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SCHOOL OF EARTH SCIENCE

GROUNDWATER RESOURCES POTETIAL ASSESSMENT IN THE EASTERN ARID AND SEMI-ARID AREAS OF ETHIOPIA: THE CASE OF FAFAN DISTRICT, JIJIGA AREA

By

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A Thesis Submitted to the School of Earth Sciences of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Exploration Geophysics

Addis Ababa

Juny 2016

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Acknowledgement

At every step during the work of this research, I have got vital assistance by a number of people and institutions, whose help is acknowledged with gratitude.

I am first very grateful to my brother Prof. Tesfaye Kidane for covering the whole expenses needed to upgrade my professional career. My heartfelt thanks then extended to Prof. Tigistu Haile for his valuable and constructive guidance all along from the field work to the completion of the research.

My deepest gratitude again goes to Ato Abdelle Abdu, hydrogeologist in Water Works Design and Supervision Enterprise at Somali Regional State of Ethiopia, for facilitating to have a field vehicle while carrying out the magnetic survey in the field.

Enormous tanks to Federal Water Works and Supervision Enterprise for proving secondary VES data, report and necessary information relevant to this work.

Abstract

A combined geophysical data involving secondary vertical electrical sounding (VES) and primary magnetic data were used with a view to determining, mapping and characterizing the subsurface layers and thickness of the overburden as well as anomalous bodies, like faults and fractures, as a means to appraising the groundwater potential in the Fafan Valley, Eastern Ethiopia. Seven northwest-southeast traverses were established from which VES data were acquired at an average station interval of 5Km and four traverses established from which magnetic data were acquired at station interval of about 200m each, the modeling and interpretation results from these were used to delimit the study area into a total of 32 points from where vertical electrical soundings were collected and 209 points from where magnetic points were carried out. For further detailed survey using the Schlumberger electrode array configuration were used for the VES data with its different applied approaches is easy and gives rapid results with high spatial resolution. The sounding data was processed and interpreted using IP2Win, WINRESIST, Surfer (V.10) and AutoCad interpretation softwares, and Geosoft (Oasis Montage) interpretation software for magnetic data.

Key words VES soundings; Magnetic technique, Aquifer

Table of Content

List of Figures

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.

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

This manuscript, as a research project for M.Sc. dissertation, deals with application of geophysical techniques for local hydrogeological study, i.e. assessing and mapping of groundwater resources and their spatial distribution.

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

The thesis has been organized in Six Chapters. The First Chapter is Introduction and presents general insight on the location, objective, methodology and scope of the study. Chapter Two is the overview of the study area and puts further emphasis on the physiographic, general geologic, hydrogeologic and tectonic aspects of the study area. The Third Chapter discusses the basic principles of the geophysical methods with emphasis on VES and magnetic surveys. Chapter Four discusses the theoretical basis of resistivity and magnetic methods. Chapter Five describes the field work, data reduction, and interpretation. And finally, the last Chapter involves conclusion and recommendation of the study.

1.2 Location and Accessibility

The study area covers about 300 km^2 and is located within the Somali Regional State of Ethiopia. Jig-jiga, the capital of Somali Regional State, is situated 630 kilometers southeast of Addis Ababa. The Fafan River basin is elongated area running SW from the Capital City for about 18km. The northern area is dominated by the narrow Karamara Range, which stretches along the NW-SE direction separating the Jerer Valley in the east from the Fafen Valley in the west.

The Study area specifically includes the Fafan District. Fafan is one of the Kebeles in the Somali Regional State of Ethiopia. As part of the Fafan zone, it is bordered by Jig-jiga, Hadew, and Chinaksen on the northeast, by Gursum on the northwest, and by Babile on the southwest. It is geographically situated at 9^{O}15'N of latitude and 42^{O}40'E of longitude and 1,445m average elevation above sea level.

The city of Jig-jiga is ringed on three sides by mountains, with only the north open to the plateau top, as well. Jig-jiga is located in the eastern highlands in the Somali Region of Ethiopia, geographically being coordinated at 9^{O}21'N of latitude and 42^{O}48'E of longitude and 1,609m elevation above sea level. The only perennial rivers in this woreda are the Fafen and the Jerer rivers. Jig-jiga has 80Kms of asphalt road and 60Kms of all-weather gravel road; only about 32-34.1% of the total population has access to drinking water. The location of the study area is shown in Figure 1.1.

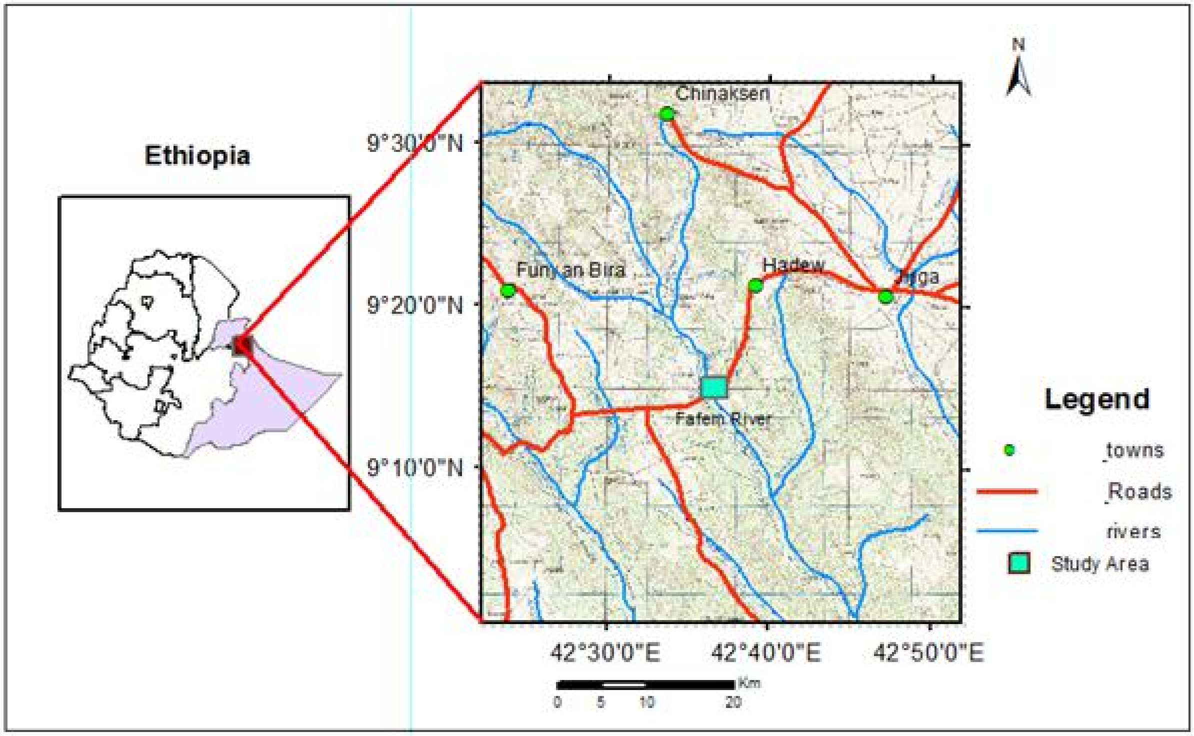

Figure 1.1 Location map of the study area.

1.3. Climate

The Fafan and Jerer River basins are adjacent to the Wabi-Shebelle River Basin. Precipitation and temperature data in the region are sparse, and were analyzed for all three river sub-basins.

The Fafen, Jerer and Wabi-Shebelle River sub-basins are characterized by a bimodal rainfall pattern with rainy and dry seasons. The north-western and eastern part of the Wabi Shebelle sub-basin (around Jijiga) receive most of their rainfall during July, August and September associated with the northward passage of the Inter-Tropical Convergence Zone (ITCZ), known locally as "Meher" season. From September to November, the ITCZ moves back in a southward direction, causing a rapid end to the rainy season during September and October. By December and January, the ITCZ moves further southwards into Kenya.

From about mid-March to May (the shorter rainy season, known locally as "Belg" season) the pressure system changes to warm, as moist and unstable air from the Indian Ocean moves in from the east and converges with a stable continental air mass from the Sahara high pressure cells.

Of note, the south-eastern part of the low lying areas of the Wabi Shebelle sub-basin that is east of 42° and south of 8° including Degehabur, Gode, Kebridehare, and Kelafo receive no rainfall in July and August and has two rainy seasons. The first is from March to May, and the second is from October to November. The March to May rains are caused by moisture from the Indian Ocean, while the October to November rains may be associated with the retreat of the ITCZ in a southward direction. Gachet (2013) includes maps showing average precipitation in January and August, and discussion of spatial variation of annual temperature range

1.4. Limitation and Objective of the Study

The geophysical survey included in the general study for groundwater assessment is limited to the southwest part of Jig-jiga. This area referred to as "OGADEN" though this regional name is also used for a much larger territory stretching beyond the limits of the catchment area of the Fafan Valley.

Multi-disciplinary studies are currently going on at Fafan and Jerer Valleys for the evaluation of groundwater potential and design of pressurized irrigation development, by the Ethiopian Water Works Design and Supervision Enterprise.

Preliminary interpretation and conceptualization of the groundwater system of the plain have been made. Accordingly, a longitudinal profile of the southwest border of the Jig-jiga Plain, showing both the topography and potentio-metric surface, reveals that the regional hydraulic gradient seems to be affected by some geologic features. One such possibility is regional scale structure(s), acting as a hydraulic barrier that impedes the movement of the groundwater. The water level contour also shows that the depth to the water table is reversed, appearing deeper at topographically low areas.

Moreover, linear geologic structures, anticipated from aerial photo and Land-Sat imagery interpretations, are thought to have some connection with the regional hydro-geological regime. This integrated geophysical investigation, as part of a research study for M.Sc. dissertation, was carried out to verify the inferred groundwater barrier and its possible connection to the linear geologic structures. Further, it also aims at establishing the hydro-Stratigraphy of the plain.

1.4.1. General Objectives

The general objective of this research is to characterize the Fafan well field, in the southwest of Jig-jiga, the Capital of Somali Region of Ethiopia, and investigate the potential of the area for deep groundwater resource through mapping of the subsurface lithologies and identification of geologic structures that could play a role in the storage and movement of groundwater.

1.4.2. Specific Objectives

The specific objectives of this Study are:

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

1.5. Methodology

Integrated geophysical tools; magnetic and electrical methods are utilized for the present research work. The methodology involved three steps: The pre-field work, Field work and post-field work.

1.5.1. Pre-fieldwork

Before going to the study area for practical data collection, a host of office work studies have been carried out. The following activities were conducted during the pre- field phase:

- Literature review on the geologic and tectonic settings of the area under study
- Collecting secondary VES data
- Investigating the geophysical instruments that was deployed in the field work
- Review of the geophysical and geological studies carried out in the area

1.5.2. Field Work

Having gone through the Pre-field work; necessary preparation for the actual field activity which are required to collect the field data was carried out as per the procedures of the respective geophysical survey technique. Accordingly, all magnetic data were collected in the field as primary data. Available secondary data were used for the electrical survey.

1.5.2.1. Electrical Resistivity Survey

- The Vertical Electrical Resistivity Survey (VES) employed in the present work on the basis of available secondary data from Federal Water Works Design and Supervision Enterprise.

1.5.2.2. Magnetic Survey

- Ground based magnetic data were collected using proton precision Magnetometer MP-2,whichworksintotalfieldmode
- GPS data were used to locate the position of the magnetic recording stations in terms of Easting, Northing and height above sea level; which were useful to correct the magnetic data for the variation in Earth's magnetic field due to the core or main effect using the International Geomagnetic Reference Field (IGRF) model
- Magnetic data were acquired randomly with a maximum station spacing of 4km and variable profile spacing, which were strongly dependent on the field conditions

1.5.3. Post Field Work

In this step, both primary magnetic and secondary VES data were processed and reprocessed using their respective mapping software packages; including IP2win, Win Resist, Surfer (V-10), and Geosoft Oasis Montaj (V-7.0). The processed data were presented in the form of different anomaly maps and anomaly profiles for interpretations and further enhancements. All anomaly maps and profiles were interpreted qualitatively and quantitatively.

Finally, the research work is compiled and presented to the School of Earth Sciences, Addis Ababa University.

1.6 Review of Previous Work

1.6.1 Summary of Previous Geological Study

The sources of information considered for review of earlier works are summarized as follows:
The relevant maps, reports and professional papers are reviewed and summarized to help understanding of the regional geological and structural relationships of rock formations in the Fafan Valley Groundwater Potential Resources Assessment.

The Ogaden Sedimentary Basin located in the southeastern part of Ethiopia covers an area of about 350,000 km^2 and is underlain by very thick succession of Late Paleozoic, Mesozoic and Cenozoic (Tertiary) ages.

The geological, structural and stratigraphical understanding of the Ogaden Basin derived from Oil Exploration works which were believed to be commenced in the 1920s. The works of these petroleum companies are summarized in Raaben et.al (1979) and Geleta (1998). Moreover, the Soviet Petroleum Exploration Expedition conducted drilling of development wells at Calub and Hilala during the period of 1986 – 1991.

The Fafan area is almost entirely located within the Ogaden Sedimentary Basin. As most of the earlier geological maps were based on photo-geological interpretations and few traverses of the geological boundaries of the lithological formations are approximated at best and require further study and upgrading for planning of any development works.

Geological Map of Ethiopia (Kazmin, 1972; Tefera et al. 1996):

According to Kazmin (1972, 1975) and Tefera et.al (1996) the south-eastern part of Ethiopia is mainly underlain by Mesozoic and Tertiary sedimentary rock successions with sporadic occurrences of Tertiary volcanic rocks and Precambrian basement rocks at the north-eastern and south-western margins of the Ogaden Basin.

Wabi-Shebele River Basin Integrated Development Master Plan Study Project – Geology (WWDSE, MCE and WAPCOS, 2004):

The study categorizes the geology of the basin into three major groups, namely, Precambrian crystalline basement rocks, Late-Paleozoic to Early Tertiary sedimentary rocks, and Tertiary to Quaternary volcanic rocks. The study area is located in the northwest part of the Wabi-Shebele basin. The geology of this area as described in the WWDSE report and shown in the geological map of the basin includes Precambrian crystalline basement rocks, Mesozoic sedimentary rocks, Tertiary sedimentary and volcanic rocks, and Quaternary alluvial deposits.

Moreover, lower Hamanlei that is less fossiliferous with inter-beds of calcareous siltstones and sandstones; upper Hamanleimicritic, locally oolitic or pellitic limestone; Urandab organogenic shale with subordinate limestone intercalations; Jessoma variegated sandstone and siltstone, Alaji basalts, and Quaternary alluvial deposits are reported to occur in and around Fafan and Jerer valleys. The extensive occurrence of Quaternary alluvial deposits in Jerer and Fafan valleys are shown in the Geological map of the Wabi-Shebele basin and hence, worth mentioning as this may have significance to the present project. The lateral and vertical extents of the Quaternary alluvial deposits in the Fafan and Jerer valleys will be defined in detail.

Geological Map of Harer Area (Yihune and Haro, 2010) and Geology of Harer Area (Haro, 2010):

The study area is located in the Harer Map sheet. In the geology (Haro, 2010) and geological map (Yihune and Haro, 2010) of the Harer sheet , a wide range of lithologies comprising high- and low-grade Precambrian basement rocks, Mesozoic sedimentary rocks, Tertiary volcanic rocks, and Quaternary sediments are mapped in the map sheet. All these rocks are also found to occur in Fafanvalley and areas to the east.

1.6.2. Summary of Previous Geophysical Survey

Groundwater Investigation in Artishek, Harshen and Jijiga zone (Shumet Kebede, 2009)

According to the report, the Harshin area interpreted geophysical resistivity survey comprises of six alternative layers. The layer with a resistivity value in the range of 10 Ohm-m, that has to be attributed to thick depositions of alterative texture of clay layers, and the relatively massive substratum could be below 80 meter depth. The massive substratum is expected to be below 250 meters depth. The report also mentioned that the overlying thick clay deposits in this area have a negative impact on transmissivity.

Groundwater investigation in Birkot area

According to this report a total of 10 Vertical Electrical Sounding survey was undertaken along the Fafan stream sheet. The interpretation of the VES shows that there exist nearly six separate geo-electric layers. The first two to three layers are interpreted as silty soil found at different degree of compaction. Below this silty soil is present shally limestone layer which is relatively thicker and found at different degree of weathering and fracturing. According to the report the probable aquifer in this area is weathered and fractured shally limestone and the depth of borehole that can penetrate this aquifer is also suggested to be 300 m.

Chapter Two

GEOLOGIC AND TECTONIC SETTINGS

2.1. Geology

2.1.1. Regional Geologic Setting

The Fafan–Jerer and adjacent eastern areas are situated in Ogaden Basin where Precambrian crystalline basement rocks, Mesozoic sedimentary rock succession, and Tertiary volcanic and sedimentary rock successions occur.

Geochronological studies carried out by Teklay et al. (1998) on Precambrian basement rocks of eastern Ethiopia around Harar and Hirna not far from the Study area indicated Archean to Paleoproterozoic ages.

The Precambrian basement exposures are found to occur in the upper reaches of Fafan and Jerer sub-basins close to the rift margin which suggest considerable upliftment. These rocks are comparable to Precambrian basement rocks of Borama area in northern Somalia and Yemen as well.

The Mesozoic sedimentary successions including mainly the basal Adigrat sandstone and limestone formations unconformably overlie the Precambrian basement that forms the floor of the Ogaden Basin. In some places, particularly south of the Study area, older Karoo sediments including Gumburo Sandstone, Bohk Shale and Calub Sandstone, which are mainly fluvial and lacustrine deposits underlie the Adigrat Sandstone. These older clastic sedimentary successions were deposited in grabens in basement terrains (e.g., Geleta, 1998).

2.2. TECTONIC SETTING

The Study area is entirely located in the Ogaden sedimentary basin situated in Eastern Africa where the Proterozoic East African Orogen (EAO), Paleozoic to Mesozoic sedimentary basins and Tertiary rifting tectonic history were recorded in Precambrian basement, Paleozoic to Mesozoic sedimentary succession, Tertiary volcanic and sedimentary rocks, respectively. The basement rocks were formed during the EAO in at the end of Proterozoic time as a result of collision between East and West Gondwana to form the supercontinent Greater Gondwana (Stern, 1994).

The Karoo rift extends in northeast direction from Kenya to Calub locality in Ogaden Basin from where it stretches east to Somalia border and join Blue Nile rift in Ogaden to form a triple junction. These structures which repeatedly down warped this part of Eastern Africa resulted in formation of thick succession of Mesozoic sedimentary rocks that also cover considerable part of the Study area.

In the Study area generally the Marda fault separates the Mesozoic sedimentary sequence from the Jessoma sandstone formation. This fault runs in northwest to southeast direction for about 900 km from southeastern margin of the MER to Somalia. The age of Marda fault is controversial as Black et al. (1974) and Purcell (1986) consider as Tertiary and Precambrian age, respectively. Whatever its age maybe the effect of Marda fault in the rocks at and around Karamara area is remarkable. The influence of the rift structures in the Study area is negligible except the northern part where nearly east to west trending structures are common.

2.3. Lithology and Stratigraphy

In Figure 2.4 is a generalized geological map of the Fafen-Jerer valleys and the adjoining eastern areas taken from a recently conducted groundwater assessment project. The following sections give the detailed description of the important units in the area.

2.3.1. Precambrian Basement Rocks

The Precambrian basement rocks are exposed in the upper reach of Fafan River excepting some hilly areas capped by Mesozoic rocks and/or Tertiary basaltic rocks; and northeast to northwest of Jijiga town. The basement rocks exposed in the area include granodiorites with associated gabbroic bodies, granitic gneisses, granodiorites and different generations of granites. The map units including the minor lithologic components found to occur in the area are briefly described as follows.

2.3.1.1. Diorite Gneisses, Amphibolite and Meta-gabbro

The diorite gneiss is grey - light grey, massive to foliated, coarse-grained and weakly banded rock. At places, particularly, in the Fafan valley, nearby Harer – Jijiga road, intense deformation resulted in compositional banding. Strongly deformed meta-gabbro and locally massive gabbro also occur adjacent to the diorite gneiss. The amphibolitic rocks defined by preferred alignment of amphibole and plagioclase minerals occur as separate extensive outcrops and as lenses within dioritic gneiss and meta-gabbros.

2.3.1.2. Granodioritic Gneiss and Granodiorite

Granodioritic gneisses are exposed extensively on both sides of the upper part of the Fafan River. A more massive granodiorite variety with less deformation is also found to occur adjacent to the Granodioritic gneiss northwest of Fafan District.

2.3.1.3. Granitic Gneisses and Granites

Leucocratic granitic to quartzo-feldspathic gneiss is also exposed at HalaHago locality and is composed predominantly of pinkish potassium feldspar and quartz and minor biotite. It is also cut by pegmatitic vein which trends with dip 63º/223º. The pegmatitic vein is simple and composed of pinkish K-feldspar and smoky quartz. The basement rock immediately underlying the lithologic contact is completely decomposed and is highly friable.

2.3.2. Mesozoic Sedimentary Successions

The Mesozoic sedimentary rock successions unconformably overlie the Precambrian basement rocks in the northwestern part of the Study area in the valley of Fafan as well as its major tributaries (see Figure2.2). These rocks comprise mainly the Lower Sandstone and Hamanlei Limestone. The younger successions, mainly Urandab and Gabredarre formations, are found to occur on flanks of Karamara mountain range and further downstream on ridges separating tributary rivers entering Fafan and Jerer and in Fafan valley itself.

