ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCES

GEOCHEMICAL AND PETROGRAPHIC CHARACTERISTICS OF CRYSTAL RICH VOLCANIC ROCKS FROM LALIBELA AREA, NORTHWESTERN ETHIOPIA.

BY
GIRMA HAILU KETSELA

A thesis submitted to the School of Graduate Studies of Addis Ababa University in Partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences (Geochemistry)

Jun/2018
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Declaration of Originality

I hereby declare that the thesis is my original master‘s degree work under the supervision of Prof. Dereje Ayalew, School of Earth Sciences, Addis Ababa University during theyear 2018. I further declare that this work has not been presented or submitted to anyother university or institution for the award of any degree or diploma. All sources andmaterials used for the thesis have been duly acknowledged.

Girma Hailu Ketsela ________________ __________________

Signature Date

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

Prof. Dereje Ayalew (Advisor) ________________ __________________

Signature Date

Acknowledgment

This thesis work is not the result of only my activity. There is a contribution of different organization and individual to compile the necessary data and laboratory analysis results.

First I would like to give my sincere gratitude to university of Gondar geology department for providing an opportunity to study my master's degree funding the research project and Addis Ababa University for their willingness to continue my learning in the field of Geochemistry..

Thesecond deepest thank goes to my advisor Prof. Dereje Ayalew for his follow-up, constructive comment, suggestion, encouragement and support to get external link for my geochemical laboratory analysis. I would also like to thank Prof. Gezahegn Yirgu for him politely support to show the study area location and sampling technique on the topographic map and dissection, it is real meant a lot for me. I would like to give great thank to Dr. Tyrone O. Rooney and Michigan state university geoanalythical laboratory technician for their polite willingness to do my geochemical laboratory analysis without any fee.

I have also great thanks to my family for their tireless support by interesting word and idea during my field work and learning. I have no words to thank my friends for their polite willingness in whole my work.

Las but not end, I would like to thank Lalibela area and Bilbala village peoples for their happiness and support during my field work, All the peoples who have direct or indirect contribution in this work have my deepest great thanks

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List of Acronyms

CIPW	Cross, Iddings, Pirsson and Washington
C^o	degree cilices
GSE	Geological survey of Ethiopia
HREE	heavy rare earth element
HFSE	high field strength element
HT	high titanium
ICP-AES	inductively coupled plasma atomic emission spectroscopy
ICP-MS	inductively coupled plasma spectroscopy
K	Kelvin
Km	kilo meter
LIP	large igneous province
LILE	large ion lithophile element
LREE	light rare earth element
LT	low titanium
MER	main Ethiopia rift
MORB	mead oceanic ridge basalt
MREE	middle rare earth element
mm	millimeter
Myr	millions year
OIB	oceanic islands basalt
Olv	olivine
Plg	plagioclase
ppb	parts per billion
ppm	parts per million
Cpxn	clinopyroxene
SEP	southern Ethiopia plateau
TAS	total alkali silicate
REE	rare earth element
WEP	western Ethiopia plateau

Abstract

The Bilbala magmatic complex is situated in northwestern Ethiopian plateau near to northern main Ethiopia rift. The aim of this work was to investigate and identify the sources involved in the petrogenesis of the pre –rift basalts of the Bilbala area around Lalibela wich located with approximate distance of 730 Km from Addis Ababa. Field observation, ptrographic analysis and geochemical data analysis are the main method used to meet the aim or objective of this study. Based on field observation and description the study area is covered by basaltic rocks. The paper presents the results of a comprehensive major element, trace element, and petrographic study of Oligocene volcanic sequences from the northwestern Ethiopian flood basalt province around Lalibela. A petrographic analysis result with field observation indicates the presence of clinopyroxene, olivine and plagioclase as phenocrysts and groundmass with Fe-Ti oxides, opaque minerals and volcanic glass. The major and trace element compositions with mineral assemblage of crystal rich basaltic rocks in the area show the HT basalts characteristics of the Ethiopian continental flood basalt. The analyzed samples result displays high contents of TiO_2 (3.36-6.87%), FeO* (11.59-15.71%), CaO/Al_2O_3 (0.89-1.989%) and enrichment of incompatible trace elements and LREE. On primitive mantle normalized diagram of the studied samples there is positive Ta and Nb anomalies, but Sr with Pb shows negative anomalies.Enrichment of LREE and a relative depletion of HREE in the studied samplesis observed and this suggest the presence of residual garnet in the source, and from trace elements concentration and ratios there is little evidence for contamination during the magmatic ascent.The Ce/Pb, Nb/Th and Nb /U ratios of the study area basaltic rocks display 21.3-51.7, 9.5-13.8 and 33.1-45.2 respectively. These elemental ratios have nearly OIB type character. The studied samples have low Zr/Nb ratios (< 10). The low Zr/Nb value of this mafic lava might imply a dominant mantle plum contribution during the genesis of the study area lavas.

Key words: Bilbala, fractional crystallization, crustal contamination, partial melting, mantle plume, depletion, enrichment.

CHAPTER ONE

1. INTRODUCTION

1.1. Background

The Cenozoic volcanic plateaus are a part of continental flood basalt relatively young age and their eruption in a region where plate movements are slow.a complete record of volcanic and tectonic activity is preserved by the nature of volcanism as changed markedly during the Oligo-Miocene-Quaternary age. The Ethiopian volcanic provinces are mainly exposed within the rift and plateaus. They are involved by different phase and mechanisms due to volcanisms takes place through fissures which means through large crack formed due to the upcoming of mantle plume. After fissural volcanism central volcanism takes in the rift zone. Regionally the study area is categorized under the pre-rift volcanic province of Ethiopia. It is situated in the northwestern Ethiopian plateau. The study area is covered by Tertiary volcanic rocks. The volcanic rocks vary in character based on composition, structure and degree of weathering. (Piccirillo et al., 1979; Mohr, 1983; Pik et al., 1998, 1999; Kieffer et al 2004; Beccaluvaet al., 2009)). They also explained the distinctive petrological features of the Ethiopian plateau as transitional tholeiitic to alkaline magmatic character of the mafic lavas, in contrast with the tholeiitic character of most continental flood basalts, and the high proportion of felsic pyroclastic rocks.

The Ethiopian volcanic can be divided into two main series: Trap Series and Rift Series. Much of the volcanic province is dominated by Tertiary basaltic flows, fed from fissures aligned along developing pairs of opposed, emerging continental margin. Trap series are those groups of formations that are formed before the perfect development of main Ethiopian rift during the time of rift initiation· They are also known as plateau volcanoes or pre-rift sequences. They are the main igneous units exposed in the northwest and southeastern Ethiopian plateaus. The age of trap series is Tertiary and their basaltic flow emanated from fissures aligned along developing pairs of opposed, emerging continental margins.

The large igneous provinces of Ethiopia which related to the afar mantle plume(Coffin and Eldholm,1994) has an estimated volume of $1.2*10^6 km^3$ flood basalts (Rochette et al.,1998) and silicic lava of $6*10^4 km^3$(Ayalew et al.,2002) covering more than 600,000 km^2(Mohr and Zenettin, 1988) and (Hoffman et al,1997;,Rochette Et al.,1998; Ayalew et al.2002; Coule et al.,2003) explained that the timing of volcanism and outpouring phase of this large amount of lavas is occurred 30 Ma ago within a space of 1-2 Ma.

Piket al.,(1998) and Kieffer et al.,(2004) said that the Ethiopian flood basalts form three distinct magma groups, which show geographical rather than temporal variation on the basis of their major and trace element composition. The LT basalts, which occupy the north-west part of the plateau, show consistently low TiO_2 contents and considerable heterogeneity in their trace element geochemistry. The HT2 basalts, which occur in the south-east part of the plateau, on the other hand, have consistently high TiO_2 contents and more homogeneous trace element signatures. Enrichment of LREE and a relative depletion of HREE in their reportsuggest the presence of residual garnet in the source, and there is little evidence for contaminationduring magma ascent.The HT1basalts display characteristics between the two other groups.

1.2 Geographic Setting of the Study Area

1.2.1Locationand Accessibility

This thesis research project areais conducted in northern part of the country withinthe Ethiopian flood basalt which located in Amhara Regional state around Lalibela town specifically at Bilbala area and covers an area of 150 .km^2. The area can be accessed from Addis Ababa through two main ways; Addis Ababa-Dessie-Woldiya-Lalibela (730km) and Addis Ababa-Bahir Dar-Woreta-Debre Tabor-Lalibela (820km). There are manyimportant all-weather and dry-weather gravel roads those are leading to different parts ofthe area. . It is about 30 km on the way of Sekota town from Lalibela.

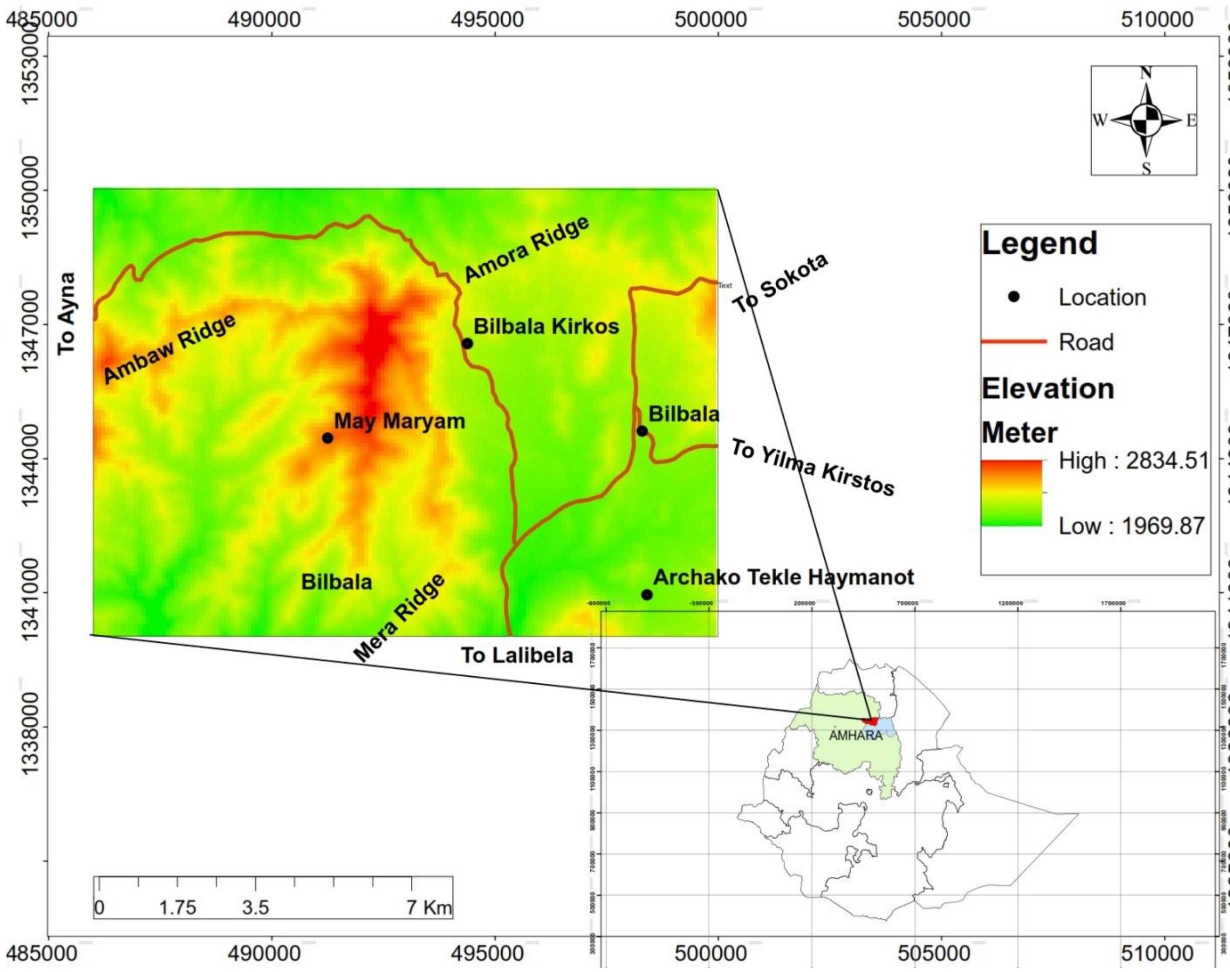


Figure 1.1. Location and accessibility map of the study area.

