INTEGRATED GEOPHYSICAL INVESTIGATIONS FOR MAPPING POSSIBLE INFLOW OF WATER FROM MERTI-FENTALE IRRIGATION CANAL INTO LAKE BESEKA, METAHARA AREA, EASTERN ETHIOPIA

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LIST OF ACRONYMS

a.s.l  above sea level
BH    Borehole
CMER  Central Main Ethiopian Rift
EARS  East African Rift System
EBCS  Ethiopian Building Code Standard
EC    Electrical Conductivity
EIS   Electrical Imaging Survey
ERT   Electrical Resistivity Tomography
ESE   East-South-East
IGRF  International Geomagnetic Reference Field

ITCZ  Inter-Tropical Convergence Zone

lat.  Latitude
long. Longitude
Ma.   Million years ago
MER   Main Ethiopian Rift
MSc   Masters of Science
NE    North-East
NMER  Northern Main Ethiopian Rift
NNW   North-North-West
NW    North-West
RMS   Root Mean Square
SE    South-East
SMER  Southern Main Ethiopian Rift
SSE   South-South-East
SW    South-West
TDS   Total Dissolved Solids
WFB   Wonji Fault Belt
WNW   West-North-West
WWDSE Water Works Design and Supervision Enterprise
ABSTRACT

This manuscript presents a master’s thesis work dealing with an integrated geophysical, magnetic and electrical resistivity tomography, survey conducted as part of a systematic investigation to understand the mechanisms for Lake Beseka’s level rise, its mitigation actions and its impact in Metahara area, eastern Ethiopia. The geophysical survey particularly aims at investigating the possible inflow of fresh water into the Lake Beseka from the Merti-Fentale irrigation canal.

Qualitative interpretation of the total field magnetic data along four profiles showed the presence of structures, which could act as paths for fresh water to recharge the lake. On the other hand, appraisal of five traverse lines of electrical imaging data revealed that the area is covered by low resistivity response region at shallow depths which are believed to result from water saturated silty clay and welded tuff subsurface horizon. Relatively medium and high resistivity responses resulting from weathered scoria, scoracious basalt; fine and coarse grained basalt are also mapped.

The current results of the integrated methods of electrical imaging and magnetic have showed good correlations, reduced the ambiguity inherent in the geophysical data interpretations, and highlight the fractured systems oriented NW-SE, E-W and NE-SW directions. These structures are seen to be extending to a larger depth and potentially act as conduits for the fresh water which come from the Merti-Fentale canal to recharge Lake Beseka.

As a further conclusion from the work, it is suggested that the amount of water which is distributed into the farmland must be in controlled manner. The land is highly fractured and water saturation arising from the secondary and tertiary canals, which are extending up to the lake periphery, are expected to be the causes for the rise in lake level.
CHAPTER ONE
INTRODUCTION

1.1 Background

The Main Ethiopian Rift (MER), which belongs to the northern most branches of the East African Rift System (EARS), is characterized by active extensional tectonics. It is seismically, tectonically and volcanically active since early Miocene time (Gidey Woldegabriel et al., 1990). To the south, the MER continues to the Kenya rift and to the north it is connected with oceanic rift system of Red Sea and Gulf of Aden at the Afar triple junction. The Lakes in the rift valley are situated within three basins: Awash basin (Lakes Koka, Beseka, Gemari, Abe), which is located in the northern Main Ethiopian Rift, the lakes region (Lakes Ziway, Langano, Abiyata and Shalla) occupying a central part of the MER, and the southern basin (Lakes Awassa, Abaya, Chamo and Chew Bahir) in the southern section of the MER. Hydrologically, basins form separate units, but hydrogeologically they may form a unique system within the rift due to the underground interconnection by NE–SW aligned regional faults (Tamiru Alemayehu et al., 2005).

Lake Beseka is located in the northern part of the MER at the near distance to the Afar triangle, which is a triple junction where three plates (Arabian, Nubian and Somalian) are pulling away from each other along the EARs to form new oceanic crust. Lake Beseka is volcanically dammed, endorheic lake, which is situated 200 kms from the capital Addis Ababa. It is habitat of a variety of birds, fishes, crocodiles and other aquatic species. The lake plays an important role in the wildlife ecology, as it is located in the northern part of Awash National Park.

Since 1976 a lake level increase of Beseka has been observed by the Ethiopian Water Ministry in Addis Ababa, in a region known for severe droughts and decreasing precipitations for the last decades. During this period its surface area has increased from 3Km$^2$ to 40Km$^2$ and the lake rose up from 946.7 m a.s.l to 955 m a.s.l (Goerner, 2005). Meanwhile, a sugar plantation and major traffic routes from Addis Ababa to Djibouti are threatened by inundation.

Most authors suggested that, the causes for the rising of water level of Lake Beseka may be the irrigation of the Abadir Farm Southeast of Lake Beseka. On the other hand, recent tectonic activity might have induced or changed the inflow from hot springs located
southwest of Lake Beseka. In addition, a tectonically triggered modification of the underground water system could be the cause of increased discharge into the lake. But, in my study, I will try to investigate the role of the diverted Merti-Fentale irrigation canal has the possible impact as the recharge into Lake Beseka.

1.2 General overview of the study area

1.2.1 Location and Accessibility

This study is conducted on Lake Beseka, one of Ethiopian rift valley lakes located at the northern of the Ethiopian rift valley about 200Kms east of the capital Addis Ababa, in Oromiya Regional State, Eastern Shoa Zone, in the district of Metahara. It is within the Main Ethiopian Rift (MER) in the Awash basin. The lake watershed lies between 39°43’-39°59’ east longitude and 8°41’-9°0’ north latitude. Beseka, fed by hot springs at 954 meters (3,130 feet), has swollen from a 3-square-kilometer pond in the 1960s to 45 square kilometers, causing the diversion of a road from Addis Ababa to Djibouti’s port, a main trade route in landlocked Ethiopia (http://www.bloomberg.com/news/mysterious-lake-threatens-ethiopian-sugar-ambitions.html). The study area is crossed by one main asphalted road and the Addis Ababa-Djibouti railway line. There is also a road from Metahara to Addis Ketema and to Metahara Sugar Factory then to Nurahira which is very important to see the southern part of the catchment.
1.2.2 Physiography

The topography of the Lake Beseka area ranges from flat to undulating plains and from hills to the high Mount Fentale. Most of the watershed is characterized by flat to undulating plains with altitudes ranging from 940 to 1100m a.s.l. Plains with small and high gradient are located in the northwestern and western part of the watershed.

Volcanic cones are also concentrated in the western part. Hills with medium slopes are located in the south, while a high slope mountain is situated in the northern part of the watershed. The most fascinating and outstanding Quaternary Fentale volcano is located north of Lake Beseka, close to the southwestern corner of the Afar Depression. The Fentale volcano rises 1000 m above the surrounding plain and reaches to 2007 m at the center of the volcano. The last volcano erupted in the 1810s, and today the volcano is characterized by emanating volcanic gasses and is believed to be an active volcano.

Figure 1-2 Topographic map of the study area
1.2.3 Climate

Ethiopia makes up the greater part of the East African ‘Horn of Africa’. At latitudes of 4 to 15°N, Ethiopia’s climate is typically tropical in the south-eastern and north-eastern lowland regions, but much cooler in the large central highland regions of the country. Mean annual temperatures are around 15-20°C in these high altitude regions, whilst 25-30°C in the lowlands (McSweeney et al., 2010).

Seasonal rainfall in Ethiopia is driven mainly by the migration of the Inter-Tropical Convergence Zone (ITCZ). The exact position of the ITCZ changes over the course of the year, oscillating across the equator from its northern most position over northern Ethiopia in July and August, to its southern most position over southern Kenya in January and February (McSweeney et al., 2010).

Metahara and its surrounding area are totally within tropical agro-climatic zone. The maximum and minimum mean monthly temperatures occurred in June and December, respectively. The mean annual maximum and minimum temperatures of the site are 29.2 °C and 22.4°C respectively. The mean annual air temperature of the area is 25.6°C. From the data in Appendix-2, it is clearly seen that the highest temperature is always before the onset of the rainy months. The rainfall regime in the study area is weakly bi-modal,
characterized by high degree of erratic nature and variability both in amount and
distribution. The main rainy season occurs July to September which is relatively reliable,
and the short rainy season occurs March to April which is usually unreliable. The mean
annual rainfall of the area, according to the Ethiopian Metrology Center’s 25 years data
(1988-2012) is 517.1 mm.

1.2.4 Soil and Vegetation

It is known that soil type is closely related to the soil parent material and its degree of
weathering. The main parent materials are basalt, ignimbrite, acidic lava, volcanic ash and
pumice, and alluvial and lacustrine sediments. The most common soil types of the study
area include: cambisols, pedzol, fluvisols, lepthosols, solonchks and luvisols. The
vegetation of the rift valley is mainly characterized by wooded grassland with Accacia of
various species. In the area of study, there are examples of Accacia woodland extensively
used by local people for charcoal production.

1.3 Objective of the study

I) General objective:
The general objective of this research is to study the theoretical background and practical
application of integrated geophysical methods to investigate possible inflow of water into
Lake Beseka from the Merti-Fentale irrigation cancel diverted from Awash River.

II) Specific objective:

- Mapping the major geological structures in the region between the canal
  route and Lake Beseka that could act as conduits for the flow of leaking
  water;
- Mapping the subsurface horizons around the lake to outline the zones of
  water saturation and their possible connection with the Lake;
- Study areas around the basaltic rock wall structures, which are left
  without cementing or plastic membrane cover as the possible source to
  recharge the Lake Beseka.

1.4 Methodology

The methodology followed in the present research processes is based on the objective
formulated in section 1.3. Geophysical methods of investigation were employed in which,
the electrical resistivity imaging and magnetic techniques used. The 2D electrical resistivity imaging and magnetic data were collected along the profiles. The spatial geophysical mapping and modeling has been assisted using software’s such as Oasis muntaj 6.4.2, RES2DINV, PROSYS-II, ArcGIS-10, Global Mapper and Surfer10 software mainly applied for map interpretation and modeling. The generalized flow chart of methodological approach is described in Figure 1.3.

1.5 Reviews of previous studies

A large number of publications on the geology, volcano-tectonic development, hydrogeology and some on geophysical studies of the Main Ethiopian Rift in general, on the northern sector in particular, have been produced in the past. Revising these studies will help to understand the regional geology and hydrogeology of the study area. Thus, in this part some of the regional and local studies have been revised and presented.

Abubeker Wubet (2007) for his MSc thesis did research over Lake Beseka with “Hydrogeochemical investigation of Lake Beseka with some selected parameters.” The paper concluded that the eastern side of the lake has a higher average pH, total dissolved solids (TDS), and electrical conductivity (EC) values than the western side of the lake.
However, the western side of the lake has a higher average temperature than the eastern side of the lake. The lake also shows a spatial variation in terms of dissolved iron concentration and dissolved cobalt; however, the spatial variation of dissolved cobalt is less significant than that of dissolved iron. The presence of the hot springs on the western side of the lake seems to affect the pH, TDS, EC and Temperature values; and their spatial variations across the surface of the lake water. The brownish-yellow color of the water of Lake Beseka is found out to be due to the trace metal iron. It is also most likely that the iron imparts the brownish-yellow color to the lake water either in form of dissolved hydrated ferric ions, or in the form of highly dispersed colloids of Fe(OH)$_3$.

