ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCES

DEVELOPING A CONCEPTUAL MODEL OF EASTERN SHALLA GEOTHERMAL PROSPECT ON THE BASES OF GEOLOGICAL AND FLUID GEOCHEMICAL OBSERVATIONS

BY

FETUM ADEM AHMED

June 2019

Addis Ababa, Ethiopia

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCES

DEVELOPING A PRILIMINARY CONCEPTUAL MODEL OF EASTERN SHALLA GEOTHERMAL PROSPECT ON THE BASES OF GEOLOGICAL AND FLUID GEOCHEMICHAL OBSERVATION

BY

FETUM ADEM AHMED

ADVISOR: GEZAHAGN YIRGU (Prof.)

CO-ADVISOR: MR. SOLOMON KEBEDE

A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for theDegree of Master of Science in Earth Sciences (Geothermal Energy)

June 2019

Addis Ababa, Ethiopia

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCES

DEVELOPING PRILIMINARY CONCEPTUAL MODEL OF EASTERN SHALLA GEOTHERMAL PROSPECT ON THE BASES OF GEOLOGICAL AND FLUID GEOCHEMICHAL OBSERVATION

BY

FETUM ADEM AHMED

Approved by the Examining Committee

Dr. Balemwal Atnafu	_______________	______________
Head, School of Earth Sciences	Signature	Date
Prof. Gezahagn Yirgu	_______________	_______________
Advisor	Signature	Date
Mr. Solomon Kebede	______________	______________
Co-Advisor	Signature	Date
	______________	_______________
Examiner	Signature	Date
	______________	_______________
Examiner	Signature	Date

Declaration of Originality

I hereby declare that the thesis is my original Master‘s degree work under the supervision of Prof. Gezahagn Yirgu and Mr Solomon Kebede, at the School of Earth Sciences, Addis Ababa University during the year 2019. I further declare that this work has not been presented or submitted to any other university or institution for the award of any degree or diploma. All sources and materials used for the thesis have been duly acknowledged.

Fetum Adem Ahmed __________________ _____________________

Signature Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Prof. Gezahagn Yirgu (Advisor) _______________ _______________

Signature Date

Mr. Solomon Kebede (Co-Advisor) _________________ ___________________

Signature Date

Abstract

The thesis is focused on developing a preliminary conceptual model of Shalla geothermal prospect in the Main Ethiopian Rift (MER), Ethiopia on the bases of geological and water geochemical information. The Shalla prospect is one of the geothermal prospects in the Lakes district of the MER, which is located about 220 kms south of Addis Ababa. The area is largely occupied by Lake Shalla which has no surface outlet and receives discharge from Lakes Ziway, Langano and Abijata. Many hot and warm springs emerge along its eastern, southern and western shores. The most important and boiling thermal springs are located at the eastern part of the shore. The main objective of this study is to develop preliminary conceptual geothermal model of the prospect. For this purpose 7 hot spring water samples for geochemical analyses and 8 exposed rock samples for petrographic analysis were taken. Based on the petrographic descriptions four major lithologic types are identified. These are ignimbrites, rhyolite lavas, basaltic flows and lacustrine sediments. From the results of analyzed water samples, an estimate of the sub-surface temperature, the water type and the water rock interactions of the springs are proposed. Chemical evaluation using a Cl-SO4-HCO3 triangular diagram suggests that the existence of **Na-Cl-HCO3** water types with a high, HCO3 and Na content and mature waters (Cl rich) in the study area. The sub-surface temperatures of the geothermal reservoirs were estimated by T-2 (Na-K), T-(K-Ca) and T-(K-Mg) geothermometers. The Na–K solute geothermometers provided reliable estimated temperatures of about 140^0C and the K-Mg geothermometers gave temperature of about 225^0C. But the K-Ca solute geothermometry provided very high temperature slightly greater than 500^0C and this is considered not suitable. The Na/400-25 K/10-$\sqrt{}$Mg ternary diagram was also applied to evaluate the equilibrium of water with reservoir rock. It is indicated that all water samples have reached in the partial equilibrium or lie in mixed zone. The preliminary conceptual model shows the general geothermal system of the prospect that includes the probable heat source and reservoir, the cap rock, recharge zone and geothermal fluid flow circulation.

Key words: Conceptual model, Eastern Shalla geothermal prospect, geothermal fluid , geothermal system, , Geothermometers, Hot spring,

Acknowledgment

Before starting acknowledging any one and any organization, I would like to give thanks to Allah for everything like for giving me a chance for Master’s degree and also for helping me from beginning to end of my work. There is nothing to do without help of Allah. Alhamdulillah.

Next to Allah, this research work is done by contribution of different organizations and individuals I would like to thank many persons and organizations, who so generously contributed to the work presented in this thesis.

Firstly I would like to give my sincere gratitude to Bahir Dar University School of Earth Sciences for providing an opportunity to study my Master‘s degree and funding a research project. Besides, special mention to the instructors and mentors at Addis Ababa University, School of Earth Sciences for their unlimited academic support during my study.

My second deepest gratitude goes to my advisors Prof. Gezahagn Yirgu and Mr. Solomon Kebede for follow-up, constructive comments, valuable suggestion, encouragement and tireless support at various times.

During the research work I got a lot of support from my friends and colleagues. I wish to express my sincere appreciation to them from deep of my heart.

My acknowledgement goes to my special persons to my husband Mr. Selahadin Muhammed Rabi and to my family, especially to my father Mr. Adem Ahmed, my mother Ms Kemerya Yassin and to my sisters Feyruz and Samiya for giving me courage and unforgettable almost unbelievable support while Iwas in the project work. They are the most important people in my world and I dedicate this thesis to them.

Table of Contents

Abstract i

Acknowledgment ii

List of Figures v

List of tables v

List of acronyms vi

1. INTRODUCTION 1

1.1. Background 1

1.2. General description of the study area 3

1.2.1. Location and Accessibility 3

1.2.2. Physiography and drainage 5

1.2.3 Climate condition and Vegetation 7

1.2.4 Population and settlement 7

1.3 Problem Statement 8

1.4 Objectives 8

1.4.1 General Objective 8

1.4.2 Specific Objectives 8

1.5. Research Methods 8

1.5.1. Introduction 8

1.5.2 Field work 9

1.5.3. Laboratory and Data analyses 10

1.6 Expected outcome and research relevance 10

1.7 Review of previous work 11

1.8 Thesis Overview 14

2. RIGIONAL GEOLOGICAL SETTING 15

2.1. East African Rift System (EARS) 15

2.2. Main Ethiopian Rift System (MERS) and its volcano-tectonic activity 16

2.2.1. Introduction 16

2.2.2. Structure and volcano tectonic activity in MER 19

2.2.2 The Wonji Fault Belt 22

3. Geology of Eastern Lake Shalla area 26

3.1. Introduction 26

3.2 Lithology and Petrographic description 27

3.2.1. Rhyolite 27

3.2.2. Ignimbrites 29
3.2.3 Recent Basaltic flows 31
3.2.4.Lacustrine Sediments 33
3.3. Geothermal Manifestations 33
3.3.1. Hydrothermal Manifestations 33
3.3.2. Steam vents and Limonite Deposits (Clay deposit) 36
4. Whole Water Chemistry results 38
4.1. Introduction 38
4.2. Laboratory Analysis 39
4.2.1. Accuracy of Analysis 39
4.3. Interpretation of Geochemical Results 41
4.3.1. Classification of water types using relative Cl, SO4 and HCO3 ternary diagram. 41
4.3.2. Chemical Geothermometry 44
4.3.3. Water-Rock interaction 47
5. Preliminary conceptual model of the prospect 49
5.1. Introduction 49
5.2. Regional structural setting and hydrothermal manifestations 49
5.3.1 Major faults 49
5.3. Water chemistry 51
5.4. Assessment of geothermal system 52
5.2.1. Heat source 52
5.2.2. Cap rock 53
5.2.3. Thermodynamic and chemical characteristics 53
5.2.4. Recharge 54
6. Conclusions and Recommendations .... **Erreur ! Signet non défini.**
6.1. Conclusions 57
6.2. Recommendations 58
Reference 59

List of Figures

Figure 1.1. Location Map of Study Area 4

Figure 1.2. Accessibility map 5

Figure 1.3. Physiographic Map of the area 2-D (below), 3-D (upper) taken from report of GSE6

Figure 1.4. Drainage map of the study area 7

Figure 2.1. Regional map of the East African Rift. E.A.P stands for East African Plateau and M.E.R for Main Ethiopian Rift on which the study area is located. (Maguire et al., 2005 pp. 270) 15

Figure2.2. Topographic map of the Main Ethiopian Rift (MER) indicating the three main sectors (northern, central and southern, i.e., NMER, CMER, and SMER). The surface faults (mapped by Agostini et al., 2011) are shown in blue. Earthquake locations and focal mechanisms for the region are from the Global Centroid Moment Tensor Project catalogue (http:// www .globalcmt .org; 1976–2012; M > 5). Red triangles identify volcanic centers thought to have been active in the Holocene (Siebert and Simkin, 2002). White stars identify major centers of population (after the Socioeconomic Data and Applications Center, http:// sedac .ciesin .columbia .edu/): (Hutchison et al., 2015). 19

Figure 3.11. Eastern Shore of Lake Shala (prospect area) 34

Figure 3.12. Mud pool at eastern shore of lake shalla (upper left), hot springs with 990C and 97.50C respectively at Eastern shore of Lake Shala (upper right and lower left), fumaroles with 57˚c in temperature North of Sembete town (lower right) 35

Figure4.2. Na-K-Mg ternary diagram for water sample from Eastern shalla geothermal prospect 43

Figure 4.3. Na-K-Mg and Cl-SO4-HCO3 piper plot diagram. 43

Figure 4.4. Geothermometry plot for sampled water from Eastern Shalla geothermal, T-(Na-K) The upper, T-(K-Mg) the middle and T-(K-Ca) the bottom 47

Figure 4.5. Na/400-K/10-√Mg plot for sampled waters from Eastern Shalla geothermal prospect 48

Figure 5.1. preliminary conceptual Mode of The prospect 56

List of tables

Table 4.1*: Analytical Methods used by Oromiya Water Work Design and Supervision Laboratory……39*

Table 4.2 *Field Measurement of Samples Collected from Eastern Shalla Geothermal Area……40*

Table 4.3. *Chemical analyses results of water samples collected from Eastern Shalla geothermal area. (Concentrations in mg/l)……41*

Table 4.4*: Deep Temperature calculated using solute geothermometers for water from Lake Shalla Geothermal area……45*

Table 4. 5. *Temperature equations (in ◦C) for geothermometers (concentrations in mg/L)*……………………………………………………………………………………......45

List of acronyms

CME	Central Main Ethiopian Rift.
EAR	East African Rift
EARS	East African Rift System
EMA	Ethiopian Mapping Agency
ESE	East South East
E-W	East west
GOE	Government of Ethiopia
GSE	Geological Survey of Ethiopia
ITCZ	Inter tropical Convergence Zone
Km-	Kilometer
Kms	Kilometers
M	Meter
MER	Main Ethiopian Rift
MoWE	Ministry of Water & Energy
NE	North East
NMER	Northern Main Ethiopian Rift
NNE-SS	North north east- South South East
N-S	North South
RRF	Roge Rafu Fault
SMER	South main Ethiopian rift
SW	South West
UNFCCC	United Nations Framework Convention on Climate Change
WFB	Wonji falt belt
YTVL	Yerer-Tullu Wellel Volcano-tectonic Lineame

1. INTRODUCTION

1.1. Background

With the increase in world population, industrialization and improvement in the standard of living, there has been a continuous increase in consumption of energy. Hot springs have been used for balneological purposes from times immemorial. However, the use of Earth's heat as a source of energy began in the early 20th century when electricity was produced for the first time from geothermal steam at Larderello, Italy in 1904 (Gupta and Roy, 2007). Alternative sources of energy are gaining importance for one's country development and geothermal energy is one of them. Gupta and Roy, (2007) suggested that today more than 20 countries generate electricity from geothermal resources and about 60 countries make direct use of geothermal energy.

A geothermal resource can be simply defined as a reservoir inside the Earth from which heat can be extracted economically (cost wise less expensive than or comparable with other conventional sources of energy such as hydroelectric power or fossil fuels) and utilized for generating electric power or any other suitable industrial, agricultural or domestic application in the near future (e.g. Gupta and Roye, 2007)

The provision of reliable and affordable electricity is indispensable to the social and economic development of any country. Accordingly, the Government of Ethiopia (GOE) has devised an Electric Power Master Plan that addresses the development of indigenous energy such as geothermal and/or wind power, with recognition of the importance of energy diversity and energy mixture.

Among other indigenous types of energy, geothermal energy has become more important as a base load power, as well as, according to Meseret and Solomon (2010), there is a need to develop geothermal energy in Ethiopia in order to

- Help substitute to fossil fuel being imported,
- Provide a major backup to hydropower electricity supply,
- Service to arid and semi-arid areas in the country where hydropower is unavailable, and
- Contribution to the United Nations Framework Convention on Climate Change (UNFCCC) effort of reducing global warming.

Geothermal manifestations occur as fumaroles, altered grounds, steaming grounds and hot springs in many locations, most of which are associated with young volcanic fields in the rift valley. Hot springs also occur on the flanks of the rift where they are associated with Tertiary faulting episodes. The manifestations are more pronounced and vigorous within the axis of the rifts than on the flanks due to the favorable hydrology and relatively shallow heat sources. According to Omenda (2007) the heat sources for the geothermal systems are related to:

- Shallow magma chambers associated with the young rhyolite volcanoes that are common in the southern Afar and MER and
- Upper mantle intrusion/ upwelling associated with the thin crust in the area that averages between 5 – 20 km

As I stated above, stable supply of enough energy is a must for industrialization. However, the access to energy in Ethiopia is relatively low, as little as 16 %, while the average access rate of Sub-Sahara Africa is 26%. In addition to the low access rate to electricity, another problem in the energy sector is that Ethiopia is too dependent on hydro power (Solomon 2016), which causes severe power interruptions especially during the dry season/drought. Therefore, strengthening the energy supply is the key for the economic growth and macro-economic stability.

Ethiopia is endowed with a huge geothermal potential along main Ethiopian Rift (MER) which has not yet been used, and has only been explored to a limited extent. Geothermal power is a reliable, low-cost, environmental friendly, alternative energy supply and an indigenous, renewable energy source, suitable for electricity generation Meseret Teklemariam and Solomon Kebede (2010).

In Ethiopia, geothermal potential survey was commenced in 1969 (Meseret Teklemariam and Solomon Kebede (2010; Solomon Kebede 2012, 2016) . Since then, step-by-step potential surveys have identified more than 22 promising geothermal sites (Solomon, 2016) for electricity development. The total geothermal potential is estimated at 10,000MW (Solomon Kebede 2016). However, deep drillings for development have taken place in only two sites (Aluto Langano and Tendaho). The Shala prospect is one of the prospect areas; The Lake has no surface outlet and receives the discharge from Lake Ziway, Langano and Abyata. Many hot and warm springs emerge along its eastern, southern and western shores. The most important and boiling thermal springs located at the eastern part of the shore. This Eastern shore of Lake Shalla shows different geothermal manifestations like hot grounds, mud pools and hydrothermal springs recorded maximum temperature ranges from 97˚c to 100.1˚c. Where so far, there are no conceptual models to understand the system and commence development.

1.2. General description of the study area

1.2.1. Location and Accessibility

Location

The study area is located lying in the Great Rift Valley around Arsi Negele, in Oromia region, in the SE part of Ethiopia, some 235 km from the Capital city, Addis Ababa, The research area lies on the Negele Arusi Sub-sheet with sheet number 0738-D1 according to topographic map distribution of Ethiopian Mapping Agency (EMA). Geographically bounded by $7^0$24'14",$7^0$22'14" N Latitude and $38^0$41'14", $38^0$29'25" E Longitude, and on the elevation of 1570m above sea level. The area coverage of the study area is approximately 516 km^2.

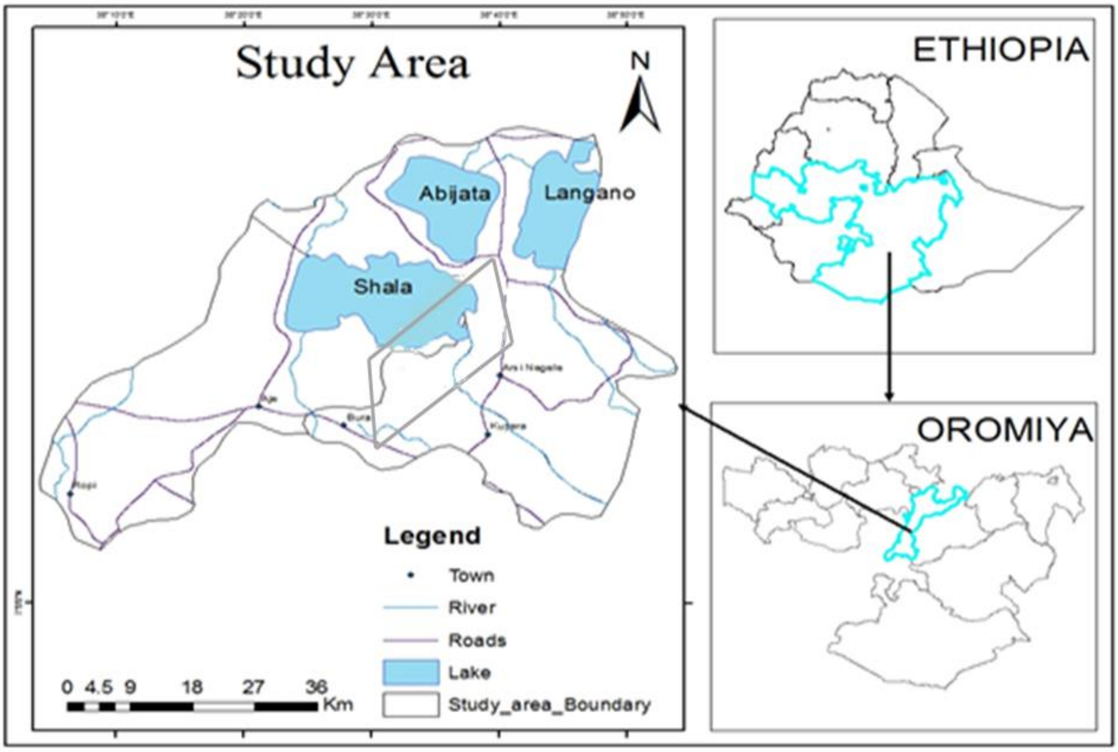


Figure 1.1. *Location Map of Study Area*

Accessibility

The area is accessible through Addis Ababa-Shashemene-Awassa road and driving through gravel road for about 20 km to the west