1.2.2 Physiographyand Drainage

The present land escape of Lalibela and its surroundings is part of the highlands of the North-central Ethiopian plateau that formed by enormous volcano tectonic events and subsequent denudation processes that took place after the Mesozoic time (Mohr,1983) and characterized by, deeply dissected gorges, plateau and high altitude continuous chain of mountains and ridges. The elevation in the studyarea ranges from 2058-2757 meter above sea level.

The BilbalaRiver is the big drainage pattern that found in the study area which varies its water content following seasonal variation. During Ethiopian summer this river gets a lot of water from different small seasonal tributary streams and form deep valley around it. There are also many streams which found in different part of the area of study.

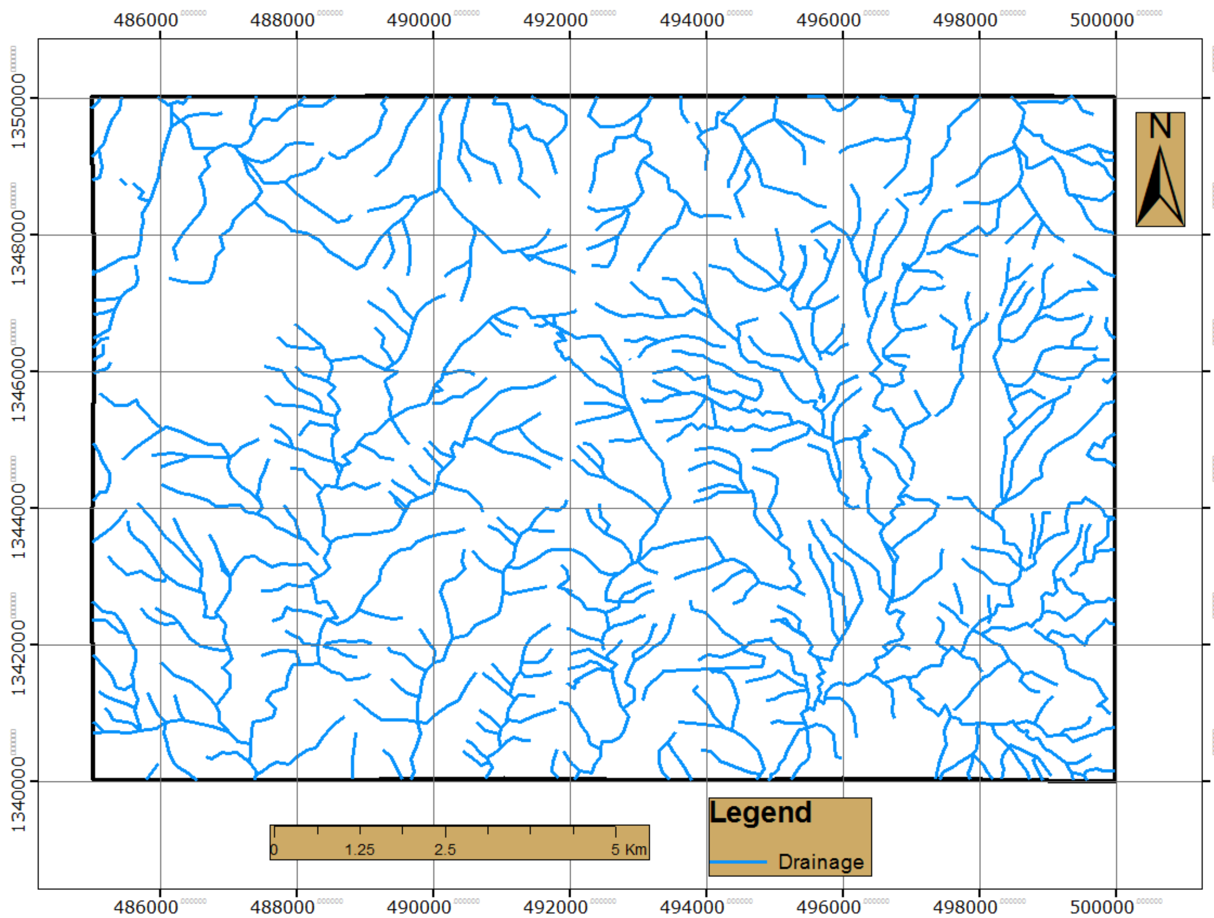
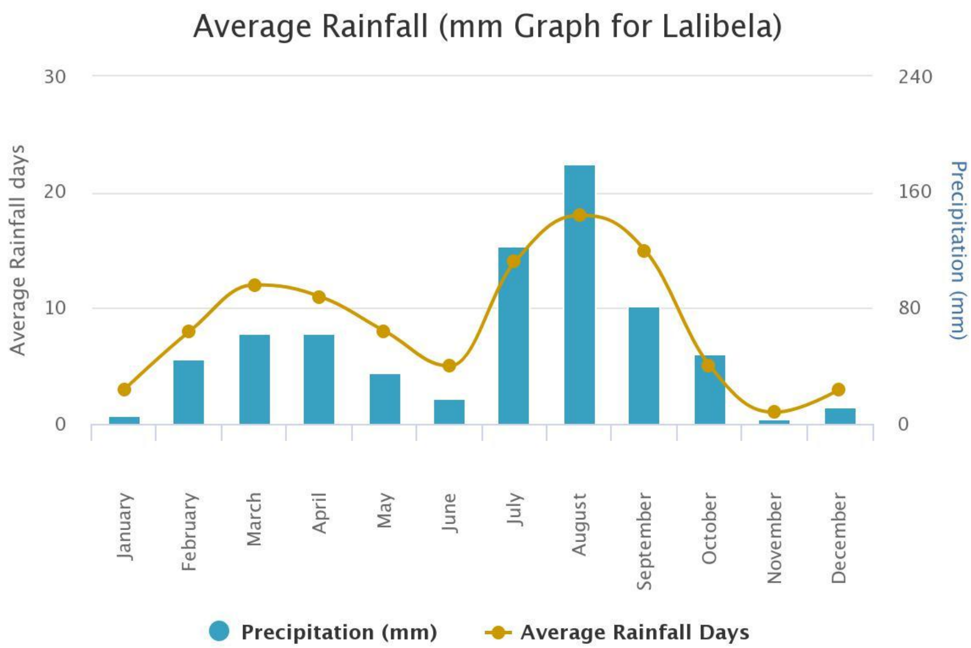


Figure 1.2 drainage pattern of the study area.

1.2. 3 Population, Climate and Vegetation

According to the population census of (2007) conducted by the Ethiopian central statistical agency the total population ofLastawereda was 117,777, of whom 58451 are men and 59326 women: out of these 14.75%(17367) are urban inhabitants.The majority of the population (97.65%) are practiced Ethiopian orthodox Christianity with2.32% of Muslim.the total population in Lalibela city was 17, 367, of whom 8,112 were males and 9,255 were females. The density of population in the study area is low. Bilbala is the smallest village in thestudy area with less than 1500 peoples. Amhara is the largestethnic group in the area that speaks Amharic language.The people in the rural area engage in farming activity. They are engaged in mixed type of farming activity both ploughing and animal rising. Teff, millet, barely, maize, beans, lentil, and peas are cultivated. Livestock'ssuch as cattle, sheep and goats are bred. Pack animals such as horses, donkeys andmule are also common.

According to metrological agency of Ethiopia (2016)data the study area has different climatic condition within a year. It is classified as warm and temperate climate. The average temperature of the year in the study areais 14.7^{0}C.May is the warmest month with an average temperature of 16.7^{0}C and December is the coolest month with an average temperature of 12.6^{0}C.August with 294.6mm of precipitation is the month which has the most precipitation on average and January has the least precipitation with an average of 12.7mm.the annual precipitation of the area is 1142.1mm.



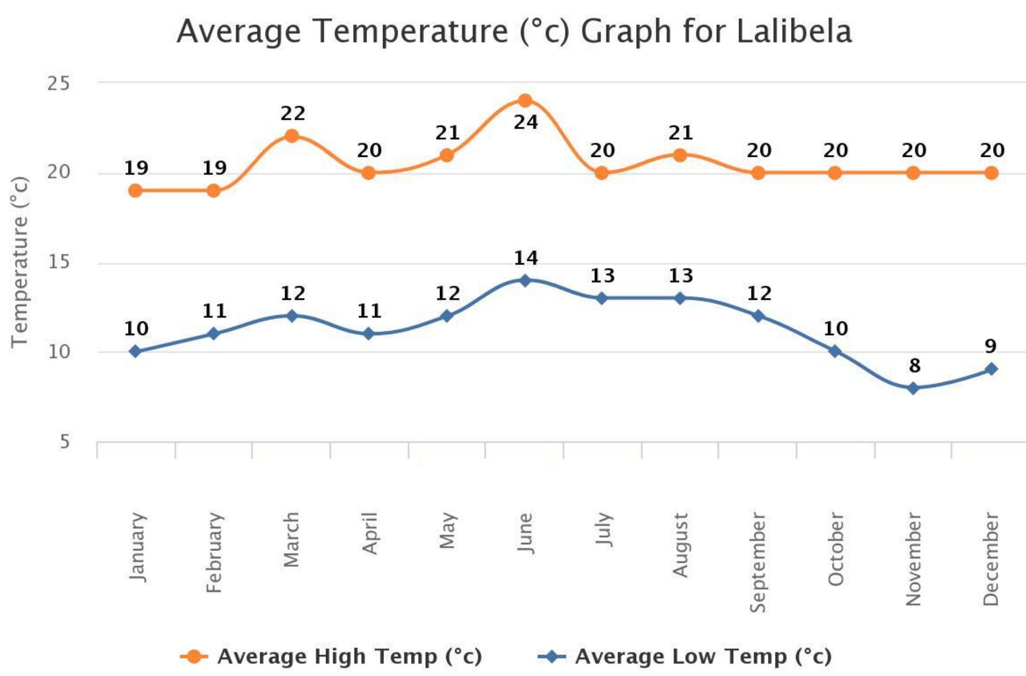


Figure 1.3 climate data graph of Lalibela area which include both rainfall and temperature of the area according to Ethiopian metrological agency (2016).

Vegetation is typically thorn savanna and dry mountain forest (Plateau area) and veryrare vegetation covers in low land, characterized by various types ofthorny bushes, small shrubs.

1.3Objectives of the present study

1.3.1. General objective

The main objective of this study is to understand petrogenesis of Lalibela area volcanic rocks based on petrographic and geochemical data.