Ashenafi Moges et al., (1981) has conducted a survey report on flood-prone areas in shewa administrative region. He and his colloquies were suggested there are three major factors for the expansion of the Lake Beseka. Firstly, small amounts of rain water in the form of run-off from the surrounding areas of higher elevation, particularly from Mt. Fentale, contribute additional water to the lake. Secondly, the mismanagement of irrigation water from the Nura Era and Abadir farms and the hot springs in the area which recharge the lake with extra ground water to account for some increase of the lake water.

Berihu Abadi (2007) for his MSc thesis did research over the Metahara area on “Brittle fracture and lake level change at Beseka: Main Ethiopian Rift, Metahara area.” The paper concluded that the flow of ground water from south of the study area (Awash River and Abadir Farm) and tectonic hot springs as well as cold springs are the main factors to the expansion of the lake come through the structures. Hence, structures play the main role in the expansion of the lake.

Eleni Ayalew (2009) had conducted a research on “Growing Lake with growing problems: integrated hydrogeological investigation on Lake Beseka, Ethiopia.” She had come with a conclusion, the groundwater system in the western section of the watershed is characterized by relatively low electric conductivity (EC) and high HC content compared to other anions. From the western section of the watershed toward the lake then to the eastern part, groundwater composition is hydro-chemically evolved in a way that EC increases and S and become significant. The presence of a high proportion of HC in the western groundwater system could indicate a recharge area where the groundwater is
continuously flushed by meteoric water and characterized by relatively quick circulating groundwater with low subsurface residence time. Significant amount of S and in the groundwater in the eastern part of the watershed on the other hand illustrates the typical nature of a discharge zone where groundwater circulation is low and characterized by longer subsurface residence time.

Goerner A. et.al. (2008) had undertaken a research over Lake Beseka with “Non-climatic growth of the saline Lake Beseka, Main Ethiopian Rift”. As indicated in the study, neither a change in local climate nor diversion of surface water for irrigation of the nearby sugar cane plantation is a major contributor to Lake Beseka’s level rise. The principal source of water that is sufficient to explain the rise in lake level is groundwater entering the lake via the hot springs.

Tenalem Ayenew (2007) had conducted a research on “Water management problems in the Ethiopian rift; Challenges for development” he come up with the main changes in the water balance of Lake Beseka come from groundwater inputs, which are related to the recent increment of recharge from the nearby irrigation fields and due to the rise of the Awash River level after the construction of the Koka dam. Prior to the construction of the Koka dam, the Awash River sometimes ran dry between December and March. However, after the construction of the dam there has been fairly steady flow of the river throughout the year. The sustained flow of the Awash throughout the year has become a source of continuous indirect recharge to the groundwater of the area, ultimately feeding Lake Beseka which is located at a relatively lower topographic position.

1.6 Statement of the problem

Lake Beseka in the Rift Valley has grown to its largest size ever amid irrigation runoff and seismic shifts in past years. Should salt waters contaminate the Awash River, they would risk Ethiopia’s oldest state-owned sugar estate and an India-funded project downstream that’s key to the government’s $5 billion plan to turn the country into a top sugar exporter.

Metahara and Addis Ketema, towns with more than 30,000 residents, the sugar estate at Metahara east of the capital as well as Tendaho’s sugar facility in the arid Afar region are at risk should the lake continue its mysterious growth. The Tendaho sugar factory 380 kilometers northeast of Addis Ababa that’s financed with a $640 million line of credit
from the Export-Import Bank of India could suffer if the Awash becomes saline. Any saline spill also jeopardizes Ethiopia government plans to develop the Afar area including building a sugar crusher at Tendaho, whose plantation will use water from a dam on the Awash to produce as much as 600,000 tons of cane a year (http://www.bloomberg.com/news/mysterious-lake-threatens-ethiopian-sugar ambitions.html).

Cotton plantations in the Middle Awash area run by the Amibara Business Group would also suffer from a salty river. The former state farms have already lost over 2,000 hectares to salt water since 1984, according to the International Water Management Institute.

Its pace of growth has increased since the regional government began constructing the Fentale canal for a 467 million-birr irrigation project in 2008 following a drought. Even with runoff from farms a probable cause of the lake’s increasing rate of growth, the Ethiopian Water Works Design & Supervision Enterprise’s efforts to pump more water didn’t reduce the expansion.

Whatever the reason for the swelling, the lake has potential to flow to Awash River and devastate Metahara Sugar Estate in the next few years. It would then also negatively impact all downstream irrigation developments in the Awash basin, including Tendaho.

This research therefore employs the use of geophysical methods to investigate the possible inflow of water into Lake Beseka from the Merti-Fentale irrigation canal diverted from Awash River and to understand the active tectonic lineaments (faults and fractures) on western side of the Lake.
1.7 Layout of the thesis

This thesis is organized into six chapters. The first chapter is a general introduction of the study which includes a general description of the study area, statement of the problem, objective, methodology and previous work. The second chapter is concerned mostly with the work of previous researchers that includes geology, hydrogeology and seismicity of the study area and its surrounding. Chapter three covers the theoretical background for the geophysical methods employed in this study. Chapter four describes the complete survey procedure, data acquisition, data processing, presentation. Chapter five covers discussions and interpretation of the different results and the last chapter contains conclusions and recommendations of the research work.
CHAPTER TWO

GEOLOGY, HYDROGEOLOGY AND SEISMICITY OF THE STUDY AREA

2.1 Geology of Main Ethiopian Rift

The Main Ethiopian Rift (MER) is a seismically and volcanically active portion of the East African Rift System (EARS) trending NE across the Ethiopian plateau. The MER developed within the Mozambique Belt, a broad Proterozoic mobile belt which extends from Ethiopia south through Kenya, Tanzania and Mozambique (Kroner, 2005). The MER is a symmetrical graben with uplifted flanks and steep border faults; it lies between lat. 5º-9ºN and long. 37º30’- 40ºE.

The Ethiopian Rift started to develop during Miocene (Davidson and Rex, 1980; Gidey WoldeGabriel et al., 1990), following a broad doming entered on the present Afar depression (Ebinger et al., 1989). During Pliocene and Quaternary, the Rift progressively deepened, evolving through a sequence of interacting half-graben segments (Hayward and Ebinger, 1996). Widespread basaltic and rhyolitic volcanic activity was commonly associated with rifting (Gidey WoldeGabriel et al., 1990; Tadiwos Chernet et al., 1998).

The MER is divided geographically into three sectors: northern, central and southern (Gidey WoldeGabriel et al., 1990). The NMER extends south from the Afar depression to near Lake Koka, with border faults that trend on average at N50ºE and have formed since 10–11 Ma. Early volcanism also began at 10–11 Ma (Tadiwos Chernet et al., 1998; Wolfenden et al., 2004). The CMER extends from Lake Koka through the lakes region to Lake Hawassa, with border faults trending on average N30ºE–N35ºE. The age of onset of extension in the CMER is still debated. According to Gidey WoldeGabriel et al. (1990) estimate the age of onset of faulting to be 8.3–9.7 Ma with earliest syn-rift volcanics at ~8 Ma, whereas Bonini et al. (2005) estimate the onset of extension and initial volcanism to be 5–6 Ma. The SMER extends south from Lake Hawassa into the broadly rifted zone of southern Ethiopia (Ebinger et al., 2000) with faults trending north–south to N20ºE.
Faulting in the SMER was well established by \( \sim 18 \) Ma (Ebinger et al., 1993; Gidey Woldegabriel et al., 1991), and volcanism began around 18–21 Ma (Ebinger et al., 1993).

The youngest part of the Rift is the axial zone, which presently coincides with the Wonji Fault Belt, mainly formed during Quaternary (Mohr, 1967, 1987). The Wonji Fault Belt is characterized by NNE–SSW trending active extension fractures and normal faults, which in many places are associated with fissural or central volcanic activity (Gibson, 1969; Mohr, 1987; Chorowicz et al., 1994; Tesefaye Korme et al., 1997). The normal faults are in most cases arranged in a right stepping en-echelon configuration (Mohr, 1968; Boccaletti et al., 1998) and the vertical throws are in the order of several tens of meters (in the axial zone; Gibson, 1969) to several hundreds of meters (in the rift margins; Gidey Woldegabriel et al., 1990; Hayward and Ebinger, 1996).

**2.1.1 Regional Structural Settings**

Two main fault systems have been distinguished in the MER: a NE-NE-trending fault system which characterizes mainly the rift margins, and a N-S- to NE-trending fault system, the Wonji Fault Belt (WFB) of Mohr (1967, 1987), which exhibits a number of sigmoidal, overlapping, right-stepping en-echelon fault zones obliquely cutting the rift floor. Similarly to other rift systems, the overall architecture of the MER is well expressed by the topography (cited in Boccaletti et.al., 1998. e.g. Hayward and Ebinger, 1996). The eastern margin is well developed and it is defined by a more or less continuous system of boundary faults, whereas the western border is marked by only a few major faults of the Mt. Guraghe area (Boccaletti, 1998). The MER attains a width of about 100 km in the central sector, between Fonko and the Langano Lake area, but narrows southward in the Abaya region, where it is bifurcated by the N-S-striking Amaro horst. This in fact separates the Ganjuli basin in the west, from the Gelana depression in the east (Boccaletti, 1998).

Distribution of volcanic rocks along the MER boundary faults show a discontinuous sequence ranging in age from the Late Eocene up to the Plio-Quaternary (Mohr, 1970; Gidey Woldegabriel et al., 1990; Ebinger et al., 1993). Late Pliocene-Quaternary
volcanism is mainly localized in the rift floor (Morton et al., 1979), although volcanic activity is also present in the Ambo area (Gidey Woldegabriel et al., 1990) and in Southern Ethiopia (Davidson, 1983). The whole volcanic succession exposed along the border faults of both margins indicates a bimodal magma system of acidic and basic associations (Gidey Woldegabriel et al., 1990; Gasparon et al., 1993).

E-W to WNW-ESE trending cross-rift oblique slip transfer faults transects the rift floor and Quaternary volcanic centers are commonly located along them (Gidey Woldegabriel et al., 1990; Ebinger et al., 1993). At places, cross-rift structures are overprinted by the WFB volcano-tectonic axis (Gidey Woldegabriel et al., 1990).

### 2.1.2 Tectonics and Volcanism

The seismically and volcanically active rift system in Ethiopia is one of the few areas worldwide where one can capture the ongoing process of continental break-up associated with a mantle plume (Wolfenden, 2004). The Main Ethiopian and Red Sea rifts also preserve a wealth of information on hominid evolution and early habitats. The Red Sea–Aden–Main Ethiopian rift–rift–rift triple junction lies on the broad Ethiopian plateau, believed to have developed above a Palaeogene mantle plume. Compilations of $^{40}$Ar/$^{39}$Ar data from the Red Sea and Gulf of Aden regions show that flood basalts and associated felsic rocks were erupted across a ~1000 km diameter region between 31 and 29 Ma, roughly coeval with the initiation of NE-directed extension in the southern Red Sea, and the Gulf of Aden.
Initial rifting in the southern and central Main Ethiopian rift (MER) commenced between 18 and 15 Ma, but little was known of rift initiation in the northern MER. Northeast-directed seafloor spreading in the Gulf of Aden has propagated westward into the Afar depression since 16 Ma; northeast-directed seafloor spreading in the Red Sea commenced at ca. 4 Ma. Seafloor spreading has yet to begin in the MER (Wolfenden, 2004).

