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INTEGRATED GEOPHYSICAL ASSESSMENT OF THE GROUNDWATER POTENTIAL IN GELAN CONDOMINIUM AREA AKAKI WELL FIELD, ADDIS ABABA, CENTRAL ETHIOPIA

A THESIS IS SUBMITTED TO THE SCHOOL OF EARTH SCIENCE OF ADDIS ABABA UNIVESITY IN THE PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN GEOPHYSICS (APPLIED GEOPHYSICS)

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This is to certify that the thesis prepared by **Robel Berhanu**, entitled "**Integrated Geophysical assessment of Groundwater Potential in GELAN condominium area AKAKI wellfied, Addis Ababa, central Ethiopia**.", submitted in partial fulfillment of the requirements for the degree of Master of Science in Applied Geophysics complies with the regulations of the University and meets the accepted standards concerning originality and quality.

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ABSTRACT

In this thesis work, an integrated geophysical method namely direct current- DC-electrical resistivity sounding (VES) and ground magnetic survey was employed to investigate the lithological and geo-structural setup of the subsurface with implications to groundwater. The geophysical survey primarily focuses on delineating groundwater saturated zones and identifying geological structural features that may act as conduits or barriers for the movement of groundwater in the subsurface.

The electrical resistivity data used for this study comprises, 10 VES points previously collected by the Water Works Design and Supervision Enterprise, the geological data has been used for the identification of the depth and extent of potential zones for the groundwater. A total of 121 magnetic data points along 5 profile lines and few randomly located measurements were taken as part of this study. The data were processed by using the appropriate software and, as a result, different profile plots and maps were obtained. Incorporating borehole log information into the geophysical data yield a more realistic interpretation of the hydrologic and geologic setup of the study area.

Joint appraisal of VES results and magnetic anomalies helped to obtain vital information required for the identifying of plausible groundwater potential zone. From interprate d of geophysical result, highly to moderately fractured and weathered basalt, and highly weathered scoriaceous basalt could be the main aquifer with adequate groundwater potential. The dominant trends of geologic structures identified from VES and magnetic survey are NE-SW and NW-SE directions.

Based on these interpretations drilling close to these structures into the aforementioned subsurface horizon (groundwater zone) could be of high productivity potential.

Keywords: Groundwater Potential, Vertical Electrical Sounding, Magnetic survey, Aquifer, Scoria

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ACRONYMS

AAWSSA----------Addis Ababa Water Supply and Sewerage Authority

AS------------------Analytic Signal

HDR---------------Horizontal Derivative

IGRF---------------International Geomagnetic Reference Field

LLA----------------Legedadi-Legetafo-Ayat Wellfield

m.a.s.l-----------meters above sea level

MER-------------Main Ethiopian Rift

nT----------------nano-Tesla

NMA------------National Meteorology Agency of Ethiopia

RTE--------------Reduction to equator

RTP--------------Reduction to pole

SWAWF---------South West of Akaki Wellfield

TDR---------------Tilt derivative

THDR------------Total Horizontal Derivative

TMA-------------Total Magnetic Anomaly

TMI-------------Total Magnetic Intensity

UBA-------------Upper Basalt Aquifer

VDR-------------Vertical Derivative

VES-------------Vertical Electrical Sounding

WWDSE-------Water Works Design and Supervision Enterprise

CHAPTER 1

1. INTRODUCTION

1.1 Background

Water has a determining role in every aspect of our life. Water is the basic nutrient for human existence; therefore, proper usage and water resources management are crucial, even more, critical as industrialization and development advances. Rapid population growth, urbanization, inability to construct additional reservoirs to tap surface water sources and the increase in demand for water in domestic and industrial production had led to a freshwater shortage in many parts of Ethiopia and increasing dependence on groundwater (Alema Tesfaye, 2009). Access to freshwater resources development is beyond the reach of the overwhelming majority of the Ethiopian population. Water exists on the surface and subsurface of the earth. Subsurface water is referred to as groundwater, whereas surface water includes; lakes, rivers, and ocean, etc. however water on the earth's surface is not fairly distributed, vulnerable to pollution, and most of the surface water is salty water, the search for freshwater leads to the necessity of ground exploration. The accessibility of clean water resources has always been the primary concern of governments and societies in basement complex areas, even in zones with abundant rainfall, the lack of adequate supply of quality and potable water is generally becoming more acute due to: ever-increasing population, pollution of surface water, and industrialization. As a result, surface water is not dependable throughout the year because of the seasonal variation and unequal distribution hence, the look for an alternative source of water is important.

Groundwater resource is the major source of water supply for many countries in the world. Likewise, groundwater is used as a source of potable water in the city of Addis Ababa City, the capital of Ethiopia, beside the existing surface water resources. Akaki wellfield has been playing an important role in providing a clean groundwater source for Addis Ababa city and the surrounding areas. Because of that, any scientific study related to the hydrological setup of Akaki wellfield brings an additional insight on using this valuable resource.

The abstraction of groundwater from the wellfields of Akaki catchment is currently not based on an understanding of drawdown levels and available potential groundwater resources in the area. Because a continuous increase in population has caused a high demand for potable water supply in the city. The existing water supply sources of the city do not have sufficient capacity to satisfy this increasing demand for freshwater. To satisfy the demand, alternative sources of water are investigated by Addis Ababa Water Supply and Sewerage Authority (AAWSSA). Therefore, AAWSSA has identified potential groundwater sources as additional sources of water supply for the city. The sites are located in the peripheries of the city and the surrounding areas and they are: Legedadi-Legetafo-Ayat (LLA), South Ayat-North Fanta Wellfield (SANFWF) recently started groundwater abstraction, Southwest of Akaki wellfield (SWAWF), Melka Kunture (MK), and Sebeta –Tefki (ST). The study is carried out on the prospective sites to assess hydrogeological characteristics to explore groundwater sources and to identify new wellfields for future development (WWDSE, 2011). Detailed hydrogeological investigation and drilling of deep test wells were started at LLA and SWAWF. However, due to a shortage of drilling companies, the LLA wellfield was suspended and focused on the Akaki area groundwater prospective (SWAWF). Akaki aquifer system serves as one of the potential sources of groundwater to provide potable water supply for the city of Addis Ababa in addition to surface water sources. Akaki wellfield has four prospective sites namely 'Wellfield 1', 'Wellfield 2', 'Wellfield 3', and 'Existing wellfield'

Since the cost for treatment of surface water is too high, surface water sources are not included in current plans for additional water supply sources. Groundwater source in the area does not require almost any treatment as compared to surface water sources since the aquifer in the area is deep enough and does not have any contact with contaminants (Moges Berbero, 2011)

Geophysics has been a tool for mapping water-bearing horizons and for identifying groundwater different characteristics. The exploration of groundwater has been performed by several methods like electrical resistivity, gravity, magnetics, remote sensing, electromagnetic, seismic. Among the methods, vertical electrical sounding (VES) is widely used in the exploration of groundwater and provides the vertical variation of resistivity of the ground with depth. Most of the time VES method is used in collaboration with a magnetic survey which use to map subsurface structure that controls the flow of groundwater. The magnetic anomaly variation is dependent on the faults, dikes, and the type of bedrock with which the survey is performed.

For groundwater resource mapping it is not the groundwater itself is targeted rather it is the geologic situation in which the water exists (Tewodros Mulugeta, 2017). These geologic structures that delineate the occurrence of groundwater are mapped by carrying out geophysical surveys. An "aquifer" is a rock that contains a usable supply of water. For an aquifer to be labeled as good, enough porosity for holding water and sufficient permeability for allowing continuous recharge of water to a well is essential. Gravel, sand, sandstone, and limestone are among the best aquifers, but they form only a fraction of the rocks in the Earth's crust. Most rocks are fine-grained or else '"tight" and store or hold a small amount of water.

1.2. Overview of the Study Area

1.2.1. Location and accessibility

Akaki Kality area is located at the GPS coordinates of 8° 53' 44.9916" N latitude and 38° 47' 20.9832" E longitude and with a mean elevation of 2060 m.a.s.l.

The Akaki wellfield (Figure 1.1) is situated to the southeast of the Akaki-Kality sub-city about 22 km south of the center of Addis Ababa with a total area of 101 km^2 and an elevation ranging between 2050 -2110 meters above mean sea level. (WWDSE 2011). The wellfield has four prospective sites named ‘Existing Akaki wellfield’, ‘Wellfield 1’, ‘Wellfield 2’ and ‘Wellfield 3’. Wellfield 1 covers an area of about 42 km^2 and comprises 12 production wells and 8 test wells. The study area, in wellfield 1 is a 6 square kilo-meters area located in front of the new Gelan condominium. The site area is traversed by Addis Ababa-Tulu Dimtu-Debre Zeit asphalt road and numerous gravel roads, which make it accessible to sites to carry out the planned study and investigation works.

As can be seen from the map (Figure 1.1) the elevation of the city decreases toward the south(2050-2110m.a.s.l). Most of the higher elevation areas chiefly present in the northern (2531-2671 m.a.s.l) and north-central part (2431-2530m.a.s.l) of the city. The images are retrieved from www.blogspot.com and Research Gate (mapping of plantation forest).

1.2.2. Climate and Rainfall distribution

Under normal conditions, air temperature decreases with increasing altitude at a mean rate of 0.7 ^{0}C for every 328 feet (Fetcher, 1998). This works also in Ethiopia; where the temperature varies accordingly with altitude with an average temperature ranging from 7-24.6 ^{0}C and a mean monthly temperature ranges between 13 ^{0}C and 18 ^{0}C.

Addis Ababa is located at 2350m above sea level. However, the study area is located in the southern lowland region of the city. In Addis Ababa, the climate is warm and temperate. As in most parts of Ethiopia, the study area has two seasonal patterns: the main rainy season, *Kiremt* ranges from June to September, contributes almost 70% of the total annual rainfall, and a minor rainy season, *Belg*, contributes moistures in the months from mid-February to mid-April (Daniel Gemechu, 1977).

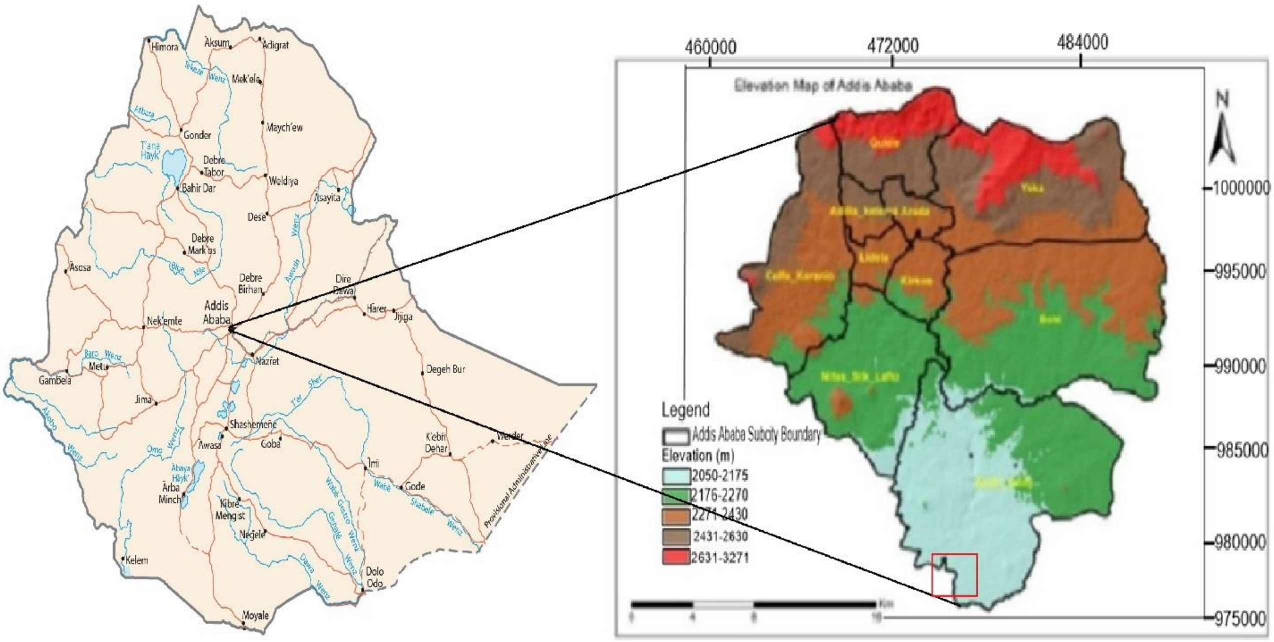


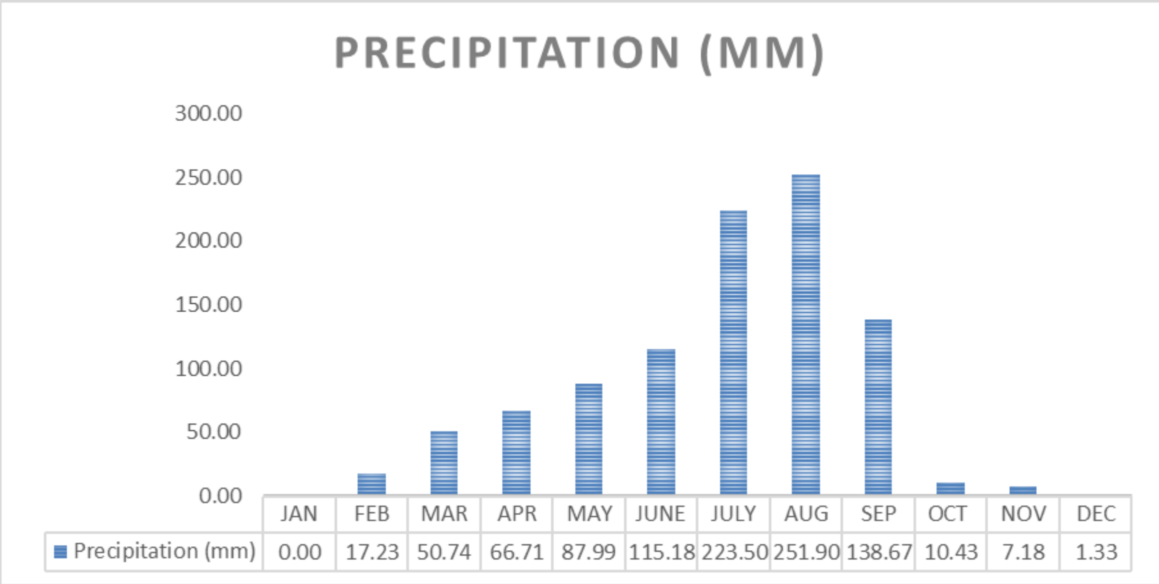
Figure 1.1. Location map of the study area within the Akaki-Kality sub-city (red rectangle)

The main rainy season is during the *Kiremt* (June, July, and August), and with a relatively small amount of precipitation in the *Belg* season (March April, and May) a short rainy season. (Figure 1.2)

And the Dry season, *Bega* (December, January, and February) May is a hot and dry month just before the rainy season (*Kiremt*) begins. Mostly in December or January (*Bega*) coldest temperatures have been recorded and the hottest is in March, April, or May (*Belg*). However, in many localities coldest temperatures were recorded in August because of the moderating influence of rainfall as classified by the central weather bureau (CWB) by Köppen and Geiger, 2020.

The average annual temperature in Addis Abeba is 17.4 °C | 63.32 °F. the maximum precipitation in the area recorded was in 2010 and was about 1242 mm | 48.89 inches per year. The driest month is January and December. There is 1.3 mm | 0.05 inch of precipitation in December. August is the month with the most precipitation, with an average of 251 mm |

9.882 inches. The daily average temperature in the Akaki area ranges from 7.7 to 28.92 ^{0}C and the annual mean rainfall is 1224 mm/yr.,



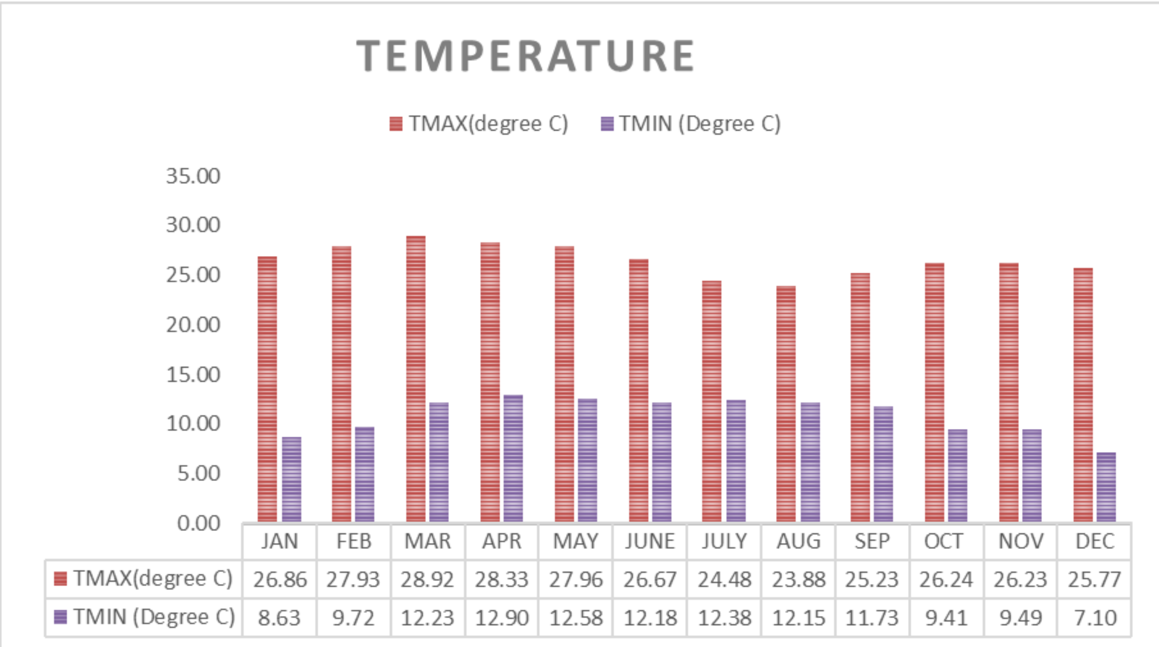


Figure 1.2. Meteorological information of Akaki area for the period from 2010-2019. (NMA, 2021)

1.2.3. Physiography

The Akaki wellfield area can be divided into three major Physiographic regions. (Figure 1.3) These are: (1) The Furi Ridge, (2) The eastern, and (3) Akaki plain physiographic regions. The Furi ridge physiographic region, the southeastern part of the Furi volcano, is drained from Northwest to the southeast into the Akaki plain, part of the radial drainage of the Furi volcano. The creeks finally lose themselves into the extensive Akaki seasonal swamp area. It rises from the surrounding area by about 700 meters. It is built of mainly trachytic flows and minor associated pyroclastic (WWDSE, 2011).

The northwestern, northeastern, and southeastern areas are underlain by Quaternary age basalt flows. It gradually slopes due west into the south-central part. This is a large and relatively little modified basalt shield of recent origin. This large mound has been built by a voluminous outpouring of basalt flows from the east–northeast trending central fissures, now marked by speckles of numerous well-preserved cinder and basalt cones. There are scattered cinder and basalt cones sticking out of the surrounding surface forming conspicuous topographic features in the site area (WWDSE 2011).

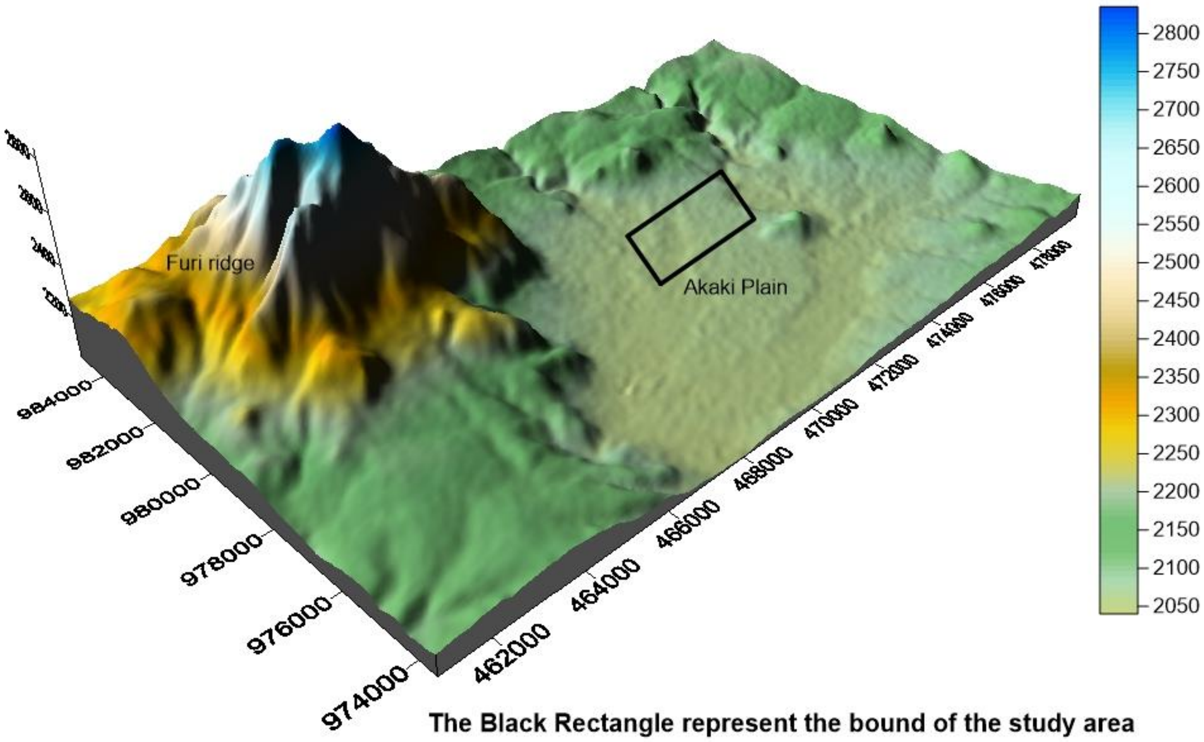


Figure 1.3. Physiography of the study area

The southcentral part of the site is a sediment depositional site, a northeast-southwest trending sort of graben structure now filled with recent alluvial sediments. It presents a flat-lying not yet modified topography. The featureless alluvial plain completely devoid of bedrock exposure lies between 2060 and 2080 meters. Akaki river meanders southeastward across the plains, in places losing itself among extensive seasonal swamps, but eventually discharging into Awash River outside the site area. The river meanders through the alluvial sediment eroding its depositions (WWDSE, 2011).

1.3. Statement of the Problem

Freshwater is necessary for society and there has to be an adequate source of water. Addis Ababa city has been under continuous demand for additional water supply for domestic, commercial, industrial, and institutional use. The increase in demand for freshwater derived from groundwater is, due to the increase in population, migration of people from rural to urban areas which have increased the demand drastically, and the surface water resource available are found to be inadequate. Moreover, the use of groundwater has an added advantage in that, once found, it is a relatively cheaper source. Further, improper usage, expansion of industrial activities, and a high amount of surface water pollution have necessitated the use of groundwater. These factors contribute to the exploration of an additional source of groundwater and exploration of subsurface lithologic structures that contribute to identifying recharge or discharge zones and also defining the type of the aquifer.

The Akaki wellfield is a lowland area in the Akaki catchment and relative to Addis Ababa city the field has a general drainage pattern leading to the south of the metropolis (like the big and small Akaki Rivers) where the wellfield developed several years ago. However, the analysis of the water level contour map for Akaki well-field indicated that 84.50% of the current pumping water levels were below the dynamic water level. Particularly, the old Akaki well-field has been severely depleted (Debebe Muleta; Brook Abate, 2020). Groundwater development optioned as an emergency water supply project without giving attention to its sustainability has resulted in drying of drilled boreholes particularly in Akaki Wellfield out of 24 drilled wells, 13 of them are abandoned as water level and discharge have significantly declined. Due to the poor understanding of the importance of groundwater, that it is a finite resource and the aquifers can become depleted as the extraction rates exceed recharge rates. Therefore, groundwater management has to be performed through reliable aquifer characterization, sustainable development, planning of conjunctive use of surface water, and artificial recharge (Debebe Muleta; Brook Abate, 2020).

Therefore, the objective of this study was to gain practical knowledge on the application of geophysical investigations in the assessment of subsurface groundwater potential. As a research problem, the outcome from this study shall bring additional insight to the characterization of the Akaki Wellfield, in particular, the Gelan area.

1.4. Objective of the Research

1.4.1. General Objective:

- ❖ The general objective of this research is the assessment of the groundwater potential of the Akaki wellfield, situated southwest of Addis Ababa by using geophysical methods.

  (Vertical Electrical Sounding-VES and Total field Magnetic measurements).

1.4.2. Specific Objective:

- Mapping the subsurface lithology of the study area and identify the potential water-saturated horizons
- Identification of geological contacts like faults, lineaments, and other structures and determining their possible role in groundwater accumulation and movement.
- Identification of depth to the water table and thickness of the aquifer (if these exist)
- Suggestion of preferable location for drilling additional boreholes, for the expansion of the water supply from the Akaki wellfield.

1.5. Significance of the study

The study enhances understanding of the geology and geological setting of the area. It provides recent geophysical data and information on hydrogeology, geologic structures, depth to the water table, and thickness of the aquifer for future researchers that survey in the study area.

In view of the recent construction of large residential complexes (GELAN CONDOMINIUM), the study will help to address one of the societal needs, clean and safe water supply, and future management.

1.6. General Methodology

The general methodologies and procedures employed in the research work are summarized in the flow chart given in figure 1.4.

Vertical Electrical Sounding (VES) is considered to be the most common method in groundwater exploration. Geophysicists and hydrogeologists use this method to assess groundwater potential, to identify its depth, to identify the thickness of the aquifer its porosity, and permeability. The geophysical method adopted in this research work for the exploration of groundwater potential is vertical electrical sounding (VES) and magnetic survey.

During the first phase, the relevant literature on the study area is reviewed; to have a general understanding of the geologic setup of the study area, in how to perform the geophysical survey and field procedures, and the applications of geophysics in the study of groundwater potential is the primary task. Collection of secondary data like VES data, borehole log, geologic, and hydrology data. Then identification of a gap in the data will be the final step before going to the field.

