

**ADDIS ABABA UNIVERSITY  
COLLAGE OF NATURAL AND COMPUTATIONAL SCIENCES  
SCHOOL OF EARTH SCIENCE**



**STREAM OF APPLIED GEOPHYSICS**

**APPLICATION OF INTEGRATED GEOPHYSICAL TECHNIQUES TO MAP  
GROUNDWATER POTENTIAL ZONES AND GEOLOGICAL STRUCTURES AT WOLDIA  
UNIVERSITY AND MECHARE MEDA, NORTH WOLLO ZONE, NORTH ETHIOPIA**

**A THESIS SUBMITTED TO**

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MASTER OF SCIENCE IN EARTH SCIENCES (APPLIED GEOPHYSICS)**

**BY**

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This is to certify that the thesis prepared by GETACHEW BELAY, entitled with: **“Application of Integrated geophysical techniques to map groundwater potential zones and geological structures at Woldia University and Mechare Meda, North Wollo Zone, North Ethiopia”** and submitted in partial fulfillment of the requirements for the degree of Master of Science in Applied Geophysics complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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## ABSTRACT

Integrated geophysical investigation using Vertical Electrical Sounding (VES) and Magnetic (with GPS coordinates) methods were conducted to investigate groundwater potential zones and geological structures at Woldia University and Mechare Meda, North Wollo Zone, North Ethiopia. The main objective of this study was to assess and evaluate groundwater potential of Woldia University and Mechare Meda and determines the location of preferred borehole sites and the depth at which the aquifers are located. The data acquired from twenty (20) VES points using Schlumberger electrode arrays with maximum half current electrode spacing ( $AB/2=700\text{m}$ ) and 220 magnetic data points (supported by the high precision height control from GPS method) were analyzed both qualitatively and quantitatively in order to know the local geology and determine aquifer bearing horizons. The qualitative analysis of VES data was accomplished by using pseudo depth sections and different geoelectric sections. Similarly, the qualitative interpretation of magnetic data was performed by using 2D magnetic profile plots. Finally, the overall qualitative interpretation was done by integrating all the above results together with the topographic and geologic map, and borehole information.

The quantitative interpretations of the VES data were conducted by modeling the VES data using WinResist and Resix-1p modeling software and constructing geoelectric sections along selected survey lines, using the result from individual VES point interpretations and lithological information from a different borehole. The VES results of the data revealed four main geoelectric layers which differ in degree of fracturing, weathering, and composition. Moreover, the vertical electrical sounding survey helped to determine the depth to the aquifer and identify groundwater potential areas, whereas the magnetic survey helped to map the basement topography and identify places having high groundwater reservoir potential. Generally, the result of interpretation specifies the study area composed of two aquifers, the first is the Upper Basalt aquifer, which is slightly confined between alluvial deposits (upper), and moderately fractured Basalt and Trachytes (lower) and the second is Lower Basalt aquifer which is confined by the moderately fractured Basalt. The depth of the upper aquifer is ranging from 20 to 60m while the depth of the lower aquifer is greater than 180m. The geological fractures found in the study area have orientation of NW–SE, and NE–SW.

**Keywords:** Pseudo and Geo-electric section; VES, GPS, Magnetic, and electrical method

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## Contents

<b>ABSTRACT .....</b>	<b>ii</b>
<b>Acknowledgment .....</b>	<b>iii</b>
<b>ACRONYMY .....</b>	<b>viii</b>
<b>CHAPTER ONE.....</b>	<b>Error! Bookmark not defined.</b>
<b>INTRODUCTION.....</b>	<b>Error! Bookmark not defined.</b>
<b>1.1Background.....</b>	<b>Error! Bookmark not defined.</b>
<b>1.2 Demographics.....</b>	<b>2</b>
<b>1.3 Description of the Study Area.....</b>	<b>2</b>
<b>1.3.1 Location and Accessibility.....</b>	<b>2</b>
<b>1.3.2 Physiography's and Drainage .....</b>	<b>4</b>
<b>1.3.3 Climate .....</b>	<b>6</b>
<b>1.3.3.1 Temperature.....</b>	<b>6</b>
<b>1.3.3.2 Rainfall.....</b>	<b>7</b>
<b>1.3.3.3 Vegetation.....</b>	<b>8</b>
<b>1.4 Statement of the Problem .....</b>	<b>8</b>
<b>1.5 Objectives of the Study .....</b>	<b>10</b>
<b>1.5.1 General Objectives.....</b>	<b>10</b>
<b>1.5.2 The specific objectives of the study are:.....</b>	<b>10</b>
<b>1.6 Materials and Methodology .....</b>	<b>10</b>
<b>1.6.1 Materials.....</b>	<b>10</b>
<b>1.6.2 Methodology .....</b>	<b>11</b>
<b>1.6.2.1 Pre-fieldwork.....</b>	<b>11</b>
<b>1.6.2.2 During-field work .....</b>	<b>11</b>
<b>1.6.2.3 Data Analysis and Reporting (post-fieldwork) .....</b>	<b>12</b>
<b>1.7 Assumptions of the Research .....</b>	<b>13</b>
<b>1.7.1 Basic research question .....</b>	<b>13</b>
<b>1.7.2 Research hypothesis .....</b>	<b>14</b>
<b>1.8 The significance of the study.....</b>	<b>14</b>
<b>1.9 Limitation of the research.....</b>	<b>15</b>
<b>1.10 The Expected output.....</b>	<b>15</b>
<b>1.11 Previous Study.....</b>	<b>15</b>
<b>1.12 Schemes of presentation.....</b>	<b>17</b>
<b>CHAPTER TWO .....</b>	<b>18</b>
<b>2. GEOLOGY OF STUDY AREA .....</b>	<b>18</b>

<b>2.1</b>	<b>Generals .....</b>	<b>18</b>
2.1.1	Tertiary Volcanic Rocks .....	19
<b>2.2</b>	<b>Regional Structure.....</b>	<b>20</b>
<b>2.3</b>	<b>Geological, Structural, and Geomorphological Investigation of North Ethiopia .....</b>	<b>21</b>
<b>2.4</b>	<b>Regional Hydro-geological Investigation of North Ethiopia.....</b>	<b>22</b>
<b>2.5</b>	<b>Geology of the Study Area .....</b>	<b>22</b>
2.5.1	Generals .....	22
2.5.2	Volcanic Unit .....	23
2.5.3	Alluvial Deposit.....	24
<b>2.6</b>	<b>Local Structure.....</b>	<b>24</b>
<b>2.7</b>	<b>Water Resource of Woldia Area .....</b>	<b>26</b>
2.7.1	Surface Water Source of Woldia Area .....	26
2.7.2	Groundwater Source of Woldia Area.....	26
2.7.2.1	General Geology and Geomorphology of Woldia Area .....	26
2.7.2.3	Hydrogeology of Woldia Area .....	27
<b>2.8</b>	<b>Groundwater Movement and Recharge around Woldia Area .....</b>	<b>27</b>
<b>2.9</b>	<b>New Water Supply Source .....</b>	<b>28</b>
<b>2.10</b>	<b>Recharge and Discharge Zone .....</b>	<b>28</b>
<b>CHAPTER THREE .....</b>	<b>29</b>	
<b>3 THEORETICAL BACKGROUNDS OF THE METHODS OF INVESTIGATION ....</b>	<b>29</b>	
<b>3.1</b>	<b>Background .....</b>	<b>29</b>
<b>3.2</b>	<b>Electrical resistivity method .....</b>	<b>30</b>
3.2.1	General.....	30
3.2.2	Fundamental principles.....	30
3.2.3	Potential due to a point source of current .....	32
3.2.7	Potential due to a point source on the ground .....	34
3.2.8	Potential difference when there are two electrodes at the surface .....	35
<b>3.3</b>	<b>Electrode configurations and field procedures in electrical resistivity survey .....</b>	<b>35</b>
3.3.1	General.....	35
3.3.2	Electrode arrangements /Configurations in Resistivity Survey .....	36
<b>3.4</b>	<b>Field procedures in resistivity survey .....</b>	<b>37</b>
3.4.1	General.....	37
3.4.2	The resistivity of rocks and minerals.....	38
<b>3.5</b>	<b>Magnetic method .....</b>	<b>40</b>
3.5.1	Introduction .....	40

3.5.2 The basic principle of the magnetic method .....	41
3.5.3 Origin of earth's magnetic field .....	43
3.5.4 Nature of earth's magnetic field .....	44
3.5.5 Temporal variations of earth's magnetic field .....	44
3.5.6 Elements of the earth's magnetic field .....	45
3.5.7 Magnetization and magnetic susceptibility of materials .....	46
3.6 Magnetic data reduction .....	46
3.6.1 Geomagnetic correction.....	47
3.6.2 Diurnal variation correction.....	47
<b>CHAPTER FOUR .....</b>	<b>48</b>
<b>4. DATA ACQUISITION AND PROCESSING .....</b>	<b>48</b>
4.1 Survey Traverse Selection.....	48
4.2 Data Acquisition and Instrumentation.....	48
4.2.1 Vertical Electrical Sounding.....	48
4.3 Data Reduction and Processing.....	51
4.3.1 VES Data Reduction and Processing.....	51
4.4 Magnetic Data Reduction and Processing .....	52
4.4.1 Magnetic Data Reduction .....	52
4.4.2 Magnetic Processing.....	53
<b>CHAPTER FIVE.....</b>	<b>54</b>
<b>5. DISCUSSION AND INTERPRETATION.....</b>	<b>54</b>
5.1 Generals .....	54
5.2 Discussions and Interpretation of VES.....	54
5.2.1 Interpreted VES Curves .....	54
5.2.2 Sliced-Stacked Section .....	56
5.2.2.1 Sliced-Stacked for different AB/2.....	56
5.2.3 Pseudo depth section and Geoelectric Section of the Profiles .....	57
5.2.3.1 Profile One .....	58
5.2.3.2 Profile Two .....	62
5.2.3.3 Profile Three.....	65
5.2.3.4 Profile Four.....	67
5.2.3.5 Profile Five.....	70
5.2.3.6 Profile Six .....	72
5.3 Results and interpretations of resistivity Survey .....	76
5.3.1 Apparent resistivity map of AB/2= 9m .....	76

5.3.2 Apparent resistivity map for AB/2= 66m.....	77
5.3.3 Apparent resistivity map of AB/2= 100m.....	78
5.3.4 Apparent resistivity map at AB/2=150m .....	79
5.4 2D Modeling.....	80
5.4.1 2D Magnetic model along profile one .....	80
<b>CHAPTER SIX.....</b>	<b>82</b>
<b>6. CONCLUSIONS AND RECOMMENDATIONS .....</b>	<b>82</b>
6.1 Conclusions .....	82
6.2 Recommendation .....	83
<b>REFERENCE .....</b>	<b>85</b>
<b>DECLARATION.....</b>	<b>88</b>

## LIST OF FIGURE

Figure 1.1 Location map of the study area.....	3
Figure 1.2 Physiographic and drainage map of the study area.....	5
Figure 1.3 Monthly max. Mean and min. Mean temperature variability of Sirinka station.....	7
Figure 1.4 Min. And the average monthly temperature (°C) of the study area (Extrapolated from Sirinka station).....	7
Figure 1.5 Monthly rainfall of the study area.....	8
Figure 1.6 Flow Chart of the methodology used in the study.....	13
Figure 2.1 Paleosoil between highly weathered basalt and highly weathered and moderately fractured basalt.....	22
Figure 2.2 Aglomeric basalt .....	23
Figure 2.3 Higly weathered and fractured basalt underling by irreguraly fractured black aphatic basalt.....	23
Figure 2.4 Weathered basalt overlaid on blackcotton clay soil.....	23
Figure 2.5 Slightly fractured aphatic basalt exposed genetober area.....	23
Figure 2.6 Black cotton soil at lower are and Alluvial deposite at river bad exposue.....	24
Figure 2.7 Geological Map of study area.....	25
Figure 3.1 Potential due to a point source of current. ....	32
Figure 3.2 potential due to a point source on the ground.....	34
Figure 3.3 Arrangement of potential and current electrode in four electrode system.....	35
Figure 3.4 Schlumberger array configurations.....	37
Figure 3.5 Elements of Earth's magnetic field (After Lillie, 1999).....	45
Figure 4.1 Instrumental setup of VES and Magnetic Survey.....	49
Figure 4.2 Location of geophysical data points with survey traverses & previous boreholes.....	50
Figure 5.1 The first Interpreted VES curves of each profile.....	55

Figure 5.2 Sliced stacked map for different AB/2.....	57
Figure 5.3 Pseudo depth section of Profile one.....	59
Figure 5.4 Magnetic profile plot and a geoelectric section of profile one.....	61
Figure 5.5 Pseudo depth section of Profile two.....	62
Figure 5.6 Magnetic profile plot and a geoelectric section along profile two.....	64
Figure 5.7 Pseudo-depth section along profile three. ....	65
Figure 5.8 Geoelectric section along profile three.....	66
Figure 5.9 Pseudo-section along profile four.....	68
Figure 5.10 Magnetic profile plot and a geoelectric section of profile four.....	69
Figure 5.11 Pseudo-depth section along profile five. ....	71
Figure 5.12 Geoelectric section along profile five.....	72
Figure 5.13 Pseudo-depth section along profile six.....	73
Figure 5.14 Magnetic profile plot and a geoelectric section of profile six.....	75
Figure 5.15 Apparent resistivity map for AB/2 = 9m.....	77
Figure 5.16 Apparent resistivity map for AB/2 = 66m.....	78
Figure 5.17 Apparent resistivity map for AB/2 = 100m.....	79
Figure 5.18 Apparent resistivity map for AB/2 = 150m.....	79
Figure 5.19 2D Magnetic modeling along profile one.....	81

**LIST OF TABLE**

Table 1.1:Climatic(classification of Ethiopia, ( Daniel Gemechu, 1997).....	6
Table 1.2:Monthly maximum mean and minimum mean temperature variability of Sirinka.....	6
Table 1.3: Extrapolated monthly maximum and minimum mean temperature variability of Sirika .....	7
Table 1.4: Monthly rainfall of the study area.....	8
Table 1.5: Transmissivity, Hydraulic Conductivity bore holeific capacity of the borehole on and around the study area.....	16
Table 1.6: Borehole information on and around the study area.....	16
Table 3.1: Resistivity value of some common geological formations(modified from Bernard,2003).....	39
Table 3.2: Resistivity of Earth material.....	39
Table 3.3:The Numerical value of different types of water(modified from Bernard,2003).....	40
Table 3.4: Property, symbol, and units of magnetic parameters .....	43

## ACRONOMY

AWWDSE-----	Amhara Water Works Design and Supervision Enterprise
Am <sup>-1</sup> -----	Ampere per meter
am-----	anti-meridian
°C-----	Degree Celsius
cm-----	centimeter
CSA-----	Central Statistical Agency
DC-----	Direct Current
1D-----	One Dimension
2D-----	Two Dimension
GPS-----	Global Position System
IGRF-----	International Geomagnetic Reference Field.
GRS-----	Geodetic References System
J <sub>r</sub> -----	Intensity of remanent magnetization
Km-----	Kilometer
K/Ar-----	potassium over Argon
masl-----	meter above sea level
m-----	meter
MER-----	Main Ethiopian Rift
mm-----	millimeter
m <sup>3</sup> -----	cubic meter
mg/l-----	milligram per liter
micros/cm-----	micros per centimeter
My-----	Million years
NBH-----	New Bore Hole
NW-----	North-West
NE-SW-----	Northeast-Southwest
NW-SE-----	Northwest-Southeast
nT-----	nano tesla
N-S-----	North-South
Ω-m-----	ohm-meter
RMS-----	Root Mean Square
SE-----	South-East
SW-NE-----	Southwest-northeast
SWL-----	Static Water Level
UTM-----	Universal Transverse Mercator
VES-----	Vertical Electrical Sounding
WGS-----	World Geodetic System
WUNBH-----	Woldia University New Bore Hole
WUOBH-----	Woldia University Old Bore Hole

## CHAPTER ONE

### INTRODUCTION

#### 1.1 Background

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

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

Access to clean water is a human right and a basic requirement for economic development. The safest kind of water supply is the use of groundwater. Since groundwater has a natural protection against pollution by the covering/shading layers, only minor water treatment is required. The largest amount of water on Earth (97.2 %) is contained in the oceans and seas as saline or salt water but on the small amount of it (2.8 %) exist as fresh water on land. This fresh water found on land is distributed as ice caps and glaciers (76.43 %), freshwater lakes (0.32%), saline-lakes (0.29 %) and very small amount of it, as streams, channels (0.004 %) groundwater and soil moisture (21.96 %), (Fetter, C.W., 2001). The amount of fresh water, which is available for domestic, industrial, and agricultural purposes, is very limited as compared to the total volume of water on the planet Earth. Due to the above reasons, the search for groundwater is vital as an immediate and sustainable solution to alleviate the scarcity of water for drinking and other domestic uses in most part of the world as well as in Ethiopia. In many developing countries, there is not only a heavy reliance on groundwater as a primary drinking supply, either collected from shallow depth dug wells or from springs, but also as a supply of water for both agriculture and industrial use. The reliance on groundwater both in the developed and developing countries is such that it is necessary to ensure that there are significant quantities of water and that the water is of a high quality. In addition to being

clean through the natural process of filtration while passing through geological formations and thus being suitable for domestic consumption, groundwater provides with replenishing able and pollution free natural resource. The use of geophysics for both groundwater resource mapping and for water quality evaluations has increased dramatically over the last 10 years in large part due to the rapid advances in microprocessors and associated numerical modeling solutions that facilitated the rapid acquisition and processing of data and their presentation in the useful form (Shakeel, 2006). The use of geophysics for groundwater studies has also been stimulated in part by a desire to reduce the risk of drilling dry holes and also a desire to offset the costs associated with poor groundwater production. Currently, the geophysicist provides useful parameters to the hydrogeological modeling of both new groundwater supplies and for the evaluation of existing groundwater contamination. In this respect, the major objectives of this study are to identify potential areas for extraction of groundwater resources within the World University and the town and minimize the risk of sinking boreholes at inappropriate areas through the use of geophysical techniques. Specifically, the technique employed involves Vertical Electrical Sounding surveys over the wider areas of the plain so as to get a general assessment of its groundwater resource.

## **1.2 Demographics**

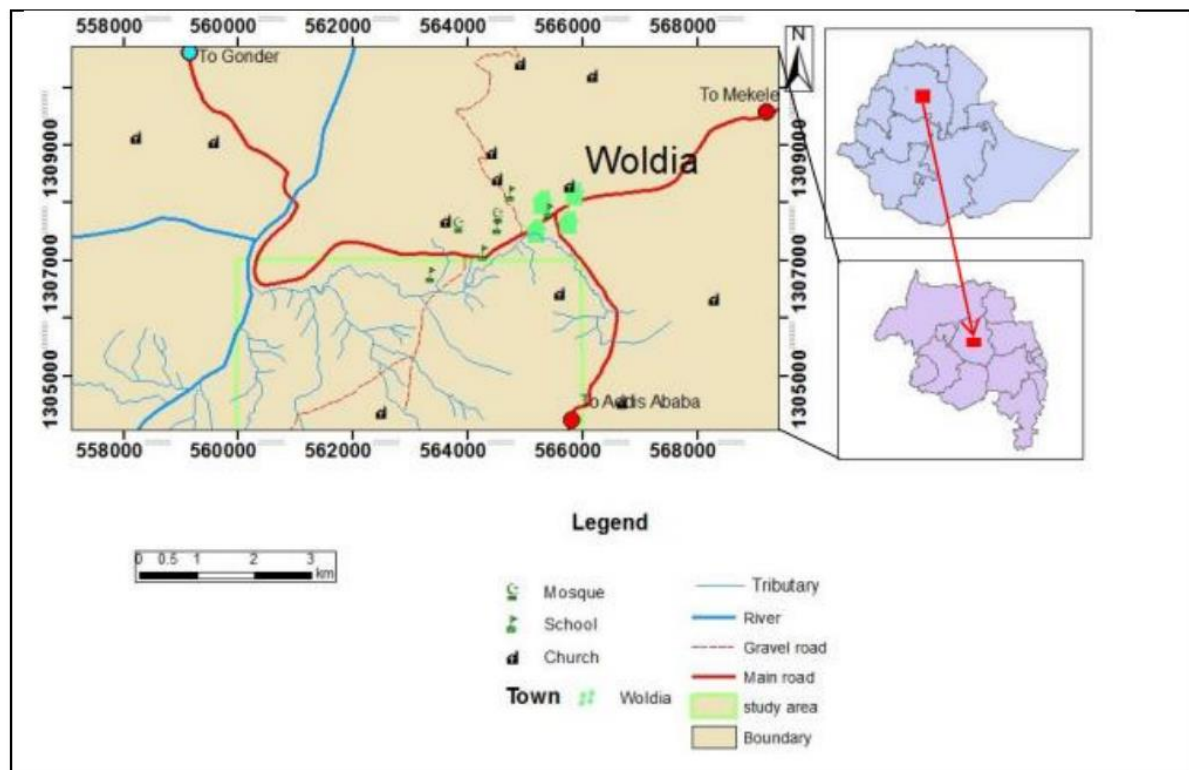
Based on the 2007 national census conducted by the Central Statistical Agency of Ethiopia (CSA), Woldia town has a total population of 46,139, of whom 23,000 are men and 23,139 women. The majority of the inhabitants practiced Ethiopian Orthodox Christianity, with 80.49% reporting it as their religion, while 18.46% of the population said they were Muslim.

The 1994 National Census reported a total population for Woldia of 24,533 in 5,413 households, of whom 11,689 were men and 12,844, were women. The two largest ethnic groups reported in the Census were the Amhara (93.92%) and the Tigrayan (4.32%); while all other ethnic groups made up 1.76% of the population. Amharic was spoken as a first language by 95.2%, and 3.75% spoke Tigrinya; the remaining 1.05% spoke all other primary languages reported. 79.75% of the population practiced Ethiopian Orthodox Christianity, and 19.44% of the population said they were Muslim.

## **1.3 Description of the Study Area**

### **1.3.1 Location and Accessibility**

Woldia also spelled Woldiya, "Wold/Weld" meaning "Son" in Ge'ez; is a hillside market town, capital of the Semien Wollo Zone, and Woreda in northern Ethiopia. Located north of Dessie and southeast of Lalibela in the Amhara Region, this town is located at geographic coordinates: latitude and longitude of 11°50'N 39°36'E and an elevation of 2112 meters above mean sea level. The town is located at about 360 km from Bahir Dar, the Regional State capital, and 521 km from Addis Ababa. The town is built on and between two symmetrical hills: Gabriel Hill on the northwest and Qaro Hill in the southeast. It is hot during the day for much of the year, but always with a refreshing breeze. At night, it cools down and thus provides an ideal temperate climate for the habitats and visitors. It is an expanding municipality, experiencing both rapid population growth as well as the increase of its jurisdiction. It has a significant, but largely undeveloped tourist potential: its breathtaking mountain vistas, history, and many old Churches represent only some of these untapped resources.



**Figure 1.1** Location map of the study area.

A notable landmark is a church, Woldia Gabriel. In terms of geology, travertine to use in the building has been working on a minor scale nearby.

Today, besides its potential attractions, Woldia already has a significant flow of tourist traffic because of its location on the main historic route of the country. This is to say that the town is

located at a juncture that leads to Lali Bella, Gondar, and Bahir Dar on the one hand and Axum, Mekelle and the Afar region on the other. Also, significant numbers of business travelers pass through the city every day on their way to or from Addis Ababa, Dessie, Semera, Mekelle, Gondar, and Bahir Dar.

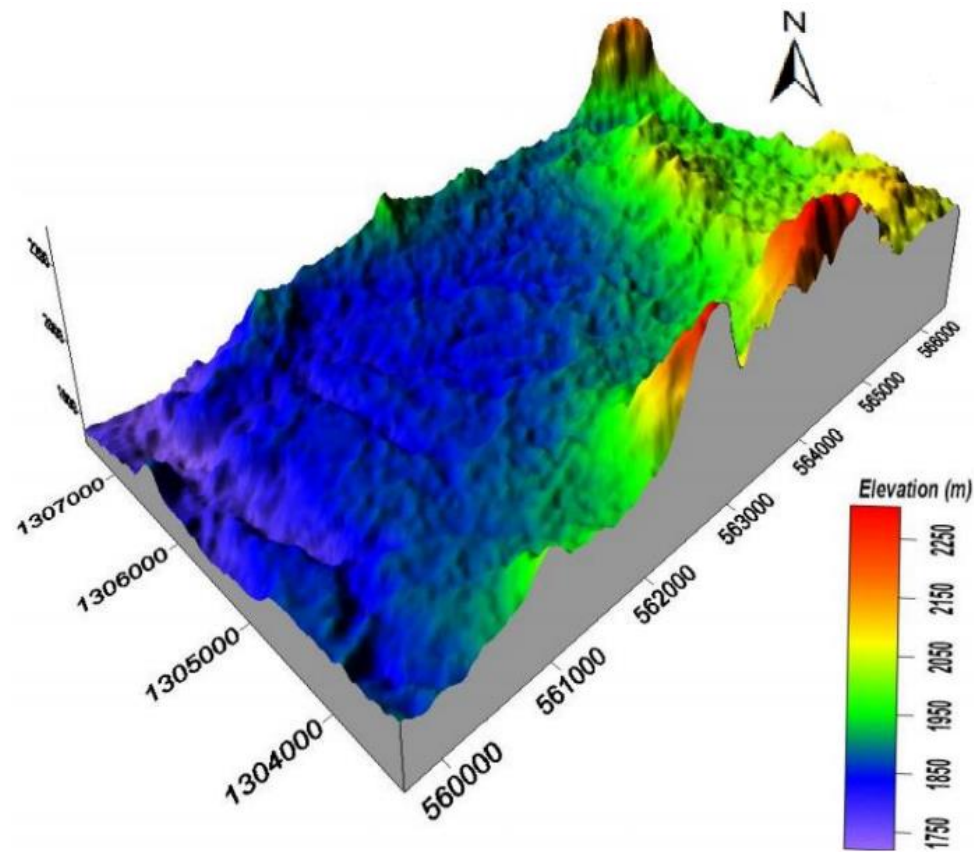
In the future, according to the Government of Ethiopia's five year growth and transformation plan, Woldia will directly benefit from being a railway center since the planned railway will cross the town in 4 directions (Egis International in association with IAU-IDF and UrbaLyon, Neighborhood Development Plan Report of Mehal Mechare, Woldia, April 2016).

Furthermore, Woldia town is one of the fast-growing cities in Ethiopia with the federal and the regional governments developing not only a University but also an international level stadium, both of which are already constructed.

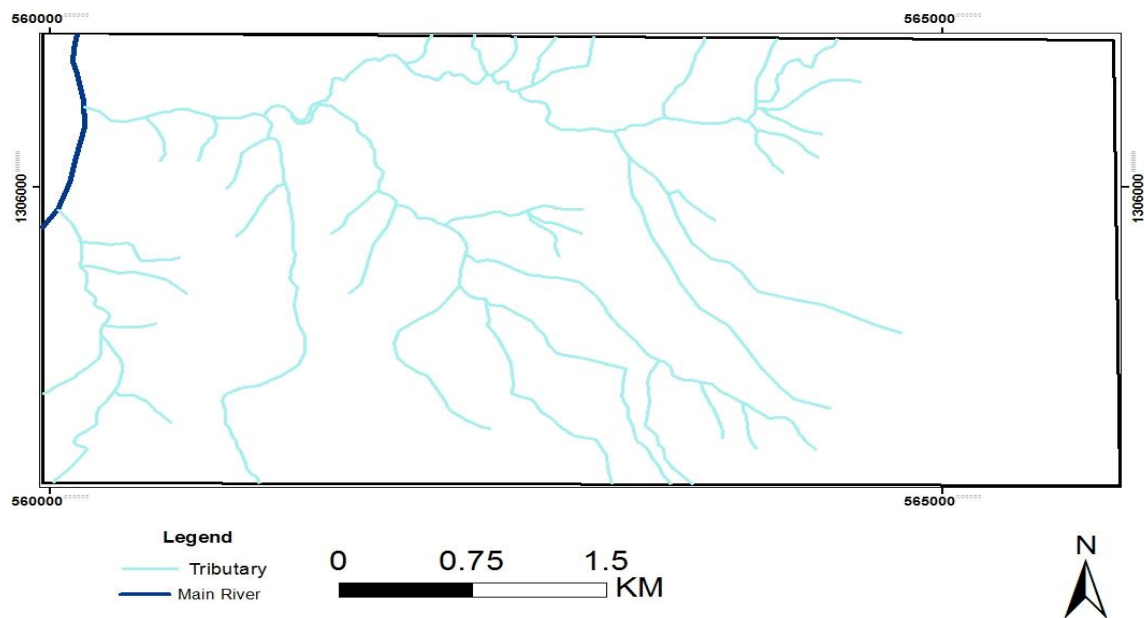
### **1.3.2 Physiography's and Drainage**

The physiography of the area depends on the general geology and structural set up of that particular area. Woldia University and Mechare Meda are situated in the graben near the escarpment adjoining the western escarpment of the rift valley and found near the Gatira river catchment. The general topography comprises of study area undulating hills, flatlands, and steep mountains. It gradually increases in elevation to the west and north-west. Gatira River, which flows to the west, is the major tributary of Tikurwaha river; which is tributary itself to the Golina River. The study area located to west and north-west of Gatira River, North East of Tikurwaha River, and Shele River.

Small valleys originated from ridges and hills form a dendritic drainage pattern at the upstream and right and left sides of the catchment where the slope is relatively steeper and becomes less dense at the flat land and gentle to flat land of the study area, (figure 1.2A). These small valleys and streams are controlled by main joints, lineaments, fractures or a combination of these.



A. Physiographic Map of the study area.



B. Drainage Map of the study area.

Figure 1.2 Physiographic and drainage map of the study area .

### 1.3.3 Climate

#### 1.3.3.1 Temperature

Climate strongly affects soil, geomorphology, surface, and subsurface nature of an area. The climate of an area is controlled by altitude, latitude, the direction of the wind and its distance from water bodies. Climatic conditions in Ethiopia and most equatorial regions are strongly influenced by their altitude. The National Meteorological Service Agency (NMSA) classified the climatic regions of Ethiopia into five climatic zones (Table 1.1).

**Table 1.1: Climatic (classification of Ethiopia, (Daniel Gemechu, 1997)**

Altitude (msl)	Temperature (°C)	Classification	Local name
Below 500	25 and above	Hot	Bereha
500-1500	20-25	Hot temperate	Kola
1500-2300	15-20	Temperate	Woina Dega
2300-3300	10-15	Cool	Dega
3300 and above	10 or less	Cool	Kur

The study area is found at the higher elevation than the Sirinka meteorological station (30km far from Woldia), as a result, the temperature data from Sirinka meteorological stations were extrapolated to the study area by allowing a decrement of 0.6 °c for 100m (Nata Tadesse, 2006). The minimum and maximum temperatures are found during the months of January and June respectively.

Accordingly; the study area lies in the Woinadega to Dega climate zone having an altitude ranges from 1776 to 2508 masl, Based on this the annual mean temperature of the study area is found to be 19.9°C.

**Table 1.2: Monthly maximum mean and minimum mean temperature variability of Sirinka.**

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	22.9	25.1	26.1	27.5	29.2	30.8	28.3	27.1	27.1	26.1	24.8	24.2
Min	11.5	12.1	13.3	15.0	15.8	16.6	16.2	14.3	14.6	12.5	10.5	10.6
Mean	17.2	18.6	19.7	21.3	22.5	23.7	22.3	20.7	20.8	19.3	17.7	17.4

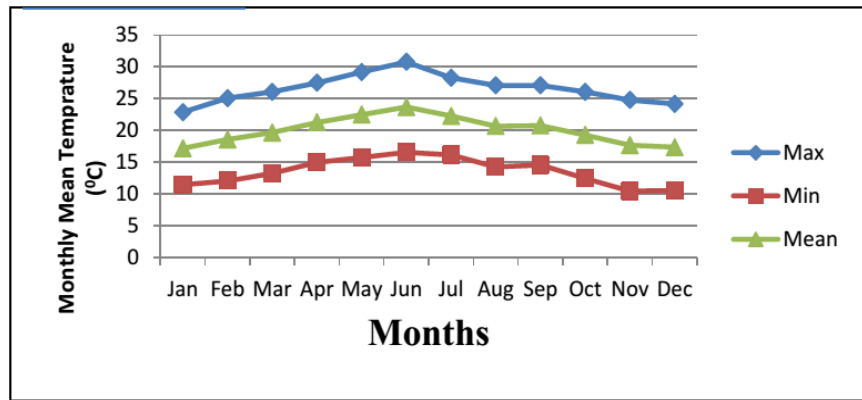


Figure 1.3 Monthly max. Mean and min. Mean temperature variability of Sirinka station.