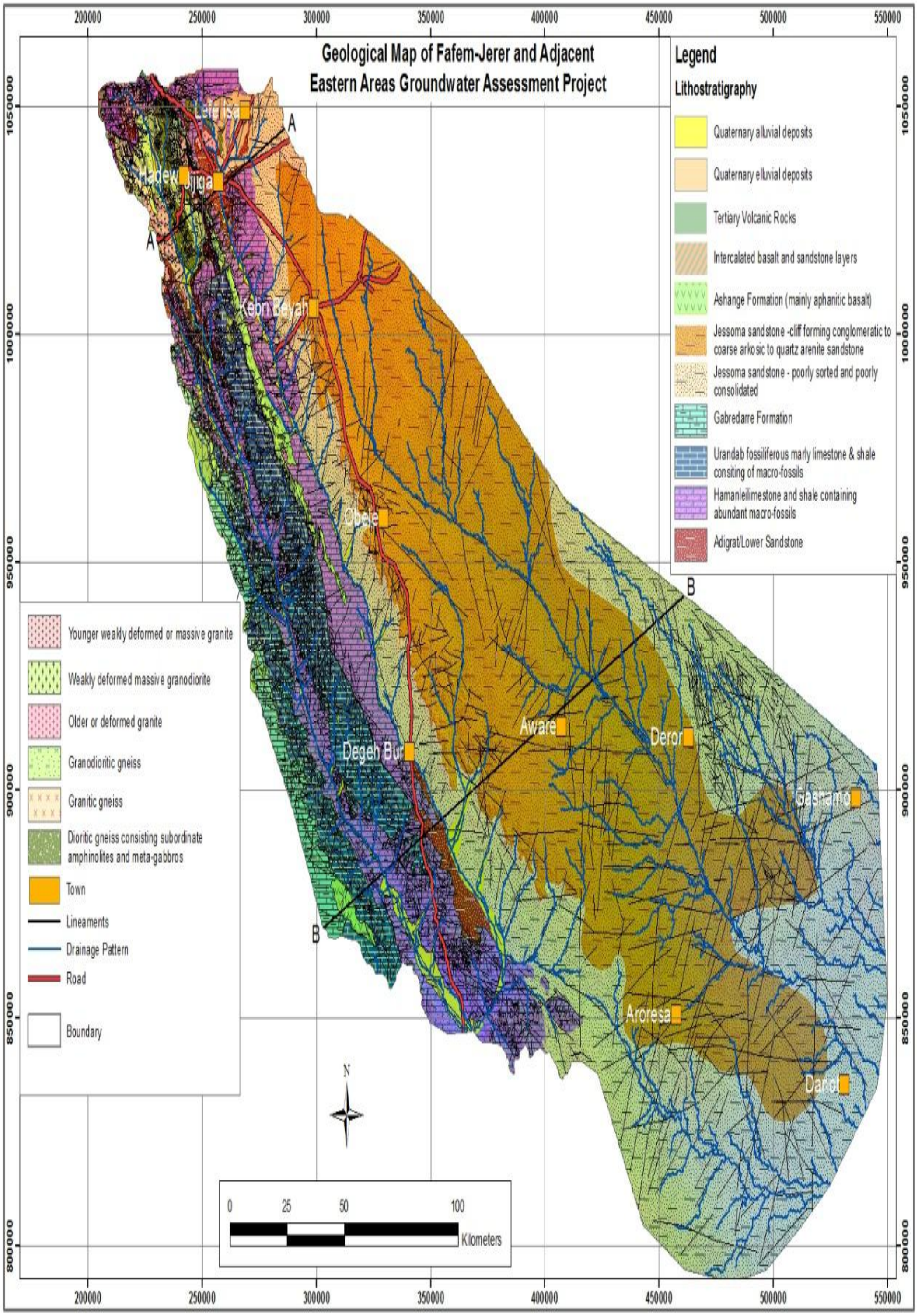

Figure 2.1 Geological map of Fafan – Jerer Sub-Basins (Adopted from WWDSE Report, 2013)

2.3.2.1. Adigrat Sandstone

This sandstone unit is mainly exposed in upper part of Fafan River valley and at the foot of Karamara mountain range. This sandstone formation is the oldest Mesozoic sedimentary succession in the Study area and is found to occur unconformably overlying the Precambrian basement rocks.

The sandstone is generally massive with inter-layering of horizontally bedded shale and mudstone. The sandstones exposed at these areas are fine to medium grained with occasional conglomeratic variety containing of quartz pebbles.

The lithological contact between the Lower/Adigrat sandstone and the underlying Precambrian high-grade gneissic and plutonic basement rocks wherever exposed is marked by unconformable relationship. At lithologic contact zones the underlying basement rocks are represented by deeply weathered, decomposed and friable basement rock materials.

2.3.2.2. Hamanlei Limestone

Hamanlei Formation represents fossiliferous limestone of Jurassic age exposed in southeastern Ethiopia mainly Ogaden region (e.g. Tefera et al. 1996 and references therein). The formation gets its name from Hamanlei locality situated between lower reaches of Fafan and Jerer valleys. As observed in the Karamara mountain range, upper Fafan valley southwest of Jijiga town the Hamanlei formation conformably overlies the Adigrat/Lower sandstone formation. The nature of the lithological contact between Hamanlei and Adigrat formation is gradational from sandstone – calcareous sandstone/fine sandstone or siltstone – shale and to sandy limestone – fossiliferous limestone. The thickness of the Hamanlei limestone is thin at places, particularly in the upper reaches of Fafan and Jerer rivers where interplay of tectonic upliftment, mass-wasting, weathering and erosional activities removed the overlying succession and upper portion of the unit. Even at places the Mesozoic sedimentary succession is uplifted and completely weathered and eroded to expose the Precambrian basement rocks. However, where overlain by the Urandab formation the thickness of Hamanlei is estimated to be more than 250 – 300 m.

2.3.3. Tertiary Volcanic and Sedimentary Rocks

The Tertiary volcanic and sedimentary rocks in the project area are represented mainly by basaltic rocks exposed along the prominent Karamara mountain range and Jessoma sandstone underlying the flat-lying plain areas situated to the east of the Jerer valley, respectively. These map units are described as follows.

2.3.3.1. Karamara Basaltic Volcanic Rocks

Karamara basaltic volcanic rock occupies the top part of the Karamara mountain range which occurs between the upper to middle reaches of the Fafan and Jerer rivers. The linearly arranged outcrops of Karamara basalt trends in NW – SE direction paralleling the Marda fault zone. It is presumed to be channeled and erupted through the Marda faults capping the Mesozoic sedimentary succession. Similar basalt is present in the southwest central part of the project area close to Degahamedo locality and further northwest to the west of Fafan River. This rock is at places bounded by regional fault/fractures trending in NW – SE orientations.

The Karamara basalt is generally aphanitic in texture exhibiting crude/broad and less developed columnar joints. The joints range from about less than 10 cm to about 30 – 40 cm and the rock is commonly used as quarry sites for construction materials.

2.3.4. Superficial Deposits

2.3.4.1. Alluvial Deposits

The upper Fafan valley, particularly along its main course, deposits considerable alluvial deposits, which range from silty clay overbank floodplain sediments and fine-coarse sand channel deposits. The thicknesses of the alluvial deposits vary from place to place. Results of previous and current well drilling in the valley indicated the maximum thicknesses of the alluvial deposits range from ~40 m to ~70 m. As the major source of the alluvial deposits are the basement rocks in the upper Fafan, the size distributions of the alluvial sediments gradually decrease downstream suggesting dominance of silty clay or clayey silt in middle and lower Fafan valley.

2.4. Hydrogeologic Considerations

The geology of individual units influences how groundwater enters, flows through, and is stored within an aquifer. The potential for alluvial sediments to be aquifers depends on the properties of the sediments that comprise the aquifer; these properties include grain size and distribution, lithology, and stratigraphy. An example of geologic properties influencing groundwater flow and storage is weathering of basaltic rock – basaltic rock typically weathers to clay and colloids, reducing reservoir porosity and permeability. Alternatively, granitic rocks, quartzite, and sandstones can themselves store or can produce gravels that can store large volumes of water. Similarly, the primary (intergranular) or secondary (karst or solution) porosity of an aquifer depends on their geologic origin, structural history, and digenesis through time.

Careful mapping and understanding of the paleogeography and the geologic and structural context is crucial to understanding and assessing the hydrogeology.

2.4.1. Hydrogeologic units

The rocks and deposits forming the hydrogeologic framework for a groundwater flow system are termed hydrogeologic units. A hydrogeologic unit has considerable lateral extent and has reasonably distinct hydrologic properties because of its physical (geological and structural) characteristics. An aquifer is “a geologic unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells” (Fetter, 2001, p. 95).The water-yielding materials in the study area are in the Fafen Valley, and consist primarily of unconsolidated alluvial deposits. Consolidated (bedrock) carbonate rocks and sandstones that underlie the unconsolidated alluvium or are exposed directly at the surface may be a source of water if the consolidated rocks are sufficiently fractured or have solution openings. Three principle rock types form aquifers in the study area: carbonate, sandstone, and alluvial sediments. Table 2.1 presents the lithostratigraphic units classified as aquifers or confining units. The primary bedrock aquifers are found in the Hamanlei and Adigrat Formations (highlighted in Table 2.1).

Table 2.1 Description of major hydrolic units in the study area (taken from USAID Final Approved Report, 2013)

Lithostratigraphic Unit	Description	Hydrogeologic Unit classification	Comments
Alluvial deposits and volcanic rocks	Unconsolidated basin-filling deposits and surface volcanic flows	Aquifer	Volcanics may serve as aquifers where fractured or scoriaceous; where dense and unfractured as confining units
Karamara volcanics	Tertiary-aged basalts	Barrier in north, leaky in the south	Where unfractured in the north of the study area they act as a confining unit or a barrier to flow where they extend above land surface
Jessoma Formation	Cretaceous-Tertiary sandstones	Aquifer	May contain a lower confining unit; serves as a major recharge area on the eastern edge of study area
Mustahil Limestone	Cretaceous carbonate rocks and alternating sandstones	Aquifer	--
Korahe Formation	Cretaceous gypsum and shales	Confining unit/barrier	--
Urandab Formation	Jurassic shales and mudstones	Confining unit	Main confining unit above the Hamanlei Formation aquifers
Hamanlei Formation	Jurassic carbonate rocks	Aquifer	High-quality aquifers due to karstification; surface exposures act as recharge zones
Adigrat Formation	Triassic-Jurassic sandstone	Aquifer	Good-quality aquifers; surface exposures act as recharge zones in the northern part of the survey area
Basement	Crystalline metamorphic rocks	Impermeable basement(unless weathered)	Base of probable aquifers

Chapter Three

THEORY OF GEOPHYSICAL METHODS

3.1. General

Geophysics, both solid Earth or applied, is the scientific method that uses the science of physics with high degree of technological development employed to observe the hidden subsurface of the Earth. In applied geophysics, geophysical methods are developed to delineate the subsurface structure and to explore underground treasures. Nowadays, geophysicists are equipped with geophysical instruments which are capable of exploring up to several kilometers deep into the interior part of the Earth. Geophysics is not only applied for the subsurface studies but is also used to investigate the ocean and land surface of the Earth, which gives rise to the environmental application of geophysics.

Geophysical surveys greatly help in studying of groundwater potential in any hydrogeological setup and locate preferred borehole locations and determine the depth of aquifers. The property and thickness of various lithological units obtained from geophysical survey at different location has been given much attention in part by a desire to reduce the risk of drilling dry holes and also a desire to offset the cost associated with poor ground in groundwater. However, geophysical surveys are not always the most effective method of obtaining the information needed. For example, in some areas drilling holes may be a more effective way of obtaining near surface information than geophysical surveys. In some investigations a combination of drilling and geophysical measurement may provide the optimum cost benefit ratio.

Depending on the source signals, geophysical methods fall 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 like gravitational and magnetic. On the other hand, the active geophysical methods involve detection of responses for artificially generated local source fields and waves such as: electrical, electromagnetic and seismic. In general, the aim of geophysical prospecting is searching for local perturbations in the naturally occurring or artificial fields caused by obscured geological features.

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

Of the number of geophysical methods that could measure variations in physical field of the Earth and its perturbations, the electrical and magnetic methods of prospecting have found major applications in groundwater investigations. This is because; the electrical methods are the most suitable to investigate the presence of saturated zones in the subsurface while the magnetic methods are, in addition to several advantages they offer, are the best tools that could map subsurface fractures detrimental for the movement of groundwater. These two methods have accordingly been used over the Fafan river basin to investigate its groundwater potential and form the main methods used in this research work. The theoretical foundations of the methods are therefore briefly discussed in the following sections.

The method of electrical survey is based on measurement of variations in electrically conducting properties of the Earth and as such measure variations in either resistivity or conductivity properties of the subsurface. Variation in resistivity is primarily caused by differences in the character of the subsurface rock and presence of water. Dry formations have poor electrical conductance and show very high resistivity. Increasing water saturation of the pores or cavities in the formation reduces its resistivity; the reduction in resistivity is partially controlled by the porosity. This occurs because water (in its natural condition) is an electrical conductor, and its presence in the interconnected cavities reduces the overall resistivity of the formation. There are, however, general differences in the resistivity of various saturated formations. Silt, clay and shale have very low resistivity, sand and gravel with fresh water have moderate to high resistivity. In addition to aquifer material, water quality also affects resistivity. Formations filled with highly mineralized water show relatively low resistivity.

Water in the fissures containing ions reduces the resistivity of the rock. In contrast, those saturated with fresh water have relatively higher resistivity (Fletcher and Driscoll as cited in Aynalem Ali, 1999).

There are two procedures of measuring variations in resistivity of the subsurface materials. These may be either sounding surveys or profiling surveys. The methods vary in the type of target they are looking for and their measurement layout. While sounding surveys, most commonly known as Vertical Electrical Sounding survey (or VES) measure the vertical variation of the subsurface resistivity at a point by assuming horizontal layer of the Earth while profiling surveys measure the lateral variation of the subsurface by assuming vertical variation in electrical properties of the Earth.

3.2.1. Fundamental Principles of Vertical Electrical Sounding Surveys

In Vertical Electrical Sounding (VES), the positions of electrodes are changed with respect to a fixed point (known as the sounding point) and the measured values reflect the vertical distribution of resistivity values on a geologic section.

Vertical electrical sounding consists of a symmetrical electrode array used to determine the resistivity of the subsurface which is assumed to be consisting of horizontally stratified layers. The procedure is used to determine the variations in resistivity in the vertical direction and is also called electrical drilling or commonly vertical electrical sounding (VES). By expanding symmetrically the distance between current electrodes about a point called the sounding point, while keeping the potential electrodes MN at the same position, provides a sounding curve corresponding to the apparent resistivity versus depth of the location. As the spacing between the current electrode increases, the investigated depth will also increase. The two most commonly used arrays in electrical sounding survey are the Wenner and Schlumberger arrays. In this work, the data which was collected by using the Schlumberger electrode array techniques. When the Schlumberger array is used, the distance between the potential electrodes is not greater than one tenth of the current electrodes spacing. The advantage of this array is that initially only the spacing between the current electrodes is increased. However, at large current electrode spacing, the measured potential becomes very low and the distance between the potential electrodes is increased. Increasing the potential electrode spacing produces a ‘step’ in the apparent resistivity curve and it is good practice to obtain an overlap between the curve segments by obtaining two readings at different potential electrode spacing for two adjacent current electrode spacing. Segments obtained at larger potential electrode spacing can be shifted in order to produce a smooth curve (Gibson and George, 2003). In electrical prospecting to determine the depth and electrical resistivity of a series of horizontal or nearly horizontal ground, it is difficult to measure both parameters. In order to solve this problem, we should calculate the potential and the electric field, due to a point source of current, at any point on the surface of a stratified earth. This has advantages because of enables one to use axial symmetry of the potential filed about the vertical axis through the current source and the additive property of the potential is also be used.

Let us choose a cylindrical system of coordinate with the origin at the point source a direct current located on the surface (Figure 3.1). The subsurface consists of infinite number of layers separated by horizontal boundary planes, the deepest layer existing to infinite depth and the other layers have finite thickness and resistivities Each of the layers is electrically homogeneous and isotropic.

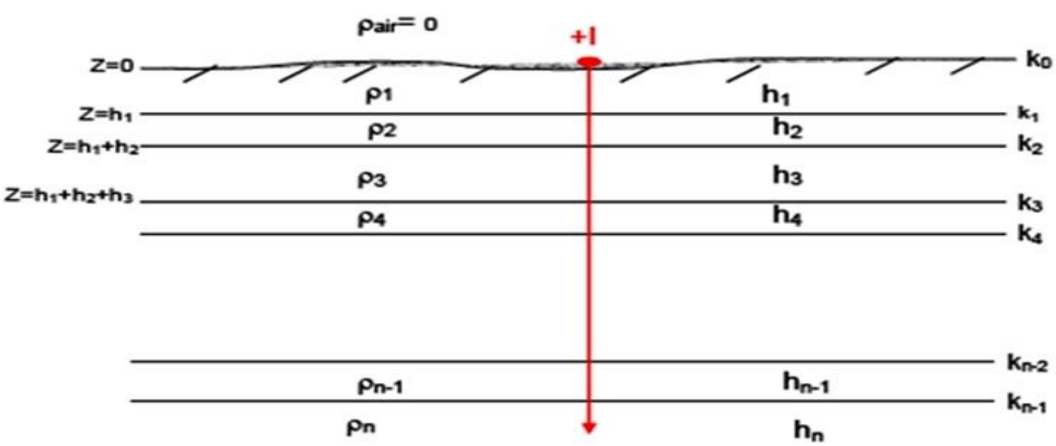

Figure 3.1 A multi-layer Earth and problem presentation for solution of the potential.

The derivative of the potential based on the above conditions was first due to Stefanescu et al., (1930).

The electrical potential field V for direct current satisfies the differential equation of Laplace, that is;

(3.1)

The potential field has a cylindrical symmetry with respect to the vertical axis line through the current source. Therefore, Laplace equation in cylindrical coordinate is most appropriate.
For a solution symmetrical with respect to the vertical axis

Thus,

(3.2)

The particular solution of equation (3.2) can be found by using separation of variables. That is;

(3.3)

Substituting equation (3.3) in to (3.2) and multiplying through the result by gives,

(3.4)

Equation (3.4) holds only if it satisfies;

(3.5)

(3.6)

Where is an arbitrary constant.
The solution of equation (3.6) is, therefore, given by

(3.7)

(3.8)

Where is the Bassel function of order zero and are constants. Combining equations (3.7) and (3.8) to give the particular solution of V(r,z)

(3.9)

are constants.
The fact that every linear combination of particular solution is also the solution of a given differential equation, one can roughly estimate all the possible values of the solution from zero to infinity allowing the general solution independent of the constants ().
And hence, the general solution of equation (3.2) can thus, be found by;

(3.10)

Where and are arbitrary functions.

From basic theory, the potential generated by a single point source of current intensity “I” located at the surface of an electrically homogeneous earth is given by;

(3.11)

Where, ρ is the resistivity of the homogeneous earth.

Using the Weber integral formula in the Bessel’s function, we can write equation (3.11) as;

(3.12)

Thus, equation (3.11) will have the form;

(3.13)

Equation (3.13) is also the solution of equation (3.2). Therefore, the combined solution will also be the solution. That is;

(3.14)

Where are arbitrary functions. Solutions of equation (3.14) are valid in all the layers of the subsurface.

However, necessarily it is the same in different layers of the subsurface. Therefore, the potential due to a point source of current at the surface of a horizontally layered earth must in each layer satisfy

(3.15)

This equation is called the Stefanescu Integral, with ‘i’ referring to the several layers of the subsurface.

Boundary conditions

For a potential set up by a single source of current at the surface of a horizontally stratified earth, the following boundary conditions are fulfilled.

1. At each of the boundary planes in the subsurface, the electrical potential must be the same. That is;

   (3.16)

2. The vertical component of the current density must be continuous on each boundary plane (the current density normal to the boundary planes)

   (3.17)

3. At the surface (z=0) the vertical component of the current density J_V (and hence that

of the electric field intensity) must be zero everywhere except in the infinitesimal neighborhood around the current source. In air $J_{air}=0$ and from condition (2), the vertical component of the current density at depth zero must be zero. Near the current source the potential must not approach infinity (must remain finite) as

at depth z=0, r→0 (3.18)

4. At infinite depth, the potential must approach zero, i.e. V=0 as Z→∞

3.2.2. Basic Principle of Resistivity for Groundwater

Groundwater, through the various dissolved salt it contains, is ionically conductive and enables electric currents to flow into the ground. By measuring the ground and subsurface resistivity therefore gives the possibility to identify conditions necessary for the presence or absence of water. In resistivity surveying, especially in vertical electrical sounding (VES), conduction in rocks is mainly due to pore fluids acting as electrolytes. Water in its pure form is poor conductor but most water contains dissolved salts which facilitate current flow. Resistivities of rocks generally depend on the water content (porosity), the resistivity of the water, the clay content and the content of metallic minerals (Bernard, 2003). The following considerations help in the determination of the resistivity of rocks.

- A hard rock without pores or fractures is very resistive to the flow of electric current. This is generally observed in hard fresh Precambrian rocks.
- Dry sand without water is very resistive.
- Porous or fractured rock bearing free water has resistivity, which depends on the resistivity of the water and on the porosity of the rock.
- Impermeable clay layer, which is wet, has low resistivity but may not contain enough yields for successful groundwater exploitation.
- Mineral ore bodies (iron, sulphides) have very low resistivity due to their electronic conduction; usually lower or much lower than 1Ohm-m (Bernard, 2003).

To identify the conditions necessary for the presence of groundwater from resistivity measurements, the absolute value of the ground resistivity must be considered. Usual target for aquifer resistivity can be between 50 Ohm-m to 2000 Ohm-m (Bernard, 2003).

To identify the conditions necessary for the presence of groundwater from resistivity measurements, the absolute value of the ground resistivity must be considered. Usual target for aquifer resistivity can be between 50 Ohm-m to 2000 Ohm-m (Bernard, 2003).

- In hard rock environment, which is considered very resistant to the flow of electric current, a low resistivity anomaly will be the target for groundwater.
- In a clayey or salty environment that is normally considered conductive, a comparatively high resistivity anomaly will most probably correspond to fresh water and thus will be the target in the case for groundwater exploration for domestic use.