1.3.2. Specific objectives

- To prepare stratigraphic section of the study area based on field observation and petrographic results.
- To characterize petrographic properties of volcanic rocks of the study area.
- To characterize the chemicalcompositional difference in basaltic rocks of the study area.
- To identify the process involved in the petrogenesis of Lalibela area flood basalts.

1.4 Statement of the problem

Petrogenetic studies of igneous rocks involve determining the history of the sources of melts, the conditions of melting, the mineralogical and chemical composition of the source during melting, the extent of the melting processes involved, and how the melt is modified by assimilation, metasomatism, differentiation, and fluids (Wilson,1989). Most studies on Ethiopian plateau magmatism have been carried out at a regional scale and detailed investigations on single sections of the plateau arescarce. Moreover, lack of a detailed geological map of any particular section of the Ethiopianflood basalt province makes it difficult to correlate much of the existing high qualitygeochemical data from various parts of the Ethiopian flood basalt province. As a result of incomplete exploration interms of petrographic and geochemical characteristicsof the volcanic rocks of Bilbala area,the aim here is to investigatethe petrography, geochemistry, and genesis of the Lalibela area specifically Bilbala area basalts, that has remainedunknown and unexplored until now.

1.5 Methodology

In order to accomplish the objective of this thesis work the following methods are used.

1.5.1. Literature review

To understand about the area different previous works which are relevant for this study on the basis of geology, tectonic setting, and petrology and geochemistry data were reviewed from published or unpublished reports, maps, journals, scientific publications.web sites, etc.

1.5.2. Field investigation

Sampling and mapping was performed from November 22 to December 15/2016 and the field traverses were primarily aimed for systematic sampling on different variety of rocks for petrographic and geochemical analysis. Rocks were described at the outcrops. Photographs were taken at representative out crop features. During traverses an attempt was made to select complete sections having compositional variation. A total of 30 rock samples were collected during the fieldwork. The sample numbers have a prefix “B” standing for Bilbala. All of the samples are collected from basaltic lava flows.

1.5.3. Data analysis and organization

1.5.3.1 Petrographic analysis

A total of 12 standard thin sections were prepared in the mineralogy and petrography laboratory of Geological Survey of Ethiopia (GSE).These thin section were prepared by cutting from rock samples, cemented to microscope slides, and ground down to 0.03mm thickness so that they readily transmit light. The thin sections were described using polarized petro graphic microscope. A detailed petrographic study /thin section descriptions/ including mineral identification, modal proportion, textural descriptions, and rock naming were performed in Gondar University petrographic laboratory. Representative mineral assemblage and textures were photographed under the microscope.

All the data collected from the various works conducted were organized analyzed and interpreted by using different computer software’s such as Microsoft Excel, IGPET and Gcdkit software.

1.5.3.2. Geochemical analysis

Samples for geochemical analysis were collected in the first phase of the field work which is discussed in section 1.5.2. The sample preparation for geochemical analysis includes making a rock powder after removing the weathered part of the rock. To do this three steps has been followed; the first step is to remove the weathered part from the surface of the rock sample and break it in to desirable sizes, the second step is to crush the broken fresh sample in a jaw crusher and finally the crushed sample were milled down to micron size particles in an agate ball automatic milling machine. The sample preparation is done at Ethiopian geological survey milling room. To minimize cross contamination of samples, after crushing and milling every single rock sample, the Jaw crusher and the ball mills are blown by an air compressor and washed out to remove any possible contaminant, then dried to continue with the second sample.Major elements are analyzed by inductively coupled plasma – atomic emission spectrometry (ICP –AES), andtrace and rare earth elements of the samples were analyzed by ICP-MS at the Department of Earth Sciences, Michigan State University Geoanalytical laboratory. Both instruments techniques make use of high temperature inductively coupled plasma.

Majorelement is analyzed by ICP-AES. Because of the sample introduced into the ICP is in liquid form solid samples have converted to liquid by dissolving it into proper solvent. The solvent is ultra-pure HNO3 and dried at 160 C^{o}. The first process called nebulization where sample is converted to a mist of finely divided droplet called aerosol, where the sample is sucked into capillary tube by a high pressure stream of Argon gas flowing around the tip of the tube. This pressure breaks the liquid into fine droplets in various sizes in the spray chamber. In the spray chamber, separation of aerosol occurred where the large droplets go to drain the fine droplet carried to the plasma. The sample mist reaching the plasma is curiously dried, vaporized, and energized through coalitional excitation at high temperature (up to 8000 K). In this case, the atomic emission emanating from the plasma is viewed in either a radial or axial configuration, collected with a lens or mirror, and imaged onto the entrance slit of a wavelength selection device. The instrument runs will include an initial calibration verification solution and a blank solution at the beginning and end of every run. A calibration verification solution will be analyzed after every sample throughout the run. The verification measurements (Standard

Reference Material 2780) must be within 10 percent of the expected value. If they are not, the problem should be corrected before continuing with next analyses.

Trace element is analyzed by ICP-MS. ICP-MS is the most accepted tool for trace element and isotopic analysis (Rollinson, 1993). The acceptability in the science is due to its detection limit is low, high accuracy and high precision. In similar to ICP AES the sample is introduced after changing in liquid form by using HNO_3. Ions are extracted from the plasma through a pin-hole sized loop into a pumped vacuum system and focused with an ion lens into a mass spectrometer. Once the ions enter the mass spectrometer, they are separated by their mass-to-charge ratio. The result is that an electrostatic filter is established that only allows ions of a single mass-to-charge ratio (m/e) pass through the rods to the detector at a given instant in time. The relative standard deviation (RSD) of the instrument is 1-2% with comparing to calibration solution of a multi-element doped solution. Matrix extraction prior to the analysis of trace elements in geochemical materials was used to remove possible isobaric interference and, eliminate signal suppression in the plasma.

1.6. Expected outcome and Research relevance

As mentioned in the problem statement the Bilbala area has not been studied in the aspect of petrography and geochemistry in detail, and this will be the very first detail study on its petro-chemical characteristics. The main expected research outputs will be as follows:

- An interpretation, based on geochemical analyses, of the petrogenesis of the mafic rocks that are exposed in the area to determine whether the rock formed by fractional crystallization from mantle, crustal melting or other processes?
- This thesis work gives some petrographic and geochemical aspects of the area for the ongoing next work.
- The research study is mainly done for the partial fulfillment of my Master‘s degree in Geochemistry and it gives some information about the area to who have an interest to work on this exposure.

1.7. Review of previous geological work

According to the work of Mohr, (1983), Mohr and Zenettin,(1988), Hofmann et al., (1997),Pik et al., (1998), Kieffer et al.,(2004) petrogenesis of Cenozoic continental flood basalt (CFB) in Ethiopia consists of Oligocene pre-rift volcanism which related to the Africa–Arabia continental break-up. Concerning the present study areaa number of reports has been done on regional scale, and some studies were undertaken in northern Ethiopia by different authors. As an example, Baker et al., (1996), and Hofmann et al., (1997), said that the occurrence of magmatism in the northern Ethiopia plateau took place within a short period of time, <5 Myr during the Oligocene with the emplacement of thick continental flood basalt

The northern Ethiopia flood volcanic succession includes basaltic lava flows, basaltic tuffs, rhyolitic, trachytic and phonolitic products (Mohr and Zenettin, 1988). In mineralogical composition the flood basalts of northwestern Ethiopia are aphyric and sparsely phyricwith phenocrysts of plagioclase and clinopyroxene with or without olivine (Mohr, 1983; Pik et al., 1998 and 1999; Beccaluva et al., 2009; Natali et al., 2016). Based on major and trace element concentration with some trace element ratio Piket al. (1998),divided flood basalt of northern Ethiopia into three types. These are low-Ti” basalts (LT), high-Ti_1” basalts (HT1) and high Ti_2 (HT2).The low-Ti basalts are transitional to tholeiitic with low TiO_2,P_2O_5,Fe_2O_3,Nb/La, high SiO2 and flat rare earth element patterns with low levels of incompatible elements that found at northwestern part of the province and the high-Ti2 basalts that found in south and east partare subalkaline that have high TiO_2,P_2O_5,Fe_2O_3,Nb/La, low SiO2 with high concentration of incompatible elements and fractionated rare earth element patterns. The high Ti1 basalts are intermediate between LT and HT2 groups. Lavas of these provinces erupted 30 Ma ago, during a short 1–2 Ma period, to form a vast volcanic plateau (Baker et al. 1996; Hofmann et al. 1997). Kieffer et al. (2004) said that the mineralogical and chemical composition of the northwestern Ethiopian flood basalts is relatively uniform. Although most of the volcanic plateau erupted in a short period between 31 and 30 Ma (Hofmann et al., 1997), the upper parts of the flood volcanic pile have ages to around 25 Ma, suggesting a relatively protracted period of flood volcanism (Ukstins et al., 2002).

Kieffer et al. (2004) said that the northern Ethiopia Oligocene pre-rift flood basalts contain melts formed within upwelling mantle plume and in some cases also from the overlaying continental crust. The large volume and widespread distribution of these basalts together with contemporaneous topographic uplift suggests that their genesis may be linked to the impact of the ‘starting-head’ of the mantle plume. The mid-Tertiary (~30 Ma) Ethiopian continental flood basalts form part of the larger Afro Arabian Igneous Province, which is related to the Afar plume and the Red Sea-Gulf of Aden (Ethiopian Rift triple junction).

The Lalibela area is mainly characterized by a 1700 m-thick sequence of high TiO_2 (HT2 magma type)picrite-basalt lavas capped by about 300 m of rhyolites, linked to the magmatic activity at the Afar plume axial zone (Beccaluva et al.,2009). According to Teferi et al.(2014) ferropicrite and picritic ferrobasalt lava flows are found near Lalibela in the Oligocene (30Ma) Ethiopian large igneous province in association with ultratitaniferous transitional basalt and picrite of second high Ti (HT2) series with high Zr/Y and low Al_2O_3/TiO_2 ratios indicating higher pressure melting or smaller degree of partial melting.Lalibela area ferropicrite and picritic ferrobasalts shows porphyritic texture with phenocryst phases of olivine and augitic clinopyroxene (Teferi et al., 2014).

1.8. Thesis Overview

The thesis is structured in six 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 and petrography of the study area basaltic rocks. In Chapter four geochemical data is presented, interpreted and the magmatic evolution of mafic rock of Bilbala areais given. Chapter five focused in discussions about the area from the previous work with this thesis result. Eventually the main conclusion and recommendation for the future study is dealt in chapter six.

CHAPTER TWO

2. REGIONAL GEOLOGIC SETTING

2.1 INTRODUCTION

Following the late Mesozoic-early Cenozoic regression of the sea to the east and southeast an epirogenic uplift of Afro-Arabia (East Africa, Arabia peninsula and the intervening regions now occupied by the Red Sea and Gulf of Aden) occurred on an immense scale as indicated by Cherenet et al. (1998). The cause and initiation of the major uplift is closely related to the first eruption of flood basalts, a mantle plume upraised the land mass which fissured under tension and permitted the ascent of magma generated by high degree of decompression melting in the mantle to form the trap series. Following this uplift tholeitic flood basalt volcanism was wide spread in the early Eocene-Oligocene to form the northwestern and southern Ethiopian plateaus (Piccirillo et al., 1979; Mohr and Zanettin, 1988; Hart et al., 1989; Ebinger et al., 1993; Stewart and Rogers, 1996).