Table 1.3: Extrapolated monthly maximum and minimum mean temperature variability of Sirika

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	22.7	24.9	25.9	27.3	29.1	30.7	28.1	26.9	26.9	25.9	24.6	24
Min	11.3	11.9	13.1	14.9	15.6	16.4	16.1	14.1	14.4	12.4	10.4	10.4
Mean	17	18.4	19.5	21.1	22.3	23.5	22.1	20.5	20.6	19.1	17.5	17.2

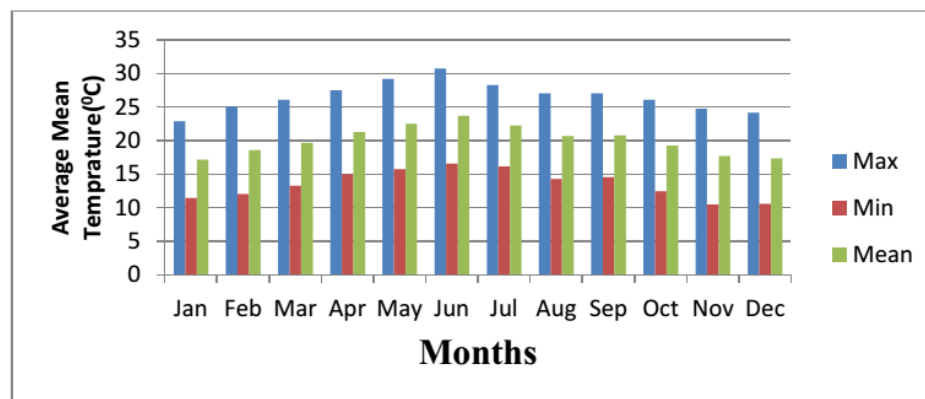


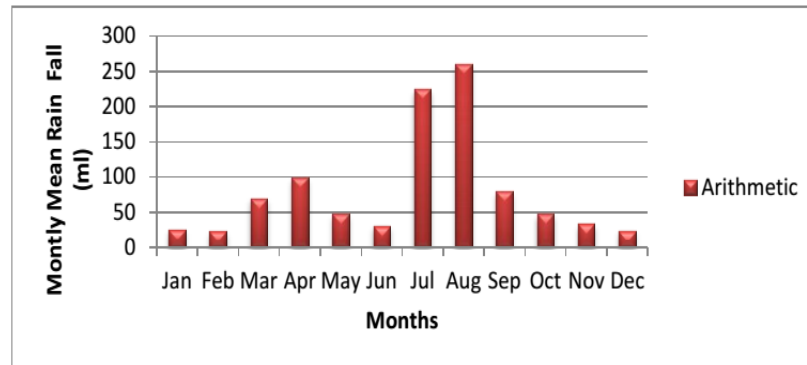
Figure 1.4 Min. and the average monthly temperature (°C) of the study area (Extrapolated from Sirinka station).

### 1.3.3.2 Rainfall

The climate of Woldia area is typically characterized by two distinct seasonal weather patterns: the wet season, which extends from June to September, contributing about 80% of the annual rainfall, and the dry season which covers the period from October to May with a minor rainy season in March and April well known for its frequent failure due to high temperature different from usual. Such climates which are characterized by alternating wet and dry seasons may favor. The climate is warming temperate to humid. The study area receives rainfall from Atlantic Equatorial Westerly during the main rainy season and from the Gulf of Aden and the Indian Ocean during March and April months (NMSA). There is low to a negligible amount of rainfall in the other months.

**Table 1.4: Monthly rainfall of the study area**

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Arithmetic	24.5	21.9	68.9	98.2	46.6	29.6	224	259	78.6	46.7	32.6	22.5	953.1
Designation	Dry	Dry	Rain	Rain	Rain	Dry	Rain	Rain	Rain	Rain	Dry	Dry	



**Figure 1.5 Monthly rainfall of the study area.**

### 1.3.3.3 Vegetation

There are different types of vegetation on around woldia town, but the types of vegetation in the study area are not diverse and consist mainly of Acacia, Eucalyptus, Fig/Shola, Tid /Junipers and Zembaba/Palm tree. The Eucalyptus trees are mostly found in homesteads/settlement areas. However, remnants of some of the tree types indicate that the area was once covered by indigenous trees. The surrounding area is dominated by open grassland and farmland showing high anthropogenic impact.

### 1.4 Statement of the Problem

Globally, it is recognized that groundwater plays a vital role in day to day activities of the human being such as domestic, industrial, and agricultural purposes. The Northern Ethiopian is one of the areas that use groundwater for vital purposes in many localities for different activities like domestic use, agricultural and industrial purposes. In the study area, there are Woldia University, towns, Villages and Pastoral residences, Large-scale Agricultures, and industries. Since the area comprises many cities with many activities such as (Mersa, Sirinka, Woldia, Kobo and Kobo-Girana Agricultural center, Hara town railway station, etc.) and large scales agricultural activities such as Kobo-Girana Agriculture center and Sirinka Agriculture institution; the demand for groundwater use for all activities is clearly understandable. The current study focuses on the assessment of groundwater potential, flow, recharge, and discharge zone, hydrostratigraphy based on the special emphasis on the geomorphological and geological structures that are used as a conduit for the recharge,

circulation, and distribution of groundwater through the sub-surface. **AWWDSE** was conducted research at the town, but the demand and supply of water still not balanced due to the increment of population number. Future more than ten factories will plant at the town and needs its own water source to use for workers and the factory itself to balance this it must need other studies to locate water potential to drill the borehole. The university uses water from Mechare well field, but most of the time water reservoirs(tanker) face problem to pump the water to upwards the university, so to avoid the interruptions of water supply and to balance the demand, the university needs its own borehole at the campus. To solve water scarcity at University and town necessary to conduct research to locate groundwater potential and recommend borehole site at the university.

Problems associated with groundwater potential assessments using geomorphology and geological structures:

- ❖ There is the scarcity of groundwater potential in many localities of the study area in which most of the water supply scheme is from the long distances of the Escarpments.
- ❖ Detail study of groundwater potential assessment is not conducted making special emphasis on the geological structures.
- ❖ The demand for groundwater use for domestic purpose, industrial and agricultural activities in this region is high but the supply is very small due to less number of boreholes.
- ❖ Supplying surface water in the area is very difficult and costly because there is no river like Abay River, Awash River etc. so that assessing groundwater is the mandatory choice.

Generally, the previous works were not carried out for groundwater investigation using an integrated geophysical technique, but the only electrical method (VES) and the problem associated with VES was the difficulty to identify weak zones at specific location and directions. Therefore, there is still an adequate problem to investigate the relation between subsurface structure and groundwater flow in the study area. Hence, the detailed study using Geophysical (Magnetic and electrical) methods to map and characterize the subsurface structure contributing to groundwater potential and water saturated horizons in the study area will be attempted in this work.

## 1.5 Objectives of the Study

### 1.5.1 General Objectives

The main objective of the study focuses on the assessment and evaluation of the groundwater potential of Woldia University and Mechare Meda and determines the location of preferred borehole sites and the depth at which the aquifers are located

### 1.5.2 The specific objectives of the study are:

- ❖ To identify the major subsurface geological units in the area by integrating magnetic and electrical resistivity and map possible water saturated horizons.
- ❖ To infer areas of maximum groundwater reservoir potential site to drill a borehole for a sufficient and sustainable yield of groundwater.
- ❖ To determine the depth to groundwater table and to locate potential drilling sites for the extraction of groundwater.

## 1.6 Materials and Methodology

The feasibility study of groundwater identification and site selection activities were done through the application of standard hydrological and geophysical techniques. The following primary and secondary data collections and methodologies used to achieve the proposed objectives.

### 1.6.1 Materials

To achieve the objectives of this research work, the following materials would be used.

#### I) Geophysical Equipment:

- ❖ Earth Resistivity Meter ((PASI 16-GLX unit).
- ❖ Proton Precession Magnetometer.

**II) Digital materials:** Software components: Arc GIS 10.3, AutoCAD -2016, GEOSOFT (V-7.0.1), and Global Mapper. But VES data interpreted by using WINRESIST, Ip2win, AutoCAD 2016, and Microsoft Excel and also to magnetic data interpreted by using Oasis Montaj (V-7.0.1) and SURFER-10, Paint and Microsoft Excel.

**III) Auxiliary materials:** Topographic map of scale 1:50,000 and Aerial photographs, Geological map of the study area and field equipment's: GPS & digital camera would be used.

## 1.6.2 Methodology

In order to achieve the objectives of this research; the methods classified as Pre-field work, During-field work, and post-fieldwork. These included reviewing different previous works, geophysical works (related to groundwater exploration and identification of geological structures) and also geological and hydro-geological pieces of literature on the study area. Two geophysical methods were employed in the study area, i.e. VES and magnetic methods of prospecting. Data from both methods were collected through/over four selected traverses/ profiles, except on profile -3 and 5, would distribute over all the study area. Both VES and magnetic data were analyzed using appropriate software listed above on the subtitle, of this chapter.

### 1.6.2.1 Pre-fieldwork

Existing data and materials were collected from different sources and were used in the surveying and analysis parts of the research work.

- ❖ Hydrogeological maps and logs, which are very crucial for geophysical interpretation, were collected.
- ❖ VES data of previous work around study area was collected.
- ❖ Borehole data (location, including coordinates, depth, year of drilled. Pumping rate, etc.) of the study area was Collected.

### 1.6.2.2 During-field work

A geophysical investigation was conducted in the proposed study area. During the fieldwork, the following activities were undertaken to achieve the objective of the proposed works.

- ❖ The traverses made in the different direction of the study area to identify the rock types, strategic setup and geological structures in order to identify the possible aquifer system and estimate their aquifer parameter which are key issues of defining the occurrence & the depth of the groundwater table.
- ❖ Water sources, namely the existing boreholes available in and around the area are assessed to conduct fieldwork.
- ❖ Vertical Electrical Sounding (VES) data was measured by using an Earth Resistivity meter (PASI 16-GLX) in different selected locations of the study area. The VES procedure primarily

assumes that the subsurface has a horizontal stratigraphy. The potential electrodes remain constant at some stations; the measurements are taken with gradually increasing distances of the current electrodes. When the distance between current probes is increased, also increased depth at which the current penetrates below the surface of the ground, i.e. increasing the depth of investigation. Hence, the vertical electrical drilling can identify resistivity of different horizontal strata below the investigation points.

- ❖ The Magnetic data measured by using Proton Precession Magnetometers with X, Y & Z directions.

### **1.6.2.3 Data Analysis and Reporting (post-fieldwork)**

The primary (220-magnetic and 15-VES) data collected from the field and secondary (5-VES) data acquired from different sources were integrated to get reliable and more accurate subsurface pieces of information. Primary geophysical raw data was processed and analysed by using Arc GIS 10.3 to plot location map of the study area and to show VES data points, magnetic data and previously drilled borehole location. And also WINRESIST, Ip2win, AutoCAD-2016 and Microsoft Excel were used to analyze VES data in addition to these Oasis Montaj (V-7.0.1), SURFER-10, Paint and Microsoft Excel were used to interpret magnetic data.

The vertical resistivity distributions below the center of the array were determined. The data are usually plotted as depth against resistivity so that the resistivity of different depths was analyzed and interpreted. The processed data were converted to resistivity model curves which reveal the subsurface model with apparent resistivity value and thicknesses of each model layer, after each resistivity stratifications were interpreted to different geological and hydrogeological logs.

All information on geological, hydrological, and geophysical inventory gathered in the fields as well as from different sources would be used to produce a geoelectric map that deduces hydrogeological logs of the site. The most important outcome of the study is to locate and select the appropriate deep borehole drilling sites and water table. Finally, information's regarding on geological, hydrological, geophysical gathered from the field as well as from different sources could be used to produce the final report.

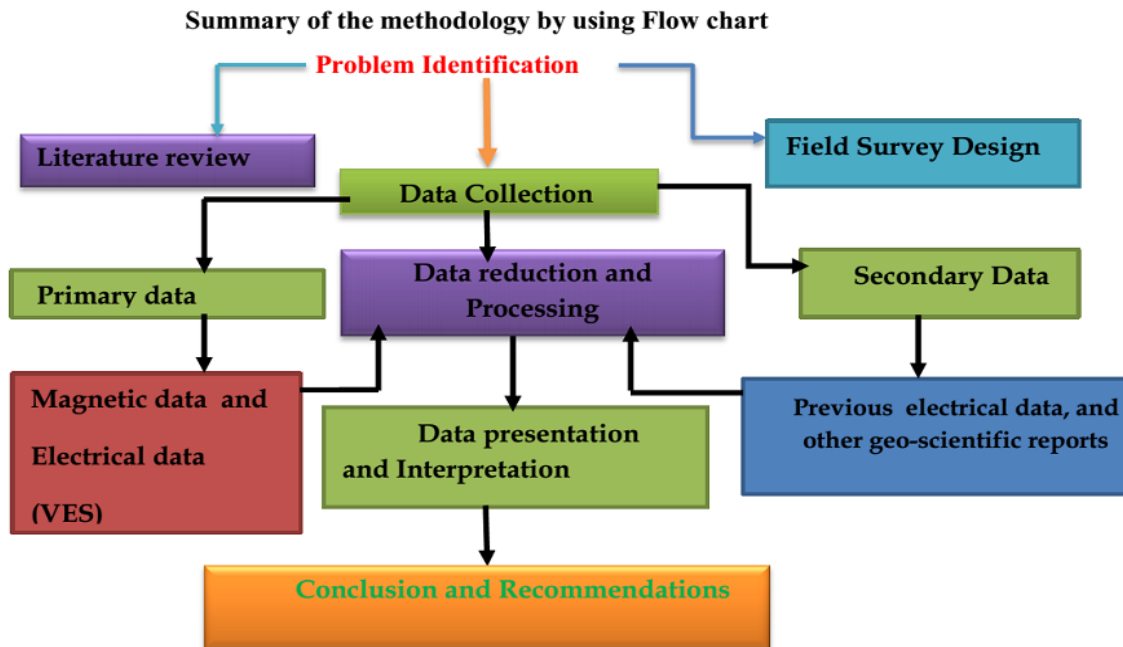


Figure 1.6 Flow Chart of the methodology used in the study.

## 1.7 Assumptions of the Research

In this research; geological and hydro-geological information is assumed as very limited. So integrated geophysical method systematically selected and affordable geophysical methods can help to understand the geological structures which control the potential, water table, and borehole site of groundwater. We expect that the geophysical surveys would demonstrate important information about the subsurface structures help to groundwater potential and water saturated horizons.

### 1.7.1 Basic research question

- ❖ What are the significant geologic structures that are important for groundwater flow, occurrence, and storage?
- ❖ How to map the saturated zone of the area?
- ❖ How to identify the groundwater table of the area?
- ❖ How to map the location of faults and fractures?
- ❖ Where to locate the drilling point?

## 1.7.2 Research hypothesis

Is there any relationship between the presence of geologic structures and the groundwater flow in the study area?

## 1.8 The significance of the study

The main significance of the output of the research is listed as follows:

- ❖ The university needs its own borehole so that this research work will be helpful for the sustainable source of water beside the Mechare well field.
- ❖ It can also serve as an initial model for other researchers, who may study the area in the future.
- ❖ It enhances the theoretical concepts of the different subjects taken academically. Hence, it will be an input to review and to see the applicability of the subject matters.
- ❖ It develops the researcher's ability to geophysical instrument and software.
- ❖ It gives a better understanding of the volcanic layers below the depth of 250 meters up to 1km depth.
- ❖ This study develops the understanding of the geological structure of the area.
- ❖ It contributes some data set for the ongoing study of exploration of groundwater in the country.
- ❖ This research work fills the existing gap of detail information and its usage in the geophysical methods in the country.
- ❖ Can solve the scarcity of water and a related problem in the University due to a shortage of water, like student disturbance and proper watering of campus plants.
- ❖ The study basically employs two geophysical methods (Electrical and Magnetic surveys) and other secondary information like Geological, hydrological, borehole and log data.
- ❖ The result of the research will be published and it will give a better recognition for the university to the scientific community.

## 1.9 Limitation of the research

Like any other research works, this study faced, a number of limitations. The main obstacles were:

- ❖ Lack of a geophysical instrument due to this the research involves by taking instrument rent from private only the use of commercially available instruments and software packages.
- ❖ Severe financial problem and necessary ingredients for the field like transport and geophysical instrument because it's far 521km from Addis Ababa.
- ❖ Shortage of software for analysis and interpretation of geophysical data. There were not any development of new instruments and software because the old software does not have all features of the software.
- ❖ Non-availability of previous geophysical work (specially Magnetic and gravity) on the area, and Lack of time-bound set for the thesis work coupled with field constraint (transport and instruments) and the field workplace were not conducive due to clashes between resident and soldiers.

## 1.10 The Expected output

This research work attempts to;

- ❖ Map locations of depth to groundwater table and to locate potential drilling sites for the extraction of groundwater in the study area.

## 1.11 Previous Study

Different Geological, Hydro-geological and Geo-morphological investigations were done around a wide area, some studies had been conducted in Northern Ethiopia (Bayessa, 2003, Asfaw et al., 2002), Geological and Geo-morphological investigation of the Eastern Amhara development corridor (AWDSE, 2002); and Hydro-geological investigations (MoWR, 1992) and, Water Supply and Sanitation study on Woldia town (Ms. Consultant, 2010) had been conducted. There are a number of the drilled boreholes on and around the study area based on the geophysical investigation. In order to evaluate the transmissivity of the prospective site resistivity logging was conducted in the existing borehole, but for interpretation of different geology and types of an aquifer six boreholes were used. In order to evaluate the transmissivity of the prospective site, resistivity logging was conducted in the existing boreholes.

**Table 1.5: Transmissivity, Hydraulic Conductivity bore holeific capacity of the borehole on and around the study area**

No.	Names of the Wells	Transmissivity (m <sup>2</sup> /day)		Hydraulic Conductivity (m/day)		Specific capacity(Q/sw) in [(l/s)/m]
		Constant Pumping Test	Recovery Test	Constant Pumping Test	Recovery Test	
1	NBH-1	32	29.2	0.639	0.583	52.6 m <sup>2</sup> /day
2	NBH-2	28.7	27.8	0.574	0.556	43.9 m <sup>2</sup> /day
3	NBH-3	52.5	60.7	1.05	1.21	43.2 m <sup>2</sup> /day
4	NBH-4	24.8	22.5	0.496	0.450	39.8 m <sup>2</sup> /day
5	WUNW	117	131	2.50	2.79	103 m <sup>2</sup> /day
6	WUOW	2.8	2.37	0.0595	0.050	3.3 m <sup>2</sup> /day

Sources: AWWDES

**Table 1.6: Borehole information on and around the study area**

No	BH ID	Specific Location	X	Y	Elevation(m)	Depth(m)	Yield(L/s)	Year of construction
1	NBH-1	Gonder Ber Tena Tabia	562880	1306438	1854	146	12.9	2011
2	NBH-2	Berberie Meda	562127	1306773	1839	140	12.9	2011
3	NBH-3	Burka	561491	1306601	1837	150	14.4	2011
4	NBH-4	Weyra Kebele	561961	1305844	1885	148	10	2011
5	BH-7	Weyra Kebele	561239	1304432	1883	121	14	2009
6	WUNB	weyra kebele	561469	1305360	1885	143	28	2012
7	WUOB	Mechare	563519	1305798	-	140	1.2	2011

Sources: AWWDES

Four main different formations have been identified in the borehole logs. The alluvial deposits cover the area up to 20m, the basalt that varies depending on the degree of weathered and fractured which continues to 200m. The third one is the trachyte that has a thickness of around 60m and the last one is the Tarmaber basalt which exists as fresh, weathered and fractured Earth material. The geologic logs of the study area indicate that the major forms of the aquifer are basaltic in composition, while the water quality analysis revealed that the water is generally fresh. The correlation was found to be difficult due to the lenticular nature of the units, rapid lateral changes within the units, and variable dips due to different centers of volcanic activity depositing materials in different places in various

periods. Since rocks of various ages are distributed in the study area aquifer characterization becomes a difficult and complex task (WWDSE, 2009).

### **1.12 Schemes of presentation**

This MSc thesis work is organized into Six (6) chapters. The first chapter deals with the introduction part (Including sub chapters titles: the Background, location of the study area, the statement of the problem, objective and significance of the study, the methodology employed, previous geophysical works, the limitations of the study and the structure of the study).

Chapter two discusses the geology, Hydrogeology, the regional geology of the study area summarized. The third chapter deals with the theoretical backgrounds of the geophysical methods applied in the present thesis works which are organized from various/different sources.

Chapter four discussed data acquisition, reduction, processing, and presentation. In this chapter, data acquiring, the type of geophysical instruments used, data processing and data presentation schemes have been discussed.

Chapter five is concerned about results, discussions, and interpretations. Here, where the different maps generated and research results are discussed and interpreted by using a different method of interpretation briefly.

Chapter Six is the last chapter of our work. In this chapter our work got conclusions. Recommendations regarding the results of the work are outlined /presented.

Finally, lists of references in an alphabetical order and in the Addis Ababa University /SINET thesis format are presented.

## CHAPTER TWO

### 2. GEOLOGY OF STUDY AREA

#### 2.1 Generals

Ethiopia is located in a geologically unique setting in the world where its geology is highly affected by faulting and tectonics. For example, the Precambrian geology exhibits two most important regional belts; Mozambique belt, and the Arabian Nubian shield, meeting in the central part of Ethiopia. Both belts are highly deformed and metamorphosed to various degrees till the late Proterozoic. After a long period of denudation, the Ethiopian landmass is subjected to deformation associated with the lithospheric extension of the East Africa. The Ethio-Afar rift segmented the country into three physiographic regions and the geology in this region and bordering plateaus are affected by several extensional faults and lineaments.

In Ethiopia, the huge volume of lavas about  $350,000 \text{ km}^3$ , which forms a pile up to 2,000 m thick, and covers more than  $600,000 \text{ km}^2$  (Mohr and Zanettin, 1988), was erupted 30 Ma years ago (Hofmann et al., 1997). The Ethiopian highlands were commonly mapped and characterized as a flood basalt province and dominated by the Tertiary volcanoes (Mohr, 1983). As a result of the tectonic process, the Ethiopia plateau (western highlands) as the whole is a great horst narrowing Northwards and gently dipping from eastern border (3000-4000m above masl) to western border (1000-1500m masl) (Marla et al, 1979). Traditionally, the Oligocene volcanism of the northwestern Ethiopian Plateau has been subdivided into three formations the Ashangi and Aiba basaltic units, separated by an angular unconformity and the upper ignimbritic Alaji unit and the younger Tarmaber basalt. This Chronostratigraphical subdivision, although only based on a few sections from the eastern and southern parts of the plateau, was assumed to be valid for the entire plateau (Merla et al., 1979).

## 2.1.1 Tertiary Volcanic Rocks

### A) Ashangi Basalt

The Ashangi basalt represents the earliest fissure flood basalt volcanism on the northwestern plateau and exposed in the northern Ethiopian plateau. The basalts are several hundreds of meters to kilometers thick of strongly weathered, crushed, tilted basalts, which lie below the major Pre-Oligocene unconformity (Zanettin and Justin-Visentin, 1974). This group consists predominantly of alkaline basalts with inter-bedded pyroclastics and rare rhyolites erupted from Fissures. They are injected by dolerite sills, acidic dykes, and Gabbro diabase intrusions. The flow ranges in total thickness from 200 to 1200m. The thickest exposed section occurs close to the rift escarpment suggesting that the main source was associated with the rift faults (Kazmin, 1975).

The upper part of Ashangi group is more tuffaceous and contains intravolcanic lacustrine deposits, including diatemitic, cherts, lignite seams and acidic volcanic and locally overlies the older part of the group with angular unconformity (Kazmin, 1975). The outcrops of Ashangi basalts are restricted to the north-central part of the Ethiopian plateau (Zanettin and Justin-Visentin, 1975).

### B) Aiba Basalt

Aiba basalts are flood basalts with rare tuffs. The flows are always evident with columnar jointing. The Aiba basalts pinch out southward and westward (Merla et al., 1979). The Aiba basalts were separated on the Ethiopian plateau as the units comprising the second major volcanic cycle. The basalts of this formation were produced by fissural eruptions and attain an aggregate thickness of 200 to 600m. They are generally aphyritic compact rock, in places showing clear stratification. As it is cited in Holfmann, the age Aiba basalt could be 30My, placing the Oligocene (Zanettin and Justin-Visentin, 1973 cited in Kazmin, 1979).

### C) Tarmaber Basalt

The Tarmaber basalts occupy a large area in the more elevated area of the northern Ethiopian plateau (northern highlands) and escarpment (Kazmin, 1979). On Ethiopian plateau, the shield volcano of the Tarmaber formation becomes progressively younger from north to south. Central type volcanism started in the north about 26 My in the lower Miocene (Tarmaber Guassa). In the southern part of

the plateau the shield volcanoes were formed from 16 to 13 my in middle- Miocene (Tarmaber Meghezez) (Zanettin et al. 1974).

Tarmaber basalt represents Oligocene to Miocene basaltic shield volcanism on the north-western and south-eastern plateau with a central type of eruption (Kazmin, 1979).

#### **D) Alaji Formation**

Towards the upper limit of the Aiba basalt, the Alaji formation is defined by the conformable first silicic (rhyolitic/ trachytic) ignimbrite horizon (Kazmin, 1979).

According to Zanettin and Justin-Visentin, (1973), and Kazmin (1979), the acidic rocks (interbedded with greater or lesser amounts of stratiform basalts) of east-central Ethiopian plateau form a large and continuous cover extending from Amba Alaji to Debre Berhan and Mugher areas. These acidic rocks lie on the "Aiba Flood basalts" and are overlain by the "Tarmaber basalts" which are the products of a central type volcanism.

### **2.2 Regional Structure**

The works done by different authors (e.g., Hofmann et al., 1997; Watchorn et al., 1998; D'Acremont et al., 2005) estimated that continental breakup in the Gulf of Aden commenced at ~35 Ma, just prior to the massive outpouring of the Ethiopian flood basalts at the Sheba ridge, Indian ocean (Hagos, 2011) and gradually propagate towards west.

The eruption of the Ethiopian traps at about 30 Ma marked the incipient breakup of Arabia from the African plate. The Afro-Arabian Rift system comprises the Red Sea Rift, the Gulf of Aden Rift, and the East African Rift, the northernmost part of which is the Ethiopian Rift. The simultaneous interactions between these rifts resulted in the separation of the Danakil and Ali Sabieh blocks and their respective counterclockwise and clockwise rotations leading towards the opening of the triangular Afar depression (Audin et al., 2004).

When it arrived at the Shukra-El Sheik discontinuity 20Ma ago, it stalled for some 13 Ma. During this time interval, several extensional basins had developed prior to the break up within the plate margins of Arabia and Somalia plates. Such is the case for example along the northeast margin of the Gulf of Aden, east of the Alula Fartaq Fracture Zone (AFFZ). After the Gulf of Aden rift managed to cross the SES discontinuity, it continued propagating further westwards between 5 and 2 Ma to the entrance of the present-day Gulf of Tadjoura and then to Asal rift at about 1Ma. Hence direction of propagation of the Gulf of Aden changed from W to WSW to NE direction during its evolution. Since

about 1Ma, the Aden rift has localized along the western edge of the Danakil block, where it has been propagating northwards in a series of discontinuous jumps (Kazmin, 1979). On the other hand, continental rifting in the Red Sea region commenced at ~28Ma, shortly after the peak trap volcanism (Hagos, 2011, and reference therein). During this evolution many extensional basins developed prior to Arabia – Africa break-up in the southern Red Sea from late Oligocene 30 Ma. Northeast oriented oceanic spreading in the south central Red Sea rift, at 14°N, initiated at ~4Ma (Wolfenden et al., 2005).

However, continental rifting has continued along its southern extensions along the Afar and propagated southeastward so that its overall trend is NW-SE. In the Afar depression, the NNW-SSE aligned volcanic edifices of Erta’Ale, Tat’Ale, Alayta, and volcanic rift of Manda-Hararo Gobba’ad rift mark the axis of the western branch of the Red Sea.

Relative motions of Africa and Somalia led to the development of the Main Ethiopian Rift (MER). Several researchers agree that extension commenced 18Ma in the southern MER, but that most of the present rift morphology developed after 12 Ma. The age of the first stage basins in the northern MER is considered to be 11 Ma whereas the basins in the Southern Red Sea are 15Ma older than those in the northern MER (Wolfenden, 2004).

### **2.3 Geological, Structural, and Geomorphological Investigation of North Ethiopia**

The geological, structural, and geomorphological study and mapping in eastern Amhara development corridor (Kobo-Robit-Minjar) had conducted by Amhara Water Design and Supervision Enterprise (2002 E.C). The major objective of the research was to conduct groundwater potential assessment of Awash Basin. To accomplish the work different methodologies like geological, geomorphological, and structural investigation have been used. Accordingly, the different lithological units identified in the project area were Mesozoic sandstones, Oligocene volcanic, Miocene volcanic, Pliocene volcanic, and Quaternary volcanic and sediments represented all spectrums of major rock types of the Ethiopian stratigraphy. Geological cross-sections have also been made across pre-determined profile sections to show the lateral continuity of the lithologic units and also the approximate thickness of units along the profile section.

## 2.4 Regional Hydro-geological Investigation of North Ethiopia

The stratigraphy of Northern Ethiopia has been described. Accordingly, the rocks that were identified were Precambrian, phanerozoic intrusive, Mesozoic sedimentary rocks, Tertiary volcanic rocks, Quaternary volcanic and sediments (Bayessa Asfaw.etal.,2002). Accordingly, the Ashangi formation, Sandstone, Tertiary volcanic and sediments were identified as regional aquifers. The productivity of these hydro-stratigraphic units was also classified in this study as high, moderate to high, moderate, low, and very low depending on different factors like hydraulic properties, topographic variation, and recharge conditions.

## 2.5 Geology of the Study Area

### 2.5.1 Generals

The study area is dominated by volcanic rocks (basalt and agglomerates). It forms part of the geological succession of northern and north-central Ethiopia and belongs to Tertiary age. Stratigraphically, the area is composed of volcanic rocks overlain by recent sediments. Volcanic rocks occupy the highest levels in the topography and are found exposed in the northeast, northwest, southwest, and southeast parts of the study area having colluvial deposits that have limited area coverage near the base. Besides to these formations, there are also none mappable lithologic units like thin paleo soil which is reddish in color and highly compacted found at the contact between different lava flows and at the contact between the different degree of weathering and fracturing of basaltic rocks (Figure 2.1).

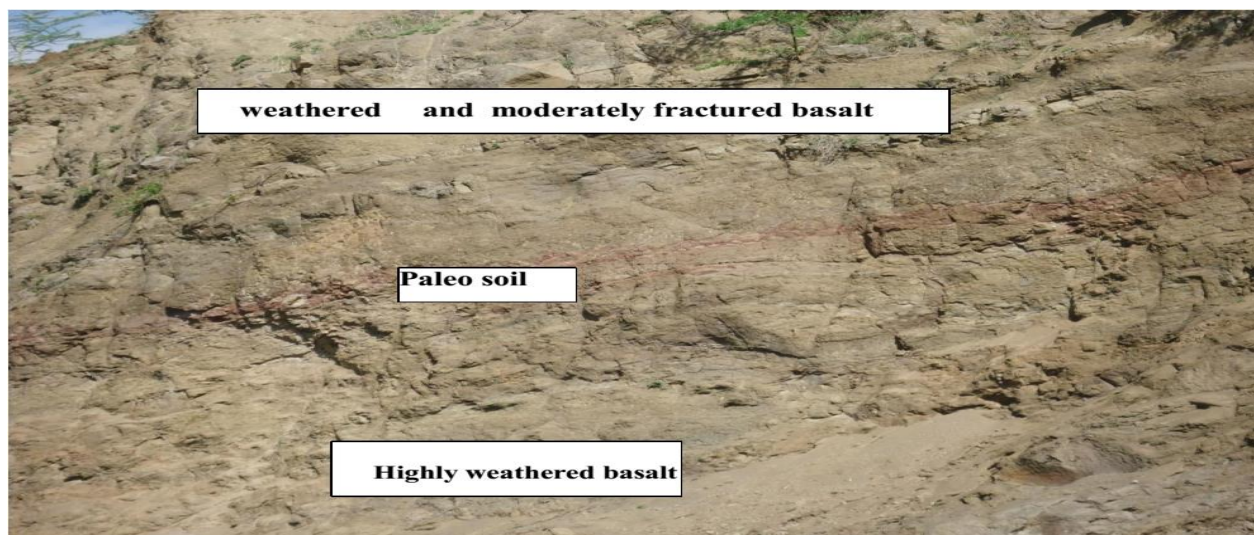


Figure 2.1 Paleosoil between highly weathered basalt and highly weathered and moderately fractured basalt.