Resistivity values of earth materials cover a wide range. The variety of resistivity has been the essential reason why the technique can be used for different applications (Loke, 2001).

In resistivity measurements, highest resistivity values are associated with igneous rocks. Sedimentary rocks tend to be most conductive due to their high fluid content. Metamorphic rocks have intermediate resistivity (Table 3-1). Granites and quartzite have high resistivity ranges; sandstone and shale have intermediate resistivity ranges (Bernard, 2003). The resistivity therefore, in a particular geological environment has an influence on the aquifer resistivity. Numerical values for various types of water are outlined (Table 3-2).

In resistivity measurements current is injected into the ground via electrodes and the resulting potential is measured also by electrodes in the ground. The outer electrodes shows the current electrodes for injecting current into the ground and the inner electrodes are the potential electrodes connected to the voltmeter (Figure 3-2).

Consider that a direct current of strength, I, is introduced in to a homogeneous and isotropic earth by means of two point electrodes as shown in the Figure 3-2. The potential difference between the two points P_1 and P_2 on the surface is given by using equation (3.19) as follows.
The potential at is,

(3.19)

Similarly, the potential at is,

(3.20)

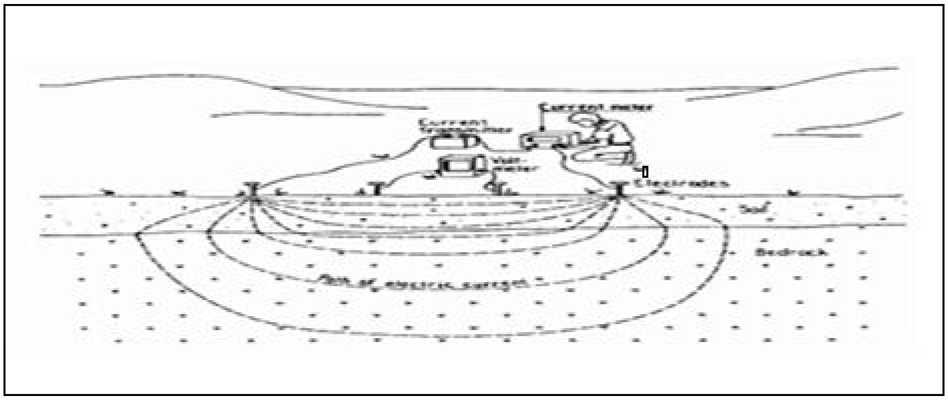

Figure 3-2 Sketch showing DC resistivity measurements (taken from Robinson and Coruh, 1988).

Table 3-1 Resistivity values for some common geological formations (takenfrom Bernard,2003).

Material	Nominal resistivity(Ω-m)
Sandstones	200–5000
Sandstone(weathered)	50-200
Clays	$1–10^2$
Gravel(saturated)	100
Basalt	$10-1.3*10^7$
Topsoil	250-1700
Sandclay/clayedsand	30–215
Sandandgravel(saturated)	30–225

Table 3-2 Numerical values for various types of water (modified from Bernard, 2003).

Type of Water	Resistivity (ohm-m)	Conductivity (micros/cm)	Salinity (mg/l)
Very fresh	200	50	35
Fresh	20	500	150
Salted	10	1000	700
Sea Water	0.3	30000	35000

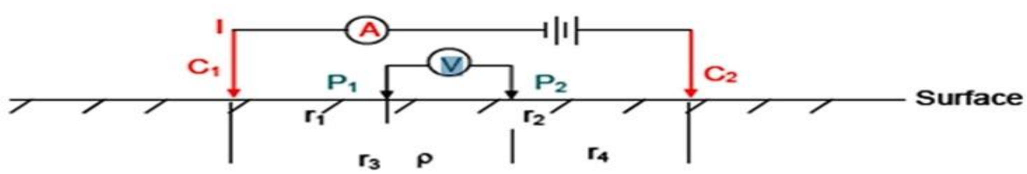

Figure 3-3 The arrangement of current and potential electrodes in a four-electrode

system.

The potential difference () is therefore,

=> (3.21)

3.2.3 The Apparent Resistivity

If the ground is homogenous, the potential difference measured is as a function of the true resistivity of the homogeneous earth and the geometric factor. But in reality the ground is locally in the homogeneous and the potential difference depends on the current applied, the resistivity of the subsurface medium and the geometrical factor (k) determined by electrode array or configurations types. The resistivity calculated from such non-homogenous ground is not a true resistivity rather it is called apparent resistivity () which can be related to the parameter as;

This apparent resistivity has to be interpreted using curve matching or inversion techniques to find estimated resistivity versus depth of the subsurface.

This are many type of electrode configurations used in ground surveys of which the most commonly used array are Wenner, Schlumberger and the Dipole-Dipole. Since, the electrode separation relate to the investigation depth and lateral solution power required, one can choose the best electrode configuration for planed survey at the initial of the survey. The expression for apparent resistivity in each of the array types will be different due to the difference in the geometrical factor (K) of each any type.

Taking the Schlumberger array in which the electrodes are symmetrically placed a point at the center of the array as shown in the figure below.

Substitutions of into equation (3.21), we have;

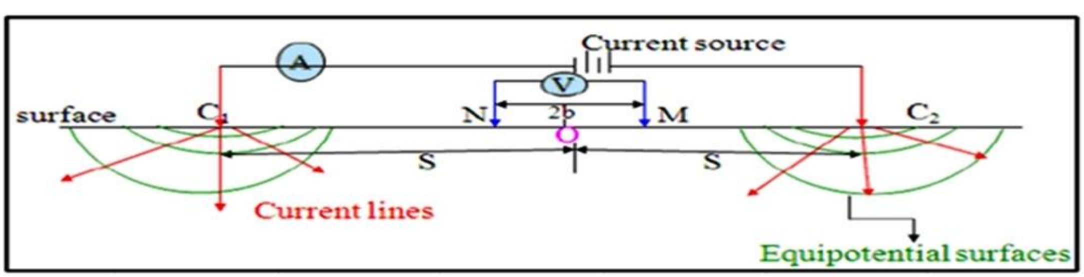

Figure 3-4 The electrode arrangement for the Schlumberger Array.

⇨ (3.22)

⇨ (3.23)

Where is the geometric factor.

3.2.4. Interpretation of VES Data

The interpretation problem for VES data is to use the curve of apparent resistivity versus electrode spacing, plotted from field measurements on bi-log scale graph paper, to obtain the parameters of the geo-electrical section: the layers resistivity and thicknesses. From a given set of layer parameters, it is always possible to compute the apparent resistivity as a function of electrode spacing (the VES curve). Unfortunately, for the converse of that problem, it is not generally possible to obtain a unique solution. There is interplay between thickness and resistivity; there may be anisotropy of resistivity in some strata; large differences in geo-electrical section, particularly at depth, produce small differences in apparent resistivity; and accuracy of field measurements is limited by the natural variability of surface soil, rock and by instrument capabilities. As a result, different sections may be electrically equivalent within the practical accuracy limits of the field measurements.

To deal with the problem of ambiguity, VES field curves can be interpreted qualitatively using simple curve shapes, semi-quantitatively with graphical model curves, or quantitatively with computer modeling.

3.2.5. Master Curves

Layer resistivity values can be estimated by matching to a set of master curves calculated assuming a layered Earth, in which layer thickness increases with depth. For two layers, master curves can be represented on a single plot.

Master curves: log-log plot with on vertical axis and on horizontal (is depth to interface)

- Plot smoothed field data on log-log graph transparency.
- Over lay transparency on master curves keeping axes parallel.
- Note electrode spacing on transparency at which (a/h=1) to get interface depth.

- Note electrode spacing on transparency at which () to get resistivity of layer 1.

- Read off value of k to calculate resistivity of layer 2 from the formula given below:

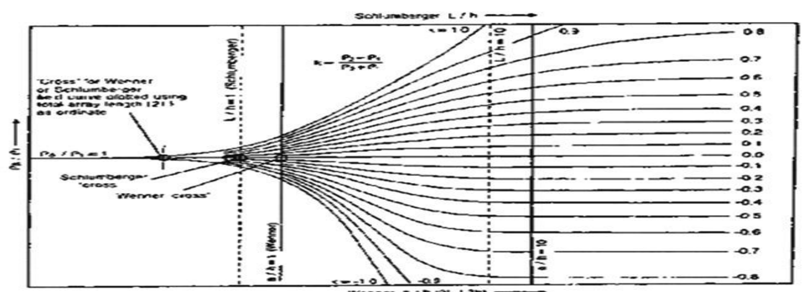

Figure 3-5 Master curve of the two layer Earth model.

3.3. The Magnetic Method of Prospecting

3.3.1. General

The Earth's magnetic field resembles the field of a large bar magnet situated near the center of the Earth. Many geological formations, by virtue of their magnetic minerals content, will behave like large buried magnets and will then have a magnetic field associated with them. These local magnetic fields will be superimposed on the magnetic field taken, in the locality of such geological formations, and show deviations from the undisturbed Earth's magnetic field.

These changes or anomalies could be large or small in magnitude, and could either increase or decrease the Earth's main field. Their influences on the main field depend on the geometry, orientation, depth of burial and magnetic properties of the body and the direction and intensity of the inducing Earth's field.

Magnetic surveys are used:

- to locate and delineate:
  - Magnetic iron ore deposits,
  - Metallic ore deposits which may have either magnetite or pyrrhotite associated with them, and
  - Geological structures like faults, dykes, and etc.
  - in groundwater studies to map the depth to the magnetic susceptible basement rock
- to provide a valuable aid to lithological mapping, as the character of a magnetic anomaly is indicative to the rock type
- in mapping structural features, which often provide a conduit for the accumulation of groundwater and, at times, act as barriers.

3.3.2. Basic Concepts and Units

3.3.2.1. Magnetic force

The force between two poles of strength, and , situated a distance 'r' apart is given by:

(3.24)

Where, r is the distance separation between them, and

is the Magnetic permeability (measure of the ease with which the magnetic field is passed through the material separating the poles)

3.3.2.2. Flux density/Magnetic induction

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

The magnetizing force (field strength) gives rise to the flux density (the cause of the magnetic field is the magnetizing force) is given by;

(3.25)

The absolute permeability of vacuum is denoted by, . Thus, the flux density due to a magnetizing force H in vacuum will be;

(3.26)

For most practical purposes, the absolute permeability of air, and even most rocks, may taken as .

3.3.2.3. The Earth's Magnetic Field

The Earth's magnetic field is akin to that of a dipole situated at the center of the earth with its magnetic moment pointing towards the Earth's geographical south. The Earth's magnetic field vector F is completely specified at any point by its elements. Figure 3.6 shows the elements of the Earth's magnetic field.

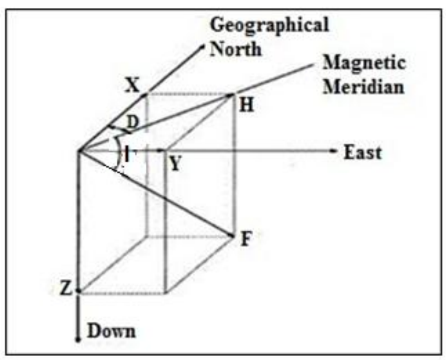

Figure 3.6 Elements of the Earth's magnetic field.

According to Figure 3-6, the Earth's total field is F makes an angle I (the inclination) with the horizontal plane. It can be measured by a dip needle and is also called magnetic dip. The angel D is the angle between geographic north and magnetic north, or the declination of H (here, H is the horizontal component of the total field vector, F) east or west of true north. In the northern hemisphere the magnetic field is directed downwards towards the north magnetic pole and in the southern hemisphere it is directed up wards and away from the south magnetic pole. At the magnetic equator the magnetic field is horizontal and at the magnetic poles the field is vertical i.e., the strength of the Earth's field varies from 25,000-30,000nT in the equatorial regions while 60,000-70,000nT, in the Polar Regions.

The amplitude of total field varies more rapidly along the N-S direction as compared to the east-west. On Figure 3-6, Z is the vertical component of the total field (F). It is directed downwards in the northern hemisphere (positive) and upwards (negative) in the southern hemisphere. H, which is the horizontal component of F, is directed towards magnetic north for both the Southern and Northern hemispheres.

3.3.2.4. Relative permeability, susceptibility and magnetization

From equation (3.25),

Then the magnetic field in a material medium is given by;

(3.27)

(3.28)

where,

,

is called susceptibility which is a dimensionless quantity. For a vacuum,

The relative permeability of the medium is therefore, defined by the ratio of ,

From equation 3.28, to obtain in vacuum a flux density equal to the density μH in the medium under consideration, we would need an additional magnetic field strength KH.

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

(3.29)

Since K is a pure number and M is measured in . Further B and H are vectors we can state equation 3.26 more generally as magnetic induction (total field within a body) and written as:

(3.30)

Then, for the x, y and z components of B, in an orthogonal coordinate system, we can describe as;

(3.31)

Equation (3.29) implies, a magnetic body placed in a magnetic field becomes magnetized by induction. The magnetization (M) is proportional to the inducing external magnetizing force. The proportionality constant K is the magnetic susceptibility which is a dimensionless quantity.

Magnetic susceptibility is a measure of the degree to which a material gets magnetized. The larger the susceptibility the greater the intensity of induced magnetization (M) and hence the bigger will be the anomaly produced relative to the Earth's field. The susceptibility of rocks is almost entirely controlled by the amount of ferromagnetic minerals, their grain size, and mode of distribution and hence is highly variable.

Table 3.3 Magnetic Susceptibility of Rocks

Earth Material	Susceptibility*10^{-3}(SI)
Limestone	0-3
Sandstones	0-20
Rhyolite	250-37700
Basalt	0.2-175

3.3.3. Magnetic Reading Noise and Correction

All magnetic data sets contain elements of noise and will require some form of correction to the raw data to remove all contributions to the observed magnetic field other than those caused by subsurface magnetic sources. In ground magnetic survey, it is always advisable to keep any magnetic objects like high electric power cable, railway and keys etc., which may cause magnetic noise, away from the sensor.

In all magnetic data, diurnal and IGRF correction can be applied. The most significant correction is for the diurnal correction in the Earth's magnetic field. Base station readings taken over a survey period of facilitate the compilation of diurnal correction.

Where, DC=Diurnal Correction

= Reading of Base Station-2.

= Reading of Base Station-1

= Reading of each magnetic survey

= Time at which the Base Station-2 Reading was taken

= Time at which the Base Station-1 Reading was taken

=Time of each magnetic profile

In order to produce a magnetic anomaly, the data have to be corrected to take into account the effect of latitude and, to a lesser extent, longitude. As the Earth's magnetic field strength varies from 25000nT at the magnetic equator to 69000nT at the poles, the increase in magnitude with latitude needs to be taken into account (Reynold, 1997).Survey data at any given point can be corrected by subtracting the theoretical filed value obtained from IGRF, from the measured value

IGRFC=DC-IGRF

Where, IGRFC is the IGRF correction

3.3.4. Interpretation of Magnetic Data

Once magnetic data have been corrected and reduced to their final form, they are usually displayed either profiles or as maps and interpretation procedures are different for the two cases.

A single magnetic anomaly can have the form of positive peak only, a negative peak only or a doublet consisting of both positive and negative peaks. In addition, the single largest unknown is whether there is any remnant magnetization and, if there is, its intensity and direction (J) need to be ascertained. It must also be remembered that many geophysical interpretation may not be unique. For this reason, it is always useful to use other geophysical methods in the same area to help constraint the interpretations. If some geological information already exists for the area, then this should be used to help with the geophysical interpretations. There are two ways of interpretation: qualitative and quantitative techniques.

3.3.4.1 Qualitative interpretation

The guideline of qualitative interpretation of a given anomaly is given in Table 3.2. (It can be determined from maps also; Structure=composition of anomaly, i.e., positive peak only, negative peak only or doublet of positive and negative peaks; k=magnetic susceptibility).

Table 3-4 Guideline of qualitative interpretation of magnetic profiles and maps (adopted from Reynold, 1997).

Applies to	Magnetic character	Possible cause
Segments of a profile and areas of maps	Magnetically quite	Low k rocks near surface
	Magnetically noisy	Moderate-high k rocks near surface
Anomaly	Wavelength	Short=near surface feature
		Long=deep-seated feature
	±Amplitude	Indicative of intensity of magnetization
Profile*	Anomaly structure† and shape	Indicates possible dip and dip direction
		Induced magnetization indicated by negative to north and positive to south in northern hemisphere and vice versa in southern hemisphere, if the guidelines does not hold, it implies significant remanent magnetization present
Profile and maps	Magnetic gradient	Possible contrast in k and/or magnetization
Maps	Linearity in anomaly	Indicates possible strike of magnetic feature
Maps	Dislocation of contours	Lateral offset by fault
Maps	Broadening of contour interval	Down-throw of magnetic rocks

3.3.4.2. Quantitative interpretation

The essence of quantitative interpretation is to obtain information about the depth to particular magnetic body, its shape and size and details about its magnetization in two possible ways. One is direct, where the field data are interpreted to yield a physical model. The other is the inverse method, where models are generated from which synthetic magnetic anomalies are generated and fitted statistically against the observed data. The degree of detail is limited by the quality and amount of available data and by the sophistication of either the manual methods or the computer software that can be used.

Chapter Four

DATA ACQUISITION AND PROCESSING

4.1. Survey Traverse Selection

The water works design and supervision enterprise (WWDSE) selected an area southwest of Wabi-Shebele river basin and adjacent Weredas for groundwater resources potential assessment on the basis of previous detailed geological, hydrogeological and geophysical surveys.

The survey was carried out to understand;

- lithologic units,
- groundwater potential zones,
- geological structures, and

- physical properties of subsurface rocks.

The methods chosen for the survey consist of VES and magnetic techniques. The area was basically selected due to the presence of thick alluvial sediments that occur along Fafan and Jerer River basins and adjacent Weredas of Somali Regional State of Ethiopia.

The geophysical observations have been carried out all along the transect lines. The layout of the geophysical observation points and traverse lines are shown in Figure 4-1.

4.2. Data Acquisition and Instrumentation

4.2.1. Vertical Electrical Sounding

VES survey was carried out along seven transect lines oriented approximately NW-SE the study area with 1 to 5Km spacing of observation points. A Schlumberger array of maximum current electrode spacing 500m (AB/2=500m) was generally used for maximum depth of interest. A total of twenty five VES points are distributed in the seven traverse lines with transect lengths ranging from 2 to 27kms. Some of these VES were located near previously drilled boreholes to obtain control during interpretation.

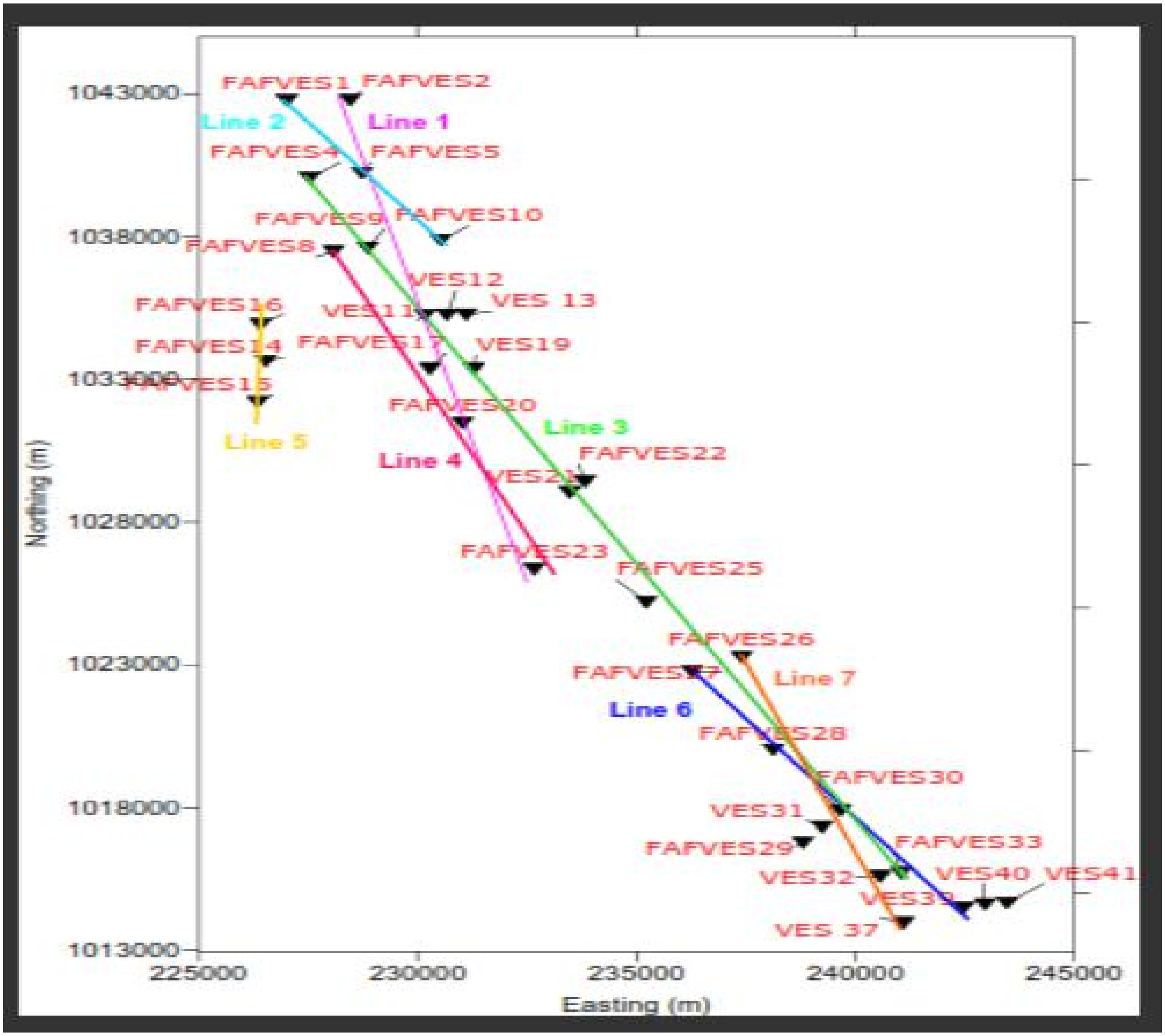

Figure 4.1 Traverse Lines of VES points of the Study Area

4.2.2. Magnetic Survey

The magnetic survey was conducted along four randomly selected traverses within the study area and collected about two hundred magnetic data at every 30m interval of survey points. The profiles were oriented about northwest-southeast in order to cross and so to detect the possible structure related to groundwater occurrence.