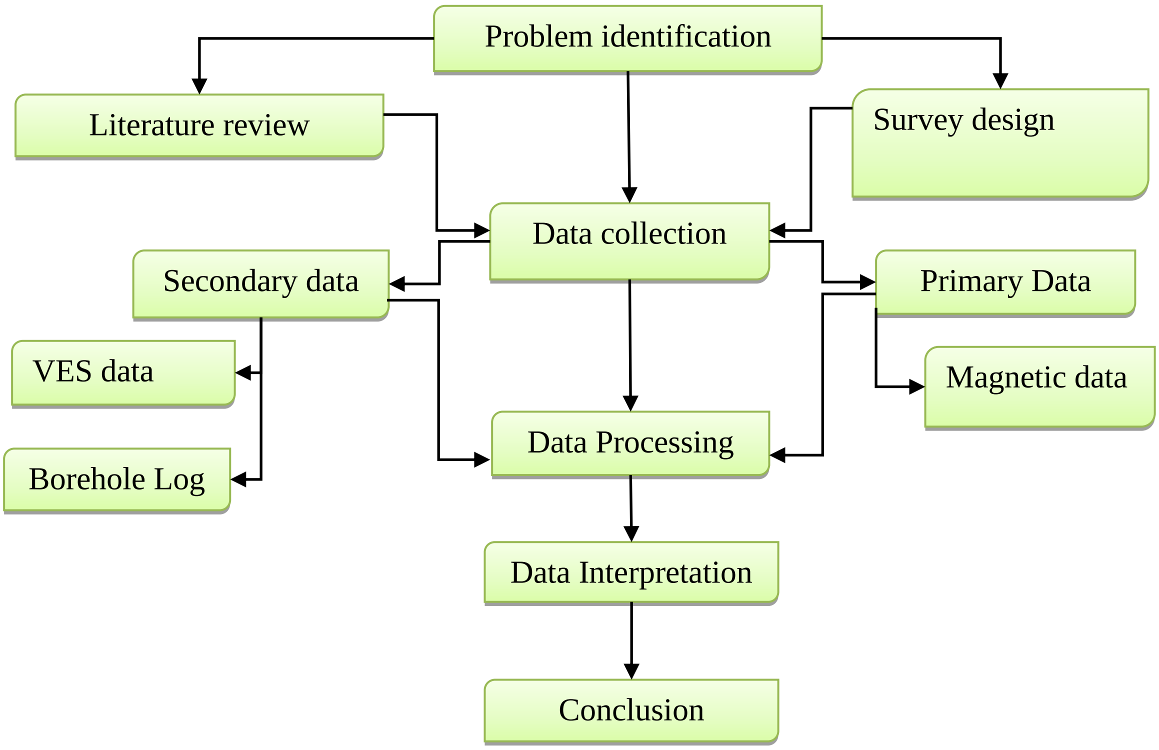


Figure 1.4. Flowchart of the methodology employed in the research work

The second phase is the collection of primary data, setup for actual field survey for collecting the necessary geophysical data using the respective technique. The magnetic survey is adopted to identify physical characteristics such as type of fracturing, jointing, and faulting, to record coordinates of major geological contacts fault lines and other pertinent features along the traverse route. And performing detailed structural mapping and analysis with emphasis on the volcanic rock, and measurement of the variation in magnetic susceptibilities of the subsurface will be measured on the field.

For this study, secondary resistivity (VES data collected by the Ethiopian Construction, Design and Supervision Works Corporation and WWDSE and primary magnetic data have been used to define the ground condition of the subsurface.

The third phase is the post-field work, which includes geophysical data correction, processing, analyzing using different software. The software that can be used in electrical resistivity surveys includes WINRESIST, IPI2win, Surfer, and AutoCAD.

Afte routine reduction (Diurnal correction) of the raw data using Excel spreadsheet, further processing, and analysis of the magnetic data was done using Geosoft Oasis Montage (V 7.0.1)

Global Mapper and ArcGIS were used for illustrating the description and physiography of the study area.

Qualitative and quantitative interpretation of the processed data in the context of the research objective was the final step.

1.7. Scope and limitation of the thesis

This research work assesses the type of aquifer, depth, and thickness of the aquifer, the potentiality of groundwater aquifer, and subsurface structures that affect the flow of the groundwater in Akaki wellfield specifically in wellfield1 GELAN condominium area.

In this work estimation of recharge, sustainability and safe yield, porosity, and permeability of an aquifer are not included. This work aid future researchers as a source of recent data and give insight on the geology and hydrogeology of the area.

Like any research, this research also faces some Limitations. In this thesis work the main limitations were:

- Limitation on finance
- Limitation of time: due to COVID-19 extended semester’s classes and assignments minimizes the allotted time for the research work, and
- Limitation on skillset: lack of expertise in geophysical data processing soft-wares and interpretation.

1.8. Literature review

Geophysical studies namely VES, Magnetic, and MT methods were done by Addis Ababa Water and Sewerage Authority (AAWSA) in supervision by Water Works Design and Supervision Enterprise (WWDSE) to get detailed groundwater investigations studies on five prospective areas and identify well fields. From these sites, the Southwest of Akaki Wellfield is one of the sites. The study was carried out on these prospective sites to assess hydrogeological characteristics to explore groundwater sources and to identify new groundwater potential areas for future development. Assessment and evaluation of existing hydrogeological data, geological mapping, detailed geophysical survey, deep test well drilling and testing, chemical quality analysis of water samples, monitoring of water quality on existing wells, etc. have been carried out by AAWSA. And leads to a conclusion; The main aquifers in Akaki wellfield are the young scoria and Scoriaceous Akaki basalt and the fractured and scoriaceous basalt (Tarmaber Basalt). The alluvial deposit, massive basalt layers in the younger basalt, pyroclastic, and silicic rocks are confining layers. The general groundwater movement is from northwest to southeast direction. SWAWF is within a wide groundwater basin that extends beyond the Akaki river basin.

Bereket Fentaw and Mihret Manaye (2011) in their hydrogeology and hydrochemistry study of Akaki-Beseka sheet mentioned that the main permeabilities that are responsible for groundwater transmission and storage are porous and fissured permeabilities, which are affected by the geomorphologic setup, climatic condition, lithology, degree, and extent of fracturing and weathering of massive rocks, grain size, sorting and type of cementing material of unconsolidated sediments and type and thickness of soil development.

A journal published by Leta Gudisa in 2010 discusses the pathway of pollutants and travel times of contaminants in the Akaki well field by the Akaki River. The flow lines of the Akaki river converge toward Akaki well field. He also describes the geologic condition as densely fractured lineaments which have high permeability and transmissivity of contaminants into the aquifer.

Molla Demilie et al. (2006) estimated the groundwater recharge in Akaki catchment, the state that the source of recharge is precipitation but climatic fluctuations result in the shortage of surface water and an increase in demand for groundwater. This groundwater is endangered by anthropogenic pollution and overexploitation.

The study carried out by Alema Tesfaye (2009) on groundwater modeling and recharge conditions of the Akaki catchment and well field, discussed the rain recharge, river bed recharge, and seepage from Aba Samuel and Legedadi Lakes describe the recharge conditions in the Akaki basin. The Akaki well field recharge conditions include the inflow from northern and northwestern upstreams. The flow lines converge toward Akaki well field from all directions.

The researchers mentioned above studied hydrogeology, hydrochemistry, travel times of contaminants, estimation of recharge, and groundwater modeling of the Akaki catchment, wellfield, and river. In their study, they have discussed pollutants/contaminants deposited to the Akaki river and flow lines that act as recharge for the wellfields that affect the quality of groundwater and how to control these contaminants since it is almost impossible to treat polluted groundwater. In addition, they also map the subsurface structures that act as a conduit that controls the recharge and discharge of an aquifer system.

Tewodros Mulugeta (2017) perform a geological study at the Tisabalima sub-basin to identify the groundwater potential zone of the sub-basin using electrical sounding for mapping geologic units of possible water-bearing horizons and Magnetic method for mapping magnetic rocks having high magnetic susceptibilities, and faults that control the groundwater occurrence and discharge zones of the area.

In the rift, the localization of groundwater is strongly controlled by the rift faults. They have a contrasting role in the movement and occurrence of groundwater. Most of the faults act as a watercourse in the flow of groundwater. In contrast to the high hydraulic conductivity of the rift fractured volcanic, some faults act as barriers to groundwater flow. This is an accustomed thing when the faults dip against the topographic slope forming local grabens and horsts. Beyond the barrier faults, most volcanic rocks do not form large extended aquifers, even if they are highly permeable (Shimeles Fikre, 2006).

The applications of resistivity sounding and magnetic method aid in the characterization of depth and type of an aquifer favorable for groundwater potential. VES is used to ensure the potentiality of groundwater and the magnetic method is used to delineate the geologic structures which control the flow system of the groundwater (Tariku Degife, 2018).

According to the above authors, the ultimate goal of the resistivity survey, specifically the VES, is to identify the resistivity variation with depth and the geoelectric properties of layers in the subsurface based on measurements situated on the surface. Apparent resistivity is measured and interpreted in terms of geology or hydrogeology, and the ultimate goal of the Magnetic survey is for identifying the geologic structures with high magnetic susceptibilities by measuring the total magnetic field and for mapping the lithology of the subsurface.

1.9. Structure of the thesis

This thesis is composed of six (6) chapters. Chapter one deals with a general introduction on groundwater resources in the study area, statement of the problem, objectives of the research, general methodology used, climatic and physiographic description of the area, and review of previous works. Chapter two (2) is composed of the geological setting of the study area. Stratigraphic units, hydrogeology, regional and local geologic descriptions are included. Chapter three presents the theoretical background of the geophysical method used in this research work i.e., VES and Magnetic Method. Chapter four (4) describes the way of data acquisition, selection of traverses, processing, and presenting the geophysical data. Chapter five (5) deals with presentations and interpretations of the processed VES and total magnetic field data. The last (sixth) Chapter is the conclusion and recommendations of the study.

CHAPTER 2

2. GEOLOGICAL AND HYDROGEOLOGICAL REVIEW

Ethiopia is a country with a broad range of geomorphic provinces A high and rugged mountainous core to cut by deep gorges and incised river valleys, fault-bound plateaus and basins, a conspicuous rift valley with multiple lakes, and neighboring plains ranging from the harshest of deserts to subtropical jungles. From the Afar depression at 110m below sea level to Ras Dashen at elevations of 4620 m above mean sea level exists. As similar as the varying geomorphology there also exists a wide range of geologic units of different ages. Cenozoic volcanic rocks and quaternary sediments cover the majority of the country's landmass (Solomon Gerra, 2000). Major coverage of the study area is quaternary age basalt and scoria cones (WWDSE, 2011).

2.1 Regional geology

Volcanic rocks of different ages are predominantly found in the Akaki river catchment. The Akaki aquifer system is characterized by tertiary volcanic rock covered with thick residual and alluvial soils (Tenalem Ayenew et al, 2008). In the catchment of Akaki wide ranges of volcanic rock weathered and fractured rocks are most common, this is due to rift tectonics that covers the catchment of Akaki River including Addis Ababa and the wellfield (Morton et. al., 1979). Northern Addis Ababa is located on older volcanic rocks of Pliocene to Pleistocene age with a large east-west running fault ridge of Entoto range marking the northern boundary of the city. Younger volcanic flows product of Furi volcano occur towards the rift in the areas southeast of the city around Akaki and Debre Zeit (Figure 2.1).

The geology of most parts of Addis Ababa comprises rocks ranging in age from Lower Miocene to the present. The dominant rock units are basalt, tuff, trachyte, rhyolite, ignimbrite, porphyritic basalt, trachy-basalt, scoriaceous and vesicular basalt, and alluvium.

Alluvial, residual, and lacustrine soils are common soil types within the Akaki catchment. Alluvial soils are found mainly in middle to lower reach of the river; residual soils are common in the upper part of the catchment; whereas lacustrine soils which are black cotton soils are common in the southern and southeastern part of the area (Moges Berbero, 2011). The north and northeastern parts of the catchment (the Entoto Mountain, the northern and north-eastern Addis Ababa) are covered with trachyte, rhyolites, basalts, and several episodes of pyroclastic materials of older volcanism that occur on the upper part and foothill sides of

Entoto ridge. The central and southern part of the Addis Ababa area is overlain by younger basaltic rocks 7-6.4Ma (Addis Ababa Basalt).

Younger volcanic material of trachy-basalt, trachyte, ignimbrites, and tuff belonging to the Wechecha, Furi, and Yerer volcanoes are recognized overlying unconformably on the Addis Ababa basalt in the western, southwestern, and eastern part of the catchment. Outcrops of ignimbrites have been observed in Bole (Eastern Addis Ababa) and Lideta areas (Central Addis Ababa) underlying the Addis Ababa basalt. Akaki (including the well-field), Dukem, and Debre-Zeit area are covered with olivine basalt, scoria, scoriaceous basalts, and vesicular basalts. In the upper part, in some places, intercalation of tuffs, sand, and gravels is also recognized. In the northeast, east, and smaller extent of the western part of Debre-Zeit, outcrops of trachyte, rhyolitic ignimbrites, and tuffs are recognized covering the area (WWDSE, 2011).

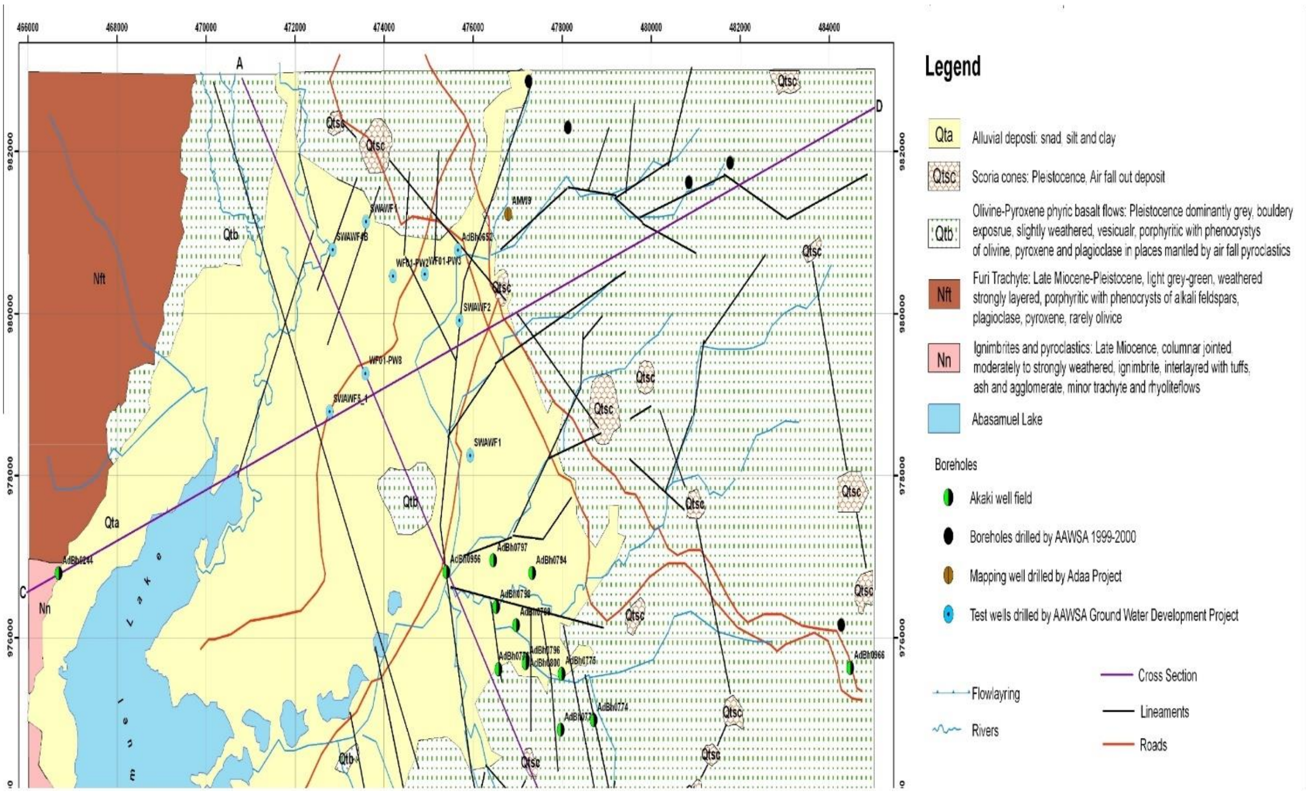


Figure 2.1. Geological map of southwest Akaki wellfield (From WWDSE, 2009)

The overburden covering the bedrocks includes soils, lacustrine and alluvial deposits. In the central, southeastern, northeastern, western (Kolfe-Keraniyo), and in northern (Gullele) part of the catchment thick in-situ soil type cover is found. The lacustrine covers Bole, Lideta, Mekanisa, Akaki-Aba Samuel area, and Dukem-Debre Zeit area. Along the Big and Small

Akaki Rivers, in the southern and southwestern part of Addis Ababa, some alluvial deposits occur and minor deposits are also present along the Kebena Rivers in the area northwest of Bole (Tadesse Yirga et al, 2004). Most soils in this area are highly eroded and form thin soil cover.

The alluvial sediments cover large parts of the Akaki River area along riverbanks. Along the Akaki River and the surroundings, the thickness of the exposed soil cover reaches up to 5m. Grain sizes are variable ranging from sand to gravel showing poor sorting. The alluvial sediments are characterized by high porosity and inter-granular permeability. These sediments constitute one of the potential aquifers in the Akaki area.

Most soil profiles are products of weathering of old basic and acidic rocks that outcrop in the central, western, and southwestern parts of Addis Ababa. Detrital materials originating from an elevated area of Entoto, Wechecha, Furi, and Yerer are carried and deposited in the pediment of Addis Ababa, as well as along the stream channels. The soils are black and their thickness varies from place to place primarily depending on the slope of the area. Clay is the dominant component of the soil in the Akaki area. The soils thickness varies from 1m to 60m around the Akaki wellfield.

2.1.1. Stratigraphic units

The geology of Addis Ababa consists of various volcanic rock units of different ages and compositions. The volcanic succession in the Addis Ababa area as suggested by previous researchers (Zanetti et al., 1974; Morton et al., 1979) is, the Miocene-Pleistocene age group, which from oldest to youngest can be listed as Alaji rhyolites and basalts, Entoto silicic, Addis Ababa basalts, Nazareth group, Bofa basalts, and alluvial and residual deposits. A brief description of these units is given as follows:

The **Alaji group** volcanic rocks (Alaji Rhyolite and Basalt) Alaji rhyolites can be categorized into two groups volcanic rocks: forming the very extensive cover of constant thickness sometimes the cover is red colored due to micro granules of iron oxides, and volcanic rock forming large relief like Entoto Mountain these are prevalently compact rocks. From the end of the Oligocene to the middle of the Miocene, volcanic rock sections of the escarpment were poured out. (Zanetti et al., 1974). This unit is underlain by tuffs and ignimbrites. These basalts have a highly varied texture that ranges from strongly porphyritic to aphyric, with grey and glassy welded tuff intercalation. Its range stretches from the top of the Entoto ridge (which borders Addis Ababa's northern suburbs) toward the north. (Haileselassie Girmay and Getaneh Assefa, 1989).

In the Addis Ababa region, the **Entoto silicic** is early Miocene silicic volcanic that may represent localized terminal episodes to massive Oligocene fissure-basalt activity rhyolites, trachyte, and trachyte with little welded tuff and obsidian. (Morton et.al. 1979). On the foothills of Entoto, the unit is unconformably overlain by Addis Ababa basalt and underlain by Alaji basalt. The Entoto silicic is mostly composed of rhyolite and trachyte with some amount of welded tuff and obsidian (Haileselassie Girmay and Getaneh Assefa, 1989). Both rhyolite and trachyte from Entoto silicic belong to Miocene-Alaji Rhyolite and basalt series according to stratigraphy established by Zanetti et al. (1974). The flow becomes thickest toward the top of Entoto ridge and thinnest at the eastern section of Addis Ababa (Haile Selassie Girmay and Getaneh Assefa, 1989). Entoto silicic are observed on the southern face of the Entoto mountain range

The oldest rock, post-dating the Entoto silicic, is the **Addis Ababa basalt**. According to Haileselassie Girmay and Getaneh Assefa (1989) These units, which are mostly found in the town's central area, are underlain by Entoto silicic and overlain by Nazareth group Lower welded Tuff. It has high strength, dark grey color, and a fine-grained texture. Microscopically it is composed of Plagioclase, pyroxene, opaque, and olivine with intergranular texture. The vesicles are filled with secondary material.

Nazareth group Lower Welded Tuff, Aphanitic Basalt, and Upper Welded Tuff are the units recognized in this category. The group is underlain by Addis Ababa basalt and overlain by Bofa basalts. The rocks mainly outcrop south of the Filwoha fault and extend to Nazareth.

In Filwoha, western Addis Ababa, and Sululta, the lower welded tuff outcrops as a small discontinuous body. It has columnar joints and is glassy with abundant flame and. it is overlain by the Aphanitic basalt and underlain by porphyritic basalt with olivine and plagioclase. The southern section of the town is covered in aphanitic basalt, particularly at Bole International Airport and Lideta Airfield. The town's southern half is covered in upper welded tuff outcroppings. It is constructed of sanidine and is gray. It is joined vertically and horizontally (glassy alkaline feldspar group), orthoclase (used in ceramic tile production), riebeckite (Sodium rich amphibole group), quartz, pumice, and unidentified volcanic fragments (Getaneh Assefa et al., 1989).

Bofa basalt Olivine porphyritic basalt, scoria, vesicular and scoriaceous basalt, and trachyte-basalt lava flows constitute these basalts. They extend southward from the Akaki River and are around 10 meters thick (Anteneh Girma, 1994). They appear to have a maximum thickness of 20 - 60m over the Akaki well field and get thinner, even absent in other places.

Alluvial and residual deposits These include alluvial, residual, and lacustrine deposits Quaternary to recent deposits. Lacustrine soils occur around Bole, Lideta, Mekanisa, between Aba Samuel Lake and Small Akaki River (WWDSE, 2011). These deposits are mainly found in some localities along small and Big Akaki Rivers, especially south and southwest of the capital city. A thick alluvial deposit occurs in the area between Akaki town and Abba Samuel Lake.

2.2. Local geology

The Akaki wellfield is situated in the southwest of Akaki town also called SWAWF (South West Akaki Well-Field) with an elevation of 2050m in south-central- 2140m in the northeast part of the wellfield. South and southwest of Addis Ababa region are covered with olivine-pyroxene phyric basalt flow (Akaki Basalt) and the Yerer volcanism affects the production of scoria cones associated with basaltic lava ascribed to Akaki units. The Akaki basalt lava flows are mostly vesicular, fresh, grey, porphyritic, and boulder exposure. The groundwater prospective site is almost exclusively covered by younger volcanic rocks of mainly vesicular and scoriaceous basalt which are known for having high to very high productivity. Overlaying layer of lacustrine and thick alluvial sediments (2.5-60m) comprised of silty clay and clay along the west-central margin of Akaki river overlying the olivine pyroxene phyric basalt lava flow. (Figure 2.2). This dispositional basin appears to represent a fault-bounded Northeast-Southwest oriented graben now filled with quaternary basalt flow and recent alluvial materials.

Lineaments, Joints, and Faults are the geologic structures that exist in the area. Lineaments are a linear topographic feature that reveals the characteristics such as Faults or subsurface structures. And Joints are a fracture or crack in a rock not accompanied by visible dislocation on either side of the rock exhibiting the jointing i.e., Few to 50 cm spacing. Lineaments are observed in the study area and from the topographic map of the study area, the Lineaments have NW-SE, and NE-SW trends (WWDSE 2011).

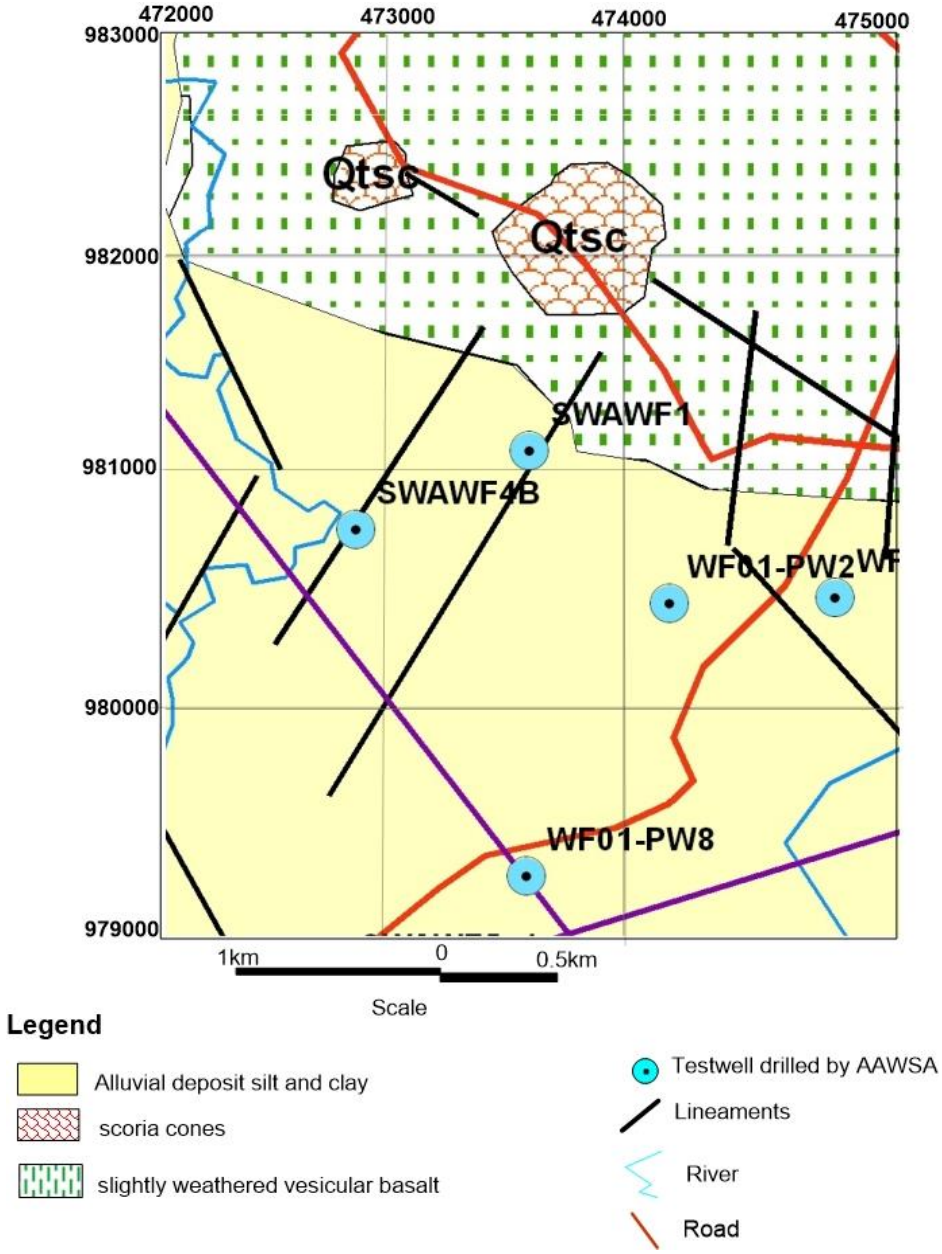


Figure 2.2. Local Geology of the study area

2.3. Hydrogeology of the study area

Groundwater occurrence, movement, and potentiality in a particular space are dependent on the permeability, transmissivity, and porosity of the aquifer, the geologic structures that encompass the surrounding aquifer, geomorphologic condition, and the climatic condition.

Hydrogeological investigations indicate that the main aquifers in and around Addis Ababa can be subdivided as fractured and jointed volcanic rocks of varying geological age and confined porous rocks of volcanic origin, such rock types include scoria, tuffs, ignimbrites, basalt pyroclastic rocks, and alluvium derived from erosion and deposition (WWDSE, 2009).

SWAWF located in the southern region of Addis Ababa is not an independent and isolated aquifer, it is part of the Ada’a-Becho groundwater system. It is within a wide groundwater basin that covers parts of the southern Abay and Upper Awash surface water basins (WWDSE, 2009). Addis Ababa gets 35% of its water supply from two dams namely Gefersa and Legedadi. And 65% of the city’s water supply is from groundwater for many years old Akaki wellfield (SWAWF) has been the source for groundwater. However, due to an increase in demand development and expansion in the old Akaki wellfield and other prospective wellfield sites (Legedadi, Ayat, and Sebeta) has been done. SWAWF is drained from NW, NNE, SE area across the wellfield into Akaki River, the NW, NE, SE areas area underlaid by quaternary age basalt flow and gradually slopes due west into the south-central part.