## 2.5.2 Volcanic Unit

Agglomerate basalt, highly weathered and fractured basalt, and fresh to slightly fractured aphanitic basalt is the volcanic rocks that found in the study area. These rocks are found outcropped in the northeast, northwest, southwest, and fractured basalt are the dominant found outcropped in the above-mentioned areas. Agglomerate is found occupying small area overlaying the aphanitic basalt in the southeastern parts of the study area (Figure 2.2).

The aphanitic basalt, which is black southeast parts of the study area, among these volcanic rocks, the aphanitic basalt and the highly weathered in color and found underlying all the other units, is generally massive to slightly fracture. Wherever it is found fractured, the dominant orientations of the fractures are N-S and NNE-SSW. The exposed thickness of the aphanitic basalt ranges from 2-6m (Figure 2.5). The highly weathered and fractured basalt is the one that is found having a significantly exposed thickness in the study area. It is found overlying the aphanitic basalt and underlying the alluvium having an exposed thickness ranging from 2-20m (Figure: 2.1, 2.3, & 2.4).



Figure 2.2 Agglomeratic basalt

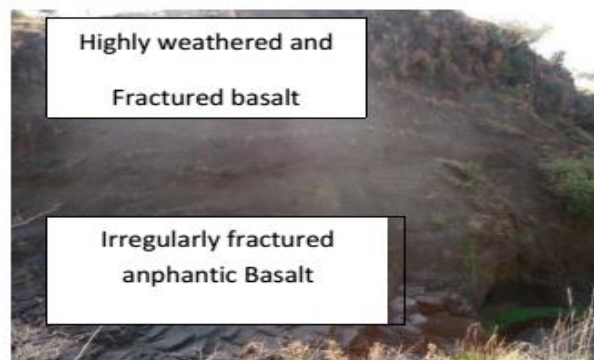


Figure. 2.3 Highly weathered and fractured basalt underlying by irregularly fractured black aphanitic basalt.

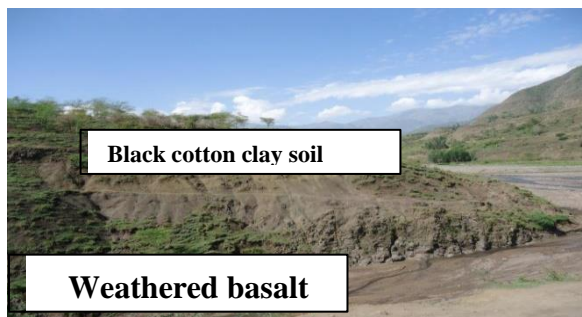


Figure 2.4 Weathered basalt overlaid overlay on blackcotton clay soil.

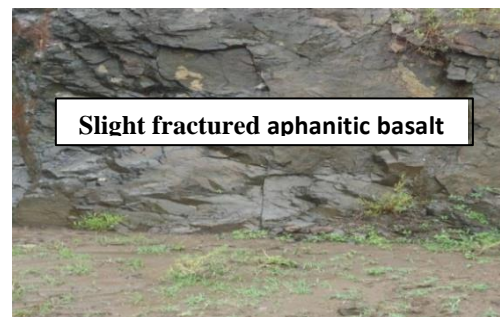


Figure 2.5 Slightly fractured aphanitic basalt exposed genetober area.

### 2.5.3 Alluvial Deposit

The alluvial is found overlying the volcanic rocks occupying the flat to flat to gentle slope area in the central, north, western south and east part of the catchment. In the catchment, alluviums are also found as the thin strip along the margin of the major rivers and their respective tributaries.

It comprises clay, silt, sand, and gravel size particles in different proportions, and has a thickness ranging from 0.5 to more than 0.8m. Though they occur in these areas of the catchment their relative abundance, however, is not uniform throughout the catchment. Towards the mountain front northeastern, northwestern and southeastern part of the study area. Where steep topographic slope exists and the gradient between the rivers are high, the alluvial sediments are thin and dominated by sub-angular to surrounded coarse-grained particles with the variable content of coarse-grained sand. In the central, northern, southern, eastern and western parts of the watershed, where the gradient of the rivers decrease downslope, the alluvial deposit is thick and consist of medium to fine-grained sand with the variable content of silt and clay( Fig 2.6 A&B ).



Figure 2.6 A. Black cotton soil at lower area.



B. Alluvial deposit at river bad exposure.

### 2.6 Local Structure

Fractures that have orientations NE-SW and NW-SE are the major geological structures found in the catchment (Figure 2.7). The space between the fractures that have an orientation NE-SW is ranging from 40 cm to 1m and the aperture is ranging from 1cm to 10cm. The space between the fractures that have an orientation NW-SE is ranging from 0.3cm to 0.5cm and the aperture is ranging from 0.1cm to less than 8cm. As it was observed in the field, with the exception in the few localities where the fractures are filled with secondary calcite, clay and rock fragments, the fractures are open and free of any precipitated secondary materials.

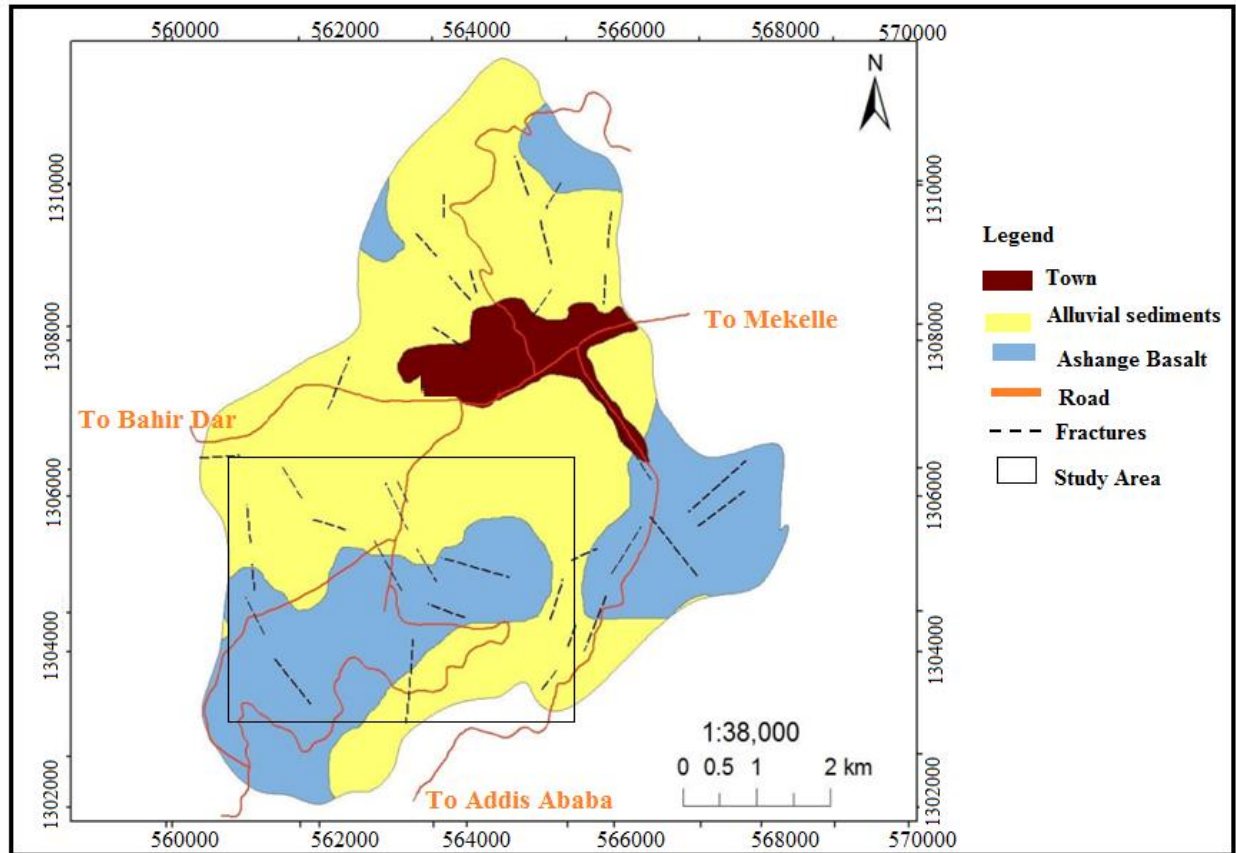


Figure 2.7 Geological map of the study area.

The geological formations found in the area surrounding Woldia town is mainly mountain forming volcanic rocks which are the part of western escarpment of main Ethiopian Rift Valley. As different studies reveal, this volcanic rock unit composes Ashange basalt at the valley bottom overlaying the upper sandstone unit and the Alage rhyolites which consist basalt, ignimbrite, rhyolites, and trachites of graben structures in areas where dissected by rift system which aligned S-N direction. The graben area is filled with alluvial materials which compose from clay to boulder size sediments forming different layers and thick up to 120m as observed from the drilling logs of the boreholes. As observed from drilling samples, coarser materials are layered in depth and fine materials at the top part. There are different structures that are formed as result of post magmatism tectonic activities acted on the basaltic rock of the area. These structures, most of them, are aligned south to North for those that are found to the west of the town, and west to East for those that are found to the East and South of the town (Metaferia consulting plc, 2011).

## **2.7 Water Resource of Woldia Area**

The Water Resource of Woldia Area was conducted by Ms. Consultant in 2010. The objective of the study was to produce feasibility study with specifications for water supply and Sanitation facilities for the projected demand of the town. To achieve these objectives both the surface water and groundwater resources of the area were examined.

### **2.7.1 Surface Water Source of Woldia Area**

Gatira river basin that drains the town and most of the rivers in the surrounding areas are intermittent. Tikure Wuha River that drains part of the western highlands of South Wello is about 3.2km west of Woldia. It is perennial and forms very wide river bed. The springs that emerge along Gatira river basin are small and most of them are intermittent (Ms. Consultant, 2010).

### **2.7.2 Groundwater Source of Woldia Area**

#### **2.7.2.1 General Geology and Geomorphology of Woldia Area**

Woldia town is located in entering mountain valley and on the western escarpment of the Afar Rift Valley. It is surrounded with high ridges on the northern and eastern sides. Mechare Meda, which is open, relatively flat and gently sloping, is on the western and southwestern side of the town. Gatira river valley and its tributaries have cut the town and created rugged terrain. Ashenge Formation, which is Eocene volcanic rock and which consists of alkaline and transitional basalt, covers Woldia and the surrounding areas. This old volcanic rock is weathered and cut by series of north-north-west and north-east trending fault and fracture lines. One of these fault lines is running parallel to Dessie - Woldia road and passes through the center of the town and other major fault lines also run parallel to Tikure Wuha valley (Ms. Consultant, 2010).

These two fault structures and other high grounds on the South and North of the town are forming a type of intering mountain valley, where thick sediments transported from the surrounding high grounds are deposited. Mechare Meda, which was ones an inter mountain valley, is filled with Quaternary alluvial deposit. Geological logs of water wells drilled in Mechare Meda and geophysical survey results show that the thickness of the alluvial deposit could reach over 80 m in some areas (Ms. Consultant, 2010).

### 2.7.3 Hydrogeology of Woldia Area

Prospect of developing exploitable groundwater source in the study area is highly dependent on the hydrogeological characteristics of the lithologic units of the surrounding areas and the possibility of ground-water recharge. The Ashenge Formation beds, volcanic rocks that form the major lithologic units of the region, do not have primary porosities that allow groundwater movement and storage. Groundwater movement and storage takes place along fracture, fault, and cooling joints of the volcanic rocks. The fractures and fault lines of the region are tensile in nature and they may form openings that allow groundwater movement and storage. There are perennial springs and seepages that emerge along the big fault line that runs parallel to Dessie-Woldia road. This may indicate that there is groundwater movement along fracture openings in the region (Ms. Consultant, 2010). The alluvial deposit that filled the enter mountain valley is thick and composed of sand, gravel silt and clay materials. The coarse-grained sediments form good water-bearing media. Geological logs of water wells drilled and geophysical surveys carried out in Mechare Meda show that the alluvial deposit could be over 80 m in some areas (Ms. Consultant, 2010). Four water wells were drilled at the edge and in Mechare Meda for Woldia Town's water supply scheme and others were also drilled in the town for different organizations (Ms. Consultant, 2010). The alluvial deposit is the main aquifer of the wells drilled in and around Mechare Meda. Transmissivity values calculated from pumping tests of the wells are varying from 10 to 312 m<sup>2</sup>/d (Ms. Consultant, 2010). Other factors such as faulty construction and development of the well may have effects on the calculated transmissivity values and yield of the well. Water wells that are drilled out of Mechare Meda have struck water-bearing zones in the weathered and fractured basalt rock beds. Their yields are relatively small compared to the wells drilled in the alluvial deposit (Ms. Consultant, 2010).

### 2.8 Groundwater Movement and Recharge around Woldia Area

Groundwater recharge, storage, and movement take place along the open zones of the volcanic rock beds and the primary porosity of the alluvial deposits. The water for the groundwater recharge of the alluvial deposit in Mechare Meda comes from seasonal runoff of Gatira valley and its tributaries and other dry river beds. Groundwater that moves through the fault and fracture openings of the basalt may also convey water that recharges the alluvial fill (Ms. Consultant, 2010). Groundwater basins in the region do not necessarily coincide with surface water basins. It is impossible to define the groundwater basin of the region and estimate the recharge at this stage. Regional groundwater studies need to be

carried out to define the groundwater basins and estimate the groundwater recharge and discharge (Ms. Consultant, 2010).

## **2.9 New Water Supply Source**

There is no sustainable and adequate surface water source around Woldia town that shall meet the demand of the town and be considered for the town's water supply scheme. It is more feasible to develop groundwater in the surroundings of the town for the future water supply scheme sources (Ms. Consultant, 2010). A detailed study is carried out in Mechare Meda, which is located just south and southwest of the town, to get more information on the hydrogeology of the lithologic units and identify a well field for the town's water supply scheme.

## **2.10 Recharge and Discharge Zone**

According to Freeze and Cherry (1979). A recharge zone can be defined as that portion of the drainage basin in which the net saturated flow of groundwater is directed away from the surface and the water table is usually lies at some depth whereas discharge zone can be defined as the movement of the net saturated flow of groundwater is directed towards the surface and the water table usually lies at or very close to the surface. Identifying the recharge and discharge area of a certain catchment is important for identifying potential sites and for water resource management and utilization. Recharge areas are mostly located at the higher topography given catchment. In the study area, recharge areas are negligible groundwater potential zone. The study area mapped as aquifer with low groundwater potentiality and aquifers with weak to negligible potentiality is the recharge area of the basin. The lowland of the study area gets recharged not only from precipitation, but also groundwater flow from upstream, left and right side of the catchment due to the presence of different structures like the fracture. Discharge areas are mostly located at lower topography in a given basin. Discharge areas in the study area are low lands of Mechare well field. The discharge area covers relatively smaller area than recharge area, which makes the Mechare well field to have moderate to low groundwater productivity.

## CHAPTER THREE

### 3 THEORETICAL BACKGROUNDS OF THE METHODS OF INVESTIGATION

#### 3.1 Background

Both solid earth and applied geophysics are the scientific methods that use the science of physics with the high advancement of technological development employed to observe the hidden subsurface of the Earth. In applied geophysics, geophysical methods are developed to explore or delineate the subsurface structure and to explore underground treasures. At the time, geophysicists were equipped with geophysical instruments which are advanced to exploring up to several kilometers deep into the interior part of the Earth. Geophysics is not only applied to the subsurface studies but is also investigating the ocean and land surface of the Earth, which gives rise to the environmental application of geophysics.

Geophysical methods for Groundwater investigations include mapping the depth of water table and the thickness of aquifers, mapping confining units, locating preferential fluid migration paths such as weak zones, fractures and fault zones, and mapping about groundwater contamination. When geophysical investigations of the interior part of the Earth involve taking measurements at or near the Earth's surface that are influenced by the internal distribution of physical properties. Analysis of the geophysical data reveals the distributions of physical properties at depths that reflect the subsurface geology. Depending on the source of signals, geophysical methods classified into two major groups: those that make use of natural fields of the Earth (passive methods), and those that require artificially generated energy as source signals (active methods). The passive methods utilize the Earth's natural fields which include; the magnetic, gravitational, electrical and electromagnetic fields. The active geophysical methods, on the other hand, involve detection of responses for artificially generated means local source fields and waves such as: electrical, electromagnetic, and seismic. In general, the aim of geophysical prospecting is searching for local perturbations in the naturally occurring or artificial fields caused by concealing geological features.

### 3.2 Electrical resistivity method

#### 3.2.1 General

The Electrical resistivity survey methods despite developed in the early 1970's and become popular from the mid-1990's, due to the primary availability of computers to run and analyzes raw data (Reynolds, 1997). And also have different applications, such as in the study of horizontal and vertical discontinuities in the electrical properties of the ground (Kearey et al., 2002), the search for geothermal reservoirs (Telford et al., 1990; Mussette and Khan, 2000); archaeological surveying (Reynolds, 1997; Mussette and Khan, 2000) and in downhole logging (Reynolds, 1997).

#### 3.2.2 Fundamental principles

The basis of the resistivity survey is that, when current is applied by conduction into the ground through a pair of electrodes, any subsurface variation in conductivity alters the current flow within the Earth, this, in turn, affects the distribution of electric potentials (Everett, 2013). The degree, to which the potential is affected at the surface, depends upon the position, shape, size, and conductivity of the materials at a certain depth. It is, therefore, possible to get information about the subsurface distribution of the constituents of measurements of the electric potential made at the surface.

Ohm's law is the fundamental physical law that governs the flow of current in the ground. It stated us, if a direct current flow through a circuit element, then the ratio of the potential drop across the element to the current flowing through it is constant.

Mathematically, it expressed as:

$$R = \frac{\Delta V}{I} \dots\dots\dots (3.1)$$

Where;

I = Current in Amperes (A)

$\Delta V$  = A potential drop in volts (V)

R = Resistance in Ohms ( $\Omega$ )

Since resistance is directly proportional to the length [L] in meters (m) of the conductor and inversely proportional to the cross-sectional area [A] in square meters ( $m^2$ ):

$$R = \rho \frac{L}{A} \dots\dots\dots (3.2)$$

By considering the continuous flow of current in voluminous media, the flow of current is based on the principle of conservation of charge, i.e.

$$(I_c)_s = -\frac{dQ}{dt} \dots\dots\dots (3.3)$$

$$I_c = \oint \vec{J} \cdot d\vec{s} \dots\dots\dots (3.4)$$

And

$$Q = \int_V q \cdot dv \dots\dots\dots (3.5)$$

Where:  $V$  is the volume bounded by the surfaces. Using equations (3.4) and (3.5) in equation (3.3)

$$\oint_S \vec{J} \cdot d\vec{s} = -\frac{d}{dt} \int_V q \cdot dv \dots\dots\dots (3.6)$$

By applying the divergence theorem on the left-hand side of the equation (3.6) we get:

$$\oint_S \vec{J} \cdot d\vec{s} = \int_V (\nabla \cdot \vec{J}) dv = \dots\dots\dots (3.7)$$

By interchanging the differentiation and integration sequence on the left-hand side of the equation (3.7)

$$\int_V (\nabla \cdot \vec{J}) dv = -\int_V \left(\frac{\partial q}{\partial t}\right) dv \text{ or } \int_V \left(\nabla \cdot \vec{J} + \frac{\partial q}{\partial t}\right) dv = 0 \dots\dots\dots (3.8)$$

Since equation (3.8) must be valid for any volume, it follows

$$\nabla \cdot \vec{J} + \frac{\partial q}{\partial t} = 0 \dots\dots\dots (3.9)$$

Equation (3.9) is the law of conservation of charge in differential form, also known as the CONTINUITY EQUATION.

For stationary value (i.e. Direct current)  $\frac{dq}{dt} = 0$ , then the equation (3.9) reduces to

$$\nabla \cdot \vec{J} = 0 \dots\dots\dots (3.10)$$

Since the stationary field is conservative,  $\mathbf{E}$  (the electric field) may be related to the scalar vector function  $\mathbf{V}$  as

$$\vec{\mathbf{E}} = -\nabla V \dots\dots\dots (3.11)$$

Where  $\mathbf{V}$ -measured in Volts ( $\mathbf{V}$ )

The relation between the current density and the electric field intensity is given by Ohm's law as

$$\vec{\mathbf{J}} = -\sigma \vec{\mathbf{E}} \dots\dots\dots (3.12)$$

**Where:** ( $\sigma$  - is a second rank tensor in anisotropic media, but it is a scalar in isotropic media,

- has a unit ‘mhos’ and is the reciprocal of resistivity; ohm/m.

Using equation (3.12), the current density becomes

$$\begin{aligned} \vec{J} &= \sigma \vec{E} = -\frac{1}{\rho} \vec{E} \\ &= -\frac{1}{\rho} (-gradV) = \frac{1}{\rho} gradV \dots\dots\dots (3.13) \end{aligned}$$

For isotropic media,  $\rho$  is a scalar function of the point of observation and  $\vec{J}$  is in the same direction as  $\vec{E}$ . In this case, from equations (3.10) and (3.13)

$$div \left( \frac{1}{\rho} gradV \right) = \dots\dots\dots (3.14)$$

$$div \frac{1}{\rho} gradV + \frac{1}{\rho} div. gradV = 0 \dots\dots\dots (3.15)$$

Equation (3.15) is called *the fundamental equation of electrical prospecting* with direct current. If the medium is homogeneous, (is independent of the coordinate axes and equation (3.13) reduces to:

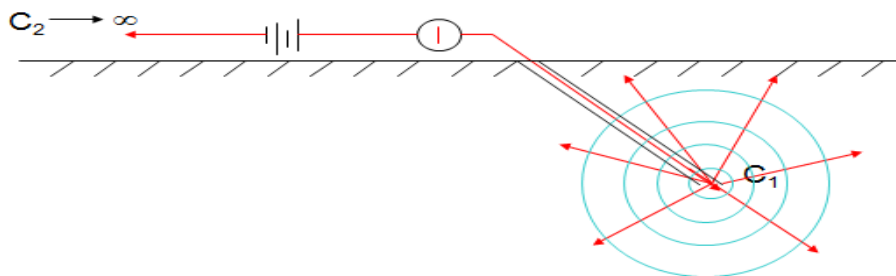
$$div.gradV = 0$$

Or

$$\nabla^2 V = 0 \dots\dots\dots (3.16)$$

### 3.2.3 Potential due to a point source of current

Let an electrode of small dimensions be buried in a homogeneous isotropic medium. The current circuit is completed through another electrode, usually placed on the surface, but in any case far enough that its influence is negligible



**Figure 3.1 Potential due to a point source of current.**

From the symmetry of the problem, the potential will be a function of ‘r’ only, where ‘r’ is the distance from the ground to the first electrode, under this condition, Laplace equation in spherical coordinates will be most appropriate and written as:

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial V}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 V}{\partial \phi^2} = 0 \dots\dots\dots (3.17)$$

Which is reduces to:

$$\nabla^2 V = \frac{d^2 V}{dr^2} + \frac{2}{r} \frac{dV}{dr} = 0 \dots\dots\dots (3.18)$$

By multiplying throughout  $r^2$ , It becomes

$$r^2 \frac{d^2 V}{dr^2} + 2r \frac{dV}{dr} = 0 \dots\dots\dots (3.19)$$

Integrating both sides of this equation, it gives

$$\frac{dV}{dr} = \frac{A}{r} \dots\dots\dots (3.20)$$

Integrating again

$$V = -\frac{A}{r} + B \dots\dots\dots (3.21)$$

Where **A** and **B** are integration constants.

**Boundary Conditions**

1. Since  $V = 0$  as  $r \rightarrow \infty$   
 $B = 0$
2. The current flows radially outwards in all directions from the point electrode.

Thus, the total current crossing a spherical surface of radius ‘r’ is given by

$$\begin{aligned} I &= 4\pi r^2 J \\ J &= \sigma E, E = -dV/dr, \rho = 1/\sigma \\ &= -4\pi r^2 \sigma \frac{dV}{dr} \dots\dots\dots (3.22) \end{aligned}$$

From equations (3.21) and (3.22)

$$I = -4\pi \sigma A$$

Or

$$A = -\frac{I\rho}{4\pi} \dots\dots\dots (3.23)$$

Where  $\rho$  is the resistivity. Hence; the potential **V**

$$V = \frac{I\rho}{4\pi} \left( \frac{1}{r} \right) \text{ or } \rho = 4\pi r \left( \frac{V}{I} \right) \dots\dots\dots (3.24)$$

The equipotential which is everywhere orthogonal to the current lines will be spherical surfaces given by  $V = \text{constant}$ .

### 3.2.7 Potential due to a point source on the ground

Consider the case where the point source, delivering  $I$  amperes of current, is located on the surface of homogeneous, isotropic Earth, and the air above has zero conductivity, This corresponds to a single probe or three electrode system used in some surface resistivity measurement layouts, Again the return current electrode is at a far-off distance

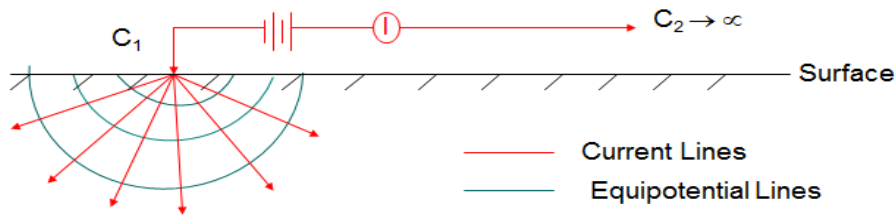


Figure 3.2 potential due to a point source on the ground.

The boundary conditions are somewhat different from the preceding case, although  $B = 0$  as before ( $V \rightarrow 0$  as  $r \rightarrow \infty$ ).

In addition

$$\frac{dV}{dz} = 0 \text{ at } Z = 0$$

(Since  $\sigma_{\text{air}} = 0$  which causes  $\frac{dv}{dz} = -E = \frac{I}{\sigma} = -\rho J$ )

From equation (3.21)

$$V = -\frac{A}{r} + B, \quad B=0$$

$$\frac{dV}{dz} = \frac{\partial}{\partial z} \left( -\frac{A}{r} \right) = -\frac{\partial}{\partial r} \left( \frac{A}{r} \right) \cdot \frac{\partial r}{\partial z}$$

$$= \frac{Az}{r^3}$$

Which is 0 at  $z = 0$ ; so the condition  $\frac{\partial v}{\partial z} = 0$  at  $Z = 0$  is already satisfied.

Further, the third boundary condition is that all the current now flows through a hemispherical surface in the lower half, so that

$$I = 2\pi r^2 J = -2\pi \sigma A$$

Or

$$J = -\sigma E = -\sigma \frac{dV}{dr} ; \frac{dv}{dr} = \frac{A}{r^2}$$

$$A = -\frac{I\rho}{2\pi} \dots \dots \dots A \dots \dots \dots (3.25)$$

So that in this case,

$$V = \frac{I\rho}{2\pi r} \quad \text{Or} \quad \rho = 2\pi r \left(\frac{V}{I}\right) \dots \dots \dots (3.26)$$

**3.2.8 Potential difference when there are two electrodes at the surface**

The arrangement of current and potential electrodes and the distances between are as shown in the following figure:

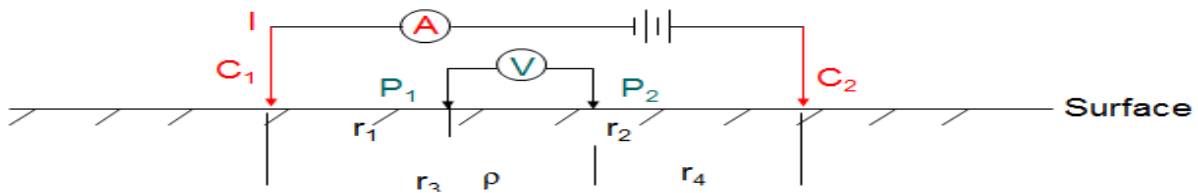


Figure 3.3 Arrangement of potential and current electrode in four electrode system.

The potential at P<sub>1</sub>,  $V_{P_1} = \frac{I\rho}{2\pi} \left[ \frac{1}{r_1} - \frac{1}{r_2} \right]$

Similarly the potential at P<sub>2</sub>,  $V_{P_2} = \frac{I\rho}{2\pi} \left[ \frac{1}{r_3} - \frac{1}{r_4} \right]$

The potential difference

$$\Delta V = V_{P_1} - V_{P_2} = \frac{I\rho}{2\pi} \left[ \frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4} \right] \dots \dots \dots (3.27)$$

After arranging the distances between the current and potential electrodes according to the well-known configurations one can determine the resistivity of the (homogeneous) ground.

**3.3 Electrode configurations and field procedures in electrical resistivity survey**

**3.3.1 General**

According to Everett (2013) at each survey station, the transmitted current and the measured potential difference across the receiver dipole along with the location of the four electrodes are measured, from which an apparent resistivity ( $\rho_a$ ), which is an intuitive indicator of the actual underlying electrical resistivity structure of the earth is calculated.

The resistivity determined through this procedure doesn't represent the true resistivity of the subsurface layers because it is highly dependent on the geometric factor, and thus on the electrode configurations and spacing employed. The apparent resistivity value is equivalent to the true resistivity value, only when the medium is homogenous, which in the real world, it is very difficult to exist (Telford et al., 1990).

**3.3.2 Electrode arrangements /Configurations in Resistivity Survey**

In spite of the availability of various electrode configurations in electrical resistivity survey (e.g. Telford et al., 1990; Kearley et al., 2002), three of the configurations (Wenner, Schlumberger, and the Dipole-Dipole arrays) are the most commonly used. Again, these survey configurations are particularly routinely applied in the search for productive aquifers in hydro-geological and geothermal investigations. The two potential and two current electrodes can be disposed over the ground in various ways and this disposition of the four electrodes gives rise to what is known as the Electrode ARRAYS, CONFIGURATIONS, LAYOUTS, or ARRANGEMENTS.

For two current and two potential electrode layouts, the potential difference is given by:

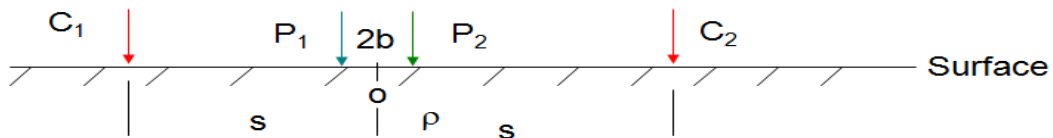
$$\nabla V = V_{P1} - V_{P2} = \frac{I\rho}{2\pi} \left[ \frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4} \right] \dots\dots\dots (3.28)$$

By using this relation expression for the apparent resistivity of the various configurations can be expressed as follows:

**A) Schlumberger Array**

The potential electrodes are moved only occasionally, and a current electrode is systematically moved outwards in steps  $AB \geq 5 MN$ .