Very few of these magnetic data were surveyed near to the previously surveyed VES points. The total magnetic intensity, the time, date and the location of data points were recorded. Data quality was controlled by measuring each observation data point two times, whereas three readings for the base stations. The survey was conducted for an average profiling distance of 1.3Km to overcome diurnal variation.

4.3. Instrumentation

Two instruments were used to acquire the VES data, namely;

- the Terrameter SAS 4000, ABEM instrument and
- OYO McOhm Mark-2 resistivity meter model 2115A.

Both instruments used for the VES surveys were powered by 12volt and 70Ampare car batteries together with other accessories such as interconnecting cables with reels and electrodes.
In addition, different accessories were used, such as;

- Hand held GPS instrument,
- Set of walki- talkies,
- Plastic meters,
- Continuity tester and
- Hammer.

The magnetic survey was carried out using the G-856AX 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.

4.3. Data Reduction and Processing

4.3.1. VES Data Reduction and Processing

4.3.1.1. VES Data Reduction

The apparent resistivity values are plotted on logarithmic transparent paper. In processing of the collected data, the apparent resistivity value on the ordinates and the electrode separation (AB/2) on the abscissa. As of the WWDSE, the resistivity measurements were made by progressively increasing the potential electrode distance (MN) for relatively large increment of the current electrode distance (AB/2). In most cases the sounding curve is segmented due to overlap measurement and cannot be interpreted as it is. To have precise interpretations the segmented curves were shifted to the small MN curve points, so that the effect could be quantified and corrections could be made in order to obtain a single smooth curve that could be processed with the computer using IP2WIN and then WIN RESIST software (Velpen, 1995).

4.3.1.2. VES Data Processing

The field results of the study are presented in both qualitative and quantitative interpretations. In the qualitative interpretation the shape of the field curve is observed to get a qualitative idea about the number and resistivity of layers. The segmented curves were shifted to the small MN curve points to have precise interpretation. The results of this method of interpretation involved slice stacked of electrical resistivity maps, geo-electric and pseudo-sections. The collected secondary VES data were plotted on a bi-log paper and interpreted by using IP2WIN software to find out initial model parameters of possible layers. Those parameters obtained from IP2WIN software were arranged and analyzed with the existing lithologic units of the area to use as an initial model in RESIST inversion software which resulted and reliable electrical parameters of the layers with tolerable error ranging 1.5-4.5%. In the quantitative method geo-electrical parameter, i.e. true resistivity and layer thickness were obtained to make geo-electrical section using AutoCAD software.

The type of the curve and model parameters of the selected four VES curves obtained from the software is presented on Figure 5-1.

A slice stacked map for different value of AB/2 reflects the lateral variation of apparent resistivity over a horizontal plane at a certain depth. In other words, these maps indicate distribution of apparent resistivity in the area against distance of current electrodes. The maximum depth penetration of the AMNB method is 1/3 to 1/4m of the maximum distance of current electrodes (Frohlich et al., 1996). These apparent resistivity contour maps for different values of AB/2 are illustrated in the Figure 5-2.

Pseudo-section qualitatively reflects the apparent resistivity distribution within the subsurface versus electrode spacing values (AB/2). These pseudo-sections are given in the Figure 5-3, 5-5, 5-7, 5-9, 5.11, 5.13 and 5.15.

Geo-electric sections, in general, show the distribution of layer resistivities and thicknesses and are believed to give a closer approximation to the actual geo-electric setting in the subsurface. In practice, most of the quantitative interpretation would be based on these sections. In order to prepare the geo-electric sections, the final model parameters (thickness and resistivity), in this work, are determined by an inversion software, RESIST. The geo-electric sections of all profile are presented in the Figure 5-4, 5-6, 5-8, 5-10, 5.12, 5.14 and 5.16.

4.3.2. Magnetic Data Reduction and Processing

4.3.2.1. Magnetic Data Reduction

Data reduction and processing is the series steps taken to remove both signal and spurious noise from the data that are not related to the geology of the study area. This process thereby prepares the dataset for interpretation by reducing the data to only contain signal relevant to the study. These steps are summarized below:

- Data checking and editing: involves the removal of spurious noise and spikes from the data that was caused by high tension power cable.
- Diurnal removal: corrects for the temporal variation of the Earth's main field which was achieved by subtracting the time synchronized signal, recorded at a stationary base magnetometer from the survey data.
- IGRF removal: removes the strong influence of the Earth's main field. This was achieved by subtracting a calculated of main field using Oasis Montaj from the diurnal corrected survey data.

Chapter Five

DISCUSSIONS AND INTERPRETATIONS

5.1. General

As discussed in the preceding section, the results of resistivity sounding survey are presented in the form of interpreted VES curve, pseudo-depth slice map and apparent resistivity pseudo-sections for the purpose of qualitative assessments and vertical geo-electric section, permitting quantitative interpretations. Again, the results of the magnetic survey also presented as curve and different maps. IGRF corrected map, analytic signal map, TDR map, and vertical derivative map, horizontal and vertical gradients of analytic signal, and RTP map for qualitative interpretation and differenced grid between residual and upward continuation map for 2D modeling.

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 obtain the initial model parameters to be entered in to inversion software (RESIST) by constraining it further with the existing boreholes. It is seen from the interpreted field curves that a very good correlation between the field data and the interpreted model sections are obtained for all the four VES points. This is attested by an RMS error of 1.5 to 4.5% obtained for the sounding data. An illustration is made using four interpreted VES curves, one each from each of the survey traverses and these are given in Figure 5-1. In the four sounding curves, a 4 to 7 layer of the subsurface is seen too well represents the subsurface (with the AB/2 of 500m used for the survey).

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, 9, 30, 66, 220 and 500. All VES points are used for qualitative assessments of the electrical nature of the geologic medium. The sounding points are almost evenly distributed so it is believed to give a good representation of the ground overall.

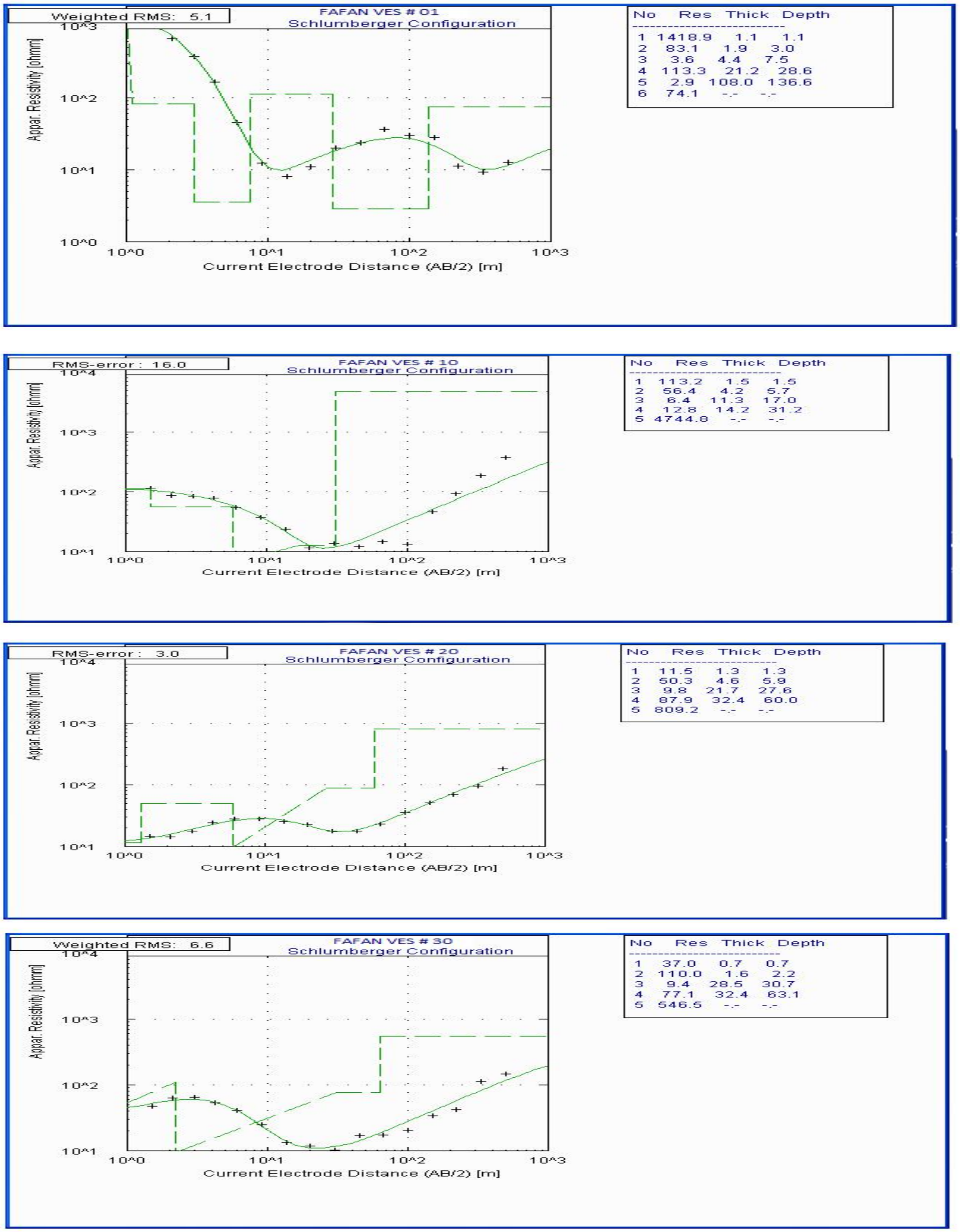

Figure 5.1 Sample Interpreted VES Curves

5.2.2.1. Sliced-Stacked for different AB/2

In Figure 5.2, the slice stacked maps were constructed for AB/2=1.5, 9, 30, 66, 220 and 500m. The choice of such spacing depends on the variability between them and to show the lateral variations of resistivity at different pseudo depth. These maps reflected the lateral variations of the electric resistivity over a horizontal plane at depth of about 0.5, 4.5, 15, 33, 110 and 250m respectively. Specifically, 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 considerably from 0-460 Ohm-m.

According to Figure 5-2 the most interesting feature that can be seen on the sliced plot is the low resistivity zones, (<120 Ω-m) that occupies the vast portion of the survey area. The value of the high apparent resistivity value zone decreases as the investigation depth increases. The high resistivity valued zones (>120 Ω-m) are observed in the Southwest parts of all selected AB/2 and very few parts in the Northwest parts of the upper three layers.

5.2.3. Pseudo depth section and Geo-electric Section of the Profiles

The reduced and filtered VES data along all survey lines were used to construct the pseudo-sections so as to identify the distribution of different resistivity values in the lateral and vertical direction. The pseudo-sections of the VES data along all traverse lines are constructed by SURFER software of version-10. The qualitative interpretation of pseudo-section gives preliminary idea for the presence or absence of groundwater potential at a given area.

The final result from one dimensional inversion of VES data along all survey lines were used to construct the geo-electric sections in order to identify the distribution of different lithologic units in the vertical direction. IP2WIN and WIN RESIST were used for the VES data inversion, whereas the plotting was carried out by using AutoCAD (V 2007). The lithologic logs from boreholes that are lying on these profiles were used to fix the thickness of each layer by grouping the rock samples on their type and degree of weathering and fracturing basis. The pseudo-depth sections along these survey lines were examined to see the relative resistivity variations when preparing geo-electric sections.

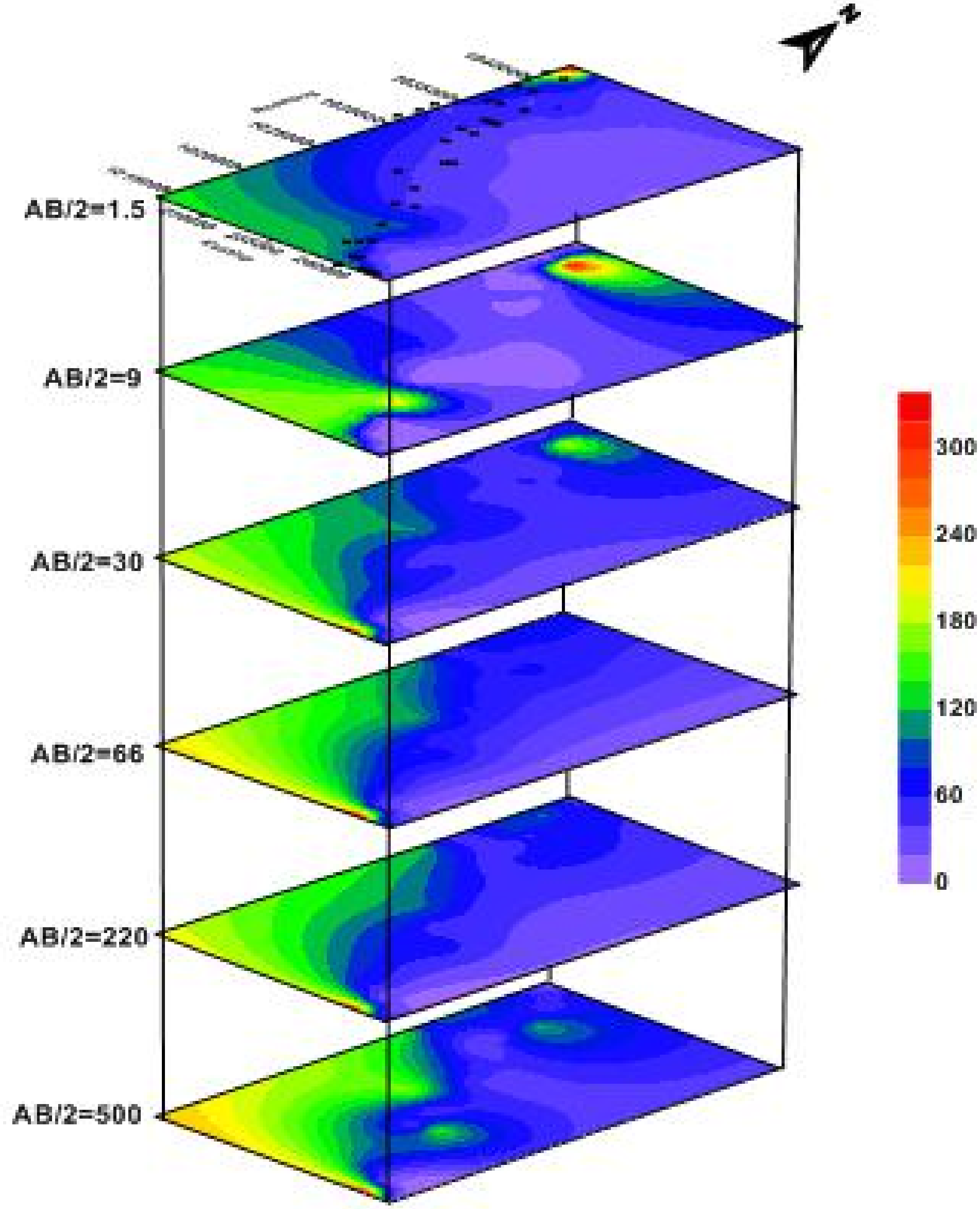

Figure 5.2 Sliced-Stacked map of different pseudo-depths (=AB/2).

5.2.3.1. Profile One

Pseudo depth sections

The pseudo-depth section constructed using V-2, 5, 11, 17, 20, and 23 that lie on the survey traverse Line-1 are given as illustration in Figure 5-3.

In the figure, there is a lateral variation in resistivity value at the southeast part of the section shows that a prominent high resistive zone that mapped between V-20 and V-23 and it extends to large depth. There is also a relatively high resistivity value at the northwest bottom of the section. However, the low resistivity valued zone is seen to cover a wide range of the section. The shallower level that dominated by a low resistivity values that ranges from 0 to 60 Ohm-m shows the overburden materials that are mainly composed of clay and silt while the deeper region with the same resistivity values being a potential water saturated horizon. The high resistive region with values >180 indicates the presence of weathered and fractured shally limestone. One can depict the presence of a structural discontinuity near the south end of the ttraverse between VES 20 and VES-23 as indicated by the dark dashed line.

Therefore, the use of apparent resistivity pseudo-depth sections, that are plotted with the raw data collected from the field without any bias of the interpreter, are very useful ways to visualize the subsurface and, in most instances, delineate zones of structural discontinuity.

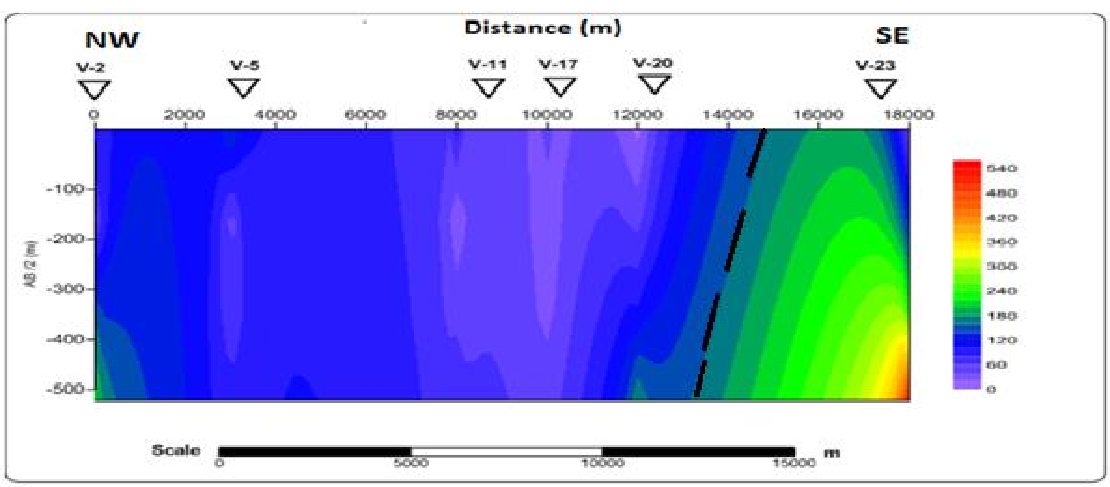

Figure 5.3 Pseudo-depth section constructed by VES points lyingalong Line-1.

Geo-electric Sections

The resulting geo-electric section constructed from the interpreted layer parameters of six VES points lying along this traverse line is given in Figure 5-4.

The first geo-electric layer having resistivity values that rangs from107-261 Ohm-m with thickness variation from 0.4 to 1m are interprated as top soil. The second geo-electric layer with resistivity values in the range 9-30 Ohm-m having thicknesses variation from 1 to 4m represents clay soil. The third geo-electric layer marked by V-2, V-5 V-11, V-17 and V-20 of resistivity values ranging from 10 to 30 Ohm-m with thickness variation from 6 to 67m reflects gravely sand. The third geo-electric layer marked V-23 having resistivity value 106 Ohm-m shows the presence of fine to medium grained sand. The fourth geo-electric layer with resistivity values varying from 800 to 970 Ohm-m manifestes to be a slightly moderately weathered gneiss.

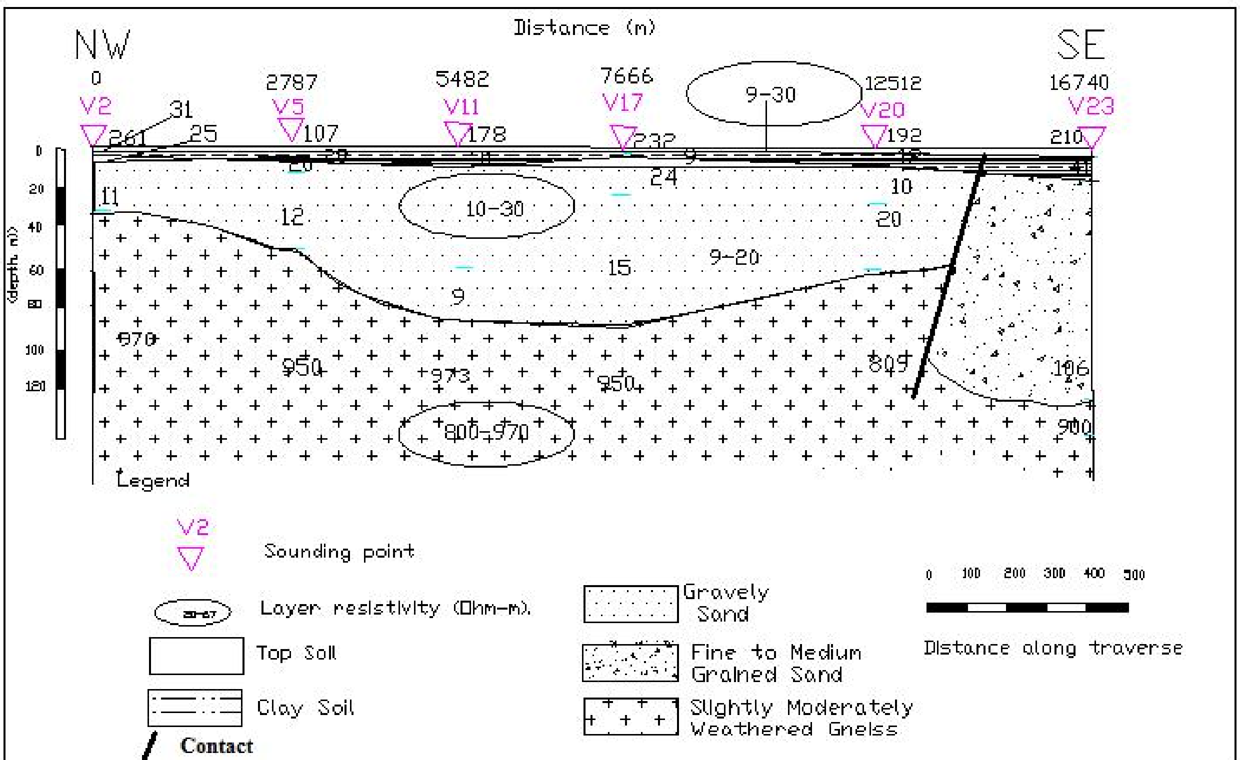

Figure 5.4 Geo-electric Section along Profile 1.