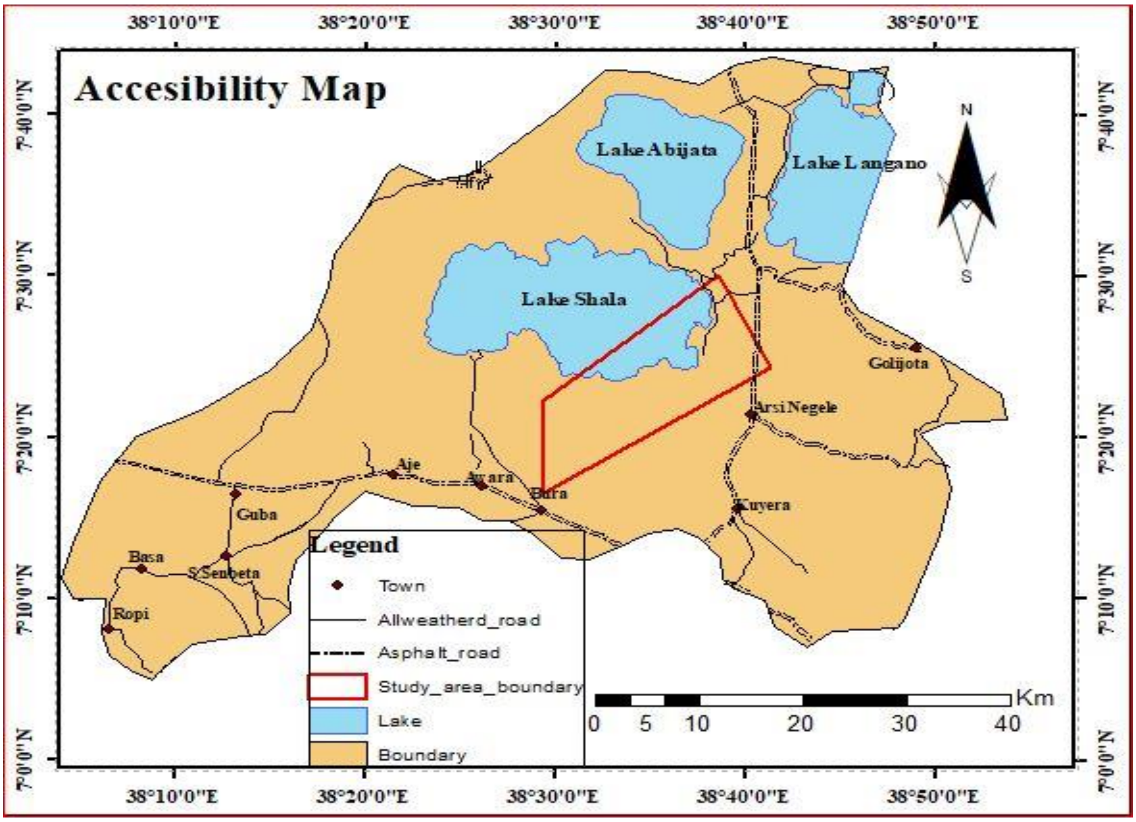


Figure 1.2. *Accessibility map*

1.2.2. Physiography and drainage

Physiography

The study area is located within Abijata-Shala national park, part of central main Ethiopian rift system; it is characterized by the presence of numerous lakes, calderas and volcanic cones. The area is surrounded by Pleistocene to Holocene phyroclastic and lake sediments.

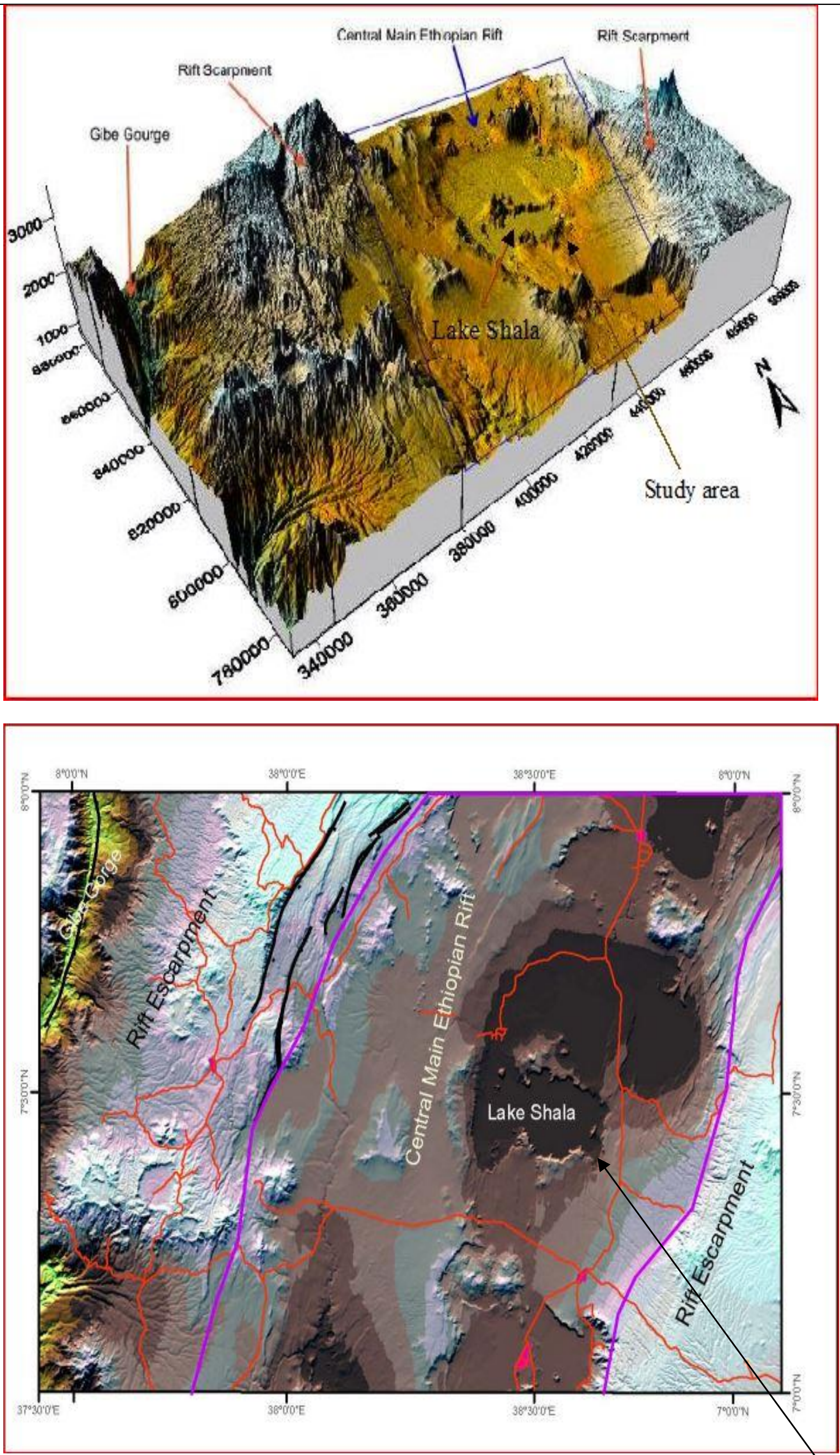


Figure 1.3. *Physiographic Map of the area 2-D (below), 3-D (upper) taken from report of GSE*

prospect area

Drainage

The drainage system of the area is characterized by parallel to sub parallel drainage system. All the streams around the area are flows in to Shala, Abijat and Langano lakes.

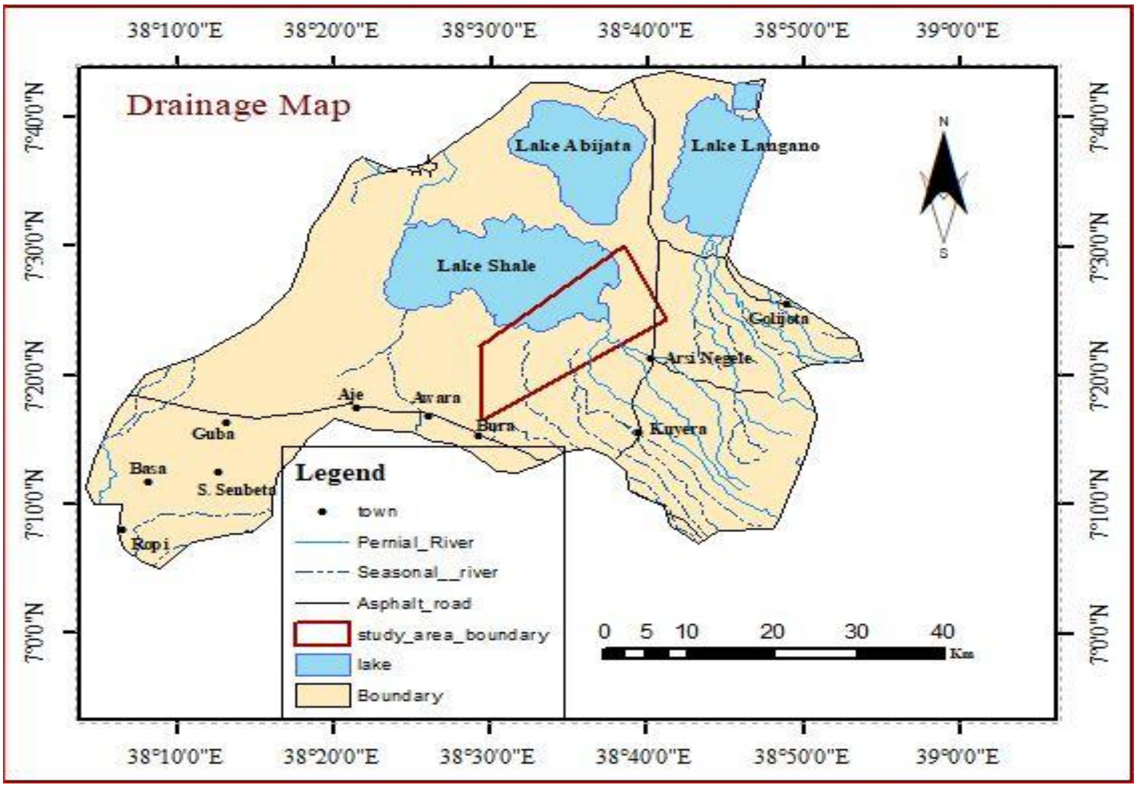


Figure 1.4. *Drainage map of the study area*

1.2.3 Climate condition and Vegetation

The study area is characterized by a semi-arid to sub-humid type of climate with mean annual precipitation and mean annual temperature of 600 mm and 25 ^{0}C close to the lakes, respectively (Bonnefille, R. 2010). The dominant vegetation is open Acacia woodland, which is extensively overgrazed and deforested because of encroachment (Bonnefille, R. 2010).

1.2.4 Population and settlement

The area designated as Park is occupied by Oromo's coming from Arsi, part of Oromiya Regional state. The people have the same culture, identity, and common traditional system which govern their society. The dominant religion is Islam. Administratively, the population is divided in smaller administrative units called Kebele

1.3 Problem Statement

There are a number of geothermal prospects in the MER and some have been studied in detail like Aluto Langano and Corbetti, but others, like Shala-Abijata Geothermal prospect have not been studied in detail.

Previous researchers studied the Shala-Abijata geothermal prospect, and identified thermal manifestations east of Shalla. However, the source area so far is not clearly known.Further, reservoir temperatures and fluid chemistry are poorly known .

Therefore, it is essential to establish a conceptual model of the hydrothermal system to postulate the source area and select well sites for the ultimate confirmation of the existence of a deep geothermal system for future development.

1.4 Objectives

1.4.1 General Objective

The main objective of this research study is to better understand the general geothermal system and to construct a preliminary conceptual model of Eastern Shalla geothermal prospect located in the central sector of the MER.

1.4.2 Specific Objectives

The specific objectives of the proposed research study are:

- To determine the type/chemistry of thermal fluids by conducting fluid geochemical analyses of the hot springs
- To assess underground deep temperatures of the prospect by conducting fluid geochemical analyses
- To estimate the depth of reservoir by using all available data

1.5. Research methods

1.5.1. Introduction

The overall work of the research are mainly divided into three phases; pre-field work, field work and post-field work. In the pre-field work assessment on literatures about the

methods that would be applied, about the study area accessibility, extent, and assessment on other relevant information related to the area are done. During field work and post-field work collecting, analyzing, synthesizing, presenting and interpreting of data are done. Two types of data are collected for the research; secondary and primary data
During the preparatory stages of the fieldwork, a logistic plan is made, and major geological structures are delineated and different lithologies are differentiated by using ArcGIS software with satellite imagery and DEM. The preliminary geological base map has been compiled from three different geological map sheets which are prepared by geological survey of Ethiopia.

After collecting data the next step is to analyze those relevant data. Most analyses are done in the laboratory. The hot water and rock samples collected from the field work are prepared for purpose of water chemistry analysis and for petrographic study respectively. Data synthesis involves collecting and integrating different data sets into coherent information for interpretation by means of software package like aquachem for water chemistry and Microsoft excel for water chemistry data

All data, including both collected during this study and those from literature, are been analyzed, interpreted and presented together. The presented data is been put into a regional context by comparing relevant literature on nearby or similar Geothermal prospects. All collected data and a discussion of the interpretation is finally being written up in a final thesis report.

During the different phases, a variety of tools are used, including standard field sampling and measuring tools, and ArcGIS, Google earth and aquachem software packages. In the following sections the main methods that applied in the research work arepresented.

1.5.2 Field work

In addition to the secondary data that originate from different sources that existed before this research; primary data are used. The main way of collecting the primary data is by means of field work. A one day reconnaissance survey and observation were done in order to assess the cost of the fieldwork, to obtain the necessary permission from the relevant authorities to carry out the work, as well as accumulating the basic field equipment. A total of 10 days field works were conducted by following traverse lines in order to achieve the objective of this study.

The main activities that was conducted during the field work were measuring Ph, temperature and Electric Conductivity (EC) of the Hot springs, taking of representative fluid and fresh rock samples for further laboratory analysis (Petrographic and geochemical analysis).

Credibility and usefulness of geochemical data depend on the methods used and the care taken in the collection of samples. The water samples from thermal features were taken as near as possible from the outlet. Water samples for major cations, and (SO_4, Cl) were collected in 125 ml polyethylene bottles and were filtered with a 0.45µm filter membrane using a hand syringe and the cations were acidified with 1:1HCl while the $SO_4$and Cl were treated with zinc acetate.

1.5.3. Laboratory and Data analysis

A. Water chemistry analysis

Seven (7) representative fluid samples were taken and chemical analyses have been done in Water work and design laboratory. It helps to determine the chemistry of hot springs/geothermal fluid

The Laboratory of the Oromiya water work design and supervision analyzed all major cations and anion. All major cations were analyzed by atomic absorption spectroscopy. Carbonate and bicarbonates were determined by titration with HCl. Chloride was determined by the Mohr method. Sulphate was determined by turbidimetry and gravimetry depending on whether sample concentrations are low or high, respectively.

The main output of water chemistry analysis is water type, reservoir temperature and water-rock interaction. This information help lastly to know the geothermal fluid is whether mature, peripheral or steam heated. As well as to classify hot spring waters as fully equilibrated with rock at given temperatures, partially equilibrated, or immature. This information will help lastly in the water classifications and understand the geothermal system.

1.6 Expected outcomes and research relevance

As mentioned in the problem statement theShala-Abijata area has not been studied in the aspect of depth of source area, reservoir temperature and fluid chemistry in detail, and this will be the first detail study on its depth and fluid chemistry as well as on its temperature characteristics. The main expected research output will be as follows:-

- ✓ It tells clearly what is the water type and its chemistry
- ✓ Temperature of the fluid and the reservoir also will be estimated
- ✓ At the end of the project, a preliminary conceptual geothermal model of the prospect will be developed
- ✓ Thus will help decision-making on selecting specific target areas from within the prospect
- ✓ It will help to select appropriate exploration methods for further detail geothermal exploration study with support of other geo scientific data
- ✓ For better understanding of the system

1.7 Review of previous work

Ethiopia is among the few countries in Africa with a significant amount of geothermal resources. These resources are found scattered throughout the Ethiopian Rift valley and in the Afar Depression, which are both part of the Great East African Rift System. The Ethiopian rift extends from the Ethiopia-Kenya border to the Red Sea in a NNE direction for over 1000 km within Ethiopia, and covers an area of 150,000 km^2. (Meseret & Solomon, 2010)

The Ziway–Shala lake system located on the basin floor of central part in MER, which composes the flat floor of Lake Ziway area (Ministry of Water & Energy(MoWE), 2012) and covers an area of about 14,640 km^2 ,it includes four lakes: Ziway, Langano, Abijata, and Shala (C. Le Turdu et al, 1999; Ministry of Water & Energy (MoWE), 2012). The basin floor is widely covered by Holocene lacustrine deposits (Ministry of Water & Energy (MoWE, 2012, Grove & Goudie 1971, Grove et al., 1975, Street 1979); However, WFB cuts those sediments at some part, and forms step-like topography. Distribution of Lake Abijata and Lake Langano is controlled by such faults (Ministry of Water & Energy (MoWE), 2012).

The Ziway–Shala lake system is currently hydrologically closed. The three northernmost lakes, Ziway, Langano, and Abijata are connected by a surface network, and groundwater flow paths move towards the southernmost Lake Shala which has the lowest elevation (1558 m) (Le Turdu et al., 1999, Tsegaye Abebe, 2000). Each of the three lakes Ziway, Langano and Abijata has an elongate shape parallel to the main trend of the MER and can be defined as tectonically controlled lakes (C. Le Turdu et al., 1999; Makin et al., 1976).

Le Turdu et at (1999) stated that the modern climate of the Ziway–Shala region varies markedly over quite short distances. It is mainly characterized by alternating wet and dry seasons following the annual movements of the Intertropical Convergence Zone (ITCZ) which separates the air streams of the northeast and southeast monsoons (Nicholson, 1996). Kingham, 1975 stated the mean annual rainfall is no more than 600 mm in the vicinity of Lake Ziway, and rises to a maximum of 1200mmat the high margins (3000 mcontour) of the MER. Mean annual temperature is less than 15ºCin the highlands and more than 20ºC in the lowlands. Evaporation ranges from more than 2500 mm on the rift floor to less than 1000 mm on the highlands. The present vegetation ranges from open woodland to bushed grassland on the rift floor. Rift shoulders are characterized by bushed grassland, then remnants of dry, montane forest and, from 3200 to 3500 m, ericaceous scrub and Afroalpine moorland (Makin et al., 1975).