The Cenozoic Ethiopian continental flood basalt is one of the youngest flood basalt on earth and is related to the opening of the Red sea and Gulf of Aden (Baker et al, 1996; George et al, 1998). These two oceanic rifts are connected to the less developed east African rift at the Afar triple junction. This triple junction is the center of a large volcanic province that is exposed in Ethiopia, Eritrea, Yemen and Republic of Djibouti (Pik et al, 1998). The Ethiopian volcanic province covers an area of about 600, 000km2 with a layer of basaltic and felsic volcanic rocks (Ukstins et al, 2002; Kieffer et al, 2004). According to the traditional classification, the Tertiary flood basalts of Ethiopia are divided into four types based on their ages (Mohr, 1983), From bottom to top these are called the Ashange, Aiba, Alaje and Termaber Formations. In contrast to the above classification, the flood basalts are geochemically classified into three distinct magma types: as low Ti basalts (LT), high Ti1 basalts (HT1) and high Ti2 basalts (HT2) (Pik et al, 1998, 1999).

The Ethiopia Large Igneous province (LIP) which is located near the triple junction of the Red sea, Gulf of Aden and East African Rifts is considered as a young example of continental flood basalt volcanism associated with continental break up. According to the works of Berhe et al.

(1987), Baker et al.(1996a), Hoffman et al. (1997), Chernet et al. (1998), George et al. (1998). Rochette et al. (1998) Ukstins et al. (2002) Kieffer et al. (2004) these flood basalts and associated felsic pyroclastic rocks are erupted at around 30 Ma ago during a relative short, <5 Myr period and formed because of the impingement of the Afar mantle plume beneath the Ethiopian lithosphere.

Initial sagging of the MER started about 15Ma and was followed by major episodes of rifting at 10, 5, 4, and 1.8 to1.6 Ma. Each stage of rifting and down faulting was accompanied by a bimodal (felsic mafic) volcanism in the rift and formation of basaltic and trachytic shield volcanoes on the rift shoulder and margins. The general consensus is that down faulting of the Afar depression started at a much earlier age and that rifting was accompanied by a voluminous flood basalt volcanism. Following the initiation of subsidence of the Afar depression and the MER, subsequent volcanism was restricted at first to the evolving rifts and then to the axial zones which later become a focus of Quaternary and recent volcanic activity (Chernet et al., 1998; Ukstins et al.,2002).

The regional geology of northwestern Ethiopian plateau has a variety of geological events which were operated in Ethiopia during the geologic past, each of them are marked by the development of new stratigraphic sequence. The Precambrian continental collusion results the formation of Ethiopian basement rocks. The Paleozoic sedimentation and the development of sedimentary basins due to the Mesozoic breakage of Gondwanaland result Ethiopian sedimentary sequence. Intra-plate rifting during Cenozoic era associated with the up-coming Afar mantle plume is the modern stratigraphic history which result Ethiopian volcanic province (Pik et al., 1999; Beccaluva et al., 2009; Natali et al., 2011,1016). The flood basalts have relatively uniform mineralogical and chemical composition (Kieffer et al., 2004) but they differ in their texture. In almost all of these areas, the basaltic rocks show two phases of eruption: a fine-grained aphanitic basalt at the base followed by a coarse-grained phaneritic basalt on the top. A discontinuous layer of thin Tertiary lacustrine deposit has been observed within most of the volcanic successions, separating the lower fine-grained from the upper course-grained basalt.

The Ethiopian volcanic provinces are the results of intra-plate rifting during Cenozoic era. This rifting is initiated by the upcoming of mantle plume from interior of the craton and results the separation of the African tectonic plate from Arabian plate initially from the north and later to the south (Pik et al., 1999; Kiefer et al., 2004; Beccaluva et al., 2009; Natali et al., 2011, 2016). Trap series are those groups of formations that are formed before the perfect development of main Ethiopian rift. They are also known as plateau volcanoes or pre-rift sequences. They are the main igneous units exposed in the northwest and southeastern Ethiopian plateaus. This series includes: Ashange group, Aiba fissural volcanism, Alaje fissural volcanism and Termaber central volcanism. Basalts from the Northwestern Ethiopian Plateau display a particularly wide compositional range (Chazot and Bertrand, 1993; Stewart and Rogers, 1996; Baker et al., 1996). The petrogenesis of Continental flood basalt provides valuable constraints on the relationships between mantle domains at the beginning of continental break-up. Such large igneous provinces consist of thick flood basalt piles, extruded over large areas.

2.2 Tectonic Setting of Ethiopian Plateau

As reported by different researcher the Ethiopian Plateau is separated into western and eastern shoulder by the Afro-Arabian Rift System. Much of the volcanic province is dominated by Tertiary basaltic flows, fed from fissures aligned along developing pairs of opposed, emerging continental margins. The volcanic are distributed asymmetrically about the Ethiopian rift system. The asymmetry matches that of the eastern uplifted highlands, comprising the broad western plateau and the narrow south-eastern plateau to either side of the rift. The thick sequence of the Trap Series flood basalts are superimposed by thick lava flows emanating from central volcanoes forming shield volcanic mountains (Berhe et al., 1987; Chernet et al., 1998; Ukstins et al., 2002; Kieffer et al., 2004).

The Main Ethiopian Rift (MER) is a roughly NE-trending sector of the East African Rift system that includes a series of rift segments extending from the Afar Depression at the Red Sea-Gulf of Aden intersection to the Kenya Rift. The MER is characterized by active extensional tectonics accommodating the ~6-7 mm/yr relative movement between the African and Somalian plates. The dynamics of mantle sources involved in Ethiopian continental volcanism and the sources interaction with continental lithosphere during ascent is reported by different authors (Mohr and Zanettin, 1988; Berhe et al., 1987; Baker et al., 1996a; Hoffmann et al., 1997; Pik et al., 1998, 1999; Baker et al., 2000, 2002; Ukstins et al., 2002; Kieffer et al. 2004; Baccaluva et al., 2009; Natali et al., 2016). Mineralogical and chemical composition of the Ethiopian flood basalts is relatively uniform and majority of them are aphyiric to sparsely phyiric with phenocryst of plagioclase and clinopyroxene with or without olivine. They are tholeiitic to transitional in composition (Piccirrillo et al., 1979; Mohr, 1983; Mohr and Zanettin, 1988; Pik et al., 1998; Kieffer et al., 2004; Beccaluva et al., 2009). The presence of picrites in the northern Ethiopian flood basalts is also described in the works of (Baccaluva et al., 2009; Teferi et al., 2014; Natali et al., 2016) and felsic lavas at upper stratigraphic levels (Ayalew et al., 2002; Ukstins et al., 2002; Beccaluva et al., 2009; Natali, 2011).

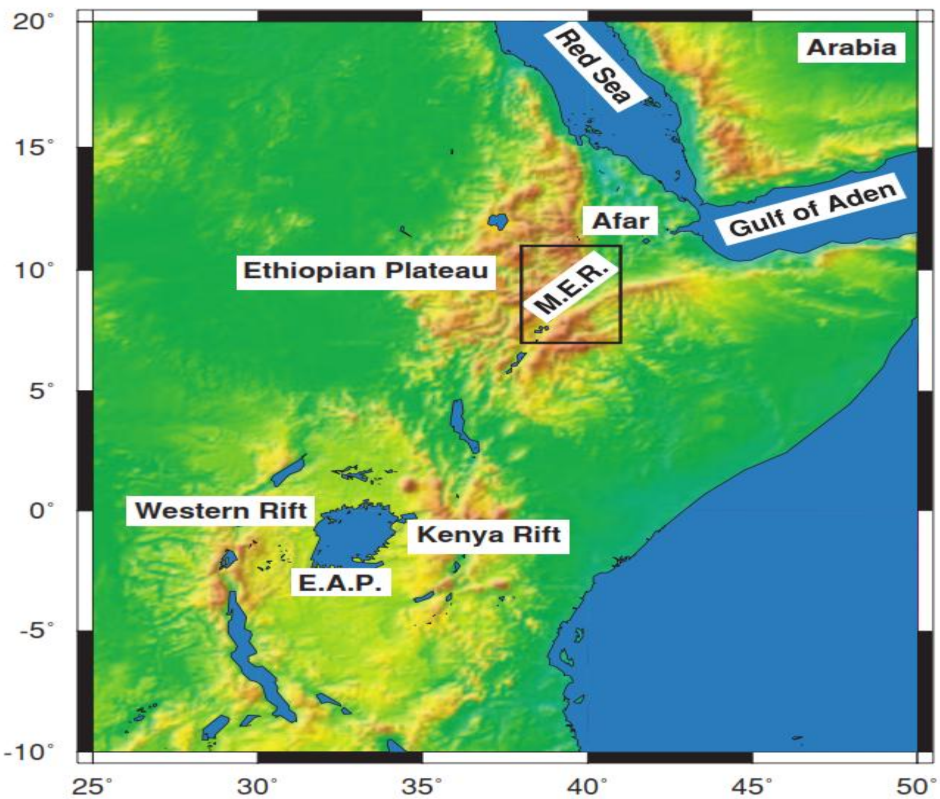


Figure 2.1.Regional map of east African Rift and Ethiopian plateau by Mackenzie et al. 2005.

2.3 Volcanic Rocks Associated with North Western Ethiopian Plateau

The plateau volcanics are cut by the rift faulting and are distributed asymmetrically about the Afar and Main Ethiopian Rift that lying to the west of the rift system is designated the Western Ethiopian plateau (WEP), while the other to the east is named the South Eastern Ethiopian plateau (SEP). The WEP comprises the northern, central, and southwestern sectors, whereas SEP includes the eastern, southeastern and southernmost part of the Ethiopian flood volcanic province.The occurrence of Cenozoic volcanism in the northwest Ethiopian flood basalts started the eruption of Ashangi basalt during Eocene/Oligocene followed by extrusion of Aiba basalts and Alajae formation during the Oligocene-Miocene. Flood basalts with interbeds of pyroclastic rocks of rhyolitic or less trachytic compositions are the characteristics of these volcanic episodes (Berhe et al., 1987; Tefera et al., 1996; Pik et al., 1998, 1999). The works of Baker et al.(1996),Hofmmann et al.(1997), Ukstins et al.(2002),Coulie, (2003) show that the eruption of the Ethiopian flood basalt and associated felsic rocks occurred between 31 Ma and 28 Ma with short time interval i.e. <5 Ma.

In the northwestern Ethiopian plateau, the volcanic succession is emplaced on the sub horizontal Mesozoic transgressive and regressive sedimentary strata. This volcanic plateau does not fit the popular image of a continental flood basalt province in that it is not a thick monotonous, rapidly erupted pile of undeformed flat lying tholeiitic basalts. Instead it is made up of several distinct volcanic centers with different magmatic character and with a large range of ages (Kieffer et al., 2004).

The major volcanic units of the North Western Ethiopian Plateau (WEP) include

- ✓ The Oligocene flood volcanic (Trap series) i.e. (Oligocene –Miocene basalts and rhyolites)
- ✓ Miocene- Pliocene shield volcanoes
- ✓ Quaternary volcanic

2.3.1 The Oligocene Flood Volcanics (Trap Series)

In the WEP the flood volcanic succession includes basaltic lava flows, basaltic tuffs, as well as a considerable volume of rhyolitic, trachytic and phonolitic products (Mohr and Zenettin, 1988). Intermediate lavas are lacking and the volcanism is of a distinctly bimodal basalt rhyolite type (Chazot and Bertand, 1993) a feature common to most continental flood basalt provinces (e.g. Karoo and Parana).

In their mineralogical composition most of the flood basalt are aphyric to sparsely phyric and contain phenocrysts of plagioclase and clinopyroxene with or without olivine. They have tholeitic to transitional chemical composition (Mohr, 1983; Pik, et al., 1998; Kieffer et al., 2004; Beccaluva et al., 2009).

