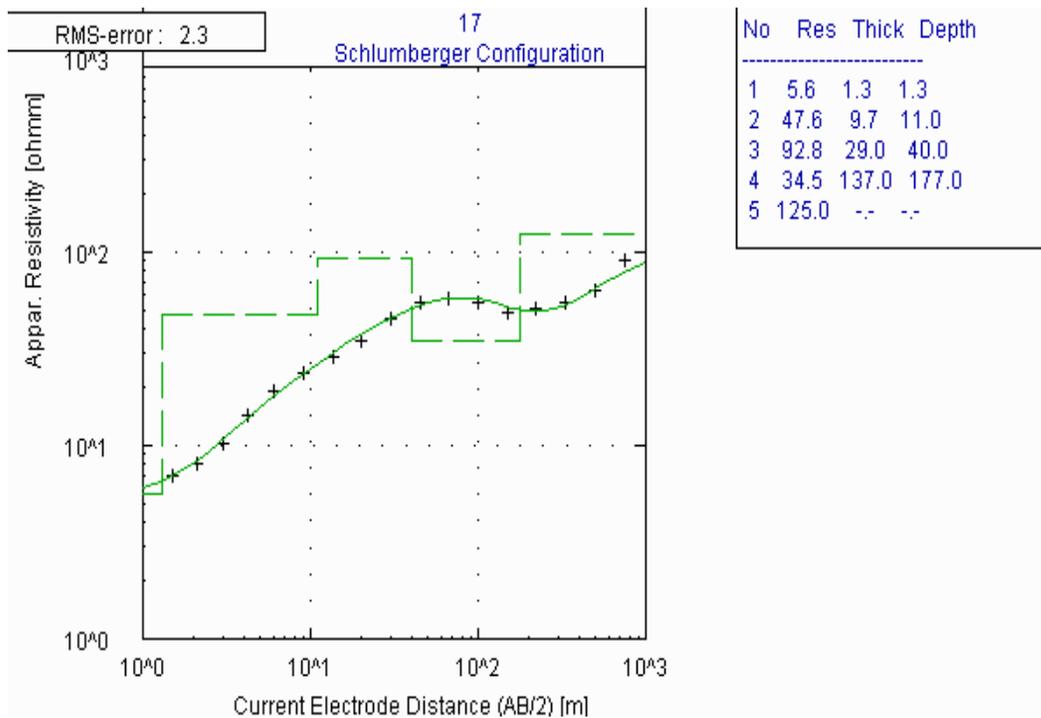
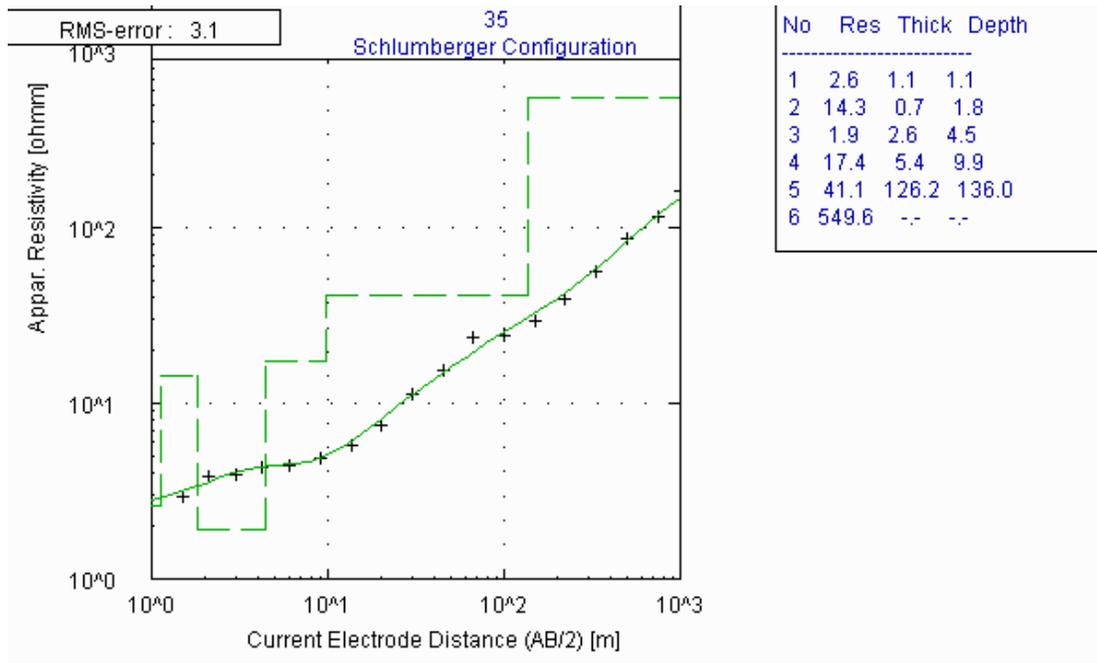