The southernmost Lake Shala, the deepest (257 m) lake of the eastern branch of the EARs, is 28 km long and 15 km wide with an area of 329 km^2 (Morandini, 1940 ,Baumann et al., 1975 , as sited in C. Le Turdu et al., 1999). The central lake basin lies in a 17 km in diameter, funnel-shaped caldera of Pleistocene age called the O'a Caldera (Mohr, 1967). Le Turdu et al (1999) suggested that the western part of the lake lies in a tectonically controlled depression. Thus, Lake Shala can be classified as a volcanically–tectonically controlled lake

Mohr et al (1980) suggested that present-day Lake Shala occupies not only the O'a Caldera, but also a tectonic depression immediately west of the caldera belonging to the northern end of the Shala–Corbetti WFB segment. The general shape of the depression has also been modified by recent regional faulting. According to C. Le Turdu et al., 1999, four main structural regions have been identified, those are:

- The Eastern Shala Fault System
- The Northwest Shala Volcanic Boundary
- The Central Basin and
- The Southern Shala Fault System

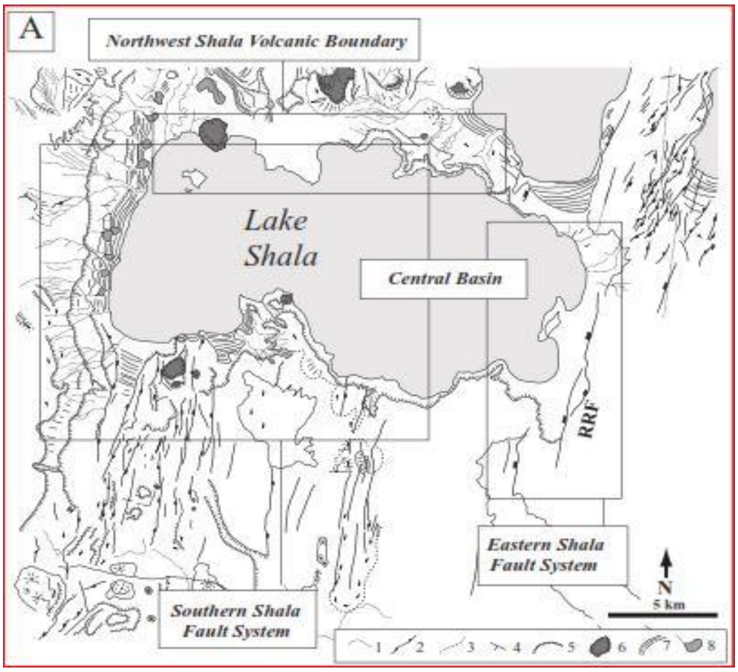


Figure 1.5 *main structural regions of Lake Shala (C. Le Turdu et al., 1999 pp. 152)*

The NNE-trending fault system belongs to the southern end of the Ziway-Shala WFB segment. It is concerned its north with the Katlo Horst through the Gale Horst to the North-Northeastern. The Eastern Shala fault systems link with the Mirrga grabon extending the offshore western plateau of Lake Langano south ward. Within this fault system the major 15 km long west facing Roge Rafu Fault (RRF) is present with an apparent throw of 50m corresponding to the tectonically rejuvenated wall of the O'a caldera. Open cracks a few meter wide, 20-30 m deep and 20-2000m long are visible in this area (Mohr et al., 1980). A major 3-km long hydrothermal field occurs on the eastern shoreline of Lake Shala near Rebo.

As a consequence of the recent volcano-tectonic activity in the area, geothermal features are well represented in the Ziway–Shala basin (C. Le Turdu et al., 1999). Hydrothermal activity is present on the western side of the MER, in the Butajira–Silte zone (Imba Koto springs) west of Lake Ziway. Within the Ziway–Shala system, steam and fumaroles exist in the Alutu volcanic centre. The largest hydrothermal fields exist on the Tulu Gudu Island of Lake Ziway, along the northern and eastern shores of Lake Langano (North Bay and Edo Laki Island, Bole, and O-itu Bay) and on the east, southeast and southwest shores of Lake Shala (UNDP., 1973, Travi et al., 1997, Baumann et al., 1975; Chernet, 1982 and, as sited in Le Turdu et al., 1999).

1.8 Thesis Overview

The thesis is structured in five chapters. Chapter one gives general information about the area of study, the purpose and methods followed in the research. Second chapter provide a regional scale overview. Chapter three gives a detail description about the lithology, petrography analysis and geological structure of the study area. In chapter four water chemistry data is interpreted. In chapter five result and discussion is presented and preliminary conceptual model of the area is modeled. Eventually the main conclusion and recommendation for the future study is deal in chapter five.

2. RIGIONAL GEOLOGY

2.1. East African Rift System (EARS)

East African rift system (EARS) is a succession of rift valleys that extend from Beira in Mozambique in the south to Afar triangle in the north (Peter, 2007). By Morly et al, (1999) stated that the East African Rift System forms a narrow (50–150 km wide), elongate system of normal faults that stretches some 3,500 km in a sub meridian direction.

The EARS is a continental branch of the worldwide mid ocean rift System that corresponds to the third arm of the Afar- Red Sea – Gulf of Aden triple junction (Peter, 2007).

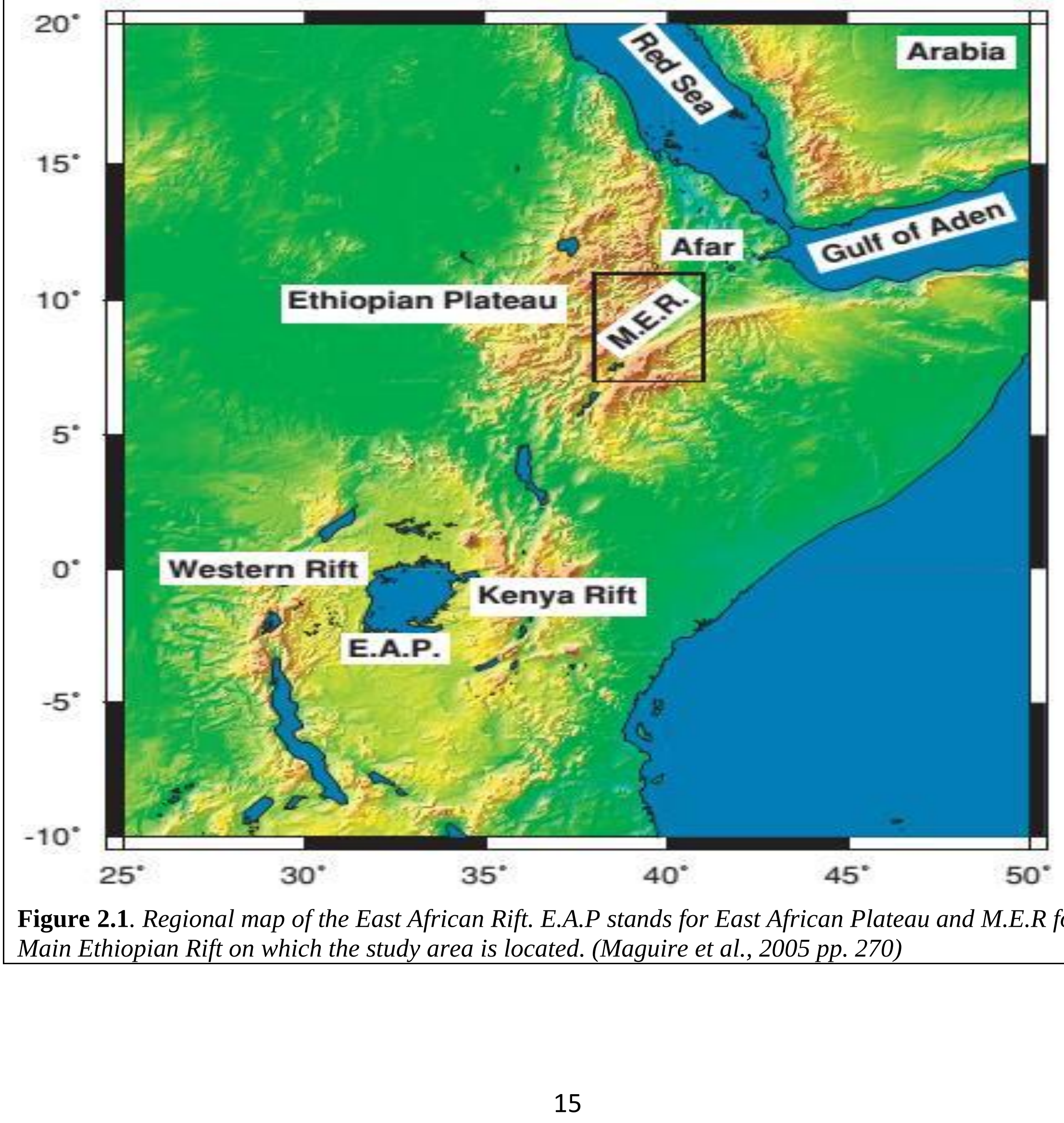


Figure 2.1. *Regional map of the East African Rift. E.A.P stands for East African Plateau and M.E.R for Main Ethiopian Rift on which the study area is located. (Maguire et al., 2005 pp. 270)*

The EARS splits into two at about 5^0 N to form the Eastern and Western branches (Peter, 2007). The two branches of the rift skirts around the Tanzania craton and formed within the Late Proterozoic belts adjacent to the margins of the craton (Mosley, 1993 and Smith and Mosley, 1993, As sited in Peter, 2007). However, the Eastern Branch that comprises the Ethiopian and Kenya rifts is older and relatively more volcanically active than the western branch that comprises Albert–Tanganyika-Rukwa-Malawi rifts (Peter, 2007).

The Eastern and western branches of the East African Rift System have undergone different tectonic histories. Morley et al, (1999) suggests the western branch can be regarded as a good model of a young continental rift while the eastern Branch is representative of a "failed" mature continental rift system. Both are characterized by large half graben systems filled by fluvial-deltaic and lacustrine sediments, and/or by volcanic and volcaniclastics (Morley et al, 1999)

At the largest scale, the topography of the EARS is characterized by two large lithospheric domes called the Afar and East African Domes (Merley et al, 1999). They are separated by the Turkana depression (600 m average elevation) of northern Kenya. The average elevations are 1,500 m for the Afar Dome and 1,200 m for the East African Dome. Away from these areas the topography ranges between 300–900 m (Ebinger et al. 1989). Both domes have diameters of about 1,000 km and are associated with large negative gravity anomalies Within the East African Dome smaller domes (perhaps associated with magmatic under plating) with radii of 100–200 km are present, notably the Kivu and Kenya Domes (Merley et al, 1999).

Peter and Meseret Teklemariam, (2010) suggests the East African Rift is one of the most important zones of the world where the heat energy of the interior of the Earth escapes to the surface in the form of volcanic eruptions, earthquakes and the upward transport of heat by hot springs and natural vapor emanations/ fumaroles.

2.2. Main Ethiopian Rift System (MERS) and its volcano-tectonic Activity

2.2.1. Introduction

The Main Ethiopian Rift (MER) is a key sector of the East African Rift System (EARS) that connects the Afar depression, at Red Sea-Gulf of Aden junction, with the Turkana depression and Kenya Rift to the South (Corti et al., 2003). The MER is an oblique rift, exhibiting an overall NE–SW trend, formed by E–W extension between the Nubia and

Somalia plates via both magmatic intrusion and tectonic faulting (Ebinger, 2005; Corti, 2009; Corti et al., 2013a).

It is a magmatic rift that records all the different stages of rift evolution from rift initiation to break-up and incipient oceanic spreading (*e.g.*, Ebinger, 2005): it is thus an ideal place to analyses the evolution of continental extension, the rupture of lithospheric plates and the dynamics by which distributed continental deformation progressively focuses at oceanic spreading centers.

The Main Ethiopian rift is a central valley some 84km wide and is extending ESE-WNW at a rate of about 2.5mm/yr (Wolfenden et al, 2004).

The MER is composed of three main different segments (Northern, Central and Southern) characterized by the occurrence of a typical bimodal magmatic activity and two distinct systems of extensional structures: a system of ~NE-SW-to N-S-trending border faults and a system of ~NNE-SSW- to N-S-trending (Corti et al., 2003; Mohr, 1983 and *Wolfenden et al.,* 2004).

The Northern MER is considered to extend from the true Afar depression up to the Lake Koka region following the middle course of the Awash River valley *(Wolfenden et al.,* 2004). Early synrift volcanism in the area started at about 10–11 Ma (*Mohr*, 1983*; Wolfenden et al.,* 2004). The Central MER encompasses most of the Lakes Region, up to the Lake Awasa area *(Wolfenden et al.*, 2004). Here, the main boundary faults trend roughly N30°–35° and the age of faulting onset is estimated to be around 8.3–9.7 Ma, while the age of the earliest synrift volcanic deposits is suggested by *WoldeGabriel et al.,* (1990) and Mohr(2004) to be ∼8 Ma.

These three segments reflect different stages of the continental extension process that is interpreted from different fault architecture, timing of volcanism-deformation and crustal lithospheric structure (e.g., Hayward and Ebinger, 1996). But commonly they are characterized by typical bimodal magmatic activity and two distinct extensional structures: ~NE-SW to N-S trending border faults and ~NNE-SSW to N-S trending, en-echelon arranged faults obliquely affecting the rift floor Wonji Fault Belt,(WFB); Bonini et al., 2005). The Border faults are major fault-escarpments separating the rift depression from the western and eastern plateaus. These faults are normally long, widely spaced and characterized by large vertical offsets (Boccaletti et al., 1998). But the WFB are arrangement of overlapping, right stepping en-echelon fault segments oblique to the main direction of the rift margins. The faults of the WFB are normally short, closely spaced and display relatively small vertical throws (<100 m; e.g., Boccaletti et al., 1998). Most of the recent (Quaternary) volcanic activity in the MER is closely associated with these fault systems. The WFB developed after 2 Ma (Ebinger and Casey, 2001). According to Keir et al. (2006), in the Southern MER the Wonji faults are relatively less developed than the other sectors of the rift.

Tsegaye Abebe et al., (1998) suggest the MER is characterized by existence of major transverse structures that extend hundreds of kilometers from rift margins. These transverses roughly oriented E-W to ENE-WSW and NW-SE. The E-W structures are represented by Yerer-Tullu Wellel Volcano-tectonic Lineament (YTVL). The YTVL extends from Tullu Wellel, near Ethiopia-Sudan border, to Ambo fault in northern limit (Tsegaye Abebe et al., 1998). The interpretation of the YTVL is controversial. However, Geophysical data, structural and Oligo-Miocene plateau volcanic indicates the transverse structure represent a pre-existing weakness zones (parallel to the trend of the Gulf of Aden e.g. Bastow et al., 2005). E-W trending transverse lineament is another one relative to the YTVL. That represents by Goba-Bonga lineament; extends across the central part of the MER (Abbate and Sagri, 1980)

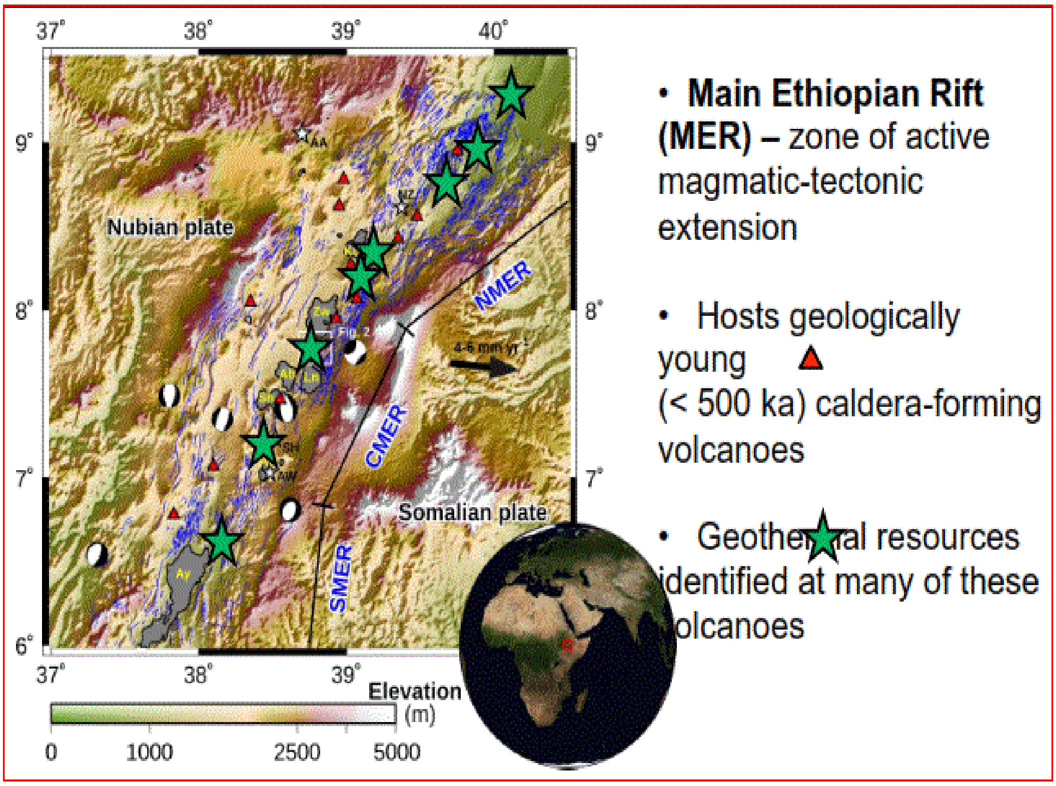


Figure2.2. *Topographic map of the Main Ethiopian Rift (MER) indicating the three main sectors (northern, central and southern, i.e., NMER, CMER, and SMER). The surface faults (mapped by Agostini et al., 2011) are shown in blue. Earthquake locations and focal mechanisms for the region are from the Global Centroid Moment Tensor Project catalogue (http:// www .globalcmt .org; 1976–2012; M > 5). Red triangles identify volcanic centers thought to have been active in the Holocene (Siebert and Simkin, 2002). White stars identify major centers of population (after the Socioeconomic Data and Applications Center, http:// sedac .ciesin .columbia .edu/): (Hutchison et al., 2015).*

2.2.2. Structure and volcano-tectonic activity in MER

Ethiopian and Somalian plateaus are dissected by the 80 km wide MER forming large escarpments extending from the Red Sea and Gulf of Aden junction in Afar depression to the Turkana depression in the south (Mohr, 1983; Boccalleti et al., 1999; Corti, 2009). This rift system shows different stages of development from initiation through break up to oceanic spreading in the north (Hayward and Ebinger, 1996). Though Ethiopian rift system is classified in to Afar and MER (Corti, 2009) it is consisting of three rift segments reflecting different orientation of the fault boundaries (Giday WoldeGabriel et al., 1990; Bonini et al., 2005; Kurz et al., 2007; Keranen and Klemperer, 2008; Corti, 2009).

NMER, CMER and SMER are the segments of MER reflecting different timing of volcanism, fault architecture, stages of extension deformation and lithospheric structure (Hayward and Ebinger, 1996). Boccalleti et al. (1999) classified the Ethiopian rift as the northeastern sector characterized by recent volcanism and the southwestern sector with abundant older volcanic products. Transverse structures such as Boru-Tura structural high located at Lake Koka separating NMER and CMER as well as the Goba-Bonga transverse lineament of Lake Hawassa between CMER and SMER are recognized by Bonini et al. (2005).