Despite the predominance of basalts, the flood volcanic (Trap series) contains significant volumes of felsic volcanic rocks usually in the upper parts of the sequence (Ayalew et al 2002; Ayalew and Yirgu, 2003). The felsic volcanic rocks are mainly friable tuffs, rhyolites and ignimbrites, interlayered with the flood basalt particularly in the upper parts of the sequence (Ayalew et al., 1999; Mohr &Zanettin, 1988; Pik, et al., 1998). Based on trace element and Ti concentrations the northern Ethiopian Oligocene trap series are divided into LT and HT (HT1&HT2) basalts (Piket al.,1998). The Cenozoic Ethiopian volcanic province which located in the northeastern part of Africa is the result of east African rift system due to impingement, uplift and extension of afar mantle plume that represented by the emission of large amount of volcanoes, trap series and afar volcanic. Mohr and Zanettin, (1988) said that the trap series which represent the intercalation of tertiary flood basalt sequence with silicic rocks is mostly occurred through fissures. Furnan et al. (2006) also suggested that the result of the Ethiopian flood basalts may be from a single, broad and deepseated mantle upwelling rising from the lower mantle i.e. the African super plume.

2.3.2 The Miocene- Pliocene Shield Volcanoes (Termaber Formation)

The flood volcanism was succeeded by emplacement of large shield volcanoes and by continental rifting (Mohr, 1983; Hoffmann et al., 1997). A number of large shield volcanoes developed on the surface of the volcanic plateau overlying the thick sequence of flood basalt. These volcanoes are conspicuous features of the Ethiopian plateau.

According to Kieffer et al. (2004) currently about 20 % of the surface of the plateau is covered by shields, the summits of the shields are about 1.5km above the flood basalt. They also calculated that the volume of the shields is about 20% of that of the flood basalts that is about $4x10^4km^3$. Simen, Mt Choke, Guguftu and Mt Guna are the main shield volcanoes on the northern Ethiopian plateau. The Simen shield volcano with age of 30.4 Ma has 4533m height (the highest point in Ethiopia) this peak rise almost 2000 m above the top of the flood basalt. Mt. choke has a basal diameter of over 1000 Km and rises to 4052m, some 1200m above the flood volcanic. Guguftu shield has 3859m peak. The age of both Choke and Guguftu is 22 Ma years.

Like the flood volcanics the shield volcanoes are bimodal and contain sequences of alternating basalts, rhyolitic and trachytic lava flows, tuffs, and ignimbrites, particularly near their summits.

The lava flows of the shield volcanoes are thinner and less continuous than the underlying flood basalts. They also are more porphyritic, containing abundant and often large phenocrysts of plagioclase and olivine. The Simen shield is tholeitic flood basalts while Choke and Guguftu are alkaline and overlies alkaline flood basalts (Kieffer et al., 2004).

2.3.3. Quaternary Volcanic Rocks

Quaternary alkali basalts (Tana lava) occur related to local rift structures north south trending extensional faults Chorowicz et al. (1998). Volcanic cones and flows of scoraceous basalts are well preserved in the Lake Tana graben. These basalts are considered Pleistocene in age. The volcanic rocks of the Lake Tana area are usually described as olivine alkaline basalts (Merla et al., 1979).

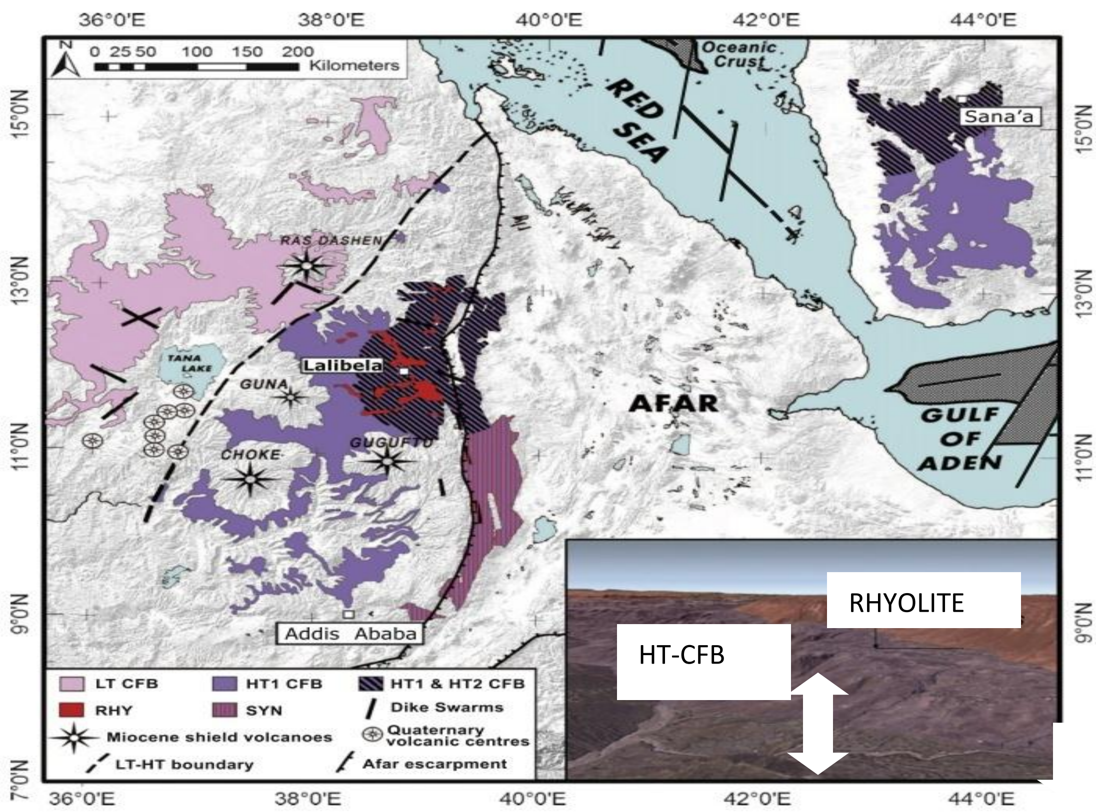


Figure 2.2 Map of continental flood basalt of the northern part of Ethiopia and Yemenconjugate marginshowing the extent of the flood volcanism and the location and modified by Natali et al. (2011) after Beccaluva et al. (2009).

CHAPTER THREE

3. Geology and Petrography of Study Area

3.1 Introduction

Lalibela area is one of the huge volcanic centers on northwestern Ethiopian plateau which shows continuous ridges. It is found between Seimen and Guguftu Miocene- Pliocene shield volcanoes, east of Lake Tana. To depict the petrographic and geochemical characteristics of the study area the approaches mentioned in the methodology part data are analyzed and compiled. Based on textural and mineralogical compositions of the rock primary name of the lithology is given during field work, later confirmed through petrographic and geochemical analysis. Twelve fresh rock samples thin sections have been prepared and examined for modal composition, mineralogy and texture. In the study area there is only basaltic lithology.

The area of study is covered by flood basalts with different degree of weathering and color variation. It is widely exposed around the mountain forming a flat lying topography continuing up to an elevation of more than 2744m. At the eastern and western end of the massif north of Lalibela an exposure of river cut a layered sequence of flows have been observed (Figure 3.1C). Based on morphology, field observation and petrographic analysis, basalts in the study area classified into two parts. These are lower basalts and upper basalts. The overall thickness of flood basalt succession in this area is estimated to be about 690m.Sometimes the rocks in the study area show slightly to moderately weathered. Flows are sampled around Bilbala village.

To understand the crystallization history and origin of the basaltic rock in the study area, detail description of the texture and mineralogy with excellent color photographs is mentioned bellow.Petrographic investigations of 12 thin sections were performed and according to this data the rock is basalt with different mineral composition. Basalts in the study area occur as massifs and are dark grey to black color on hand spacemen with fine grain minerals. The main minerals that could be identified on hand spacemen are pyroxene and plagioclase with some olivine. Under cross polarized light microscope the studied basalts in Bilbala area have porphyritic, subophitic and interstitial texture. Clinopyroxene, plagioclase and olivine are the main phenocrysts in basalt of the study area.

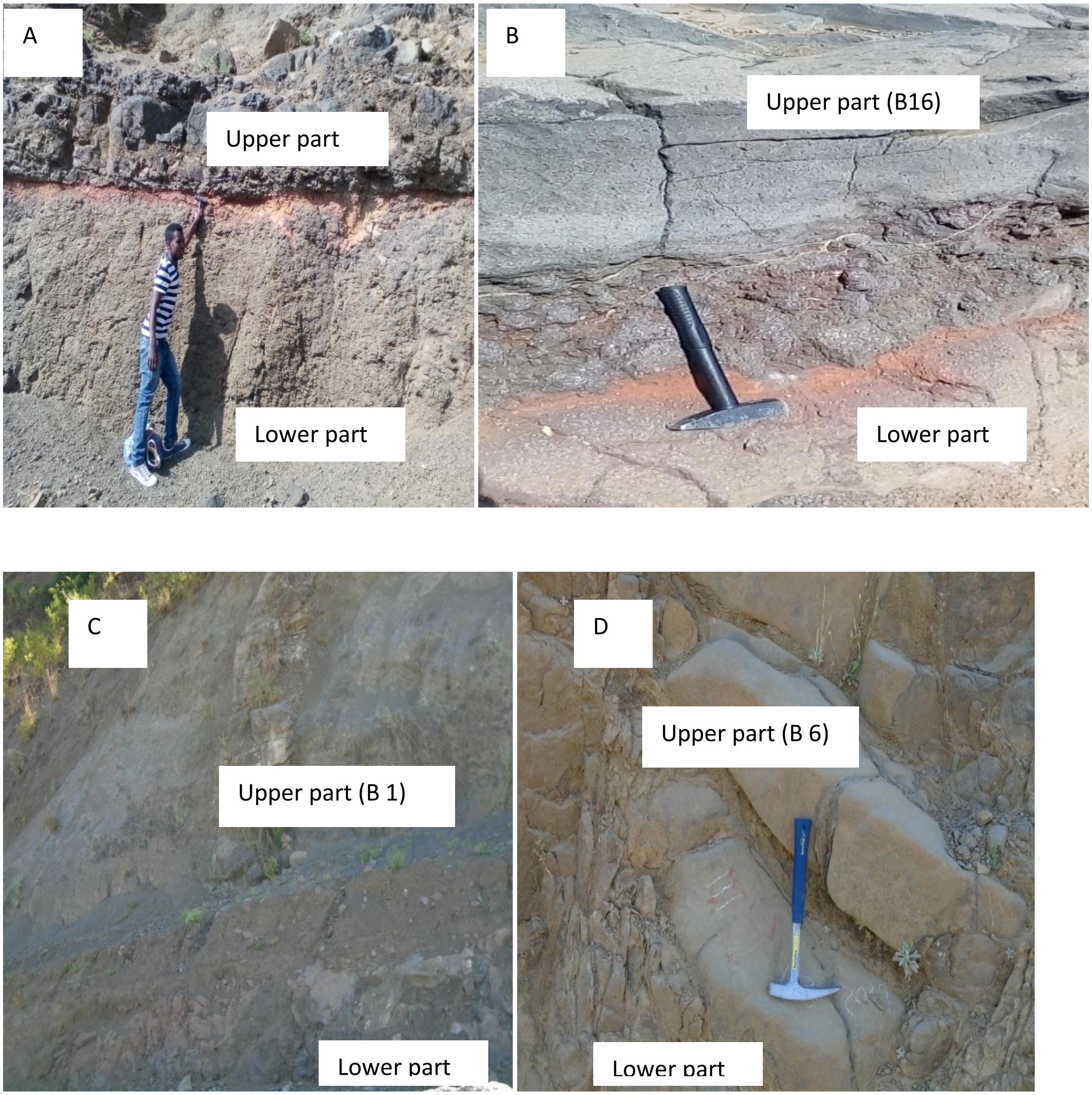
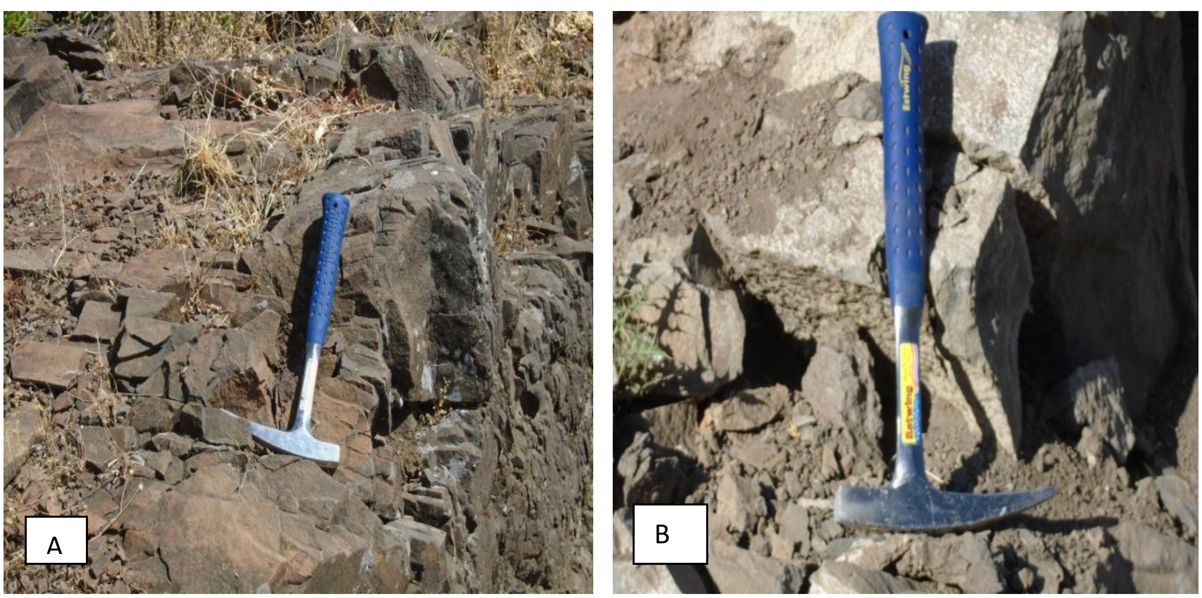