2.1.3 Seismic activity

The seismicity of the region is controlled and influenced by the active Ethiopian Rift System which divides the country into two along the NE–SW direction. The epicentral map of the region shown in Fig. 2.2 indicates that small and intermediate size earthquakes are dominant and that seismic activity in the region is not uniformly distributed but is
characterized by clustering at preferred locations with sporadic activity in between. The structural pattern shows that the region, characterized by a complex fault pattern trending mainly around NE–SW, separates the Somalian Plate from the Nubian Plate (Tilahun Mammo, 2005).

![Figure 2-2 Seismicity of the region with seismic source zones (Tilahun Mammo, 2005)](image)

Based on the seismicity and the knowledge of the geology and tectonics the region can broadly be divided into three seismogenic provinces or seismic source zones. These are the Afar Depression, the Escarpment and the Ethiopian Rift System seismic source zones (Fig. 2.2). Each zone is, therefore, distinguished by its own specific tectonic, geologic and seismic characteristics. In each zone earthquakes are assumed to occur randomly, that is, every point in the zone has the same probability of being an epicenter (Tilahun Mammo, 2005).

According to Asrat Worku (2011), the country is divided into five zones approximately equal seismic risks depending on the known distribution of earthquakes. These zones are no damaging zone (0 zones), less damaging zones (zone 1 and 2) and zones of major damaging (zone 3 and 4). From the seismic hazard map of Ethiopia, the Metahara and its
surrounding area falls at the zone 4 as shown in Figure 2.3. This map is based on the amplitude of the ground acceleration to be expected during 100 years return period.

According to this map, each seismic zone of 1 to 4 is assigned a constant bedrock acceleration ratio, $\gamma$, of 0.03, 0.05, 0.07 or 0.1, whereas zone 0 is considered seismic free. Addis Ababa belongs to Zone 2 with $\gamma = 0.05$. Many cities and big towns like Mekele, Desse, Semera, Adama, Hawassa and Arba Minch, of which some are capitals of federal states, all belong to Zone 4 with $\gamma = 0.1$ (Asrat Worku, 2011).

2.2 Geology of the study area

2.2.1 Lithology

Lake Beseka is situated in a 20 km graben on the axial part of the rift floor in the northern part of the MER, which in turn is part of the EARS. Being part of the MER, the study area has been under intensive volcanic and tectonic activities during the Quaternary period. The lake watershed is bordered by older volcanoes and a rift margin to the east,
and to the north it is bordered by young Quaternary complexes of Fentale, and to the west by Kone. The products of these recent volcano complexes, along with fissural basalt, rhyolite and alluvial and lacustrine sediments, form the common rock types in the study area.

2.2.1.1 Dino ignimbrites

Dino ignimbrites are consisting of dark to green ignimbrite, with a thickness of about 30m (Seifu Kebede, 1987). These rock units are found mainly in the southeastern part of the watershed and to the north; they are covered by recent sediments in the area of Abadir farm.

2.2.1.2 Pleistocene basalts

Most of the study area and shores of Lake Beseka are underlain by Pleistocene to sub-recent basalt, often coarse grained with phenocryst (Halcrow, 1978). Pleistocene basalts are exposed in most fault scarps and form the southeastern and western edges of Lake Beseka. It is assumed that Pleistocene basalts mainly represent lava pouring through fault fissures rather than being the product of volcano eruption.

2.2.1.3 Kone-Trachyte to Rhyolite

A substantial portion of the southwestern part of the lake watershed is covered by undifferentiated lava flows of trachytic to rhyolitic composition with minor ignimbrite intercalations, which are believed to the product of the kone volcanic complex.

2.2.1.4 Fentale Ignimbrite

The Fentale volcano complex consists of two cladera volcanoes, the older Tinish Fentale and the younger Fentale volcano. The caldera collapse of the Fentale volcano was accompanied by the eruption of voluminous ash flows, which solidified to form welded tuffs (Elc-electoconsult, 1987). The pyroclastic deposit of Fentale ignimbrite is a very extensive welded ash-flow system, which caused the summit caldera to collapse (Gibson, 1970). The eruption and collapse of the main Fentale caldera resulted in widespread deposition of Fentale ignimbrite, which is a common rock type in the northern part of the study area.

The Fentale ignimbrite is a widely distributed rock formation in the northern part of the watershed, especially occupying the lower slopes of Fentale Mountain and the northern
shores of Lake Beseka. Fentale ignimbrite is characterized by isolated blisters on its surface that were formed in the presence of steam pockets.

2.2.1.5 Lacustrine and alluvial sediments

Lacustrine and alluvial sediments are the youngest rock formations in the lake watershed. Alluvial deposit of clays and silts are found at the Metahara and Abadir sugar farms, while lacustrine sediments are found around the perimeter of the Lake. Alluvial sediments are deposited by the River Awash during flood times and can reach up to a thickness of about 40 m in the study area (Seifu Kebede, 1987). The lacustrine deposits include silts, clays, and tuff, are mostly found associated with volcano-clastic sediments. Lacustrine sediments are mainly fine-grained silty sands often encrusted with salts, which may probably represent an accumulation of volcanic ash, reworked by the lake (Halcrow, 1978). Raised beaches, corresponding to higher lake levels exist around the perimeter of the lake.
2.2.2 Geologic Structures of the study area

According to Gibson and Tazieff (1970), the faults which are found both to the northeast and southwest of the Fentale volcano frequently cut a hard compact welded-tuff unit. This makes the nature of the faulting particularly evident. In this region it is clear that many of the fractures are not normal faults with predominantly vertical movement along a steeply dipping fault plane. Instead may be simple open fissures with little or no vertical movement. The hard, resistant nature of the country rock allows one to demonstrate unequivocally that these open fissures have been produced by a tensional separation which may exceed 2m. Transitional types to ‘normal’ faults also occur in which there is a small amount of tensional separation and some vertical displacement.

To the southwest of Fentale are two further swarms of recent faults, each with its active or recently active silicic center. The en-echelon arrangement of the swarms emphasizes that here the most important direction of faulting is not parallel to the rift margin but inclined at an angle of about (Gibson et. al., 1970).

2.2.3 Hydrogeology of the study area

The disruption of lithologies by cross cutting faults and the variability of volcanic structures make the hydrogeology of the rifted volcanic terrain in Ethiopia very complex (Seifu Kebede et al., 2007). The intricate spatial and temporal distribution of volcanic rocks, their wide compositional and textural variability, their different degree of fracturing and weathering and the existence of active tectonic structures in the region create a complex aquifer system in the Ethiopian rift.

The study area is affected by several fault systems and is covered by volcanic rocks varying from fissural basaltic to viscous acidic lava flow, and pyroclastic deposits to sediments occurring in an inter-fingering manner.

The main water-bearing formation is a mixed aquifer system of fractured and weathered basalts, welded tuffs and pyroclastic deposits (Eleni Ayalew, 2009). Recent and sub-recent basalts in the study area are intensely affected by fractures, and create highly permeable aquifer zones around Lake Beseka. These basalts are fresh and highly jointed; and have a high degree of permeability and productivity (Tesfaye Chernet, 1990). In addition to being affected by fractures, the basalts are characterized by primary porosities such as vesicular cavities, cooling joints and scoraceous intercalations. These porosities
play an important role in creating favorable conditions for the formation of a weathered permeable zone.

Pyroclastic deposits are the other water-bearing formation in the area composed of fractured and/or weathered welded tuff, and non-welded tuff with pumice and volcanic breccias. Pyroclastic deposits of the Fentale group show a wide range of hydrogeological features, and are characterized by moderate to low permeability. This is due to the fact that non-welded tuff aquifers have different pyroclast sizes, sorting arrangements, levels of pumice and breccia intercalations and are affected by different extents of weathering. Coarse-grained pyroclastic deposits (pumice) are fairly permeable compared to fine grained deposits (ashes and cinders) (Elc-electroconsult, 1987).

Welded ash flows (ignimbrites) are characterized by very low primary porosities, as they are formed by the fusion of rock fragments at high temperatures. In the study area, fracturing and weathering have affected the welded tuff to different degrees, and as a result, it varies from fresh, massive to jointed, toward slightly to highly fractured and weathered ignimbrite. To the west and south of Fentale, welded tuffs are characterized by moderate permeability due to fractures and the abundance of fresh, columnar joints with blisters and crevasses (Eleni Ayalew, 2009). However, the permeability of welded tuffs tends to decrease east of Fentale, as joints are filled with clay materials due to weathering (Seifu Kebede, 1987).

CHAPTER 3
THEORY OF GEOPHYSICAL METHODS

3.1 General

The geophysical methods employed over the inflow zone of Lake Beseka area in this research work involve the electrical methods and the magnetic methods. The electrical method of surveying employed for this work is the 2D electrical resistivity imaging or electrical resistivity tomography (ERT). These two methods have specific advantages over the other geophysical techniques that make them attractive for the objectives of the work. The electrical method is suitable for mapping subsurface saturated zones and when
used in combination with magnetics, especially the 2D imaging, is suitable for mapping vertical and near vertical contacts between geologic units and subsurface weak zones, zones of fluid circulation.

3.2 Direct Current Resistivity Method

3.2.1 Introduction

The purpose of electrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. This ground true resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock (Loke, 2004). Electrical resistivity surveys have been used for many decades in hydrogeological, mining and geotechnical investigations. More recently, they have found increased importance and application for environmental surveys.

In the resistivity method, artificially-generated electric currents are introduced into the ground and the resulting potential differences are measured at the surface. Deviations from the pattern of potential differences expected from homogeneous ground provide information on the form and electrical properties of subsurface inhomogeneity (Kearey et al., 2002).

3.2.2 Resistivity Field Procedures

Depending on the type of problem to be solved, there are two common field procedures in electrical resistivity surveying. The procedures are dependent on whether one is interested to look into variations in resistivity in the vertical direction and/or variations in resistivity in lateral directions. Most of the geologic problems to be solved are also covered by either of these techniques.

3.2.2.1 Vertical Electrical Sounding (VES)

Vertical electrical sounding (VES), also known as ‘electrical drilling’ or ‘expanding probe’, is used mainly in the study of horizontal or near-horizontal interfaces. The current and potential electrodes are maintained at the same relative spacing and the whole spread is progressively expanded about a fixed central point. Consequently, readings are taken as the current reaches progressively greater depths. The technique is extensively used in geotechnical surveys to determine overburden thickness and also in hydrogeology to define horizontal zones of porous strata (Kearey et al., 2002).
3.2.2.2 Constant Separation Traversing (CST)

Constant separation traversing (CST), also known as ‘electrical profiling’, is used to determine lateral variations of resistivity. The current and potential electrodes are maintained at a fixed separation and progressively moved along a profile. This method is employed in mineral prospecting to locate faults or shear zones and to detect localized bodies of anomalous conductivity. It is also used in geotechnical surveys to determine variations in bedrock depth and the presence of steep discontinuities (Kearey, 2002).