According to Bonini et al. (2005) MER is the roughly NE trending rift system where rifting starts in SMER (21- 20 Ma) due to northward propagation of the Kenyan rift. SMER shows northward propagation up to Goba-Bonga transverse lineament whereas the northern sector of the rift start to develop by 11 Ma and propagates southward until the Boru-Tura structural high. (Bonini, et al., 2005; Tsegaye Abebe et al., 2010)

The CMER developed at 9.7-8.3 Ma with significant rifting at 5-3 Ma accompanied by eruption of voluminous silicic magmas and reactivation of SMER as a function of the counter-clock wise rotation of the Somalian plate (Bonini et al., 2005). Tadiwos Chernet (1995) and Kurz et al. (2007) described the NMER as oriented NE in the Afar depression where as both the CMER and SMER orient along NNE-SSW direction.

On the other hand, Corti (2009) suggest that MER extends along NE-SW direction at the Red Sea – Gulf of Aden triple junction in the Afar depression and N-S in the south at the Turkana depression. The NMER is oriented N40°E where it is bounded by the Arboye and Sire boundary faults in the southeastern and by the Ankobor and Boru-Tura structural high in the Northwest side (Wolfenden et al., 2004). In the case of CMER, the boundary faults are oriented at an average trend of N30°E, where the western margin is well expressed by the N25°E–N35°E trending and ESE-dipping Guraghe and Fonko faults, whereas the eastern margin is well represented by the N30°E trending and WNW-dipping Asela–Langano fault system (Corti, 2009). The border fault is characterized by minor transverse structures in which the NE-SW trending structure meets the NW-SE trending structure near Langano resulting in the „S" or „Z" morphology (Le Turdu et al., 1999).

In the Debre Zeyt area, the NE–SW trending rift margin and the N–S Boru-Tura structural high give rise to the major Addis Ababa rift embayment (Corti, 2009). The direction of stress field for extension in the CMER was oriented roughly along ESE-WNW with local variations to E-W and NW-SE (Bonini et al., 2005). This gives the oblique slip pattern on NE-SW trending fault pattern. According to Bonini et al. (2005)

the rift margin in the CMER is formed around 6 Ma but Giday WoldeGabriel et al. (1990) proposed that it is formed at 8Ma. Most of the active strain in the CMER is localized within the WFB (Bonini et al., 2005).

In the SMER the boundary faults are oriented N0°E to N20°E due to rotation of the rift valley from N20°-35° to N 5°-20° (Corti, 2009). It is characterized by the Chencha major fault in the west, which is curvilinear in shape oriented N–S and N40°E and the Agereselam linear shaped NNE–SSW trend boundary fault in the east (Corti, 2009). According to Giday WoldeGabriel et al. (1990) the Agereselam boundary fault was formed at 10Ma whereas south of Lake Abaya extensional deformation initiated at 20-21 Ma ago (Bonini et al., 2005).

The rift floor of the MER is affected by widespread deformation related to faulting along the Wonji Fault Belt (WFB) formed at 2 Ma (Bonini et al., 2005; Kurz et al., 2007). It is oblique to the direction of main rift margins forming „S" shaped curvature resulting in sigmoidal geometry (Corti, 2009). N-S trending Kenyan rift gives rise to the development of SMER at about 20-21 Ma and lasted up to 11Ma in which the northward propagation of the Kenyan rift is hindered by Goba Bonga transverse lineament (Wolfenden et al., 2004; Bonini et al., 2005).

Accordingly, this propagation is due to the combined effect of mantle plume movement and the existence of pre-existing structures (Bonini et al., 2005 and reference therein).

In addition, southward migration of deformation from Afar (Bonini et al., 2005) is evident from the existence and re-activation of pre-existing tectono-magmatic structures in southern Afar at around 10-11 Ma (Wolfenden et al., 2004). Basically faults, fractures, shear zones, joints, dike swarms of Bale mountain, micro folds and deformed fiames are reported in tertiary rocks of highland and plateaus of Arsi and Bale areas with columnar structure in the lower lava flows of Wabi gorge and other highlands (Workineh Haro et al., 2014). In the Bale area Lake Gadeb is developed due to the composite effect of local faulting during Mio- Pliocene and topographic increase from local shield volcanism (Eberz et al., 1988). In addition primary structures such as bedding and lamination are reported in Mesozoic sediment in the north eastern part of Asela sheet (Workineh Haro et al., 2014).

2.2.2 The Wonji Fault belt

According to C. Le Turdu et al (1999), this 8-km wide belt of normal fault maintains NNE structural orientation along the entire length of the main Ethiopian rift. In the central sector Ethiopian rift, the WFB is dextrally offset in to four en echelon rift-axis segment. According to Le Turdu et al (1999), from N-S those are:-

1. The Gedemsa-East Ziway
2. Ziway –Shala
3. Shala-Corbete and
4. Duguna-Abaya segment

C.Le Turdu et al (1999) suggested that within the Ziway-Shala region the WFB formed along the Eastern marginal graben of this sector. According to Mohr et al (1980) Caldera-topped shield volcanoes occur at each WFB offset:

1. The Aluto caldera b/n the Gedemsa East Ziway and Ziway-Shala segment
2. O'a caldera (presently occupied by lake Shala) b/n the Ziway-Shala and Shala-Corbetti segment and
3. Corbetti caldera at the south end of the Shala-Corbetti segment

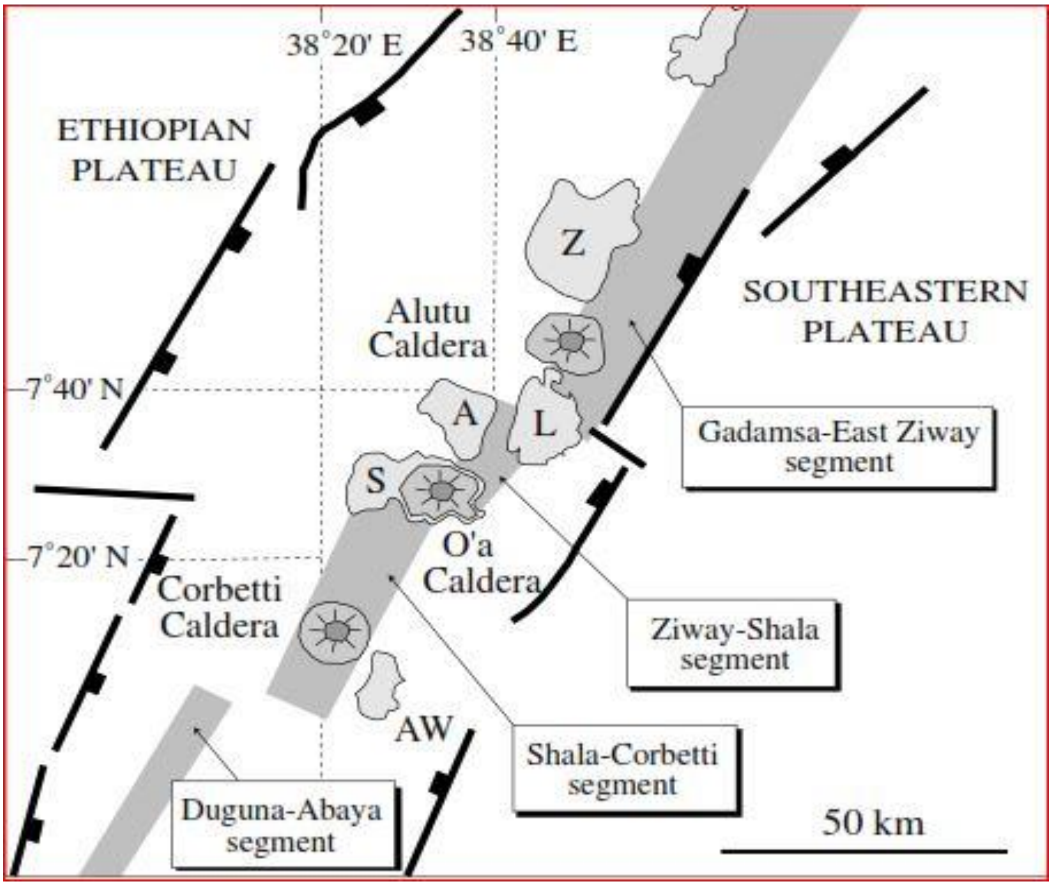


Figure 2.3. *Structural sketch map of the Wonji Fault Belt showing the four en e´chelon, NNE-trending segments within the Ziway–Shala lake basin system. Three shield (caldera) volcanoes are present at each WFB offset. From north to south these are the Alutu Caldera, the O'a Caldera, and the Corbetti Caldera. AW= Lake Awasa; S=Lake Shala; A=Lake Abijata; L= Lake Langano; Z =Lake Ziway (Le Turdu et al., 1999, pp. 142)*

Magmatic activity in the MER seems to have been episodic rather than continuous (Giday Woldegabriel et al., 1990). That is mainly occurred broadly in two geologic periods; Late Tertiary and Quaternary.

Magmatic activity in Ethiopia generally started with the eruption of Oligocene (~30-35 Ma) voluminous flood basalts (e.g., Mohr and Zanettin, 1988; Ebinger et al., 1993; Gezahegn Yirgu et al., 2006), followed by a complex shield volcano activity (e.g., Kieffer et al., 2004). But in the Southern MER the Tertiary volcanic activity started earlier than other MER sectors at ~45 Ma. This initial volcanic activity in the Southern MER ended around 30 Ma (Zanettin et al., 1978). This volcanic episode was characterized by eruption of tholeitic to alkaline flood basalts and interbedded felsic lavas and pyroclasts (e.g., Mohr and Zanettin, 1988; Kieffer et al., 2004). Flood basalt activity is temporally unrelated to the rifting but there was later magmatism which was strictly related to the tectonic evolution of the MER segments. Close to the rift margin the western and eastern plateau is characterised by Miocene-Pliocene volcanic activity. On western margin, volcanic activity mostly restricted to YTVL (Tsegaye Abebe et al., 1998) that forms aligned central silicic volcanoes. These volcanoes become younger towards the rift fromhe 7 Ma Nekemt edifice to the Pliocene-Quaternary volcanoes such as Wenchi, Wechacha, Furi and Yerer (e.g., Tsegaye Abebe et al., 1998).

After this prevalent Mio-Pliocene volcanism, the Quaternary magmatic activity becomes restricted in the rift floor which is associated with WFB. The Quaternary stages of the Ethiopian rift opening have been marked by eruptions of huge amounts of volcanic products. The eruption is with a large prevalence of silicic rocks, minor basalts and scarce or absence of intermediate compositions (Mohr, 1971; Mohr and Zanettin, 1988; Peccerillo et al., 2003; 2007). Such a bimodal distribution of volcanism is a common feature of many volcanoes, especially in the continental rift, but its genesis is still debated (e.g., Peccerillo et al., 2003).

Peter (2007) suggests geothermal manifestations occur as fumaroles, altered grounds, steaming grounds and hot springs in many locations, most of which are associated with young volcanic fields in the rift valley. Hot springs also occur on the flanks of the rift where they are associated with Tertiary faulting episodes. The manifestations are more pronounced and vigorous within the axis of the rifts than on the flanks due to the favorable hydrology and relatively shallow heat sources. According to Peter (2007) the heat sources for the geothermal systems are related to:

- Shallow magma chambers associated with the young Rhyolite volcanoes that are common in the southern Afar and MER and
- Upper mantle intrusion/ upwelling associated with the thin crust in the area that averages between 5 and 20 km.

As a consequence of the recent volcano-tectonic activity in the Central Main Ethiopian Rift, geothermal features are well represented in the Ziway–Shala basin. Hydrothermal activity is present on the western side of the MER, in the Butajira–Silte zone (Imba Koto springs) west of Lake Ziway. Within the Ziway–Shala system, steam and fumaroles exist in the Alutu volcanic centre. The largest hydrothermal fields exist on the Tulu Gudu Island of Lake Ziway, along the northern and eastern shores of Lake Langano (North Bay and Edo Laki Island, Bole, and O-itu Bay) and on the east, southeast and southwest shores of Lake Shala (UNDP, 1973; Baumann et al., 1975; Chernet, 1982; Travi et al., 1997 as sited in Le Turdu et at., 1999).

3. Geology of Eastern Lake Shalla area

3.1. Introduction

According to previous studies rifting in the Ethiopian Rift started around 15 to 14 Ma in Miocene time. Lithologies comprised in the study area are Pleistocene-Holocene in age. Since the study area is foundin the central segment of the Ethiopian rift floor, associated volcanic products are recent

The rock units are described according to their stratigraphic positions (Fig.3.2). From the oldest to the youngest, the major lithological units identified in the area are; rhyolitic lava flow, ignimbrite, basaltic lava flow and lacustrine sediments.

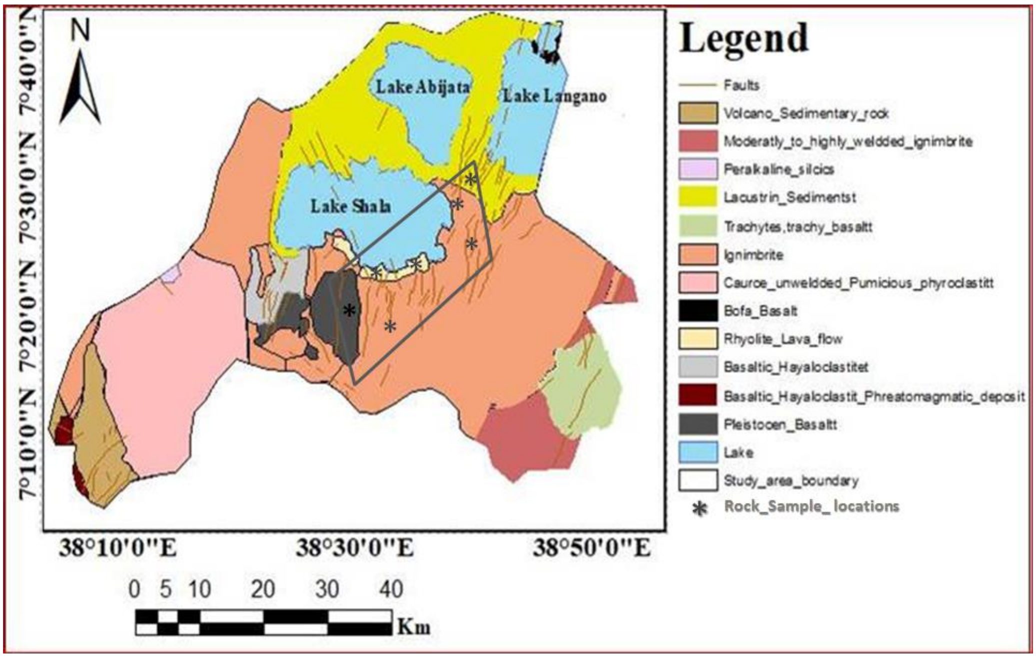


Figure 3.1. Geological map of the study area modified from GSE

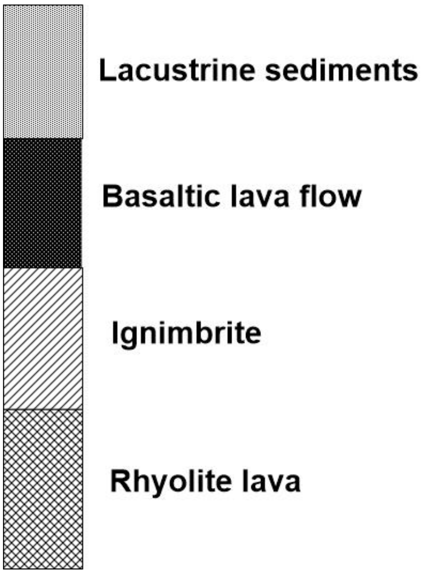


Figure 3.2 *Stratigraphic sketch of the area: shows the eruption column.*

3.2 Lithology and Petrographic description

Based on the various compositions of lithological units and the help of age determination from previous studies, four lithologic types are identified. These are rhyolite lavas, ignimbrites, basaltic flows and lacustrine sediments.

3.2.1. Rhyolite lava

This volcanic unit is largely exposed at the rim of O'a caldera. It is greenish to pinkish in color and characterized by aphyric texture. At the northeastern parts of the caldera rim, these rhyolite lavas are found as lithic components in the moderately welded ignimbrite.

Figure 3.3. *Exposure of rhyolite lava*

Two samples (sh-06 and sh-07) are prepared for thin section study. The rock is porphyritic with dominant quartz and sanidine phenocryst. Minor amounts of opaque minerals, alkali pyroxene and albite are also found. Sanidine has subhedral to anhedral broken features and most of the quartz are showing euhedral shape.

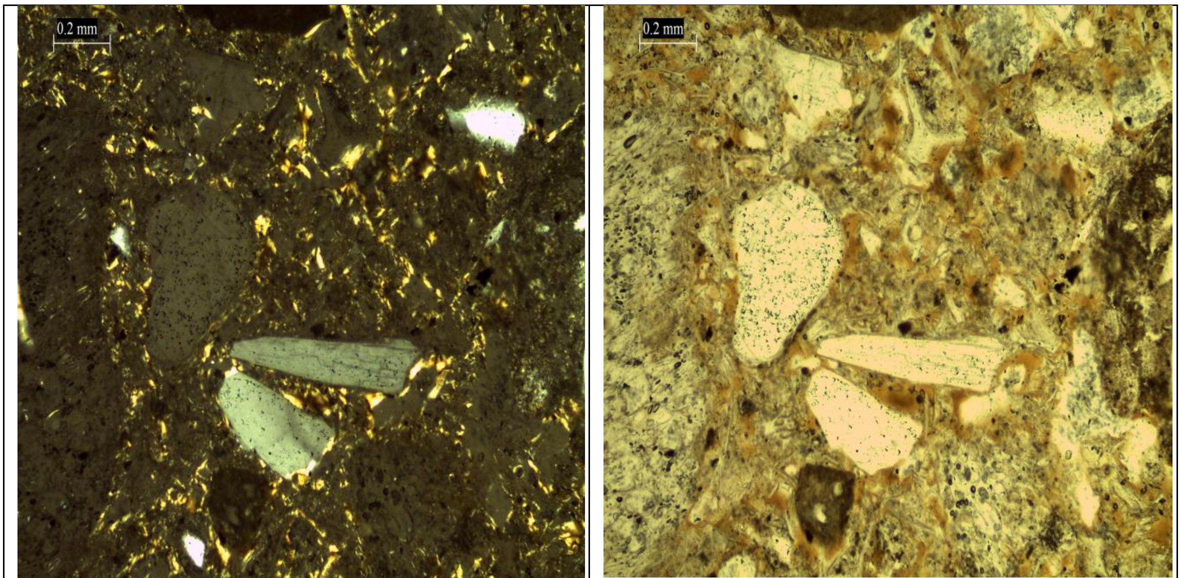


Figure 3.4: *Microphoto picture of rhyolite (sh-01); XPL (Left) and PPL (right)*

3.2.2. Ignimbrites

This phyroclastic flow deposit is the eruptive product of O'a caldera volcano (around 0.24 Ma; Mohr et al 1980), which is now occupied by lake Shalla,. Ignimbrites that erupted from this 17 km widecaldera are widely exposed in eastern and southwestern parts of Lake Shalla. This unit can be classified in to two sub-units based on their degree of welding.