Figure 3.1.The variable basaltic rocks of the study area i.e. A & B from lower basalt while C & D from upper basalt**.**

3.2 Lower Basalts

These basalts mostly cover the lower part of gently sloped area and have very fine grain. The minerals are not visible with naked eye. The area coverage of this basalt is small when compared with upper basalt. It is exposed around flat parts of hillside and stream cut which have highly to moderately weathering effect. It has yellowish and brown weathered color, with dark gray fresh color. It is compositionally mafic with very fine gain sized particles due to rapid cooling of lava flows at the surface of the earth and texturally aphanitic. Since this rock unit is very fine grain sized, it is impossible to identify all the essential minerals within the necked eye in the hand specimen. For this reason, a microscope is required for their Mineralogical description of the rock types. They are specifically located around Bilbala village and gently sloped areas to the northern, southern and eastern parts of Bilbala.Two samples (B13 and B16) are prepared for petrographic analysis and the analyzed result shows interstitial texture. In microscopic observation the visible mineralogical modal proportion for (B13), 62%pyroxene, 20% plagioclase, 15%opaque minerals and 3%volcanic glass, but for (B16) sample the mineralogical modal proportion vary from sample (B13) by 45% pyroxene,37% plagioclase, 15% opaque, and 3% volcanic glass.



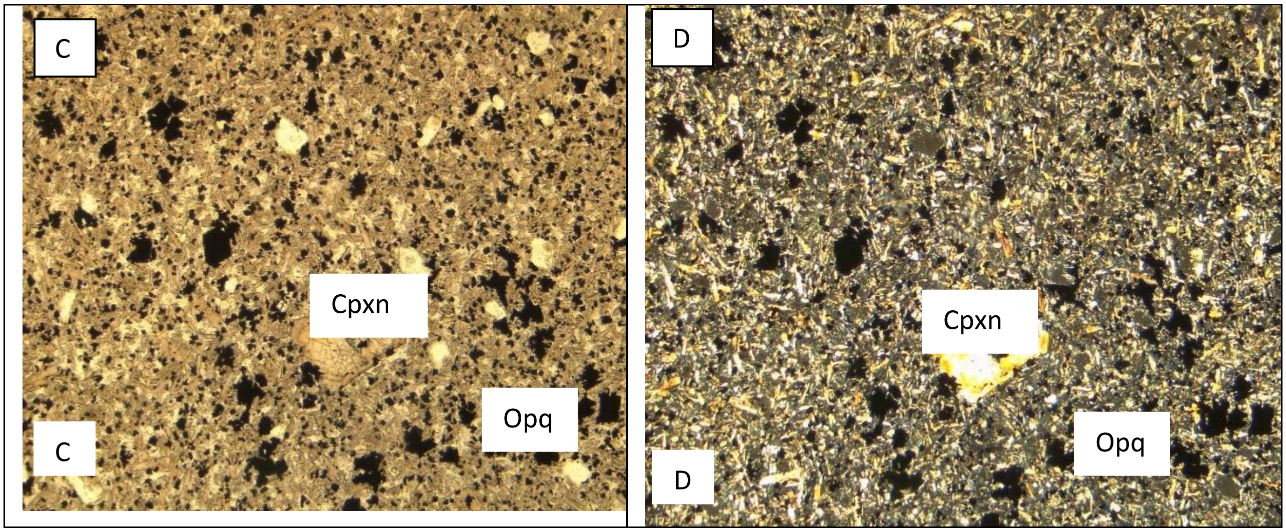


Figure 3.2. The lower basaltic sample B13 (A & B) from the study area with petrographic analysis (C & D) result and show yellowish gray to light grey color, it is highly weathered with fracture patterns.

3.3 Upper Basalts

This type of basalt show slightly to moderately weathering effect with black to dark gray fresh color and found by forming continuous ridges. It is phaneritic basalts of the study area that cover most part of the area, with dominated crystals of visible minerals. The approximate thickness of this basalt is 460m. It is fine to coarse grained in texture. Plagioclase and pyroxene with some olivine minerals are easily distinguished in hand spacemen. From this area ten representative samples are selected for petrographic analysis and the result shows that except one sample (B11) all the others are porphyritic in texture. i.e. phenocryst of pyroxene and olivine lie on the ground mass of fine grained pyroxene, plagioclase and opaque minerals with different modal proportion of its constitute minerals (Table 3.1). The remaining one sample (B11) which is fine grained on handspecimen observation show subophitic texture i.e. plagioclase grains partially enclosed in pyroxene grains with pyroxene, plagioclase and opaque minerals ground mass. It has 53% plagioclase, 37% pyroxene, 7% opaque and 3% olivine minerals in modal proportion. The detail petrographic analysis result descriptions of the analyzed samples are given bellow (Table 3.1).

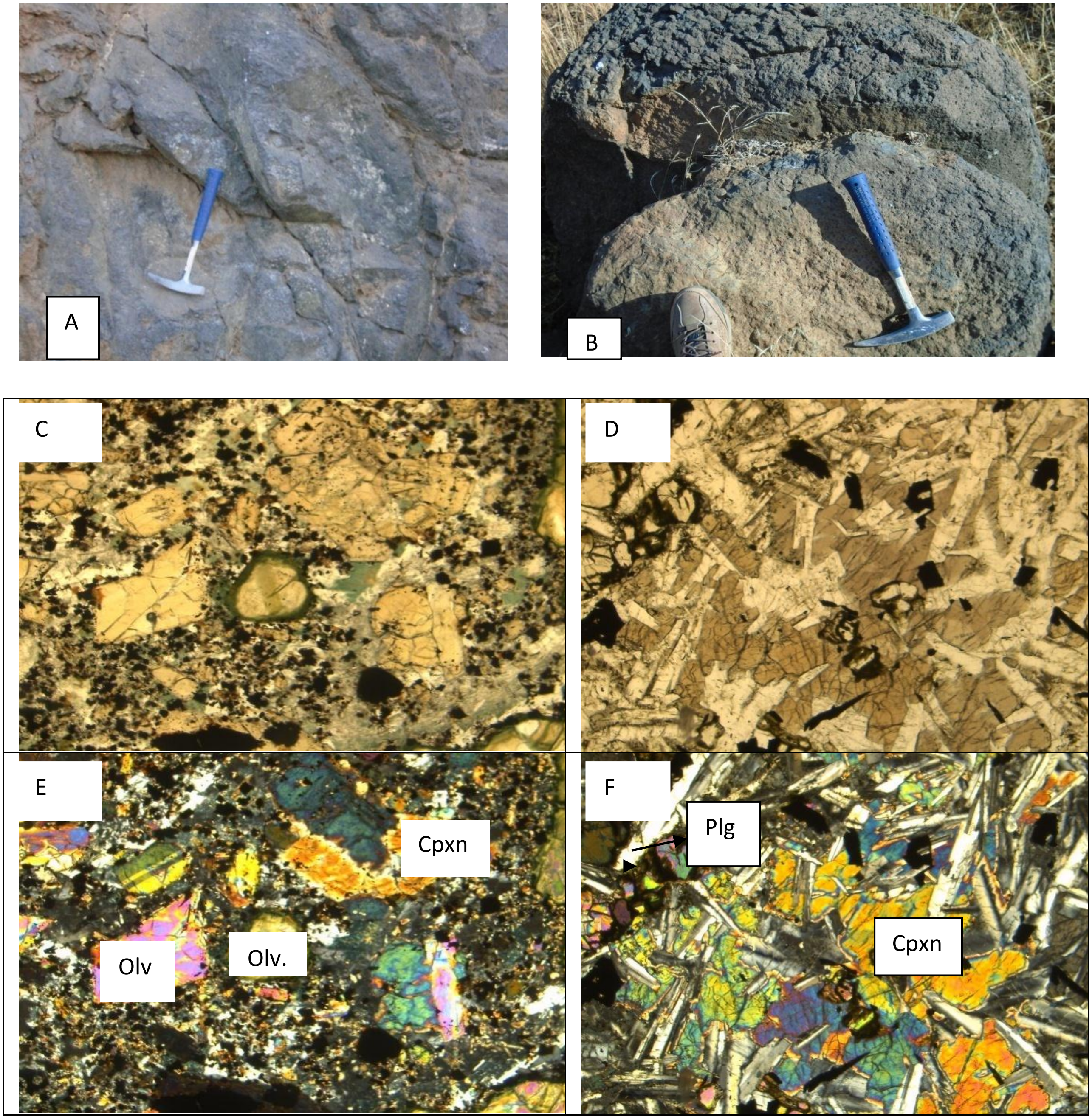
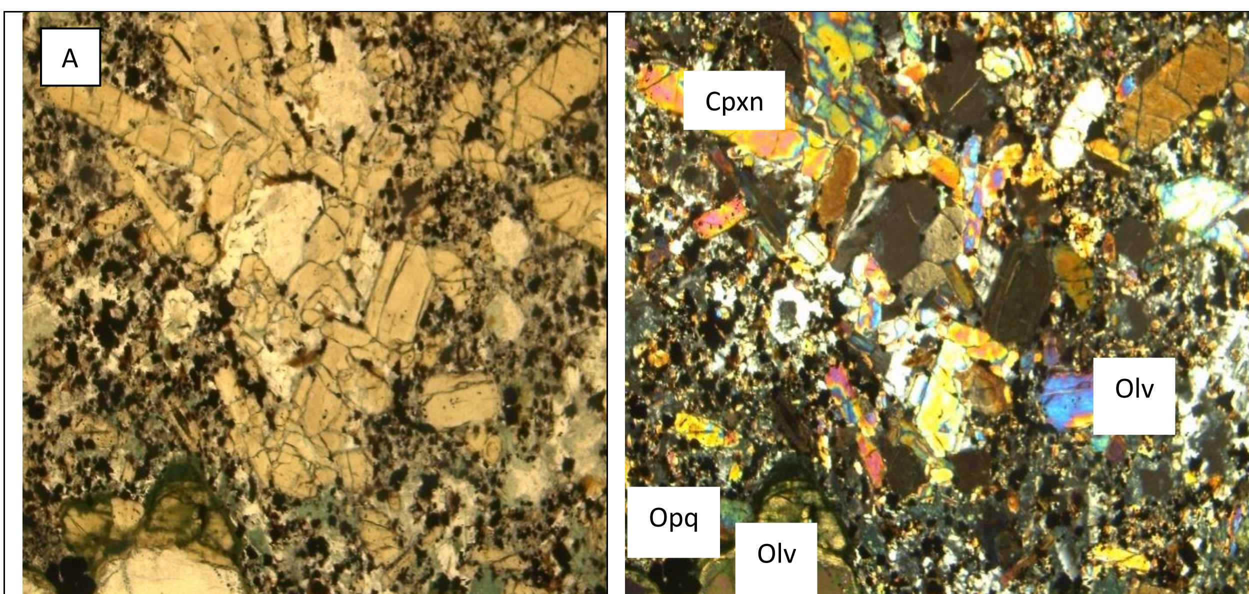