The major recharge to the aquifer comes from precipitation and river channel losses. Major direct recharge is expected in most of the permeable aquifer zone. Oligocene-Miocene basalt coves the recharge zones, Pyroclastic rocks cover most of the surrounding of Addis Ababa, Young basalt flow and scoria deposit covers surrounding parts of Akaki, Alluvial deposits along the Akaki river flood plain are the major geological developments that are governing the hydrogeological conditions of the region. Hydrogeological investigation in the prospective site enables us to understand groundwater level depth TDS and transmissivity of the aquifer. The groundwater depth increases from northwest to southeast.

Aquifer type of the study area

The main aquifers in and around Addis Ababa are fractured and jointed, confined porous rocks of volcanic origin with varying geological ages. Largely alluvial and unconsolidated formations associated with scoria and other rocks of volcanic origin form good aquifers in the southern, southwestern, and southeastern parts of Addis Ababa. The older volcanic rocks consisting of trachyte, tuff, ignimbrites, and ash flows as well as older basalts are characterized by low to moderate permeability and productivity aquifers, while the younger volcanic rocks of mainly vesicular and scoriaceous basalts are known to have high to very high productivity aquifers (WWDSE, 2011).

According to drilled borehole data in the study area, in the North-western part of the study area weathered and Fractured Basalt, and scoriaceous Basalt are the main aquifer, similarly in the central and western part of the study area weathered fractured basalt and scoriaceous basalt is the main aquifer. In the eastern margin, the aquifer is Scoria, scoriaceous basalt, and fractured vesicular basalt (WWDSE, 2011).

Lithologic and hydrologic characteristics of the Hydrogeologic units: Four principal hydrogeological units are recognized in the Akaki area groundwater prospective site.

- Alluvial layer: Composed of clay and silty clay
- Upper basalt aquifer (UBA): It is slightly confined where it is overlaid by alluvial sediment other parts of the site is unconfined. Depending on the occurrence and thickness of the scoria penetrated. The static water level varies from place to place from 5 to more than 90 meters. It seems to be interconnected with the lower aquifer through major faults in the area.
- Confining layers – moderately fractured basalt and massive basalts: The main confining unit between the upper and lower aquifer is the slightly to moderately fractured basalt and the lowest confining unit could be massive basalt layers.
- Lower Basalt aquifer (LBA): Lower Basalt aquifer (LBA) is composed of tertiary Tarmaber basalt composed of dominantly scoriaceous basalt and highly to moderately fractured vesicular basalt.

CHAPTER 3

3. THEORETICAL DESCRIPTION OF THE GEOPHYSICAL METHODS OF INVESTIGATION

3.1 General

Geophysics is a subject in natural science concerned with the physical properties and processes of the earth and its surrounding environment. Geophysics uses the principles of physics for identifying the geologic situation of the subsurface, what geologic setting perturbs the existing earth fields, how does the artificial source signal is modified after passing through the earth, and so on. The methodology for obtaining geological information from geophysical datasets is the focus of this subject. Geophysics chiefly covers potential fields methods (gravity and magnetic) because these datasets are readily available (Passive Methods), however, it also comprises seismic and electrical, and electromagnetic geophysical methods which are Active methods.

Based on source signal Geophysical methods can categorize into two: Passive method and Active method. The Passive geophysical survey measures the variation of the earth's naturally occurring field or properties, what geologic conditions contributed/caused variations, and what these variations imply will be interpreted. It's just the measurement of spatial differences in these fields (gravity and magnetic surveys) to deduce something about the geology under the surface. The Active geophysical survey involves injecting artificial sources into the ground and then measuring how the earth responds to the induced signal, what has been injected into the earth's interior received through a reader/ detector. The received signal is altered by the geology of the subsurface.

In the field of applied geophysics, the geoelectric methods have been important for about a century, particularly for shallow and near-surface investigations. Geoelectric technologies are often utilized to find underground targets that are both conductive and resistive. The intention in ground resistivity surveys is to determine the conductive/resistive nature distribution of the subsurface by surveying on the ground surface. The geoelectric behavior of the earth is dependent on various geologic parameters such as the mineral and fluid content, porosity, and degree of water saturation in the rock (De Giorgi, 2019).

Geophysical technologies play a critical role in groundwater exploration. Its main goal is to correctly and effectively assess the concealed subsurface hydrogeological setting. The contrast between the physical properties such as the features, objects, and layers and their surroundings is the foundation of all geophysical approaches. Geophysical methods can detect inhomogeneous features or targets in water, water-covered soil, or sediments that are not typical of the surrounding "host" material. In the process of groundwater exploration, careful implementation techniques and/or a combination of methods is most vital to become successful in exploration, technologically as well as cost-effectively. It is an inarguable concept that groundwater cannot be detected directly using only one of the geophysical approaches. Therefore, the interpretation is appropriate in a broad understanding of the subsurface hydrogeological condition and the geological setting is a must.

Groundwater exploration, archeological prospecting, mineral exploration, and the detection of structural features are all examples of applications where integrated geophysical interpretation is applied. Moreover, the structural features, stratigraphic units, groundwater potentiality, and depth to the basement rocks are commonly represented using an integrated geophysical interpretation for diverse geophysical tools such as resistivity and magnetic. The electrical methods are the most suitable to investigate the presence of saturated zone in the subsurface whereas, Magnetic surveys are the best tool in mapping the subsurface structures like fractures that alter the movement of the groundwater. In addition, Geophysical surveying results are more effective when they are integrated with a drilling activity or known geological condition. The drilling or stratigraphic information is vital for the successful analysis of and interpretation of data. In this study, VES and Magnetic methods are adopted to reassess the groundwater potential in Gelan condominium area Akaki Wellfield.

Different methods have been used to abstract groundwater from basement aquifers. The most common are boreholes and dug wells. Each of these abstractions has its advantages and limitations. Boreholes are quick to drill and can easily penetrate hard basement rock to a depth of 100 meters and more, it is suitable for the abstraction of water from a fractured deep aquifer. However, due to the cost of drilling is expensive and insufficient drilling companies, it is risky to drill without adequate study and appropriate funds in the borehole location. Dug wells are suitable for thick near-surface aquifers. The main advantage of dug wells is that they can store a large amount of readily accessible water. Wells also has a large internal surface area, which maximizes seepage from the aquifer. The main limitations are can’t go deeper and the presence of hard rock that is impenetrable.

3.2. Theory of the electrical resistivity method

Electrical resistivity is an active geophysical method that uses the principle of variation in resistivity for the determination of the electrical property of the subsurface, which can yield information on the structure, composition, and content of buried formation. It is the measurement of the variation in resistivity or conductivity of the subsurface, these variations in resistivity values alter the flow of current and results in a difference in the distribution of electric potential.

This method is based on resistivity contrast between different rocks and soils in the subsurface. Resistivities vary tremendously from one material to another. For example, a good conductor such as copper has a resistivity of $\sim 10^{-8}$ Ohm m, an intermediate conductor such as wet topsoil has a resistivity of ~10 Ohm m, and a poor conductor such as sandstone has a resistivity of $\sim 10^{8}$ Ohm m. Due to this great variation, measuring the resistivity of an unknown material has the potential for being very useful in identifying that material, given little further information about the materials that constituent the underground layers.

The primary objective is to measure the variation in these resistivity values and relating it to a priori knowledge of earth materials resistivity values (Loke, 2001). As is mentioned earlier the electrical conductivity of Earth's materials varies over many orders of magnitude. This is dependent on several factors, including the type of rock, porosity, pore connectivity, fluid nature, and solid matrix metallic content. Pore space, pore geometry, and fluid saturation are the most significant factors. Porosity exists mostly in joints and fractures; Table 3.1 represents the porosity percentage of sedimentary materials. Results from the resistivity survey when interpreted efficiently give sufficient useful clues about the nature and setup of the subsurface material.

Common Earth materials and their percentage porosity is given in Table 3.1 show porous materials like clay, silt, sand, and gravel likely are conductive or have low resistivity response. On the contrary sandstone, shale and limestones are compacted rock thus has low pore spaces and resistive in nature. However, the porosity alone does not decide the conductive or resistive behavior of the Earth material it also relates with the connectivity of the pore spaces and the fluid saturation in the pore spaces.

Table 3.1. Representative porosity range for sedimentary materials (taken from Geonic Ltd.1980)

Material	Porosity %
Soils	50-60
Clay	45-55
silt	40-50
Medium to coarse mixed sand	35-40
Uniform sand	30-40
Gravel	30-40
Sandstone	10-20
Shale	1-10
Limestone	1-10

Geoelectric resistivity depends mainly on the lithology, water content, porosity, and ionic concentration of the pore fluid (Khalil, 2010). Therefore, the ambiguities in interpretation may occur and the observed VES data must be calibrated with the existing borehole data to give resistivity ranges for the various lithologic units, (Khalil, 2006). Due to relatively easy field procedure, cost-efficient, and good for shallow depth exploration VES is the most suitable method in groundwater prospecting.

3.2.1. Instruments in electrical resistivity method

Taking resistivity measurements needs two essential apparatus, one part is the source of the current capable of delivering power of order 100W, the other part of the apparatus is for measuring the voltage at various points on the ground. i.e., the potential difference. The basic equipment includes the transmitter, receiver, electrodes, current and potential wires, hammer, and recording sheet.

3.2.2. Principle of VES

In vertical electrical sounding(VES), The depth of penetration of electric current is dependent on the spacing of the current electrodes, using the Schlumberger array two current electrodes (A and B) inserted at some distance apart from each other for injecting current source into the ground, and two potential electrodes (M and N) at a proper distance between to the sounding point and the outer current electrodes for measuring the difference in potential under normal condition i.e. when the material below is of uniform nature the equipotential lines would be regular. But in cases where the material is not uniform i.e., The equipotential lines would indicate obvious distortion or irregularities, including the probable location of rock masses with varied properties, if it has regions with high or low conductivity. The positions of current electrodes are changed symmetrically with respect to a fixed survey point known as the sounding point while keeping the potential electrodes MN at the same position, provide a sounding curve corresponding to the apparent resistivity versus depth of the location, the measured values reflect the vertical distribution of resistivity values on geologic setting (Kearey et al., 2002).

Resistance is often encountered in physics when discussing the resistance of an ideal cylinder of length L and Cross-sectional area A of uniform composition. The resistivity ρ appears as the material-specific constant of proportionality in the expression for the total resistance of the cylinder,

$$R=\rho\left(\frac{L}{A}\right) \tag{3.1}$$

In resistivity survey, the total resistance R is obtained through Ohm`s law,

$$R=K*\left(\frac{V}{I}\right) \tag{3.2}$$

Where V is the potential difference between the potential electrodes M(P1) and N(P2), I is the induced current into the ground through current electrodes A(C1) and B(C2), K is the Geometric factor which is dependent on the electrode configuration.

An AC source is in series with an ammeter, which measures the total I going into the ground through the electrodes at points A and B. A voltmeter attached to the two electrodes at points M and N measures the potential difference V between the points. The ratio (V/I) potential difference to the current is the resistance. The geometric factor k(m) is calculated as a function of electrode spacing the resistance reading multiplied by this factor gives the apparent resistivity value.

In the Schlumberger array, the potential electrodes are placed at equidistance about the sounding point and the same goes for the current electrodes gradually increasing the current electrodes increase the depth of investigation of the array (Figure 3.1 and Figure 3.2) For lateral resistivity variations, the Schlumberger array is also utilized for profiling. Typical profiling involves shifting MN potential electrode pairs between larger fixed AB current electrode pairs. The major limitation of this array is the relatively poor horizontal coverage with increased electrode spacing.

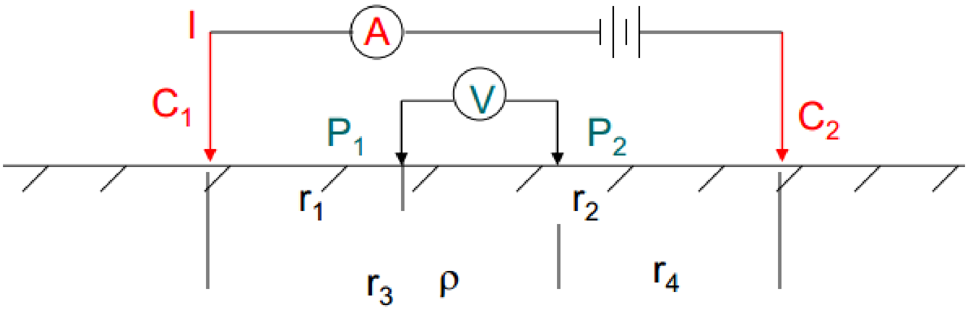


Figure 3.1. Schlumberger electrode configuration

Potential at P_1 (equation 3.3)

$$V_{p_1} = \frac{I\rho}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2}\right] \qquad (3.3)$$

Similarly, Potential at P_2 is given in equation 3.4

$$V_{p_2} = \frac{I\rho}{2\pi}\left[\frac{1}{r_3} - \frac{1}{r_4}\right] \qquad (3.4)$$

The potential difference between the potential Electrodes P_1 and P_2 is given by

$$\Delta V = V_{p_1} - V_{p_2} = \frac{I\rho}{2\pi}\left[\frac{1}{r1} - \frac{1}{r2} - \frac{1}{r3} + \frac{1}{r4}\right] \qquad (3.5)$$

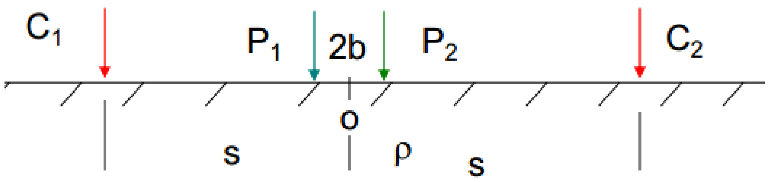


Figure 3.2. The Electrode disposition for a typical array

$r_1=s-b$, $r_2= s+b$, $r_3=s+b$, $r_4=s-b$

Substituting these values equation 3.5 becomes

$$\Delta V = \frac{I\rho}{2\pi}\left[\left(\frac{1}{s-b} - \frac{1}{s+b}\right) - \left(\frac{1}{s+b} - \frac{1}{s-b}\right)\right] \qquad (3.6)$$

$$\Delta V = \frac{I\rho}{2\pi}\left(\frac{2b}{(s^2-b^2)}\right) \tag{3.7}$$

From Equation 3.7 the apparent resistivity for the Schlumberger array can be calculated as

$$\rho_{as} = \pi\left(\frac{s^2-b^2}{2b}\right)\left(\frac{\Delta V}{I}\right) \tag{3.8}$$

where, $\pi(\frac{s^2-b^2}{2b})$ is the Geometric factor (K)

The qualitative and quantitative interpretation in resistivity method is governed by two principles:

1. If an underground material is homogeneous, the resistivity values would be of a regular character.
2. If the subsurface material is non-homogeneous that is consists of layers and distinct structures then these irregularities can be inferred from the variation in resistivity values.

In measuring the resistivity of a certain area gradually increasing the distance between the electrodes and changing the direction of survey profiles, the geoelectric property of the ground is determined. The raw apparent resistivity data was then plotted on a log-log scaled graph as half the current electrode (AB/2) and the change in the number of curvatures (n). n+2 is the proposed number of layers. An abrupt change on the resistivity curve (rise or fall) indicates the existence of low zones such as aquifers, fractured zone, buried valleys, etc.

The electrical resistivity method of geophysical prospecting is the most suitable in groundwater investigation. Electrical conduction in most rocks is due to the movement of ions in a pore fluid acting as an electrolyte. Groundwater through the various dissolved salts it contains it is ionically conductive and enable electric current to flow into the ground., Consequently measuring the ground resistivity gives the possibility to identify the presence of water, by taking into consideration the following properties 1 o

- Hard rock with no pores or fractures, as well as dry sand devoid of water or clay, are extremely resistive: several tens of thousands of Ohm-m.

- The resistivity of a porous or fractured rock bearing freshwater is determined by the resistivity of the water and on the porosity of the rock: several tens to several thousand-Ohm-m
- A water-bound impermeable clay layer has a low resistivity of several units to several ten Ohm-m.
- Mineral ore bodies (iron sulfide) have very low resistivities due to their electronic conduction: usually lower or much lower than 1 Ohm-m.

To identify the existence of groundwater from electrical resistivity survey, it is important to look at the absolute value of subsurface resistivity, through Archie Law: for a practical range freshwater resistivity range from 10 to 100 Ohm m a usual target for aquifer resistivity can be between 50 to 2000 Ohm m. Mostly relative values in resistivity or resistivity contrast are considered when it comes to detecting groundwater. In a resistant environment like hard rock, a low resistivity anomaly will be targeted, while in a conductive environment like salty and clayey environment high resistivity anomaly is the target that indicates the presence of fresh water.

Throughout most of the 20th century, Vertical Electrical Sounding (VES) was the dominant geophysical resistivity method. It has been used all over the world for three primary purposes: geotechnical investigation, groundwater exploration, and mineral exploration. The Wenner electrode configuration stated in the ASTM G57 standard or the Schlumberger electrode configuration is used for VES. (The Schlumberger method is most commonly used for groundwater and mineral exploration because it is less labor-intensive than the Wenner method).

3.2.3 Electrical properties of Earth materials

Of all the geophysical properties of rocks, electrical resistivity is by far the most variable. Values ranging as much as 10-1000 orders of magnitude may be encountered, and even individual rock types can vary by several orders of magnitude. Table 3.2 and Figure 3.3 represents the variation of the mean values of resistivity in ohm-m and conductivity of soil types, this information can be used to correlate the resistivity survey results with their appropriate values. From the figure:

- freshwater, shales, and clay exhibit 1-100 Ohm-m
- saltwater massive sulfides and graphite exhibits 0.01-1 Ohm-m.

- igneous and metamorphic rocks, dolomite, conglomerate, and limestone exhibit very high resistivity values.

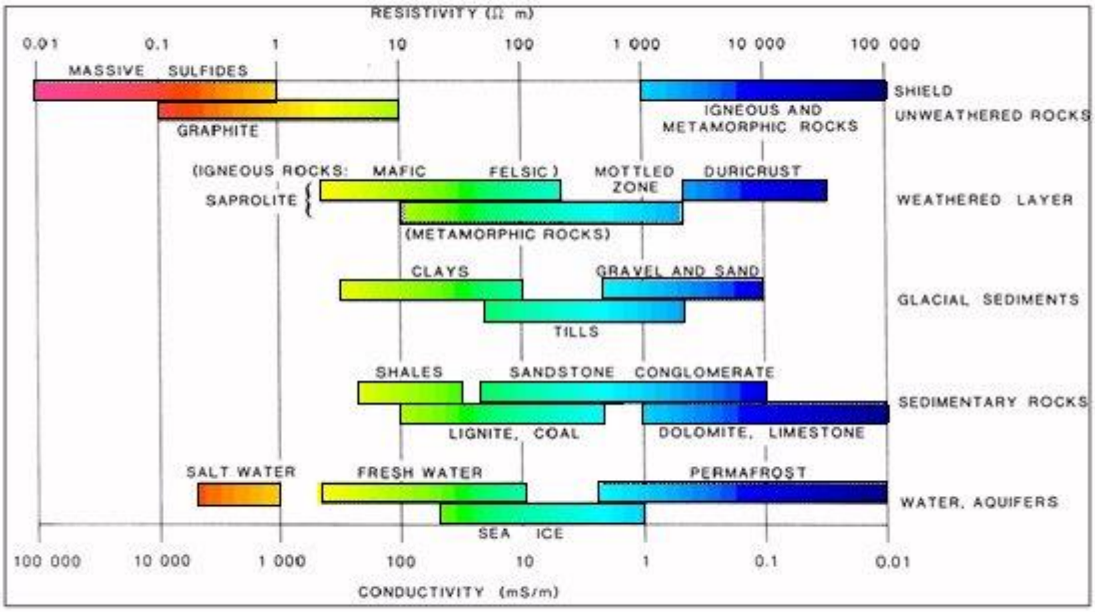


Figure 3.3. Resistivity/ conductivity ranges of Earth materials

Table 3.2 Soil resistivity values for different compositions of the earth (Adopted from Electricalengineeringtoolbox.com)

Type of soil	**Mean value of resistivity in Ω-m**
Silty alluvium	20-100
Soft clay	50
Compacted clay	100-200
Clayey sand	50-500
Silicious sand	200-300
Chalky soil	100-300
Limestone	1000-5000
Fissured limestone	500-1000
Schist shale	50-300
Mica shist	800
Granite and sandstone	1500-10000
Fertile soil compacted damp fill	50
Soil, swampy	1-30

Factors that will decrease the resistivity of a rock:

- Add more pore fluid
- Increase the salinity of the pore fluid - more ions to conduct electricity
- Fracture rock to create extra pathways for current flow
- Add clay minerals

- Keep fluid content constant, but improve interconnection between pores

Factors that will increase the resistivity of a rock

- Remove pore fluid
- Lower salinity of pore fluid
- Compaction - fewer pathways for electric current flow
- Lithification - block pores by deposition of minerals
- Keep fluid content constant, but decrease connection between pores.

3.3. The Magnetic Method

A magnetic method is a passive geophysical method that is used to measure the variation of the existing geomagnetic field and the magnetic response due to magnetic materials. Naturally occurring magnetic minerals like magnetite in rocks govern the magnetic behavior of the rock. A magnetic survey aims to investigate subsurface geology based on anomalies in the Earth's magnetic field resulting from the magnetic properties of the underlying rocks (Kearey et al., 2002).

The magnetic method has been used as a tool for exploration geophysicists in their search of mineral-bearing ore bodies, oil-bearing sedimentary structure, to locate and map buried magnetic material (such as buried metal waste, pipes, and electric wires, and to identify faults and other crustal weakness structures that affect the groundwater flow path. In addition, the method is also used for regional geologic mapping. The essential feature is the measurement of the magnetic field intensity, and sometimes the measurement of magnetic inclination/dip, and declination (departure from geographic north) at several stations.

Power lines, buildings, and metallic debris can cause interference while measuring the magnetic susceptibility of the subsurface. Magnetic Susceptibility is the measured physical property in a magnetic survey. The solar storms may also cause fluctuation in reading, Magnetic storms in the earth's upper atmosphere can cause rapid variations in the inducing field, though the operation of a base station will allow the correction for most such variations.

3.3.1. Instruments in magnetic surveying

The measurement of a magnetic field at a certain location is the measure of the amplitude of the anomalous field. As a UAV navigation company, magnetic data can be collected by two types of magnetometers, absolute and relative. Absolute magnetometers measure the total geomagnetic field at that exact location whereas relative magnetometers measure the variation of the total geomagnetic field relative to base station measurement. Relative magnetometers are used in this survey for the measurement of the earth's total magnetic field strength

In this study for the collection of magnetic field data, Earth Magnetometer Model EM2 was used (Figure 3.4). EM2 measures the Earth's magnetic field with a resolution of 1nT (1 gamma). Its resolution is about 0.002% of the typical Earth field strength. It measures small variation from location to location in the earth field and is used to locate buried magnetic objects or materials. The magnetometer signal is not attenuated by rock, dirt, mud, or water. Therefore, the target can be detected at great depth.

The instrument has three components the black stick, "L" shape sensor, and the meter display in the magnetometer showing the field in micro-Tesla (µT). To make measurements, place the stick on the ground vertically with the point (at the bottom) downward. Aligning the "L" shape sensor to the magnetic North direction or actual field direction with the help of a compass. Pressing the "Reset" button and a relative maximum field will be displayed, taking three measurements at the same location and the mean reading in the field at that location. Walking to the next station and pressing the "Reset" button for the next measurement. For accurate measurement avoiding swinging a stick or letting it blow away by the wind from the vertical, is essential. A small deviation from the vertical will produce a significant difference in reading because the Earth field is a vector so the reading is dependent on the angle of the stick. GPS provides accurate positioning of the survey point of the magnetometer; it is also used to identify the azimuth of the reference mark.

Figure 3.4. Earth Magnetometer EM2

3.3.2. Basic concepts

When one records a magnetic observation in a certain location most of the fields emanate from inside of the earth's main field B_m (coupled fluid motion in the outer core), the external field (B_{ext}) due to the interaction of the earth ionosphere with the solar wind is a relatively small portion of the observed total magnetic field. And the third component of the observed total magnetic field is magnetized crustal rocks or magnetically induced subsurface bodies B_{rm}, and remnant magnetization. The data signal contains the source/ inducing signal (B_m) as well as the response (B_{rm}) from magnetized material and the external field. Equation 3.9 represents the total magnetic field

$$\mathbf{B_T} = B_m + B_{rm} + B_{ext} \qquad (3.9)$$

The solar winds interact with the earth's magnetic field and allow charged particles to flow in the ionosphere. These charged particles produce an external magnetic field resulting in small variation(20-50nT) in the reading. These variations caused by charged particles throughout the day are corrected by diurnal Correction.

Magnetization (*M*) is a vector quantity that describes an object's potential to be magnetized, Magnetization has the same direction as the earth's field because the earth's field is different at different locations. The final magnetization of rock is dependent on the cooling process through its Curie temperature (500-600 ^{0}C) exhibit either remnant or permanent magnetization. Above Curie temperature, the dipoles are prevented from aligning with the magnetic field by thermal agitation. Such high temperature is reached at the lower region of the continental crust and below Moho under the ocean.

$$M = KH \tag{3.10}$$

where K is magnetic susceptibility of the material, H is Earth's magnetic field

Magnetic force: the magnetic force is given by Coulomb's law for magnetic poles. The force F between two magnetic poles of strengths m_1 and m_2 separated by a distance r is given by

$$F = \frac{\mu_0 m_1 m_2}{4\pi \mu_R r^2} \tag{3.11}$$

where μ_0 magnetic permeability of vacuum and μ_R is the relative magnetic permeability of the medium separating the poles (~1 for air). The force is attractive if the poles are of different signs and repulsive if they are of an alike signs.

The magnetic field B (equation 3.12) due to a pole of strength m at a distance r from the pole is defined as the force exerted on a unit positive pole at that point. (Kearey et al., 2002).

$$B = \frac{\mu_0 m}{4\pi \mu_R r^2} \tag{3.12}$$

3.3.3. The Earth's main magnetic field

According to Sir William Gilbert, the Earth acts like a giant bar magnet (magnetic field lines flow from positive to negative, positive in the southern hemisphere to negative in the Northern hemisphere) situated near the center of the Earth inducing its secondary magnetic field to ferrous materials like magnetite (Abera Alemu, 2020). These materials have measurable magnetic susceptibility resulting in induced fields. However, this theory has a shortcoming since at great depth the earth's temperature excessed Curie temperature, a point at which all materials lose magnetization and become neutral.

The Earth's main magnetic field originates in electric currents circulating in the liquid outer core but can be largely modeled by a dipole source at the Earth's center (Milsom, 2003). The Earth's magnetic field south end is oriented toward the north magnetic pole. The field is dipolar, vertically downward at the magnetic north pole and vertically upward at the magnetic south pole, and horizontal at the magnetic equator. It is both the remnant and induced magnetic responses that are used to map an exploration area and calculate the susceptibility of rock types. In the absence of an external magnetizing field, due to permanently magnetized particles of rock, some rocks have measurable magnetization related to the earth's magnetic field in the geologic past (Abera Alemu, 2020). Rock magnetism is the area of interest during a magnetic survey whereas the external field and earth's main field are corrected using drift correction and IGRF correction respectively. Remnant and Induced magnetization are the remaining magnetizations of crustal material after a magnetic field has been removed. However, due to the small value of remnant magnetization in the continental crust, the natural remnant magnetization is ignored.