A. Strongly welded ignimbrites

It is characterized by massive, rich in lithics and crystals grayish to deep greenish in color. The lithics are relatively bigger (pebble sized) embedded in ash matrix. This unit has cavities big enough to hold fingers. Usually it is overlain by weakly welded ignimbrite and unwelded pumice fall deposits. Glass fiamme are identified in this unit following strong welding with abundance in quartz and feldspar grains.

Figure 3.5: Strongly welded ignimbrite

Fiamme's in the ignimbrite

Three samples (sh-27, sh-, sh-) were prepared for thin section study. The samples show large crystals of sanidine , sub hedral hornblende and some greenish pyroxene minerals . Basically, the groundmass shows dominantly volcanic glass with flow textures associated with flow banding.

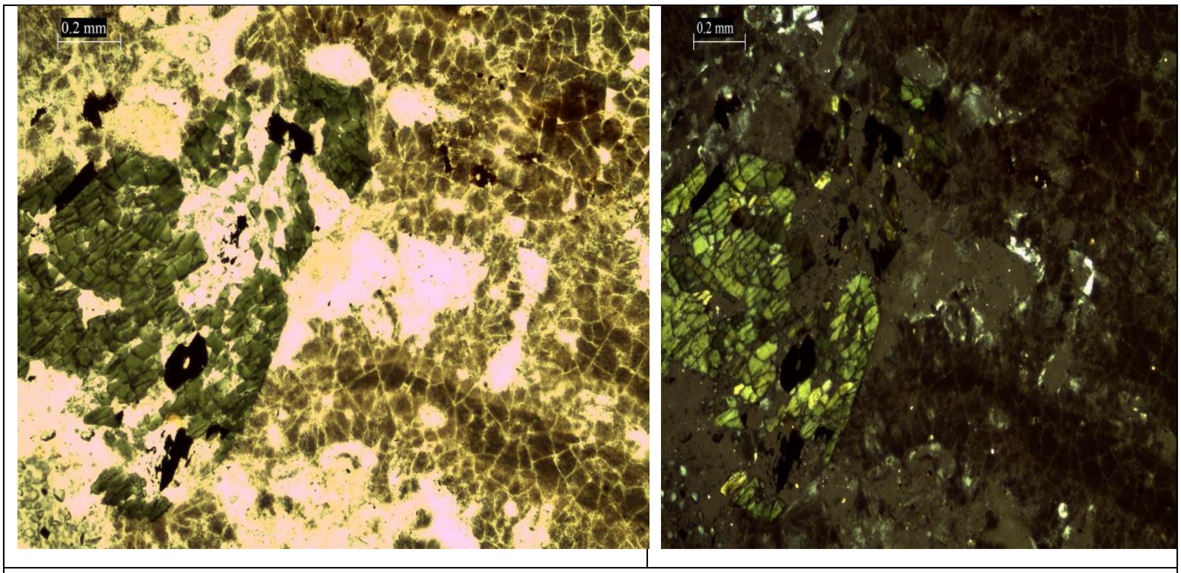


Figure 3.6: *Microphoto picture of basalt (sh-01); XPL (Left) and PPL (right)*

B. Moderately welded ignimbrite

It is easily distinguished phyroclastic flow due to its weak welding. Pumice and ash are common as lithics. It is underlain by strongly welded massive ignimbrite. Its color varies from pinkish, yellowish to beige. Often this sub-unit is extensively affected by hydrothermal alteration. Calcite and silica minerals are frequently found as veins in different orientations, in many part of this ignimbrite. Large rhyolitic and trachytic rock fragments are observed as lithic components in many parts of this ignimbrite. . This is possibly the ignimbrite that erupted from O'a caldera at around 0.24Ma (Mohr et al 1980) which is largely exposed in the eastern parts of the study area.

Figure 3.7. *Moderately welded ignimbrite*

3.2.3 Recent Basaltic flows

There are basaltic lava flows exposed south of Lake Shalla. It is characterized by lava flow which is extensively vesiculated where the vesicles are wide enough to hold two finger tips. There are red scoracious cones on top of the basaltic deposit. These lava flows are mostly overlain by unwelded pumice deposits, lacustrine sediments and phreatomagmatic ash deposits.

Figure 3.8. *Basaltic flow*

One basalt sample is prepared for petrographic analysis (sh-05), This sample shows ophitic and slightly prophyritic texture (see on Fig.3.9). Phyroxene, some altered olivine and plagioclase minerals are found as phynocrysts. In addition it shows vesicular texture due to the vesicles which have a circular shape with 0.5mm diameter.

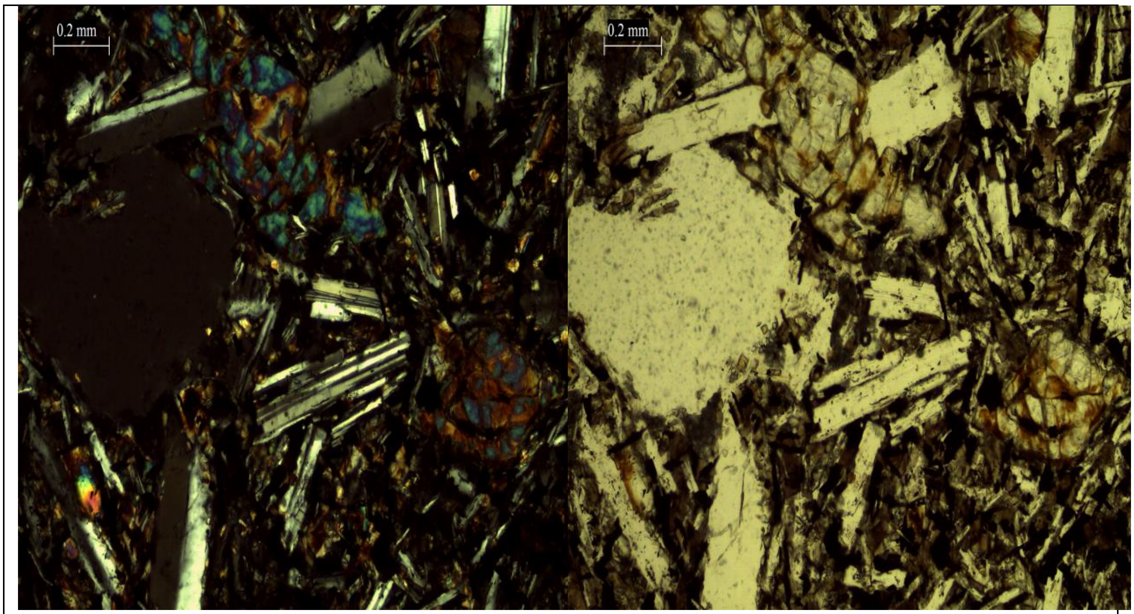


Figure 3.9. *Microphoto picture of basalt (sh-05); XPL (Left) and PPL (right)*

3.2.4. Lacustrine Sediments

Eastern shores of Lake Shala are covered with well stratified sediments of volcanic origin. Layered, depicting grading, due to good sorting, clastic sedimentary deposits like brownish to reddish conglomerate, pinkish siltstones and debris flow cover the hanging wall of Kakicha-Aneno fault. There are preserved fossil remains in some of these sedimentary rocks.

One sample (sh-04) is collected for petrographic analysis. The rock thin section shows clastic texture/fabric (see fig.3.10) with larger minerals of sanidine and quartz. Sanidine minerals are irregularly broken. The groundmass is also composed of volcanic glass and some associated quartz minerals. In addition opaque minerals are observed that may result from hematization alterations. It is clearly visible that this sample is ash dominated.

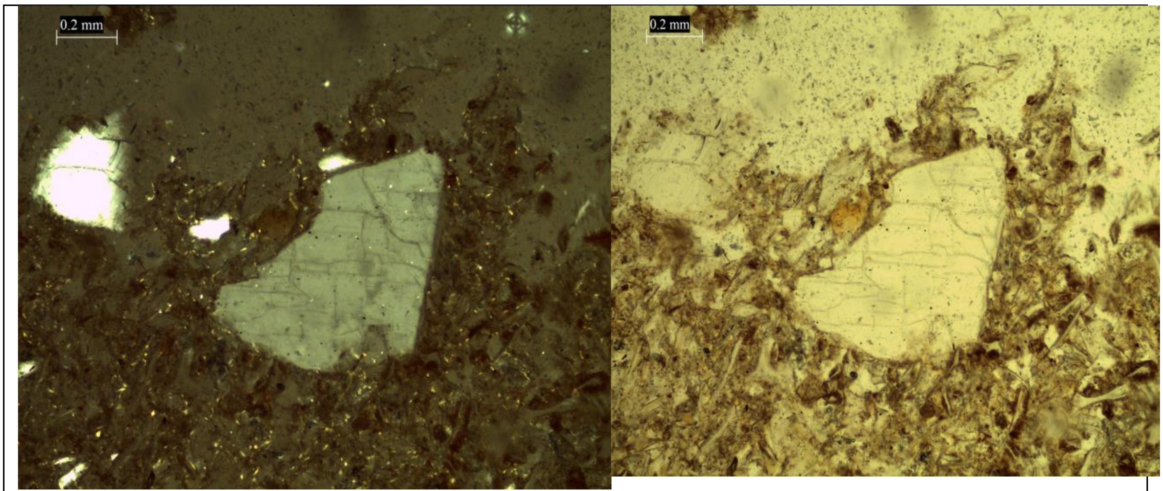


Figure 3.10: Microphoto picture of Sediments (sh-04); XPL (Left) and PPL (right)

3.3. Geothermal Manifestations

3.3.1. Hydrothermal Manifestations

Hydrothermal manifestations in geothermal fields are surficial evidence for the possible existence of geothermal fluids at depth (Hochstein, 1990). Their occurrence and physical character can give some indications of conditions at depth

In geothermal exploration, geothermal manifestations of different forms are carefully mapped. O’a caldera, now occupied by Lake Shala with more than 250 m depth (Coroline et al) has hydrothermal springs in its eastern and southern shores.

Figure 3.11. *Eastern Shore of Lake Shala (geothermal prospect area)*

Eastern shore of Lake Shalla, where well layered volcano-sediments dominate, hot grounds, mud pools and hydrothermal springs are abundant. The maximum recorded temperatures from these hot springs range from 97^0 C to 100.5^0 C.

In terms of hydrothermal alteration, lacustrine sediments of Eastern Shalla and the weakly welded ignimbrites are mostly affected by hot fluids coming from underneath through joints, fractures and faults where permeability of underground formations is relatively high and where silica and calcite are the most common alteration minerals.

Figure 3.12. *Mud poosl at eastern shore of lake Shalla* ***(upper left),*** *hot springs with 99^{0}C and 97.5^{0}C respectively at Eastern shore of Lake Shala* ***(upper right and lower left)****, fumaroles with 57°C in temperature North of Sembete town* ***(lower right)***

In order to have a good geothermal system there must be heat source (preferably magmatic), fluids (to transport the heat), reservoir (rocks of high permeability), recharge area and cap rocks (preventing heat loss). In the study area, the following conditions exist:

- Young volcanoes in the rift axis as heat source
- Weyo -Lafto, Kakicha – Aneno and Shibibo – Golja faults acting as conduits or pathways for meteoric water to get infiltrated (recharge zones)
- lacustrine sediments are useful as cap rocks to prevent loss of heat/steam

Figure 3.13. *Hot spring emanating from stratified volcano-sediments, Eastern Shala lake shore*

3.3.2. Steam vents and Limonite Deposits (Clay deposit)

On the eastern shores of Lake Shala, there are steam vents emanating at higher ground elevation, and only steams come out from these vents. Limonite deposits also foundin this area at different locations. It precipitated from steam on the ground surface and has reddish color but when temperature decreases it become green and dark green.

Figure 3.14. *Limonite deposits from different location and steam veins. Upper left) Limonite deposit at higher ground elevation, Upper right) steam vent at the top of hot springs, Lower left and lower right) limonite deposit at lower ground elevation.*

4. Whole Water Chemistry result

4.1. Introduction

Geochemistry is one of the most effective ways of studying geothermal resources, both at the exploration and exploitation stages (Wanjie, 2012). Chemical compositions of the thermal waters are useful in evaluating subsurface temperatures and determining water origin. The study of the origin and evolution of volcanic and geothermal fluids is one of the main concerns of geothermal resource study (Craig, 1963; Ellis and Mahon 1964; Marini, 2000).

Geothermal fluids contain a wide variety and concentration of dissolved constituents. The chemical parameters often cited to characterize geothermal fluids are total dissolved solids (TDS) and pH (Arnorsson et al., 1990). The amount of chemical salts dissolved in the waters is measured by TDS using conductivity meter and acidity or alkalinity of the fluid is measured by PH. These two parameters can be measured in the field. The conductivity meter determines TDS by measuring its electrical conductivity. The more the dissolved salts, the higher the electrical conductivity. According to Giggenbach, (1988), the TDS of the geothermal fluids are usually composed mainly of sodium (Na), calcium (Ca), potassium (K), chlorine (Cl), silica (SiO2), sulfate (SO4), and bicarbonate (HC03) and minor amount of fluorine (F) and boron (B).

Water chemistry was initially analyzed in terms of relative concentration of major anions (HCO3, SO4 and Cl) and major cations (Na, K, Ca and Mg) by means of the triangular diagrams. Nowadays, the geochemical data is processed by different softwares.

The chemical composition of geothermal fluids are used to constrain some parameters like reservoir temperature, type of water, salinity, and extent of fluid–rock interactions (Fridricksson et al., 2016). Temperature and local geology have some role on the amount and nature of dissolved chemical species in geothermal fluids . Most of the time, lower-temperature geothermal resources have lower amount of dissolved solids than higher temperature resources. Prolonged water-rock interaction liberates ionic species and produces a saturated silica solution (Arnorsson et al., 1990). When geothermal fluids move through rocks, they react chemically with the rocks, which themselves are usually chemically complex. Minerals in the reservoir rocks may be selectively dissolved by the fluids while other minerals may be precipitated from solution or may substitute for certain elements within a mineral (Arnorsson, 2000). These changes in the reservoir rocks may cause volume changes and this change can affect the permeability and porosity of the rocks.

4.2. Laboratory Analysis

All major cations and anions were analyzed at the Laboratory of the Oromiya Water Works Design and Supervision by using the methods given in Table 4. 1. The analysis results are given in Table 4.3.

Table 4.1: *Analytical Methods used by Oromiya Water Work Design and Supervision Laboratory*

Elements Analyzed	Method of Analysis
Na	Atomic Absorption Method
K	" " "
C a	" " "
Mg	" " "
CO_3	Electrometric Titration Method
HCO_3	" " "
CO_2	" " "
Cl	Mohr Method
SO_4	Turbidimetric Method
Ph	Electometric method
Conductivity	Conductivity Meter

4.2.1. Accuracy of Analysis

The reliability of the chemical analysis must be confirmed before any data processing and interpretation work is carried out. The common method that used to verify the accuracy is to check the ion balance. This is done by comparison of the sum of the molal concentration of positively charged species multiplied by their valence, against the sum of the molal concentrations of negatively charged species multiplied by their valence.

$$\Sigma\, m\, i\, z\, i = 0;\ m = \text{molality, and } z = \text{valence charge}$$

In most solutions the dominant ions are Na+.K+, Ca2+, Mg2+, Cl-, HCO3-, and SO4-2. Therefore,

$$mNa + mK + 2mCa + 2mMg = mCl + mHCO3 + 2mSO4$$

An adequate ion balance is good to within |5%|, using the following equation:

$$\boldsymbol{\delta \text{ charge } \% = (\Sigma \text{ cations} + \Sigma \text{ anions}) / (| (\Sigma \text{ cations} + \Sigma \text{ anions} |)*100}$$

δ charge % represents for percentage difference of cations and anions. The above formula estimate that the error due to measurement and the presence of free ions is minimal, and chemical analysis with a **δ** charge % value between -5% and +5% is considered to be successful. If this is not the case the analysis is poor or all the important species have not been determined. Using this approach, it is found thatthe chemical analysis of most of the samples fall within the range given above, with the exception of some outliers.

Table 4.2 *Field Measurement of Samples Collected from Eastern Shalla Geothermal area*

Feature Name	Coordinate		T(^{0}C)	PH/ T(^{0}C)	E.Cond. (µS/cm)/ T°C	TDS Mg/l
	Easting	Northing				
LKS-1	0459737	0826617	94.3	9.24/47.8^{0}C	207 /45.5°C	207/45.2°C
LKS-2	0459737	0826633	97	9.4/44.8^{0}C	214/46.2°C	219/44.7°C
LKS-3	0459787	0826595	100	9.4/39.7^{0}C	203/43.3°C	202/43.6°C
LKS-4	0459707	0826602	91.9	9.4/55.4^{0}C	203/51.3°C	203/50.6°C
LKS-5	0459740	0826593	99	9.3/46.3^{0}C	208/46.4°C	206/49.5°C
LKS-6	0459739	0826591	97	9.2/45.8^{0}C	212/43.6°C	210/48.4°C
LKS-7	0459739	0826689	94	9.4/41.6^{0}C	20550.1°C	207/46.3°C

Table 4.3. *Chemical analyses results of water samples collected from Eastern Shalla geothermal area. (Concentrations in mg/l).*

Feature Type	PH/ 25 T°C	EC/ 25 T°C	TDS/ 25 T°C	Na	K	Ca	Mg	CO3	HCO3	Cl	SO4
LKS-1	8.8	9500	4750	1656.0	40.3	2.5	3.62	270.0	1115.0	1794.4	20.0
LKS-2	8.9	9440	4720	1951.0	41.4	2.8	3.54	270.0	115.0	1874.4	19.5
LKS-3	8.9	9350	4680	1642.0	41.4	3.1	3.7	270.0	1095.0	1909.4	16.04
LKS-4	8.8	9490	4730	1710.0	40.6	3.0	3,69	270.0	1107.0	1810.6	19.9
LKS-5	8.8	9485	4740	1649.0	40.6	2.9	3.66	270.0	1114.0	1802.3	17.02
LKS-6	8.9	9370	4680	1702.0	41.3	2.8	3.58	270.0	1095.0	1900.1	16.09
LKS-7	8.9	9360	4670	1810.0	41.2	3.1	3.52	270.0	1105.0	1910.1	19.02

4.3. Interpretation of Geochemical Results

From the chemical analysis given above in Table 4 it is possible to see that all hot springs have high pH values (8.8-8.9). It shows that the sampled waters are slightly alkaline. The alkaline nature of the waters indicate that there are no significant hot water rock interaction, near surface, therefore we can infer from the geochemical information most likely represents the deep thermal conditions.

Also the thermal springs have higher amount of Na, K, HCO3, and Cl, content and low amount of Ca, Mg, and SO4.It's possible to see the water type of the prospect.