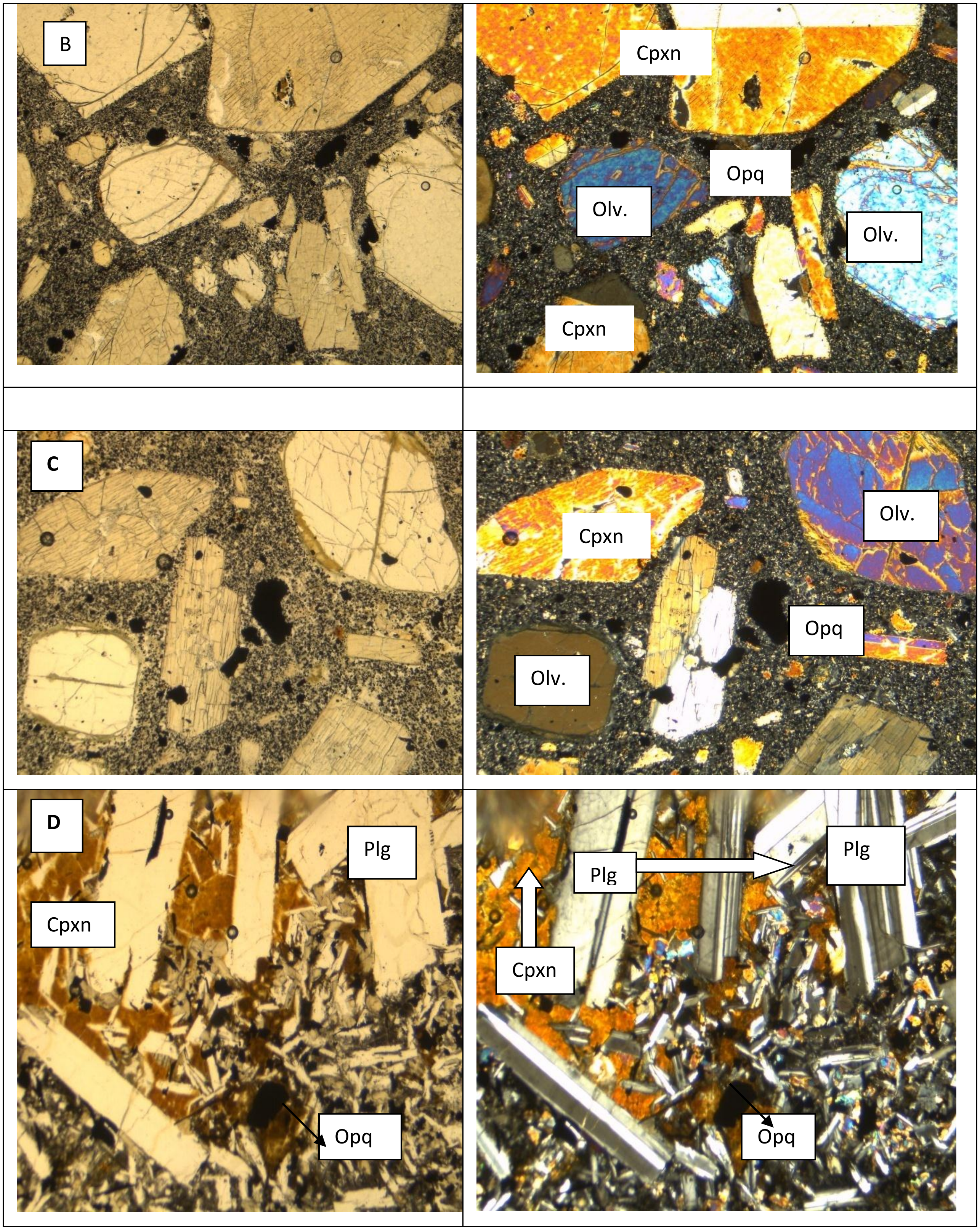
Figure3.3. upper basalts of the study area with its petrographic analysis result for sample B18 (A, C& E) and sample B11 (B, D & F). The photo is taken by 10x magnification for all petrogrhaic data.   .

3.4. Texture of the study area basaltic rocks

Based on the texture of the analyzed sample in petrographic microscope the basaltic rocks in the study area divided into three. These are porphyritic texture for coarse grained upper basalt, subophitic texture for fine grained upper basalt and interstitial texture for lower basalts.

Basaltic rocks with porphyritic texture found in different upper basalt samples of the study area. Bilbala, ymra road side,Bilbala river side,Archeko area,Sekota road side and Wachira around Ambawa ridge are the local area names that the porphyritic texture basaltic rock samples taken from the north east direction of Lalibela town. These basaltic rocks cover most of the study area with dark gray in color and fine to coarse grained texture on handspecimen description. Pyroxene, olivine and plagioclase are the main phenocrysts minerals in the sample. The groundmass is dominated by fine grained pyroxene, plagioclase and opaque minerals. In some sample there are voids that filled by calcite minerals. Subophitic texture basaltic rock observed in one sample of the upper basalts in the study area and plagioclase grains partially enclosed in pyroxene grains. The groundmass is composed of pyroxene, plagioclase and opaque minerals. In handspecimen description this basaltic rock is dark grey with fine grained texture. Interstitial texture basaltic rock in the study area is observed in the lower basalts sample with groundmass of fine grained interstitial pyroxene, plagioclase and opaque minerals. This basaltic rock sample is taken around Amora ridge on the way of Sekota from Lalibela and near Bilbala River of the study area.




B
Cpxn
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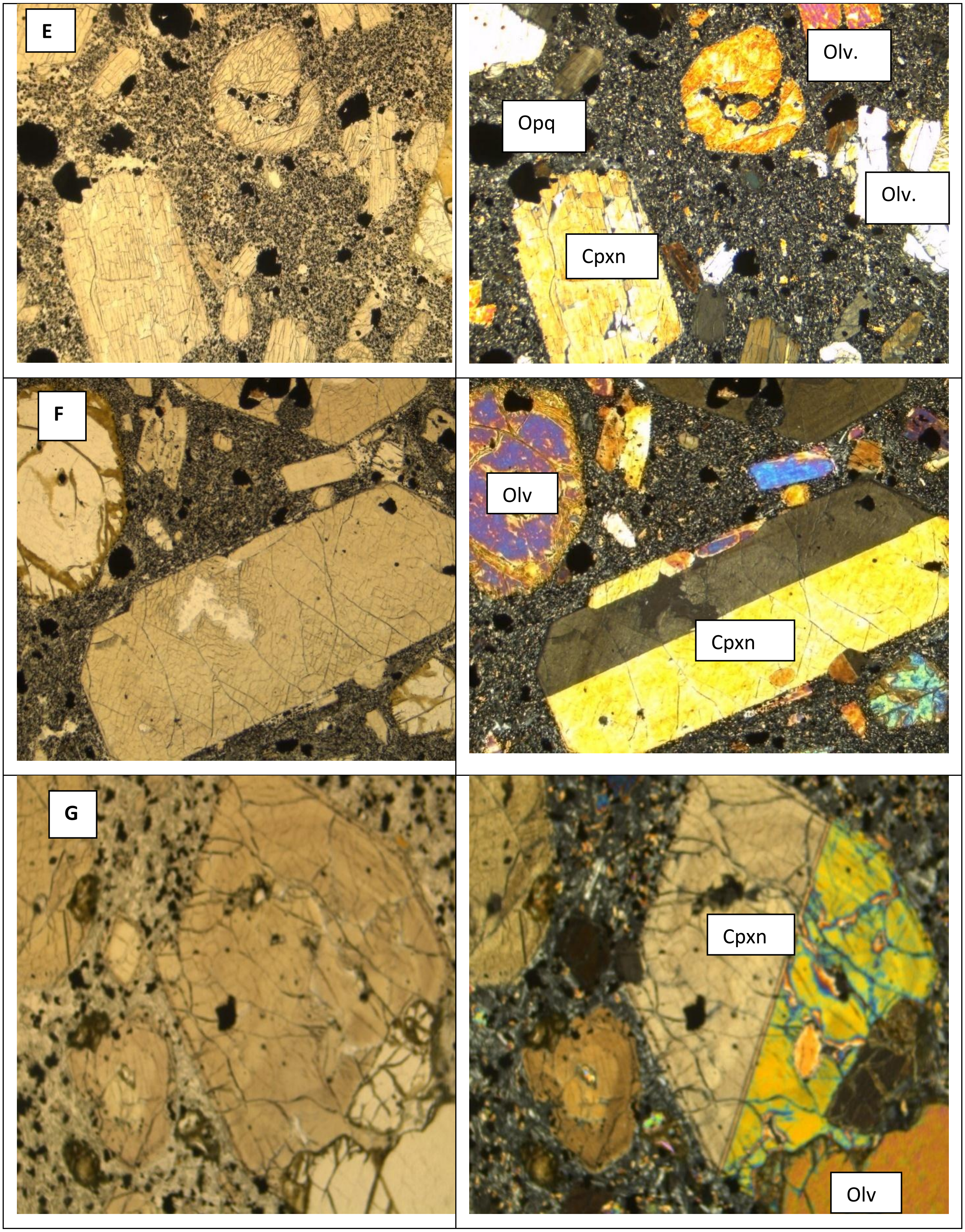
E
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Olv

Figure 3.4. Petrographic view of the study area different upper basalt with different texture and phenocrysts size in both plane polarized (left) and cross polarized (right) light. (A, B, C, E) shows the variable phenocrysts of olivine and pyroxene (clinopyroxene), (D) shows plagioclase phenocrysts and photo (F, G) displays pyroxene twining. Symbols stand for olivine (Olv.), pyroxene (Cpxn), opaque (Opq.) minerals.