The geomagnetic (Earth's magnetic) field at or near the surface of the Earth originates largely from the Earth's outer core. This field can be described in terms of the "declination D" which is the horizontal angle between geographic and magnetic north, "inclination I" is the dip in which the magnetic field lines are pointing in relation to the Earth's surface, and the "total Field T_F" (Figure 3.5). The Earth's field has a strength of approximately 70,000 nano-Tesla (nT) at the magnetic poles and approximately 25,000 nT at the magnetic equator.

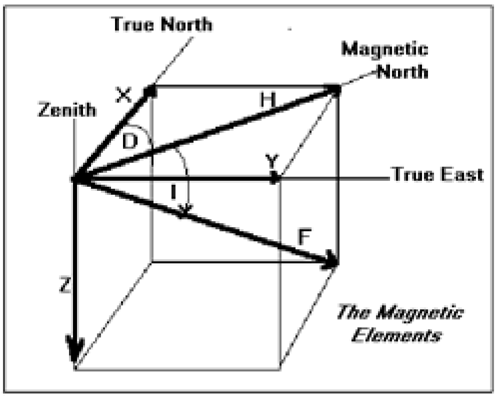


Figure 3.5. Elements of Geomagnetic field, Inclination, and Declination (adopted from NOAA, 2010)

3.3.4. Magnetic properties of Earth materials (Rock susceptibility)

The susceptibility is very small for most natural materials and may be either negative (diamagnetism) or positive (para-magnetism) in accordance with the direction of the inducing (geomagnetic) field with the induced body's field. According to Breiner (1973), the magnetization of soils points out that soils reflect their parentage, and that some, as a result, will be considerably more magnetic than others. Magnetite, pyrrhotite, and maghemite, all of which have Curie temperatures of about 600 ^{0}C, are the only important naturally occurring magnetic minerals and, of the three, magnetite is by far the most common. (Milsom, 2003). Because magnetite concentrations can be expected in sediments where streams carrying heavy metals lose velocity, distributing streams, in alluvial fans, and also in glaciated terrain (particularly eskers, outwash, and beach deposits). In highly organic soils, maghemite, a relatively magnetic form of hematite, can be produced. As a result, the magnetic susceptibility of soils can be laterally variable and, because they are close to the magnetometer, give rise to very localized anomalies of significant magnitude.

The susceptibility describes the ability of a rock to be magnetized and it is dependent on the change in lithology. Rock susceptibility depends on the magnetite content, so most rocks that have a significant concentration of Ferro- and or Ferri-magnetic minerals will have the highest susceptibilities. Basic and ultrabasic rocks have the highest susceptibility, while igneous and metamorphic rocks have intermediate to low susceptibilities. Sedimentary rocks generally have very small susceptibility (Milsom, 2003).

In rocks, susceptibility is mainly dependent on the volume percent of magnetite. This mineral is common in igneous and metamorphic rocks and is present at least in trace amounts in most sediments. Magnetite is by far the most common geologic magnetic material. (Grant, 1965)

3.3.5. Magnetic surveying and data reduction

The reduction of magnetic data is necessary to remove all causes of magnetic variation from the observations other than those arising from the magnetic anomaly effects of the subsurface. (Kearey, 2002). The Earth magnetic field has variation through time, the buried anomalous body need to be isolated to be interpreted into geologic feature and structures. To identify the magnetic field information about the survey area of interest the effects of regional field and temporal variation have to be corrected. By recording the time at which a magnetic reading had been taken and subtracting the magnetic field strength of base station recording in accordance with the time of the day, temporal variation can be eliminated.

Diurnal/Drift correction

As the Earth rotates, beneath the ionosphere the observed intensity of the geomagnetic field fluctuates with a range of amplitude of about 10-30nT at the Earth surface and with a period of one day.

Diurnal variation correction is the difference observed in base station measurement after perturbed measurements in the stations throughout the day with respect to the time of observation. The use of diurnal correction is to distinguish the temporal variation of Earth’s magnetic field from geographic variation. Diurnal correction should be made to account for the geomagnetic field’s temporal variation, which is primarily caused by particle and electromagnetic radiation from the sun perturbing the ionosphere of the earth, and thus the geomagnetic field (Khalil, 2012). The diurnal variation ranges to tens of nano-Tesla(nT) during a normal day however, the variation might rise to several hundreds of nT associated with the magnetic storm. In the study area, static local base stations were situated as near as to the survey area and free from magnetic sources such as power lines and buried magnetic materials, continuously reading at the base station is done during the survey period. This serves as a reference during the processing and removing the variation of the magnetic field with time.

International Geomagnetic reference field (IGRF):

The IGRF is an internationally agreed series of global spherical harmonic models of the Earth’s magnetic field whose sources are mainly in the Earth’s outer core. IGRF is the theoretical model of the earth’s main field that describes the variation of Earth’s main field (dipole field) and its spatial and secular variation with latitude, longitude, and time (Abera Alemu,2020). IGRF correction is done to remove the effect of geomagnetic earth’s field from the survey data by subtracting the IGRF and delineate the effect of targeted residual anomaly (Kearey, 2002) IGRF model describes the field and its secular change. In this work, IGRF correction had been applied by an online IGRF calculator (Figure 3.6) to the diurnally corrected total magnetic intensity.

B

Latitude	Longitude	Altitude	Date	Version
8.867	38.75	2.07	2021-05-16	13

Comp	D	I	X	Y	H	Z	F
MF	2.313	2.643	35598	1438	35627	1644	35665
SV	1.5	7.6	17.5	15.9	18.1	79.8	21.8

Figure 3.6. Geomagnetic Elements from IGRF calculator (The IGRF Model (13th Generation) (bgs.ac.uk))

Regional-Residual mag anomaly separation

Wavelength filtering is a method of magnetic data processing designed to remove either the high wavenumber noise (due to small near-surface sources) by the low-pass filter. Or the longer wavelength component (due to regional anomalies) by a high-pass filter (Personen et al., 1994). Effective output in the wavelength filtering depends on the right choice of the cut-off frequency used in the filter design (El-Gawad et al.,2006). Geosoft Oasis montaj software(V-7.0.1) was used in applying the high-pass filter, low-pass filters, and upward continuation to enhance and differentiate the shallow (residual) and deep (regional) anomalies.

Magnetic anomalies are a function of two parameters: orientation of the Earth's magnetic field with respect to the target object and the distribution of magnetic susceptibility in the subsurface. Magnetic anomalies with the same susceptibility distribution will be different if the distribution is at a different location. In addition, if the earth's magnetic field is in the same direction as the induced field the susceptibility will be positive (Paramagnetic/ferromagnetic) whereas in the opposite direction of the two fields results in negative susceptibility (Diamagnetic).

Data enhancement and Qualitative interpretation: For qualitative interpretation, the following profile plots were done.

Reduction to pole (RTP)

RTP is important for survey areas that are far from the Earth's magnetic poles. The measured total magnetic intensity needs to be corrected for latitude since the magnetic field lines of the Earth have a different inclination. An anomaly at the poles will image directly above the source body, however, if the source body is away from the poles the anomaly will be shifted rather than being directly above the body (Ravat, 2008). Doing RTP shifts the anomaly to be directly above the source body (Figure 3.7). Since there is a positive and negative anomaly and the source body the transition point where it moves from negative to positive is usually where the body is present assuming there is no remnant magnetization. After performing RTP the observed anomaly will have a positive maximum directly at the center of the body.

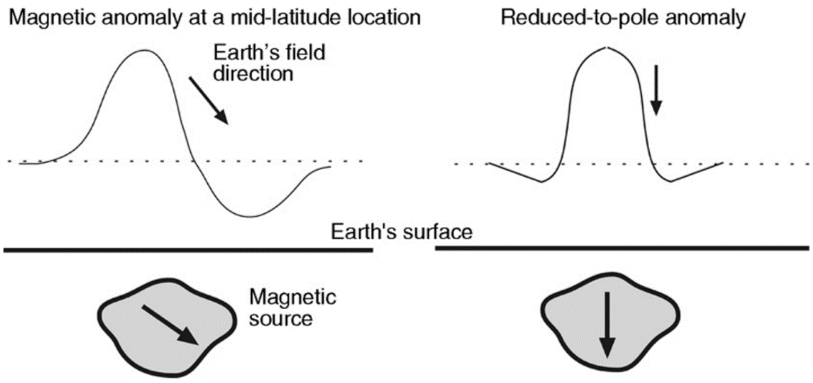


Figure 3.7. principle of reduction to pole (RTP), (taken from Ravat,2007)

The goal of RTP is to take an observed total magnetic field map and produce a magnetic map that would result in an area being surveyed at the magnetic pole. This method involves removing the dependence of the magnetic data on magnetic inclination. Assuming that all the observed magnetic fields are due to induced magnetic effects, pole reduction can be calculated in the frequency domain (Grant and Dodds, 1972). However, the study area has a low magnetic latitude zone where RTP results have distorted output, to overcome the instability of RTP reduction to equator (RTE) method is used to obtain the desired output. RTE is used when the survey area is the low magnetic latitude of low inclination area where RTP has distorted output.

Analytic signal

Analytic Signal is typically formed from a combination of the horizontal and vertical gradients of a magnetic anomaly. It has both amplitude and direction, but it is usually its "Amplitude Function". Analytic signal enhances high-frequency signals coming from shallow sources, widens anomalies, and removes the effect of magnetization direction, geological strike, and geological dip. Besides shifting the anomaly peak to coincide (approximately) either with the center of the magnetic source or with its edges.

Horizontal Derivative

Is employed for the investigation of anomalous source occurring at shallow depth, i.e., the residual anomaly. Applying horizontal gradient filter to the observed residual magnetic anomaly derivates in the x and y-direction. The horizontal derivative method is based on the theoretical ground that the maximum horizontal gradient of the residual anomaly occurs directly above the edge of the body if the edges are vertical and well separated (Abera Alemu, 2020).

Upward continuation

Continuation methods (Upward and Downward) projects the observed anomaly to higher or Lower elevation according to the desired response i.e., applying upward continuation minimizes the effect of higher frequency components associated with local and/or near-surface anomalies by projecting the observed anomaly to a higher elevation allowing to enhance the large-scaled deep sources, longer wavelength features of the anomalous body. i.e., serve to filter out the residual or shallow depth anomaly and enhances the regional anomaly. This is analogous to the low-pass filter.

Euler Deconvolution

The theory of the Euler deconvolution depth technique is based on the Eulers homogeneity equation (Abera Alemu, 2020). The magnetic field and its gradient are related to the location of the source of an anomaly, with the degree of homogeneity expressed as a "structural index". The structural index (SI) entails the degree of fall off of the field with distance from the causative source. This method is a tool used in quantitative interpretation for gravity and magnetic methods, to determine the depths of the geologic contact(lineaments) between sedimentary rocks and basement rocks. Besides locating the anomalous magnetic sources.

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CHAPTER 4

4. DATA ACQUISITION AND PROCESSING

4.1. General

In this thesis work vertical electrical sounding and magnetic survey had been used in order to assess the groundwater potential in Akaki wellfield 1 (Gelan Condominium area). For this work, of the study area secondary VES data is, acquired from Water Work Design and Supervision Enterprise (WWDSE) and primary magnetic field data were collected by the researcher.

4.2. Data acquisition parameters used for VES survey

A total of 10 sounding point data used in this study were acquired using the Schlumberger array. As shown in Figure 4.1, the sounding points lie along 3 profile lines and were conducted with transect separation ranging from 1.4km to 1.9km and with a maximum half current electrode spacing of 1000m (AB/2=1000) this guarantees sufficient current-penetration to assess the maximum depth of interest.

4.3. Processing of resistivity data

The raw apparent resistivity data as a function of half current electrode spacing is plotted in IPI2win software to obtain an initial model of the layer parameter and such as depth and thickness of the layer in addition to the respective layer resistivity values. The model parameters obtained from IPI2win were then used in WinResist software. The initial model parameter is given as an input to the WinResist software along with the measured field data. After a certain number of iterations, the final model parameter that provides the best fitting between the field data and theoretical curve will be obtained and adopted as the true resistivity and thickness/depth values of the subsurface layers.

The end of iteration processes the Root Mean Square Error (RMS error) of the final model parameter in the present study has a range from 1.8 to 4.8. These layer parameters were used to construct the Geo-electric section on AutoCAD 2009.

The true resistivity values are dependent on the mineralogical composition of the rock, order of fracturing and weathering, and also degree of water saturation filling the pore spaces. These reasons cause wide variation in resistivity resulting in difficulty in varying rock types based on resistivity and conductivity values thus it is important to correlate the data with properly logged representative boreholes. In this study 7, borehole logs in proximity to the survey area (as illustrated in Fig 4.1) were used to constrain the depth and lithologic units under each profile line.

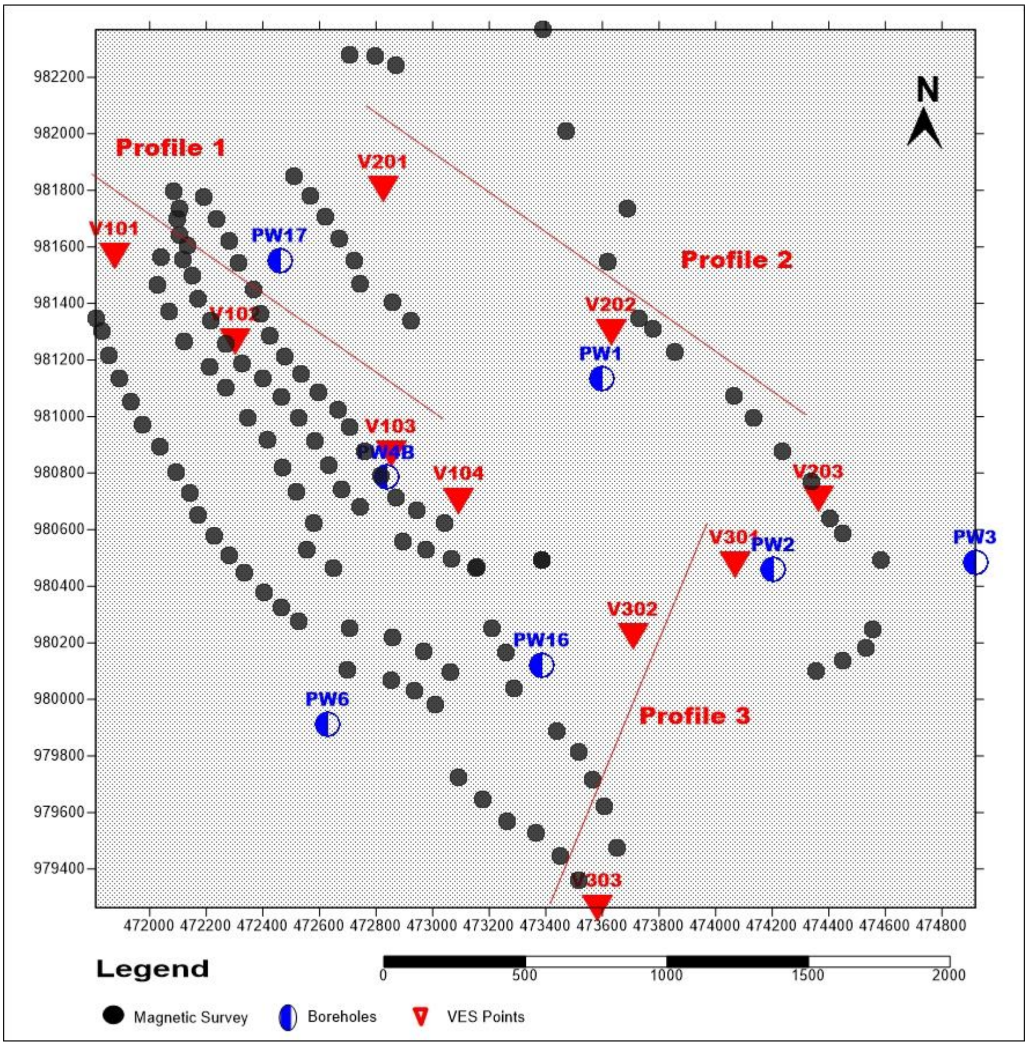


Figure 4.1. Distribution of VES, borehole, and magnetics data points

4.4. Presentation of electrical resistivity data

Resistivity data can be represented as Slice-stacked Section, Pseudo-depth section, and Geo-electric section. Slice stacked section is done at selected 7 AB/2 spacing to illustrate the lateral variation of apparent resistivity over a horizontal at a certain depth. The maximum depth penetration of the Schlumberger array is 1/3 to 1/5 of the maximum distance of current electrodes (Frohlich et al., 1996).

Pseudo depth section is done along the three VES profile lines, gives preliminary idea for high potential for groundwater by examining the apparent resistivity variation, aside from giving a hint of dipping layer. The geoelectric section illustrates the layer parameters represents the geoelectrical stratification of the area under study is constructed.

4.5. Data acquisition and distribution of magnetic survey

A total of 123 magnetic field data were collected along 5 profile lines and on random points with a station interval of 70-100m, was collected. Magnetics profile lines are selected based on a geologic map of the area i.e., perpendicular to the geologic strike. However, due to the expansion of cities and new roads, the existence of high-tension power lines and farmlands were the challenges in surveying along with profiles in the survey area. At a data point reading was taken repeatedly to increase the accuracy and quality of the data then the mean reading is readily available for the diurnal correction.

The instrument used to collect the total magnetic field data was Earth Magnetometer EM2 which is suitable for determining both the location and depth of a buried target of magnetic material. Hand-held GPS was used to record the X-Y coordinates and elevation information for each magnetic data point.

4.6. Reduction and processing of magnetic survey data

Data reduction and processing is a crucial step in removing unwanted signals and/or reducing noise from the actual field data. Diurnal correction is done by subtracting the diurnal variation from each reading and removal of IGRF was done to the collected total magnetic field data, to determine the total magnetic field anomaly. This data was grided by the minimum curvature technique in the Geosoft Oasis montaj (V- 7.0.1) software which includes both the regional and residual anomalies. By using high-pass and low-pass filters residual and regional anomalies can be separated and since the area of interest is the residual anomaly it is further enhanced by analytic signal, and tilt derivative maps.

4.7. Presentation of magnetic survey results

The magnetics survey data were presented in a grid map of the residual and regional anomaly, analytic signal map, tilt, and horizontal derivative maps, Euler deconvolution plots for depth to causative body/source mapping are done and finally, 2D magnetic modeling was done.

CHAPTER 5

5. PRESENTATION AND INTERPRETATION

5.1 General

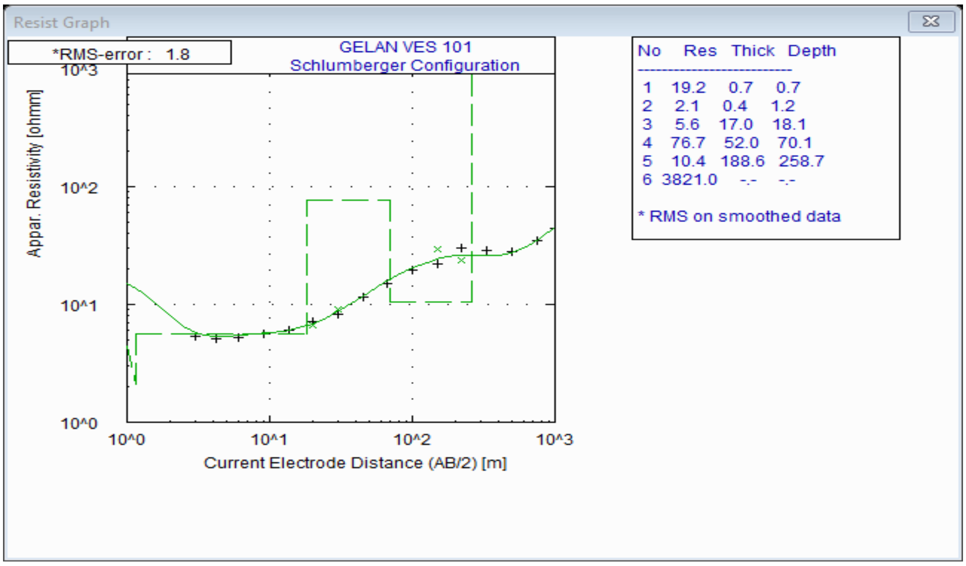
In this thesis work, a geophysical survey for the collection of primary magnetic data and secondary resistivity sounding data were obtained. For reliable interpretation of VES and magnetic survey, it is essential to obtain lithologic information from borehole logs nearby the area. Interpretation is made by integrating the results in VES, magnetic, and borehole log data.

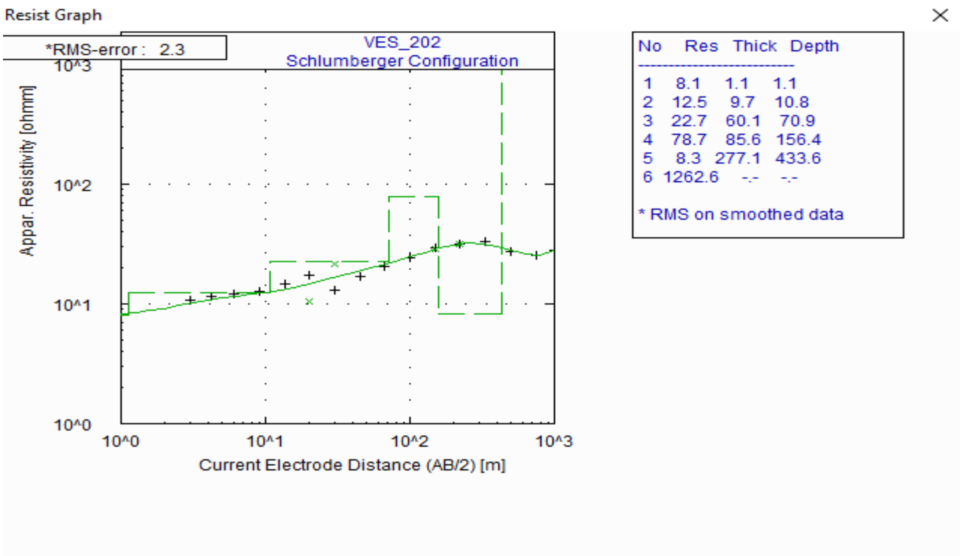
In this study a total of 10 VES along three profile lines as shown in Figure 4.1 were used, the sounding data are presented and interpreted as individual VES curves, apparent resistivity slice-stacked map, pseudo-depth sections map, and geoelectric sections. The slice-stacked section and apparent resistivity pseudo depth section along the profile lines are done and represented in contour map using Surfer software (Geotomo, V-10). The geo-electric section map along the profile traverse is done based on the layer parameters of the individual VES curve models correlating with borehole log information. In the study area, 7 boreholes were used to constrain the data, and for reliable interpretation, from these boreholes 5 of them are productive. The geo-electric section is plotted in AutoCAD 2009 software.

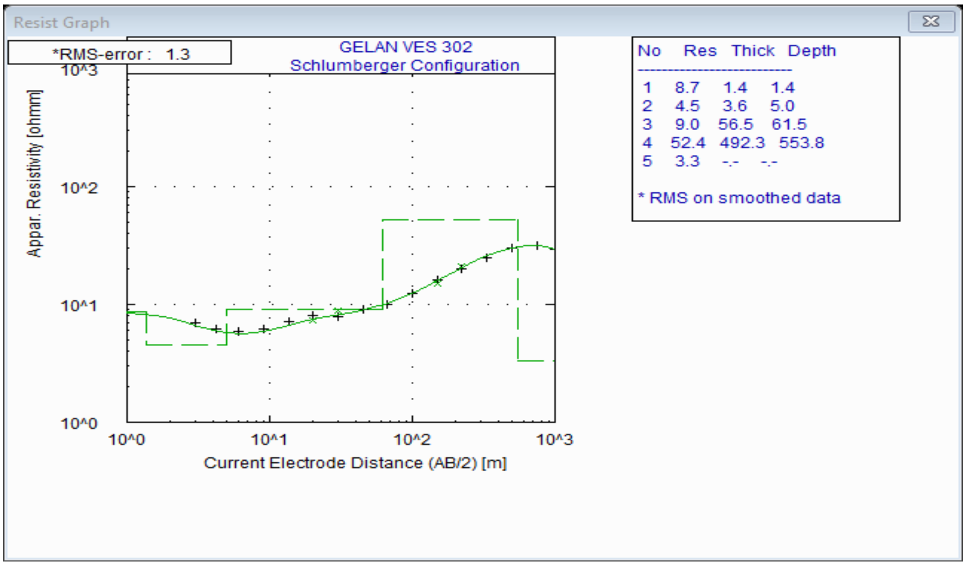
5.2. Presentation, Result, and Interpretation of VES

5.2.1 Interpreted VES Curves

The apparent resistivity values versus AB/2 graphs are plotted in a bi-log scale graph using the software IPI2win and initial model parameters (layer resistivity and depth) were obtained. These values are taken as a model parameter for inversion software WinResist to obtain the true resistivity and depth of lithologic units beneath the survey profile. As shown in Figure 5.1 the black crosshair plot represents the acquired field data and the green line is the calculated (by WinResist) theoretical curve, some of the best fitting individual VES curves (VES 101, VES 202, and VES 301) are illustrated below. The VES curves of the 10 sounding points are compiled in Appendix 1.







Figures 5.1. Illustration of the processing and interpretation of individual VES curves

5.2.2. The Slice Stacked Section

The slice stacked section provides good assistance to visualize lateral and vertical apparent resistivity distribution in addition to subsurface geological variation in both lateral and vertical directions. And aid for qualitative assessment in the electrical response of the geologic medium.