Subsequently, the highly weathered and fractured gneiss and moist gravely sand observed inthe geo-electric layer of depth varying from 35 to 88m with lateralresistivity variation from 9-20

Ohm-m seems to be weak zone that gives a promising information for the presence of groundwater potential resources.

5.2.3.2. Profile Two

Pseudo depth section

The pseudo-depth section is constructed using V-1, 5, and 10 of traverse line-2 (see Fig. 5.5).

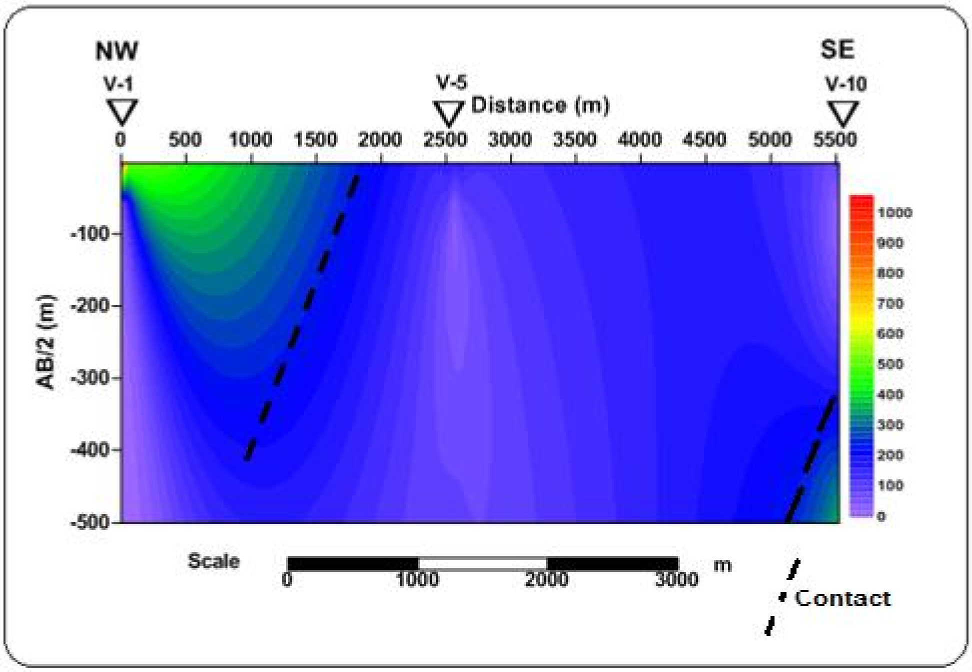

Figure 5.5 Pseudo Depth Section Constructed by VES Points Along Line-2

According to the Figure, there is a lateral variation in resistivity showing a high resistivity value at the top and bottom of Northwest and Southeast ends of the section, respectively. The high resistivity valued region that does not extend to large extent is mapped between V-1 and V-5, whereas the rest of the section is seen to have low resistive. The shallower level that dominated by a low resistivity values that ranges from 0 to 100 Ohm-m shows the overburden materials that mainly composed of clay and silt while the deeper region with the same resistivity values being a potential water saturated horizon.

Geo-electric Section

The resulting geo-electric section constructed from the interpreted layer parameters of three VES lying along profile 2 is given in Figure 5-6.

The resistivity values of VES points along this traverse line show a big variation near-surface of the geo-electric layer in the range between 113 and 1419 Ohm-m. The Difference in the resistivity values is due to the variation in the amount of grain size. Areas With high resistivity values indicate the presence of gravel and sand as top soil, while those with low resistivity values showing the presence of clay intercalation with sand. This lateral variation in resistivity extendes from 0.5-1.3m thicknesses and the expected lithologic dscription for this layer is top soil with alluvial cover (sand, clay and silt).

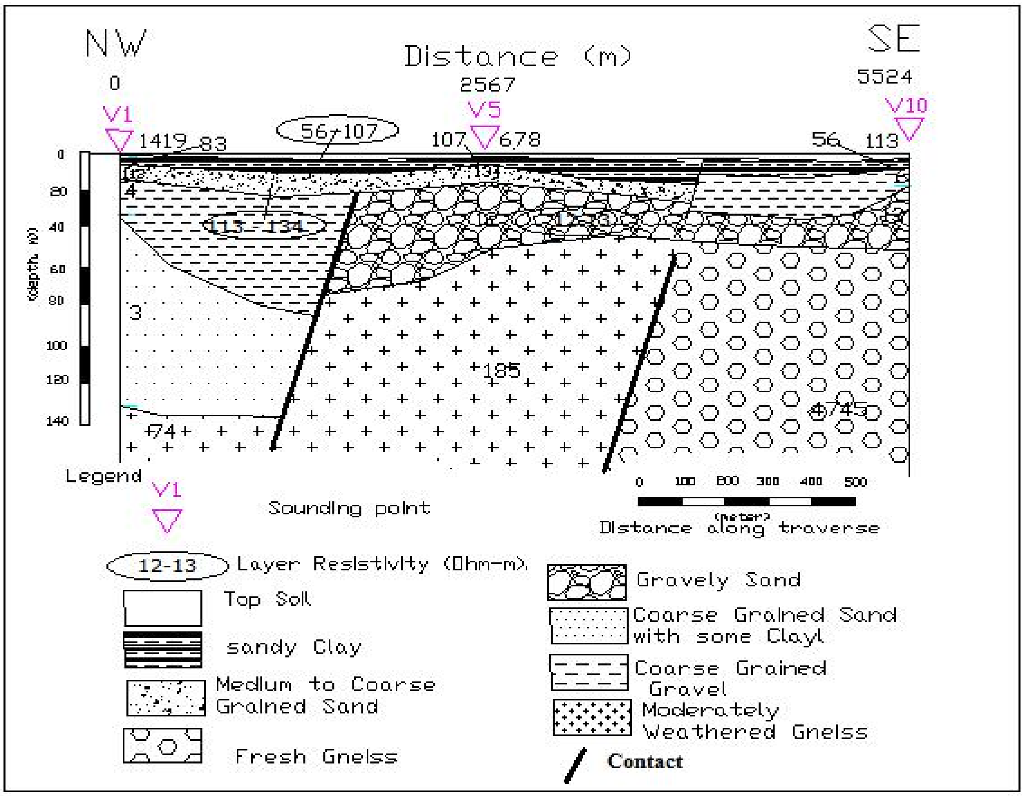

Figure 5.6 Geo-electric Section along Profile 2.

The second geo-electric layer is marked between V-1 and V-5 with resistivity variation from 56 to 107 Ohm-m. This lyer hasa thickness variation from 2 to 17m which likely reflects the presence of sandy clay.

The third geo-electric layer marked by V-1 and V-5 with resistivity value ranging from 113 to 134Ohm-m of thickness variation from 8 to 17m corresponds tomedium to coarse grained sand.While the geo-electric section of the same layer marked by V-10 with resistivity value 6 Ohm-m and thickness between 7 and 25m reflectes the presence of coarse grained gravel.

The expected lithologic description of the fourth geo-electric layer manifasted by V-1 having resistivity value 4 Ohm-m of depth 8m is coarse graind gravel. Whereas the geoelecctric section of the same layer marked by V-5 and V-10 is assumed to be gravel.

The fifth geo-electric layer marked by V-1 with resistivity valu of 3 Ohm-m found at depth 137m may represent coarse grained sand with some clay.

The last geo-electric layer marked by V-1 and V-5 with restivity values of 74 and 185 Ohm-m shows the presence of moderately weathered gneiss, while the last geo-electric layer marked by V-10 and resistivity 4745 Ohm-m is representing fresh gneiss.

5.2.3.3. Profile Three

Pseudo depth section

The pseudo-depth section constructed by V-4, 9, 11, 19, 21 and 25 that lie on the survey traverse line-3 is given in Figure 5-7.

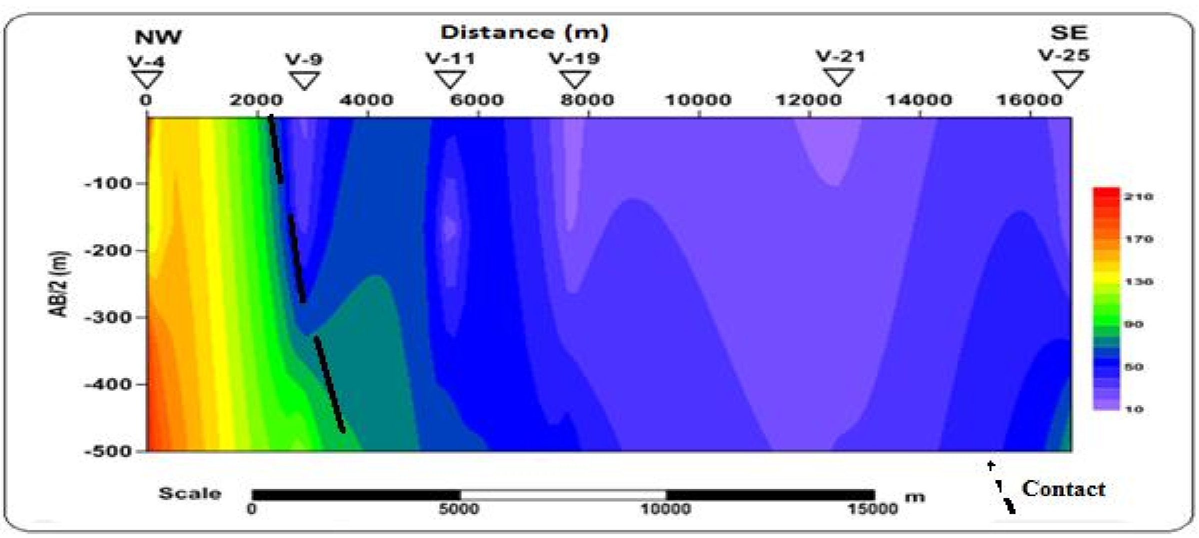

Figure 5.7 Pseudo Depth Section Constructed by VES Points AlongLine-3

The figure shows that , the lateral resistivity variation decreases as one goes from NW to SE with a very high resistivity value is dominating over the NW side region of the section. This highly resistive zone is bounded between the first two VES points of traverse line-3 (V-4 and V-9). On the other hand, the region between V-19, 21, and 25 is a highly conductive zone of the section. The highly resistive region shows that the presence of other formation like fracture, while the shallower level which is dominated by a low resistivity values, interpreted as a response of overburden materials that mainly composed of clay and silt, whereas the deeper level with low resistivity value from 10-50 Ohm-mhas an implication for the presence of weak zone that saturated with a potential groundwater resource. The fractured zone having values within the range of 90 to 210 Ohm-m.

5.2.3.4. Profile Four

Pseudo depth section

As can be seen in Fig. 5.9, this section is constructed by V-8, 17, 20, and 23 that lie on traverse Line-4.

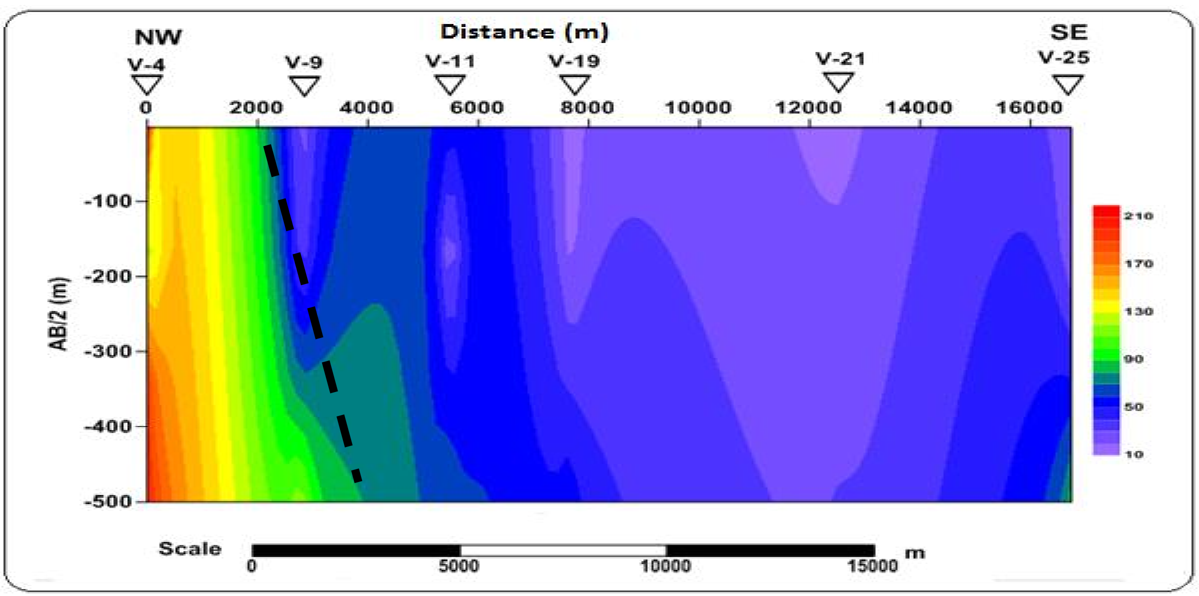

Figure 5.7 Pseudo-depth section constructed by VES points along Line-3.

From the figure, we can observe that the lateral resistivity variation showing a highly resisitivity values at the NW bottom and SE end of the section, while the rest of which is seen to be conductive region. The high resistivity valued regions are mapped at the foot of V-8 and part of the area between V-20 and V-23, as well. This high resistivity zone extends to deep at SE side of the section.Moreover, except the left bottom and the right border of the region, almost all of the other part of the area has low resistivity. And the resistivity of this high conductive zone which covers wide area of the section ranges from 0-60 Ohm-m, Whereas the unsaturated zone is having 180 to 540 Ohm-m. As a result, the region with low resistivityis interpreted as a weak zone that shows the presence of saturated groundwater potential.

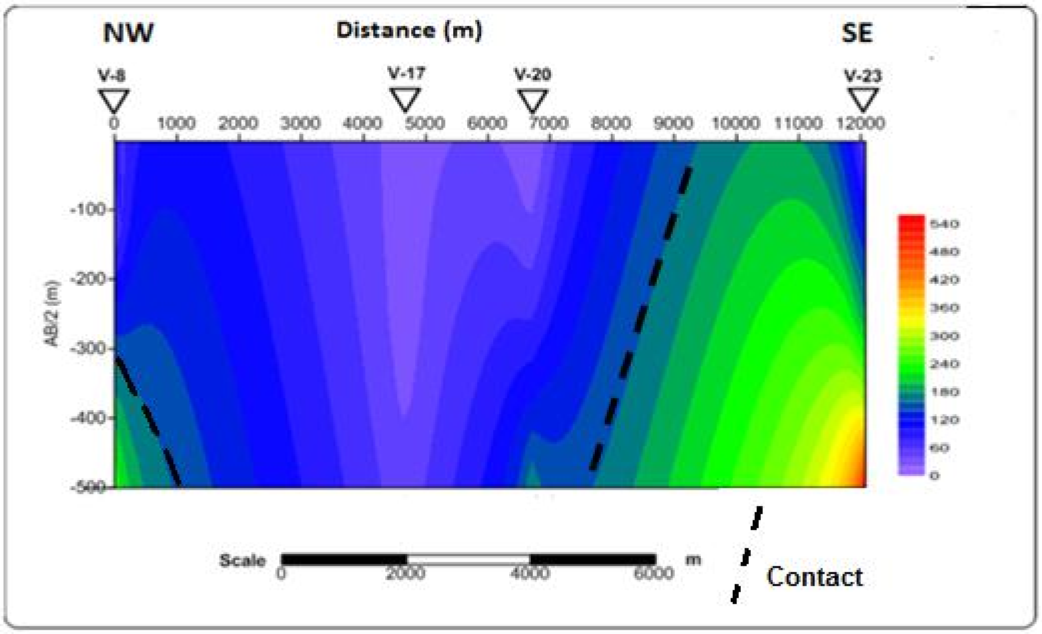

Figure 5.9 Pseudo Depth Section Constructed by VES Points Along Line-4

Geo-electric Section

The first layer of this geo-electric section with resistivity variation ranges from 187 to 232 Ohm-m is expected to be top soil.

The second layer having resistivity variation between 9 to 40 Ohm-m stands for clay soil. The third layer of this section that marked by V-17 and V-20 having resistivity variation between 9 to 24 Ohm-m corresponds to gravely sand. On the other hand, the third geo-electric layer marked by V-8 and V-23 with resistivity values of 111 and 106 Ohm-m, respectively, is thought to be fine to medium grained sand with some clay.

The last layer of this section with resistivity signature ranging from 800 to 950 Ohm-m slightly moderately weathered gneiss.

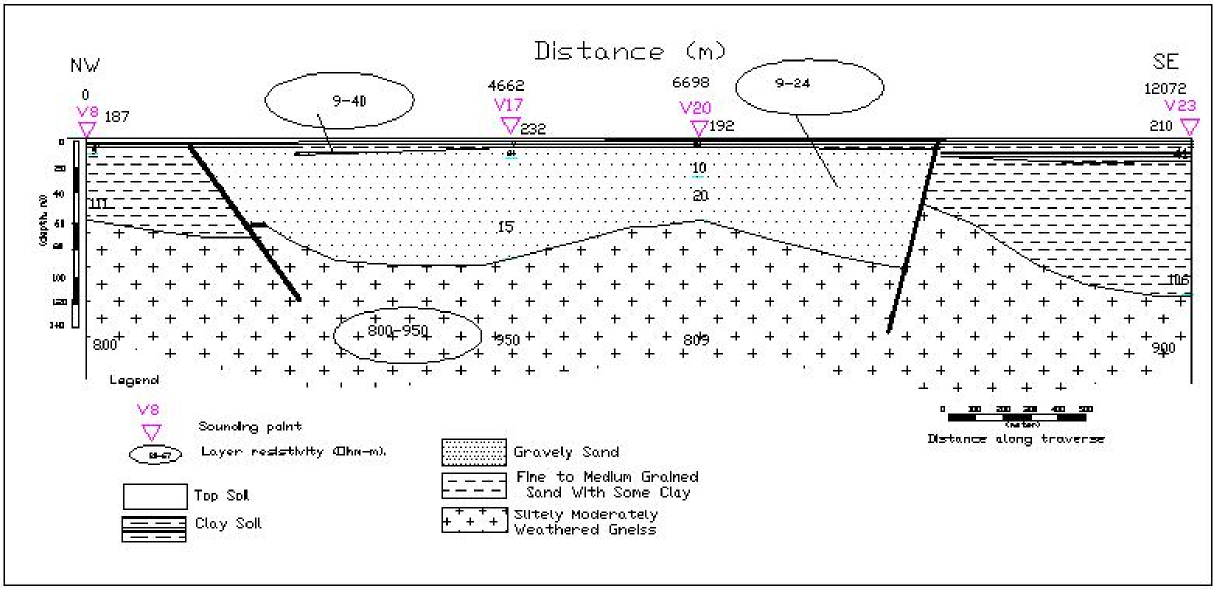

Figure 5.10 Geo-electric Section along Profile 4

5.2.3.5. Profile Five

Pseudo depth section

This section is constructed using the VES points V-16, 14, and 15 of traverse line=5 (see in Figure 5.11).

Accordingly to the figure, the resistivity of the section increases with increasing depth of investigation. The NW deeper region of the section is dominated by a high resistivity value and extends to the SE region getting thicker and and thicker coves both the deeper and upper level this region, while the shallower zone of the section is dominated by low resistivity value. The lowlying region with resistivity values >160 Ohm-m is composed of sedimantary rock. Whereas, the shallower region with low resistivity value is compsed of silt and clay while a weak zone showing the presence of saturated groundwater potential between AB/2=100 and 300m.

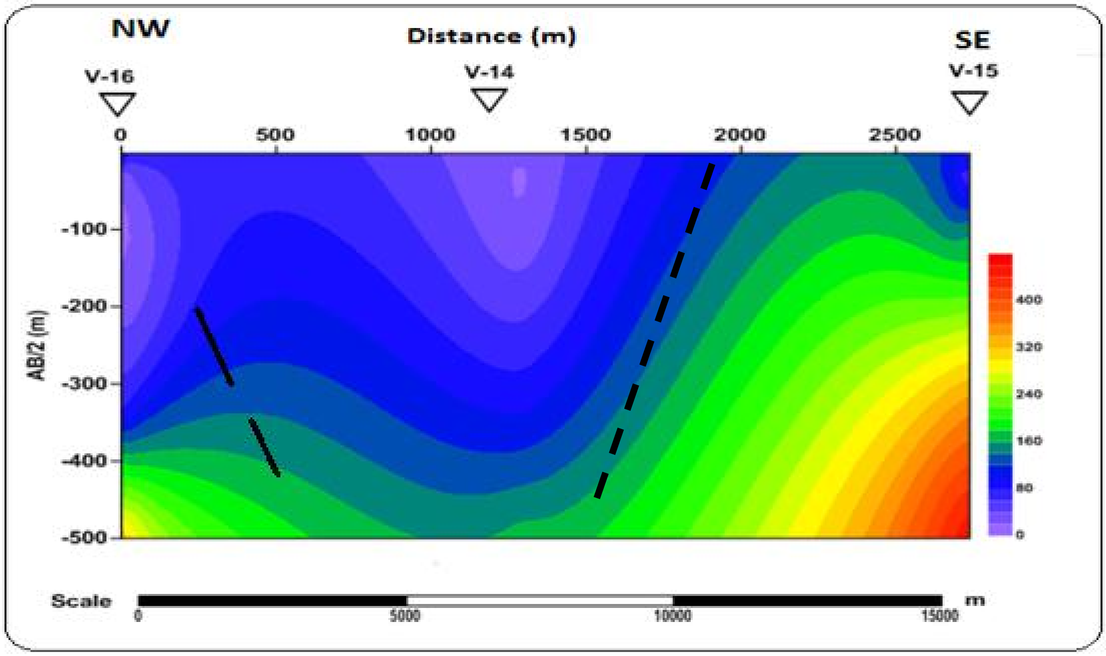

Figure 5.11 Pseudo Depth Section Constructed by VES Points Along Line-5.