In this system, the electrodes are symmetrically placed about a point at the center of the array



**Figure 3.4 Schlumberger array configurations.**

- Here  $r_1 = s - b$ ;  $r_2 = s + b$ ;  $r_3 = s + b$ ;  $r_4 = s - b$  and therefore from (3.28)

$$\nabla V = \frac{I\rho}{2\pi} \left[ \left( \frac{1}{s-b} - \frac{1}{s+b} \right) - \left( \frac{1}{s+b} - \frac{1}{s-b} \right) \right]$$

$$\nabla V = \frac{I\rho}{2\pi} \left( \frac{2b}{s^2-b^2} \right) \dots\dots\dots (3.29)$$

$$\rho_{as} = \pi \left( \frac{S^2 - b^2}{2b} \right) \left( \frac{\nabla V}{I} \right) \dots \dots \dots (3.30)$$

**Where:** The geometrical factor, in this case, is  $\pi \left( \frac{S^2 - b^2}{2b} \right)$

The ratio  $\frac{\nabla V}{2b}$  is the *potential gradient* or the *intensity* of electric field. Both Wenner and Schlumberger arrangements are called symmetrical arrays.

### 3.4 Field procedures in resistivity survey

#### 3.4.1 General

Resistivity survey, irrespective of the array configurations employed, make use of two types of survey procedures, depending upon the objective of the intended investigation, i.e. Whether the survey objective is to identify vertical electrical variation in resistivity with depth or identify lateral resistivity variations along a profile.

Accordingly, when the vertical resistivity variation is to be mapped, a survey procedure called, Vertical Electrical Sounding, commonly abbreviated as VES. However, Resistivity profiling is used when the survey objective is to identify the lateral variation in resistivity associated/related to with lateral variations in geology and structures. The Summary of these two types of resistivity survey procedures is presented as follows:

**Resistivity Sounding;** also called Electrical Drilling or Vertical Electrical Sounding (VES) is a resistivity procedure in which the vertical variation of resistivity of the subsurface is mapped. Vertical Electric Sounding (VES) is a straightforward electrical resistivity method usually conducted using one of two electrode arrays: Schlumberger or Wenner array(s).

A Vertical electrical sounding or (VES) is a 1D resistivity method that provides deep information of the subsurface with minimal equipment and personnel. It is one of the oldest methods for acquiring resistivity and one of the least expensive to conduct per unit depth. The VES method can be quite versatile for reconnaissance surveying or when there are equipment limitations. The data from vertical electrical sounding are more sensitive to general electrical structure than another 1D electromagnetic method, such as TDEM, because high resistivity contrasts are better resolved with VES. According to Telford et al. (1990), these types of survey, the potential electrodes ( $P_1$  and  $P_2$ ) remain fixed; while the current electrodes ( $C_1$  and  $C_2$ ) spacing is expanded symmetrically about the center of the spread. When a current electrode

separation becomes large, it may be necessary to increase the potential electrodes spacing in order to get a measurable potential.

**Resistivity profiling;** also called Lateral Inhomogeneity Hunting (LIH), is a procedure in which the variation of resistivity in the lateral direction is determined. This is usually done with fixed electrode spacing as Wenner array. A series of apparent resistivity measurements are made by moving the whole electrode array from place to place along a profile. If values are obtained along several parallel profiles, a contour map of apparent resistivity can be prepared and interpreted depending upon the objective of the investigation what we want to determine at the proposed area.

### 3.4.2 The resistivity of rocks and minerals

Mainly the electrical conduction in subsurface rocks and earth materials occur in three ways: Electrolytic conduction (where conduction is due to ions in an electrolyte); Dielectric (Conduction made in weakly conducting material as a result of externally applied current) and Electronic (Referring to the process by which metals allow electrons to move and carry a charge) (Reynolds, 1997).

Rocks have physical properties that are most commonly utilized in geophysical investigations are Density; Thermal conductivity; Magnetic susceptibility; Elasticity; Electrical resistivity or conductivity and Radioactivity.

There is a criterion to meet when the charge to moves through conducting material and to conduct electricity. With this respect, electrical conduction in most rocks is due to the movement of ions in electrolytes, i.e. Conduction in rocks is electrolytic (Reynolds, 1997, Kearey et al., 2002 and Everett, 2013).

According to the expression of Kearney et al. (2002), Most rocks conduct electricity by electrolytic process rather than electronic processes i.e., The availability of pore spaces (means Porosity) of the rocks and pore fluid characteristics is the major geologic factors that affect the resistivity of rocks and earth materials. The degree of porosity, where the electrolytes of rocks and earth materials, mainly dependent on the degree of fracturing, the availability of fault, cracks, and fissure structures in the rock.

**Table 3.1: Resistivity values of some common geological formations (Modified from Bernard, 2003).**

Types of material	Resistivity ( $\Omega\text{-m}$ )
Basalt	10 - $1.3 \times 10^7$
Topsoil	250 – 1700
Sandstones	200 - $5 \times 10^3$
Clays	1 - $10^2$
Sandstone (weathered)	50 – 200
Gravel (saturated)	100

According to right-hand rule, a general rule of thumb that follows is then, the resistivity of rocks decrease with increasing porosity, salinity and temperature of pore fluids (Everett, 2013). This is because the interconnected pore fluids provide paths for conduction, the high saline pore fluids have a greater concentration of ions available for conduction, and the high temperature enhances/ increases the mobility of ions and also the conduction i.e. Its conductivity.

For water-bearing rocks and earth materials, the resistivity decreases with increasing: Fractional volume of the rocks occupied by water (i.e. water content); free ion content or Salinity of the connate water (i.e. water quality); Temperature and Interconnection of the pore spaces (i.e. Porosity and permeability).

According to Mussett and Khan (2000) due to the inverse relationship between temperature and resistivity, when the resistivity decreases with increasing temperature. This relation has an important application for resistivity survey in geothermal explorations to locate the geothermal area and also in a volcano-geophysics to infer the presence of magma. The electrical properties of most rocks in the upper part of the earth's crust are dependent primarily on the amount of water in the rock and its salinity. Saturated rocks have high conductivities than unsaturated and dry rocks. The higher the porosity of the saturated rocks, the higher it's conductivity. The conductivity of rocks increases as the salinity of saturating fluid increases. The presence of clays and conductive minerals also increases the conductivity of the rocks. Depending upon resistivity; Earth materials classified into three categories; summarized as in the following table.

**Table 3.2: Resistivity of Earth Material**

Category	Resistivity ( $\Omega\text{m}$ )
Low resistivity	< 100 $\Omega\text{m}$
Medium resistivity	100 to 1000 $\Omega\text{m}$
High resistivity	>1000 $\Omega\text{m}$

The resistivity ( $\rho$ ) of rocks and minerals displays a wide range. For example, graphite has a resistivity of the order of  $10^{-5}$  ohm-m; whereas some dry quartzite rocks have a resistivity of more than  $10^{12}$  ohm-m. The resistivity of the geological materials ranges from  $1.6 \times 10^{-8}$   $\Omega$ m for native silver to  $10^{16}$   $\Omega$ m for pure sulfur. According to Reynolds (1997) Igneous rocks tend to have the highest resistivity followed by metamorphic rocks but overlapping resistivities, with sedimentary rocks characterized by low resistivity, but most conductive due to their high pore fluid content.

**Table 3.3: The Numerical values of different types of water (Modified from Bernard, 2003).**

Types of water	Resistivity(ohm-m)	Conductivity(micros/cm)	Salinity(mg/L)
Fresh	20	500	150
Very fresh	200	50	35
Seawater	0.3	$3 \times 10^4$	$3.5 \times 10^4$
Salted	10	$10^3$	700

According to Kearey et al.,( 2002) the considerable overlap between the resistivity of different rock types made a determination of the lithology's using solely of resistivity surveys impossible and resistivity surveys are often constrained by other independent methods for genuine interpretations of the geology of mapped areas..

### 3.5 Magnetic method

#### 3.5.1 Introduction

The magnetic method is a very popular and inexpensive approach for near-surface metal detection, Engineering and environmental site characterization projects often begin with a magnetometer survey as a means of rapidly providing a layer of information on where utilities and other buried concerns are located.

The principle of operation is quite simple. When a ferrous material is placed within the Earth's magnetic field, it develops an induced magnetic field. The induced field is superimposed on the Earth's field at that location creating a magnetic anomaly. Detection depends on the amount of magnetic material present and its distance from the sensor. The anomalies are typically presented on color contour maps. Common uses of magnetometers include: locating buried tanks and drums, fault studies, mineral exploration, geothermal exploration, mapping buried utilities, pipelines, buried foundations, fire pits for archaeological studies. In the geothermal application the main objective of the magnetic study is to contribute with information about the relationship among the geothermal activity, the tectonic and stratigraphy of the area by means of the

anomalies interpretation of the underground rocks' magnetic properties (Escobar, 2005). Most of the rocks are not magnetic; however, certain types of rocks contain enough minerals to originate significant magnetic anomalies. The data interpretation that reflects differences in local abundance of magnetization is especially useful to locate faults and geologic contacts (Blakely, 1995).

Magnetic profiling is a passive method that involves measurement of localized variations in the amplitude of the geomagnetic field resulting from buried ferrous targets, such as underground storage tanks and pipes and variations in the magnetic susceptibility of near-surface materials. The amplitude and shape of the anomaly caused by buried ferrous objects will depend on the target's shape, orientation, and susceptibility. In certain instances, magnetic data can be interpreted quantitatively, and transformed into constrained geological models. More typically, however, magnetic data are interpreted qualitatively and simply used to verify the presence or absence of magnetically susceptible materials or features.

**3.5.2 The basic principle of the magnetic method**

**A) Magnetic force and units**

According to Telford et al.,(1990) the theories of the magnetic field are similar to both electric and gravity in that point magnetic poles are analogs to point electrical charges and point masses. If two magnetic poles of strength  $m_1$  and  $m_2$  are separated by a distance  $\mathbf{r}$ , a force,  $\mathbf{F}$ , exists between them. If the poles are of the same polarity, the force will push the poles apart, and if they are of opposite polarity, the force is attractive and will draw the poles together. The equation for the force *is* written as follow:

$$\vec{F} = \frac{M_1 M_2}{4\pi\mu r^2} \hat{r} \dots\dots\dots (3.31)$$

Where  $\mu$  is the magnetic permeability of the medium separating the poles;  $m_1$  and  $m_2$  are pole strengths

$\hat{r}$  = is the unit vector from  $m_1$  to  $m_2$  and  $\mathbf{r}$  is the separation distance between two masses  $M_1$  and  $M_2$

$\mu$ =permeability = $\mu_r\mu_0$

$\mu_r$ =relative permeability (  $\approx 1$  for air and many rocks)

$\mu_0$ =permeability of free space = $4\pi \times 10^{-7}$ henery/m

The magnetic force is the outcome of the electromagnetic force, one of the four fundamental forces of nature. It occurs when the objects interact in which there is charge in motion.

Two charge containing objects moving with the same direction of motion has an attractive magnetic force between them. Were as, two objects containing moving in opposite directions have a repulsive force between them.

The SI unit of magnetic force:  $1N = 1C \left(\frac{m}{s}\right) (T)$

$$1T = \frac{1N}{C \left(\frac{m}{s}\right)} = \frac{1N}{Am}$$

A magnetic field of one Tesla is a very powerful magnetic field. Sometimes it may be convenient to use the gauss, which is equal to  $\frac{1}{10^4}$  of a Tesla ( $1\text{gauss} = \frac{1}{10^4} T$ ). The magnetic field of the Earth varies at the surface, but has the strength of about one gauss.

**B) Magnetic Flux**

Magnetic flux, informally speaking, is a measure of the number of magnetic field lines going through an area. If the field is constant, flux is given by:

$$\Phi_B = B \cdot A = BA \cos \theta \dots\dots\dots (3.32)$$

The area vector in the dot product is a vector that points perpendicular to the surface and has a magnitude equal to the area of the surface.

The SI unit for magnetic flux;  $\Phi_B$  is the tesla-square meter;  $Tm^2$ . This is also known as Weber (Wb). The flux per unit area,  $\frac{\Phi_B}{A}$  is the flux density denoted by  $\vec{B}$  and is measured in  $\frac{\text{Weber}}{m^2} = \text{Tesla}$ .

$\vec{B}$ , which is also called the magnetic induction is a vector quantity. The Cgs units of flux density were Gauss, equivalent to  $10^{-4} T$  (Reynolds, 1997).

To measures magnetic induction it is better to use subunit, Nano Tesla (nT) because Tesla is large to use practically in geophysical work ( $1nT = 10^{-9} T$ ).

**C) The relationship between Relative permeability, susceptibility, and magnetization**

If the medium is different from vacuum we can write the relation between  $\mu$ (magnetic permeability= $\mu_r\mu_0$ ),  $\mu_r$ (relative permeability ( $\approx 1$  for air and many rocks)),  $\mu_0$ (permeability of free space = $4\pi \times 10^{-7}$  henery/m),  $\vec{B}$  (magnetic flux density) and magnetic field,  $\vec{H}$

$$\begin{aligned} \vec{B} &= \mu\vec{H} \\ \vec{B} &= \mu_r\mu_0\vec{H} \\ \vec{B} &= \mu_0\vec{H} + \mu_0(\mu_r - 1)\vec{H} \end{aligned}$$

$$\vec{B} = \mu_0 \vec{H} + \mu_0 K \vec{H}$$

where  $k = \mu_r - 1$ , that is  $\mu_r = 1 + k$

For materials in which  $\vec{M} = k\vec{H}$ , the magnetic permeability can be defined in terms of the magnetic susceptibility as follows:

$$\mu = \mu_0(1 + \kappa)$$

Relative permeability ( $\mu_r$ ) defines the ratio between the magnetic permeability of the material and the permeability of free-space:

$$\mu_r = \frac{\mu}{\mu_0}$$

The magnetic flux density depends on the magnetization within the material and can be written as:

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) \dots\dots\dots (3.33)$$

Where  $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$  is the permeability of free- space. The permeability of free-space represents the relationship between  $\vec{H}$  and  $\vec{M}$  when the material is non-magnetic.

According to the above definitions, both magnetic susceptibility and magnetic permeability are diagnostic physical properties associated with the magnetic characteristics of materials. In the literature, it is common to see physical property tables which use  $\mu$ ,  $\mu_r$ , or  $\kappa$ . For most rocks, the susceptibility is small and characterizing the magnetic properties in terms of  $\kappa$  is convenient. Parameters used to define magnetic properties and their associated units are tabulated below.

**Table 3.4: property, symbol, and unit of magnetic parameters**

Property	Symbol	Units
Magnetic field Intensity	$\vec{H}$	A/m
Magnetic flux density	$\vec{B}$	T
Magnetization	$\vec{M}$	A/m
Magnetic susceptibility	K	Unitless
Magnetic permeability	$\mu$	H/m
Relative permeability	$\mu_r$	Unitless

### 3.5.3 Origin of earth’s magnetic field

Although several theories have been forwarded to explain the origin of the magnetic field of the earth, the Magneto-Hydrodynamic (MHD) theory seems to have received reasonable acceptance. According to MHD theory, the geomagnetic field is believed to be generated by the core field caused by the rapid and complex flow of highly conductive, metallic iron in the outer core. The

magnetic source is thought to be a self-excited dynamo in which highly conductive fluid moves in a complex manner caused by convection (Telford et al., 1990).

### 3.5.4 Nature of earth's magnetic field

According to Telford et al. (1990), there are different types of the geomagnetic field on the earth. The main fields more important concerning with geophysical exploration are listed as follows.

#### A. Main field

- It varies relatively slowly and it's originated from the inner side of the piles of earth.

#### B. A small field

- When it compared with the main field, it varies rapidly and originates outside of the earth.

#### C. Spatial variations of the main field

- It is nearly constant in time and space in addition to this it is smaller than the main field which and caused by local magnetic anomalies in the near-surface crust of the earth and are targets of magnetic surveying.

### 3.5.5 Temporal variations of earth's magnetic field

Earth's magnetic field has different variations. The most commonly used magnetic field variations are explained as follows:

#### A. Secular variations

- ❖ These are longer period variations of the Earth's magnetic field of usually greater than a year (Mudge and Dentith, 2014). Although their mechanism is not understood well, several theories indicate that they are due to changes in electric currents producing the internal field (e.g. Dobrin and Savit, 1988; Mudge and Dentith, 2014)
- ❖ There are also variations in the inclination and declinations of the field; in which the geomagnetic field of the earth has reversed its polarity a number of times in the geologic time as revealed from a number of paleomagnetic studies, with the most recent one occurred about  $7 \times 10^5$  years ago (Mudge and Dentith, 2014).

#### B. Diurnal variations

- ❖ It is smaller but more rapid oscillations in the earth's field with a period ranging from a day and amplitude averaging 25Gamma (Dobrin and Savit, 1988).
- ❖ It occurs due to changes in the external field related to sources external to the earth. These are chiefly due to electric currents flowing in the ionosphere, the ionized layer of the upper atmosphere, and are associated with radiation from the Sun (Dentith and Mudges, 2014).
- ❖ Have direct significance to magnetic prospecting method of exploration.

### C. Magnetic Storms

- ✓ According to Dentith and Mudges (2014); it is rapid variations of the field with periods of milliseconds ( $10^{-3}s$ ) to minutes appearing as irregular bursts lasting from hours to several days' even months.
- ✓ Due to its rapid motion; magnetic surveying must stop during such events because it occurs rapidly too, in an unpredictable way also effects are not feasible to correct (Dobrin and Savit, 1988).

### 3.5.6 Elements of the earth's magnetic field

The elements of earth's magnetic field to describe the magnetic field strength and direction in a vector form within a given position can be decomposed into its components.

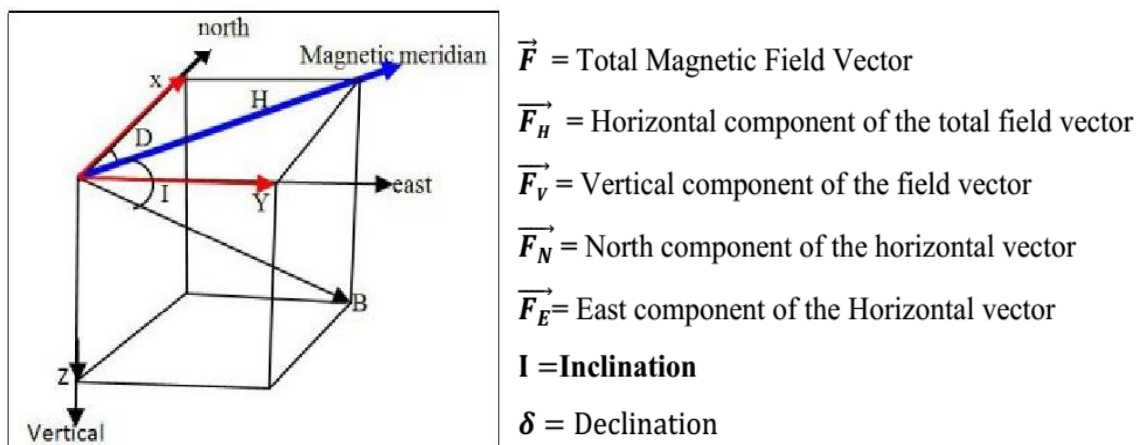


Figure 3.5 Elements of Earth's magnetic field (After Lillie, 1999).

From figure above, we can derive the following relations

$$\vec{F}_H^2 + \vec{F}_V^2 = \vec{F}^2$$

$$\vec{F} = \sqrt{F_N^2 + F_V^2}$$

$$\begin{aligned}
 &= \sqrt{F_N^2 + F_E^2 + F_V^2} \\
 \vec{F}_H^2 &= \vec{F}_N^2 + \vec{F}_E^2 = \\
 i &= \tan^{-1} \left( \frac{F_V}{F_H} \right) \\
 \delta &= \tan^{-1} \left( \frac{F_E}{F_H} \right) \dots \dots \dots (3.34)
 \end{aligned}$$

**3.5.7 Magnetization and magnetic susceptibility of materials**

**A) Magnetization**

The Sources of Magnetism is the motion of charge and electron itself. Every electron in an atom behaves as a magnet in two ways, each having two magnetic dipole moments: Spin magnetic dipole moment resulted due to the “rotation or orbiting” of an electron.

According to Milsom (2003), if a body is placed in an external magnetic field (also called inducing field), it acquires small magnetization which is proportional to the inducing field. When the source field is applied to earth materials it causes the earth to become magnetized. Magnetization is the ratio of dipole moment per unit volume. This is a vector quantity because a dipole has the strength and a direction. For many cases of interest, the relationship between magnetization **M** and the source **H** (earth’s magnetic field) is given by:

$$\vec{M} = K\vec{H} \dots \dots \dots (3.35)$$

Where  $\kappa$  is the magnetic susceptibility. Thus the magnetization has the same direction as the earth's field because Earth's field is varied at different locations on the earth, due to the same object gets magnetized differently depending on where it is situated. As a result, magnetic data from a steel drum buried at the North Pole will be very different from that from a drum buried at the equator. Magnetic susceptibility ( $\kappa$ ) quantifies the magnetization ( $\vec{M}$ ) of a rock or mineral experiences when it is subjected to an applied magnetic field ( $\vec{H}$ ).

**3.6 Magnetic data reduction**

Reduction of data from magnetic survey helps to remove the effects of temporal variations in the Earth’s magnetic field those occur during the course of the survey. Like gravity reduction, planetary-scale spatial variations in the field are compensated for, but in contrast, elevation-

related variations in the magnetic field are minor. As the Earth’s magnetic field varies from nearly  $2.5 \times 10^4$  nT at the magnetic equator to  $6.9 \times 10^4$  nT at the poles, the increase in magnitude needs to be taken in to account (Reynolds, 1997). Survey data at any given location can be corrected by subtracting the theoretical field value ( $F_{th}$ ), obtained from the International Geomagnetic Reference Field (IGRF) from the measured observed value ( $F_{ob}$ ). To drop out all causes of magnetic variation from the observations other than those arising from subsurface geology; it is necessary to make a correction of raw data from the magnetic survey.

**3.6.1 Geomagnetic correction**

As stated by Reynolds (1997) in order to produce a magnetic anomaly map of a region, the data have to be corrected to take into account the effect of latitude and to a lesser extent longitude. Survey data at any given location can be corrected by subtracting the theoretical field value  $B_{th}$ , obtained from the International Geomagnetic Reference Field (IGRF) from the measured value,  $B_{ob}$ . Therefore, the magnetic anomaly ( $\Delta B$ ), obtained by subtracting the diurnal correction ( $\delta_D$ ) and geomagnetic correction ( $B_{th}$ ) is given by:

$$\Delta B = B_T - \delta_D \dots\dots\dots (3.36)$$

**3.6.2 Diurnal variation correction**

According to Kearey et al. (2002), magnetometers do not drift and base station readings are taken solely to correct for temporal variation in the measured field. The effects of diurnal variation may be removed in several ways. On land, the magnetometer is read at a fixed base station periodically throughout the day.

## CHAPTER FOUR

### 4. DATA ACQUISITION AND PROCESSING

#### 4.1 Survey Traverse Selection

The Amhara Water Works Design and Supervision Enterprise (AWWDSE 2008, 2009) and MS-consulting PLC (2011) selected an area south-west of Woldia town and around the National stadium of the town to be studied in detail for groundwater resources potential based on previous detailed geological; hydrogeological and previous VES surveys. The area was planned to be studied for detailed investigation to understand groundwater potential zones, different lithological units, geological structures and the physical characters of subsurface rocks. The two geophysical techniques; magnetic and VES methods are chosen for this survey. The area was basically selected due to the presence of thick alluvial sediments that occurred Mehal mechare and shele River course.

The geophysical observations have been carried throughout along all the transect lines. The diagrammatic layout of the geophysical observation points (VES and Magnetics) and lines are indicated in Figure 4.1.

#### 4.2 Data Acquisition and Instrumentation

##### 4.2.1 Vertical Electrical Sounding

The objective of VES used to correlate the variation of resistivity with depth below a recognize point of the ground surface and to integrate it with the available geological notification in order to indicate the depth and resistivities of the existing layers.

When we started our geophysical investigation the first step was identifying the traverse appropriate to our survey. VES review was carried out along six (6) transect lines or profiles oriented approximately north east-south west within the area and observations were made at around 1km (1000m) sounding station spacing. Schlumberger array using current electrode spacing 500m ( $AB/2=500m$ ) was generally used to the maximum depth of investigation. A total of Twenty VES distributed on Six (6) different lines were surveyed in the study area with transect separation ranging from 1km to 2.5km.



**Figure 4.1 Instrumental setup of VES and Magnetic Survey.**

The VES was done at an average interval of 450m. The current electrode spacing selected for these surveys were AB/2 (meter): 1.5, 2.1, 3.0, 4.2, 6.0, 9.0, 13.5, 20.0, 30.0, 45.0, 66.0, 100.0, 150.0, 220.0, 330.0 and 500.0 and the potential electrodes spacing where MN/2 (meter): 1.0, 12.0, and 90.0. The overlap readings were taken at the point of current electrode spacing; AB/2; 20.0, 30.0, 150.0 and 220.0 m in order to avoid the ambiguity of inhomogeneity.

Some of these VES: VES-4; VES-6; VES-7; VES-8; VES-12; VES-13; VES-15; and VES-20 were approximately located near previously drilled boreholes to obtain a good result during the interpretation of data. The maximum distance between that different VSE was 1500m and observation VES points generally located at a separation distance of 3.5km interval, however, at places, these positions were shifted approximately up to 0.5km in line and sometimes off the transect lines to find suitable measurement ground.

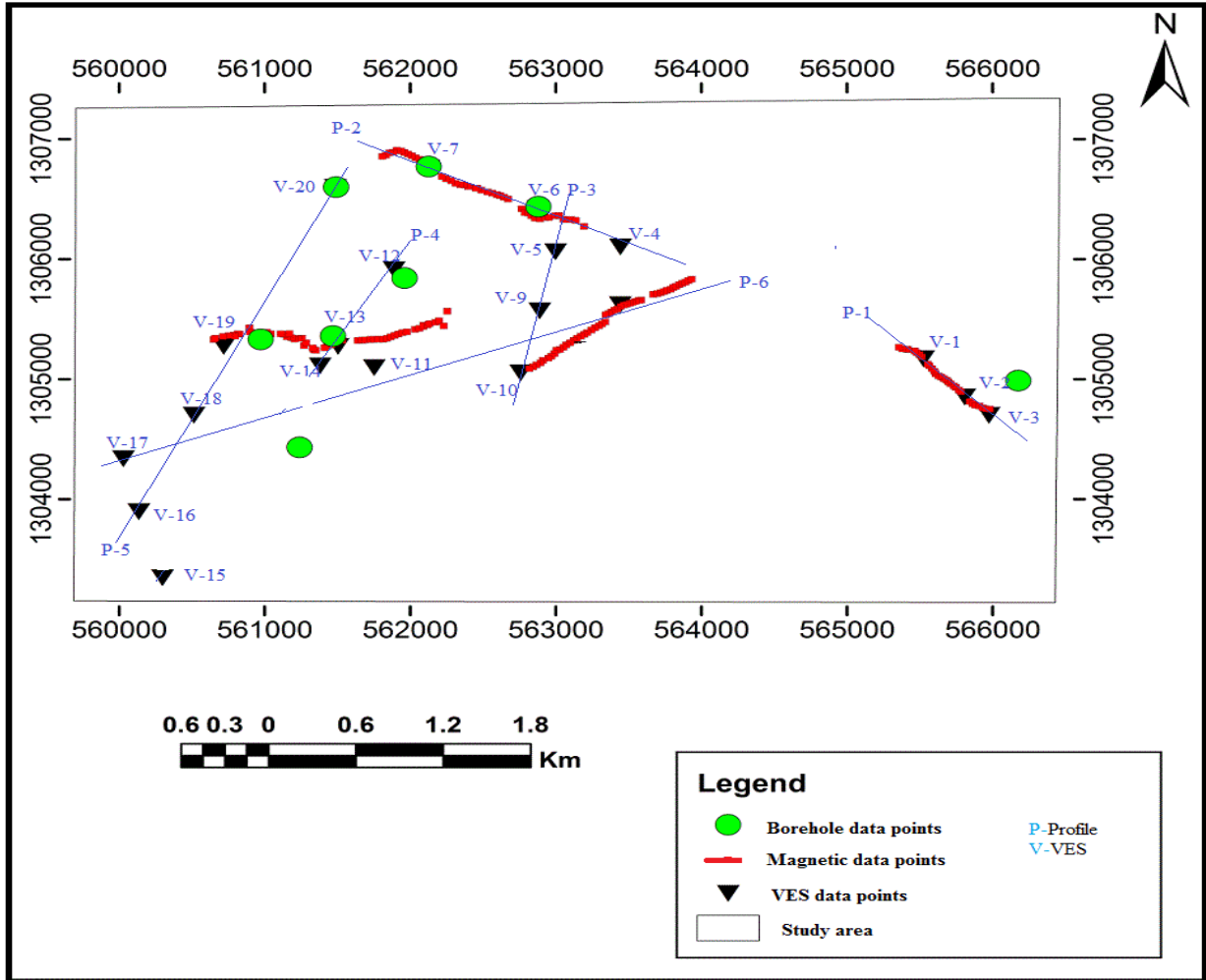


Figure 4.2 Location of geophysical data points with survey traverses and previous boreholes.

The instrument employed in the Vertical Electrical Sounding (VES) survey was the Earth resistivity meter unit (PASI; GL-16) having a maximum current output of 2A and 12 V. Handheld (777) GPS was used to record VES point locations.

The locality/locations of VES points were recorded and also the apparent resistivities for different electrode spacing were calculated. To control data quality we were used log-log graph paper to plot and examining the VES data in the field for each data point. The spread directions were duly recorded and these were used during data processing session for anisotropic correction purposes.

#### 4.2.2 Magnetic Survey

The magnetic survey was conducted by Proton Precession Magnetometer and the total field of the magnetic survey was conducted along VES lines and observations were made every 30m along all transect lines of the VES. A total of two hundred twenty data points was acquired

with transect separation similar to that of the VES, i.e. ranging from 1km to 2.5km. The profiles were oriented about northwest-southeast in order to cross and to detect the possible structure related to groundwater occurrence. Few magnetic data were surveyed around the previously drilled boreholes. The date, time of measurement, total magnetic intensity, and the location of magnetic data points were recorded. Data quality was controlled by measuring data and taking base station readings at the origin and the end of 500m interval of the magnetic survey for the profile to overcome diurnal variation. And also the measurement was recorded early morning 11:30 am and 9:15 pm to minimize the effect of diurnal fluctuations due to the weather condition. Portable Proton Precession Magnetometer; which is a versatile and rugged tool for such a survey and, handheld GPS was used for recording the time and position of the measured point during the magnetic survey.

### **4.3 Data Reduction and Processing**

#### **4.3.1 VES Data Reduction and Processing**

##### **A) VES Data Reduction**

By using logarithmic transparent paper the apparent resistivity value was plotted on it. In this paper the processing of collected data, the apparent resistivity value putted on the ordinates and the electrode separation ( $AB/2$ ) on the X-axis/ abscissa. The resistivity measurements were conducted by progressively increasing the potential electrode distance (MN) to 1.0; 12.0 and 90.0 m to increase the voltage relatively large increment of current electrode distance ( $AB/2$ ). Most of the time, the sounding curve is segmented due to overlap measurement and cannot be interpreted as it is. According to Velpen (1995) to increase the accuracy of the interpretation the segmented curves were shifted to the small MN curve points, then the effect could be quantified and corrections could be made in order to get a single smooth curve that could be processed by the computer using IP2WIN and WIN RESIST software.

##### **B) VES Processing**

By applying both quantitative & qualitative explanation method the field result of the study could be presented. In the qualitative interpretation method, the shape of the field curve is observed to provide an idea qualitatively about the types/number of layers and resistivity of layers. The segmented curves were shifted to the small MN to have precise interpretation.

The results of this method of interpretation involved Geo-electric section, pseudo-sections and slice stacked of electrical resistivity maps. The VES data collected in the field were

plotted on a bi-log paper with the modules of 62.5mm and interpreted by using IP2WIN software to find out initial model parameters of the possible layers.

Those parameters obtained from IP2WIN software were arranged and analyzed with the lithological units of existing boreholes to use as an initial model in RESIST inversion software which resulted and reliable electrical parameters of the layers with a tolerable error from 1.5-4.5%.

Geoelectrical parameter; True resistivity & layer thickness were obtained from quantitative method to made geo-electric section using the software AutoCAD, 2016. From the software, we obtained the type of curve and model parameter of the first curve of each profile and presented in Figure 5.1.