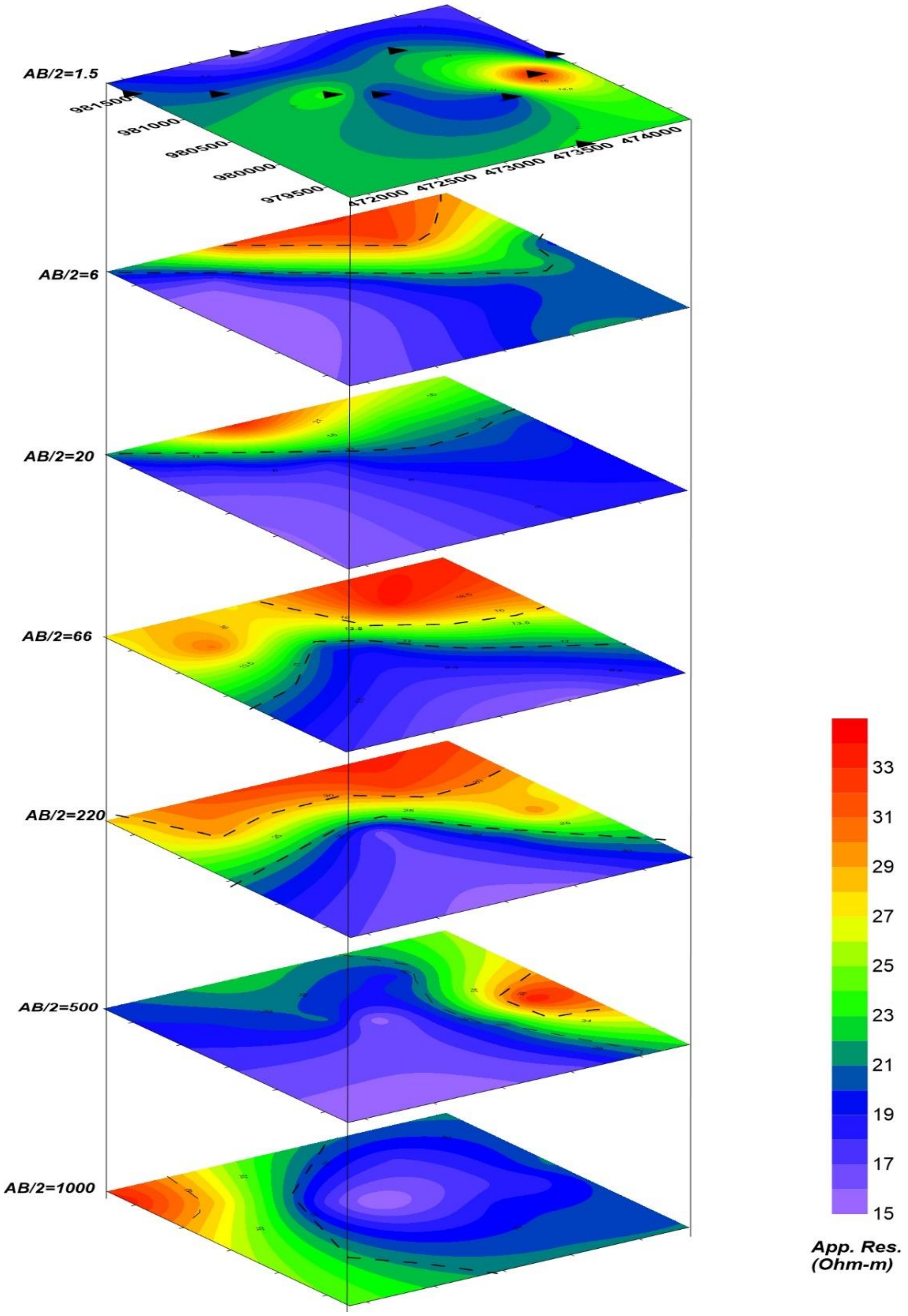


Figure 5.2. Slice stacked section for AB/2 of (1.5, 6, 20, 66, 220, 500, 1000)

As shown in Figure (5.2), the slice stacked section is done at selected AB/2=1.5, 6, 20, 66, 220, 500, and 1000m. It shows the relative variation of apparent resistivity values at a certain penetration depth of induced current on the subsurface since the gradual increment of current electrode spacing increases the depth of penetration. This section is done on Surfer software (Geotomo, V-10).

According to the slice stacked plot values of high apparent resistivity zones observed in the north, northeastern and northwestern part of AB/2 (6, 66, and 220). The low apparent resistivity values are observed in the central and southeastern region of the survey area for all AB/2 values except for AB/2 of 1000. On the other hand, high resistivity values are observed in the Eastern region for AB/2=1.5, 220, and 500.

5.2.3 Pseudo-depth and geoelectric section

5.2.3.1. Profile line 1

Pseudo-depth section

The pseudo depth section for the apparent resistivity on profile line 1 has a direction of NW-SE trend as illustrated in Figure 5.3. The line has a total length of 1500m consists of four VES points (101,102,103 and 104) with an average spacing between VES points is 500 m.

The top layer is a thin layer beneath VES 101 gets thicker along with the profile to VES 104 having very low resistivity ranging from (7.7-11.5 Ohm-m) characterized as topsoil cover. The figure shows higher resistivity values, at a deeper depth and higher resistivity values are observed in the NW direction i.e., under VES 101 indicating the presence of fresh rock act as a basement for the upper aquifer. However lower resistivity values are observed along with the profile at a deeper depth. The bottom layer of this profile line directly below VES 102, 103, and 104 has an intermediate resistivity range of 20-32 ohm-m, which is possibly the response of highly weathered and fractured basalt. This layer can be taken as a potential water-bearing horizon.

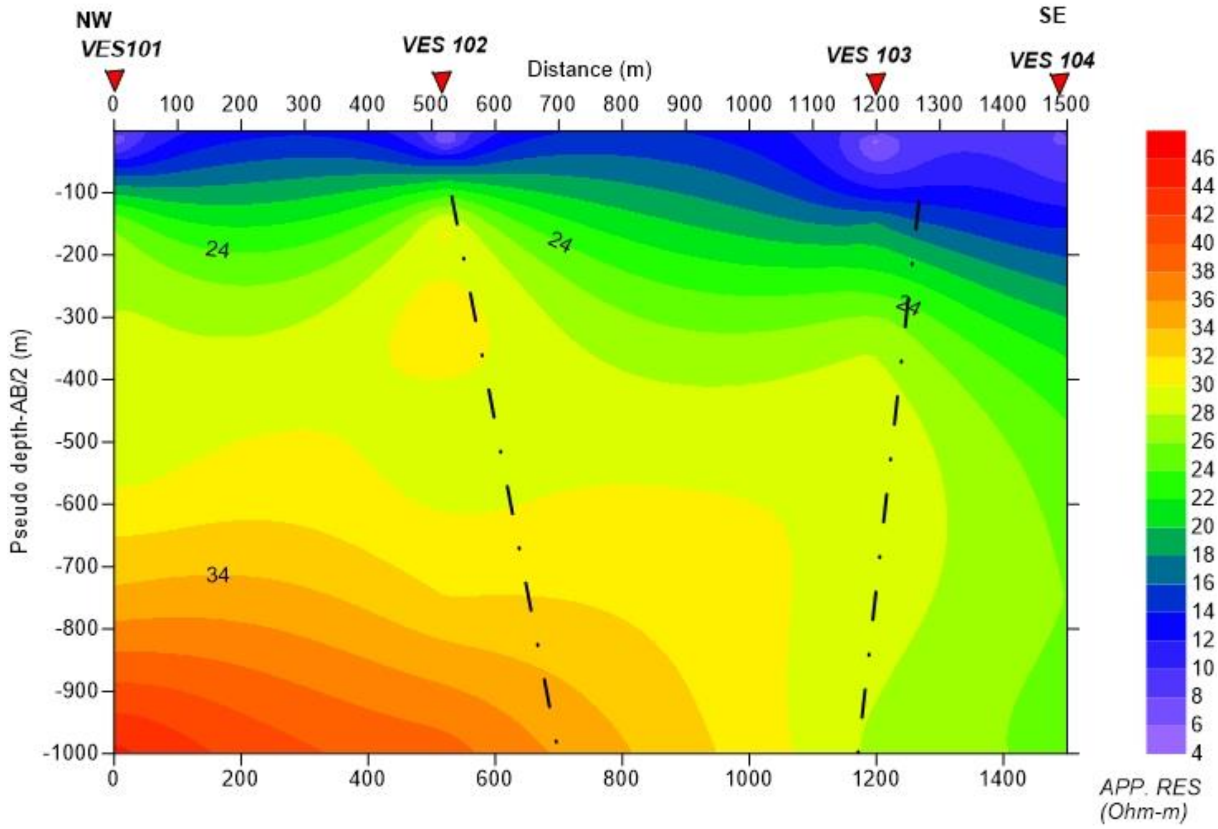


Figure 5.3 Pseudo-depth constructed from the VES lying on profile Line 1, Akaki Wellfield, Addis Ababa

Geoelectric Section (Profile-1)

The geo-electric layer is done along profile 1 shown in Figure 5.4 has four sounding points is represented by four to five geoelectric layers. The profile line exhibited in the figure below has 1.5km long. WF01PW17 is the closest borehole for VES101 and 102 and WF01PW4B is close to VES 103 and 104. These two boreholes information (compiled in Appendix 2) was used to constrain the depth and identify the lithostratigraphic units. The subsurface beneath this section is characterized by 5 layers in the NW direction and 4 layers along with the profile to the SE direction.

The ground elevation undulates gently from 2060- 2066 m.a.s.l. The uppermost layer has a lower resistivity range of 11-19 ohm-m. It is a thin layer topsoil cover with a thickness of almost 1m attributed to highly decomposed volcanic rock. The subsurface below this layer is characterized as clay with a very low resistivity range from 2-10 Ohm-m, the layer thickness increases to the SE direction. The thickness of this layer has a variation from 10-64 m.

Underlying the second layer, two distinct regions can be deduced; under VES 101 and 102 a layer that has high a resistivity range of 77-128 ohm-m with smaller thickness; and underneath VES 103 and 104, 20-36 ohm-m of resistivity is observed both regions are likely to be the response of moderately to highly fractured basalt. This layer has a varying thickness, a relatively thin layer of 40-52m beneath VES 101 and 102. For VES 103 and 104 a thicker layer of 346-675m. The highly fractured zone of this layer is expected to have good groundwater potential.

The fourth geoelectric layer at deeper depth beneath VES 101,102 and 103 has extensive coverage on the profile having lower resistivity values in contrast with the upper and lower layers, underneath VES 104 this is the last geoelectric layer. The resistivity range of 6-19 Ohm-m corresponds to fractured basalt intercalation with clay. The layer has around 190m thickness. According to this and the above layers, and the borehole log data the degree of fracturing and alteration of clay increases to the SE direction of the profile line.

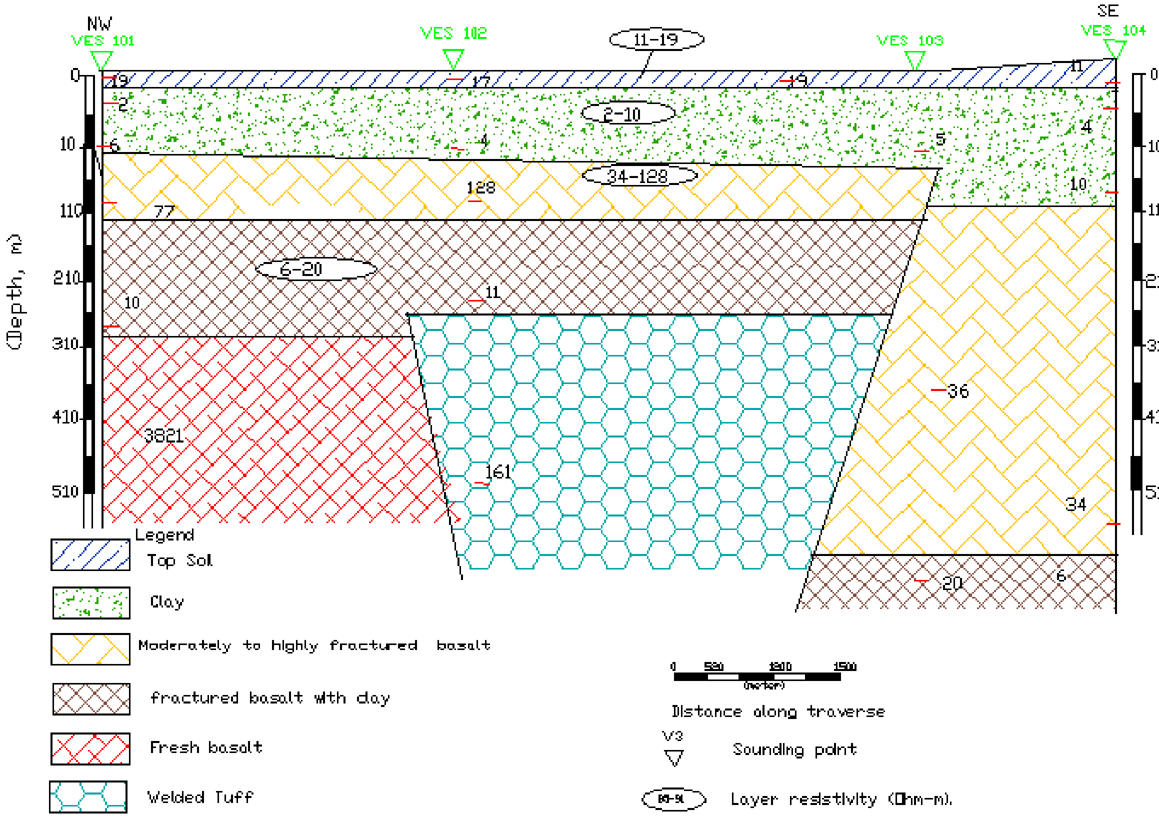


Figure 5.4. Geo-electric section from VES profile Line-1, Akaki Wellfield, Addis Ababa

The last geoelectric layer manifests two zones, a layer extending to infinite depth as observed: the first zone of VES 101 and 102 with the resistivity value of 3821 ohm-m is the response of fresh basalt. The second region between VES 102 and VES 103 with the resistivity value of 160 Ohm-m is likely to be the response of welded tuff. A weak zone can be proposed between VES 101-VES 102, and between VES103-V104.

5.2.3.2 Profile line 2

Pseudo-depth section

This pseudo depth section is parallel to profile 1, it is done based on 3 sounding points of VES 201,202, and 203. The profile line is oriented in NW-SE direction with a total length of 1890m and average sounding point spacing of 960m.

The pseudo-depth section plotted below (Figure 5.5) indicates that the top layer has almost equal thickness throughout the profile line exhibiting low resistivity ranging from 4-8Ohm-m which can be corresponded to top clay soil. As depth increases the apparent resistivity has a small variation, beneath each sounding point high apparent resistivity values are indicated in the contour map. At deeper depth, the high apparent resistivity zone is shown directly under VES 201 which is possibly a slightly weathered or decomposed volcanic unit. The extensive region in the middle point of the profile direction exhibits low resistive coverage. This conductive region can possibly be a good potential zone for groundwater.

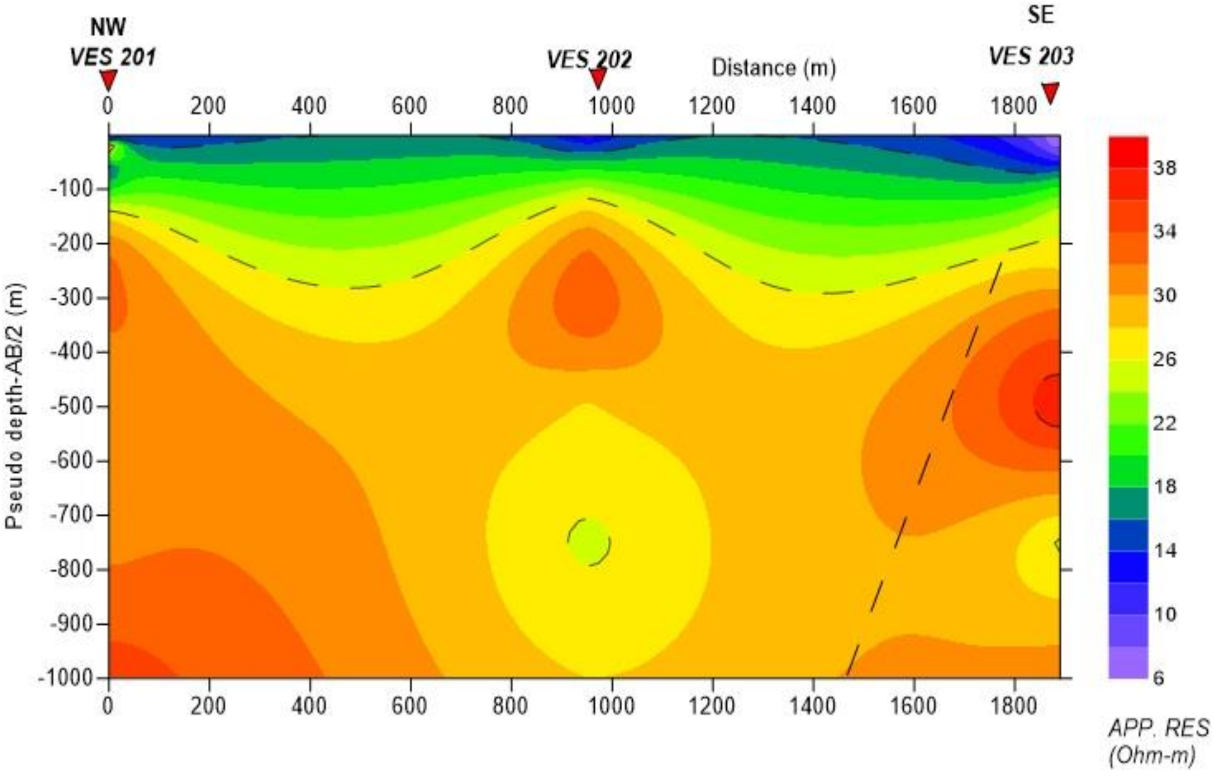


Figure 5.5. Pseudo-depth section from VES on profile Line-2 Akaki Wellfield, Addis Ababa

Geoelectric Section (Profile-2)

The geoelectric layers along this profile presented in Figure 5.6 have three VES points and are characterized by five geoelectric layers. The profile length extends to 1.9km and the ground elevation gently slopes to southeast direction from 2084-2073 m.a.s.l. Two boreholes namely WF01PW1 and WF01PW2 (given in Appendix 2) are used to constrain the depth and correlate the lithologic information with resistivity parameters of interpreted sounding curves.

The uppermost layer has resistivity variation from 3-8 Ohm-m is characterized as topsoil has a thin layer under VES 201 and 202 the thickness varies from 1-8m. The layer thickness increases along with the profile. Underlying this layer, a depositional high resistivity material of 88 ohm-m is obtained from model parameters of individual VES curves this is possibly the response of yellowish decomposed volcanic rock. However, this layer does not extend throughout the profile.

The second geoelectric layer has a resistivity range of 6-23 ohm-m corresponds to moderately weathered vesicular basalt. This layer depth starts from 10 m extending up to 70m at VES 202. This zone of the layer can be taken as a low potential groundwater source at the shallower depth that can be considered as the upper aquifer.

Underlying this layer, a higher resistivity layer of 18-111 ohm-m is obtained from interpreted VES curves and borehole information accordingly this is the response of moderately to highly weathered scoriaceous basalt. This layer exhibits almost the same thickness of 82m underneath VES 201 and 202, whereas the thickness increases to the SE of the profile(521m). According to the profile plot, this unit has a good groundwater potential between VES 202 and VES 203 at a shallow depth of 50m as observed from the GE section. The degree of weathering at this area increases with depth comprising with the reduction of resistivity values and borehole log data of AKWFPW1 and AKWFPW2(given in Appendix 2d and 2c).

The fourth geoelectric layer resistivity small variation from 8-9 Ohm-m in the central part of the profile and its thickness varies from 245-277 under VES 201 and 202. And expected to be present at greater depth underneath VES 203. This interpreted resistivity zone relatively relate to the highly weathered scoriaceous basalt or highly weathered basalt with intercalation of clay.

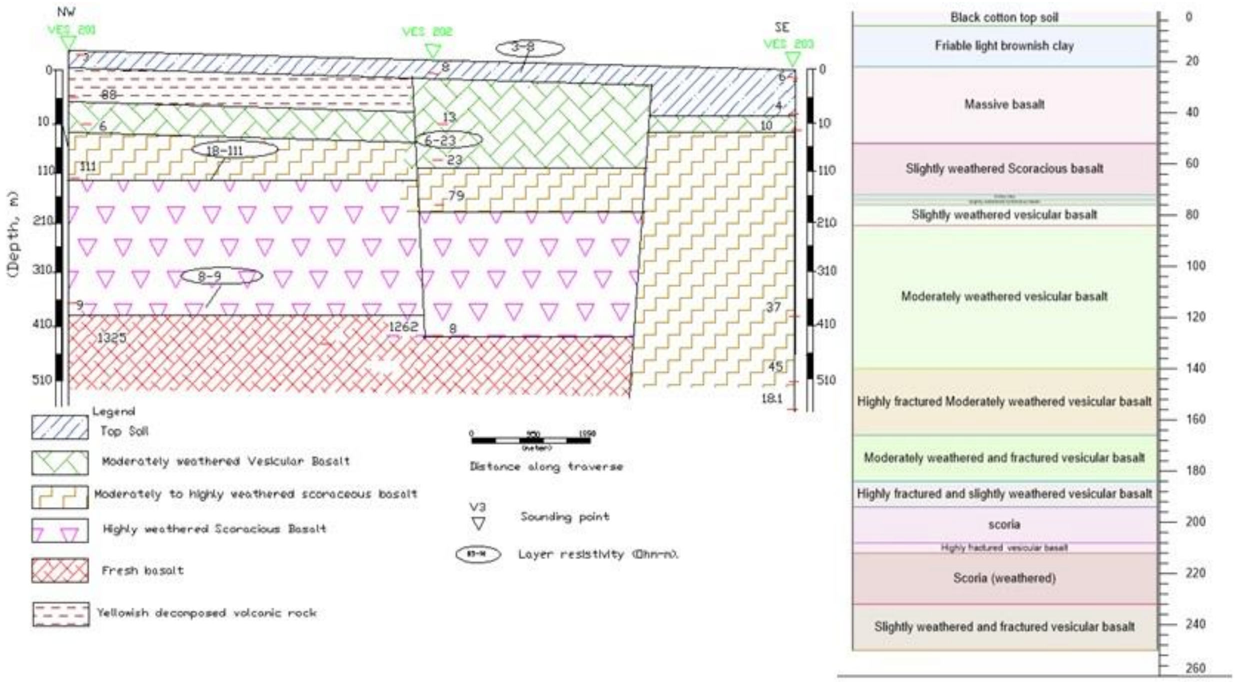


Figure 5.6. Geo-electric section VES profile Line-2, Akaki Wellfield, Addis Ababa and Borehole log of PW2

The last geoelectric layer has high resistivity values ranging from 1262-1325 ohm-m and corresponds to massive basalt which acts as a confining unit for the upper aquifer. The lower boundary could not be determined due to its extensive thickness.

The geologic map along this profile indicates two lineaments across the profile line and these lineaments result in subsidence in the middle part of the profile.

5.2.3.3. Profile line 3

Pseudo-depth section

This profile line has NE-SW orientation. This profile consists of 3 VES points are plotted on the traverse line 3 with an approximate spacing of 450 and 950 m in accordance with the suitability of the field for the data collection a total length of 1400 m.

The pseudo-depth contour map shown in Figure 5.7 shows the presence of 4 conspicuous, slightly dipping layers which can be related to different lithology. The pseudo depth section based on VES 301,302, and 303 shows no significant lateral variation in apparent resistivity in the top layer sections. Whereas, shows a gradually increasing resistivity with depth. The layers dip toward SW, at shallow depth low resistivity layers associated with topsoil (clay) having resistivity from 4-9 Ohm-m. The thickness of this layer increases at VES 302 and 303.

Underlying this conductive layer, a moderately resistive bed with apparent resistivity ranging from 20-28 ohm-m is likely to be the response of slightly weathered and fractured vesicular basalt and can be considered as a potential water-bearing horizon. This layer exhibits maximum layer thickness on the SW direction of the profile line beneath VES 303, relatively higher resistivity is observed at intermediate depth under VES 301.

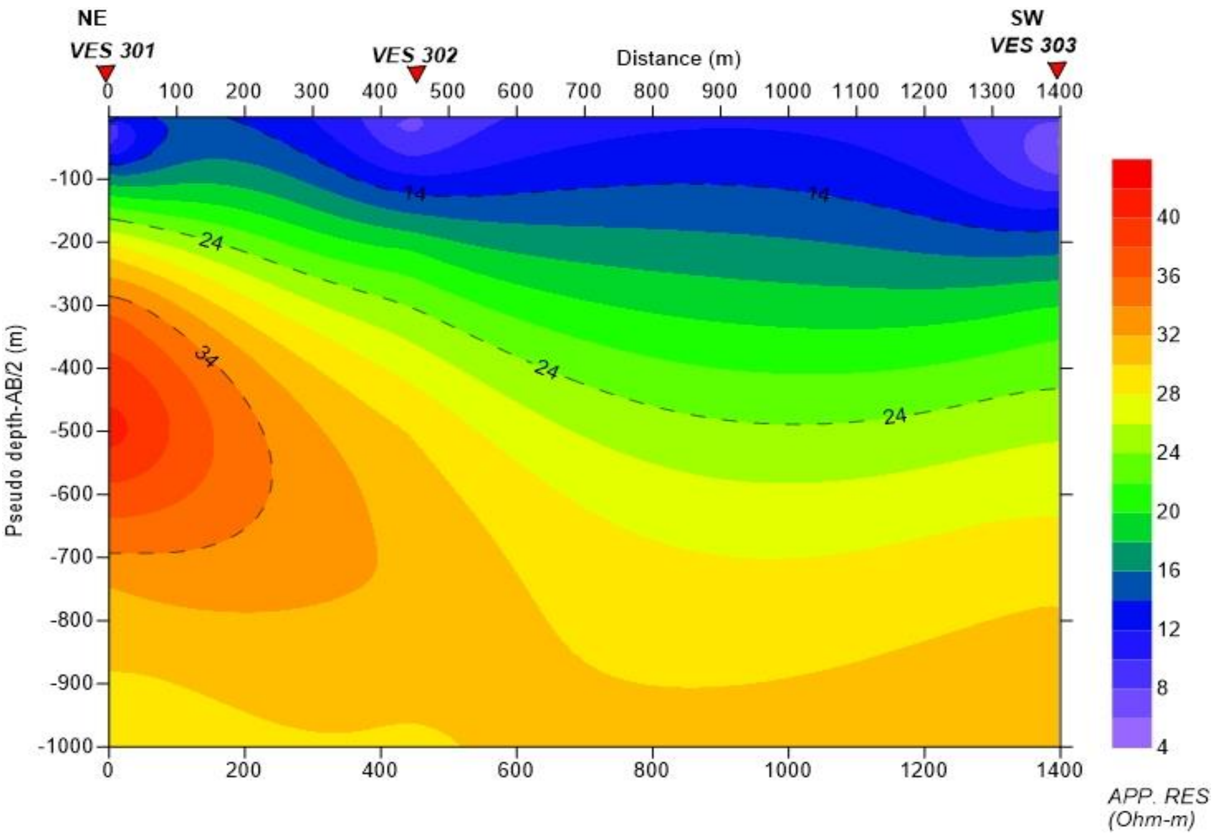


Figure 5.7. Pseudo-depth section from VES on profile Line-3, Akaki Wellfield, Addis Ababa

Geoelectric Section (Profile-3)

The resulting geoelectric section along the third profile line 3 is presented in Figure 5.8 extending for 1.4km. This Geo-electric section is constructed from interpreted layer parameters of 3 sounding points. The ground elevation undulates very gently from 2071-2066 m.a.s.l toward the SW direction. Lithologic logs from nearby boreholes specifically AKWFPW2 near VES 301 and AKWFPW16 near VES 302 were used to constrain the depth and identify the lithologic units in addition to VES 301, 302, and 303 resistivity and depth model parameters.

The top layer is dominantly represented by low resistivity ranging from 7-9 Ohm-m and corresponds to black cotton soil or decomposed volcanic rock. This layer has an almost equal thickness along the profile (1.4-2.0m). The underlying unit of the very low resistivity layer dips to SW direction with very low resistivity value, varying from 2-6 ohm-m is likely the response of dry brownish silty clay during field survey this layer is exposed in some parts of the survey area where the top layer is washed out. This geoelectric layer has a thickness variation from 4-34 m.

The intermediate layer has the resistivity range of 9-13 ohm-m having a 44-56m thickness corresponding to slightly weathered scoriaceous basalt. As can be observed from the borehole log of AKWFPW2 (Appendix 2c) the degree of weathering increases with depth from slightly to moderately weathered and at a deeper level to highly weathered.

The bottom geoelectric layer has extensive coverage of this profile with resistivity range from 47-71 ohm-m is possibly the response of moderately weathered and fractured basalt. This layer's thickness generally increases to the SW direction and attain maximum thickness underneath VES 303. The depth of this unit ranges from 50m-553m under VES 301 and 302 and extends to infinite depth under VES 303. Due to the nature of basalt, its resistivity response, and order of fracturing and weathering this layer can be considered as an aquifer with considerable thickness.