Geo-electric Section

This geo-electric section is constructed by three VES points that lie along profile 5 is given in Figure 5.12. The first layer of this section having resistivity signature varies from 128 to 294 Ohm-m represents top soil. The second of which with resistivity variation between 24 and 30 Ohm-m reflects the presence of clay soil with some infilling of calcites. The third layer of this section has resistivity variation between 13 and 54 Ohm-m. This resistivity range may be correspond to fine to medium grained sand with some clay. The forth layer of the section marked by V-16 and V-14 with resistivity signature ranging from 41 to 42 Ohm-m may represent coarse grained sand. The same layer of this section marked by V-15 having resistivity value of 302 Ohm-m may stands for fine sand with moderately weathered gneiss.

The fifth layer marked by V-16 having resistivity of 6 Ohm-m coresponds to the presence of gravely sand. And the last layer of this section with resistivity signature 450 Ohm-m may be fine sand with moderately weathered geiss. Whereas the last layer marked by V-14 and V-15 having resistivity variation between 921 and 1019 Ohm-m is assumed to represent a slightly and moderately weathered gneiss.

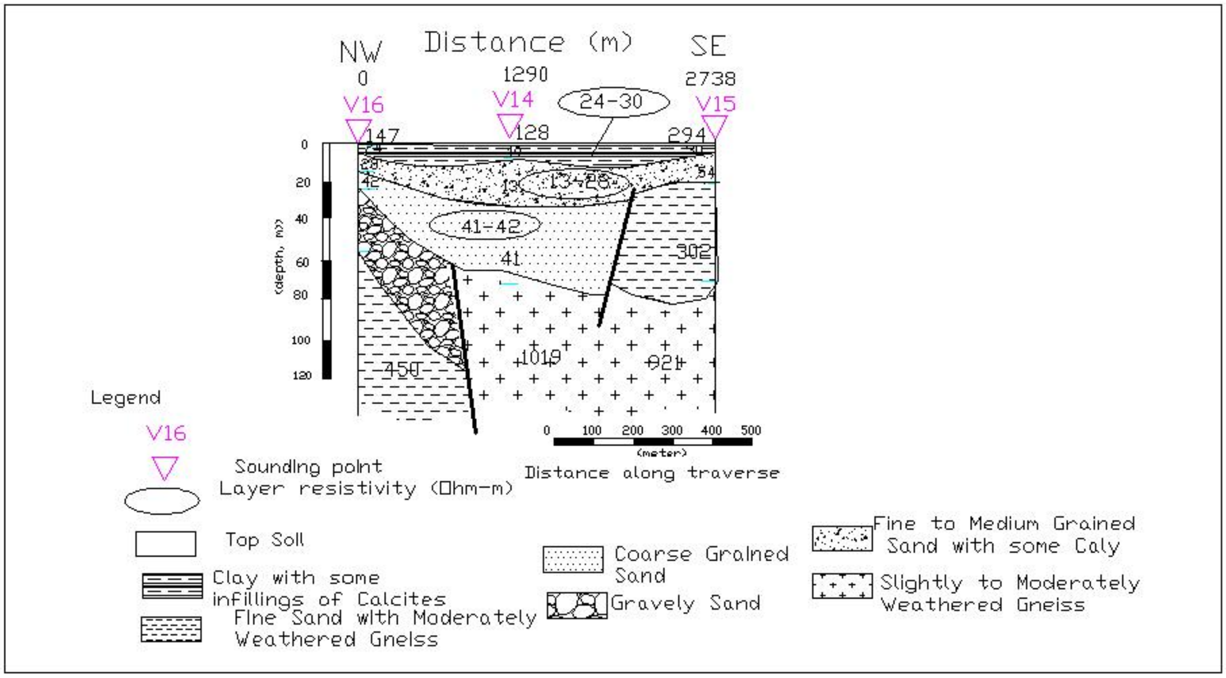

Figure 5.12 Geo-electric Section along Profile 5.

5.2.3.6. Profile Six

Pseudo depth section

The pseudo-depth section is constructed using V-28, 29, 30 and 39 that lie along traverse line-5 (see Figure 5.13).

According to the figure, there is a high resistivity value is mapped at V-29 but the middle portion of this region having relatively conductive zone. The NW border and SE portions are dominated by high conductive zones. The high resistive region of value >80 gives an information about the presence of fractured zone The shallower level that dominated by a low resistivity values <50 Ohm-m shows the overburden materials that mainly composed of clay and silt while the deeper region with the same resistivity values being a water bearing horizon.

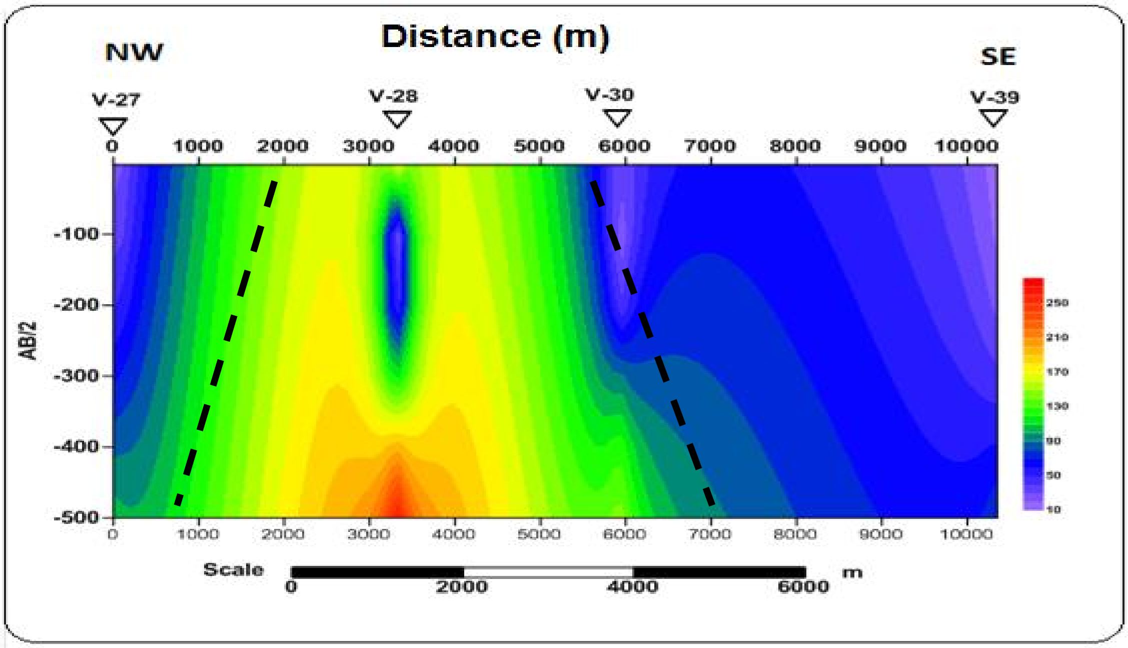

Figure 5.13 Pseudo Depth Section Constructed by VES Points Along Line-6

Geo-electric Section

The resulting geo-electric section constructed by the interpreted layer parameters of four VES points lying along this profile is shown in Figure 5-14.

The top geo-electric layer with a resistivity range of 17 to 235 Ohm-m may be interprated as top soil. The second geo-electric layer having resistivity values ranging from 4 to 15 Ohm-m likely reflects clay soil. The third layer of the section with resistivity signature between 15 and 37 Ohm-m may be fine to medium grained sand. The fourth layer marked by V-27 and V-39 with resistivity value of 5 Ohm-m is thought to represent medium to coarse grained sand with some clay. The expected lithologic description of the same layer marked by V-28 and V-30 with resistivity variation from 70 to 77 Ohm-m may be sandy clay formation. The fifth layer of V-27 having resistivity value 94 Ohm-m likely corresponds to the moderately weathered gneiss, while the fifth layer at V-39 with resistivity value 20 Ohm-m reflecting fine to medium grained sand. The last layer at V-27 marked by resistivity value 280 Ohm-m is assumed to be corrosive top soil. But the rest of the layer with resistivity varying from 445 to 550 Ohm-m attributes fresh to moderately weathered gneiss.

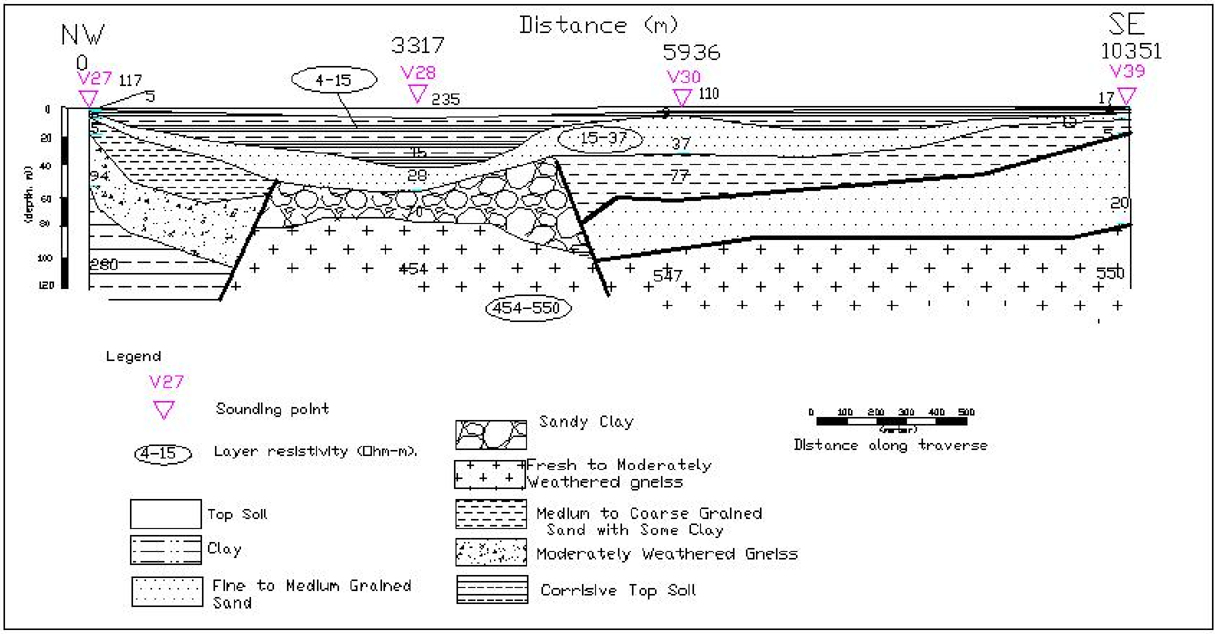

Figure 5.14 Geo-electric Section along Profile 6.

5.2.3.7. Profile Seven

Pseudo depth section

As can be seen in Figure 5.15, this section is constructed by V-8, 17, 20, and 23 that lie on traverse line-7.

From the figure, we can observe that a wide portion of the NW region is dominated by a high conductive zone. while the SE part is being a high resistive region. The high resistivity valued portion of the SE region tells the presence of weathered and fractured shally limestone. On the contrary, the high conductive zone with resistivity values <100 of the shallower region is composed of silt and clay while the deeper portion of this region showing the presence of a saturated zone of groundwater.

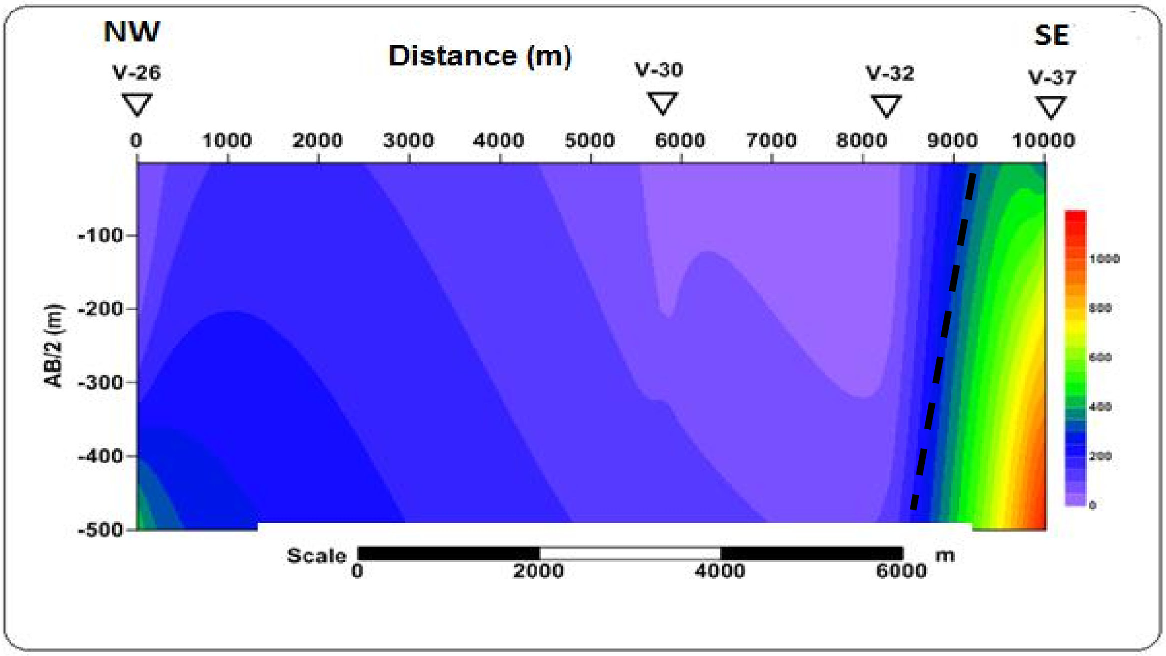

Figure 5.15 Pseudo Depth Section Constructed by VES Points Along Line-7.

Geo-electric Section

The geo-electric section constructed by the four VES points along profile 7 is given in Figure 5-16.

The first layer of this section shows a big resistivity variation in the range between 61 and 1239 Ohm-m. The expected lithologic description of this layer may be top soil. The second layer with lateral variation in resistivity between 13 and 37 Ohm-m likely represents a sandy clay formation. The third layer of resistivity value ranging from 9 to 35 Ohm-m probably reflects the presence of fine to medium grained sand, whereas this layer with resistivity value 380 Ohm-m represents moderately weathered gneiss. The fourth layer with a resistivity range of 77-88 Ohm-m is expected to be medium to coarse grained sand with some clay, and again the same layer marked by V-32 and V-37 with resistivity value 11 and 826 Ohm-m, respectively, may reflect their respective formation as fine to medium grained sand and a slightly moderately weathered gneiss. The last layer marked by V-26 and V-30 with their resistivity variation between 543 and 547 Ohm-m would probably respond as moderately weathered gneiss, whereas this layer with resistivity values in the range between 5055 and 7000 Ohm-m representing fresh gneiss.

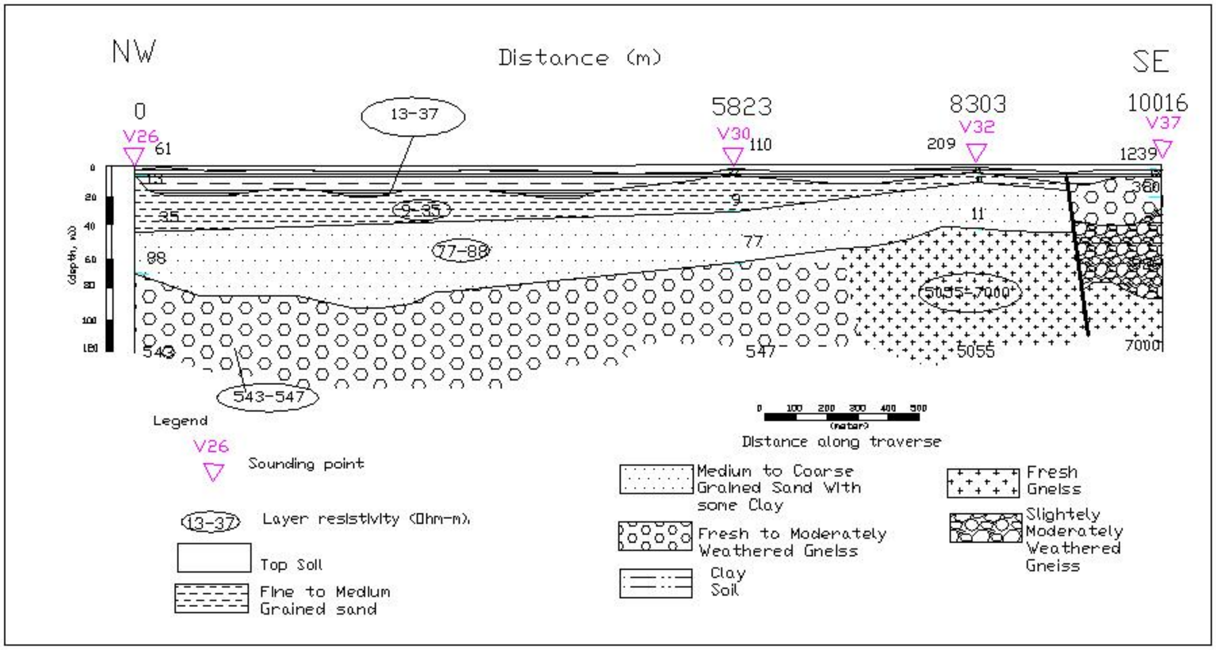

Figure 5.16 Geo-electric Section along Profile 7.

5.3. Discussions and Interpretations of Magnetics

5.3.1. Magnetic Data Presentation

Magnetic geophysical surveys measure small, localized variations on the measurement of susceptibility contrast between the anomalous body & the rock around it in the Earth's magnetic field. Ferromagnetic minerals particularly magnetite are the main source of local magnetic anomalies. The magnetic properties of naturally occurring materials such as magnetic ore bodies and basic igneous rocks allow them to be identified and mapped by magnetic surveys. Strong local magnetic fields or anomalies are also produced by buried steel objects. Magnetometer surveys find underground storage tanks, drums, piles and reinforced concrete foundations by detecting the magnetic anomalies they produce.

5.3.2 Results and Interpretations of Different Anomaly Curves and Maps

The first step in Magnetic data processing is to calculate the diurnal correction for each profile. The diurnal correction for each profile is calculated using the state of the arts of geophysics and deducted from their respective datum. This recursive procedure provided us with corrected data for each profile. The final step in magnetic data processing is the preparation of magnetic profiles and maps that display magnetic anomalies of geologic interest. In this report, a magnetic profile for each profile line is presented.

5.3.2.1 Observed Total Magnetic Field Anomaly Curves

The fact that most sedimentary rocks and surface-cover formations (including water) are effectively nonmagnetic means that the observed anomalies are attributable to the underlying igneous and metamorphic rocks (the so-called "magnetic basement"), even where they are concealed from direct observation at the surface.

In almost all of the magnetic profiles the magnetic anomalies are characterized by a very sharp inflection point or change of slope which might be the manifestation of the relatively sharp transition from one mode of lithologic formation to the other.

The amplitudes of the anomalies are also characterized by relatively higher magnitude and dominated by short wavelength anomalies which can be assumed that the magnetic anomalies are caused by shallow sources.

The whole magnetic profiles are undertaken in the Fafan river valley which is dominated by unconsolidated sediments.

As in Figure 5.17, the magnetic profile 1 has low magnetic anomaly at about 250m distance. Unlike profile 1, profile 2 (shown in Figure 5.18) shows a shorter wavelength of high magnetic anomalies that ranges from 900m to 1200m. This magnetic anomaly is characterized by anomalous body of shallower level.

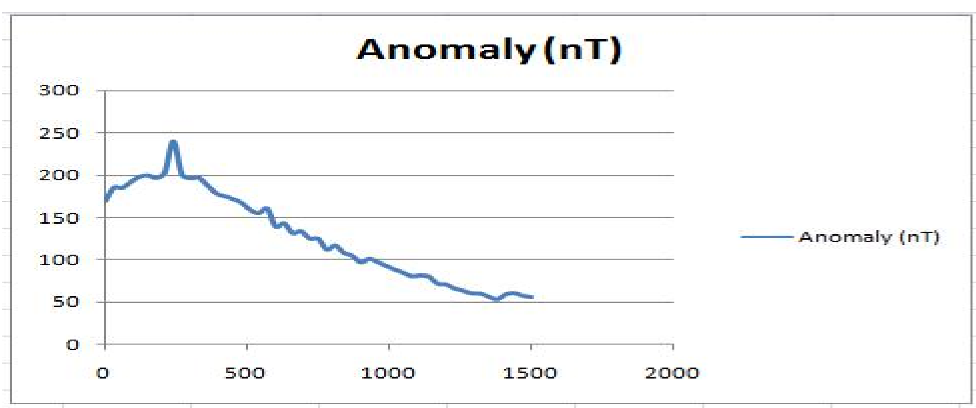

Figure 5-17 Magnetic Anomaly Curve along Profile 1

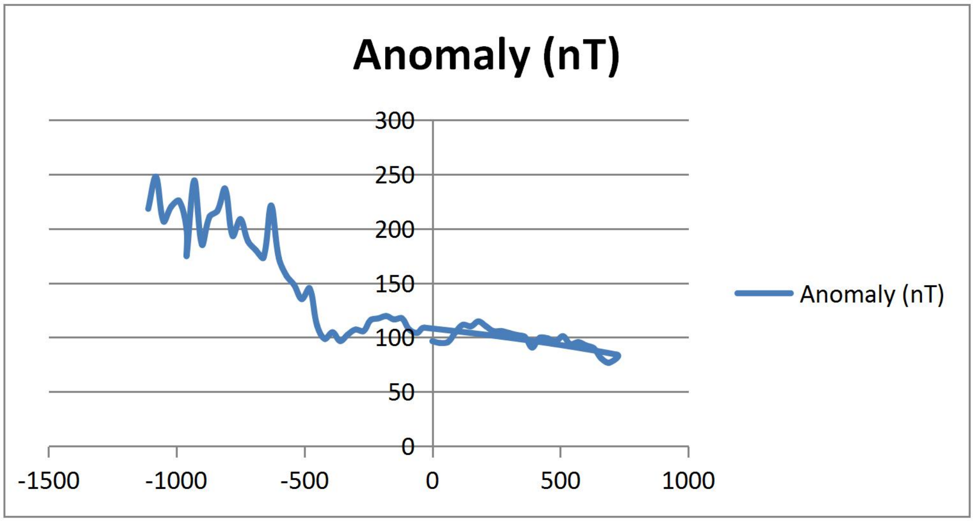

Figure 5-18 Magnetic Anomaly Curve along Profile 2.