Most recent electrical resistivity surveys, especially those desiring to map variations in resistivity in both vertical and lateral direction employ a combination of both the sounding and profiling techniques. This combination of techniques is possible thanks to the development in electronic circuitry resulting in switching and automatic recording of data-the resistivity imaging or tomography techniques. In addition to acquiring large volume of data in a short period, these techniques provide one with a high resolution 2D image of the subsurface.

3.2.3 Electrical Resistivity Tomography (ERT)

Electrical tomography is a 2D imaging technique showing the variations in the ground resistivity along a section. It is based on the same principles as such other classical electrical methods like sounding or profiling. A controlled current (I) is injected into the ground with two electrodes, while measuring the potential (V) between two other electrodes. The resistance is calculated using Ohm's law. The material parameter resistivity ($\rho$), which is the inverse of electrical conductivity ($\delta$) is related to the resistance via a geometrical factor. To build an electrical image of the ground (a 2D section of resistivity), numerous measurements are carried out for various combinations of potential and current electrodes (Donat et.al., 2001). The Wenner configuration (constant offset between electrodes) has been used. The first step in the data interpretation consists in building a pseudo-section obtained by plotting the apparent resistivity versus the depth (proportional to the offset between electrodes) for each midpoint of a given electrode configuration. This representation leads to a qualitative image where neither the resistivities nor the depths are correct.

It is necessary to inverse the pseudo-section in order to determine a vertical resistivity section as a function of a true depth. The inversion of the data is carried out according to an iterative process which aims at minimizing the difference between the measured
pseudo-section and a calculated pseudo-section based on a model. This model is updated after iteration until reaching an acceptable agreement between measured and calculated data or until no further improvement is possible. The data are processed with the RES2DINV software (Donat et al., 2001).

Figure 3-1 Hematic drawing illustrating the principle of multi-electrode electrical imaging surveys (EIS) (Tigistu Haile, 2010)

3.2.4 Forward Modeling

In the forward modeling problem, the subsurface resistivity distribution is specified and the purpose is to calculate the apparent resistivity that would be measured by a survey over such a structure (Loke, 2004). A forward modeling subroutine is in fact also an integral part of any inversion program since it is necessary to calculate the theoretical apparent resistivity values for the model produced by the inversion routine to see whether is agrees with the measured values (Loke, 2004).

According to Loke (2004), there are three main methods to calculate the apparent resistivity values for a specified model. They are (i) analytical methods, (ii) boundary element methods and (iii) the finite-difference and finite-element methods. Analytical methods are probably the most accurate methods, but they are restricted to relative simple geometries (such as a sphere or cylinder). Boundary element methods are more flexible, but the number of regions with different resistivity values that is allowed is somewhat limited (usually less than 10). In engineering and environmental surveys the subsurface can have an arbitrary resistivity distribution, so the finite-difference and finite-element methods are usually the only viable choice. These methods can subdivide the subsurface
into thousands of cells with different resistivity values. However, the analytical and boundary element methods are useful independent methods that can be used to check the accuracy of the finite-difference and finite-element methods.

**3.2.5 Basic Inverse Theory**

In geophysical inversion, we seek to find a model that gives a response that is similar to the actual measured values. The model is an idealized mathematical representation of a section of the earth. The model has a set of model parameters that are the physical quantities we want to estimate from the observed data. The model response is the synthetic data that can be calculated from the mathematical relationships defining the model for a given set of model parameters (Loke, 2004).

All inversion methods essentially try to determine a model for the subsurface whose response agrees with the measured data subject to certain restrictions. In the cell-based method used by the RES2DINV and RES3DINV programs, the model parameters are the resistivity values of the model cells, while the data is the measured apparent resistivity values (Loke, 2004).

In all optimization methods, an initial model is modified in an iterative manner so that the difference between the model response and the observed data values is reduced. The set of observed data can be written as a column vector $y$ given by

$$ y \quad \quad (3.1) $$

where $m$ is the number of measurements. The model response $f$ can be written in a similar form.

$$ f \quad \quad (3.2) $$

For resistivity problems, it is a common practice to use the logarithm of the apparent resistivity values for the observed data and model response, and the logarithm of the model values as the model parameters. The model parameters can be represented by the following vector

$$ \theta \quad \quad (3.3) $$

where $n$ is the number of model parameters. The difference between the observed data and the model response is given by the discrepancy vector $g$ that is defined by...
In the least-squares optimization method, the initial model is modified such that the sum of squares error $E$ of the difference between the model response and the observed data values is minimized.

To reduce the above error value, the following Gauss-Newton equation is used to determine the change in the model parameters that should reduce the sum squares error (Lines and Treitel 1984).

where \( \Delta \) is the model parameter change vector, and \( J \) is the Jacobian matrix (of size \( m \) by \( n \)) of partial derivatives. The elements of the Jacobian matrix are given by

that is the change in the \( i^{th} \) model response due to a change in the \( j^{th} \) model parameter. After calculating the parameter change vector, a new model is obtained by

In practice, the simple least-squares equation (3.6) is rarely used by itself in geophysical inversion. In some situations the matrix product might be singular, and thus the least-squares equation does not have a solution for. Another common problem is that the matrix product is nearly singular. One common method to avoid this problem is the Marquardt-Levenberg modification (Lines and Treitel 1984) to the Gauss-Newton equation that is given by

where \( I \) is the identity matrix. The factor \( \lambda \) is known as the Marquardt or damping factor, and this method is also known as the ridge regression method (Inman 1975).

This method has been successfully used in the inversion of resistivity sounding data where the model consists of a small number of layers (Loke, 2004). To overcome this problem, the Gauss-Newton least-squares equation is further modified so as to minimize
the spatial variations in the model parameters (i.e. the model resistivity values change in a smooth or gradual manner). This smoothness constrained least-squares method (Ellis and Oldenburg, 1994) has the following mathematical form.

\[ (3.10) \]

where \( A \) and \( B \) are the smoothing matrices in the x-, y- and z-directions. \( \alpha \) are the relative weights given to the smoothness filters in the x-, y- and z-directions.

In some cases, the subsurface geology consists of a number of regions that are internally almost homogeneous but with sharp boundaries between different regions. One simple method to implement an norm based optimization method using the standard least-squares formulation is the iteratively reweighted least-squares method (Wolke and Schwetlick, 1988). The optimization equation in (3.22) is modified to

\[ (3.11) \]

with

where \( A \) and \( B \) are weighting matrices introduced so that different elements of the data misfit and model roughness vectors are given equal weights in the inversion process.

### 3.2.6 The relationship between geology and resistivity

Igneous and metamorphic rocks typically have high resistivity values. The resistivity of these rocks is greatly dependent on the degree of fracturing, and the percentage of the fractures filled with ground water. Thus a given rock type can have a large range of resistivity, from about 1000 to 10 million \( \Omega \cdot \text{m} \), depending on whether it is wet or dry. This characteristic is useful in the detection of fracture zones and other weathering features, such as in engineering and groundwater surveys (Loke, 2004).

Sedimentary rocks, which are usually more porous and have higher water content, normally have lower resistivity values compared to igneous and metamorphic rocks. The resistivity values range from 10 to about 10000 \( \Omega \cdot \text{m} \), with most values below 1000 \( \Omega \cdot \text{m} \). The resistivity values are largely dependent on the porosity of the rocks, and the salinity of the contained water (Loke, 2004).

Table 3.1 Resistivities of some common rocks, minerals and soils (Loke, 2004)
Unconsolidated sediments generally have even lower resistivity values than sedimentary rocks, with values ranging from about 10 to less than 1000 Ω.m. The resistivity value is dependent on the porosity (assuming all the pores are saturated) as well as the clay content. Clayey soil normally has a lower resistivity value than sandy soil. However, note the overlap in the resistivity values of the different classes of rocks and soils. This is because the resistivity of a particular rock or soil sample depends on a number of factors such as the porosity, the degree of water saturation and the concentration of dissolved salts (Loke, 2004).

3.3 THE MAGNETIC METHOD

The other method employed in the work is the magnetic method of prospecting. Geomagnetic methods can be used in a wide variety of applications and range from small-scale investigations to locate pipes, cables and metallic objects in the very near surface, and engineering site investigations, through to large-scale regional geological mapping to determine gross structure, such as in hydrocarbon exploration (Reynolds, 1997).
3.3.1 Basic concepts and units of Geomagnetism

Within the vicinity of a bar magnet a magnetic flux is developed which flows from one end of the magnet to the other (Fig. 3.2). This flux can be mapped from the directions assumed by a small compass needle suspended within it. The points within the magnet where the flux converges are known as the poles of the magnet. A freely-suspended bar magnet similarly aligns in the flux of the Earth’s magnetic field.

![Diagram of magnetic flux and poles](image)

Figure 3-2 Lines of magnetic flux around a bar magnet (after Reynolds, 1997)

The pole of the magnet which tends to point in the direction of the Earth’s North Pole is called the north-seeking or positive pole, and this is balanced by a south-seeking or negative pole of identical strength at the opposite end of the magnet (Kearey et al., 2002).

Magnetic poles always exist in pairs of opposite sense to form a dipole. When one pole is sufficiently far removed from the other so that it no longer affects the other, the single pole is referred to as a monopole (Reynolds, 1997).

The force $F$ between two magnetic poles of strengths $A$ and $B$ separated by a distance $r$ is given by

$$F = \frac{\mu_0 A B}{4\pi r^3}$$

(3.12)

where $\mu_0$ and $\mu_r$ are constants corresponding to the magnetic permeability of vacuum and the relative magnetic permeability of the medium separating the poles (Kearey et al., 2002). The force is attractive if the poles are of different sign and repulsive if they are of like sign.
The magnetic field \( B \) 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

\[
(3.13)
\]

Magnetic fields can be defined in terms of magnetic potentials in a similar manner to gravitational fields. For a single pole of strength \( m \), the magnetic potential \( V \) at a distance \( r \) from the pole is given by

\[
(3.14)
\]

The magnetic field component in any direction is then given by the partial derivative of the potential in that direction.

The SI unit of \( B \) is expressed in Vs(Weber (Wb)). The unit of the Wb is designated the tesla (T). The c.g.s unit of magnetic field strength is the gauss (G), numerically equivalent to T.

Common magnets exhibit a pair of poles and are therefore referred to as dipoles. The \textit{magnetic moment} \( M \) of a dipole with poles of strength \( m \) a distance \( l \) apart is given by

\[
(3.15)
\]

The magnetic moment of a current-carrying coil is proportional to the number of turns in the coil, its cross sectional area and the magnitude of the current, so that magnetic moment is expressed in A.

The intensity of induced magnetization of a material is defined as the dipole moment per unit volume of material:

\[
(3.16)
\]

where \( M \) is the magnetic moment of a sample of length \( L \) and cross-sectional area \( A \). is consequently expressed in A.