The lateral variation of apparent resistivity over a horizontal plane at certain depth could be reflected at a different value of  $AB/2$  as a slice stacked map. That is, this map indicates the distribution of apparent resistivity of the area across the distance of current electrodes. According to Frohlich et al. (1996), the maximum depth, sharpness, or penetration of the AMNB method is  $1/3$  to  $1/4$  of the maximum distance of current electrodes. The differential value of  $AB/2$  on Figure 5.2 used to illustrate the apparent resistivity contour maps.

Qualitatively the Pseudo-section indicates the apparent resistivity distribution within the subsurface versus electrode spacing values ( $AB/2$ ). The plots of all pseudo-sections are given in the Figure 5.3, 5.5, 5.7, 5.9, 5.11 and 5.13.

Geo-electric sections are diagrammatic section of stratified layers which is gathered from electrical (resistivity) depth probing or drilling, where layers are determined by their apparent resistivities. These sections are useful in identifying water-table levels and understand whether water is saline or fresh at the water-table. The final model parameter (thickness and resistivity) was used in order to prepare this section. All of the sections generated by inversion software RESIST. All sections of the profiles are presented in the Figure 5.4, 5.6, 5.8, 5.10, 5.12, and 5.14.

#### **4.4 Magnetic Data Reduction and Processing**

##### **4.4.1 Magnetic Data Reduction**

To avoid both signal & spurious noise from the data that are not connected to the geology of the site; the reduction and processing of data are taken with a serious step. In another

word the data set for interpretation by reducing the data to only contain signal relevant to the task. These steps are summarized below:

- i. **Data checking and editing:** involves the removal of spurious noise and spikes from the data that was caused by the metallic material from the building and high tension power cable.
- ii. **Diurnal removal:** By subtracting the time synchronized signal, recorded at a stationary base magnetometer reading (base station) from the survey data to correct the temporal variation in the Earth's main field.
- iii. **IGRF removal:** means the removal of the strong impulse of the Earth's main field. To achieve this we were subtracting the value of the main field calculated using Oasis Montaj from the diurnal corrected survey data.

#### 4.4.2 Magnetic Processing

The processing of the magnetic data revealed a set of processes such as diurnal correction, IGRF correction, and magnetic and geographic referencing. All processed profile curve is used for qualitative interpretation of the data. The aim of magnetic maps is to get a clear view of the subsurface structures and estimation of the relative depth of the magnetic anomaly sources when we interpreted qualitatively. To determine the depth of shallow subsurface structures (faults and dikes), the weak zone of the surface (fractures and contacts) of the studied area qualitative interpretations has been used. These methods of interpretations are Euler deconvolution and 2D magnetic modeling, but cannot apply Euler deconvolution because I have conducted magnetic data profile wise. The analysis and processing were done by a specialized computer program (Oasis Montaj V-7.0.1). All processes of magnetic data are represented by profile curve and 2D model in the next chapter.

## CHAPTER FIVE

### 5. DISCUSSION AND INTERPRETATION

#### 5.1 Generals

As presented in the preceding chapter, the results of a resistivity sounding survey are presented in the form of interpreting VES curve, apparent resistivity pseudo-sections, and pseudo-depth slice map for the purpose of qualitative assessments and vertical geo-electric section, permitting quantitative interpretations. Frequently, the results of the magnetic survey also presented as a 2D magnetic profile curve and different maps. IGRF corrected map, TDR map, analytic signal map, and horizontal and vertical gradients of the analytic signal, vertical derivative map, and an RTP map of qualitative interpretation and difference grid between residual and upward continuation map for 2D modeling. Then, Euler deconvolution and 2D model for quantitative assessments. In this section, the results would be presented and discussed profile-wise by correlating with geo-electric section except for the slice map for VES.

#### 5.2 Discussions and Interpretation of VES

##### 5.2.1 Interpreted VES Curves

Apparent resistivity versus electrode spacing plotted on a bi-log scale is interpreted using the IP2Win to acquire the initial model parameters to be entered into inversion software (RESIST) by constraining it further with the existing boreholes. It is seen from the interpreted field curves that a very valid correspondence between the field data and the interpreted model sections are acquired for all the four VES points. This is asserted by an RMS error of 1.5 to 4.5% obtained from the sounding data. An illustration is made using three interpreted VES curves, one each from each of the survey traverses and these are given in Figure 5.1. In the three sounding curves, 6 to 7 layers of the subsurface are seen too well to represent the subsurface (with the AB/2 of 500m used for the survey). The rest of the interpreting VES curve is established in Annex-1.

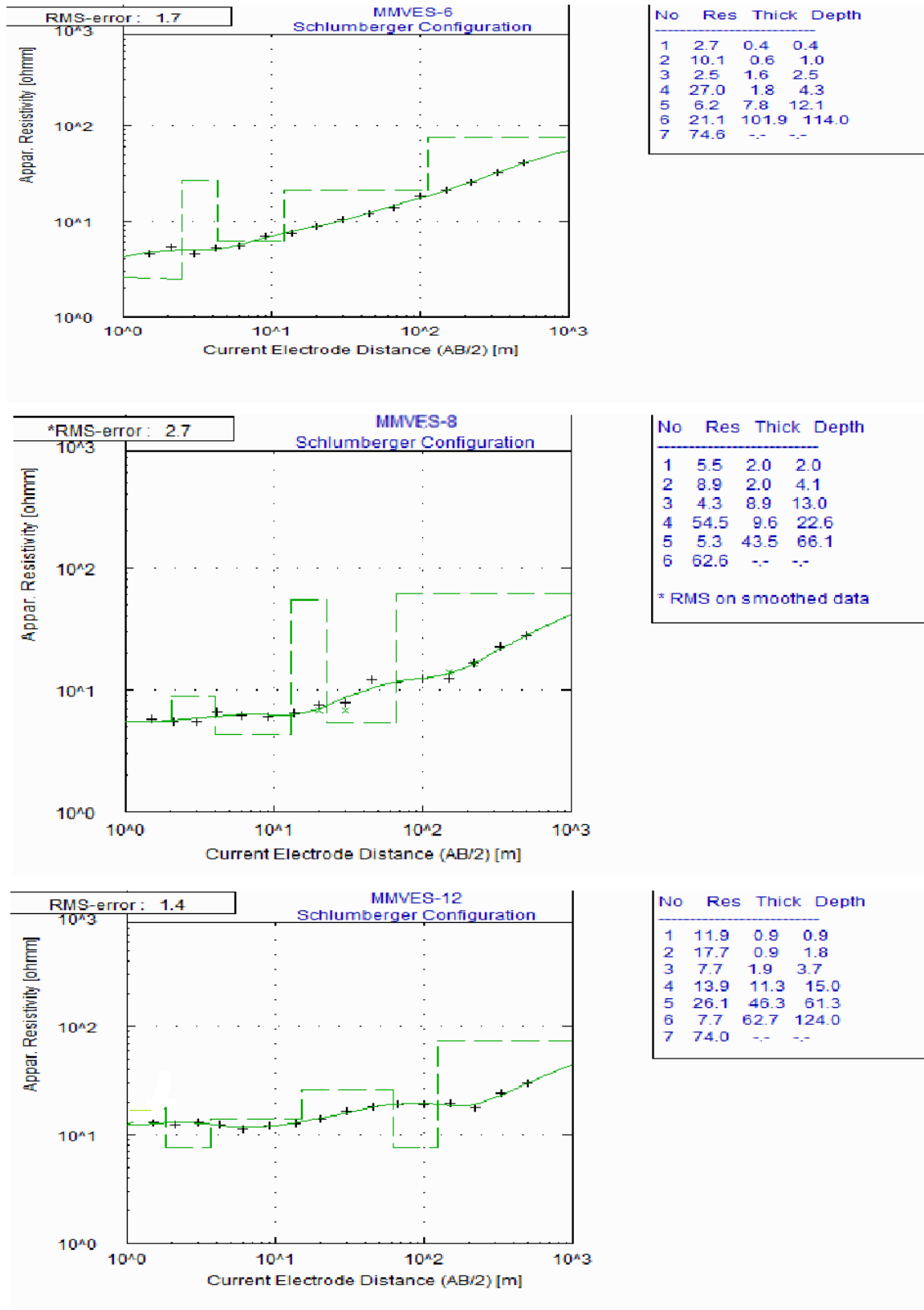


Figure 5.1 The first Interpreted VES curves of each profile.

## 5.2.2 Sliced-Stacked Section

The apparent resistivity sliced pseudo-depth map shown in Figure 5.2 is prepared by superimposing the two-dimensional apparent resistivity plan maps for selected AB/2 values of 1.5, 45, 100, 150, and 500m. All VES points are used for qualitative assessments of the electrical nature of the geologic medium. The sounding points are almost smoothly distributed so it is believed to afford a good representation of the ground overall.

### 5.2.2.1 Sliced-Stacked for different AB/2

In the figure below, the slice stacked maps were constructed for AB/2=1.5, 45,150 and 500m. The choice of such spacing depends on the variations between them and to show the lateral variations of resistivity in different pseudo-depth. These maps reflected the lateral variations of the electric resistivity over a horizontal plane at a depth of about 0.75, 22.5, 75, and 250m respectively. Particularly, the map shows the relative variation of the apparent resistivity value of the whole area laterally as well as vertically at different depths of the spacing of current electrodes. It is found that the apparent resistivity value varies extensively from 0-54Ω-m.

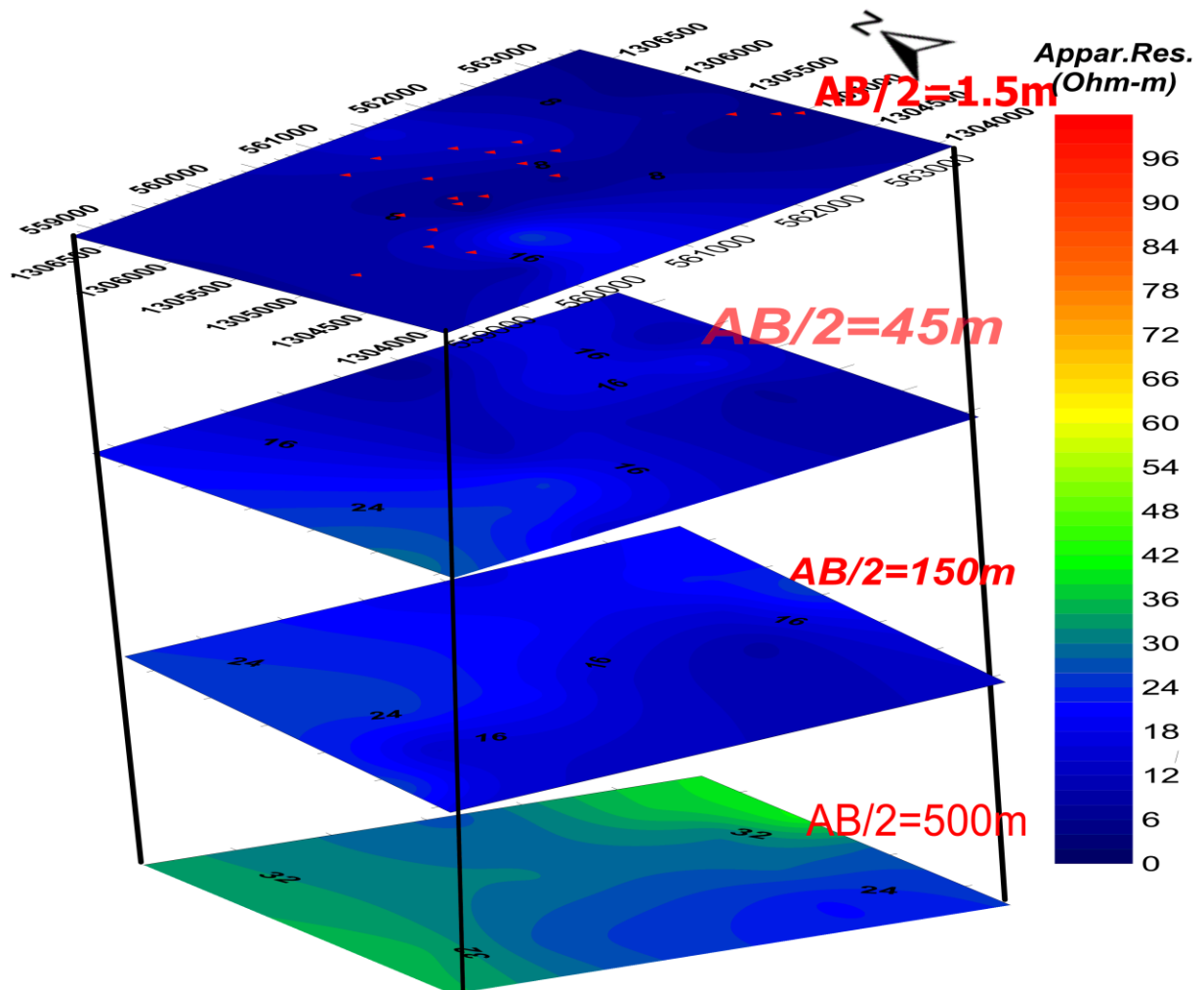


Figure 5.2 Sliced stacked map for different AB/2.

From Figure 5.2, more of the area under this sliced plot is the low resistivity zone, ( $<32\Omega\text{-m}$ ) that holds the vast fragment of the survey area. The value of the high apparent resistivity value zone increase as the investigation depth increases. The value of the low apparent resistivity zones observed in all parts of the area for  $AB/2 = 1.5, 45,$  and  $150\text{m}$ . But for  $AB/2 = 500\text{m}$  northeast and southwest part dominated by relatively high resistivity zone. However, relatively high resistivity zone increase with depth up to  $AB/2=500\text{m}$  and finally low resistivity zone dominate in all  $AB/2$  except some parts of  $AB/2 = 500\text{m}$ .

### 5.2.3 Pseudo depth section and Geoelectric Section of the Profiles

The pseudo section is an important method to introduce the data in a pictorial form and as an initial guide for further quantitative interpretation. One useful, practical application of the pseudo section is in identifying bad apparent resistivity measurements that usually appear as

points with unusually high or low values. The pseudo section gives a distorted picture of the subsurface because the shapes of the contours relying on the type of array used as well as the true subsurface resistivity. Geoelectric sections are diagrammatic section of stratified layers which is gathered from electrical (resistivity) depth probing or drilling, where layers are identified by their apparent resistivities. Such sections are useful in determining water-table levels and determining whether water is saline or fresh at the water-table.

After reduction and filtering of VES data along with all survey lines, we were used to constructing the pseudo-sections in order to determine the distribution of different resistivity values in the vertical and lateral direction. Pseudo sections give a proper impression of the subsurface resistivity structure. However, pseudo sections are pseudo for two reasons: True depth not known and Shapes are distorted. One useful, practical application of the pseudo section plot is for picking out bad apparent resistivity data points, which have unusually high or low values.

The software's which were used for the composition of a pseudo-section of the VES data were SURFER (Version-10) software. The qualitative interpretation of pseudo-section yields preliminary information for identification of high potential of groundwater and inquiry to identify relative resistivity variation for preparing Geo-electric sections.

The ultimate result of the one-dimensional inversion of VES data along all survey lines was used to build the geoelectric sections in order to identify the distribution of different lithological units in the vertical direction. The software's which were used for the inversion of the VES data were IP2WIN and WIN RESIST whereas the plotting was carried out by using AutoCAD (Version-2016). The lithological logs from boreholes that are lying on these profiles were used to fix the thickness of each layer by grouping the rock samples based on their type and degree of weathering and fracturing. The pseudo-depth sections along these survey lines were examined to see the relative resistivity variations when preparing Geo-electric sections.

### **5.2.3.1 Profile One**

This traverse line is the centered beneath Woldia University oriented in an NE-SW direction and running almost parallel to St. Tekle Haimanot church and West of Asphalt road from Addis Ababa to Woldia and Mekelle. The line has a total length of about 0.4 km and there are 3 VES (VES points 1-3 with average VES point spacing of about 0.133 km.

### A. Pseudo depth section Along Profile One

The pseudo-depth sections constructed for VES-1, 2, and 3 that lie on the survey profile line-1 are given in Figure 5.3. According to this figure, there is a lateral variation in resistivity in the top of the right side, central and bottom part of the section with prominent relatively high resistivity top zones mapped between VES-2 and VES-3. This high resistivity zone is extending to large depth. Otherwise, the vast region under the section shows extensive coverage of the low resistivity zone. The resistivity ranges (2 to 60Ω-m) of this low resistivity region are indicative of potential water saturation, especially between the distance 0 to 300 m shows very low resistivity zone with resistivity value 25Ω-m and it indicates high potential water saturation.

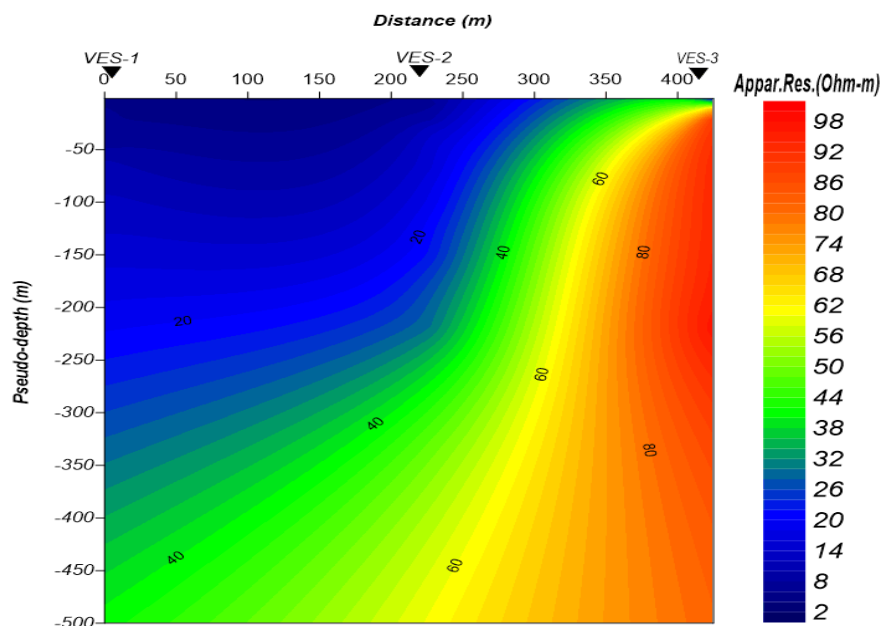


Figure 5.3 Pseudo depth section of Profile one.

### B. Goelectric Section along profile one

The resulting goelectric section constructed from the interpreted layer parameters of the three VES laying on this traverse/profile is given in Annex-1. A borehole GBH-1 (WWDSE, 2011) is located near profile-1; was also used to constrain the depth and identify the lithological units beneath/below these VES points during modeling. In essence, the lithological description of the borehole depth section (given in Annex-2) with their resistivity parameters from each interpreted VES was used to arrange the goelectric section shown below (Figure 5.4). Figure 5.4 shows, four layers of the section.

The topmost part of the cross-section has resistivity values that range from 2-10Ω-m. This layer is probably related to brownish clay soil with the thickness ranging 1.7m at VES-1 and 0.9m at

VES-2. Here the top layer on figure 5.4 is somehow it has a small thickness mean not exaggerated.

The second layer, geologically represented by highly weathered and fractured basalt and the range of layer resistivity is 23-38 $\Omega$ -m. The location of resistivity values interpreted as 25 $\Omega$ -m with thickness 2.5m beneath VES-1, below VES-2 resistivity 20 $\Omega$ -m having thickness of about 1.8m .This layer is promising to high ground water potential.

The third layer, has resistivity values that range from 66-84 $\Omega$ -m, geologically represented by moderately weathered basalt, has resistivity 66 $\Omega$ -m with thickness 7.5m and 84 $\Omega$ -m at the depth of 22.2m with a thickness 12.2m and 78 $\Omega$ -m at the depth of 49.4m with a thickness of 27.2m under VES-3

The bottom layer locates beneath 60m depth with resistivity range 10-46 $\Omega$ -m at the depth of range from 65-110m with an average thickness about 60.6m geologic represented by weathered and fractured basalt , it has good ground water potential to drill borehole.

From the figure (5.4) shown below, the discontinuities of geological structures are identical in horizontal position in the curve and plausible Earth model. The geoelectric section and magnetic curve show the same pattern in geological structures which may be concluded as fractures, contact, or faults. The inferred geological discontinuities (structures) exist at an approximate horizontal distance of 350m on the magnetic and electrical result.

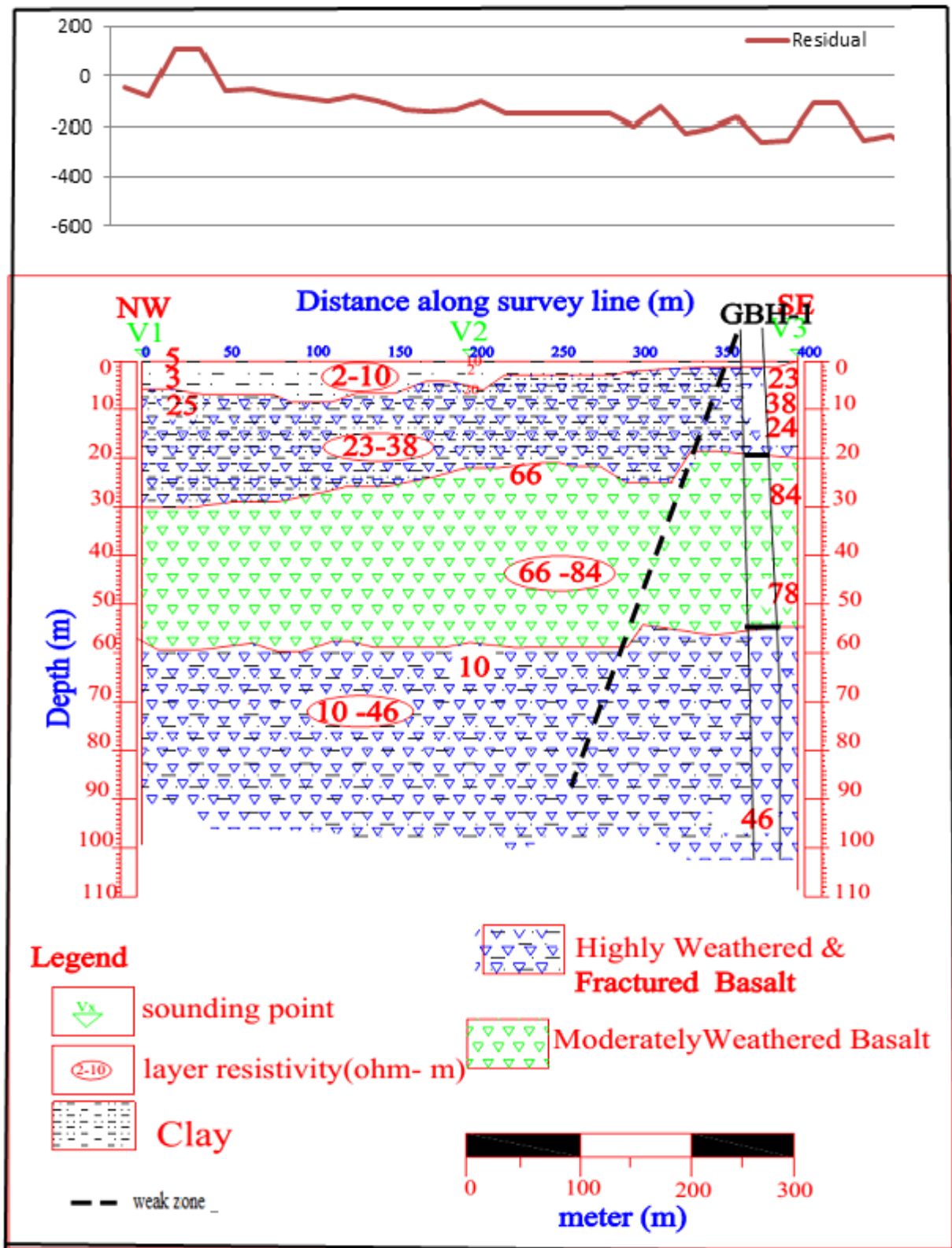


Figure 5.4 Magnetic profile plot and a geoelectric section of profile one.

### 5.2.3.2 Profile Two

This traverse line is the centered above Woldia Stadium oriented in the NE-SW direction and running almost parallel to Woldia International Stadium and West of Asphalt road from Addis Ababa to Woldia. It's located near to W-6 and NBH-2 around Gatira River. The line has a total length of about 0.8 km and there are 3 VES (VES -4, 6 and 7 with average VES point spacing of about 0.266 km).

#### A. Pseudo depth section Along Profile Two

The pseudo-depth sections constructed for VES-4, 6, and 7 that lie on the survey traverse line-2 are given in Figure 5.5. According to this figure, there is negligible lateral variation in resistivity in the section with the extended low resistivity at the top zones mapped between VES-4 and VES-6 but the relatively high resistivity exists at the bottom zone mapped at VES-4 beneath 400m depth. Otherwise, the major region of this profile at the top and right side of the section has a relatively very low resistivity at all VES points. The large area of the section has low resistivity ( $<36\Omega\text{-m}$ ). The vast region under the section shows extensive coverage of the low resistivity zone. The resistivity ranges (0 to  $32\Omega\text{-m}$ ) of this low resistivity region are indicative of the good potential of water saturation.

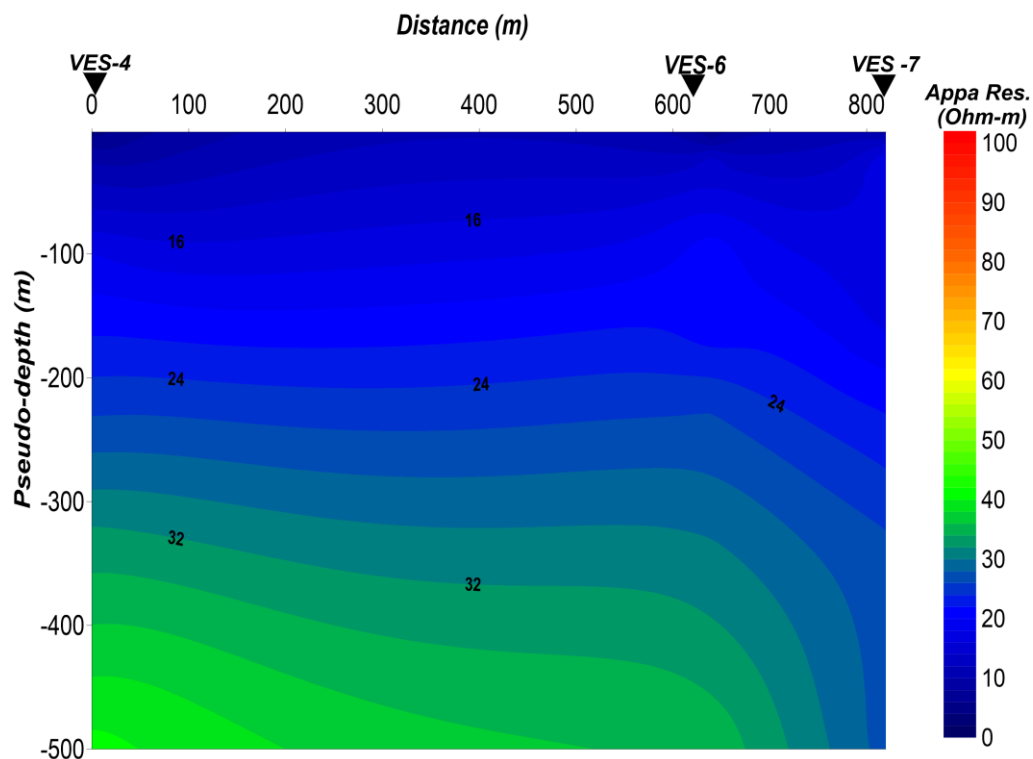


Figure 5.5 Pseudo depth section of Profile two.

## B. Geoelectric section along profile two

The resulting geoelectric section constructed from the interpreted layer parameters of the three VES lying on this traverse is given in Figure 5.6. A borehole NBH-2 (AWWDSE, 2011) is located near profile-2; especially close to VES-6 was also used to constrain the depth and identify the lithological units beneath these VES points during modeling. In essence, the lithological description of the borehole depth section (given in Annex-2) with their resistivity parameters from each interpreted VES was used to construct the geoelectric section shown below (Figure 5.6).

Near-surface geoelectric layer that has a very low resistivity ranging from about 3-10 $\Omega$ -m. The resistivity of beneath VES-4 is 4 and 7 $\Omega$ -m with a thickness 2.6 and 2.2m respectively, under VES-6, the resistivity values are 3 and 10 $\Omega$ -m with a thickness of 0.4m and 0.6m respectively and under VES-7, the resistivity value of this layer is 8 $\Omega$ -m with a thickness of 2.8m. Those similar and low resistivity values indicated the presence of clay intercalation with sand and the thickness variation is about from 0.4-2.8m and may be attributed to the topsoil with alluvial cover (0-10m silty clay).

The second geoelectric layer is marked by resistivity values ranging from 24 to 62 $\Omega$ -m. The thickness variation is from 1.8-10.5m. This layer likely shows that moderately fractured basalt silty sand and sand with gravel, medium grain sized. This layer has good potential of ground water because the relatively low resistivity values dominate all VES under this section, i.e. less than 62 $\Omega$ -m.

The thickness of the next layer varies from 15.3-101.9m and depth 30.3m to 114m, with the lateral variation of resistivity from 13-21 Ohm-m. The lithologies of this layer may be coarse sand within a depth of 30-42m, moderately fractured basalt within a depth of 42-52m, fractured (slightly, moderately and highly) within a depth of 52-84m, highly fractured and weathered basalt within a depth of 84-102m and highly fractured or altered basalt within a depth of 102-122m depth.

From the geoelectrical point of view, the bottom layer in the sequence seems to be more promising for its high potential of groundwater. The resistivity signature, within this section, ranges from 13-21 $\Omega$ -m is a thought to be a response of a conductive basaltic rock. The most likely lithological compositional interpretation is that; this layer may comprise highly weathered and fractured scoriaceous basalt with a possible intercalation of clay materials.

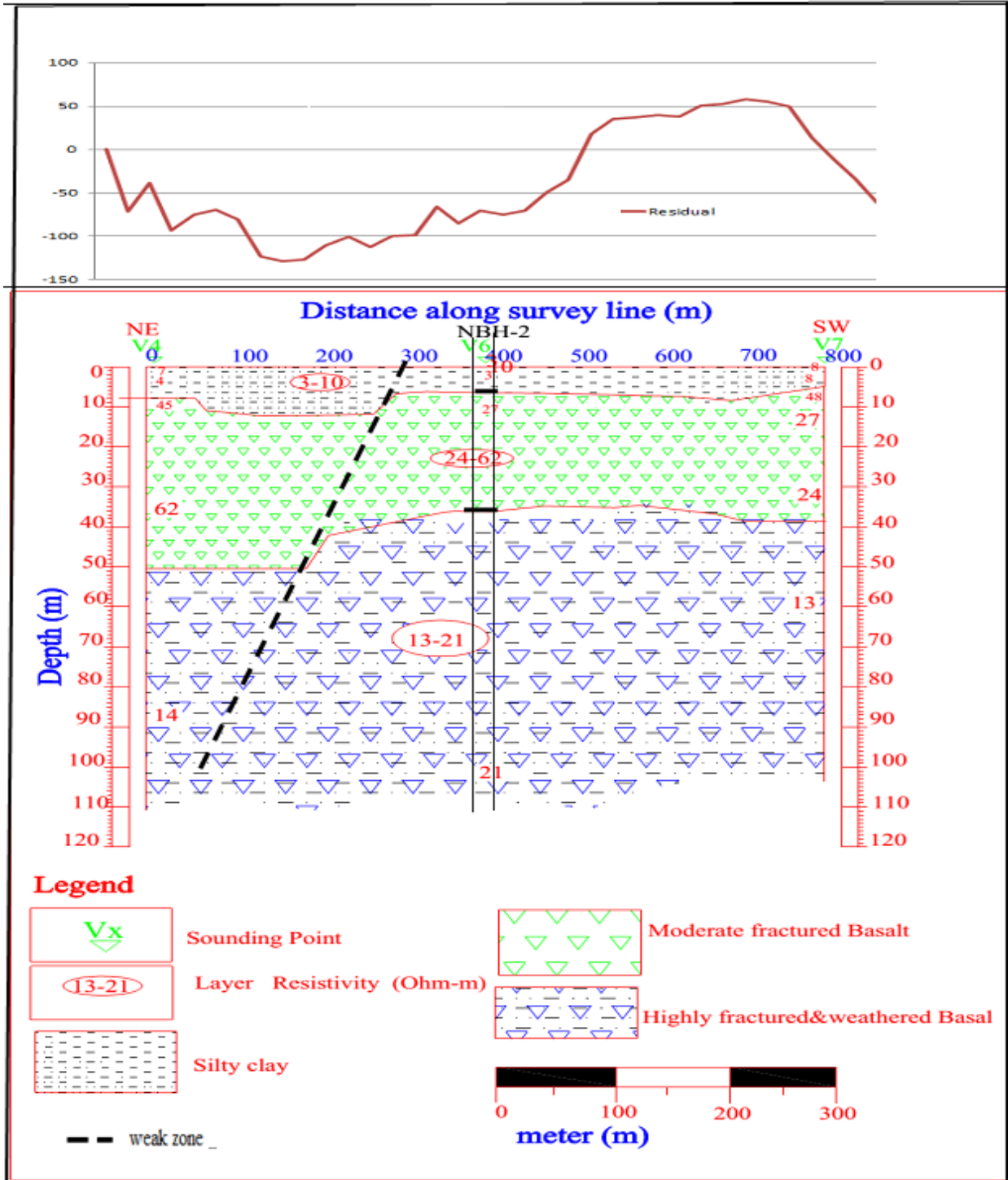


Figure 5.6 Magnetic profile plot and a geoelectric section along profile two.