According to Figures 5.19, profile 3 shows long and narrow wavelength which indicates to have higher magnetic intensities. The causes of these wider wavelength magnetic anomalies are located at relatively deeper depths.

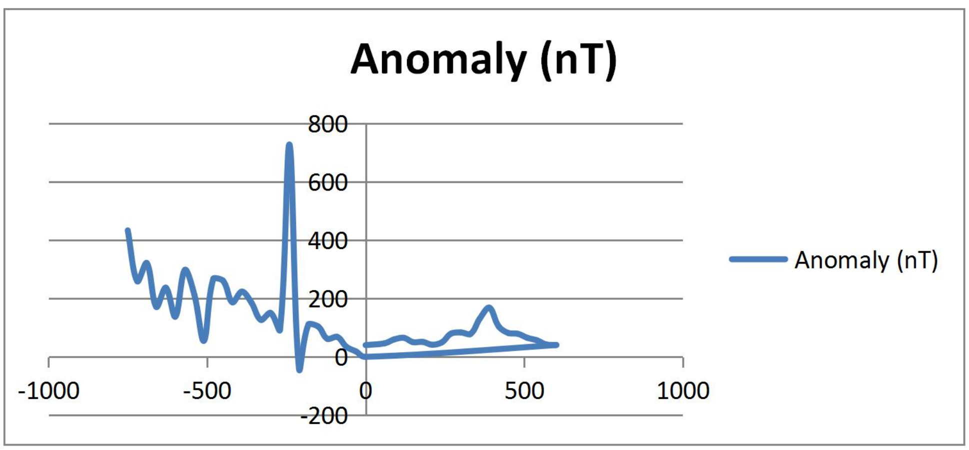

Figure 5-19 Magnetic Anomaly along Profile 3

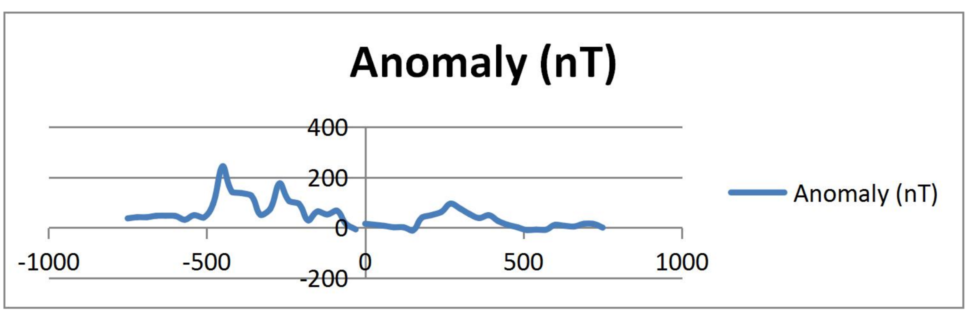

Figure 5-20 Magnetic Anomaly Curve along Profile 4

Profile 4 in Figure 5.20, illustrates a presence of relatively short wavelength magnetic anomaly at 400 m and higher and wider wavelength magnetic anomaly from on the left side the curve. And hence, the former magnetic anomaly is assumed to be caused by shallow sources while the later one is by relatively deeper sources.

5.3.2.2 Observed Total Magnetic Field Anomaly Map

The observed total magnetic field anomaly map was created after the diurnal corrections and removal of the IGRF model field from the field-collected data, Figure 5-21.The total magnetic field anomaly map depicts low anomalies in north, southwest, southeast, and the central part of the study area. The intermediate magnetic anomaly is observed dominating at the southwest, northeast and southeast margins of the study area. The low and high magnetic anomalies are also seen to have demarcation borders marked by the intermediate anomaly. A high magnetic anomaly can be observed in the northwest and semi-central part in the map.

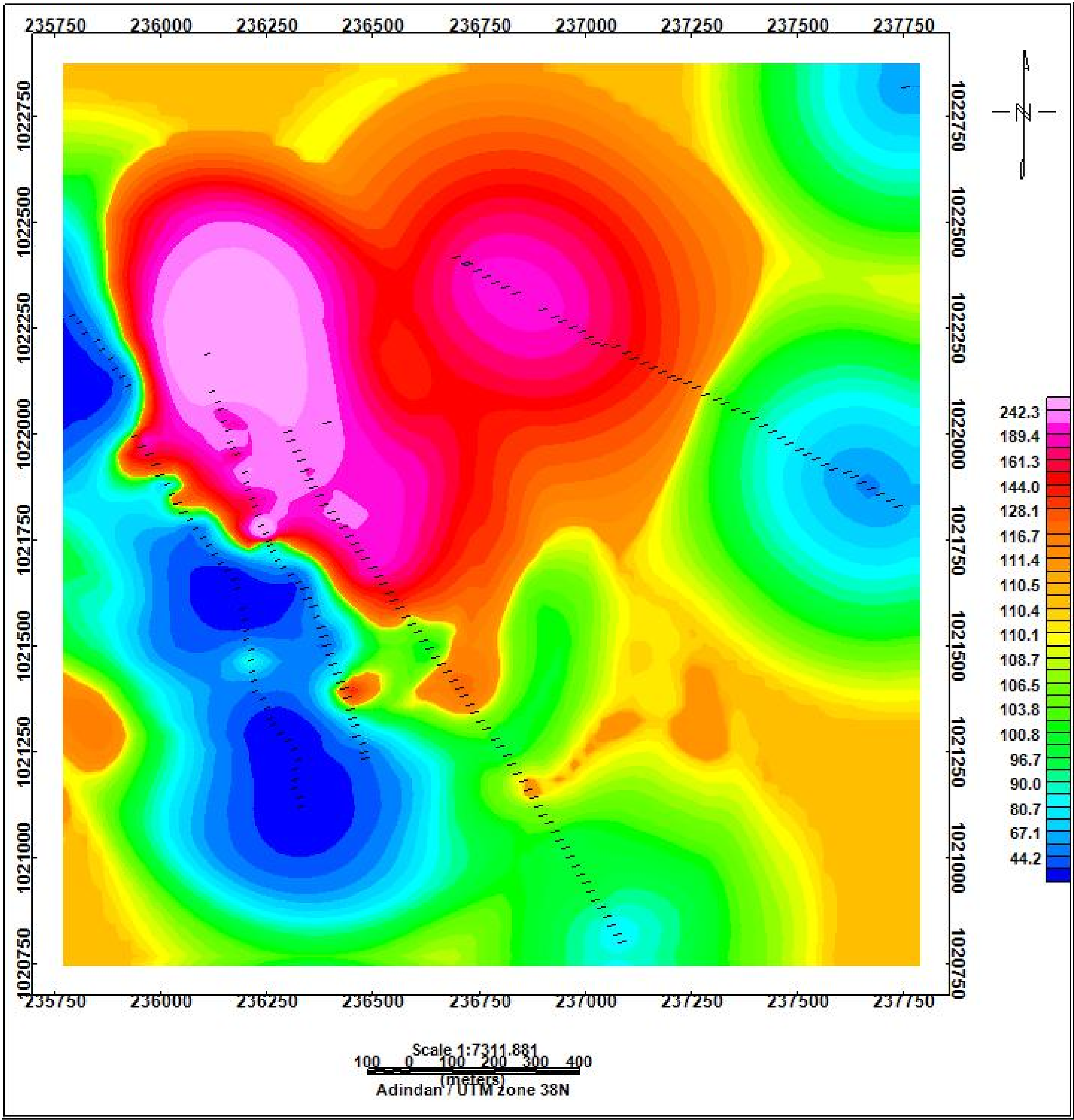

Figure 5.21 Observed Total Magnetic Field and Post Map of the Study Area

Chapter Six

CONCLUSION AND RECOMMENDATIONS

6.1. Conclusions

Geophysical Survey especially, Vertical Electrical Sounding (VES) and Magnetic survey were carried out in Fafan. A total of 32 VES were collected for preparation of this research. All these VES data were carried out In Fafan Valley. On the other hand total of 209 primary magnetic data were surveyed along four traverse lines. .The VES survey in the Fafan river valley shows that the unconsolidated sediment which is the water bearing horizon is shallow below which moderately to slightly weathered basement (gneiss) is found.

The magnetic survey showing anomalous bodies are characterised by sharp and rapidly changing inflection points which is interpreted as rapidly changing lithologic variations at that points. These anomalies are relatively higher in amplitude and shorter in wavelength which is interpreted as they are mainly caused by local variations which mostly emanates from shallow sources.

- Based on the available VES and magnetic data thus, We
  - out-lined the inferred subsurface groundwater barriers
  - delineated other linear geologic structures that were anticipated by other techniques
  - mapped the saturated zone and
  - traced the regional configuration of the water table of the study area

Generally the survey envisages the presence of plausible aquifers, geological horizons, geological structures and static water level of the survey area.

6.2. Recommendations

As part of this study, based on geological and structural features, future detail assessment sites are proposed to be considered taking into consideration the findings of other studies such as hydrogeology and availability of irrigable lands and presence settlement centers in the vicinity.

- Marda Fault Zone is a prominent structural feature not only in the research area but also in the horn of Africa as it extends from southeast of Afar Depression to Indian Ocean for more than 900 km in NW – SE direction.
- The particular faults associated with the Marda Fault Zone are expected to extend to great depth and generally have sub-vertical dip. Therefore, these faults have affected all lithostratigraphic units (Precambrian basement rocks, Mesozoic sedimentary strata, Tertiary Sedimentary and volcanic rock units) found to occur along the zone. Hence, Marda fault zone represent potential area for groundwater occurrence requiring detailed assessment all along its stretch, particularly Fafan and Jerer valleys.
- The occurrence of Mirio Uplift, which may behave as a barrier, to the south of the present study area may expand its potentiality for groundwater occurrence calling for systematic integrated investigation.
- Major fault/fracture structures in Jessoma sandstone which trends NW – SE and control the flow of tributary streams to Ogaden River Basin is apparently potential site for groundwater as it represents down faulted area.
- Susabani fault/fracture zone extending from Susabani locality to across Jerer valley and beyond in NE – SW direction represent a major structural discontinuity/weakness. Interplay of NE – SW and nearly east – west fault/fracture systems in the southeastern part of the project area is considerable. As such, geologically the aforementioned zones could be considered as potential sites for groundwater assessment particularly where these structures cross Jerer and Fafan valleys which are in turn controlled by the Marda faults.
- Middle Fafan valley is the most intensely tectonized place in the project area. Therefore, zones of intersections of major faults/fractures and numerous secondary or minor faults/fractures should be given attention in the search for potential groundwater resources.
- Detailed mapping and geophysical surveys at areas affected by geological structures need to be carried out for groundwater potentiality.

6.3. References

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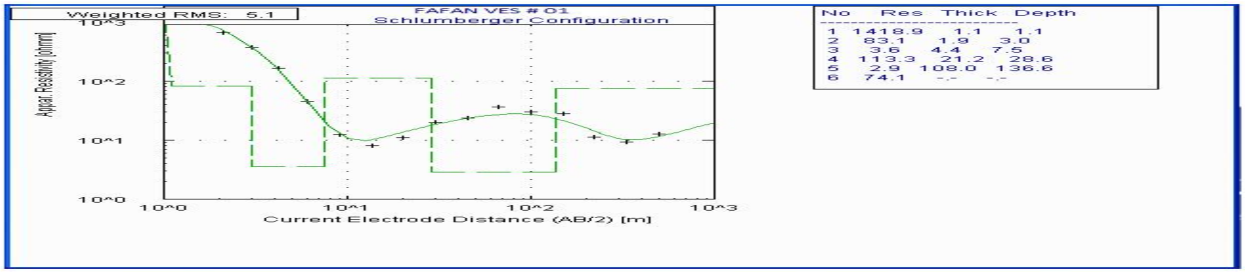
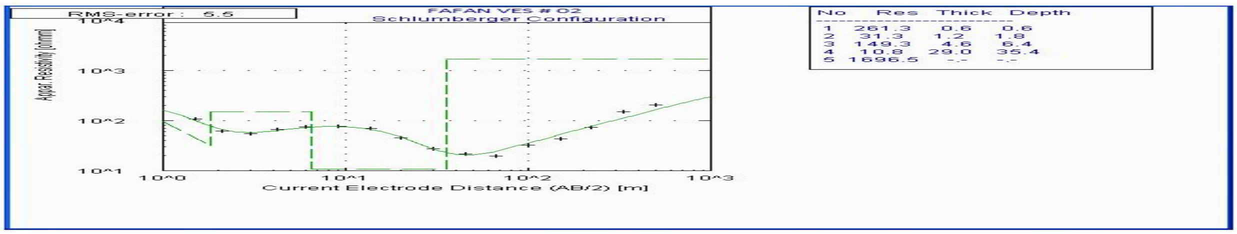
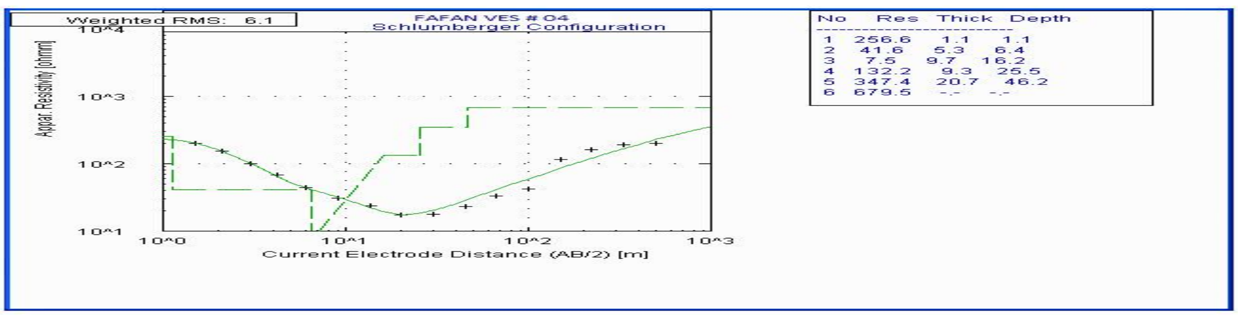
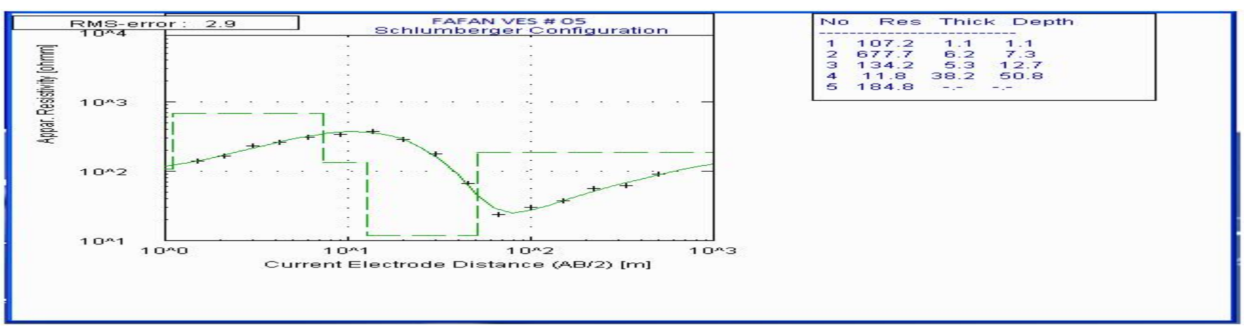
Appendices

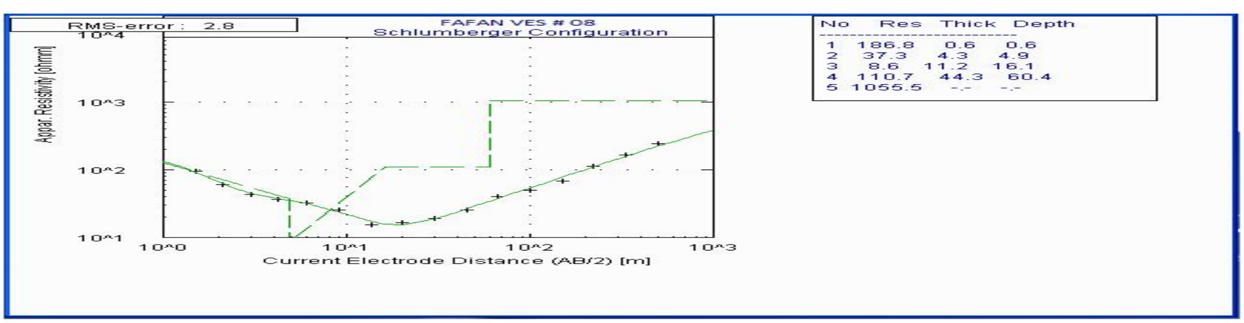
Annex 1: Interpreted VES curves of the each sounding points.

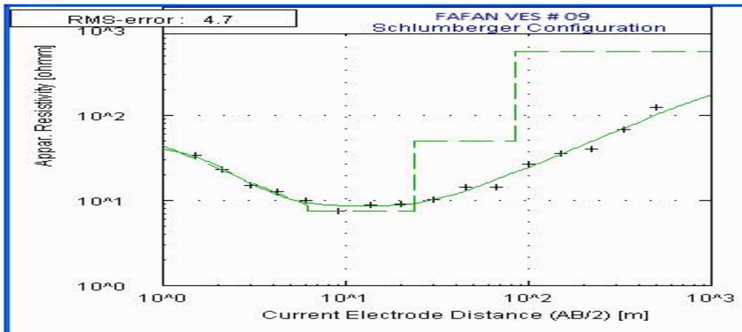




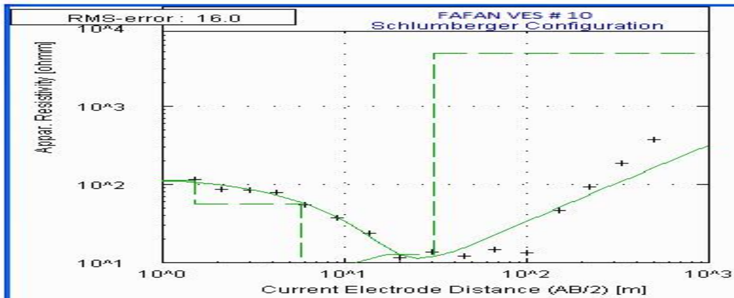




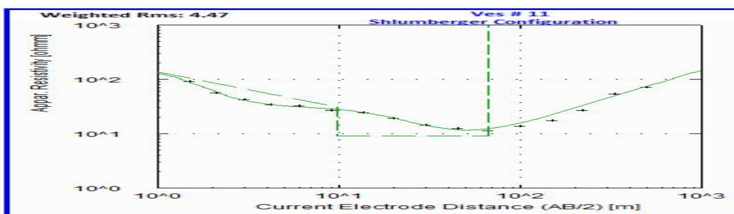




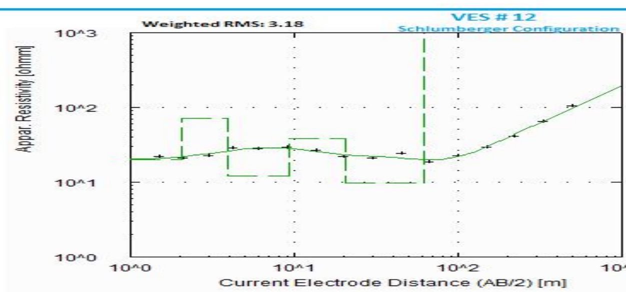
No	Res	Thick	Depth
1	46.1	0.9	0.9
2	8.8	5.2	6.2
3	7.5	17.3	23.5
4	50.0	61.2	84.7
5	565.3	-.-	-.-



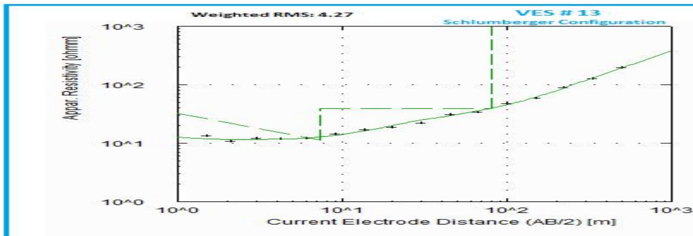
No	Res	Thick	Depth
1	113.2	1.5	1.5
2	56.4	4.2	5.7
3	6.4	11.3	17.0
4	12.8	14.2	31.2
5	4744.8	-.-	-.-