The induced intensity of magnetization is proportional to the strength of the magnetizing force \( H \) of the inducing field:

\[
(3.17)
\]
where $k$ is the magnetic susceptibility of the material. Since $H$ and $H$ are both measured in A, susceptibility is dimensionless in the SI system.

In a vacuum the magnetic field strength $B$ and magnetizing force $H$ are related by

$$ B = \mu_0 H $$

where $\mu_0$ is the permeability of vacuum (4). Air and water have very similar permeability to and so this relationship can be taken to represent the Earth’s magnetic field when it is undisturbed by magnetic materials (Kearey et al., 2002).

When a magnetic material is placed in this field, the resulting magnetization gives rise to an additional magnetic field in the region occupied by the material, whose strength is given by. Within the body the total magnetic field, or magnetic induction, $B$ is given by

$$ (3.18) $$

Substituting equation (3.6)

$$ (3.19) $$

where $\mu$ is a dimensionless constant known as the relative magnetic permeability. The magnetic permeability is thus equal to the product of the relative permeability and the permeability of vacuum, and has the same dimensions as. For air and water is thus close to unity.

### 3.3.2 Nature of the Geomagnetic Field

As far as exploration geophysics is concerned, the geomagnetic field of the Earth is composed of three parts:

1. The main field or Diploe field, which is produced in the fluid outer core of the earth and accounts for the very large regional variations in the total field intensity and direction.
2. The external magnetic field, which is produced by electric currents in the earth’s ionosphere consisting of particles ionized by solar radiation and put into motion by the solar tidal force.
3. The anomalous magnetic field or rock magnetism, which is produced by ferromagnetic minerals and rocks in the earth’s crust (Telford et al.). The earth’s total magnetic field is given by

$$ (3.20) $
3.3.3 The Earth’s Magnetic Elements

A vector is used to represent the earth’s magnetic field at an observation site. At any point on the Earth’s surface, the magnetic field $\mathbf{B}$ has some strength and points in some direction. This vector quantity has a vertical component $Z$ and a horizontal component $H$ in the direction of the magnetic north. The horizontal component $H$ of the magnetic field $\mathbf{B}$ can be further decomposed into a component $X$ in the geographic north direction and a component $Y$ in the geographical east direction. The terms which are used to describe the direction of the magnetic field $\mathbf{B}$ are *declination* ($D$), the angle between geographic and the magnetic north. The angle of declination is measured positive through east and varies from 0 to 360 degrees, and *inclination* ($I$), the angle between the horizontal $H$ and field $\mathbf{B}$. Angle of inclination $I$ varies from - to. These seven magnetic elements are related in the following ways:

\[
(3.21)
\]

\[
(3.22)
\]

Figure 3-3 The earth’s magnetic field elements (Reynolds, 1997)

3.3.4 Instrumentation

A magnetometer is a more complex instrument which measures both the orientation and strength of a magnetic field. When the magnetic field of a rock sample is measured, the result is actually a measure of the field as it is being affected by the earth’s magnetic field, as well as any other large bodies of magnetic rock which are nearby. Magnetometer surveys measure small, localized variations in the Earth's magnetic field. Magnetometers are highly accurate instruments, allowing the local magnetic field to be measured to
accuracies of 0.002%. There are several types of instruments on the market. The common ones used for commercial applications are the proton precession, fluxgate, cesium vapor and gradiometer magnetometer systems. The systems operate on broadly similar principles utilizing proton rich fluids surrounded by an electric coil. A momentary current is applied through the coil, which produces a corresponding magnetic field that temporarily polarizes the protons. When the current is removed, the protons realign or precess into the orientation of the Earth's magnetic field. The precession generates a small electrical current in the surrounding coil, at a frequency directly proportional to the local magnetic field intensity. Gradiometers measure the magnetic field gradient rather than total field strength, which allows the removal of background noise (Mariita, 2007).

3.3.5 Data Acquisition

Ground magnetic measurements are usually made with portable instruments at regular intervals along more or less straight and parallel lines which cover the survey area. Often the interval between measurement locations (stations) along the lines is less than the spacing between lines.

Intense fields from man-made electromagnetic sources can be a problem in magnetic surveys. Steel and other ferrous metals in the vicinity of a magnetometer can distort the data. Large belt buckles, etc., must be removed when operating the unit. A compass should be more than 3 m away from the magnetometer when measuring the field. A final test is to immobilize the magnetometer and take readings while the operator moves around the sensor (Mariita, 2007).

Data recording methods will vary with the purpose of the survey and the amount of noise present. Methods include: taking three readings and averaging the results, taking three readings within a meter of the station and either recording each or recording the average. Some magnetometers can apply either of these methods and even do the averaging internally (Mariita, 2007).

3.3.6 Magnetic Data Reduction and Processing

Processing of magnetic data includes the correction for daily variations in the Earth’s magnetic field and the removal of the regional magnetic field from our data.

Diurnal removal corrects for the temporal variation of the Earth’s main field. This is achieved by subtracting the time-synchronized signal, recorded at a stationary base
magnetometer, from the survey data. This procedure relies on the assumption that the temporal variation of the main field is the same at the base station and in the survey area. Best results are obtained if the base station is close to the survey area, the diurnal variation is small and smooth and electromagnetic induction effects are minimal (Lilley, 1982).

Geomagnetic reference field removal removes the strong influence of the Earth’s main field on the survey data. This is done because the main field is dominantly influenced by dynamo action in the core and not related to the geology of the (upper) crust. The removal is achieved by subtracting a model of the main field from the survey data. The International Geomagnetic Reference Field (IGRF) is generally used for this purpose. This model accounts for both the spatial and long period (>3 year) temporal variation (secular variation) of the main field (Lewis, 2000).

The above are the two main reductions that are necessary when one conducts magnetic survey over a limited area in which case corrections like regional or normal and magnetic storm correction are not normally required.

After data processing, the data ideally only contains information about magnetic anomalies. The processed data is usually presented in the form of magnetic anomaly and analytic signal maps.

### 3.3.7 Analytic Signal

The analytic signal method, known also as the total gradient method, as defined here produces a particular type of calculated gravity or magnetic anomaly enhancement map used for defining in a map sense the edges (boundaries) of geologically anomalous density or magnetization distributions (e.g., basement fault block boundaries, basement lithology contacts, fault/shear zones, igneous and salt diapirs, etc.). The analytic signal or total gradient is formed through the combination of the horizontal and vertical gradients of the magnetic anomaly. The analytic signal has a form over causative body that depends on the locations of the body (horizontal coordinate and depth) but not on its magnetization direction (Ansari and Alamdar, 2009).

According to Roest et al. (1992) the amplitude of analytic signal of the magnetic anomaly of a 3D source can be given by the following formula:
3.3.8 Magnetic Properties of Rocks and Minerals

The magnetic susceptibility and remnant magnetization of rocks are the properties of interest in magnetic surveys. Susceptibility is a measure of the ability of a rock to acquire a magnetization in the presence of a magnetic field. Remnant magnetization is the permanent magnetization of rock and is not dependent on any contemporary external field.

The susceptibility of a rock usually depends on its magnetite content. Sediments and acid igneous rocks have small susceptibilities whereas basalts, dolerites, gabbros and serpentinites are usually strongly magnetic. Weathering generally reduces susceptibility because magnetite is oxidized to hematite, but some laterites are magnetic because of the presence of maghemite and remnant magnetized hematite (Milsom, 2003).

Table 3.2 Typical Magnetic Susceptibilities some common rocks and minerals in rationalized SI units (Milsom, 2003)

<table>
<thead>
<tr>
<th>Common rocks</th>
<th>Ores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slate</td>
<td>0-0.002</td>
</tr>
<tr>
<td>Dolerite</td>
<td>0.01-0.15</td>
</tr>
<tr>
<td>Greenstone</td>
<td>0.0005-0.001</td>
</tr>
<tr>
<td>Basalt</td>
<td>0.001-0.05</td>
</tr>
<tr>
<td>Granulite</td>
<td>0.0001-0.05</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>0.00025-0.01</td>
</tr>
<tr>
<td>Salt</td>
<td>0.0-0.001</td>
</tr>
<tr>
<td>Gabbro</td>
<td>0.001-0.1</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.00001-0.0001</td>
</tr>
</tbody>
</table>

Table 3.2 Typical Magnetic Susceptibilities some common rocks and minerals in rationalized SI units (Milsom, 2003)
CHAPTER FOUR
DATA ACQUISITION AND PROCESSING

4.1 Electrical Resistivity of 2D Imaging

4.1.1 Instrumentation and Data Acquisition

The electrical resistivity imaging data was collected using the IRIS instrument SYSCAL R1 PLUS Switch-72. This is an all-in-one multi-node resistivity imaging system. It features an internal switching board for 72 electrodes and an internal 200W power source. The output current is automatically adjusted (automatic ranging) to optimize the input voltage values and ensure the best measurement quality. The system is designed to automatically perform pre-defined sets of resistivity measurements with roll-along capability. In the 5 m version, four multi-core cables with 18 electrodes takeout each is connected on the back of the resistivity meter. These heavy-duty cables are available with standard 5 or 10 m electrode spacing. Customized cables can also be assembled for special arrays or non-standard applications (http://www.iris-instruments.com/product/Brochure/syscal.html).

Compact, easy-to-use and field proof, the SYSCAL R1 PLUS Switch-72 measures both resistivity and chargeability (IP). It is ideal for environmental and civil engineering applications such as pollution monitoring and mapping, salinity control, depth-to-rock determination and weathered bedrock mapping. It can also be used for shallow groundwater exploration (depth and thickness of aquifers).

![Instrumentation of 2D electrical imaging](image)

A twelve volt external battery was used for this survey. In the survey, the instrument is normally put at the center, where the deepest depth is recorded, and the four cables reels
spread on both side of the resistivity meter. The two cables are in one side of the resistivity meter while the other two are spread on the other side of the resistivity meter. The setup of the instrument at the field is indicated in Figure 4.2.

![Diagram of 2D Electrical Imaging setup](image)

**Figure 4-2 General Field layout of 2D electrical imaging with the main (72 electrode layout) and the roll-along Sequences (Hailemariam Siyum, 2011)**

The 2D Electrical Imaging data are acquired systematically along traverses which were selected to collect a representative and detailed information about the area around the Lake Beseka parallel to the Merti-Fentale irrigation canal. Totally five profile lines were selected for the survey, all profiles are nearly parallel to the Merti-Fentale irrigation canal with S-N orientation (Figure 4.3).

The first profile (P1) is surveyed by one main and four roll-along sequences which cover a horizontal distance of 720m, the second profile (P2) is surveyed by one main and six roll along sequences which cover a horizontal distance of 900m, the third profile (P3) is surveyed by one main and seven roll-along sequences which cover a horizontal distance of 990m, the forth profile (P4) is surveyed by one main and three roll-along sequences which cover a horizontal distance of 630m and the fifth profile (P5) is surveyed by one main and five roll-along sequences which covers a horizontal distance of 810m. The main sequence contains 648 data points covering 360m horizontal distance while each of the roll-along sequences contain 297 data points covering a horizontal distance of 90m.