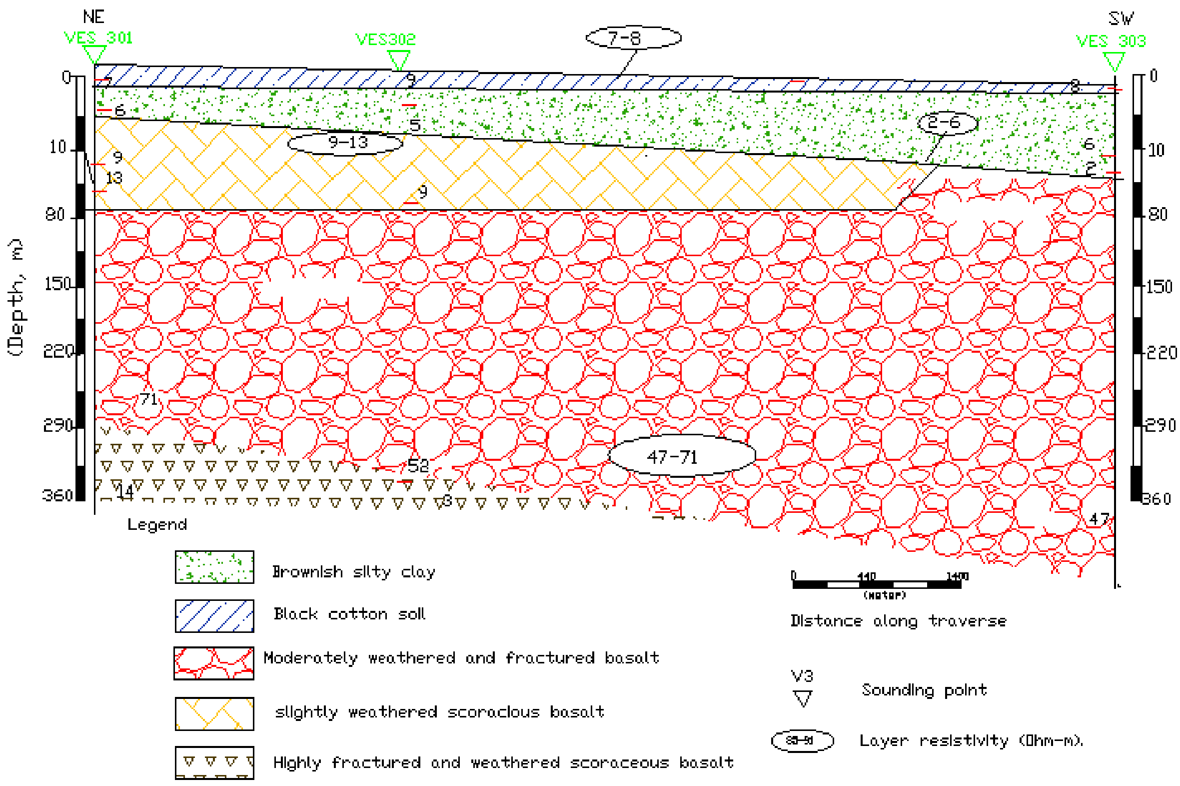


Figure 5.8. Geo-electric section from VES on profile Line-3, Akaki Wellfield, Addis Ababa

A layer at a depth of 290m underneath VES 301 has been observed from this section. This unit is expected to be highly fractured and weathered scoriaceous basalt it has almost a similar geologic unit as underneath VES 203 and it is assumed to be extended. The layer has a resistivity of 14 ohm-m and the thickness generally decreases and vanishes along the profile to the SW direction. From the groundwater potential point of view, the highly fractured and weathered scoriaceous basalt unit can be assumed to have groundwater potential.

The lithologic information of the boreholes; depth section and lithologic description is given in Appendix 2

5.3. Presentation, Interpretation and discussion of magnetic data

General

The main purpose of a magnetic survey is to identify and describe the subsurface structures associated with groundwater flow and accumulation. After the removal of Diurnal variation and IGRF, the total magnetic field anomaly data were processed and grided to produce an anomaly map of the study area. Oasis Montaj (V-7.0.1) software was used for plotting, gridding, filtering, and mapping magnetic survey data.

The anomaly of interest in the magnetic survey measurement is, magnetic field related with the rock magnetism that is in shallow depth (Residual) because it relates with the existence of subsurface rock of contrasting susceptibility. The observed TMA is the superposition of the regional and residual anomaly.

5.3.1. Observed total magnetic field anomaly (TMA)

In this research work, digital filters were used to separate residual anomalies from the regional part. In addition, enhancements were made to the residual anomaly in order to delineate localized structures associated with the groundwater flow.

The total magnetic field anomaly map (Figure 5.9) shows a strong anomaly of around 2000nT in the North, NE directions, and the central part whereas low anomaly is observed in the western and eastern directions of the map this could relate to either the existence of geologic contact/lineaments or the existence of fractured weathered rock unit and thick soil cover. However, to differentiate these anomalies separation of the regional and residual anomaly using anomaly enhancement procedures are necessary.

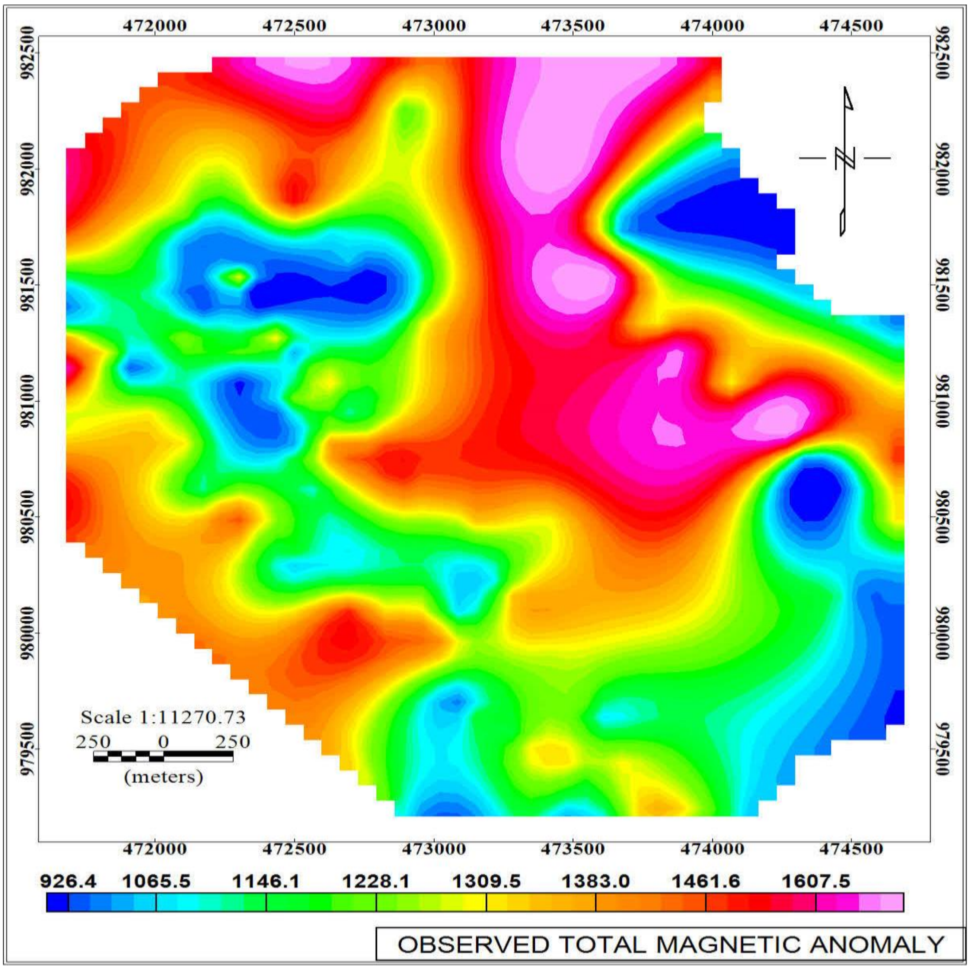


Figure 5.9. Observed Total Magnetic Anomaly Map of the study area.

5.3.2. Reduction to Pole (RTP) and Reduction to Equator (RTE)

When making measurements apart from polar areas the magnetic anomaly is asymmetrically distorted by the magnetic declination and inclination. As mentioned in the previous chapters applying Reduction to Pole or Reduction to the Equator transforms and relocates the total magnetic anomaly data to be above the source and remove the influence of magnetic latitude on the anomaly which is significant for the anomalies caused by the crustal material (induced magnetization).

However, at low latitudes (low inclinations), both anomaly and noise parallel to the declination will experience high, directionally-selective amplification, the anomaly will be complicated, and applying RTP produces poor quality data, Besides its unstable nature to the acquired data close to the magnetic equator (Luo Y. et al., 2010). Low latitude often means an absolute inclination less than 20^0, routine RTP computation may become problematic (Li,2008).

In this case reduction to the equator (RTE) is used in low magnetic latitudes, such as the study area (*I*= 2.64°), because it makes the magnetic field of the earth and magnetization of the magnetic sources appear horizontal (as in the magnetic equator), centers the peaks of the magnetic anomalies over their sources and removes the asymmetry of the magnetic anomaly due to nonzero magnetic inclination (Oni et.al., 2020). As a result, the total magnetic anomaly is enhanced by reduction to the equator (RTE) and a complied map is generated as Figure 5.10.

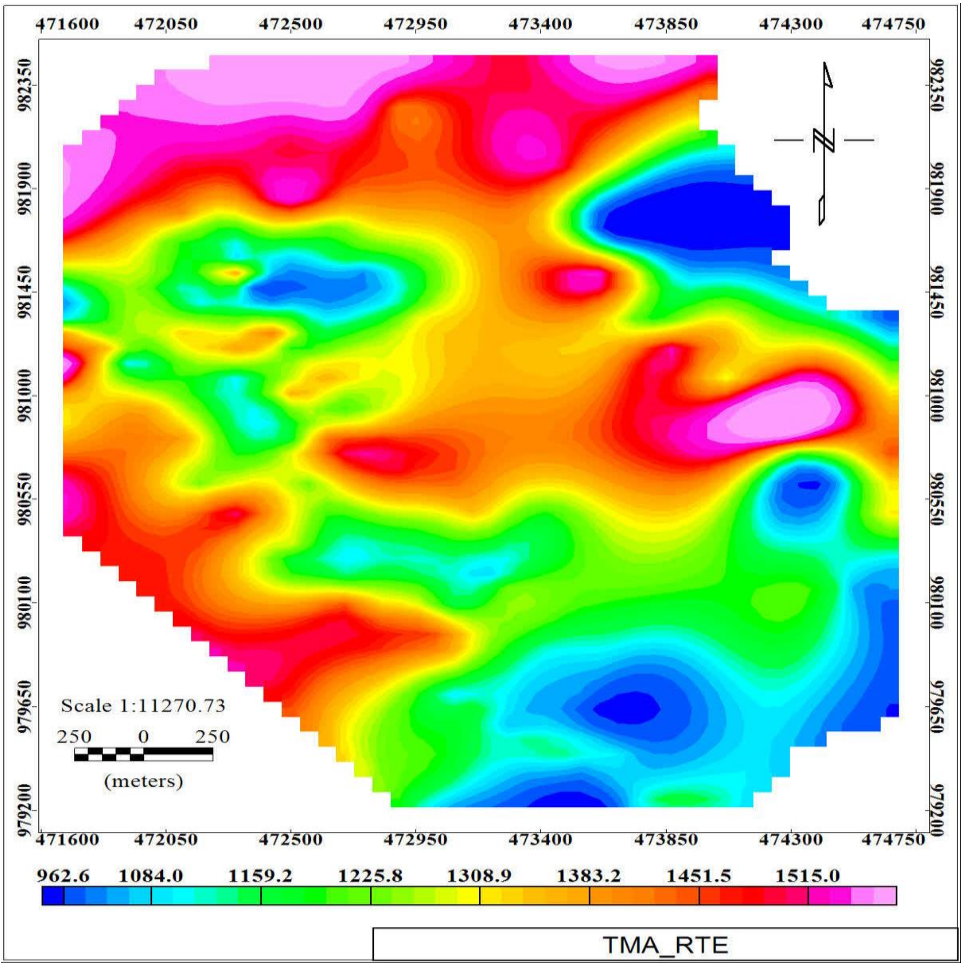


Figure 5.10. Reduced to equator total magnetic anomaly map

Regional-Residual mag anomaly separation

5.3.3. The Regional anomaly

The low-pass filter is applied to enhance the longer wavelength anomalies derived from deeper anomalous sources and attenuate the shorter wavelength of the near-surface anomalies (Pesonen et al., 1994; Roest and Pilkington, 1993). As a result, the regional anomaly map is obtained by performing a low pass filter to the reduced to equator TMA grid. (Figure 5.11).

As illustrated in Figure 5.11 the low anomaly in the NE part of the study area can be associated with the existence of Scoria Cones. And high anomaly observed in northern and NE could be deep-seated competent bedrock or shallower thickness of overburden with slightly fractured volcanic rock materials.

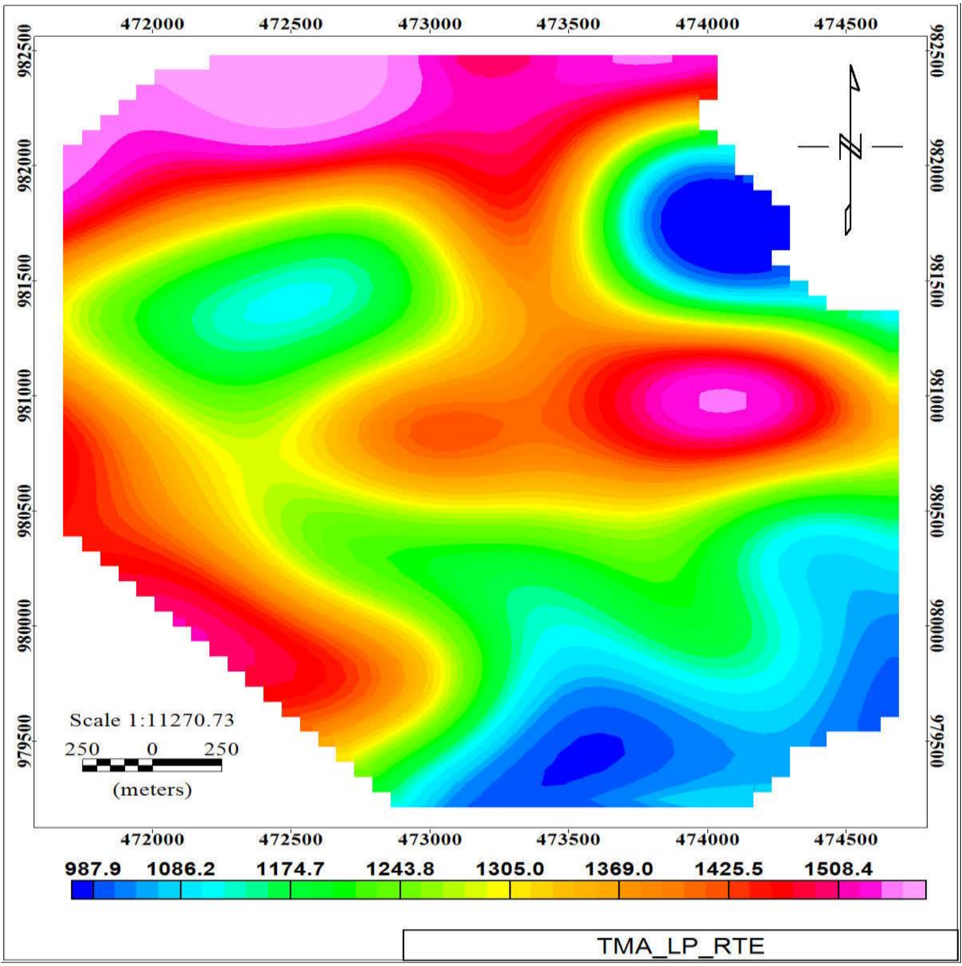


Figure 5.11 Regional magnetic anomaly map of the study area. (By Low-pass filter)

5.3.4. Upward continuation

Upward continuation is applied to the TMA at a height of 200m from data points to provide undistorted magnetic anomaly from deep-seated and/or high amplitudes sources. It is apparent that the attenuation of the shallow source anomalies in the upward continuation process permits a clearer or enhanced view of the deeper anomaly sources (Roberts et al., 1990).

As shown in Figure 5.12, the regional magnetics anomaly varies from 1080nT-1500nT. High and intermediate magnetic anomaly is observed in the northern part, the central and western part of the study area. Whereas the southern portion of the study area is dominated by a very low anomaly. The upward continuation regional map shows an almost similar result as compared with the low pass filter of the total magnetic anomaly.

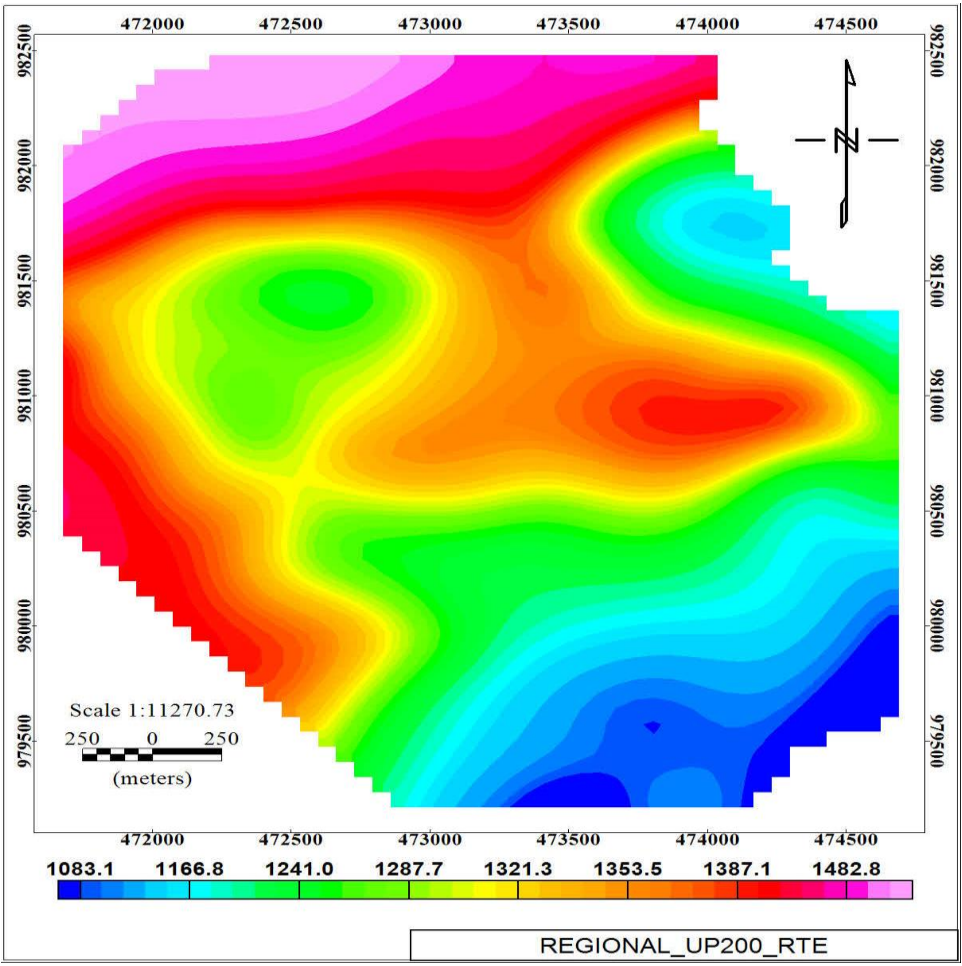


Figure 5.12. Regional magnetic anomaly map of the study area. (Using Upward Continuation)

5.3.5. Residual anomaly

High-pass filters attenuate long wavelength low frequency of the regional anomaly and accentuate shorter wavelength and high-frequency anomalies. As a result, the residual anomaly is obtained by applying a High-pass filter to the RTE total magnetic anomaly (Figure 5.13). Further enhancement of the residual anomaly (Analytic signal map, Tilt and Horizontal derivative maps, and Euler- depth) aid in precise and easier interpretation.

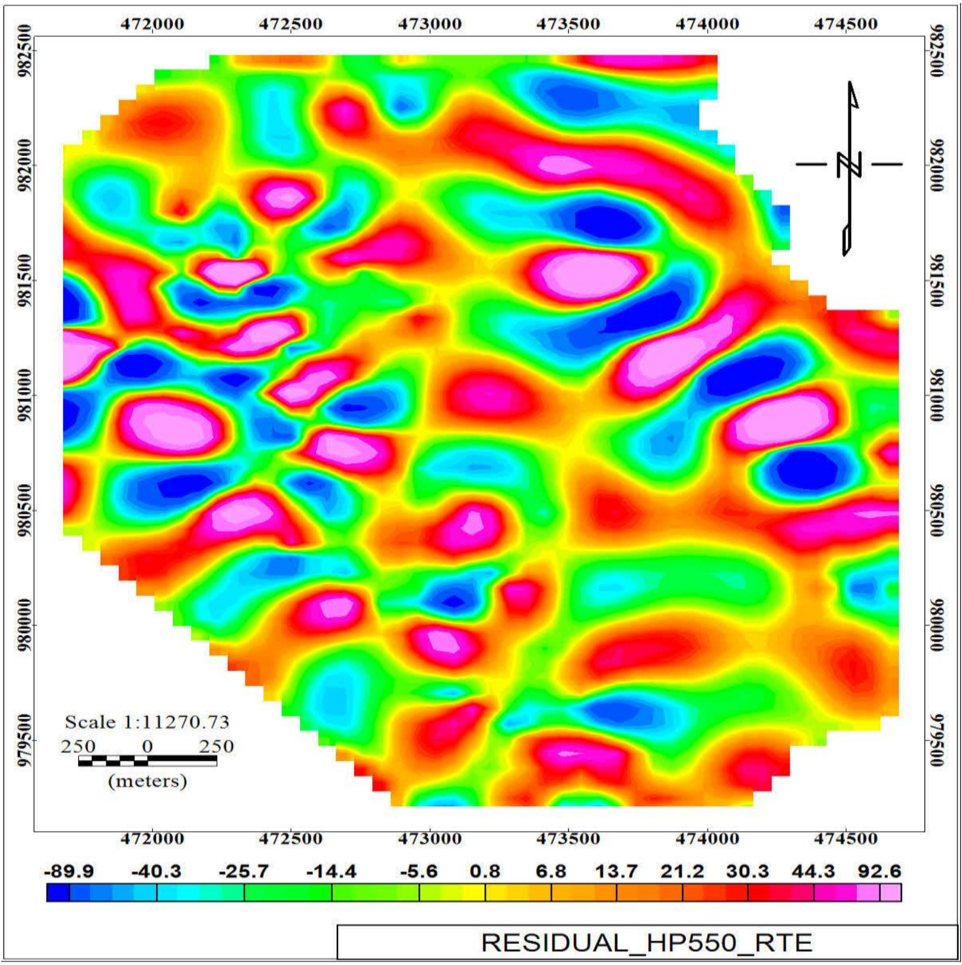


Figure 5.13. Residual anomaly map of the study area.

5.3.6. Analytic signal

Analytic signal map generates good horizontal location for contacts and other sources regardless of geological dip or geomagnetic latitude. Analytic signal filter accentuates a picture of the near subsurface condition by removing the dependency of an anomaly on the direction of magnetization and maximum amplitude is exactly over a magnetic contact of the causative body. Furthermore, if the analytic signal filter is performed to the RTE residual anomaly produces a better result to accurately map linear geologic structures than when performed to the total field anomaly directly. Since dislocation of the peak of the amplitude is eliminated in the analytic signal estimation of the reduced to equator data.

As Figure 5.14 shows a high anomaly in the western eastern and central part of the study area associated with magnetic contacts due to the existence of the study area in the MER margin most of the contact trend is NE-SW direction.

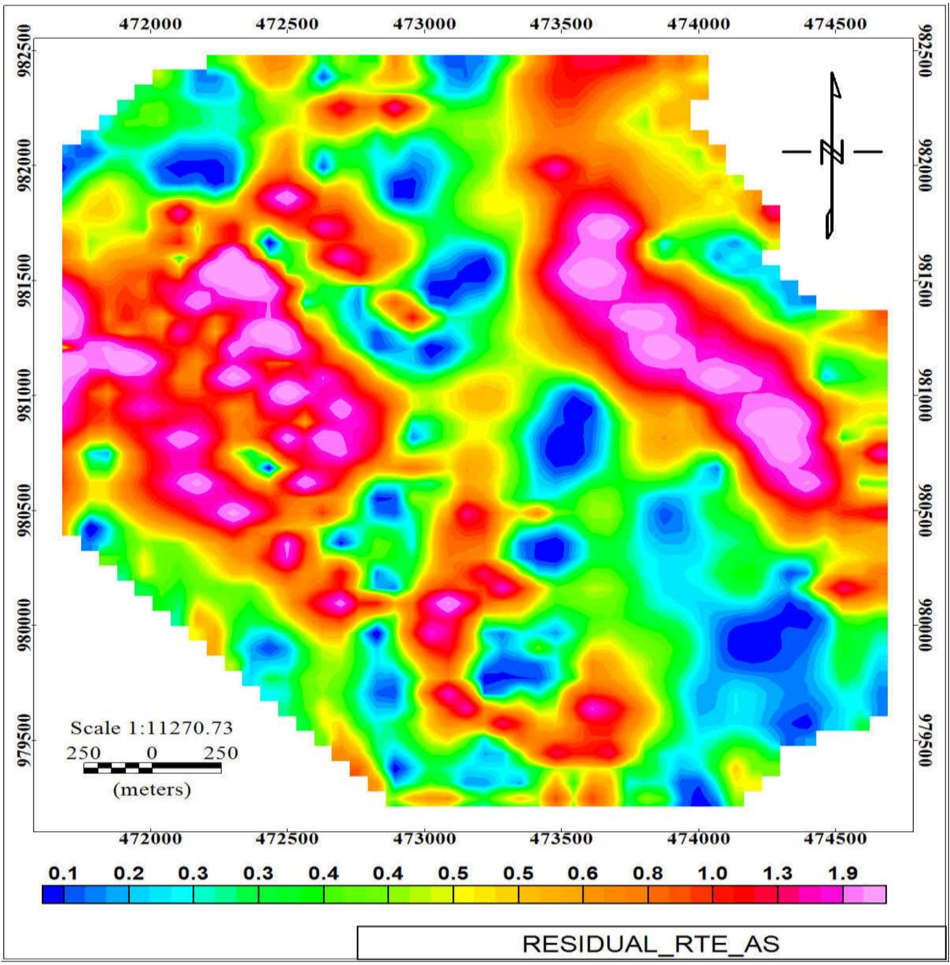


Figure 5. 14. Analytic Signal Map of the Residual Anomaly.

5.3.7. Tilt derivative

This method uses to visualize the magnetic contrast in an indication of features like faults, and lineaments in addition it amplifies shallow depth (residual) structures of the magnetic anomaly. The tilt derivative is the tan inverse of the ratio of the vertical derivative and absolute value of the total horizontal derivative

$$TDR=\tan^{-1} (VDR/THDR)$$

TDR crosses through zero at or near the edges of a vertical-sided source, positive over the center of the causative source, and is negative outside the source region. As shown in Figure 5.15; Due to the nature of the arctan trigonometric function, all amplitudes of the tilt are restricted to values between + π/2 and - π/2 regardless of the amplitude of the VDR and THDR (Verduzco et.al., 2004).