From the above Figure 5.6, the magnetic curve and geoelectric section show the same pattern in geological structures which may be concluded as discontinuities of geological structures like faults, fractures, contact. The inferred geological structure exist at an approximate horizontal distance of 300m, on magnetic and electrical analysis.

### 5.2.3.3 Profile Three

This traverse line is the centered beneath Millennium High school and near to the Gatira River in between W-6 and NBH-2. It crosses Profile-2 and 6. Approximately, it oriented in the N-S direction and running almost parallel to Millennium High school. The line has a total length of about 0.5 km and there are 3 VES (VES -5, 9 and 10 with average VES point spacing of about 0.166 km.

#### A. Pseudo depth section Along Profile Three

The pseudo depth section constructed for 3 VES that lie on traverse Line/profile-4 are given in Figure 5.7. According to this figure, most part of the section with low resistivity zones and the very low resistivity at the top zone of VES-5 and between VES-9 and 10. Relatively high resistivity zone is found at the bottom of the section below a depth of 450m. Although the larger area under the section shows extensive coverage of low resistivity horizon (2 to 24 $\Omega$ -m) and it is promising to high groundwater potential.

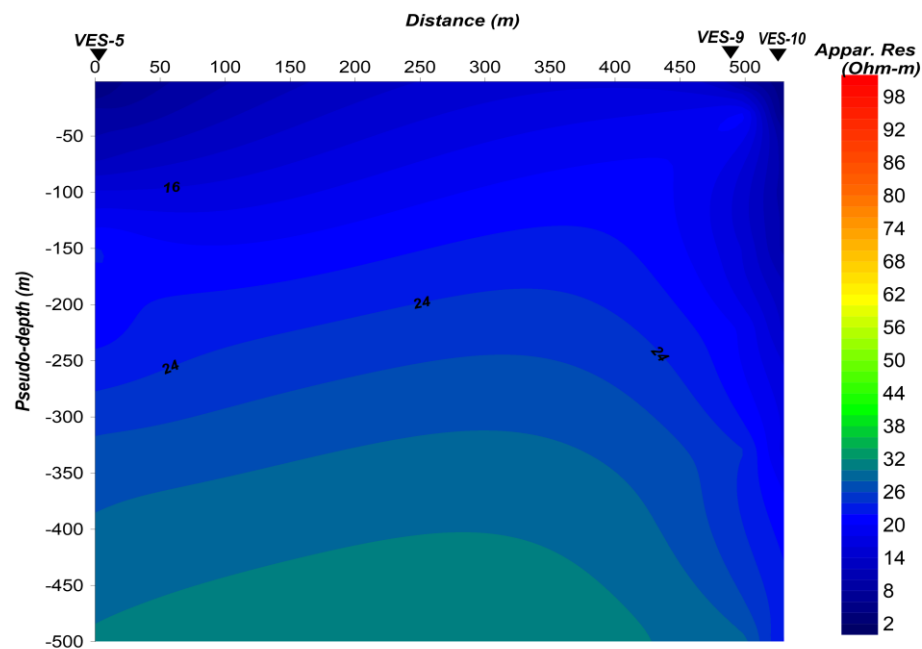


Figure 5.7 Pseudo-depth section along profile three.

#### B. Geoelectric section along profile three

The geoelectric section of profile three (Figure 5.8) was constructed from the model parameters of VES point data found along profile three (VES-5, 9 and 10). The borehole, NBH-2 (100m far from this profile) located around VES-5 was used to constrain (fix) depth for profile three, VES-5 and later parameterize the resistivity values and depths of the other VES points using this

value. Annex-2 shows the lithological log of NBH-2 which was used to fix the depth and type of layers when a geoelectric section of profile three was modeled.

The geoelectric cross-section (Figure 5.8) infers the shallow subsurface lithologic units in the study area which are represented by geoelectric units (having a small and large thickness).

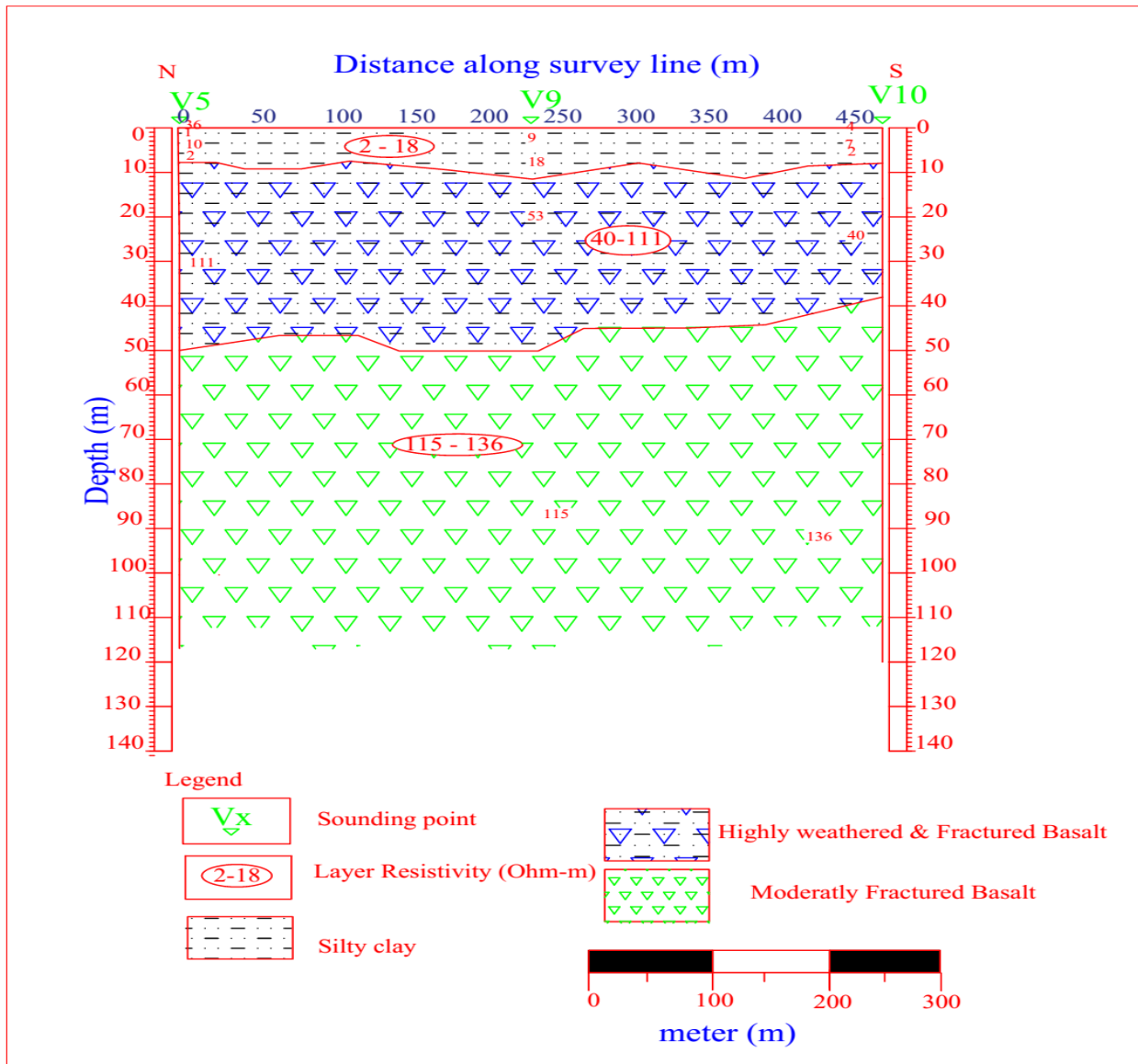


Figure 5.8 Geoelectric section along profile three.

The resistivity value of upper parts  $\rho_1$  (2 -18 $\Omega$ -m) correlated to the silty clay from depth 0-6m, silty sand from 6-12m, and with gravel, medium grain sized, and coarse sand from 30-40m depth. The second layer on the section starting from the northeast and it extends eastern part of the section beneath VES-9 and 10, with the medium resistance horizon  $\rho_2$  (40-111 $\Omega$ -m). Geologically, this layer represents highly weathered and fractured basalt from a depth of 42-52m.

In the pseudo-depth section of profile three, it is shown as low apparent resistivity value to the pseudo-depth of 75m beneath VES-9 and the drilled borehole around this place, NBH-2 has a groundwater yield of greater than 12.9 l/Sec, due to such reason the section between VES-9 and 10, i.e., The second layer of the section may indicate the resemblance in water-bearing capacity and yield of the aquifer, means has good groundwater potential.

The bottom resistivity layers (115-136 $\Omega$ -m) which are starting from northeast parts of the section and it extends towards southeast with an average depth of 130m. Geologically represented as moderately fractured basalt might be a good source of groundwater at a shallow depth up to 87-120m.

#### **5.2.3.4 Profile Four**

This traverse line is the center between Mehale Mechare and Gola Mechare near to profile -5 and it crosses profile-6 from this profile, two VES's located around the previous borehole, which is VES-12 located on NBH-4 and VES-13 found in between mehal mechare and Mechare Abo near to WUNBH. The line has a total length of about 0.9 km and there are 4 VES (VES -12, 13, and 14 with average VES point spacing of about 0.6 km.

##### **A. Pseudo depth section Along Profile Four**

The pseudo-depth sections constructed for VES-12, 13, and 14 that lie on the survey traverse line-4 are given in Figure 5.9. According to this figure, there is slit lateral variation (very low to low or low to very low resistivity zone) in resistivity in the section at the top zones mapped for all VES points. The resistivity of the section between VES-12 and 14 is increased with depth. The top of a section between VES-12 and 14 shows very low resistivity value range (5 to 11 $\Omega$ -m) and it shows the shallow potential of water saturation up to 200m depth. The right side of the section (around VES-14) has a relatively small resistivity than the other side of it. This region under the section shows good coverage of the low resistivity zone. The resistivity ranges (4 to 20 $\Omega$ -m) of this low resistivity region are indicative of good potential water saturation. More on the right side of the region has good shallow water saturated zone.

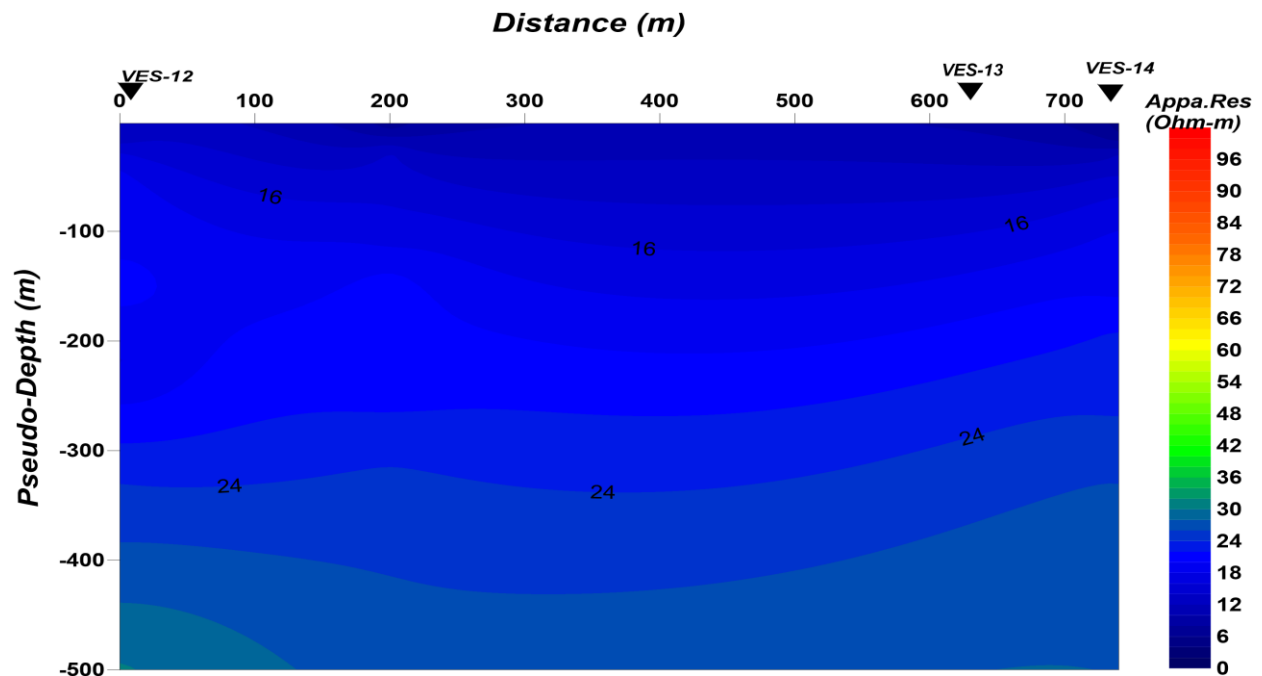


Figure 5.9 Pseudo-section along profile four.

### B. Goelectric section along profile four

The resulting goelectric section constructed from the interpreted layer parameters of the four VES lying on this traverse is given in Figure 5.10. In essence, the lithological description of the borehole depth section, WUNB (given in Annex-2) with their resistivity parameters from each interpreted VES was used to prepare the goelectric section shown below (Figure 5.10). The top goelectric layer is the combination of three interpreted VES curve for simplification of the model. It has low resistivity variation ranging from 3-19 $\Omega$ -m with thickness variation from 0.9-12.9m and may be attributed to clay and silty clay soil.

The second goelectric layer is marked by relatively high resistivity variation ranging from 18-29 $\Omega$ -m. The thickness variation is from 7.6m-12.9m. This layer likely reflects highly weathered and fractured basalt intercalated with trachyte. This goelectric section has good potential of groundwater under VES-13 and 14, because WUNB located near to VES-13 with average yield 28L/s the lithological data of this borehole indicate deposit (gravel, pebble) and dark brown soil within a depth of 30m.

The third goelectric layer that corresponds to the moderately saturated layer manifests resistivity value varies slightly, i.e., 8-9 $\Omega$ -m with a thickness variation of 15.3m-18m and may be represented as moderately weathered and fractured trachyte with sand, gravel and clay, slightly weathered and highly fractured and weathered basalt. The bottom layer is saturated

geolectric layer is detected at the location of VES-12, 13, 14, and 15 with resistivity variation ranging from 18-23Ω-m and most likely represents moderately fractured and weathered basalt and highly fractured and weathered trachyte. This layer also has good potential of groundwater as compared to the above layer.

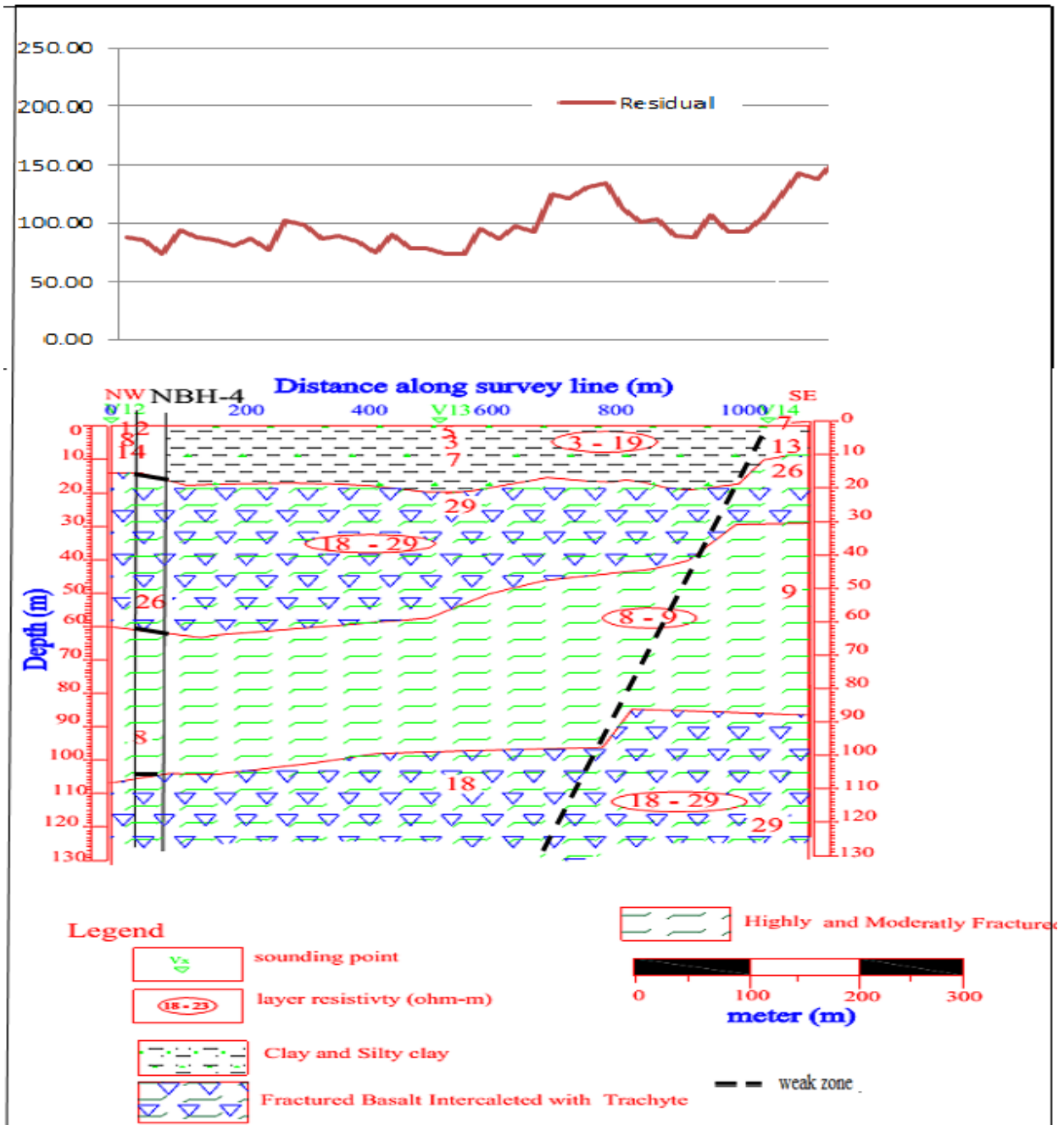


Figure 5.10 Magnetic profile plot and a geoelectric section of profile four.

From the above figure, the discontinuities of geological structures are identical in horizontal position in the curve and plausible Earth model. The geoelectric section and magnetic curve

show the same pattern in geological structures which may be concluded as fractures, contact, or faults. The inferred geological discontinuities (structures) exist at an approximate horizontal distance of 1000m on the magnetic and electrical result.

#### **5.2.3.5 Profile Five**

This traverse line is centered at mehale mechare and its elongated towards Shelle River. It is near to profile-4. From this profile, VES-20 is near to NBH-3. The line has a total length of about 1.4 km and there are 5 VES (VES-16, 17, 18, 19 and 20 with average VES point spacing of about 0.28 km

##### **A. Pseudo depth section Along Profile Five**

The pseudo depth section constructed for the 5 VES that lie on the survey traverse Line-5 are given in Figure 5.11. According to this figure, there is a lateral variation in resistivity in the section with prominent high resistivity away from the top zones mapped between VES-16 and VES-18 but the relatively high resistivity exists near to the top zone mapped at VES-17. This high resistivity zone is extending to a large depth at VES-19. Otherwise, the right side of the section has relatively very small resistivity near to VES-19 and 20. The large area of the top of the section has low resistivity ( $<32\Omega\text{-m}$ ) and the deep depth of VES-16, 17 and 18 has relatively low resistivity value. The vast region under the section shows extensive coverage of the low resistivity zone. The resistivity ranges (2 to  $36\Omega\text{-m}$ ) of this low resistivity region are indicative of good potential water saturation. Specially beneath VES-18, very low resistivity region is indicative of good potential water saturation horizon, because topographically the region dominated by the deposit of Alluvial sediments and also the vast region between VES-19 and 20 shows a good potential of the water bearing horizon.

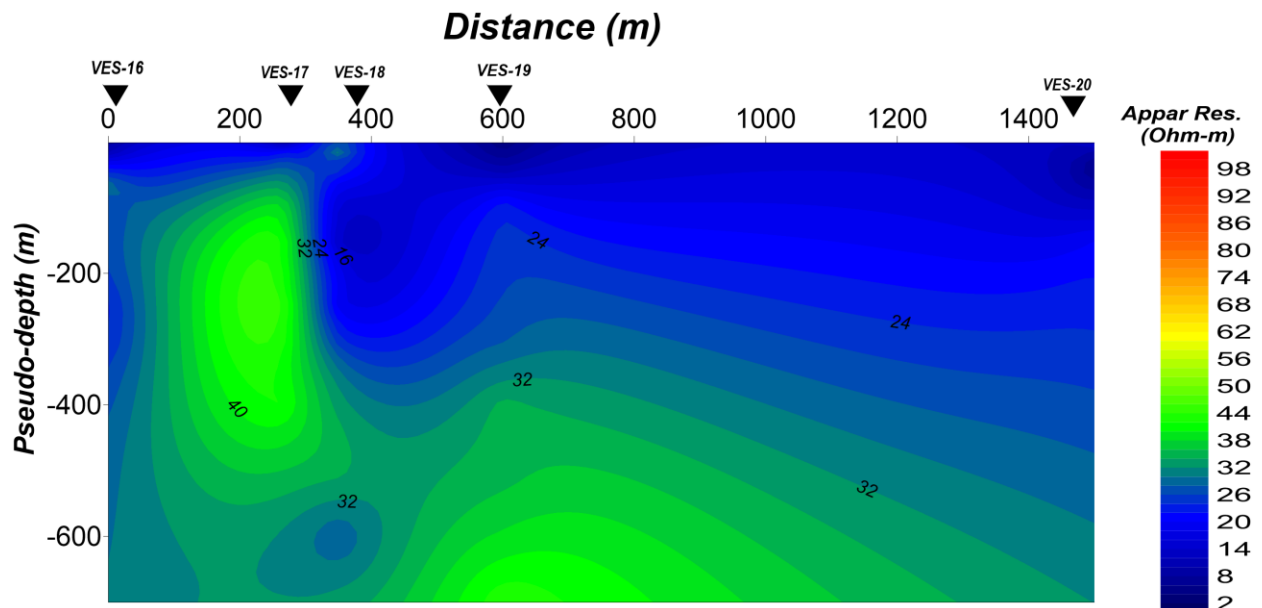


Figure 5.11 Pseudo-depth section along profile five.

### B. Geoelectric Section along profile five

The resulting geoelectric section constructed from the interpreted layer parameters of the five VES laying on this traverse/profile is given in Figure 5.12. In essence, the lithological description of the borehole depth section, NBH-3 (given in Annex -2) with their resistivity parameters from each interpreted VES was used to arrange the geoelectric section shown below (Figure 5.12).

The near-surface geoelectric layer that has variable resistivity ranging from about 2-116 $\Omega$ -m. The differences between the resistivity values not high due to slight variation in the amount of grain size. Areas with low resistivity values indicated the presence of silty clay intercalation with sand and the depth variation is about from 0-10m, while those with relatively high resistivity values indicated the presence of gravel and sand as topsoil.

The second geoelectric layer is marked by resistivity values ranging from 16-33 $\Omega$ -m. The depth variation is from 42-60m. Depending upon the borehole lithological description, this layer probably indicates sand with gravel

The third geoelectric layer that agrees to the highly weathered and fractured basalt with clay layer manifests resistivity value, relatively high variation in resistivity value, i.e., 10-165 $\Omega$ -m with depth variation from 65-125m. . This layer of the section may indicate the resemblance in

water-bearing capacity and yield of the aquifer, means has good groundwater potential, mean it is a promising layer of high potential ground water with in a depth of 60-110m.

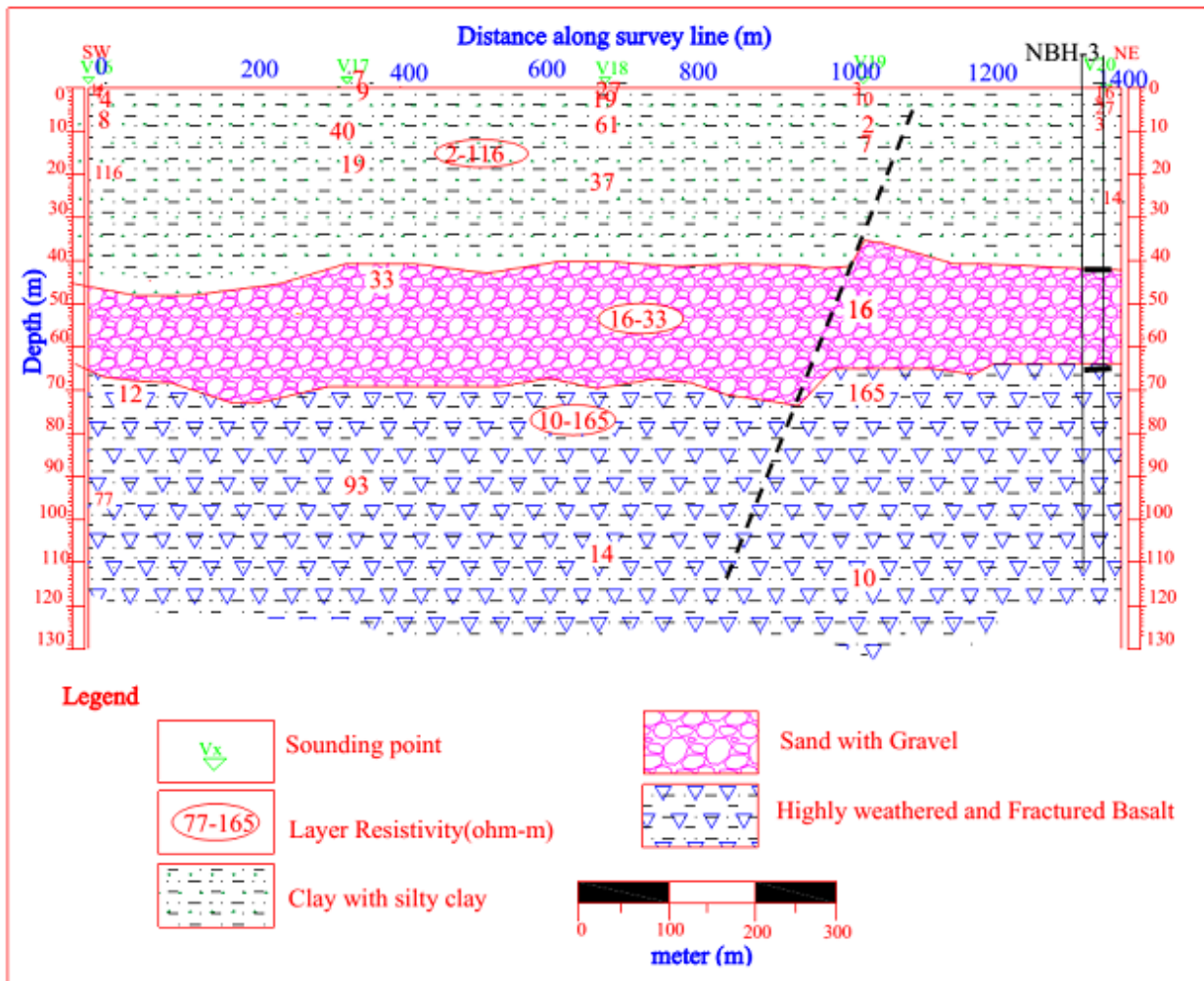


Figure 5.12 Geoelectric section along profile five.

### 5.2.3.6 Profile Six

This traverse line is the centered mehale mechare and Mechare Abo. It crosses the three profiles; profile-13, 4 and 5. BH-7 located around this profile. The line has a total length of about 1.6 km and there are 4 VES (VES -8, 11, 17 and 18 with average VES point spacing of about 0.4 km

#### A. Pseudo depth section along profile Six

Figure 5.13 shows the pseudo-depth section constructed for the 4 VES points that lie on this survey traverse Line-6. According to this figure, there is a lateral variation in resistivity, some part of the section is very low resistivity zones mapped beneath VES-8, 11 and 18 with a

resistivity range of 1.1Ω-m to 24Ω-m, but the relatively high resistivity exists near to the top zone mapped at VES-17 and it's extending to large depth. And also relatively high resistivity exists at the high depth of VES-8. The large area of the top of the section has a small resistivity (<40Ω-m) and the deep depth of VES-11 and 18 has very small resistivity value. The vast region under the section shows extensive coverage of the low resistivity zone. The resistivity ranges (0 to 32Ω-m) of this very low resistivity region are indicative of potential water saturation, with the need to closely look into the opportunity of this low resistivity resulting from higher mineralized groundwater. Generally from this profile the region beneath VES-11and 18, shows that good water-bearing horizon and have the good water potential to drill the borehole.

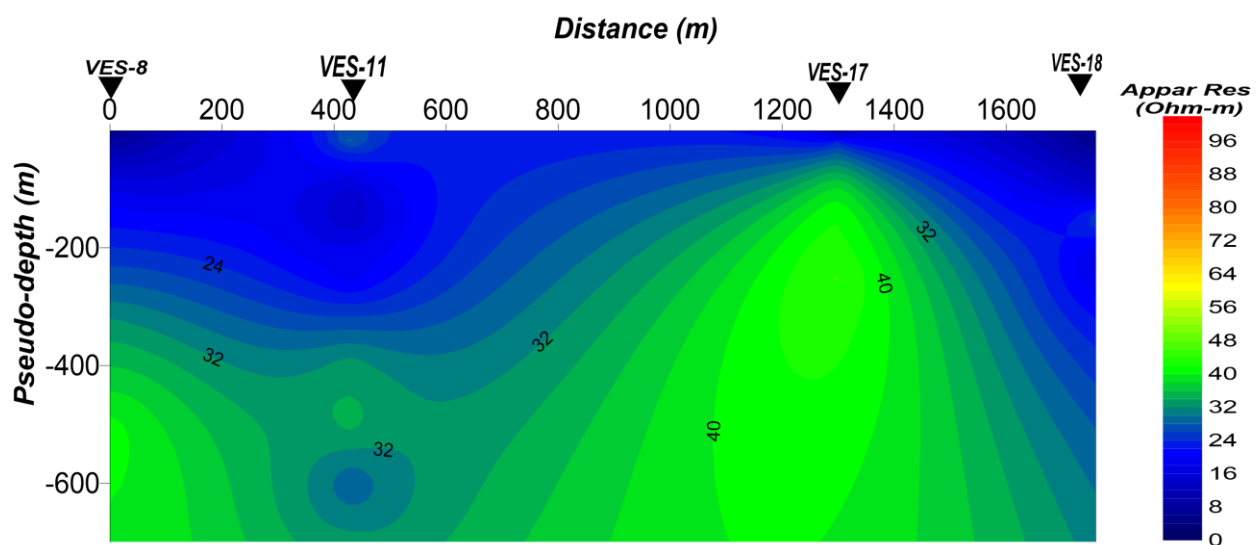


Figure 5.13 Pseudo-depth section along profile six.