### 4.1.2 Electrical Resistivity Tomography Data Processing and Presentation

The data generated at field from each main and roll-along sequences were downloaded to a computer using the Prosys-II software.
The data obtained in the prosys–II software is started from 90m for each roll-along. Because of this, the roll-along sequences were adjusted with proper distance before add to the main sequence. In the case of roll-along one the data started from 90m, so no distance adjustment is needed. The 2\textsuperscript{nd} roll-along sequence data sheet was recorded after 90 meter of the first roll-along data; it was shifted by 90 meter after getting in the Prosys-II software. This step was continued for the rest roll-along data by increasing total roll-along distance by 90 meter that means 180m to the 3\textsuperscript{rd} roll-along, 270m to the 4\textsuperscript{th} roll-along and 360m to the 5\textsuperscript{th} roll-along, 450m to the 6\textsuperscript{th} roll-along and 540m to the 7\textsuperscript{th} roll-along. After adjusting the distance, the roll-along sequence was added to the main sequence. After the summation, the summed data is filtered, by automatic filtering, and the noisy data is rejected.
Figure 4-4 An example of the measured, calculated and inverted 2D model of electrical resistivity section of an electrical imaging survey.
Finally the filtered data is saved in the Prosys-II software in “.dat” format and exported to RES2DINV software for processing. The filtered data, which is exported to RES2DINV software, is inverted by least square inversion and with 5-8 iteration processes a representative earth model which would give similar subsurface apparent resistivity is produced for the purpose of analysis.

An automatic iteration process that fits the modeled data with the calculated one proceeds to analyze the data. A root mean square error (RMS) of the process was 2.3-10.6% and it was taken to be acceptable. The final output of RES2DINV software, the inverted 2D model resistivity section, is the processing product of 2D survey, an example of which is given in Figure 4.4. Topography is not incorporated to the 2D electrical resistivity section because the project site, especially the sections where the survey lines are laid out, is on flat terrain. Finally such figures are used for interpretation purpose and to correlate the results of 2D imaging analysis with results of other methods.

4.2 MAGNETIC SURVEY

4.2.1 Data Acquisition and Instrumentation

Magnetic data were collected using a Proton Precession Magnetometer Scientrxi IGS-2 in the field data acquisition. The unit has an operating range of 20000nT to 100000nT with absolute accuracy of 62nT at 100000nT and 1nT at 50000nT. It has a 2 sec reading time with a resolution of 0.1nT. The surveying was stated by establishment of a base station within the study area at a place which is easily accessible and as far as possibly free from magnetic noise.

In addition to the magnetic readings the geographic coordinates of the point at which the readings are taken and the time of reading is recorded using Global Positioning System (GPS). Similar to that of the electrical imaging data, magnetic data are collected along the predefined profile lines, which were used to conduct electrical imaging surveys. Magnetic data were collected from 227 data points with average spacing of 20m along the selected profile lines. At the field survey two magnetic readings were taken for a specific point and then average of this readings were used for the processing and interpretation purpose. The distribution of magnetic data in the study area is shown in Figure 4.3 above.
4.2.2 Magnetic Data Processing and Presentation

For the purpose of diurnal correction the magnetic data collected at field was recorded in Microsoft excel. Using this software the diurnal variation of each point was calculated based on the reading of the base station. Then diurnal correction was done by subtracting the diurnal variation of each reading point from the reading taken by Proton Precision Magnetometer at that specific point. I haven’t implemented the International Geomagnetic Reference Field (IGRF) correction that removes the effect of geomagnetic references field from the survey data. This is because, the IGRF correction is need for the regional study but, my project area is almost a point as compared to the globe. Finally the total magnetic field intensity anomaly, obtained by subtracting the diurnal variation value from the survey data, was used for processing to produce total magnetic intensity map, models and profile plots using Oasis Montaj 6.4.2 and Microsoft excel software. In addition, other data enhancement technique was applied to produce magnetic map, which may help to highlight particular characteristics or features to aid qualitative interpretation. Analytic signal was done by using Geosoft software package program called MAGMAP.
CHAPTER FIVE
RESULTS, DISCUSSION AND INTERPRETATION

5.1 ELECTRICAL RESISTIVITY 2D IMAGINING AND MAGNETIC PROFILES

5.1.1 Introduction

Meaningful geological interpretations for all profiles were done by integrating the geological information from the boreholes log data, range of resistivity values from the 2D electrical resistivity imaging sections and the magnetic profiles. A borehole dug at the nearest position for each profile by WWDSE for ground water data investigation around Lake Beseka areas was employed for correlation purpose. The depth of the boreholes is varies from 28.3m up to 73m while the depth of investigation of the 2D electrical imaging is 65m so that, the correlation is made only for the first 65m depth. Furthermore, a correlation between the inverse model electrical resistivity section and the magnetic anomaly profile plot, which is surveyed along the same survey line with the 2D electrical resistivity imaging, is done. In the following sections the results of the individual profile lines and their interpretations are presented.

5.1.2 Profile Line-1

Profile one (P1) runs from coordinates 588203E, 973055N to 588021E, 973649N at elevation 1018m to 1023m covering a length of 720m. It is aligned in a near S-N direction. On this profile, electrical resistivity imaging data were collected from 1836 data points, however, about 1784 data points were used for inversion after automatic filtering and deleting the noisy data by inspection from the data set.

The least square inversion, done using RES2DINV software, were resulted a good quality inversion model section (Figure 5.1B) with RMS error of 6.9% after six iteration processes. The aim of the survey was to map the presence of fractures or weak zones that could potentially act as conduits for the water that may come from the un-membraned basaltic rock walls of the Merti-Fentale canal and to map the zones within the area that are affected by tectonic activities. Overall, the model actually shows large variation subsurface ranging from low to high electrical resistivity zones (9.07-6148Ωm).
Figure 5-1 Interpretation of geophysical data of profile-1 (A) magnetic anomaly profile plot, (B) 2D inversion model electrical resistivity section and (C) borehole log BH-62.
The profile can be viewed as different geological stratification based on inverse model electrical resistivity section and borehole BH-62 data. The electrical resistivity value of the top layer is very low and varies from 9.07-148 Ωm. This could be the response of the relatively dry top soil of moist brown silt clay, silty sand, and highly to completely weathered ignimbrite and rhyolite intercalation possibly water saturated from irrigation excess water of secondary and tertiary canals. The depth of the layer increases from the south to north direction and ranges from 1.25 to 17.3m and has a thickness approximately 16m.

The second layer with electrical resistivity ranges 376 to 6148Ωm is likely to be the response of the highly to completely weathered and fractured massive vesicular basalt, scoracious basalt and moisture volcanic ash. The thickness of this layer goes up to 29m with the greater thickness at a distance of 350m from the middle part of the line. From the inverted sections, five zones of subsurface weakness are clearly apparent. Three regions of subsurface discontinuity extending to greater depth and located around 280m, 420m and 520m at the middle part of the survey line are indicated. These could be interpreted as fractured zones through which fluid circulation from the surface and shallow depths are possible. These fractures may be act as the recharge path of water for Lake Beseka from the un-membraned basaltic rock wall of Merti-Fentale canal.

The third layer has the electrical resistivity value like the top layer is very low and varies from 9.07-148Ωm. This could be the response of welded tuff and volcanic ash possibly water saturated.

The analytic signal profile plot along the 2D electrical resistivity imaging of profile-1 shown on top part of Figure (5.1A), it shows variation of analytic signal versus distance along the traverse. The signature obtained from the analytic signal plot along this traverse shows considerable variation in slope. As shown from the plot the slope of the analytical signal has shown considerable variation at 90m, 300m and 480m. These change in slope of analytical signal could be associated with the presence of weak zones that could be interpreted as fractured lines. These zones are clearly demarcated in the electrical resistivity plot as well and are indicated in the section as dotted lines.
5.1.3 Profile Line-2

Profile two (P2) runs from coordinate 587430E, 975865N to 587766E, 976602N at elevation of 1034 to 1042 covering a distance of 900m. It is aligned in a near S-N direction and lies parallel to the Merti-Fentale irrigation canal. Accordingly, data was collected from 2430 data points, in which after filtering the noisy data only 2403 data points were used for the inversion purpose.

The inversion model section of this profile (Figure 5.2B) is produced by least square inversion with the RES2DINV software having RMS error of 4.5% after 8 iterations. The different segments of the inversion model section are grouped into three layers based on the information from the borehole log (BH-60) data collected by WWDSE and it is correlated with the magnetic anomaly profile plot developed from a survey data conducted along the same survey line (Figure 5.2A).

According to the grouping, the upper geo-electric layer of this profile also extends nearly up to 11.45m depth. The apparent resistivity value of this layer ranges from 2.26-92.3Ωm, which is may be the response of the top soil which is composed of white stiff silt clay, wet brown clay and Pleistocene to sub recent basalt intercalations. This layer has greater thickness and highly saturated in the southern part as compared with the northern part of the study area. Within this layer and at its bottom, at a distance of 280m, 580m and 860m along the traverse, is a depleted apparent resistivity response and this low resistivity area may be as the result of the saturated top soil and structural weakness.

The layer underlying this conductive top layer could be welded tuff and highly fractured scoracious basalt extending from a depth of about 11.45 to 31.3m and it is approximately 20m thickness from the underlying layer. When the inverse model section is closely examined, three zones of subsurface weakness are clearly apparent. However, two regions of subsurface discontinuity extending to greater depth and they are located around 280m and 580m. These are deduced to be fractures that are may be used as the conduit for the water possibly seeping from the Merti-Fental canal. The last layer is an extensive region of relatively high resistivity (92.3-12968Ωm), again with discontinuity regions extending to depth at four locations.
Figure 5-2 Interpretation of geophysical data of profile-2 (A) magnetic anomaly profile plot, (B) 2D inversion model electrical resistivity section and (C) borehole log BH-60.
This layer is interpreted as the welded tuff and highly fractured basalt and the variations in resistivity are the responses of various degree of weathering and alteration of the rock units.

The analytic signal profile along the 2D electrical imaging of profile-2 is also shown in the top part of Figure (5.2A). This profile also shows significant slope variations in the magnetic analytic signal signatures along the traverse. The plot exhibits considerable slope variation at 280m and 580m. These could be responses of fractures filled with water saturated materials showing variation in slope. There is a positive correlation between the magnetic anomaly plots with the 2D electrical imaging profile in detecting the masked weak zones.

5.1.4 Profile Line-3

Profile three (P3) runs from coordinate 590451E, 980555N to 590727E, 981500N at elevation of 999m to 1008m. It was conducted along similar orientation with the above two profiles and it covering a length of 990m. Accordingly, data was collected from 2727 data points, in which after filtering the noisy data only 2681 data points were used for the inversion purpose.

The inversion model section of this profile (Figure 5.3B) is produced by least square inversion with the RES2DINV software having RMS error of 10.6% after 5 iterations. Analogous to the above two profiles, the different segments of the inversion model section are clustered into three layers in conformity with the geological information from the borehole BH-50B. And it is correlated with the magnetic anomaly profile plot (Figure 5.3A) developed from survey data conducted along similar survey line.