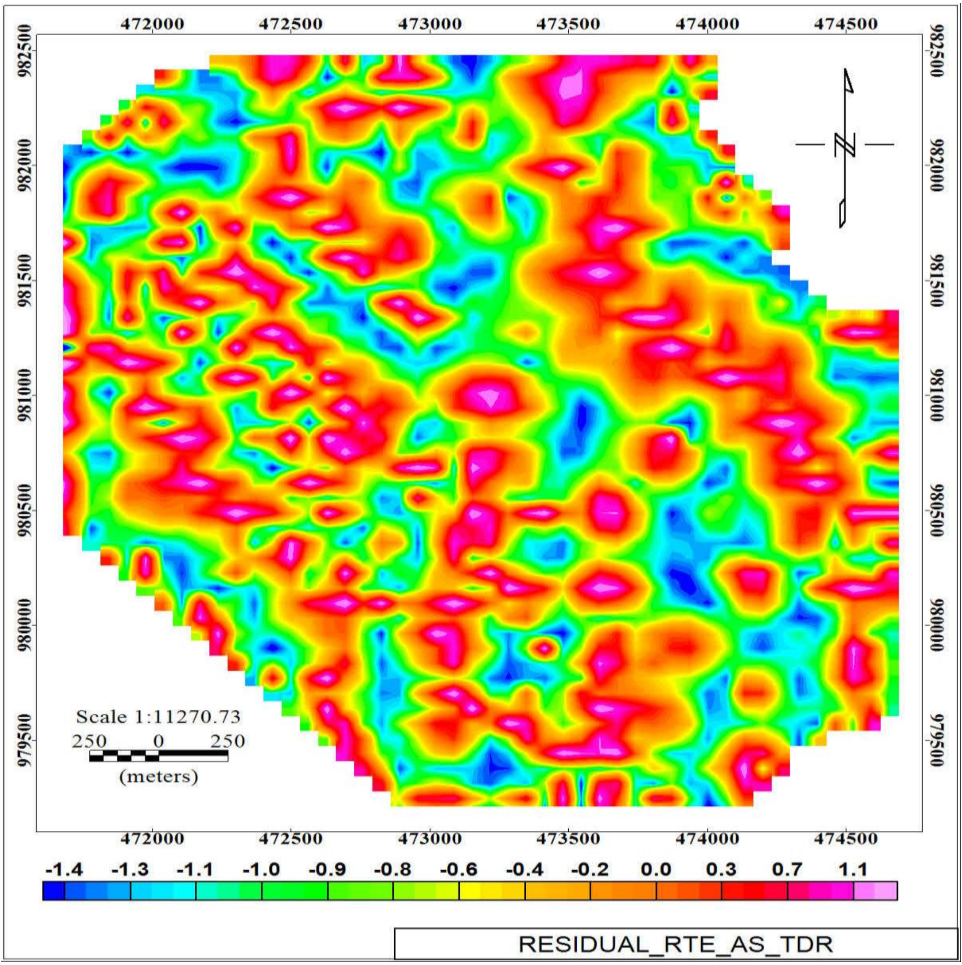


Figure 5.15. Tilt derivative map of the residual anomaly

5.3.8. Total Horizontal derivative map (THDR)

THDR is useful for near-surface bodies with near-vertical contacts, the maximum horizontal gradient of measured magnetic anomaly will occur nearly over the contact. This method is used to inspect the location of fault and contact features and lateral extent of anomalous source. Anomaly peak over the edge and minimum at the center (Figure 5.16). It also equalizes signals from shallow and deep sources but is less sensitive in depth to source estimation. This method is used to inspect the location of fault and contact features and lateral extent of anomalous source.

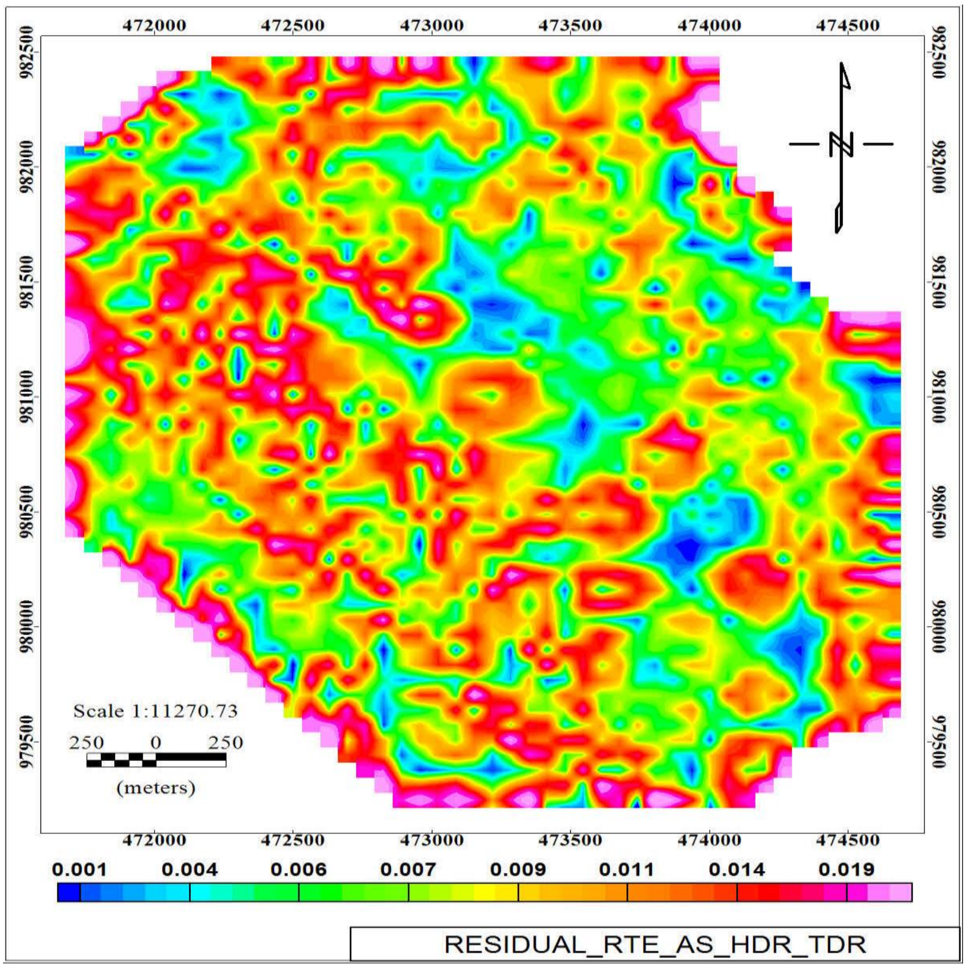


Figure 5.16 Total Horizontal Derivative map of the residual anomaly

5.3.9. Euler Deconvolution Depth Map

The Euler deconvolution is an interpretive tool in the magnetic potential field that involves setting an appropriate SI index value for the determination of the depth and locating magnetic sources (Reid et al. 1990). The Euler deconvolution can describe the nature, spatial location, and depth of anomalous source body it also entails the degree of fall off of the field with distance from the causative source. This method requires only a little a priori knowledge about the magnetic source geometry and is independent of the magnetization vector. Since the nature of geologic structures mapped in the study area are linear features SI index of 1 was used.

As illustrated in Figure (5.17), generally shows shallow depth magnetic sources up to 350m depth. Shallower depth (50-150m) magnetic sources are represented as red circles and show clustering of solution in the southern and eastern and southeastern direction of the study area associated with lineaments. According to groundwater point of view areas with clustering solution, at a shallow depth with the range of 50-150 m depth linear structures associate with the groundwater flow and could also be good for the recharge of groundwater, drilling close to these structures is advisable for groundwater potential zone.

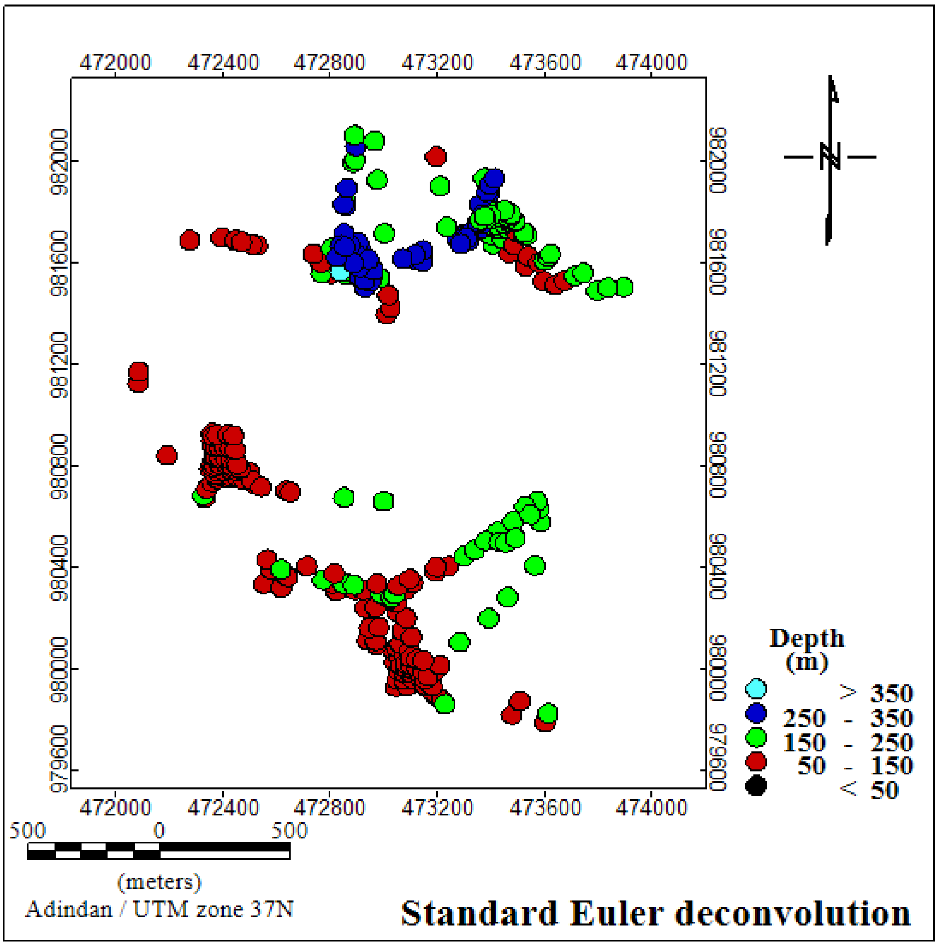


Figure 5.17. Standard Euler Deconvolution Depth map of the study area (SI=1)

5.3.10. 2D modeling

Is done along with a VES profile 2 to describe the lithologic layer of the subsurface and map contacts by taking account of the magnetic contrast. Lithologic layers and respective layer numbers and thickness were taken from the geoelectric section, and from the magnetic profile plot, the erratic change of anomaly could be associated with geologic contact in the subsurface. GMSYS menu in the Oasis Montage software was used to generate a model relying on the magnetic response of the subsurface. The result obtained from this modeling shows two lineaments crossing the profile. This modeling process is constrained by the borehole log and GE section of the profile (Figure 5.18).

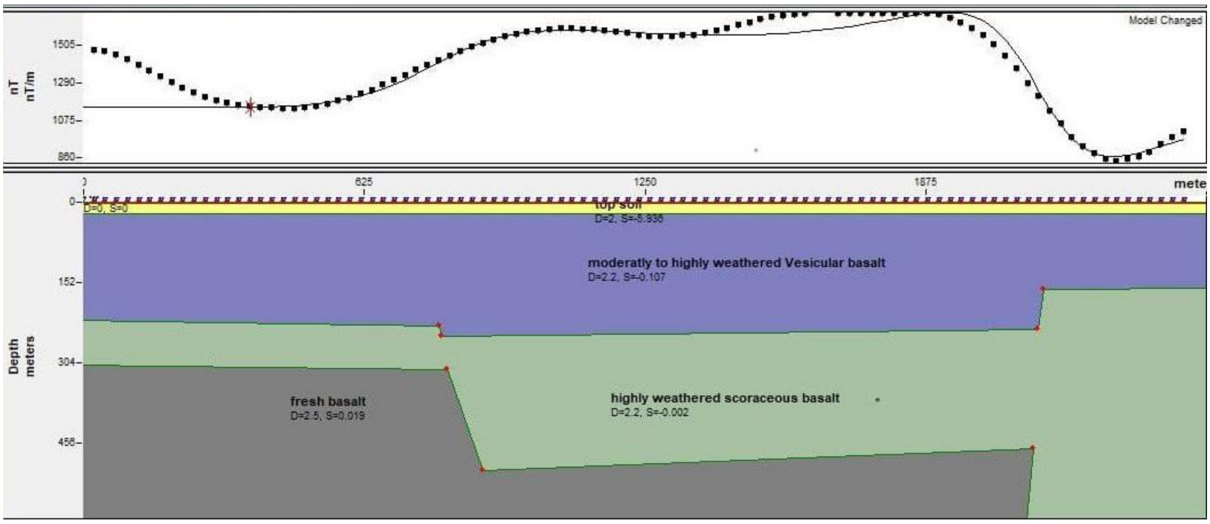


Figure 5.18. 2D Magnetic Modelling

5.4. Integration of the geophysical results

The results obtained from geoelectric sections and slice-stacked section show a potential area in the central, southern, and northeastern area, similarly from Euler deconvolution map and analytic signal maps represent shallow depth structures in the central, southern, and northeastern parts.

The area in VES profile 1 shows groundwater potential at the central region of the study area where clustering solution in the Euler deconvolution exists. In addition, from the regional anomaly map existence of a fresh rock unit at depth is observed this could be the lower confining unit.

The area in VES profile 2 shows as shown in 2D modeling has two lineaments across the profile related to the flow of groundwater. A potential area in the northeastern part of the study area could also be associated with some shallow depth structures from the Euler deconvolution map. This verifies the VES results in delineating potential zones.

The area in profile 3 shows groundwater potential in the southern region of the study area. Similarly in the southern region of Euler deconvolution and residual map of the study area also show shallow depth structures that can contribute to the recharge of the aquifer.

CHAPTER 6

6. CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This study was conducted at Akaki Wellfield situated South of Addis Ababa city, Central Ethiopia. With the aim of assessing the groundwater potential zones and identifying the lithostratigraphic structures contributing to the groundwater flow and accumulation. Integrated geophysical methods namely VES and magnetic survey were employed to achieve the desired objective. By making use of the available geological information, well log information, and geophysical data detailed geophysical analysis and interpretation are made area and depth-wise.

A total of 10 VES points with a maximum current electrode spacing of 1000m (i.e., AB/2=1000m) were used along 3 profile lines. Presented as slice-stacked section, pseudo-depth sections, and geoelectric sections. These section plots enabled us to understand;

- The variation of resistivity along a profile and in-depth.
- The geologic dip/ dipping layers are predominantly the lithostratigraphic units of the subsurface.
- The conductive and resistive layers and their respective thickness, the low resistive layers (shallow or deep) having a considerable thickness could be associated with the water-bearing horizon in the study area.

A total of 122 magnetic data points at random distribution and 5 profile lines are presented as a 2D magnetic anomaly map showing the variation in magnetic field distribution in the study area. The natural remnant magnetization field is not considered in this survey.

Regional and residual anomaly plots presented in previous chapters delineate the effect of deep and shallow magnetic anomalies respectively. Analytic signal of the residual anomaly representing weak zones (faults and fractures) at shallower depth has a good correlation with the geologic map’s fault zones.

The area is dominated by slightly weathered basalt and vesicular basalt and the alluvial deposit has significant coverage. In addition, scoriaceous basalt outcrops at the north and northeastern part of the study area.

Accordingly, the integrated geophysical study result delineates, highly to moderately fractured scoriaceous basalt and moderately weathered and fractured basalt with resistivities generally below 50 ohm-m are expected to be water-saturated.

- Moderately to highly fractured basalt near profile line 1 is considered the main aquifers in the study area. This layer has a considerable thickness starting at a depth of 110m and with a thickness of 500m.
- The main aquifer zones in the study area are associated with highly weathered scoriaceous basalt. The area underneath VES 203 having resistivity value of 18-45 ohm-m attributed to highly weathered scoriaceous basalt considered as an aquifer starting at a depth around 50-60m and moderately weathered vesicular basalt under VES 202 at shallower depth can also be considered as a water-bearing horizon.
- The vast area of profile three starting at a depth from 50m has an intermediate resistivity value from 47-71 ohm-m attributed to moderately weathered and fractured basalt. This unit can be water-saturated for the development of a sinking borehole under VES 303 can produce a good potential since the layers dip toward it contributing to the groundwater flow direction.

Due to the fact that expansion of cities and small towns surrounding Addis Ababa and also the study area, and the presence of high-tension power transmission lines and the main road crossing the study area was the biggest challenge in collecting magnetics data.

6.2 Recommendation

According to the results obtained from the study; the following points has been recommended

- Traverse 1: On the basis of the geoelectric section along profile 1. It is possible to suggest the area between VES 103 and VES 104 with 34-36 ohm-m resistivity, in addition from the Euler deconvolution map presence shallow depth structures in the traverse will contribute to groundwater recharge. The location has the water-bearing horizon and is suitable for groundwater potential source test well is recommended at a depth of 110m.
- Traverse 2: The area between VES stations 202 and 203 having a resistivity of 18-45 ohm-m attributed to highly weathered scoriaceous basalt appears more plausible for drilling test borehole up to a depth of 50m.

- Traverse 3: A drilling site for sinking borehole is recommended under VES 303 at a depth of 50m may yield a good volume of groundwater

Additional VES survey with closer spacing between the station point is recommended for a detail understanding of the aquifer zone.

It is recommended to perform detailed structural mapping of the geologic structures to further understand the extension of faults, fractures, and weak zones. In addition to dipping directions associated with the groundwater flow.

It is highly recommended to perform a detail study of the hydrogeology and geochemistry of the study area to understand the quality of groundwater, permeability, and porosity of the aquifer.

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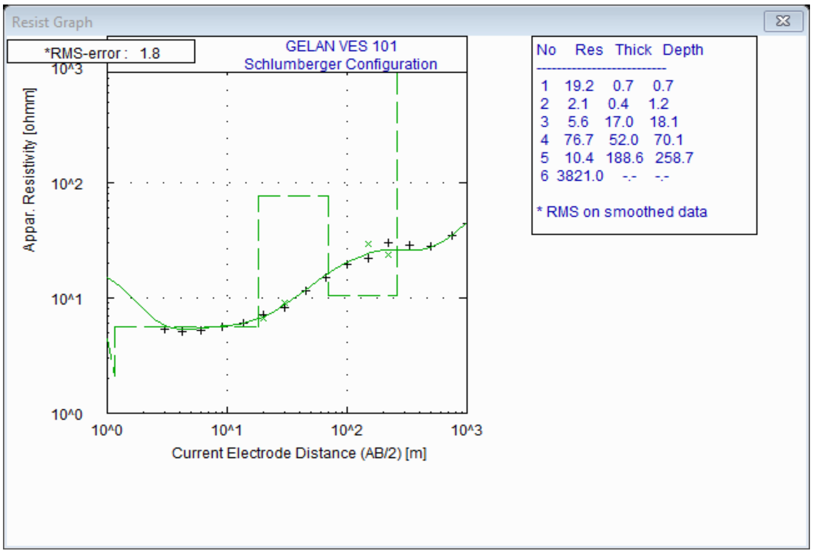
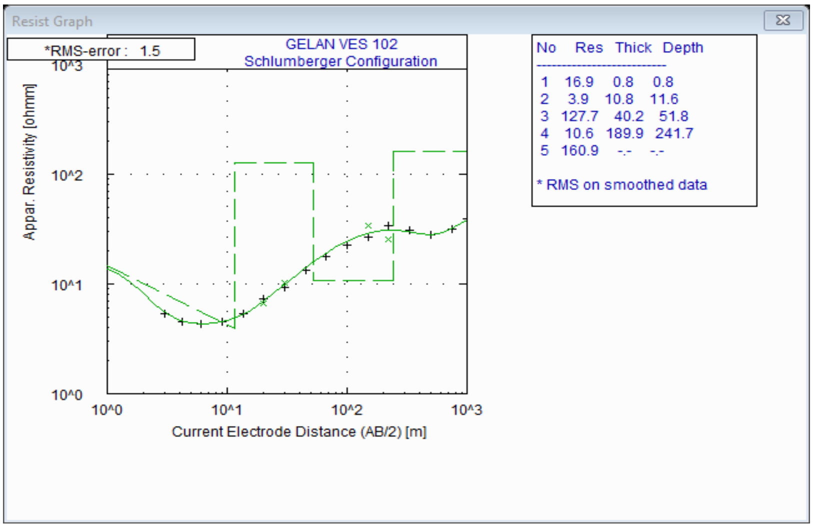
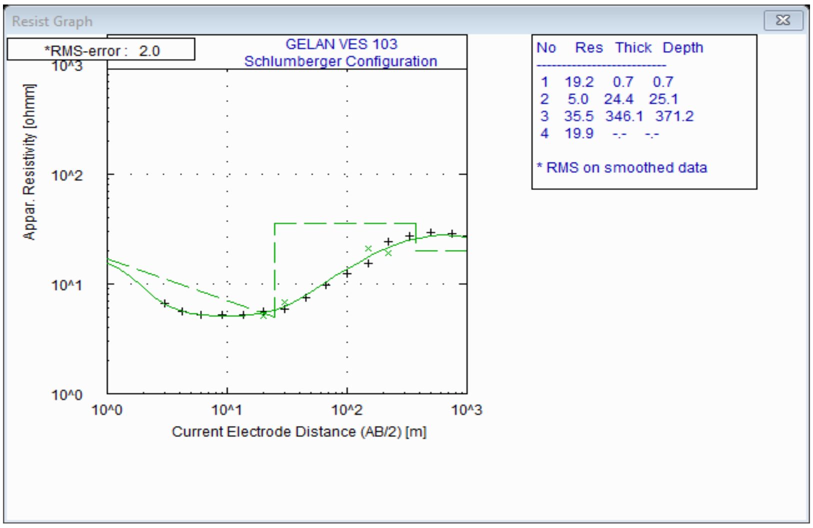
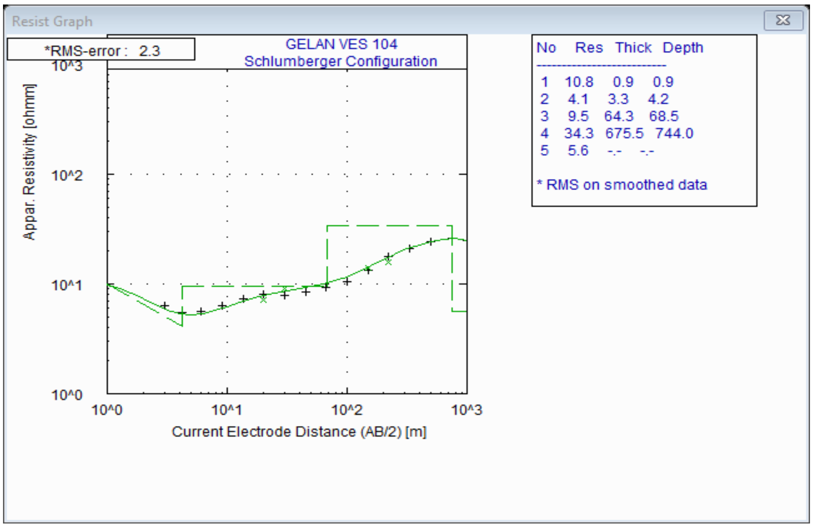
APPENDICES

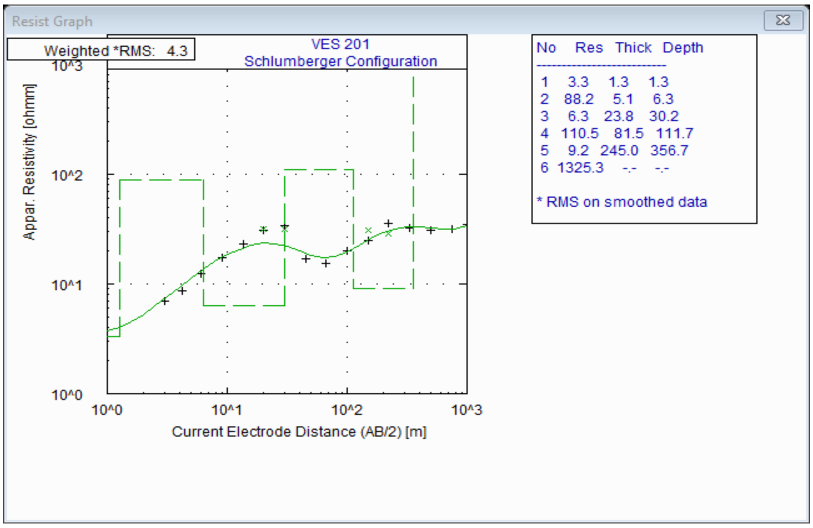
Appendix-1 Interpreted 1D VES Curves

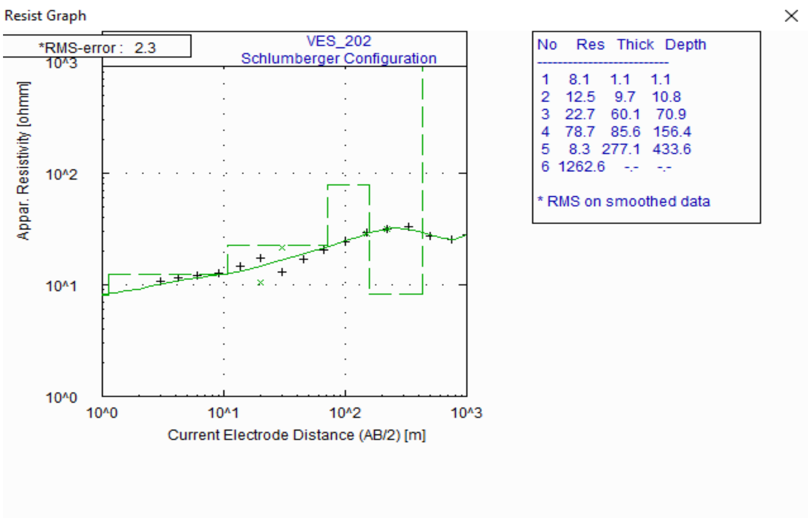


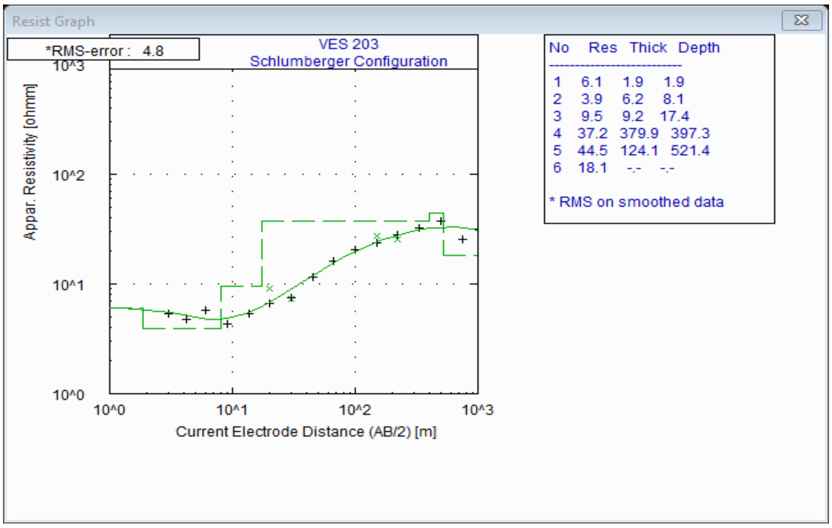


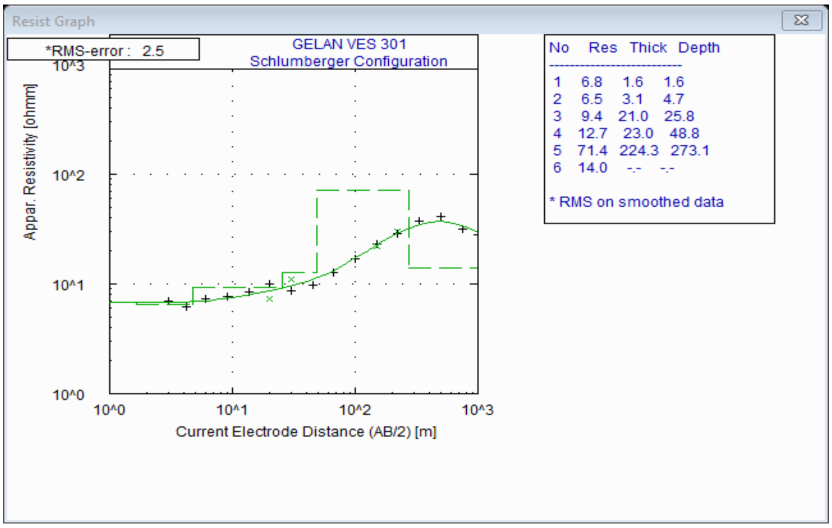


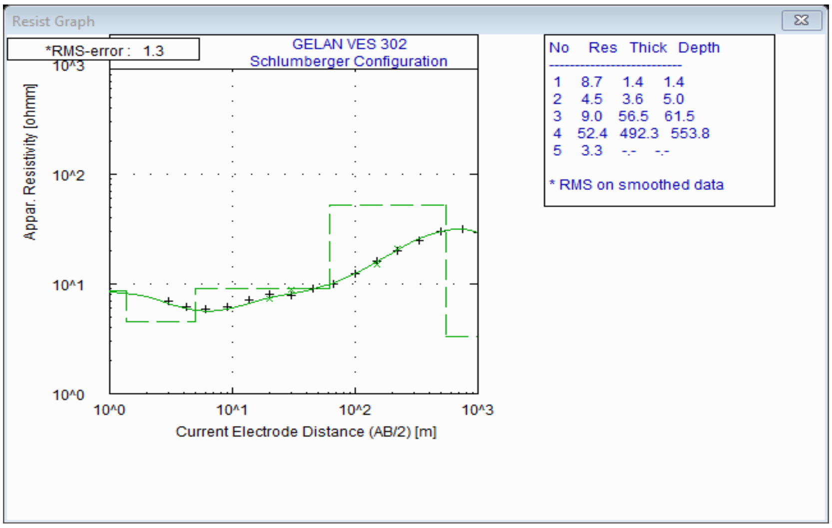

Resist Graph
*RMS-error : 2.3
GELAN VES 104
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 10.8 0.9 0.9
2 4.1 3.3 4.2
3 9.5 64.3 68.5
4 34.3 675.5 744.0
5 5.6 -.- -.-
* RMS on smoothed data