4.3.1. Classification of water types using relative Cl, SO4 and HCO3 ternary diagram.

The classification of water types in geothermal system is to see if they are suitable for the application of chemical geothermometers (Giggenbach and Goguel, 1989). This classification of natural waters primarily is based upon the contents of the following seven major dissolved chemical species: Na, K, Ca, Mg, CO_3, HCO_3, Cl, and SO_4. A correlation study among these chemical species is carried out by means of water type classification and Na-K-Mg Ternary diagram to know concentration of Na-K- and Mg, Figures 4.1 and 4.2, respectively and also by means of Piper diagram, Figure 4.3 to show the water type result and Na content in one diagram.

The Cl, SO4, HCO3 triangular plot is used for initial classification of geothermal water samples (Giggenbach, 1988, Giggenbach and Goguel, 1989). This is also a convenient means to distinguish water type and helps to assess rapidly the water compositions of the geothermal fields, as these anions are the most abundant solute components of the fluid. The diagram (Figure 4.1) depicts that the discharge fluids of the hot springs belong to mature NaCl compartment just above the Na-HCO3 peripheral water compartment. As depicted from the figure, the sampled hot springs possess the percentage ratio of 60% to 40% chloride to bicarbonate, respectively.

From the analyzed chemical data of the fluid which is given in Table 4.3, the water types belong to a Sodium-Chloride-Bicarbonate, slightly alkaline type of water with pH of 8.8 and 8.9.

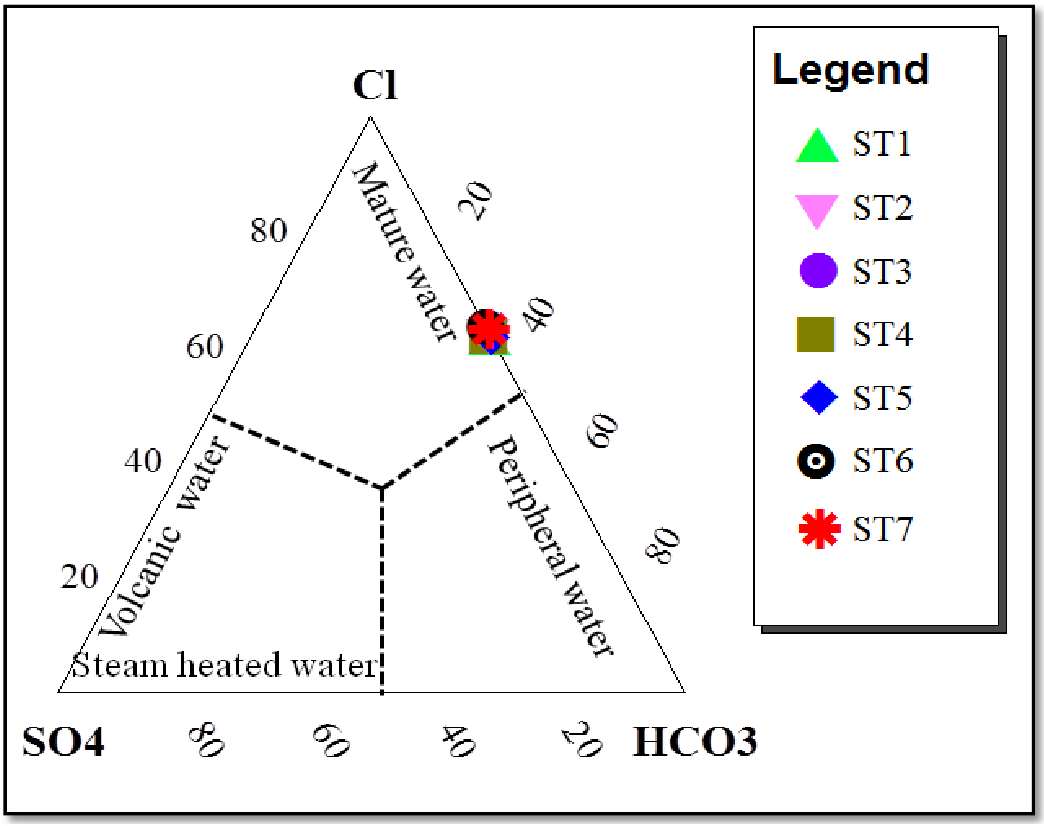


Figure 4.1. *Cl-SO4-HCO3 ternary diagram for water sample from Eastern Shalla geothermal prospect*

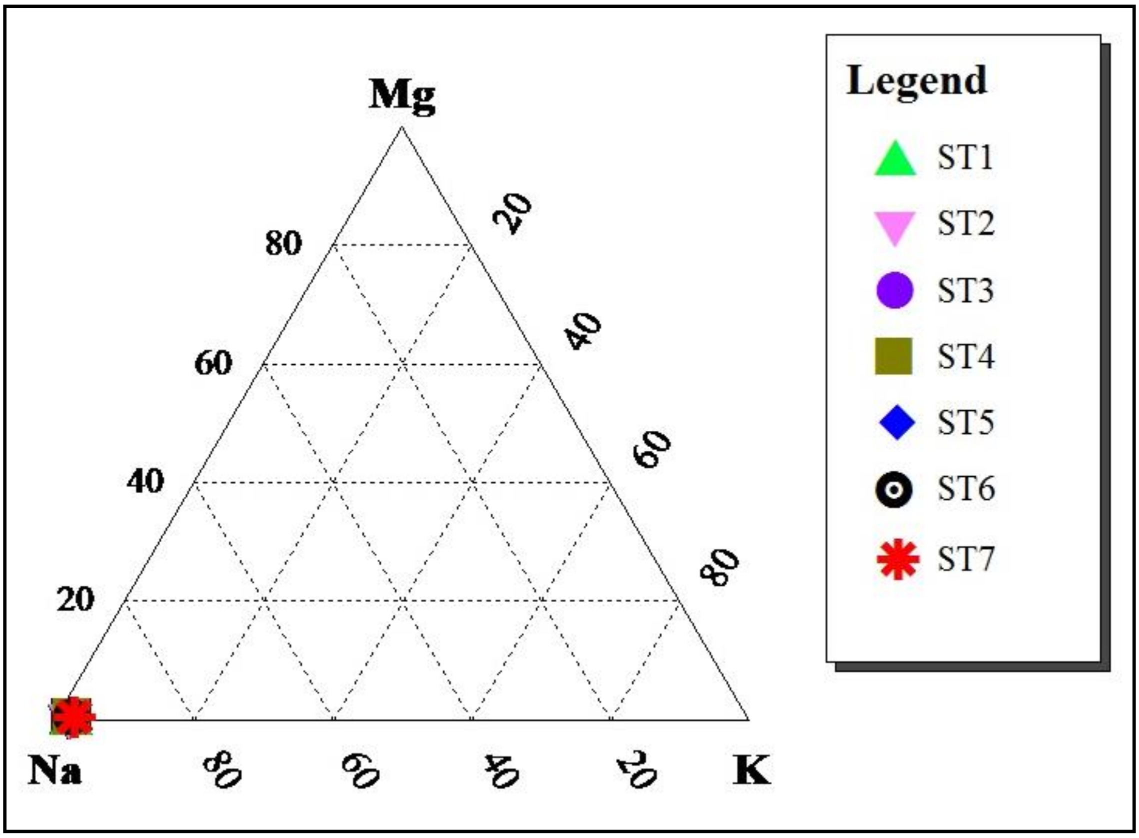


Figure4.2. *Na-K-Mg ternary diagram for water sample from Eastern Shalla geothermal prospect*

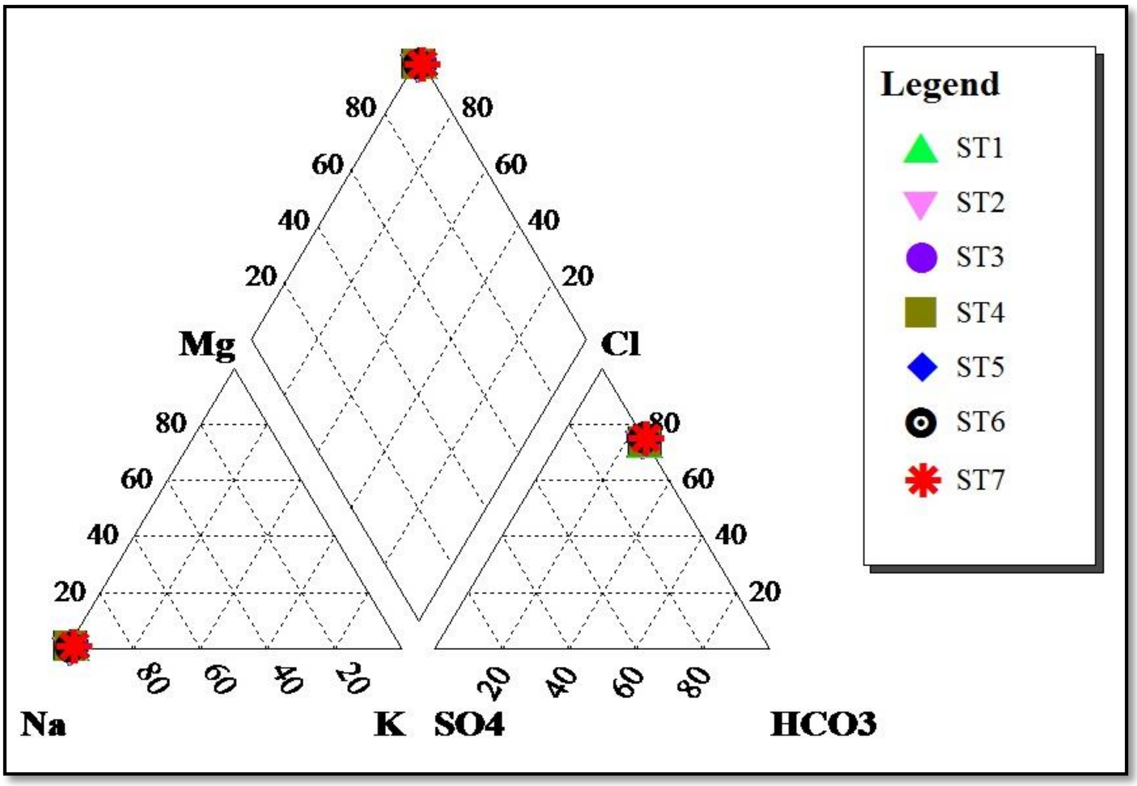


Figure 4.3. *Na-K-Mg and Cl-SO4-HCO3 Piper plot diagram.*

4.3.2. Chemical Geothermometry

One of the parameters to know in the assessment of thermal systems for practical use is the actual temperature of the reservoir, which can be characterized using chemical geothermometry. In order to characterize the reservoir temperature of the study area and to evaluate the degree of attainment of fluid–rock equilibrium, quantitative chemical Geothermometers are used.

Chemical geothermometers are developed on the basis of temperature dependent chemical equilibrium between the water and the minerals at the deep reservoir conditions (Arnorsson, 2000, Tonany , 1970 and 1971).

For applications of chemical geothermometers, near neutral to slightly alkaline pH samples with relatively low SO4 and high chloride are important. Samples which are more alkaline with high SO4 are not suitable for the application of chemical geothermometers.

The deep temperatures calculated using different chemical geothermometers are given in Table 4.4 and the result is plotted in Figure 4.4. The temperatures obtained using cation geothermometers generally have different temperature values. The K-Ca geothermometer has given extremely high temperature values due to the disproportional content of K to Ca in all sampled springs and it is rejected because of its unbelievable and unrealistic results.

The Na-K geothermometers have given very low deep reservoir temperature values than the other geothermometers for the Shalla springs. This is because the Na contents of the Shalla hot springs are very high due to the lake water effect that can contaminate the reservoir chemistry. It is also because of relatively high content of K than Ca and Mg. As a result, the ratio of Na/K becomes relatively low.

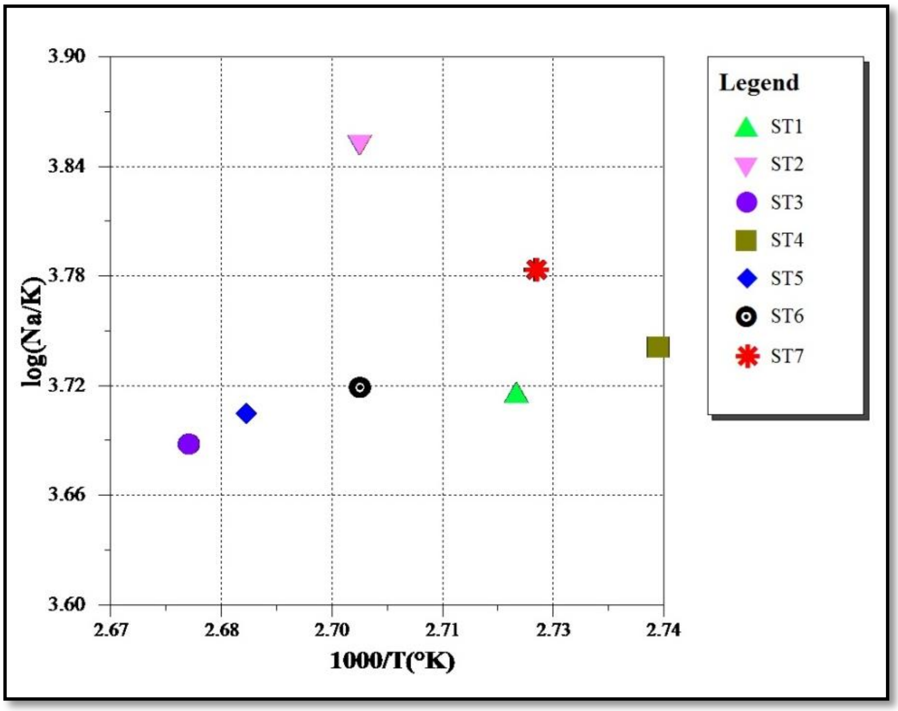
However, Na–K and K-Mg solute geothermometers provided more reliable subsurface temperature estimates for the investigated waters than K-Ca geothermometers. Na-K gives more suitable result and this relates to the fact that those are less influenced by mixing with shallow groundwater and re-equilibration processes during the upflow. This was found to be the case in many investigated samples.

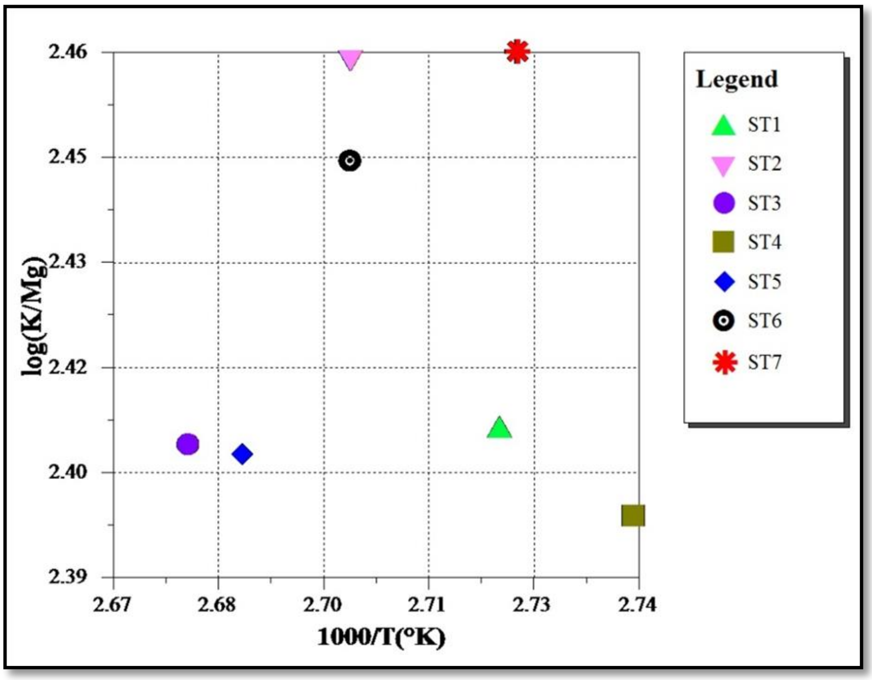
Table 4.4: *Deep temperatures calculated using solute geothermometers for waters from Lake Shalla geothermal area.*

Feature Code	T-2(Na-K)	T-(K-Ca)	T-(K-Mg)
LKS-1	141	511	224
LKS-2	133	508	226
LKS-3	142	502	224
LKS-4	139	501	223
LKS-5	142	504	224
LKS-6	141	506	226
LKS-7	137	501	225

Table 4. 5. *Temperature equations (in ◦C) for geothermometers (concentrations in mg/L)*

Geothermometer	Source	Equations
Na-K T2°C	Giggenbach et al 1983	1390/(1.75+log(N a+K)-273.15
K-Ca T°C	Tonani 1980	1930/(3.861-log(K/Ca)-273.15
K-Mg T°C	Fournier in preparation	2330/(7.35-log(K2/Mg)-273.15


3.90
3.84
3.78
3.72
3.66
3.60
log(Na/K)
2.67
2.68
2.70
2.71
2.73
2.74
1000/T(°K)
Legend
ST1
ST2
ST3
ST4
ST5
ST6
ST7


2.46
2.45
2.43
2.42
2.40
2.39
log(K/Mg)
2.67
2.68
2.70
2.71
2.73
2.74
1000/T(°K)
Legend
ST1
ST2
ST3
ST4
ST5
ST6
ST7

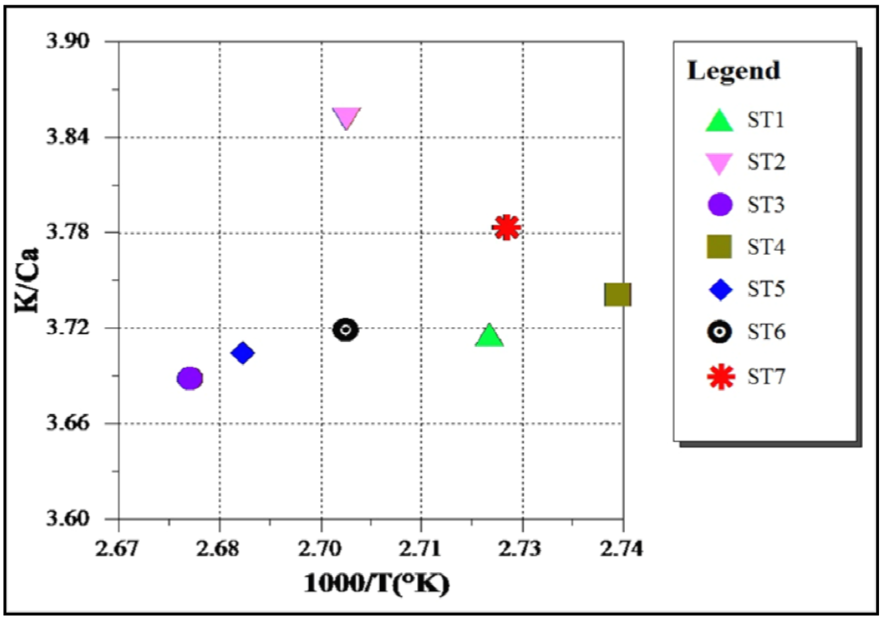


Figure 4.4. *Geothermometry plot for sampled waters from Eastern Shalla geothermal, T-(Na-K) upper, T-(K-Mg) middle and T-(K-Ca) bottom*

4.3.3. Water-Rock interaction

The interaction of fluids within hydrothermal systems with close volcanic-magmatic associations can be evaluated in terms of two end member processes: initial rock dissolution adding cationic components in proportion close to those in the original rock, and eventual rock equilibration with minerals, thermodynamically stable over the major water-rock equilibration zones within the system (Giggenbach, 1988). For assessment, the degree of attainment of water rock interaction data have been plotted on the t Na/400-25 K/10-√Mg ternary diagram of Giggenbach (1988) given below in Figure 4.5 which can be used to classify hot spring waters as fully equilibrated with rock at given temperatures, partially equilibrated, or immature. Figure 4.5 is indicates that all water samples have not reached the full equilibrium line but are in the partial equilibrium or mixed zone of the figure, which might suggest that they are partially equilibrated with the reservoir rock.