The 2D electrical resistivity section obtained on this profile is characterized by a high degree of fracturing. Along the profile, the upper layer of this profile is very thin in thickness which is not more than 10m and it shows lateral variation along the survey line. This layer has apparent resistivity value which ranges from 4-155Ωm as a response of the fresh, jointed vesicular basalt and massive fine grained basalt. The second layer has an apparent resistivity value ranging from 155Ωm to 202Ωm and also has an average thickness of 42m beneath the upper layer and depth varying between 10m to 52m and extends to depths 65m between 520m and 760m at the central section.
Figure 5-3 Interpretation of geophysical data of profile-3 (A) magnetic anomaly profile plot, (B) 2D inversion model electrical resistivity section and (C) borehole log BH-50B.
This horizon, which has higher resistivity value, could be geologically interpreted as fine to coarse grained scoria, fresh, massive welded tuff and fresh, jointed, fine grained vesicular basalt. It is likely representing the zone of water possibly passes into Lake Beseka. This layer appears to be a single unified block which was later broken apart into a number of blocks due to the tectonics activities. From the inverted sections, five zones of subsurface weakness are clearly apparent. These regions of subsurface discontinuity extending to greater depth and located around 150m, 330m, 560m, 740m and 900m. These could be interpreted as fractured zones through which fluid circulation from the surface and shallow depths are possible. Under this layer, there is a very low resistivity zone within the depth of 55-65m. It is bounded by two intruded basaltic rocks. Therefore, the very low resistivity at the greater depth is possibly due to welded tuff, silty clay and water percolation from the surface along the fractures.

The analytic signal signature obtained from the residual magnetic plot along this traverse shows considerable variation in slope. As shown from the plot the slope of analytic signal has shown considerable variation at 150m, 330m, 560m, 740m and 900m. These slope changes roughly coincides with the 2D electrical resistivity profile plot to identify the weak zones. The analytic signal profile clearly shows the presence of weak zones which could be interpreted as fractures from the 2D electrical resistivity section.

5.1.5 Profile Line-4

Profile four (P4) runs from coordinate 593465E, 984022N to 593233E, 984605N at elevation of 960m to 967m covering a length of 630m. It is surveyed along a near SE-NW direction and lies South-East of the WWDSE camp. On this profile, electrical imaging data were collected from 1539 data points. However, about 1524 data points were used for inversion after automatic filtering and deleting the noisy data by inspection from the data set.

The least square inversion, done using RES2DINV software, were resulted a good quality inversion model section (Figure 5.4B) with RMS error of 2.3% after 6 iterations. In correlation the section with the available borehole BH-02, the same number of layer like in the other profiles discussed above were obtained.
Figure 5-4 Interpretation of geophysical data of profile-4 (A) magnetic anomaly profile plot, (B) 2D inversion model electrical resistivity section and (C) borehole log BH-02.
The first layer of the segment signaled a very deplete apparent resistivity response ranging from 5.25 to 34.6Ωm at this zone could be attributed to weathered welded tuff, pumice, fractured ignimbrite and the saturation of layer from seepage water from the canal. The thickness of this layer varies from 1.25 to 14m and it is characterized by a high degree of fracturing.

The apparent resistivity of the second layer is relatively high and ranges from 55.5-143Ωm which may be the response of weathered scoracious basalt, scoria and basalt. This layer extends to 53.3m (approximate thickness of 40m).

At a distance of 400m and 490m this layer shows a relatively deplete apparent resistivity response and this low resistivity area may be the result of structural weakness at the middle and north-west of the section.

Beneath this second layer, there is a small region almost similar to the top layer in apparent resistivity response, again with discontinuities regions extending to depth at two points. This layer is interpreted as the response of welded tuff, which could be saturated by the ground water.

The slope of the analytic signal profile (Figure 5.4A) conducted along profile four one show considerable variations in slope at a distance of 300m and 490m from the south-east part of the study area. These changing in slope depicted in the profile plot line indicate the presence of weak zones. Furthermore, the location at which all the structures found in both, magnetic and electrical resistivity tomography, methods nearly coincides.

5.1.6 Profile Line-5

Profile five (P5) runs from coordinate 593992E, 984028N to 594235E, 984794N at elevation of 959m to 960m covering a length of 810m. It is surveyed along a near S-N direction and approximately 300m far from the resort/lodge, in which it is located at the western edge of Lake Beseka, presumably parallel and approximately 500m far from profile four.

On this profile, electrical resistivity imaging data were collected from 2133 data points. However, about 1946 data points were used for inversion after automatic filtering and deleting the noisy data by inspection from the data set.
Figure 5-5 Interpretation of geophysical data of profile-5 (A) 2D inversion model electrical resistivity section and (B) borehole log BH-57.
The least square inversion, done using RES2DINV software, were resulted a good quality inversion model section with RMS error of 8.3% after 5 iterations. The geo-electrical segments in the inverse model resistivity section of profile-5 are grouped into three geological layers in conformity with the geological information from the borehole BH-57 in Figure 5.5.

When the inverse model section is closely examined, the first layer shows a relatively medium apparent resistivity response that varies from 14.3 to 141Ωm. This resistivity variation in the geo-electric section could be due to a dry top soil of silty sand and a highly weathered ignimbrite. The thickness of this layer extends from the surface up to 9m and its thickness increase as goes to the north. The second layer has a relatively highly deplete apparent resistivity ranges of 0.465 to 14.3Ωm also has an average thickness of 33m and extends to depths of 65m between horizontal distance of 400m and 610m. The geological interpretation of this layer is it comprises greenish fresh and hard welded tuff. This layer is affected by salinity and is with high moisture content as a result of seeping water from the secondary and tertiary canals. The layer underlying this conductive layer could be weathered basaltic rock extending from a depth of about 43 to 65m (22m thickness from the above layer) and it has a horizontal extension up to 400m and a small portion of it is found at 660m.

From the inverted sections, two zones of subsurface weakness are clearly apparent, which are extending to greater depth around 400m and 610m from the beginning of the survey line is indicated. These could be an extension structure of profile-4 and interpreted as fractured zones. This may act as the recharging path of water for the Lake Beskea.

5.2 MAGNETIC DATA

An important objective in the interpretation of potential field data is to improve the resolution of observed data. In magnetic prospecting, in areas of limited exposure, delineating lateral change in magnetic susceptibilities provides information not only on lithological changes but also on structural trends (oruc et.al., 2011). Ground magnetic survey was carried out in West of Lake Beseka along the traverses over which the electrical imaging surveys were carried out, during June of 2013. The main target of the survey was to identify and delineate qualitatively the basement rock structures, their distribution and trends, in the study area. After applying all the necessary reductions, the magnetic anomaly maps are prepared.
5.2.1 Profile Line-1

The survey was located between latitudes 588118 and 588012 and longitude 973264 and 973709. The survey was conducted along profiles taking S-N directions. From the total magnetic field map Figure 5.6A three main anomaly zones outlined. These zones named as, A a high magnetic anomaly zone with amplitude greater than -96nT, an intermediate zone B between the range -96nT and -196nT, and C marked by low amplitude less than -196nT are observed distributed within different parts of the surveyed area.

Zone A occupies most part in the southern and north-west localities. The low magnetic zone C is observed to be disturbed as broad zones in the north-western and central area and the intermediate zone B covers most parts of the study area between the high and low magnetic anomaly zones.

The analytic signal method, known also as the total gradient method, produces a particular type of calculated gravity or magnetic anomaly enhancement map used for defining the edges (boundaries) of density geologically anomalous density or magnetization distributions. Analytic signal maxima have the useful property that they occur directly over faults and contacts, regardless of structural dip which may be present, and independent of the direction of the induced and/or remnant body magnetizations (Saad et al., 2010).

As can be observed from the analytic signal map the south central and the outermost south eastern corner localities are marked by low and intermediate analytic signal. These localities correspond to the high magnetic zone A shown in the total magnetic field map. The broken line in Figure 5.6C is marked as NW-SE and N-S lineament showing possibility of fractures in the area that might extend beyond the two directions.

5.2.2 Profile Line-2

The survey was located between latitudes 587558 and 587686 and longitude 976134 and 976717. The survey was conducted along profiles taking S-N directions. From the total magnetic field map Figure 5.7A three main anomaly zones outlined.

These zones named as, Zone A a high magnetic anomaly zone with amplitude greater than 92nT that could possibly be the response from rocks which have high susceptibility. The second zone is an intermediate zone B between the range 92nT and -260nT. This region covers the middle section western and the north-east portion of the map, and zone
Figure 5-6 Profile-1 survey (A) Magnetic Anomaly Map (B) Magnetic Residual Map (C) Analytic Signal Map
C marked by low amplitude less than -260nT are observed distributed within the extreme eastern part of the surveyed area.

The analytic signal map Figure 5.7C reveal important features that could interpret as structural weaknesses. These features are directly related to the magnetic susceptibility of the causative bodies as well as the structures. As can be seen from the Analytic signal map the NW and SE localities are marked by low analytic signal. These localities correspond to the high magnetic zone A shown in total magnetic anomaly map. The magnetic low zones indicated zone C in Figure 5.7A are observed to be associated to strong analytic signal amplitude in the NE-SW and N-S area where as in the central part, north-west intermediate low and south-west intermediate high analytic signal amplitude characterizes the area. The traces of the N-S and NE-SW lineaments at depth are evidenced from the fracture around western edge of sub recent basalt.

5.2.3 Profile Line-3

The survey was located between latitudes 590499 and 590853 and longitude 980771 and 981913. The survey was conducted along profiles taking S-N directions. From the total magnetic anomaly map Figure 5.8A three main anomaly zones outlined. These zones named as, Zone A, a high magnetic anomaly zone with amplitude greater than -127nT that could possibly be the response from basic rocks which have high susceptibility. This zone occupies most part in the north-east and south-west localities. The second zone is an intermediate zone B between the ranges -127nT and -293nT are observed distributed within different parts of the survey area, and zone C marked by low amplitude less than -293T are observed distributed within the central eastern and extreme south eastern part of the surveyed area.

As can be seen from the analytical signal map the north eastern, western central and the southern localities are marked by high analytic signal. The analytic signal (Figure 5.8C) was calculated for the target area of interest to extract the location of magnetic sources contacts or edges.

Analysis of the analytic signal confirm the existence of abnormal limiting/or bounding structures (anomaly peaks). These lineaments/contacts are trending NE-SW directions and marked as dividing the positive anomalies in their respective places.
Figure 5-7 Profile-2 survey (A) Magnetic Anomaly Map (B) Magnetic Residual Map (C) Analytic Signal Map
Figure 5-8 Profile-3 survey (A) Magnetic Anomaly Map (B) Magnetic Residual Map (C) Analytic Signal Map
5.2.4 Profile Line-4

The survey was located between latitudes 59.3262 and 59.3045 and longitude 98.4464 and 98.3635. The survey was conducted along profiles taking S-N directions. From the total magnetic anomaly map Figure 5.9A three main anomaly zones outlined. These zones named as, Zone A, a high magnetic anomaly zone with amplitude greater than -39nT that could possibly be the response from sub-recent basaltic rocks which have high susceptibility. This zone occupies most part in the northern localities. The second zone is an intermediate zone B between the ranges -39nT and -233nT are observed distributed within different parts of the survey area, and zone C marked by low amplitude less than -233nT are observed distributed within the south-western part of the surveyed area.