### B. Geoelectric section along profile Six

The resulting geoelectric section constructed from the interpreted layer parameters of the 4-VES laying on this traverse is given in Figure 5.14. In essence, the lithological description of the borehole depth section, BH-7 (given in Annex-2) with their resistivity parameters from each interpreted VES was used to provide the geoelectric section shown below (Figure 5.14).

From the section given in Figure 5.14, it is seen that the subsurface consists of different geoelectric horizons. The layer representing the top part of the section, whose resistivity values show lateral variations of resistivity range 2-55Ω-m up to a depth of 50m. Beneath these layers is a relatively low resistivity horizon (2-12Ω-m), clay covering the region from the West of the line towards East direction. Its thickness extends from a depth of about 2m to 8.9m. From

lithological description of BH-7, the layer represented by clay with minor gravel. The low resistivity response of this layer that shows it is possible to water saturated zone. Towards the northeastern side of the line, the resistivity values suggest the presence of a structure somewhere between VES-11, 17 and VES-18.

The second layer mapped with the survey spacing used is again a region showing relatively high resistivity (15- 67 $\Omega$ -m), geologically represented by boulder, gravel with minor clay. It has a considerable thickness 9.6m-88.6m thick that extends from an average depth of 55 to 85m depth. This layer of the section may indicate the resemblance in water-bearing capacity and yield of the aquifer, means has good groundwater potential, mean it is a promising layer of high potential ground water with in a depth of 55-90m.

The bottom layer of this section with the survey spacing used is a region showing relatively low resistivity (14-18 $\Omega$ -m), geologically represented by gravel. From the point of view of the objective of the study/survey, the regions on the southeastern side of the line (i.e. Between VES-17 and VES-18) are zones that a borehole sunk to depths in excess of 130 m will likely tap groundwater.

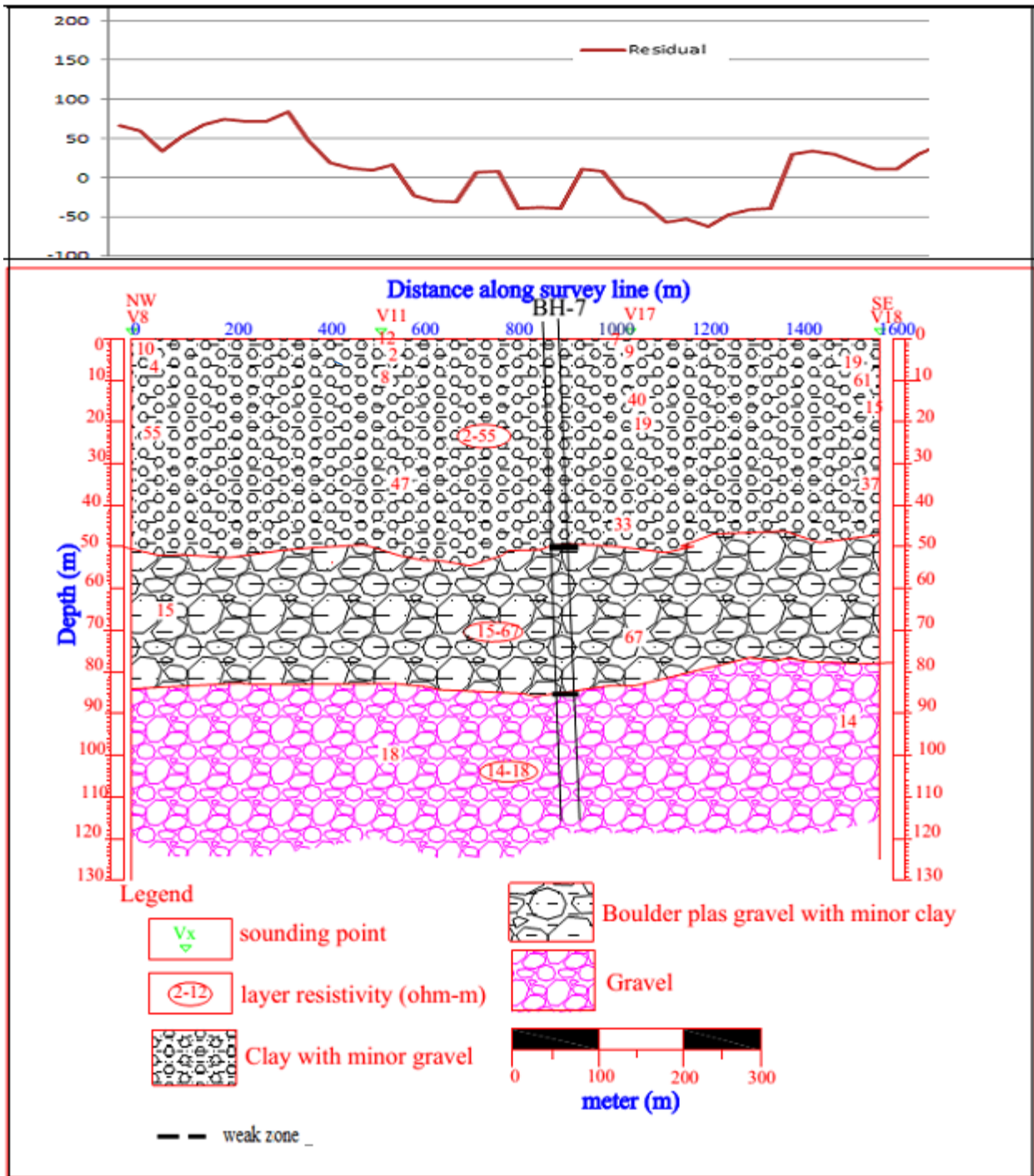


Figure 5.14 Magnetic profile plot and a geoelectric section of profile six.

From the above figure, the discontinuities of geological structures are identical in horizontal position in the curve and plausible Earth model. The geoelectric section and magnetic curve cannot show the same pattern in geological structures, because the lithological description of

BH-7 indicate strong geological structure rather than weak zones, which may be concluded as fractures, contact, or faults. But, magnetic curve shows geological structure, which may be concluded as fractures, contacts, or faults. The inferred geological discontinuities (structures) exist at an approximate horizontal distance of 600m, and 1200m on the magnetic and electrical result.

### **5.3 Results and interpretations of resistivity Survey**

For the intention of conveniences, six profiles, which are supposed to represent the area, have been selected and the apparent resistivity distributions at different electrode depths (separations) have been considered in map formation and consequent interpretations. Because, consistent readings among the selected profiles have been achieved at electrode separations of ( $AB/2= 9m, 45m, 66m, 100$  and  $150m$ ), the corresponding apparent resistivity maps are generated for the respective electrode separations.

The interpretations of the electrical survey results are alone of qualitative in terms of the apparent resistivity maps being generated for different electrode separations or depths.

All of the apparent resistivity maps presented here are generated using the sulfur-10, by gridding the respective apparent resistivity values at the respective  $AB/2$  from the profiles considered. For instance, the apparent resistivity map for  $AB/2 = 9m$ , was generated by gridding the apparent resistivity values of all VES points from all six profiles. The same applies to the other maps in different  $AB/2$ 's mentioned.

Accordingly, the results of the resistivity survey in Woldia University - Mechare Meda area are presented as follows.

#### **5.3.1 Apparent resistivity map of $AB/2= 9m$**

As shown in Fig 5.15 that the Eastern and southwestern part of the study area is characterized by medium resistivity value zones. This medium resistivity zone tends to extend laterally in approximately E-W and NNW-SSE directions. This medium resistivity zone is flanked by relatively very low to low resistivity zones in the south, north, and most of the central part of the study area. The Central low and very low resistivity zone is associated with the topographically highly weathered and fracture, alluvial sediment and Ashangi basalt.

The flanking low resistivity zones appear to be associated with Ashangi basalt and alluvial sediments.

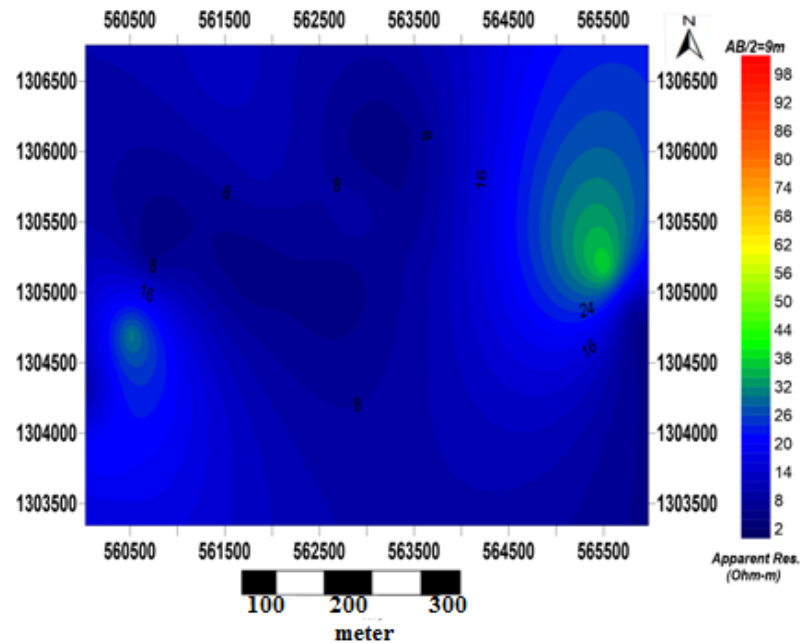


Figure 5.15 Apparent resistivity map for  $AB/2 = 9m$ .

### 5.3.2 Apparent resistivity map for $AB/2 = 66m$

This apparent resistivity map (Fig.5.16), clearly shows that the central part of the mapped area is characterized by low to very low resistivity with E-W and N-S direction and, and southern direction. Northeastern part relatively characterized by high to very high resistivity zones. Within the broad high resistivity, zones are locally limited, very high resistivity zones forming the peak values in the study area. The resistivity values gradually decrease as one goes towards the NW and SW direction. Topographically this low resistivity zone characterized by highly weathered fracture basalt and Ashangi basalt.

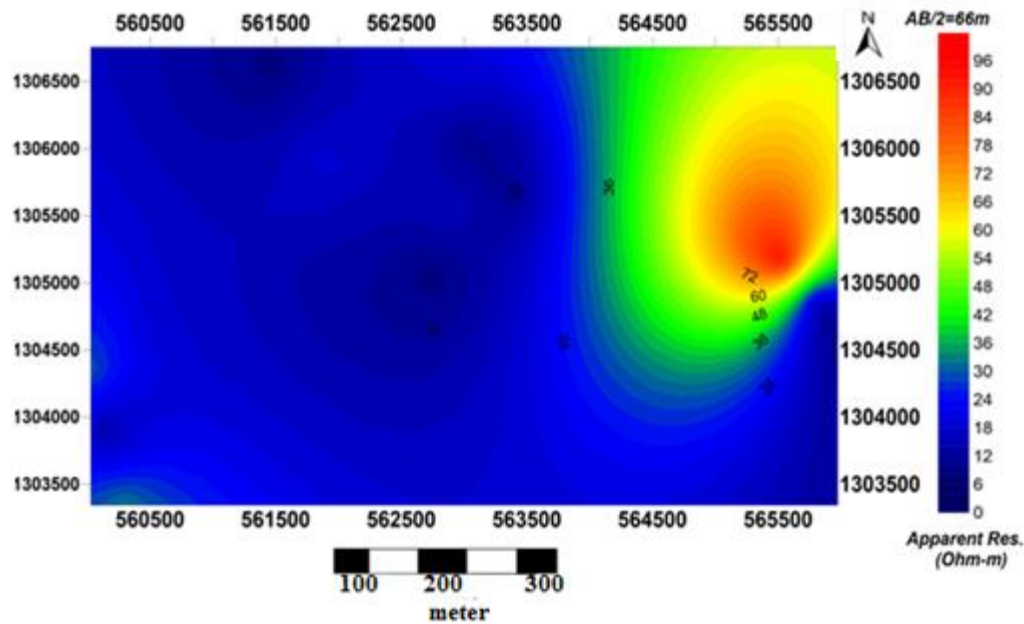


Figure 5.16 Apparent resistivity map for  $AB/2 = 66m$ .

### 5.3.3 Apparent resistivity map of $AB/2 = 100m$

For understanding the electrical resistivity distribution sake, the mapped area can be classified into three electrical resistivity zones as representing high to very high, intermediate, and low to very low electrical resistivity regions.

Accordingly, this map (Fig.5.17) is characterized by high to very high resistivity zones on its eastern, and NE parts, with regions of an intermediate resistivity towards west of these regions and zones of low to very low electrical resistivity towards NW, SW and western part of the study area, but very low resistivity zone in the central part and to the edge of South East direction, topographically dominated by Ashangi basalt, highly and slightly weathered fractured basalt. The central part of the area, i.e. Mehal Mechare is good for high groundwater potentials.

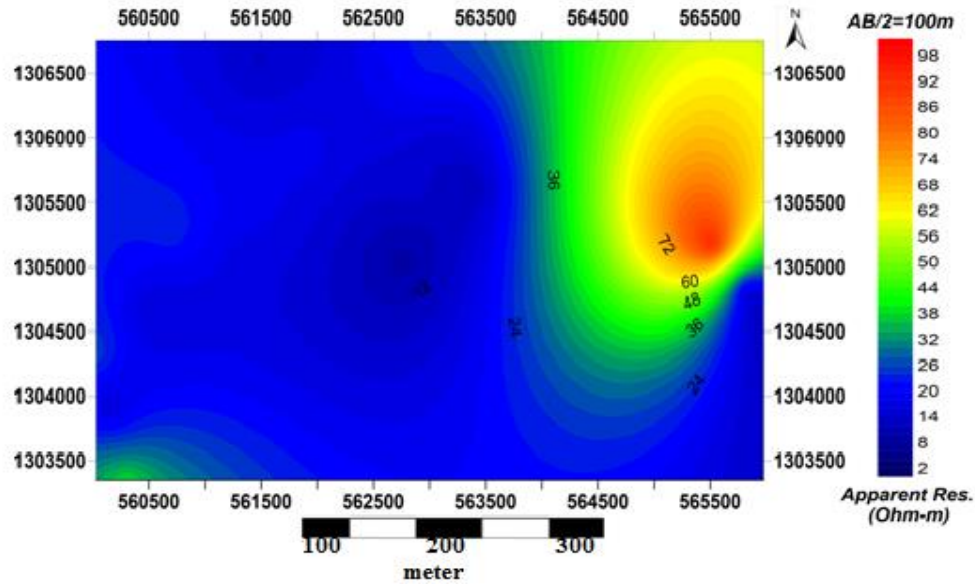


Figure 5.17 Apparent resistivity map for  $AB/2 = 100m$ .

### 5.3.4 Apparent resistivity map at $AB/2=150m$

In this map (Fig 5.18) the apparent resistivity value indicates from relatively very low to low resistivity zone and very low resistivity zone is located in southern, central, and southeastern part of the study area which is interpreted as the presence of highly saturated alluvial, alluvial sediment deposit around Mehale Mechare and Gola Mechare area.

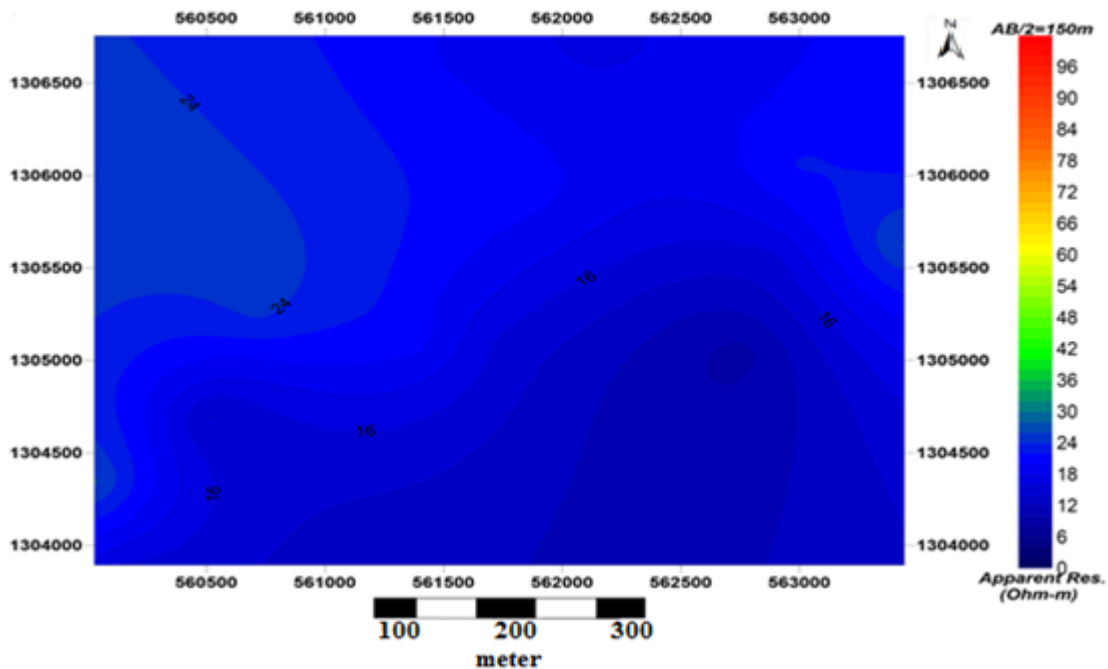


Figure 5.18 Apparent resistivity map for  $AB/2 = 150m$ .

## 5.4 2D Modeling

2D Modeling is done using the GM-SYS modeling software. It is an interactive forward modeling program which calculates the magnetic response from a user-defined hypothetical geological model. Any difference between the model response and the observed magnetic field are reduced by refining the model structure. It should be noted that magnetic models are non-unique, i.e. many earth models can produce the same magnetic response, and similarly, several geological lithologies may be interpreted from a given model block's susceptibility properties. It is therefore important to use as many independent sources of information as possible to constrain the model. The 2D model created by GM-SYS extends to depths of 50km by default and it changes with depth (Z-direction) and along the profile (X-direction, perpendicular to strike) (GETECH Group plc., 2007). Accordingly, 2D magnetic modeling is developed from the interpreted layer parameters of the VES (geo-electric section of VES) and borehole data (GBH-1 and NBH-2) which is found in the Annex-2. The developed model has an error of fewer than 4.5% and it perfectly matches with all the maps and curves developed along the profiles from the different methods in displaying the layering, fault and contact location. Based on this model, the faults and contacts are located around a depth of 65-270m.

### 5.4.1 2D Magnetic model along profile one

The 2D magnetic model (Fig.5.19) is constructed along profile one runs in a NE - SW direction which is aimed to show variation in magnetic susceptibility and lithological units. The 2D magnetic model (Fig. 5.19) constructed along profile one consists of four layers based on the depth/lithology of GBH-1, interpreted layer parameters of the VES (geo-electric section of VES) and magnetic susceptibility constraints considered for the initial model. A further adjustment of these parameters resulted in a fit between the observed and calculated magnetic values (Fig. 5.19).

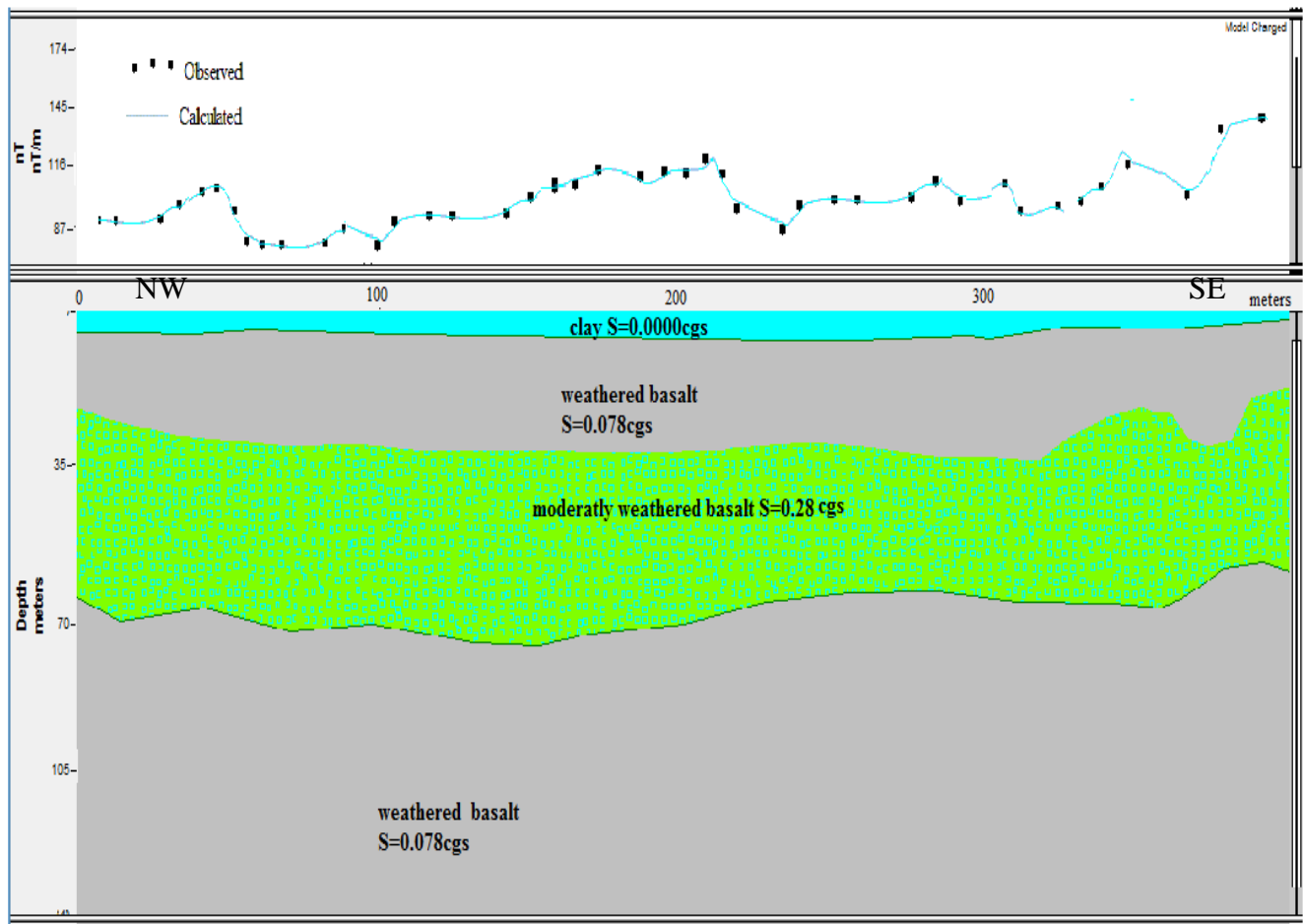


Figure 5.19 D Magnetic modeling along profile one.

The final magnetic model corresponding to the first layer consists of relatively low magnetic susceptibility near surface topsoil products with an average magnetic susceptibility value of about 0.000001cgs. The average thickness of this layer varies from 1-6 m. The second Layer has an average magnetic susceptibility value of 0.078cgs is interpreted as the weathered basalt. The third layer shows thick moderately weathered basalt, with average thickness 20-65m. The fourth layer is interpreted as weathered basalt rocks with an average thickness depth from 70-130m. The model shows that the existence of faults below a depth of 25m. The model shows that the existence of faults below a depth of 25m. From the geoelectric section, the scoria and basalts are varying in their degree of weathered and fracture. Again the remanence of the basalt also varies in each of the layers

## CHAPTER SIX

### 6. CONCLUSIONS AND RECOMMENDATIONS

#### 6.1 Conclusions

Based on the result of interpretations and discussions, the following conclusions have been drawn using the synthesis of data presentation approaches:

1. The Ashange formation of basalt and alluvial deposited that covers most parts of the region around Woldia town is a poor aquifer. It can transmit and store groundwater only along its fracture openings. The main water-bearing formation of the well is highly fractured and weathered basalt.
2. Mechare Meda is an inter the mountain valley filled with materials transported from the surrounding high grounds. The grain size of the filled sediment deposit varies from clay to gravel and it could be over 80 m thick in some parts of the filled valley. The coarse-grained deposits in Mechare Meda are good water-bearing zones and they have high transmissivity.
3. The apparent resistivity pseudo-depth sections and the true resistivity geoelectric sections show the influence/existence of shallow as well as deeper low resistivity horizons which are potential zones of groundwater saturation. The large thickness and low resistivity of these horizons is an indicator of high groundwater potential in the study area.
4. The most important geologic units engagement over the survey area that is likely to bear groundwater (based on the degree of fracturing and weathering) are alluvial deposits and basalts.
5. Comparison of the geophysical interpretations with drilled borehole results shows that the results of the geophysical survey are the good correlation with the borehole lithological logging results.
6. The geologic structures (faults, fractures, and contacts) play the powerful role in the occurrence and movement of the groundwater in the study area. The highly to moderately weathered and fractured basalts and sand layer supply more for the recharge and movement of the groundwater through the wake zones and faults.

7. The water table of the study area varies from 20 to 60 meters deep that increase more towards the northwest of the study area.
8. Some of the significant locations and depths of water-bearing horizons over the survey traverse lines are as follows:
  - ❖ Profile -1: As shown in Figure 5.4, the water-bearing horizon is mapped to be at the depth below 20m and a borehole selectively drilled to a depth of range between 100m and 300m.
  - ❖ Profile -2: A borehole preferably drilled to a depth below 30m and between VES-4 and VES-6 may yield the high volume of groundwater (Figure 5.6).
  - ❖ Profile -3: From Figure 5.8, the depth of the water-bearing horizon is at the depth 50m for VES-9, and 10.
  - ❖ Profile -4: As shown in the Figure 5.10, at the depth below 30m has the water-bearing horizon. The borehole preferably drilled to a depth below 60-150m for VES-12 and 13.
  - ❖ Profile-5: As shown in the Figure 5.12, at the depth below 40m has the water-bearing horizon. The borehole preferably drilled to a depth below 70m for VES-19 and 20.
  - ❖ Profile -6: As shown in the Figure 5.14, at the depth below 60m has the water-bearing horizon. The borehole preferably drilled to a depth below 60m for all VESs.

These have been indicated as preferred locations for the sinking of boreholes to extract the good amount of groundwater. A drilling program- both test and production- is suggested to focus on these areas.

## 6.2 Recommendation

Generally, based on the outcome of this study, the following thoughts are highly recommended.

1. The wells should be drilled through the alluvial deposited and the weathered and fractured sections of the basalt rock. The depths of the wells could be about 120 m, but it may reach 150 m depending on the conditions. The supervising hydrogeologist should determine the final depth of the wells.

2. Gatira valley should be kept free of polluting materials and the town's waste should be managed properly to minimize pollution of the well field. As the well is found very nearer to the river called Gatira, river treatment mechanisms must be implemented.
3. It is highly recommended that to study detailed structural geological investigations for mapping the orientation of fractures, faults, and weak zones as well as their natures like a strike, dip, and their extension.
4. The aquifer system of the area is controlled by the structural lines such as faults, weak zones, so that drilling is recommended to be done at places having the low resistivity at large AB/2 separation.
5. Even if there are Six (6) already drilled boreholes (some of them are recommended as a result of this work) in the study area, depending on the need and necessity of the people, the following three boreholes are recommended for drilling. The first borehole is recommended at or around VES-4, VES-12, and VES-19 with UTM coordinates (560960, 1305320), (561458, 1305350) and (561481, 1306501) respectively.
6. Additional detailed magnetic survey inside and outside of the area is recommended to investigate/explore the extension of faults that are behaving to serve as a conduit for groundwater flow.
7. To understand the basin, the amount of precipitation and evaporation which are used to estimate the percolation of surface water to the groundwater, further hydro-geological and regional hydrological investigations are recommended.
8. For additional the investigation of drilling point and the quality of the groundwater in the area; It is highly recommended that to study detailed time-domain electromagnetic survey and geochemistry.
9. The additional VES survey is recommended in the horizontal and perpendicular direction of the existing profiles for detail investigation for the extension of low resistivity zones.
10. Agricultural activities, industrial and domestic waste disposals are going to be the potential threats for the pollution of the water sources in the basin, as a result, serious attention has to be given for such activities in the future.

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### DECLARATION

I, the undersigned, hereby declare that the thesis entitled with: **“Application of integrated geophysical techniques to map groundwater potential zones and geological structures at Woldia University and Mechare Meda, North Wollo Zone, North Ethiopia”** is my original work carried out under the supervision of Professor Tigistu Haile and Dr.Dessie Nedaw and has not presented to any University or institution for the award of any degree or diploma program and all sources of materials used for the thesis are duly acknowledged.

Name of the candidate

Signature

Date

Getachew Belay

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge and it has been submitted for examination with my approval as University advisor.