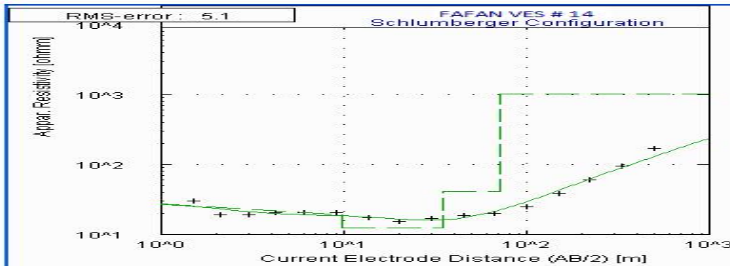
No	Res	Thick	Depth
1	178	0.66	0.66
2	30.9	9.15	9.81
3	9.01	56.8	66.6
4	6057	— —	— —



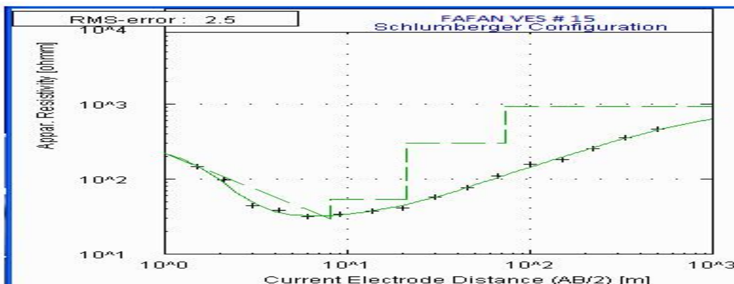
No	Res	Thick	Depth
1	20.50	2.60	2.60
2	83.60	2.13	4.73
3	25.00	3.44	8.17
4	45.30	9.27	17.40
5	8.76	35.30	52.70
6	8829.00	— —	— —



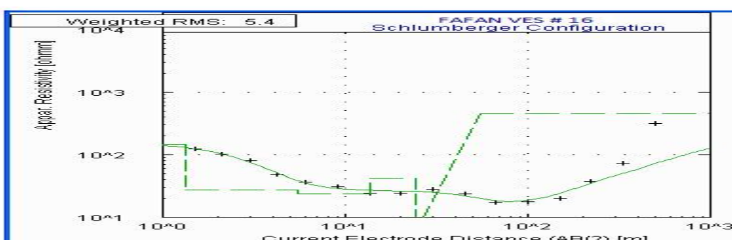
No	Res	Thick	Depth
1	84.00	0.16	0.16
2	11.40	7.12	7.28
3	39.00	73.00	80.20
4	6962.00	— —	— —



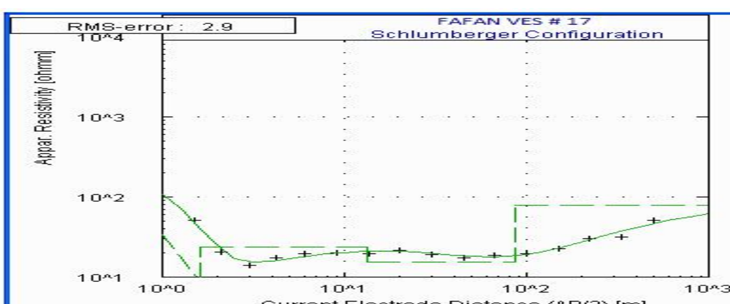
No	Res	Thick	Depth
1	28.3	0.8	0.8
2	18.9	9.0	9.8
3	12.5	24.7	34.5
4	41.2	36.8	71.3
5	1018.6	-.-	-.-



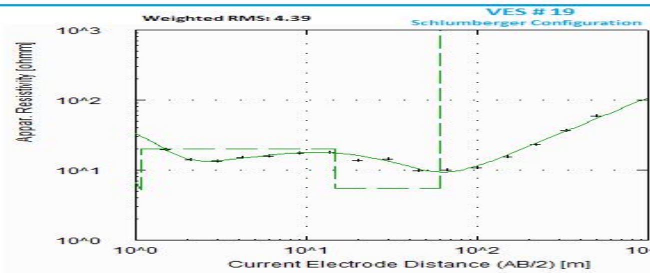
No	Res	Thick	Depth
1	293.9	0.7	0.7
2	29.6	7.2	8.0
3	53.7	12.9	20.9
4	301.7	51.5	72.4
5	921.4	-.-	-.-



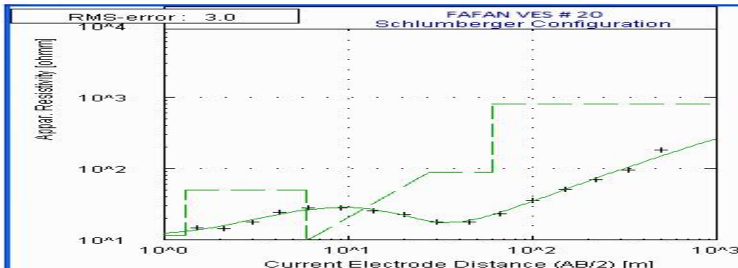
No	Res	Thick	Depth
1	146.8	1.3	1.3
2	27.6	4.2	5.5
3	23.9	8.1	13.6
4	42.2	10.4	24.1
5	5.9	30.4	54.5
6	450.0	-.-	-.-



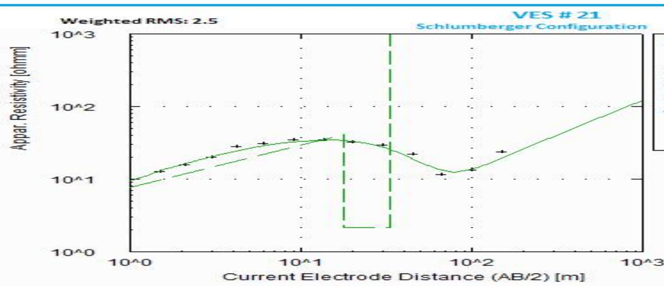
No	Res	Thick	Depth
1	231.6	0.5	0.5
2	8.8	1.1	1.6
3	23.7	11.8	13.5
4	15.3	74.1	87.5
5	78.5	-.-	-.-



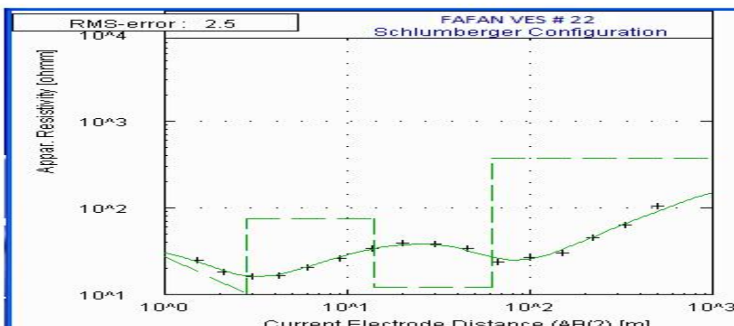
No	Res	Thick	Depth
1	62.30	0.51	0.51
2	5.25	0.56	1.07
3	20.00	13.60	14.70
4	5.51	45.60	60.30
5	7930.00		



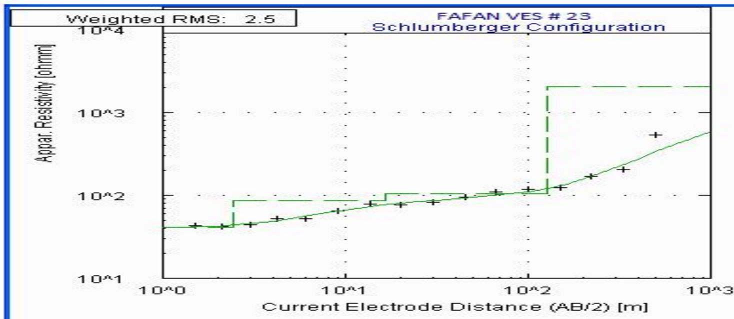
No	Res	Thick	Depth
1	11.5	1.3	1.3
2	50.3	4.6	5.9
3	9.8	21.7	27.6
4	87.9	32.4	60.0
5	809.2	-.-	-.-



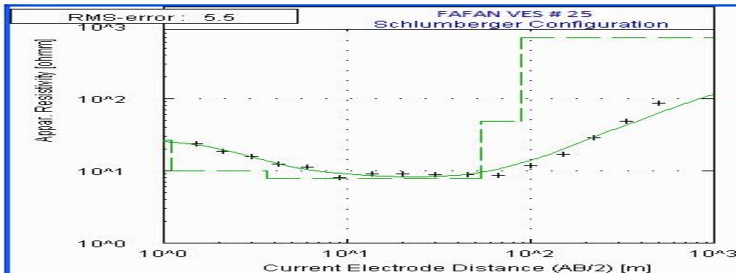
No	Res	Thick	Depth
1	4.45	0.38	0.38
2	41.60	17.20	17.60
3	2.17	15.30	32.90
4	1152.00	— —	— —



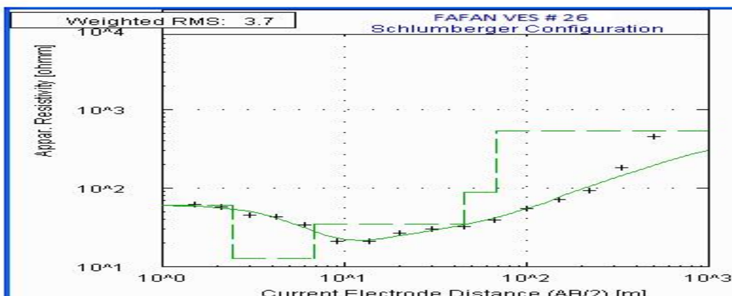
No	Res	Thick	Depth
1	36.5	0.7	0.7
2	10.2	2.1	2.8
3	75.1	11.3	14.1
4	12.3	47.7	61.8
5	370.4	-.-	-.-



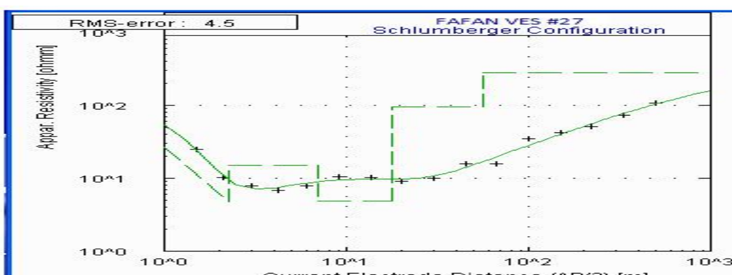
No	Res	Thick	Depth
1	40.9	2.4	2.4
2	86.5	14.0	16.5
3	106.0	111.9	128.4
4	2047.9	-.-	-.-



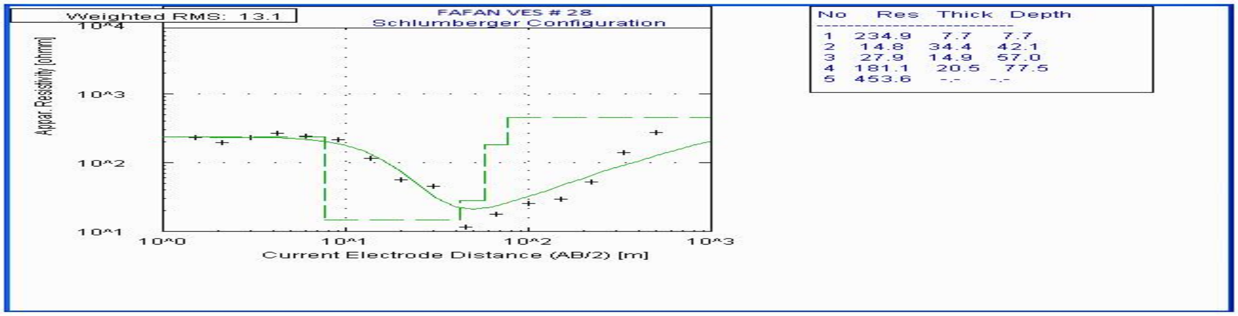
No	Res	Thick	Depth
1	27.0	1.1	1.1
2	10.0	2.5	3.6
3	8.0	49.9	53.6
4	49.0	35.1	88.7
5	697.2	-.-	-.-

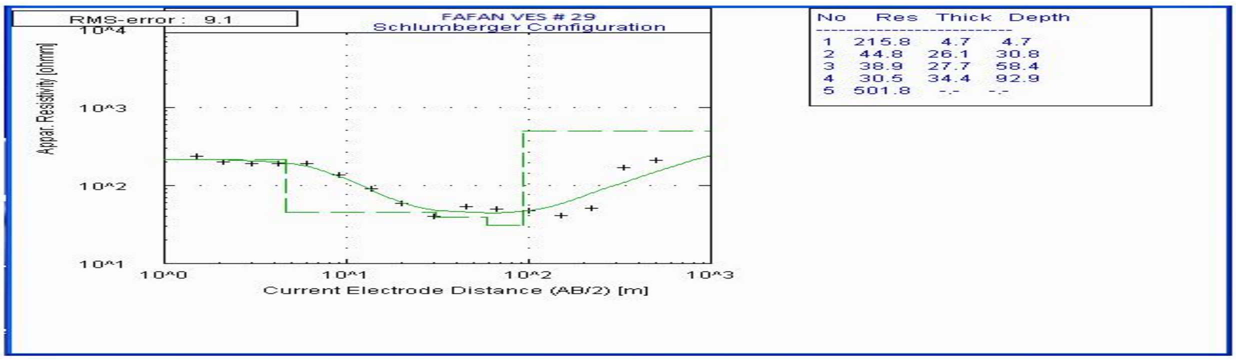


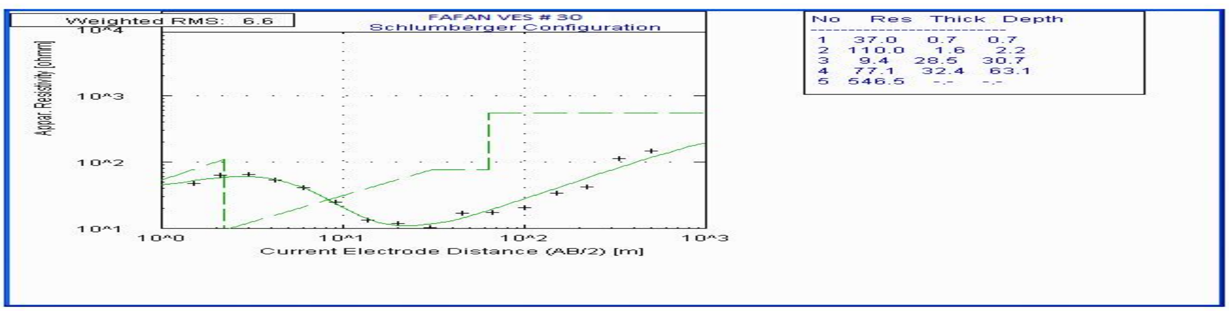
No	Res	Thick	Depth
1	60.6	2.5	2.5
2	12.6	4.4	6.8
3	34.8	38.4	45.3
4	87.7	23.3	68.6
5	542.2	-.-	-.-

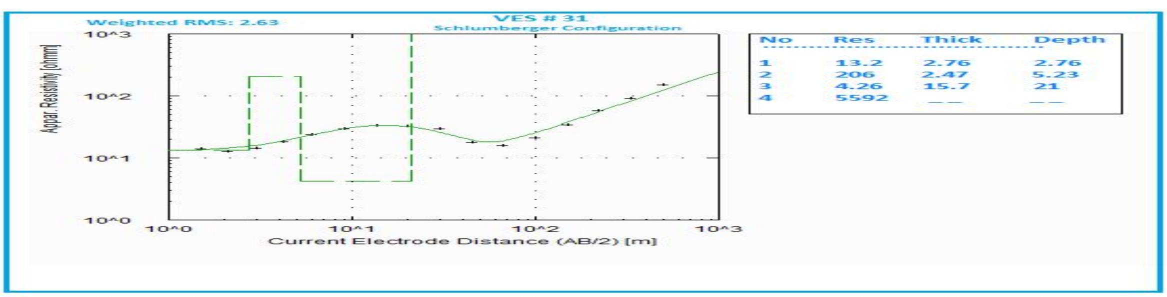


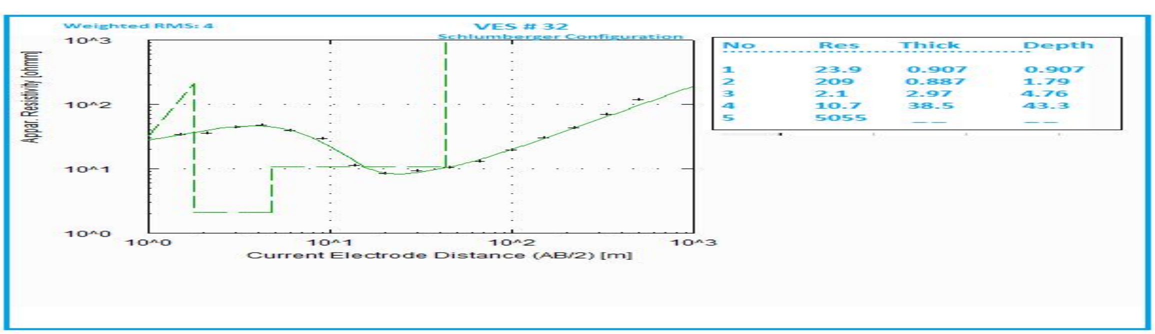
No	Res	Thick	Depth
1	117.1	0.5	0.5
2	4.8	1.8	2.2
3	15.1	4.7	7.0
4	4.9	10.9	17.8
5	94.2	38.1	56.0
6	279.8	-.-	-.-

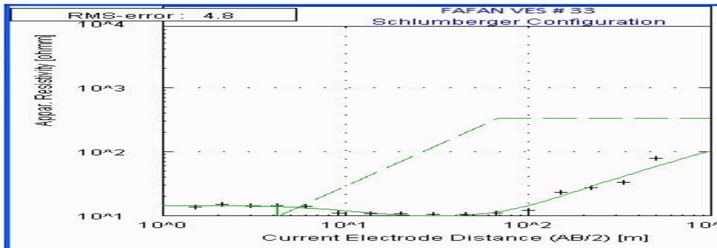

Weighted RMS: 13.1
FAFAN VES # 28
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 234.9 7.7 7.7
2 14.8 34.4 42.1
3 27.9 14.9 57.0
4 181.1 20.5 77.5
5 453.6 -.- -.-


RMS-error : 9.1
FAFAN VES # 29
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 215.8 4.7 4.7
2 44.8 26.1 30.8
3 38.9 27.7 58.4
4 30.5 34.4 92.9
5 501.8 -.- -.-

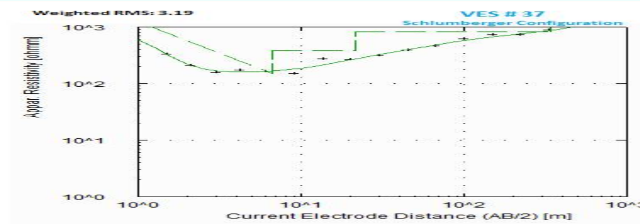

Weighted RMS: 6.6
FAFAN VES # 30
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 37.0 0.7 0.7
2 110.0 1.6 2.2
3 9.4 28.5 30.7
4 77.1 32.4 63.1
5 546.5 -.- -.-


Weighted RMS: 2.63
VES # 31
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 13.2 2.76 2.76
2 206 2.47 5.23
3 4.26 15.7 21
4 5592 __ __

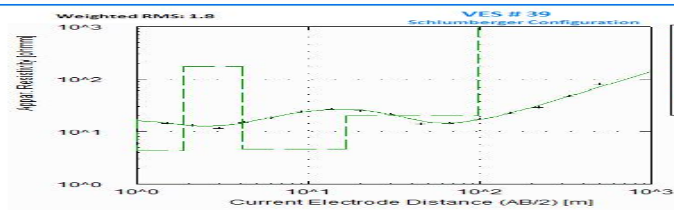

Weighted RMS: 4
VES # 32
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 23.9 0.907 0.907
2 209 0.887 1.79
3 2.1 2.97 4.76
4 10.7 38.5 43.3
5 5055 __ __



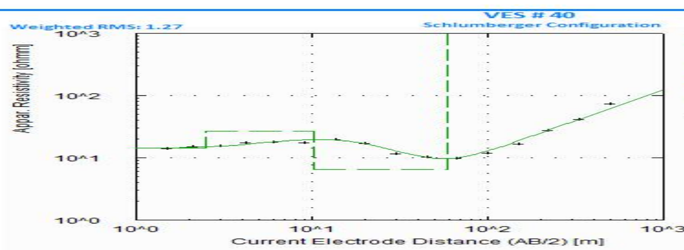
No	Res	Thick	Depth
1	14.5	1.3	1.3
2	14.3	2.9	4.2
3	9.7	7.5	11.7
4	9.2	55.6	67.3
5	331.1	-.-	-.-



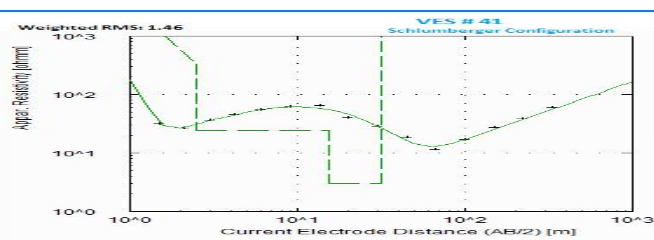
No	Res	Thick	Depth
1	1239.00	0.46	0.46
2	151.00	6.23	6.69
3	380.00	14.60	21.30
4	826.00	318.00	339.00
5	7000.00	__	__



No	Res	Thick	Depth
1	17.43	1.00	1.00
2	4.35	0.88	1.87
3	175.70	2.29	4.16
4	4.68	12.49	16.66
5	20.20	82.12	98.77
6	5788.00	__	__



No	Res	Thick	Depth
1	14.70	2.47	2.47
2	26.42	7.89	10.36
3	6.53	48.96	59.32
4	5693.00	__	__



No	RES	Thick	Depth
1	3258.00	0.25	0.25
2	9.00	0.65	0.90
3	332.90	1.58	2.48
4	24.12	12.84	15.31
5	3.03	16.00	31.32
6	7727.00	__	__