The amplitude of the analytic signal has desirable properties for the interpretation of magnetic anomalies (Nabighian, 1974); specifically, the maxima of this function overlie the source edges and are related to the source depth.

From the observation of the analytic signal map the west central and the south western, extreme north eastern corners are marked by high analytic signal. These localities correspond to the low magnetic zone A and intermediate zone B shown in the total magnetic field map. Analysis of the analytic signal (Figure 5.9C) confirms the existence of abnormal bounding structures (anomaly peaks). These high analytic signal zones are trending in the NE-SW and N-S direction.

5.2.5 2D Profile Modeling

Modeling is done using the GM-SYS modeling software. It is an interactive forward modeling program which calculates the magnetic response from a user defined hypothetical geological model. Any difference between the model response and the observed magnetic field are reduced by refining the model structure. It should be noted that magnetic models are non-unique, i.e. many earth models can produce the same magnetic response, and similarly, several geological lithology may be interpreted from a given model block’s susceptibility properties. It is therefore important to use as many independent source of information as possible to help constrain the model.

According to 2D magnetic modeling is developed along profile-1 from the analytic signal map as shown in Figure 5.10. This model is developed based on the information from the inverted model section of electrical resistivity imaging and the borehole data (BH-62).
Figure 5-9 Profile-4 survey (A) Magnetic anomaly Map (B) Residual Magnetic Map (C) Analytic Signal Map
The developed model has an error 0.664 and it matches with all the maps and curves developed along profile from the different methods in displaying the layering and fracture location. Based on this model, the fractures are located at 110m, 280m, 600m and 660m from the north and this is consistent with the map and model discussed above.

Figure 5-10 2D magnetic modeling along profile-1
CHAPTER SIX
CONCLUSION AND RECOMMENDATION

6.1 Conclusions

An integrated geophysical survey for investigating the possible inflow of water into Lake Beseka from the Merti-Fentale irrigation canal has been conducted around Lake Beseka, around Metahara area. The site is located close to Metahara town, 200Kms east of Addis Ababa, at western side of Lake Beseka parallel to Merti-Fentale irrigation canal. The geophysical surveys included ground total field magnetic and 2D electrical resistivity imaging surveys. From the resistivity and magnetic data collected at field different maps and curves including inverted 2D model section maps, magnetic anomaly maps, analytical signal maps, and magnetic anomaly profile plots were developed using different mapping and interpretation software. These plots were closely examined for interpretation, mostly qualitative, of the results of the work. Borehole/lithological log data were also used for correlation during interpretation. Based on the combination of geophysical methods employed in the survey and correlation with existing borehole data the following results are obtained.

- A number of vertical or nearly vertical fractured zones were mapped over all the electrical resistivity imaging lines. These structures are extending to a larger depth and potentially act as conduits for the fresh water which come from the Merti-Fentale canal to saturate the subsurface and the excess waters flow into Lake Beseka. It is concluded that the contribution of these vertical structures to the increase in volume of Lake Beseka is significant.

- From 2D imaging maps, the shallow to intermediate depth subsurface in the study area is interpreted to comprise of three layers, of which the top most layers are highly saturated by fresh water. The sources of these large areas of fresh saturating fluid are believed to be from the leakage of the Merti-Fentale canal.

- The high degree of saturation seems to arise not only from the leakage of the canal but improper and excessive irrigation in the farms.

- Ground magnetic signatures have been used to interpret the position of possible related structures. The magnetic analytic signal images are used to highlight these targets. These maps have identified different lithological units and show maxima over the discrete bodies of prominent structures.
High disturbance in the magnetic anomaly characterizes the study area. The disturbances diagnose the presence of the local and traces of the regional structures in the area and the analytic signal map shows these structural features that have a depth extent.

The analytical signal /or total gradient method delineated a number of NW-SE, N-S and NE-SW trending structures.

The change in slope in the magnetic profile plots depicted the presence of vertical and nearly vertical contact zones that correspond well with the electrical tomography maps that as well indicate the presence of fractured zones. Furthermore, there is a very good / in fact remarkable correspondence in the location of these weak zones and structures, from the magnetic and electrical resistivity tomography, plots.

There is excess irrigation water flowing from the canal leakage or improper irrigation in the farms that could indeed contribute to the accelerated Lake Beseka level rise.

6.2 Recommendations

Based on the discussion and conclusions made above the following points are recommended and/or suggested:

- The un-cemented, not piped or geo-membrane covered canal routes especially in areas of basaltic rocks must be given special consideration to protect leakage of water from the canal. Extensive works are required to isolate or line up these zones using pipes, cement or plastic membranes.

- The amount of water which is siphoned out from the canal into the farmland must be in controlled manner. It is observed that the subsurface is highly water saturated and the excess irrigation waters from the secondary and tertiary canals which are extending up to the lake periphery could be an important factor for Lake Beseka level rise.

- The activity of pumping and draining the Lake water into the Awash River during rainy seasons is not the best alternative to bring the level of the Lake under control. The lake level is still rising due to irrigation excess water from the nearby Abadir farm and the Merti-Fentale Project canal and the remedy should also focus on managing these water schemes.
- The farmers who are farming at the western side of the Lake, using the water from the canal, should be educated to manage and use the irrigation waters more economically like using drop water irrigation methods.
- Additional electrical imaging and ground magnetic surveys must be conducted at the western side of the Lake, to fill the gaps in between the traverse lines, so as to ascertain the extension of the fractures mapped with this survey into even elevated and non-flat areas of the canal path.
REFERENCES


65


APPENDICES

Appendix 1 Geographical coordinates of geophysical imaging data points

This line is on the western side of the lake crossing two low lying depressions (Stream sections) in an area where there could potentially be flow to the lake from the canal passing west of the line.

<table>
<thead>
<tr>
<th>P.No.</th>
<th>Area</th>
<th>Electrode No.</th>
<th>Easting</th>
<th>Northing</th>
<th>Elevation</th>
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<td>973236</td>
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<td>973300</td>
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Line running nearly S to N in the Amuma valley. We have set the line in the lowest portion where the basaltic flows taper the valley outlet towards lake Beseka.

| P2    | Amuma     | Easting     | 587430      | 975865      | 1042      |
|       |           | Northing    | 587472      | 975935      | 1036      |
|       |           | Elevation   | 587511      | 976016      | 1035      |
|       |           |             | 587542      | 976090      | 1035      |
|       |           |             | 587594      | 976184      | 1035      |
|       |           |             | 587645      | 976264      | 1035      |
|       |           |             | 587684      | 976334      | 1035      |
|       |           |             | 587707      | 976430      | 1035      |
|       |           |             | 587735      | 976517      | 1034      |
|       |           |             | 587766      | 976602      | 1034      |

West of Beseka lake parallel or along to a canal/ diverting Awash river. This is in the farm land for mainly corn, onion and pepper. To check whether the water in the canal is sipping/ percolating in the ground water system. S-N orientation.

| P3    | South Illala | Easting     | 590451      | 980555      | 1005      |
|       |              | Northing    | 590476      | 980638      | 1005      |
|       |              | Elevation   | 590500      | 980727      | 1004      |
|       |              |             | 590521      | 980811      | 1004      |
|       |              |             | 590547      | 980896      | 1003      |
|       |              |             | 590597      | 980984      | 1003      |
|       |              |             | 590597      | 981071      | 1003      |
|       |              |             | 590612      | 981159      | 1003      |
|       |              |             | 590638      | 981244      | 1003      |
|       |              |             | 590665      | 981329      | 1003      |
|       |              |             | 590696      | 981415      | 1003      |
|       |              |             | 590727      | 981500      | 1003      |
|       |              |             |             |             | 1005      |
|       |              |             |             |             | 1005      |
|       |              |             |             |             | 1007      |
|       |              |             |             |             | 999       |

This line is on the west side of the lake, south-east of the WWSDE camp. It run from south to north nearly parallel to the lake and is ≈ 300 m from the resort/lodge.

| P4    | Illala     | Easting     | 593992      | 984028      | 960       |
|       |           | Northing    | 594013      | 984113      | 960       |
|       |           | Elevation   | 594045      | 984197      | 964       |
|       |           |             | 594072      | 984282      | 964       |
|       |           |             | 594097      | 984367      | 964       |
|       |           |             | 594131      | 984538      | 964       |
|       |           |             | 594162      | 984538      | 964       |
|       |           |             | 594188      | 984622      | 964       |
|       |           |             | 594214      | 984709      | 964       |
|       |           |             | 594235      | 984794      | 964       |

≈ 500 m west of line-4 following the valley line oriented “SW-NE” and presumably running parallel to line-4.

| P5    | Illala     | Easting     | 593465      | 984022      | 963       |
|       |           | Northing    | 593429      | 984102      | 963       |
|       |           | Elevation   | 593393      | 984185      | 964       |
|       |           |             | 593356      | 984265      | 964       |
|       |           |             | 593356      | 984350      | 965       |
|       |           |             | 593285      | 984431      | 967       |
|       |           |             | 593286      | 984434      | 963       |
|       |           |             | 593255      | 984517      | 963       |
|       |           |             | 593233      | 984605      | 960       |
### Appendix 2 Temperature and Rainfall data of Metahara area

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<th>Rainfall (mm)</th>
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</tr>
<tr>
<td>Mar</td>
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<td>49.4</td>
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<tr>
<td>Apr</td>
<td>26.9</td>
<td>46.8</td>
</tr>
<tr>
<td>May</td>
<td>27.8</td>
<td>35.4</td>
</tr>
<tr>
<td>Jun</td>
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<td>24.1</td>
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<td>Jul</td>
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Appendix 3 Lithological log of borehole
## WELL LOG

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<th>Drilling Date</th>
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<td>591413</td>
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| SWL | 951.65 |       |                   |

**Scales (1: xxx)**

- **Vertical**
- **Horizontal**

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<th>Depth [m]</th>
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<th>Annulus</th>
<th>Casing</th>
<th>Screen</th>
<th>Lithology</th>
<th>Elev. [m]</th>
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72
## WELL LOG

**Well Ident:** BHI-02  
**Drilling Method:** PERCUSSION  
**Drilling Date:** 09/09/96

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**Scales:** (V: xxx)  
- Vertical  
- Horizontal

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<td>995</td>
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- Gravel Pack  
- Well thoroughly developed for 24 hours by pumping and surging
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<td>31.55</td>
<td>Greenish</td>
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</tbody>
</table>

**Lithology**
- Bily sand.
- Greenish fresh and hard welded tuff.
- Greenish weathered.
DECLARATION

I hereby declare that the thesis entitled “Integrated Geophysical Investigations for the possible inflow of water from Merti-Fentale Irrigation Cannel into Lake Beseka, Metahara area, Eastern Ethiopia” has been carried out by me under the supervision of Dr. Tigistu Haile during the year 2013 as part of Master of Science program in Exploration Geophysics. I further declare that this work has not been submitted to any other University or institution for the award of any degree or diploma and all sources of material used for the thesis have been duly acknowledged.

Addisu Haile Tedla

Signature

Place and date of submission: School of Earth Sciences, Addis Ababa University

June, 2014