In other words, these samples have experienced one or more cooling processes, but their chemical compositions adjusted only slightly to new environmental temperatures. The general attainment of equilibration temperature indicates the system is a mature system.

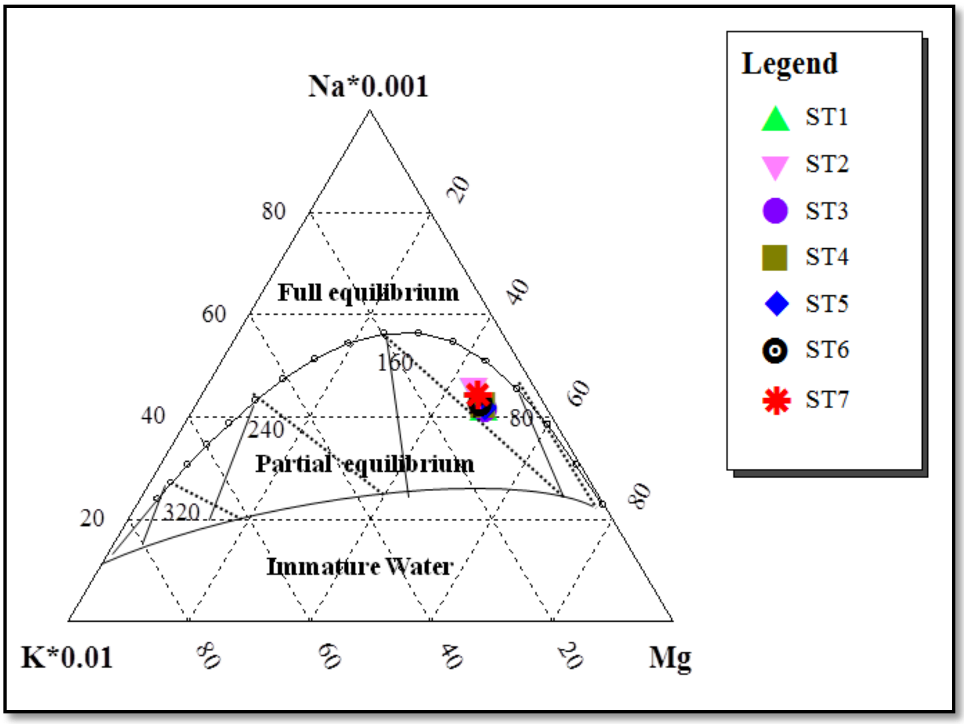


Figure 4.5. *Na/400-K/10-√Mg plot for sampled waters from Eastern Shalla geothermal prospect*

5. Preliminary conceptual model of the prospect

5.1. Introduction

The present geological and geothermal investigations were integrated with secondary geophysical and geochemical data that offer optimistic information for geothermal system components. Source of heat, reservoir characteristics, and the presence of confining rocks above the aquifers are essential in addition to the requirement of sufficient water and recharge mechanism.

On the bases of the results derived from the geovolcanological, structural and geochemical data, a preliminary geothermal model of the Eastern Shalla prospect can be reconstructed and a scheme of the geothermal fluid circulation proposed. It should be noted that a geothermal "Conceptual Model" is defined as the model that reflects the knowledge of the system of its main characteristics and dynamics (fluxes of heat and fluids circulations) and describes those geoscintific elements and the main physical-chemical processes which may affect the behavior of the system. The model proposed here is based only on geology and water chemistry and lacks the main elements of geophysics. Thus, the conceptual model is preliminary and accordingly describes the Shalla geothermal system, merging mainly qualitative information for the essential features of the fluid, and includes setting of the prospect from the geothermal point of view: inferred heat source, cap-rocks, recharge and hydrodynamic and chemical characteristics of the geothermal system.

Thus the following interpretations were attempted based on results obtained from surface geological and geothermal field work, petrography and water chemistry analysis of hot springs in order to evaluate the existence of favorable geothermal system components by considering the data sets.

5.2. Regional structural setting and hydrothermal manifestations

In terms of structural setting of the area, several faults, volcanic center, crater and caldera, hydrothermal springs, fumaroles and altered grounds have been identified.

5.3.1 Major faults

Most of the faults of WFB segments were initiated all over the MER around 1.6 Ma (Caroline et al). The major normal faults in the area are oriented NNE-SSW, NE-SW and N-S direction.

A. NNE-SSW trending faults

The names referring to the major faults in the study region are just local names aimed to identify them easily from the map that can be correlated with already published report. Weyo-Lafto normal fault is part of the WFB segment trending in NNE direction and measuring more than 8 km long. This fault affects the weakly welded ignimbrite unit with oserved downthrow of about 100 m around Weyo Medhane Alem church and gradually dies out south of Negele-Arsi town.

Some 3 km west of this fault there is another one called Kakicha-Aneno fault which affects the highly welded greenish ignimbrite. This fault has downthrow of about 190m at the locality Roge-Rafu and an apparent throw of 50 m corresponding to the tectonically rejuvenated wall of the O’a Caldera. Open cracks a few meters wide, 20–30 m deep and 20–2000 m long are visible in this area (Mohr et al., 1980).

Chancho fault, found in the eastern part of the study area, bounds the Lake Abijata basin to the east and can be correlated with East Abijata fault (EAF) (Caroline et al.). It trends in NNE-SSW direction with more than 20m downthrow. Weakly welded beige ignimbrite of O’a caldera is affected by this fault. This 10km long fault dies out towards northwwest of Lake Abijata.

B. NE-SW and N-S trending faults

Bedena fault, found 8km south of Lake Shala and oriented in N-S direction cuts the recent basaltic lava flows. It is more than 6 km long with 20 m downthrow towards east. Lebu-Sero fault is ~6 km long trending in NNE-SSW direction around Lebu locality and changes its orientation in to NE-SW direction around Sero locality affecting the unwelded pumice and the lithic-rich ignimbrite. North of Sero, it exhibits more than 100m displacement and dies out gradually south towards the young a’a type basaltic lava flow.

Shibiba-Golija fault bounds the western shore of present-day Lake Shalla. It is oriented in N-S direction somewhere around Shibibo extending for about 4 km and changes its trend to NNE-SSW direction further north near Mount Golja. This fault plane faces east and cuts ignimbrites and lacustrine sediments of western Shalla lake.

To the south-west of Lake Shalla, there is a volcanic depression or crater now occupied by Lake Hara Chitu that has hot springs associated with the collapse of the crater (Mohr et al., 1980). In the southern shore of Lake Shalla, there are many hot springs all coming out from joints of similar NNE-SSW trend. These hot springs have maximum recorded temperatures ranging from 50^0C to 56^0C.

North of Sembete town there are fumaroles wich the local people use for medical purposes. In terms of hydrothermal alteration, the phreatomagmatic deposits of southern Shalla and Hara Chitu, the lacustrine sediments of eastern Shalla and the weakly-welded ignimbrites are mostly affected by hot fluids coming from underneath through joints, fractures and faults where permeability of underground formations is relatively high and where silica and calcite are the most common alteration minerals (Mohr et al., 1980).

5.3. Water chemistry

The types of water discharged from the sampled hot springs are purely Sodium Bicarbonate type water. While the position of the plot on Figure 3 depicts that the above-mentioned waters are above the equilibrium line which could show the non-equilibrium condition with respect to the reservoir rock.

As the Sodium to Potassium ratio (Na/K) is very high it would be unrealistic to use the temperature obtained from Na-K geothermometry. However, this results needs to be re-assessed in the future.

The springs contain high concentration of Sodium and very low content of Potassium which makes the ratio very high. In principle the concentration of these two elements could vary depending on the reactions of feldspar but their ratios are not affected by dilution or by boiling. That is why using them for geothermometry would have been useful to estimate the maximum reservoir temperature.

The Shalla geothermal prospect has relatively high level of the total dissolved solids at the reservoir and high HCO3 content could be potential for calcite scaling.

For assessment, the degree of attainment of water rock interaction data have been plotted on the triangular diagram of Giggenbach (1988). We see from this diagram that all water samples have not reached the full equilibrium line but are in the partial equilibrium or mixed zone. In other words, these samples have experienced one or more cooling processes, but their chemical compositions adjusted only slightly to new environmental temperatures. Thus, the Na–K geothermometer, re-equilibrating very slowly upon cooling, is suitable for these samples. It provides the most reliable subsurface temperature estimates with 133^{o}C -149^{o}C for the investigated hot spring samples. Generally from this diagram and from the Na-K ratio one can deduce that these waters are far from equilibrium and the general attainment of equilibration temperature indicates the system is a mature system. However it needs further study to conclude as the number of samples taken are small and did not contain the isotope analyses

The calculated reservoir temperatures of Shalla hot springs using the quartz geothermometry are in the range of 167°C to? °C. The Na-K geothermometry could not be suitable to calculate the temperature as it has a very high ratio.

5.4. Assessment of the geothermal system

5.2.1. Heat source

The Ethiopia rift system is undoubtedly a region of positive thermal anomaly attendant to volcanic and tectonic activity within which local anomalies are associated directly with volcanism and /or hydrothermal systems due to heat flow from shallow magma chambers, clearly illustrated by the close association of surface geothermal manifestations.

It is to be noted that the possibility of a magmatic chamber to act as a suitable heat source for the formation of a geothermal system is governed by several factors, namely,

A. Persistence in time: - The presence of numerous recent volcanic products witnesses the extended persistence of the magmatic chamber(s) that fed such volcanism.
B. Thermal manifestations:- The extensive occurrence high temperature hot springs, evidence for the existence of a heat source that heat up the underground water

C. Volume: - The volume of the erupted products can indirectly reflect the volume of the magmatic chamber(s) from which they drive.

D. Depth: - The wide occurrence of differentiated volcanic products from parental basaltic magma may indicate the existing of magma at reasonable depth. However such assumptions have to be confirmed by geophysical methods.

When we look at the possible heat source of the prospect, Lake Shalla is located within the caldera or tectonic depression. The depression is semicircular in structure which has resulted from voluminous volcanic eruptions in the past with some remnant magmatic chambers. Extensive thermal manifestations mainly located at the eastern part indicate the existence of heat source close to the eastern part of the caldera

5.2.2. Cap rock

The lateral extent of surface geothermal manifestations and hydrothermal alteration along geological structures, i.e. faults and lineaments indicate that there is impermeable cap rock in the area that broadly blocks the upward movement of steam and water. In the geological setting of the Shalla prospect, the occurrence of thick lacustrine sediments composed primarily of silt and clay possess, little permeability are considered as cap rock of the system. Therefore, medium temperature geothermal system rising along the eastern part is considered to be capped by extensive lacustrine sediments. However, these observations and assumption have to be verified using geophysical methods.

5.2.3. Thermodynamic and chemical characteristics

The thermodynamic and chemical characteristic of the Shalla prospect is inferred on the basis of the nature and composition of the thermal manifestations of the area in the form of thermal manifestation. These manifestations consist of hot springs, mostly concentrated in the eastern sector of Shalla caldera. The manifestations appear to occur along or at the intersection between NNE-SSW and NNW-SSE trending faults.

The application of geothermometry functions to the water samples of the eastern Shalla hot springs indicates wide range of estimated temperatures, from 140^0C (Na-K)-T2 to about 220^0C(K-Mg)-T. These temperature values are relatively lower compared to the adjoining thermal prospects such as Aluto-Langano and suggest the water-dominated nature of the Shalla geothermal system and reservoir of medium enthalpy.

The chemical composition of the reservoir is estimated from the chemistry of the hot springs. The geothermal fluids have a Na-CL-HCO3 composition and slightly alkaline with TDS of slightly over 200mg/l.

5.2.4. Recharge

From geomorphological and tectonics points of view, the geothermal system of the prospect is expected to have groundwater recharge from both eastern and western rift escarpments. However, this assumption has to be verified with surface and groundwater isotopic studies. Meteoric water infiltrating deep into the ground, upon getting in proximity of the proposed active heat source represented by a magmatic intrusion tends to heat up and to up flow along sectors characterized by intense fracturing and faulting and hence by good permeability as well as by thinning or termination of the cap-rock.in the specific case of Eastern Shalla sector. It is proposed that the heat source may occur at approximate depth of about 5-10 kms and that the sector of enhanced permeability is found at the intersection of the major tectonic structures.

These fluids rise up to a depth of a few kilometers, where their temperature is presumably up to slightly over 150^0C. The uprising of the heated fluids is restricted by the presence of impervious formations (cap rock), which is formed mainly by impervious lacustrine sediments. Fluids, therefore, tend to expand laterally through fractured rocks and to install convective cycles, typical of geothermal systems. The outflow of the system represented by the thermal manifestations is supposed to take place mostly along the main NNE-SSW trending faults intersecting the geothermal system on the eastern part.

The subsurface geological structure of the study area is also modeled by referring to other geothermal areas of similar setting where detail field investigations and deep drilling have been undertaken, particularly that of Aluto-Langano geothermal prospect. The Aluto volcanic stratigraphy and structural setting is constrained by data from the deep exploration wells [Gizaw, 1993; Gianelli and Teklemariam, 1993; Teklemariam et al, 1996]. From well temperature and pressure measurements, these authors inferred that the geothermal reservoir is >2000 m beneath the surface. This is supported by magnetotelluric results [Samrock et al, 2015] that confirm the presence of a high resistivity body at those depths. There, the main aquifer is likely to be a sequence of ignimbrites (Huchiston et al, 2016).

When we look at the Aluto model, thick sequence of basalt lavas (Bofa Basalts) 500–1000 m thick are identified (Teklemariam et al., 1996). The basalts are pervasively altered and sealed by deposition of hydrothermal alteration minerals (Hochiston, et al 2015) and as a result, they exhibit poor permeability (Gizaw, 1993). Overlying the basalts, a layer of interbedded sediments and volcanic tuffs are encountered. These units are also highly altered and sealed by deposition of clay minerals (Teklemariam et al., 1996). This clay rich zone appears to correlate with a low-resistivity zone identified by Samrock et al.(2015) at depths of 500–1500 m.

For Aluto, it is unclear whether the cap rock for the geothermal reservoir is made up by Bofa Basalt or the altered tuffs and sedimentary layers above. It is considered that the Bofa basalts and altered sediments-tuffs together provide a capping lithology for the system (between 500 and 1500 m), although it is possible that the basalt unit serves as a reservoir along the contacts and where it is fractured and brecciated. (Hutchiston et al, 2016). Above the cap layers, peralkaline rhyolite volcanics erupted from the Aluto volcanic complex are encountered and comprise alternating layers of rhyolite lavas and volcaniclastic deposits (Huchiston, et al 2016).

In the case of Shalla geothermal system, there is little or no information on the subsurface volcanic stratigraphy.. However, for the purpose of constructing a preliminary geothermal model for Shalla geothermal prospect, a simple working assumption is made such that Shalla and Aluto geothermal prospects are broadly similar in their volcanic stratigraphy and tectonic structures. This assumption is made on the bases of the close geographic proximity of the two volcanic complexes, their location on the active Wonji Fault Belt and strong correlation of their volcanic and tectonic histories. However such an assumption needs to be confirmed in the future by detail investigations, drilling and geophysical methods.

Considering the findings from this study and those of Aluto-Langano, all components for the geothermal system of Shalla have been characterized and constructed in a logical preliminary model shown below in Figure 5.1.

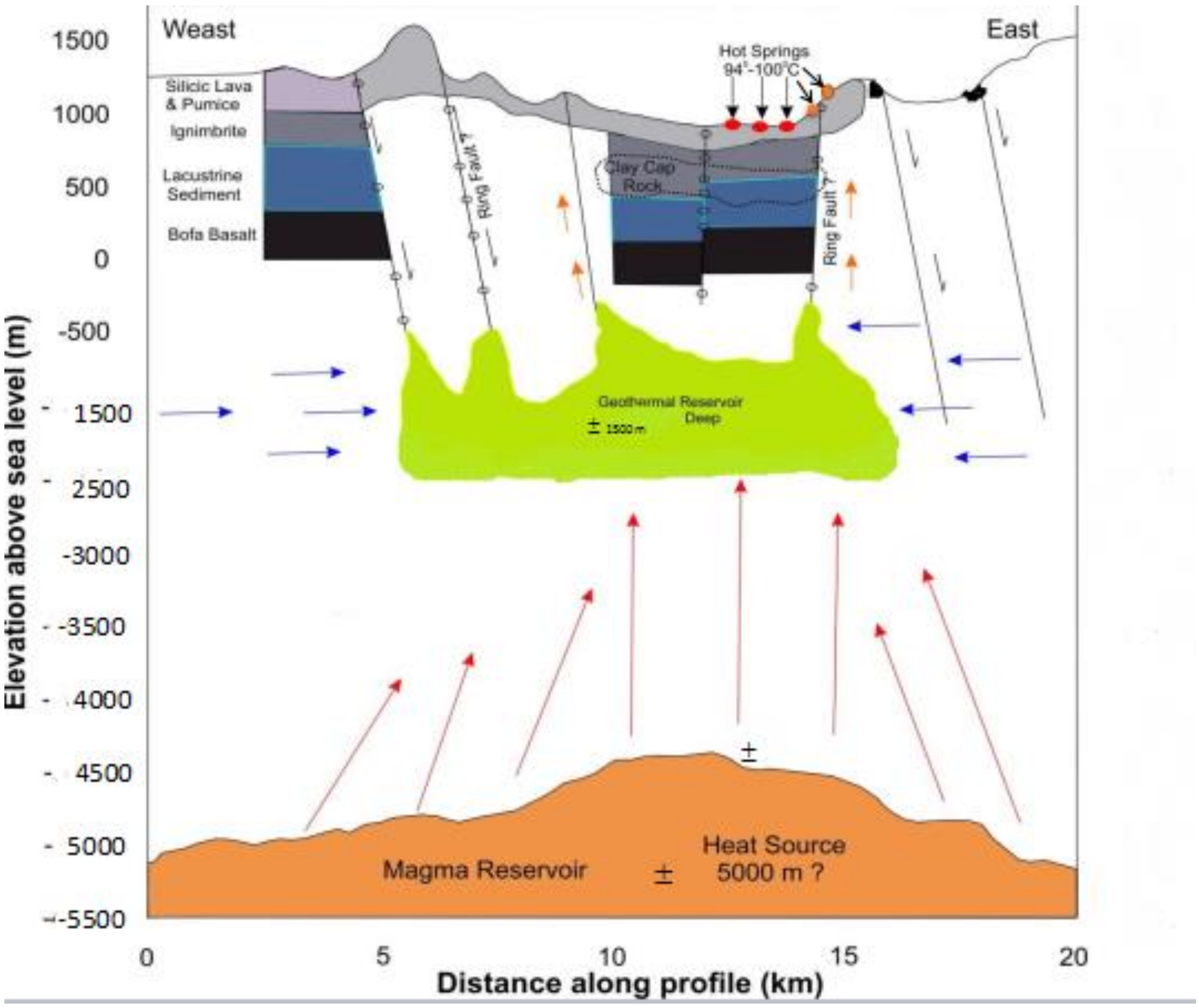


Figure 5.1. *preliminary* ***c****onceptual Mode of The prospect*

6. Conclusions and Recommendations

6.1. Conclusions

Based on field geological observations, petrographic descriptions and whole water geochemistry data a preliminary conceptual model of the geothermal system of Shallahas been devloped. From this study, the following conclusions are made.