Fig.A.5, Interpretation result of V₁₇



FiFig.A.6,

Interpretation result of V₃₅

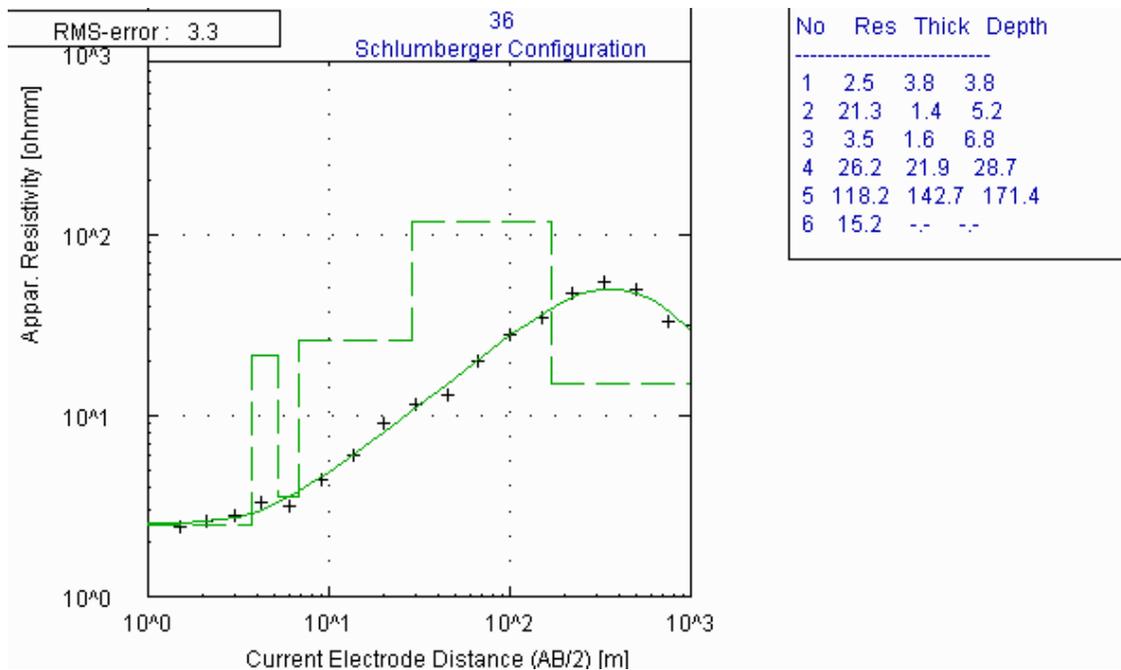


Fig.A.7.Interpretation result of V₃₆

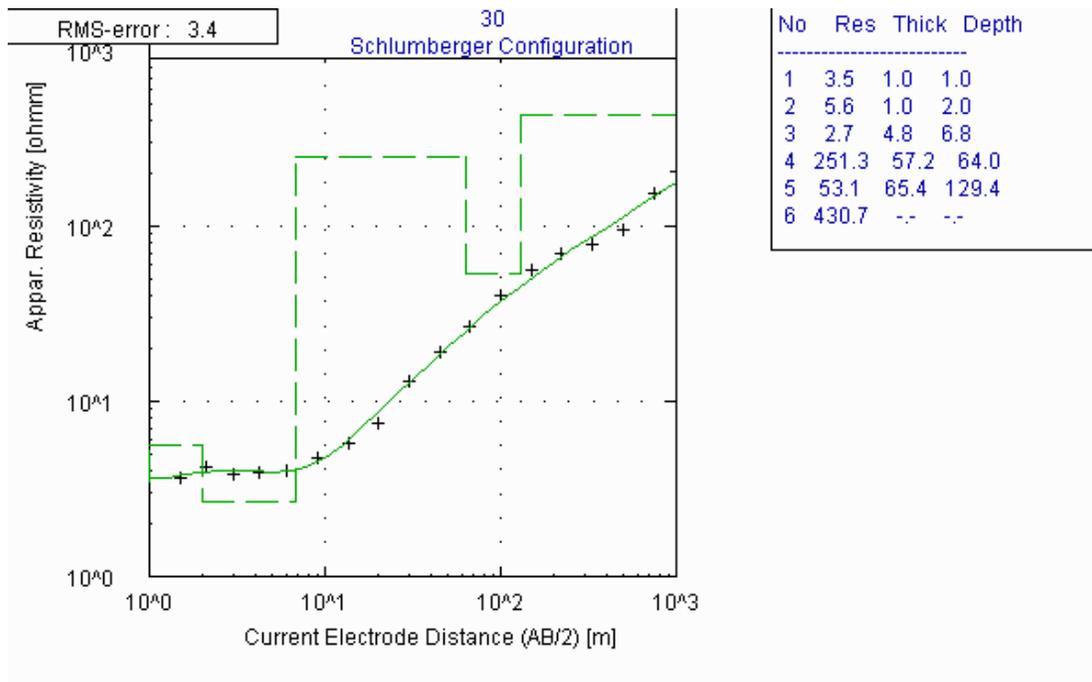


Fig.A.8, Interpretation result of V₃₀

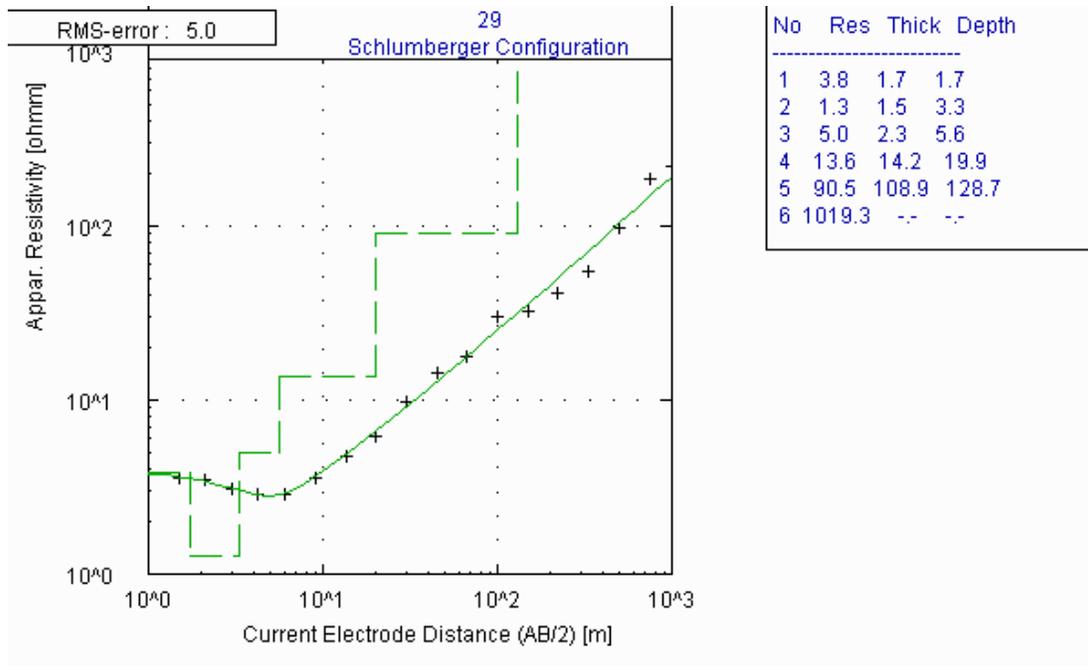


Fig.A.9.Interpretation result of V_{29}

DECLARATION

I, the undersigned declare that this thesis is my original work and has not been presented for a degree in any other university. All sources of material used for the thesis have been duly acknowledged.

Name: Mengesha Sisay

Signature: _____

Date: November, 2008

The thesis has been submitted for examination with my approval as university Advisor.

Dr.Shimeles Fisseha