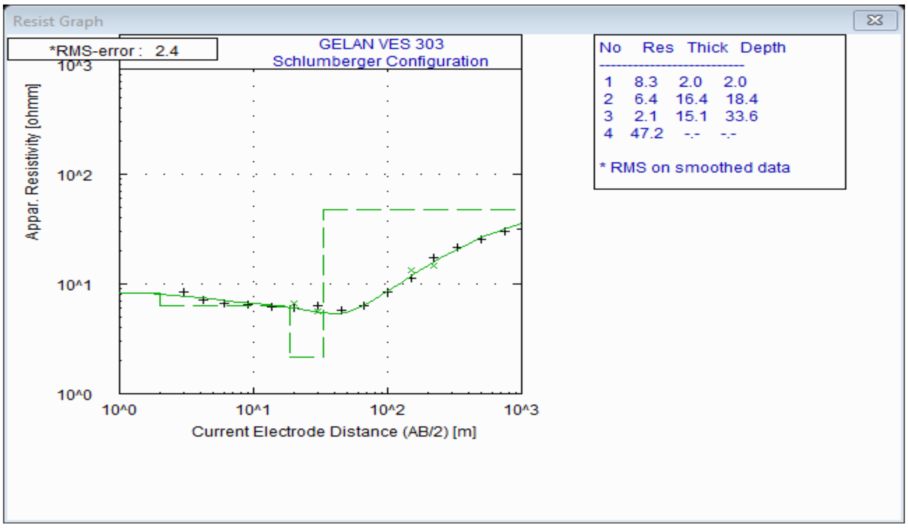

Resist Graph
Weighted *RMS: 4.3
VES 201
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 3.3 1.3 1.3
2 88.2 5.1 6.3
3 6.3 23.8 30.2
4 110.5 81.5 111.7
5 9.2 245.0 356.7
6 1325.3 -.- -.-
* RMS on smoothed data


Resist Graph
*RMS-error : 2.3
VES_202
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 8.1 1.1 1.1
2 12.5 9.7 10.8
3 22.7 60.1 70.9
4 78.7 85.6 156.4
5 8.3 277.1 433.6
6 1262.6 -.- -.-
* RMS on smoothed data


Resist Graph
*RMS-error : 4.8
VES 203
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 6.1 1.9 1.9
2 3.9 6.2 8.1
3 9.5 9.2 17.4
4 37.2 379.9 397.3
5 44.5 124.1 521.4
6 18.1 -.- -.-
* RMS on smoothed data

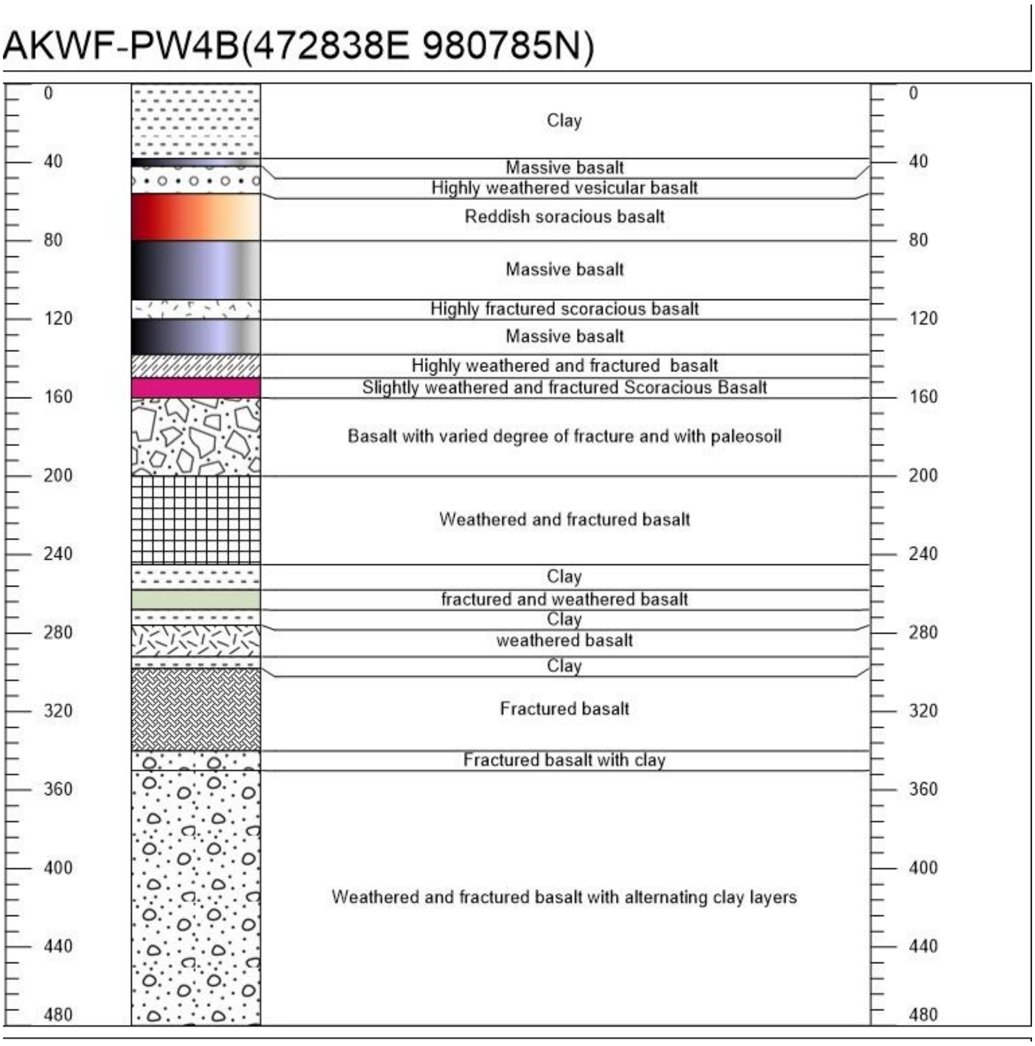

Resist Graph
*RMS-error : 2.5
GELAN VES 301
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0 10^1 10^2 10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 6.8 1.6 1.6
2 6.5 3.1 4.7
3 9.4 21.0 25.8
4 12.7 23.0 48.8
5 71.4 224.3 273.1
6 14.0 -.- -.-
* RMS on smoothed data


Resist Graph
*RMS-error : 1.3
GELAN VES 302
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 8.7 1.4 1.4
2 4.5 3.6 5.0
3 9.0 56.5 61.5
4 52.4 492.3 553.8
5 3.3 -.- -.-
* RMS on smoothed data

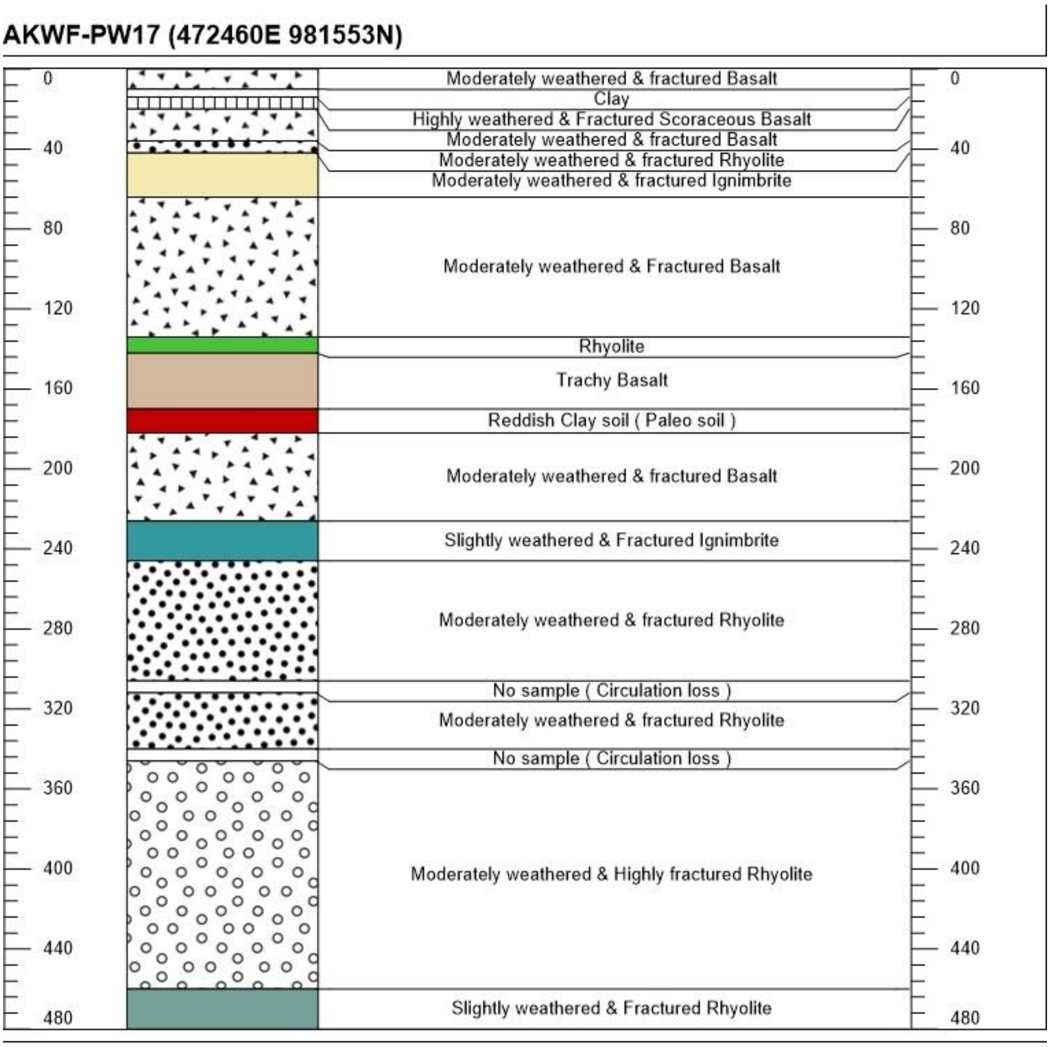


Appendix 2 Borehole Log

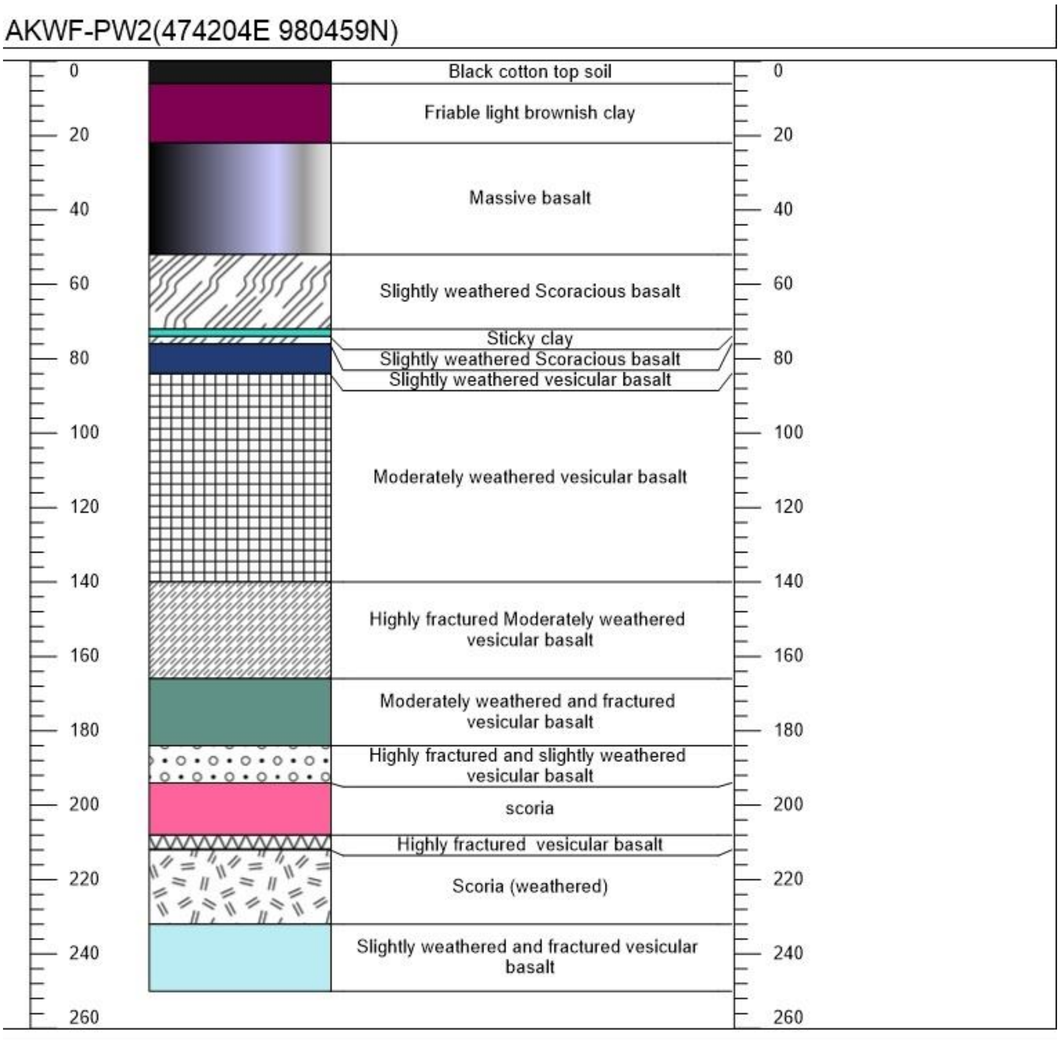
A)



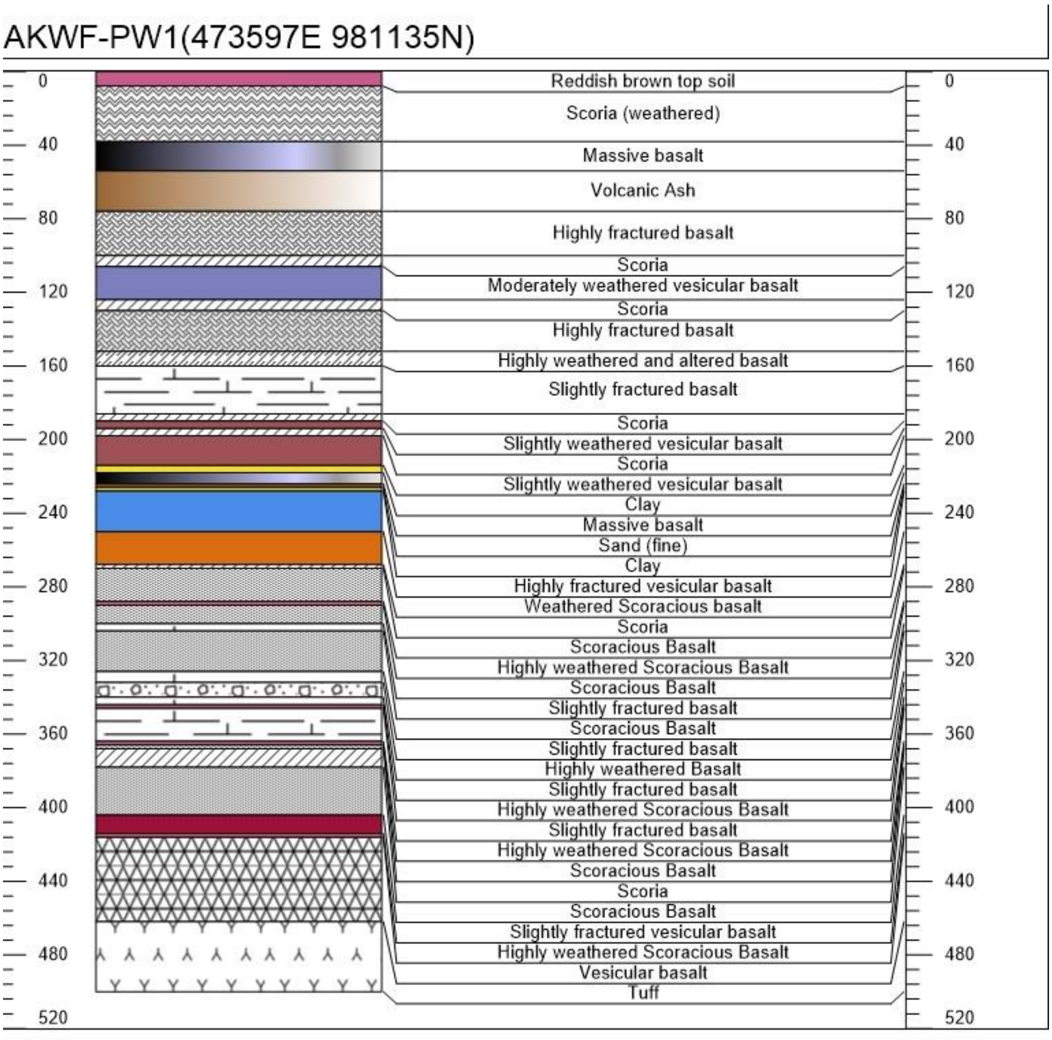
B)


AKWF-PW17 (472460E 981553N)
0
40
80
120
160
200
240
280
320
360
400
440
480
Moderately weathered & fractured Basalt
Clay
Highly weathered & Fractured Scoraceous Basalt
Moderately weathered & fractured Basalt
Moderately weathered & fractured Rhyolite
Moderately weathered & fractured Ignimbrite
Moderately weathered & Fractured Basalt
Rhyolite
Trachy Basalt
Reddish Clay soil (Paleo soil)
Moderately weathered & fractured Basalt
Slightly weathered & Fractured Ignimbrite
Moderately weathered & fractured Rhyolite
No sample (Circulation loss)
Moderately weathered & fractured Rhyolite
No sample (Circulation loss)
Moderately weathered & Highly fractured Rhyolite
Slightly weathered & Fractured Rhyolite

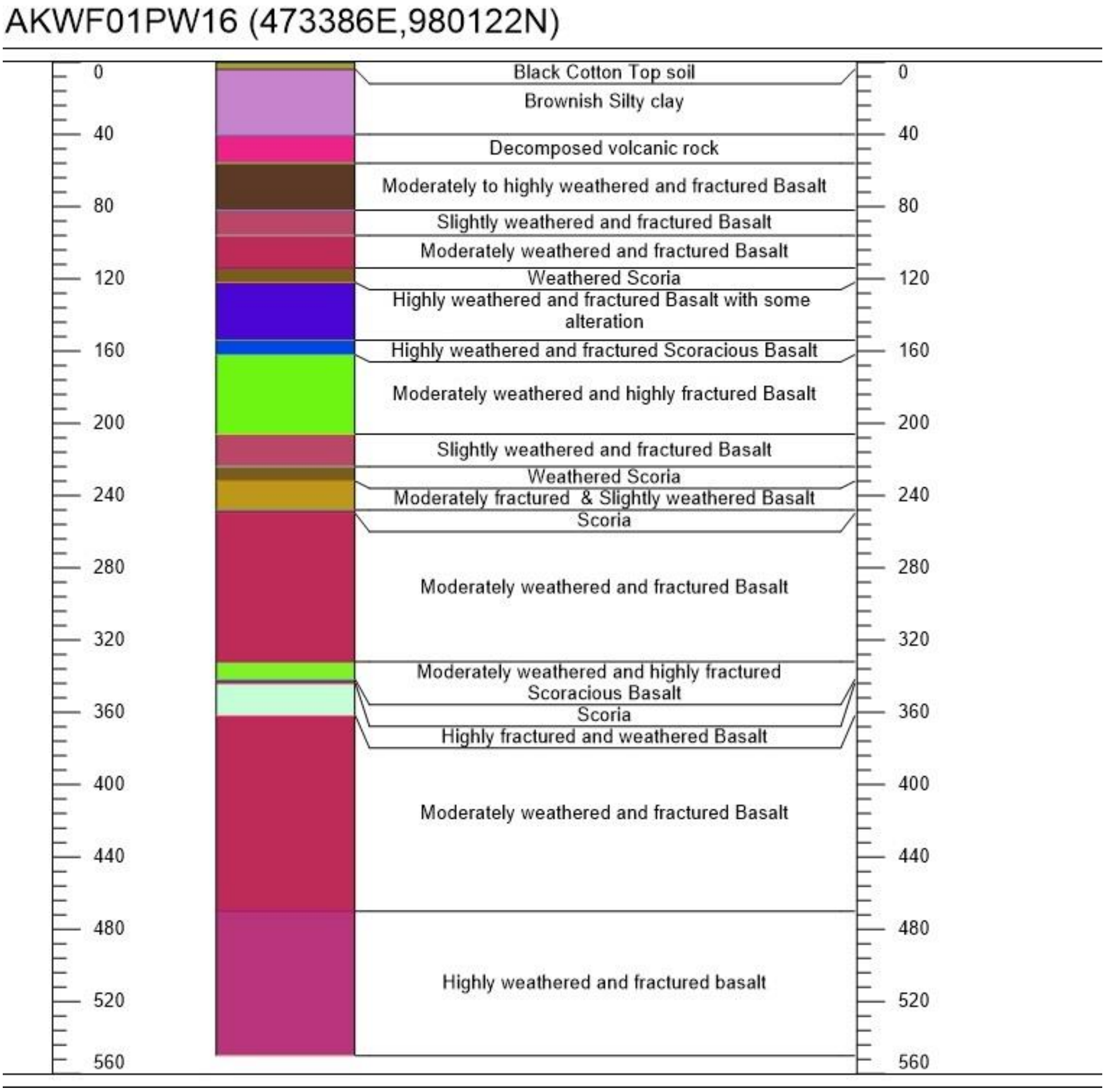
C)


AKWF-PW2(474204E 980459N)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Black cotton top soil
Friable light brownish clay
Massive basalt
Slightly weathered Scoracious basalt
Sticky clay
Slightly weathered Scoracious basalt
Slightly weathered vesicular basalt
Moderately weathered vesicular basalt
Highly fractured Moderately weathered vesicular basalt
Moderately weathered and fractured vesicular basalt
Highly fractured and slightly weathered vesicular basalt
scoria
Highly fractured vesicular basalt
Scoria (weathered)
Slightly weathered and fractured vesicular basalt

D)


AKWF-PW1(473597E 981135N)
0
40
80
120
160
200
240
280
320
360
400
440
480
520
Reddish brown top soil
Scoria (weathered)
Massive basalt
Volcanic Ash
Highly fractured basalt
Scoria
Moderately weathered vesicular basalt
Scoria
Highly fractured basalt
Highly weathered and altered basalt
Slightly fractured basalt
Scoria
Slightly weathered vesicular basalt
Scoria
Slightly weathered vesicular basalt
Clay
Massive basalt
Sand (fine)
Clay
Highly fractured vesicular basalt
Weathered Scoracious basalt
Scoria
Scoracious Basalt
Highly weathered Scoracious Basalt
Scoracious Basalt
Slightly fractured basalt
Scoracious Basalt
Slightly fractured basalt
Highly weathered Basalt
Slightly fractured basalt
Highly weathered Scoracious Basalt
Slightly fractured basalt
Highly weathered Scoracious Basalt
Scoracious Basalt
Scoria
Scoracious Basalt
Slightly fractured vesicular basalt
Highly weathered Scoracious Basalt
Vesicular basalt
Tuff

E)


AKWF01PW16 (473386E,980122N)
Black Cotton Top soil
Brownish Silty clay
Decomposed volcanic rock
Moderately to highly weathered and fractured Basalt
Slightly weathered and fractured Basalt
Moderately weathered and fractured Basalt
Weathered Scoria
Highly weathered and fractured Basalt with some alteration
Highly weathered and fractured Scoracious Basalt
Moderately weathered and highly fractured Basalt
Slightly weathered and fractured Basalt
Weathered Scoria
Moderately fractured & Slightly weathered Basalt
Scoria
Moderately weathered and fractured Basalt
Moderately weathered and highly fractured Scoracious Basalt
Scoria
Highly fractured and weathered Basalt
Moderately weathered and fractured Basalt
Highly weathered and fractured basalt
0
40
80
120
160
200
240
280
320
360
400
440
480
520
560