1. The exposed volcanic rocks in the study area include: rhyolite lavas, ignimbrites, basaltic flows and lacustrine sediments.
2. The geological structures observed in the study area are joints and normal faults trending NNE-SSW, NE-SW and N-S that imitate the regional tectonic structure of the Main Ethiopian Rift.
3. The Eastern Shalla sector displays some important features supporting the existence of a geothermal system, characterized by a presence of a large caldera, with rejuvenated recent volcanic and structural systems.
4. Occurrence of extensive hot spring activities is also indirect evidence for the existence of a geothermal system at depth in which deep-seated fluids pickup magmatic heat and rise up along major sub-vertical fractures and reaching the cap rock constituted of sedimentary units, and spreading laterally to form convective cells of the proposed geothermal system.
5. The sector of higher permeability and hence better development of convective circulation is supposed to be the eastern Shalla sector that has been subjected to a higher intensity of rift faulting.
6. The geothermal fluids have a Na-Cl-HCO3.composition and are slightly alkaline with TDS of slightly over 200 mg/l. The low TDS values and the near neutral to slightly alkaline nature of the fluids is considered favorable chemistry for development, as it would not negatively impact future power plant and surface facilities.
7. The proposed overall reservoir fluid temperature is intermediate compared to higher temperature fields such as Corbetti and Aluto. However, with such intermediate temperatures the field can be developed for power generation using

recent technologies of binary power plants that could utilize medium temperature thermal fluids.

6.2. Recommendations

The present work lacks pertinent data and information that could be obtained from additional surface exploration methods and that could have improved the level of knowledge of the system. These gaps include: fluid isotope geochemistry and geophysical data (gravity, resistivity and passive seismics). Therefore, the following studies are recommended for a better understanding of the geothermal system:

1. Fluid isotope geochemical study : to identify recharge areas, fluid passages and age of the thermal waters,
2. Gravity and resistivity studies: to identify buried structures, potential heat sources and their depth, vertical and lateral extent of potential reservoirs,
3. Passive seismic studies: as an additional evidence of the depth to the potential anomaly and selection of more seismically active zones as targets for future potential drilling.

It is evident that the above additional surveys should have to be conducted first, before any future drilling activities.

References

Abbate, E. and Sagri, M. (1980). Volcanites of Ethiopian and Somali Plateaus and major tectonic lines. *Atti Convegni Lincei* **47**:219-227.

Arnorsson, S. (2000). Isotopic and chemical techniques in geothermal exploration, development and use. Sampling methods, data handling, interpretation. International atomic energy agency, Vienna, 351 pp.

Arnorsson, S. and Gunnlaugsson, E., (1990). New gas geothermometers from geothermal exploration – Calibration and application. Geochim. Cosmochim. Actta, 49: 1307- 1325.

Ayele, A. Meseret,T. and Solomon, K. (2002), Geothermal Resources Exploration in the Abaya and Tulu Moye- Gedemsa Geothermal Prospects, Main Ethiopian rift, Ethiopia. Compiled Report.

Bastow, I., Stuart, G. Kendall, J. and Ebinger, C. (2005). Upper-mantle seismic structure in a region of incipient continental breakup: northern Ethiopian rift. *Geophysical Journal International* **162**(2):479-493.

Boccaletti, M., Bonini, M., Mazzuoli, R., Bekele Abebe, Piccardi, L. and Tortorici, L. (1998). Quaternary oblique extensional tectonics in the Ethiopian Rift (Horn of Africa). *Tectonophysics* **287**(1):97-116.

Boccaletti, M., Mazzuoli, R., Bonini, M., Trua, T. and Bekele Abebe (1999). Plio-Quaternary volcanotectonic activity in the northern sector of the Main Ethiopian 107 Rift: relationships with oblique rifting. *Journal of African Earth Sciences* **29**(4):679-698.

Bonini, M., Corti, G., Innocenti, F., Manetti, P., Mazzarini, F., Tsegaye Abebe and Pecskay, Z. (2005). Evolution of the Main Ethiopian Rift in the frame of Afar and Kenya rifts propagation. *Tectonics.* **24**(1).

Bonnefille, R. (2010). Cenozoic vegetation, climate changes and hominid evolution in tropical Africa. *Global and Planetary Change* **72**(4):390-411.

Charles Wanjie (2012). Overview of geothermal surface exploration methods. Presented at Short Course VII on Exploration for Geothermal Resources, organized by

UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, 15 pp.

Chernet, T.(1982).Hydrogeology of the lake region, Ethiopia Ministry of mine and energy, Ethiopian Institute of Geological survey, *Mem*. **7**: 97 pp

Le Turdu, C. et al. 1999, The Ziway–Shala lake basin system, Main Ethiopian Rift: Influence of volcanism, tectonics, and climatic forcing on basin formation and sedimentation, 135–177

Corti, G. (2009). Continental rift evolution: from rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa. *Earth-Science Reviews.* **96**(1):1-53.

Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P., Sokoutis, D., (2003). Analogue modelling of continental extension: a review focused on the relations between the patterns of deformation and the presence of magma. Earth Science Reviews

Corti, G., Sani, F., Philippon, M., Sokoutis, D., Willingshofer, W. and Paola Molin. (2013). Quaternary volcano-tectonic activity in the Soddo region, western margin of the Southern Main Ethiopian Rift, *Tectonics*.**32** :861–879.

Craig, H. (1963). The isotopic geochemistry of water and carbon in geothermal areas. Nuclear geology in geothermal areas, Spoleto, 17-53.

Ebinger, C., Bechtel, T., Forsyth, D. and Bowin, C. (1989). Effective elastic plate thickness beneath the East African and Afar plateaus and dynamic compensation of the uplifts. *Journal of Geophysical Research: Solid Earth (1978–2012).* **94** (B3):2883-2901.

Ebinger, C. and Casey, M. (2001). Continental breakup in magmatic provinces: An Ethiopian example. *Geology*. **29**(6):527-530.

Ebinger, C., Deino, A., Tesha, A., Becker, T. and Ring, U. (1993). Tectonic controls on rift basin morphology: evolution of the Northern Malawi (Nyasa) Rift. *Journal of Geophysical Research: Solid Earth (1978–2012).* **98**(B10):17821-17836.

Ellis, A.J. and Mahon, W.A.J. (1964). Natural hydrothermal systems and experimental hot water/rock interactions. Geochim. Cosmochim. Acta, 28: 1323-1357.

Fridriksson, T., Padrón, E., Óskarsson, F. and Pérez, N. M. (2016). Application of diffuse gas flux measurements and soil gas analysis to geothermal exploration and 144 environmental monitoring: Example from the Reykjanes geothermal field, SW Iceland. Renewable energy, 86: 1295-1307

Gezahegn Yirgu, Ebinger, C. and Maguire, P. (2006). The afar volcanic province within the East African Rift System: introduction, *Geological Society, London, Special Publications.* **259**(1):1-6.

Geological survey of Ethiopia, Basic Geosciences mapping Directorate. (2012) Geology geochemistry and gravity survey of the Hosaena areaa

Geological survey of Ethiopia(GSE) (2016), Consultancy Services for Geothermal Surface Exploration in Tendaho Alalobeda, Ethiopia. Unpublished technical report, GSE, Addis Ababa, Ethiopia.

Geological Survey Of Ethiopia Hydrogeology, Engineering geology and Geothermal Department (GSE) (2004). Geochemical study of the Aluto-Langano Geothermal Field and the surrounding areas. Unpublished technical report, GSE, Addis Ababa, Ethiopia, 32pp.

Gianelli, G., and M. Teklemariam (1993), Water-rock interaction processes in the Aluto-Langano geothermal field (Ethiopia),J. Volcanol. Geotherm. Res., 56, 429–445.

Giggnbach W.F., (1988). Geothermal solute equilibria: derivation of Na-K-Mg-Ca geoindicators, *Geochemica et Cosmochemica Acta.* **52**: 2749-2765.

Giggnbach,W.F.(1991). Chemichal techniques in geothermal exploration.In:D'Amore, F.(coordinator),Aplication of Geochemistory in geothermal reservoir development, *UNITAR/UNDP*,*Rom*e. 119-142

Gizaw, B. (1993), Aluto-Langano geothermal field, Ethiopian Rift Valley: Physical characteristics and the effects of gas on well performance, Geothermics, **22**(2), 101–116.

Grove A.T., Street, A.F., Goudie,A.S.(1975). Former lake levels and climate change in the rift vally of southern Ethiopia, *George's.* **141**: 177-202

Grove A.T., Goudie, A,.,1971. Late quaternary lake levels in the rift vally of southern Ethiopia and elsewhere in tropical Africa, *Nature*. **234**: 403-405.

Hayward, N. and Ebinger, C. (1996). Variations in the along-axis segmentation of the Afar Rift system. *Tectonics* **15**(2):244-257.

Hutchison, W., Mather, T. A., Pyle, D. M., Biggs, J. and Gezahegn Yirgu (2015). Structural controls on fluid pathways in an active rift system: A case study of the Aluto volcanic complex. *Geosphere* **11**(3):542-562.

Hutchison, W., J. Biggs, T. A. Mather,D. M. Pyle, E. Lewi, G. Yirgu, S. Caliro,G. Chiodini, L. E. Clor, and T. P. Fischer(2016), Causes of unrest at silicic calderas in the East African Rift: New constraints from InSAR and soil-gas chemistry at Aluto volcano, Ethiopia,Geochem. Geophys. Geosyst., 17, 3008–3030.

Keir, D., Ebinger, C., Stuart, G., Daly, E. and Atalay Ayele (2006). Strain accommodation by magmatism and faulting as rifting proceeds to breakup: 110 seismicity of the northern Ethiopian rift. *Journal of Geophysical Research: Solid Earth (1978–2012).* **111**(B5).

Keranen, K. M., Klemperer, S. L., Julia, J., Lawrence, J. F. and Nyblade, A. A. (2009). Low lower crustal velocity across Ethiopia: Is the Main Ethiopian Rift a narrow rift in a hot craton, *Geochemistry, Geophysics, Geosystems.* **10**(5).

Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., . . . Jerram, D. A. (2004). Flood and shield basalts from Ethiopia: Magmas from the African superswell. *Journal of Petrology.* **45**(4):793-834.

Kingham, T.J. (1975). Rainfall records for the southern Rift Valley of Ethiopia. Land Resources Div., U.K. Min. *Overseas Devel., Tolworth, Supplementary Report.* **18**: 50 pp.

Le Turdu, C et al. (1999). Influence of pre-existing oblique discontinuities on the geometry and evolution of extensional fault patterns: evidence from the Kenya Rift using SPOT imagery, In: Morley, C. (Ed.), Continental Rifting in East

Africa, Processes and Evolution: as Revealed by Hydrocarbon Exploration. *Am. Assoc. Pet. Geol. Spec. Publ*.

Makin, M.J., Kingham, T.J., Waddams, A.E., Birchall, C.J.,Teferra, T. (1975). Development prospects in the Southern Rift Valley, Ethiopia. Land Resources, Div., U.K. Min. Overseas Devel., Tolworth, *Land Resources Study* **21**: 270 pp.

Makin, M.J., Kingham, T.J., Waddams, A.E., Birchall, C.J., Eavis, B.W.(1976). Prospects for irrigation development around Lake Ziway, Ethiopia. Land Resources Div., U.K. Min.Overseas Devel., Tolworth, *Land Resources Study*. **26**: 407pp.

Marini, L. (2000). Geochemical techniques for the exploration and exploitation of geothermal energy. University of Genoa, Genoa, Italy, 82 pp

Meseret Teklemariam. (2012): 'overview of geothermal resource utilization and potential in the east african rift system' **In:** *Presented at Short Course III on Exploration for Geothermal Resources,* organized by UNU-GTP and KenGen, at Lake Naivasha, Kenya, Octo.24 – Nov.17.

Meseret Teklemariam and Solomon Kebede (2010), Strategy for Geothermal Resource Exploration and Development in Ethiopia, Geological Survey of Ethiopia, Addis Ababa, Ethiopia

Ministry of Water & Energy (MoWE) (2012), The Study on Groundwater Resources Assessment in the Rift Valley Lakes Basin in the Federal Democratic Republic of Ethiopia, Addis Ababa.

Mohr, P.A. (1967). The Ethiopian Rift System. Bull. Geophys. Observ., *Addis Ababa University* **11**:1–65.

Mohr, P.A. (1987). Patterns of faulting in the Ethiopian rift valley. *Tectonophysics* **143**;169–179.

Mohr, P.A.(1983). Ethiopian flood basalt province. *Nature* **303**: 577–584.

Mohr, P., Mitchell, J.G. and Raynolds, R.G.H. (1980), Quaternary volcanism and faulting at O'a Caldera, Central Ethiopian Rift. *Bull. Volcanol*. **43**: 173–189.

Morandini, G.(1940). Le caratteristiche di alcuni laghi dell'Africa Orientale Italiana, *Riv. Geogr. Ital*. **47**: 67–76.

Morley, C. (1993). Interaction of deep and shallow processes in the evolution of the Kenya Rift, *Tectonophysics.* **236**: 81–91.

Morley, C. (1999). Tectonic evolution of the East African Rift System and the modifying influence of magmatism. *Acta vulcanologica* **11:**1-20.

Nicholson, S.E. (1996). A review of climate dynamics and climate variability in eastern Africa. In: Johnson, T.C., Odada, E.O. (Eds.), The Limnology, Climatology and Paleoclimatology of the East African Lakes. *Gordon and Breach, Amsterdam*, pp.25–56.

Omenda,P.A. (2007). 'The geothermal activity of the east African rift' **In:** *Presented at Short Course II on Surface Exploration for Geothermal Resources*, organized by UNU-GTP and KenGen, at Lake Naivasha, Kenya, November 2-17.

Peccerillo, A., Barberio, M., Gezahegn Yirgu, Dereje Ayalew, Barbieri, M. and Wu, T. (2003). Relationships between mafic and peralkaline silicic magmatism in continental rift settings: a petrological, geochemical and isotopic study of the Gedemsa volcano, central Ethiopian rift. *Journal of Petrology*. **44**(11).

Peccerillo, A., Donati, C., Santo, A., Orlando, A., Gezahegn Yirgu and Dereje Ayalew (2007). Petrogenesis of silicic peralkaline rocks in the Ethiopian rift: geochemical evidence and volcanological implications. *Journal of African Earth Sciences.* **48**(2):161-173

Smith, M and Mosley,P.(1993). Crustal heterogeneity and basementinfluence on the development of the Kenya rift. East Africa. *Tectonics.* **12**: 591-606

Solomon Kebede (2016). Country Update On Geothermal Exploration and Development in Ethiopia, Geological Survey of Ethiopia, Addis Ababa.

Solomon Kebede (2012). Geothermal Exploration and Development in Ethiopia: Status and Future Plane, Geological Survey of Ethiopia, Addis Ababa.

Street, F.A. (1979). Late Quaternary lakes in the Ziway–Shala Basin, Southern Ethiopia. Unpublished Ph.D. thesis, University of Cambridge, 475 pp.

Tadiwos Chernet (1995). Petrological, geochemical and geochronological investigation of volcanism in the Northern Main Ethiopian Rift-Southern Afar transition region. Unpublished Phd. Thesis, Miami University, Ohio, USA.

Ravi, Y., Chernet, T., Gibert, E.(1997). Study of the hydrological behaviour of the lakes region in the Ethiopian Rift using hydrological, hydrochemical and isotopic data: palaeohydrological implications. International Symposium Flood basalts, Rifting and Paleoclimates in the Ethiopian Rift and Afar Depression. Addis Ababa, February 3–14, abstr. 43.

Samrock, F., A. Kuvshinov, J. Bakker, A. Jackson, and S. Fisseha. (2015), 3-D analysis and interpretation of magnetotelluric data from the Aluto-Langano geothermal field, Ethiopia,Geophys. J. Int., 202(**3**), 1923–1948.

Tonani, F. (1970). Geochemical methods in prospecting for hot water. Geothermics, 2: 492-5150.

Tonani, F. (1980). Some remarks on the application of geochemical techniques on the geothermal exploration. Proc. Adv. Eur. Geoth. Res., 2ndSympo. , Strasbourg, 428-443.

Tsegaye Abebe, Maria Laura Balestrieri and Giulio Bigazzi (2010). The Central Main Ethiopian Rift is younger than 8 Ma: confirmation through apatite fission-track thermochronology. *Terra Nova*. **22**: 470–476.

Tsegaye Abebe, 2000: 'Geological limitations of a geothermal system in a continental rift zone: example the Ethiopian rift valley'. **In:** *Proceedings World Geothermal Congress*, Kyushu - Tohoku, Japan, May 28 - June 10.

United Nation Development Program (UNDP) (1973). Investigation of geothermal resources for power development: Geology, geochemistry and hydrology of hot springs of the East Africa rift system within Ethiopia. Unpublished technical report, (UNDP), United Nations, New York, 146pp.

WoldeGabriel, et al (1990). Geology, Geochronology, and Rift basin Development in the Central Sector of the MER. *The Geological Society of America Bulletin*, **102**:439-458.

Wolfenden, E., Ebinger, C., Gezahegn Yirgu, Deino, A. and Dereje Ayalew (2004). Evolution of the northern Main Ethiopian rift: birth of a triple junction. *Earth and Planetary Science Letters* **224**(1):213-228.

Zanettin, B., Justin-Visentin, E., Nicoletti, M. and Petrucciani, C. (1978). The evolution of the Chencha escarpment and the Ganjuli graben (lake Abaya) in the southern Ethiopian rift. *Neues Jahrbuch fur Geologie und Palaonotologie,Monash* **8:**473-490.