Signature

Date

Prof. Tigistu Haile  
(Advisor)

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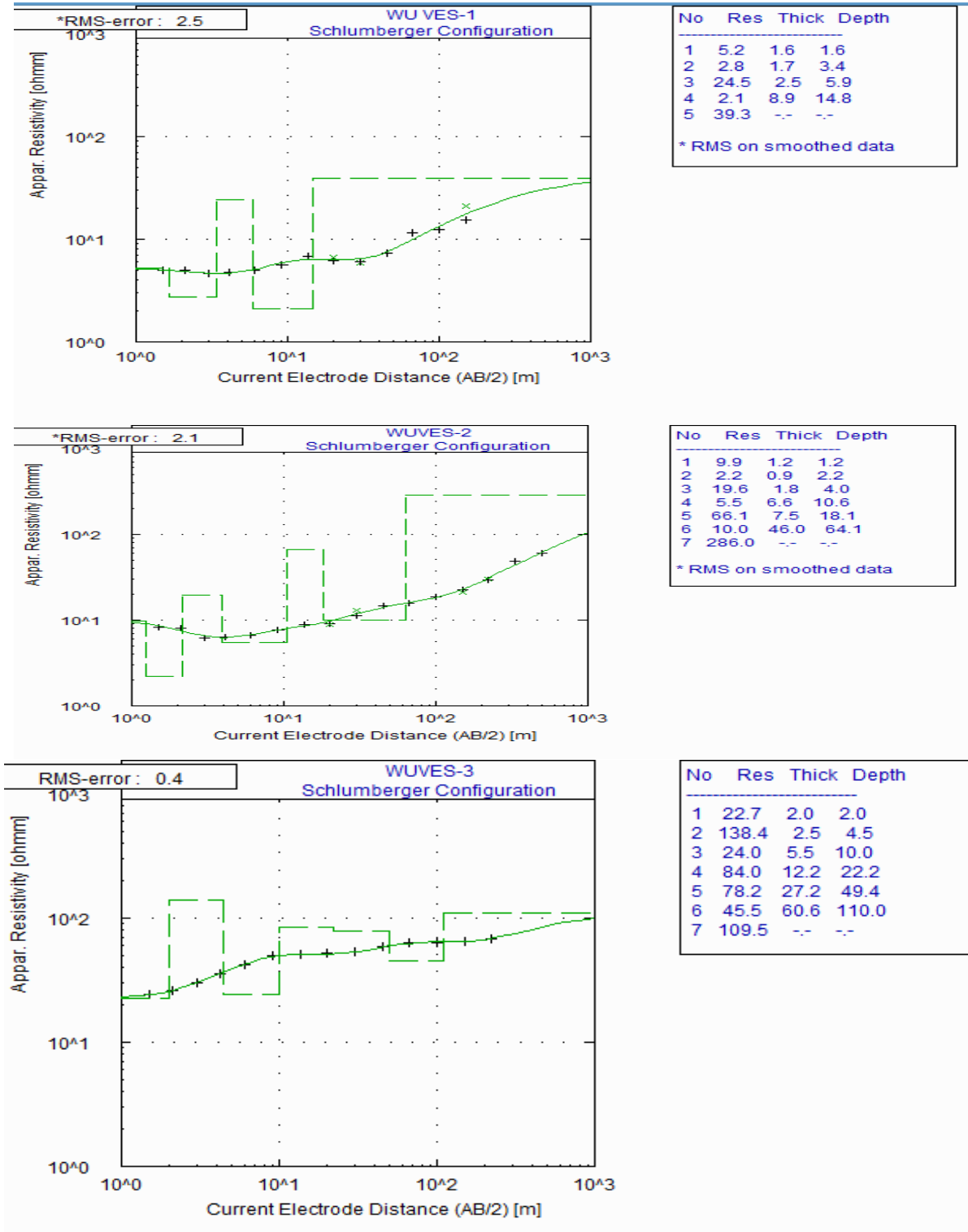
Dr.Dessie Nedaw  
(Co-Advisor)

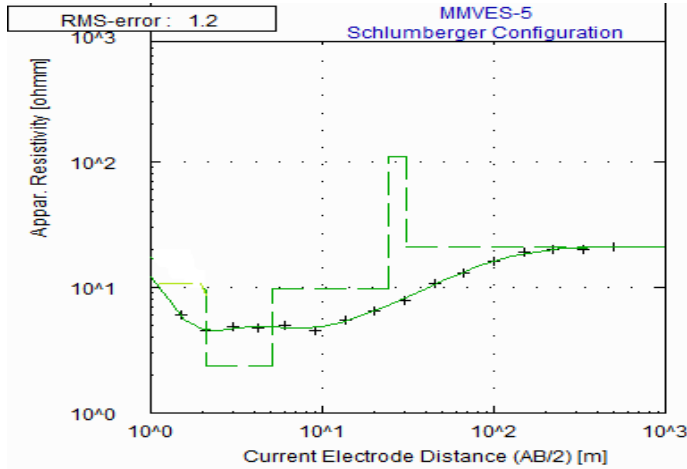
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APPENDICES

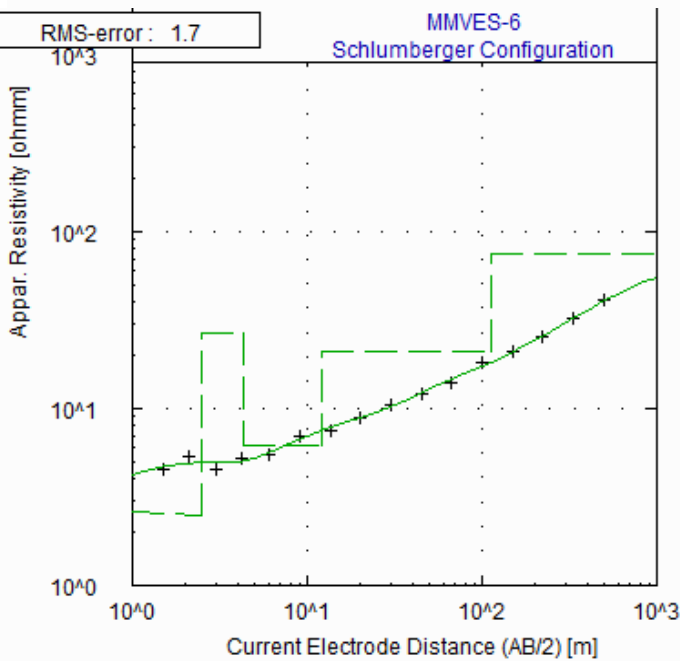
Annex 1: INTERPRETED VES CURVES OF THE EACH SOUNDING POINTS





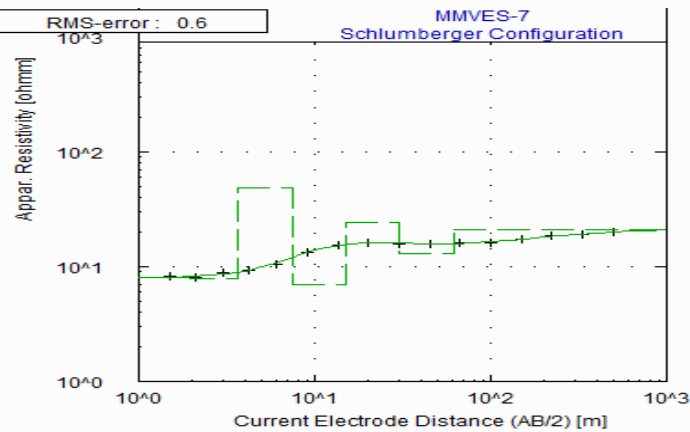
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6	111.0	6.7	30.8
7	21.0	--	--



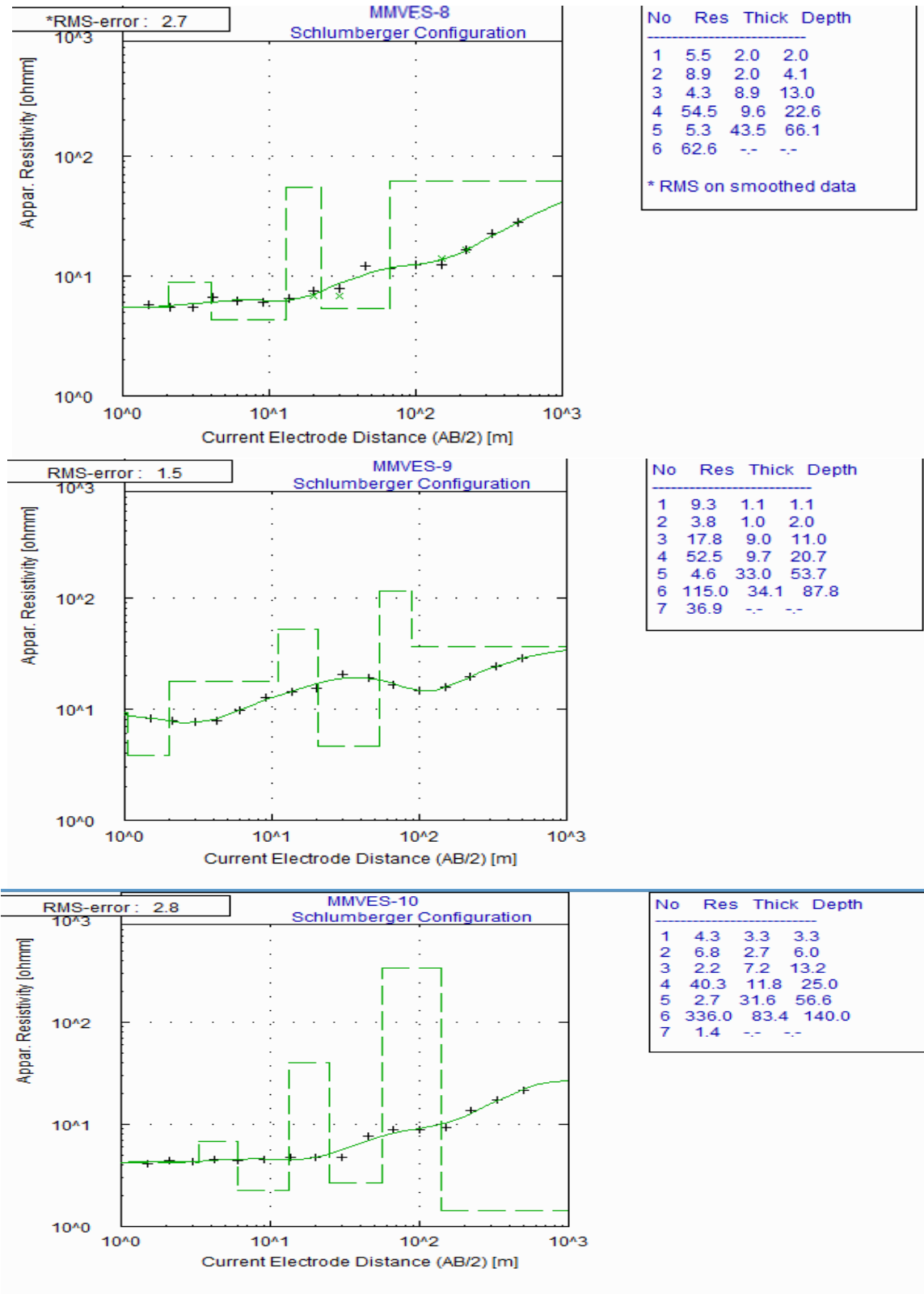
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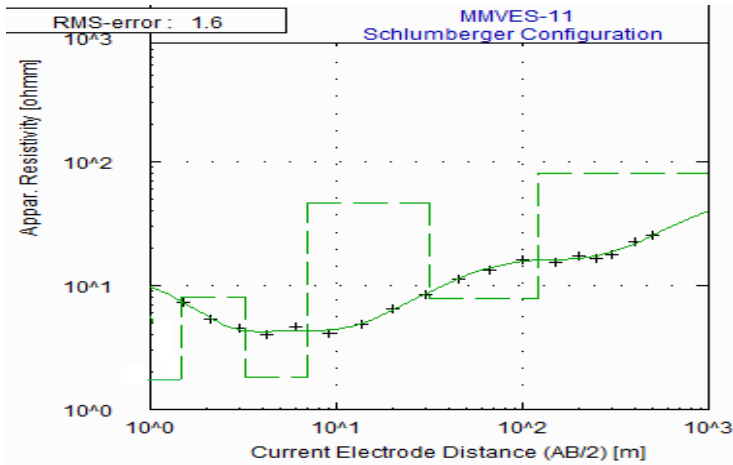
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5	6.2	7.8	12.1
6	21.1	101.9	114.0
7	74.6	--	--



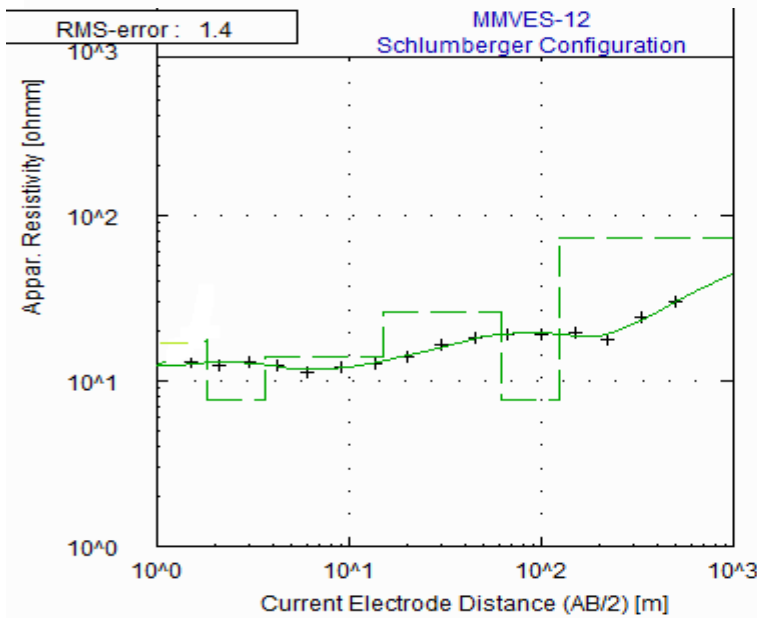
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5	24.0	15.3	30.3
6	12.9	30.9	61.2
7	21.2	--	--

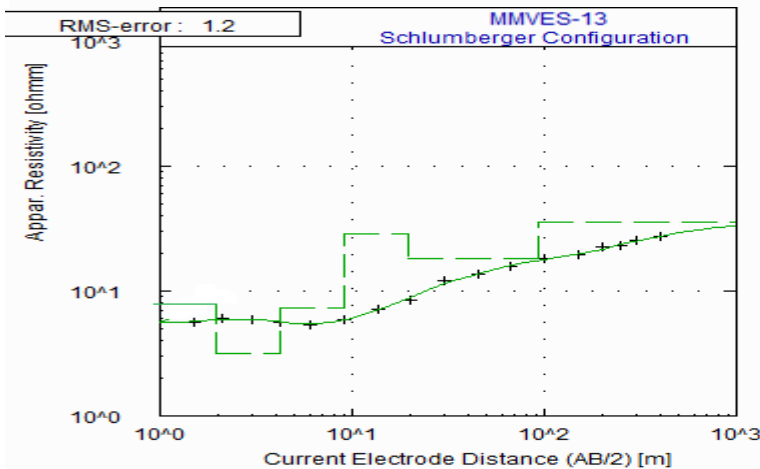




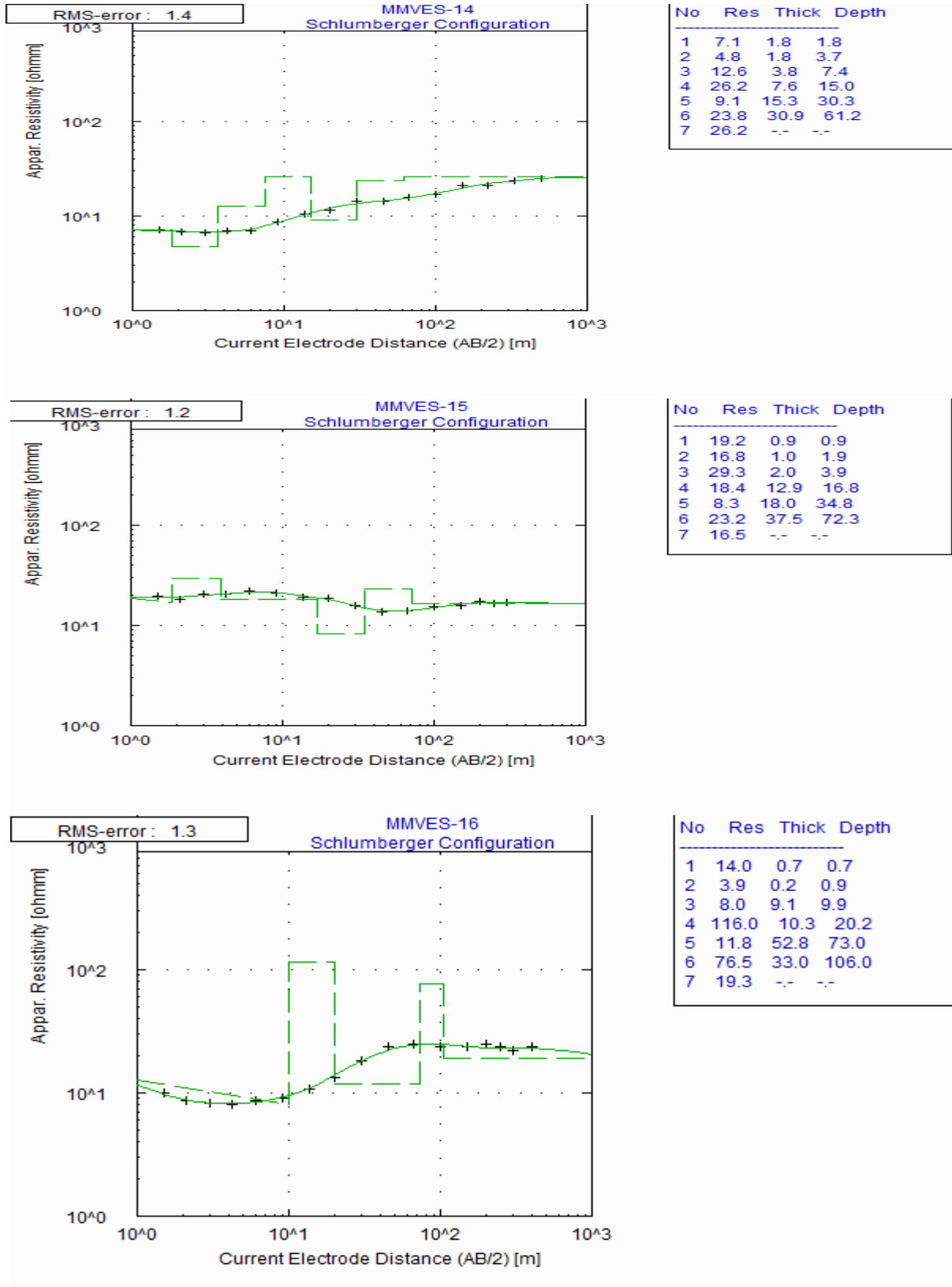
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5	46.7	24.6	31.6
6	7.9	90.4	122.0
7	80.7	--	--

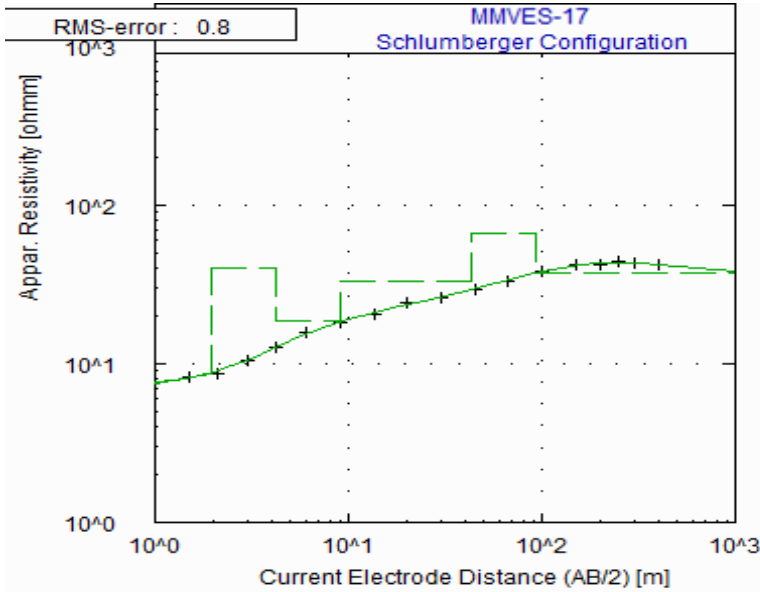


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2	17.7	0.9	1.8
3	7.7	1.9	3.7
4	13.9	11.3	15.0
5	26.1	46.3	61.3
6	7.7	62.7	124.0
7	74.0	--	--

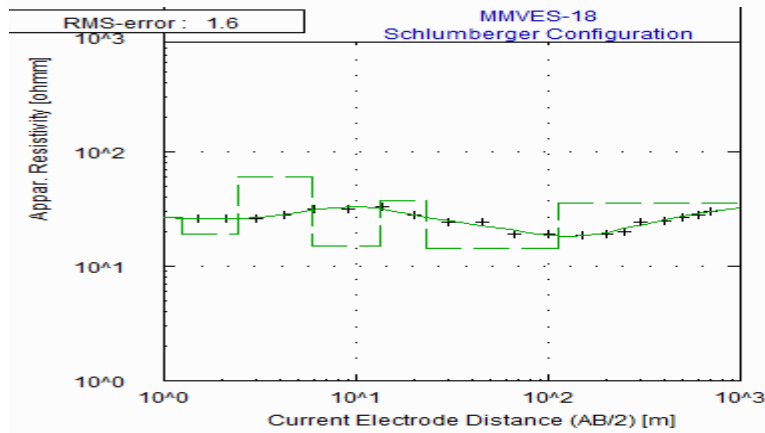


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3	3.2	2.3	4.2
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5	29.0	10.6	19.7
6	18.1	73.5	93.2
7	35.8	--	--

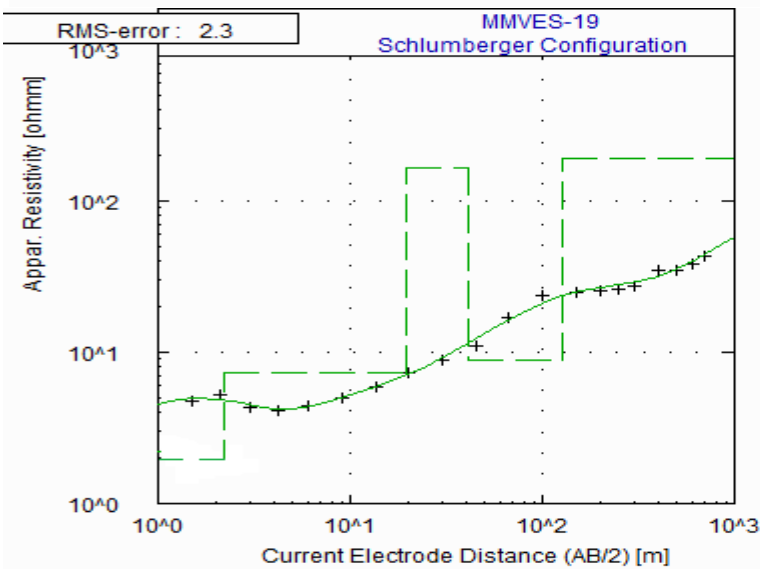




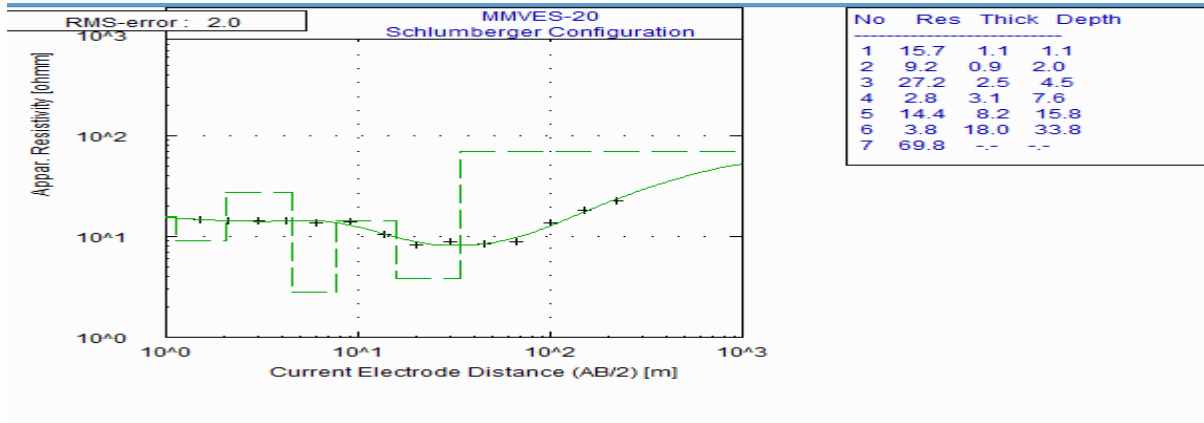
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4	18.7	4.9	9.1
5	32.9	33.6	42.7
6	67.0	49.7	92.5
7	37.7	--	--



No	Res	Thick	Depth
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2	18.9	1.1	2.4
3	60.5	3.5	5.9
4	15.2	7.3	13.2
5	37.4	10.2	23.4
6	14.4	88.6	112.0
7	35.9	--	--



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3	1.7	1.2	2.2
4	7.3	17.4	19.6
5	165.0	21.6	41.2
6	8.9	85.8	127.0
7	191.0	--	--



**Annex 2: Bore holes**

**A. Summary of the lithological logs for newly drilled boreholes and BH-7**

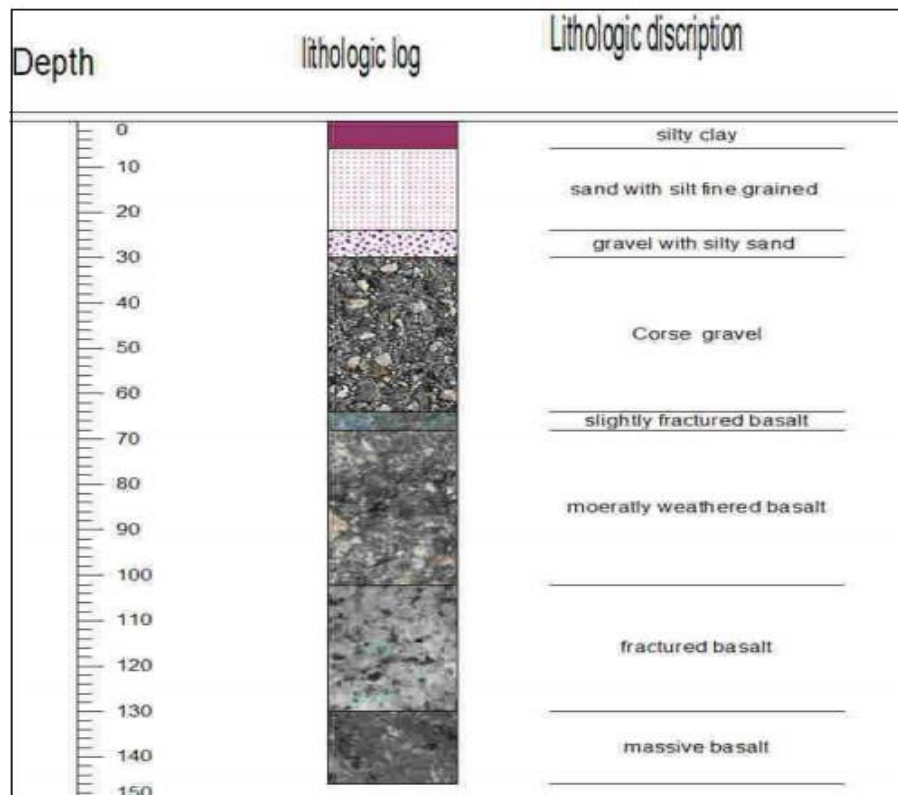
NBH-1		NBH-2		NBH-3	
Depth (m)	Lithological description	Depth (m)	Lithological description	Depth (m)	Lithological description
0-6	Silt clay	0-6	Silty Clay	0-10	Silty Clay
6-24	Fine sand and silt	6-12	Silty Sand	10-42	Clay
24-30	Gravel, silt and sand	12-30	Sand with gravel, medium grain sized	42-46	Coarse gravel
30-64	Coarse gravel	30-42	Coarse sand	46-54	Sand
64-68	slightly fractured basalt	42-52	Moderately fractured basalt	54-60	Coarse gravel
68-102	Moderately weathered basalt	52-54	Slightly fractured basalt	60-80	Highly fractured and slightly weathered Basalt
102-130	Fractured basalt	56-66	Highly fractured basalt	80-120	Moderately fractured basalt
130-148	Massive basalt	66-84	Moderately fractured basalt	120-130	Slightly fractured basalt
		84-102	Highly fractured and weathered basalt		
		102-122	Highly weathered/ altered basalt		
		122-150	Slightly fractured basalt		

NBH-4		BH-7	
Depth (m)	Litho logical description	Depth (m)	Litho logical description
0-6	Silty clay	0-19	Clay
6-16	Silty	19-20	Gravel
16-20	Highly weathered basalt	20-55	Clay
20-28	Basalt, fractured	55-67	Boulder with gravel
28-34	Coarse gravel	67-73	Clay
34-40	Fractured trachyte	73-85	Boulder
40-60	Highly fractured and slightly weathered trachyte	85-97	Sandy gravel
60-78	Moderately fractured trachyte	97-109	Gravelly clay
78-90	Highly fractured and slightly weathered trachyte	109-121	Clay with sand and Boulder
90-106	Fractured basalt intercalated with trachyte		
106-120	Coarse gravel		
120-126	Moderately weathered and fractured basalt		
126-148	Massive Basalt		

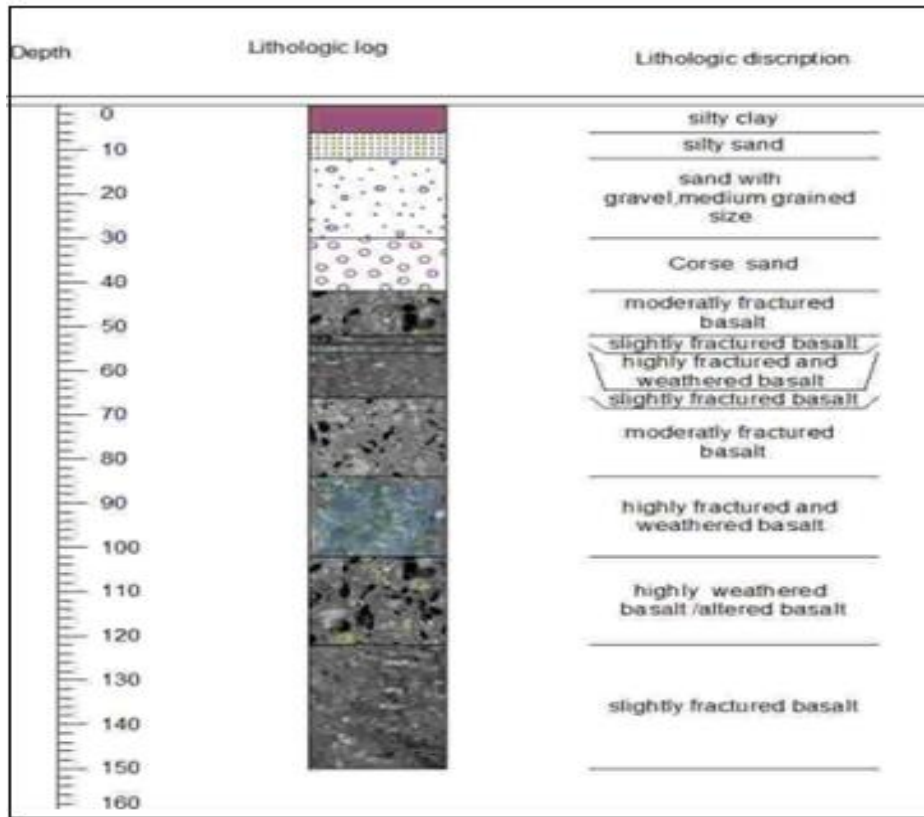
**B. Lithological Description of Genetober Deep Well (GBH-1)**

Genetober Deep Well (GBH-1)	
Depth (m)	Lithological Description
0-4	Brownish clay
4-12	Highly weathered basalt
12-18	Moderately weathered and slightly fractured basalt
18-30	Highly fractured and slightly weathered basalt
30-36	Highly weathered and fractured basalt
36-40	Slightly weathered and fractured basalt
40-54	Highly fractured and moderately weathered basalt
54-58	Slightly weathered and fractured basalt
58-78	Highly fractured and moderately weathered basalt
78-88	Highly weathered and moderately fractured basalt
88-98	Highly fractured and moderately weathered basalt
98-112	Fresh basalt
112-128	Highly fractured and moderately weathered basalt
128-138	Slightly weathered and fractured basalt
138-148	Moderately weathered and fractured basalt
148-152	Fresh basalt

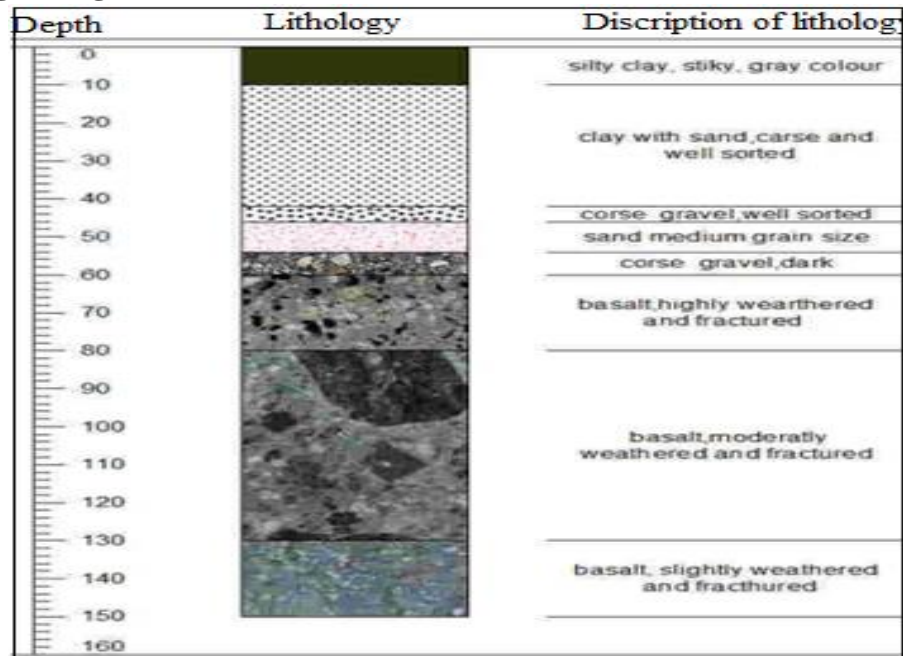
**C. New Bore Hole one (NBH-1)**



**D. Lithological log of new bore hole two (NBH-2)**



**E. Lithological log of new bore hole three (NBH-3)**



**F. Lithological log of Woldia University New Bore Hole (WUNBH)**