Table 3.1 Petrographic Analysis result and description of the study area upper and lower basaltic rocks.

Upper basalt

Sample #	**Rock type (field name)**	**Texture**	**Modal composition**	**Rock name (petrographic name)**
B1	phaneritic basalt	phaneritic texture	41% pyroxene, 34% plagioclase, 12% olivine, 10% opaque minerals and 3% volcanic glass. It has phenocrysts of pyroxene and olivine with ground mass of fine grained pyroxene, plagioclase and opaque minerals.	Pyroxene rich basalt
B3	phaneritic basalt	phaneritic texture	42% plagioclase, 36% pyroxene, 15% opaque, and 8% calcite minerals. Phenocrysts pyroxene and olivine lie on the ground mass of fine grained pyroxene, plagioclase and opaque minerals. Voids are filled by calcite.	Plagioclase rich basalt
B4	phaneritic basalt	phaneritic texture	42%pyroxene,36%plagioclase,13%opaque,4%calcite,3% volcanic glass and 2% olivine. Phenocrysts of pyroxene and olivine lie on the ground mass of fine grained interstitial pyroxene, plagioclase and opaque minerals. Voids are filled by calcite.	Pyroxene rich basalt
B6	phaneritic basalt	phaneritic texture	43%pyroxene, 37%plagioclase, 12%opaque,5% olivine and 3% volcanic glass. Phenocrysts of pyroxene lie on the ground mass of fine grained pyroxene, plagioclase and opaque minerals.	Pyroxene rich basalt

B7	phaneritic basalt	phaneritic texture	44%pyroxene,36%plagioclase,14%opaque,4%olivine.and2% volcanic glass. Phenocrysts of pyroxene and olivine lie on the ground mass of fine grained interstitial pyroxene, plagioclase and opaque minerals.	Pyroxene rich basalt
B11	phaneritic basalt	phaneritic texture	53%plagioclase, 37%pyroxene, 7%opaque and 5 % olivine minerals. Plagioclase grains partially enclosed in pyroxene grains. Ground mass is composed of pyroxene, plagioclase and opaque minerals.	Plagioclase rich basalt
B14	phaneritic basalt	phaneritic texture	45%plagioclase, 40%pyroxene, 12%opaque and 3 % volcanic glass. Phenocrysts of pyroxene lie on the ground mass of fine grained interstitial pyroxene, plagioclase and opaque minerals.	Plagioclase rich basalt
B15	phaneritic basalt	phaneritic texture	46%plagioclase, 42%pyroxene, 7%opaque and 5 % volcanic glass. Phenocrysts of plagioclase lie on the ground mass of fine grained interstitial pyroxene, plagioclase and opaque minerals.	Plagioclase rich basalt
B18	phaneritic basalt	phaneritic texture	43%pyroxene,29%plagioclase,15%opaque,10% olivine and 3% volcanic glass. It has phenocrysts of pyroxene and olivine with ground mass of fine grained pyroxene, plagioclase and opaque minerals.	Pyroxene rich basalt
B20	phaneritic basalt	phaneritic texture	41%pyroxene,39%plagioclase,13%opaque,5% olivine.and2% volcanic glass. Phenocrysts of pyroxene and olivine lie on the ground mass of fine grained pyroxene, plagioclase and opaque minerals.	Pyroxene rich basalt

			Lower basalt	
B13	Aphanitic basalt	Aphanitic texture	62%pyroxene,20%plagioclase, 15%opaque.and3%volcanic glass. Ground mass composed of fine grained interstitial pyroxene, plagioclase and opaque minerals.	Pyroxene rich basalt
B16	Aphanitic basalt	Aphanitic texture	43%pyroxene,33%plagioclase,13%opaque,11% .and2% volcanic glass. Ground mass composed of fine grained interstitial pyroxene, plagioclase and opaque minerals.	Pyroxene rich basalt

Olivine occurs as subhedral to anhedral crystals and makes 2- 12% of the total volume of the analyzed rocks. They are about 0.001mm to 2mm in diameter and show irregular cracks and slight alteration along the cracks in some samples. Plagioclase have light gray color and consists 34- 54% of the total volume with dimensions of about 0.005mm to 5mm in the different sample. Large plagioclase phenocrysts range from 5 to 10 mm in length. Clinopyroxene have colorless, pale green, yellow-green, brownish green color and constitute 34- 62% of the total volume and are about 0.002mm to 4mm in length. Opaque minerals are found as black color crystals and occur in the groundmass. They occupy 7- 15% of the total rock volume and are about 0.003mm to 0.001mm in diameter.

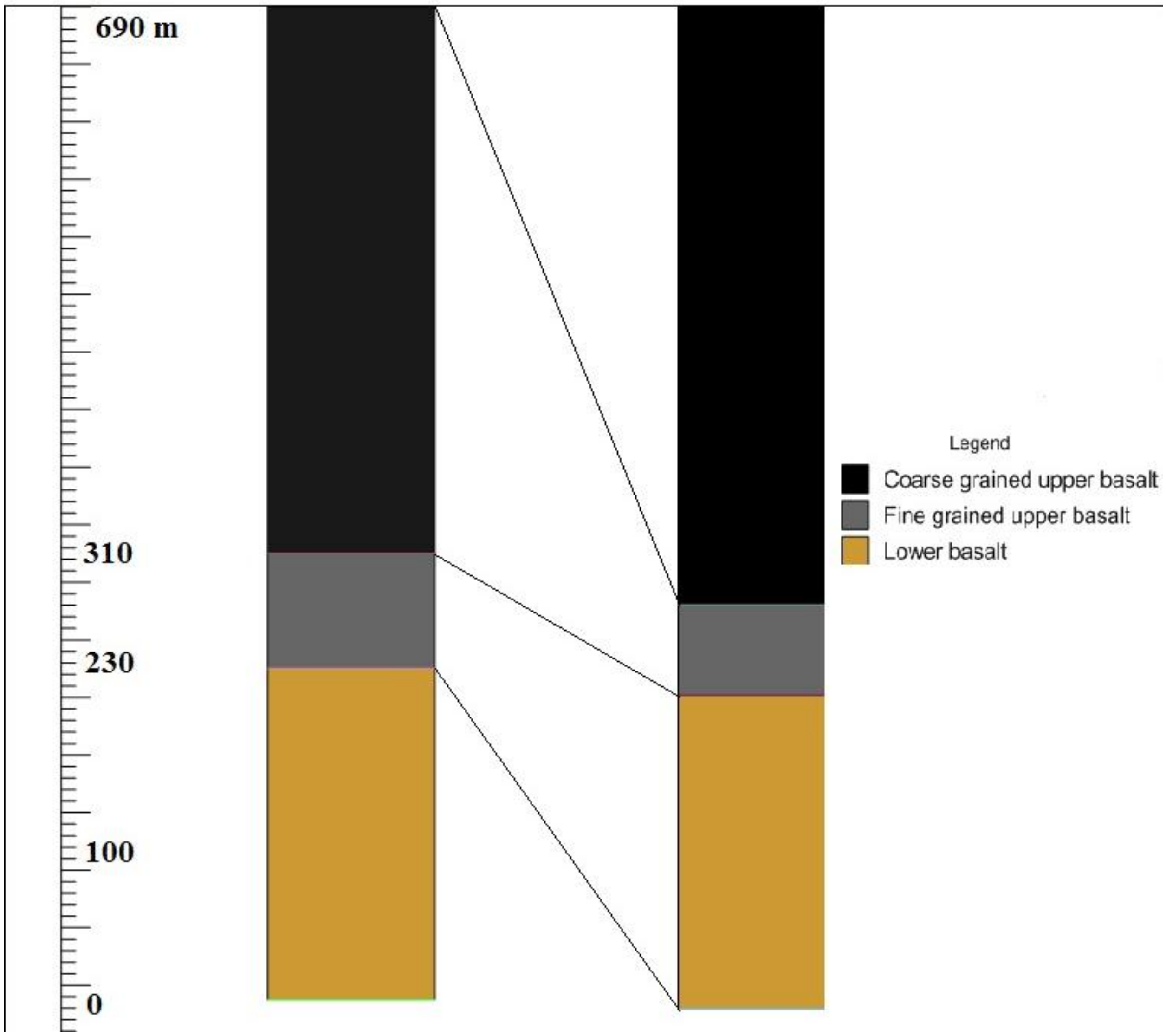


Figure. 3.5 stratigraphic section of the study area lower and upper basaltic rocks

CHAPTER FOUR

4. GEOCHEMISTRY

4.1. Introduction

To study the magmatic evolution of any volcanic products geochemistry is the main method that used widely today. This method mainly depends on the relative signature of the elemental composition that enables to understand the geologic process. Nowadays the geochemical data is processed by different software. Four major types of geochemical data are identified according to Rollinson (1993); major, trace, volatile and isotope. From the four types only two of them major and trace are used in this study, to understand the evolution of the study area.

The total numbers of collected samples for the geochemical analysis purpose are ten. The geochemical results of the studied samples are presented on Table.4.1. The samples are carefully prepared in powder form in Ethiopian geological survey Milling room. The powdered sample is analyzed by analytical method of Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) for major element and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) for trace element. Detail instrumentation or procedures for both (ICP-AES & ICP-MS) analytical instruments for major and trace elements are given in chapter one.

From the geochemical analysis the result are mainly major and trace elements concentration data. To use for the research purpose the data must be integrated or synthesized. The data integration is done by a software packages; Microsoft excel 2007and GCDkit 4.1version. The outputs from the software are in the form of graphs that help to understand mainly the magmatic evolution of the magmatic complex by depending on those representative geochemical samples. In addition to primary geochemical data there are some secondary data adopted from previous works that were done on the surrounding of Lalibela for comparison.

4.2. Major Elements Geochemistry

Major elements are elements such as Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and Pin oxide form, which predominate in any rock analysis. The main goal of using major element geochemistry is to understand magmatic process. Major elements which present in high concentrations (>1Wt %), control to a large extent the mineralogy and crystallization or melting behavior in igneous systems. Rollinson (1993) also gives the use of major elements data in rock classification, in the construction of variation diagrams and as a means of comparison with experimentally determined rock compositions, whose conditions of formation are known. major elements with trace elements together also used in the identification of the original tectonic setting of igneous rocks.

The analyzed samples major element data are recalculated or normalized to 100% volatile free to use for the interpretations and to draw the graphs. This is done by subtracting the volatile concentration (that is presented as LOI) from total concentration of major elements. The major element laboratory result of the ten samples collected from the study area is used in oxide, elemental and CIPW norm form. In major element analytical result, the concentration of Fe is given in the form of Fe_2O_3. This result is recalculated from volatile free base as FeO* (total concentration). First FeO is calculated by multiplying Fe_2O_3 by 0.8998 and then FeO* is calculated as FeO* = FeO + Fe_2O_3 (Rollinson 1993). The CIPW norm calculation is a method of working out the mineralogy of a rock from major element chemical analysis, because the mineralogy of the norm is entirely dependent on major element chemistry, fine or coarse grained. Finally, it gives a different mineralogical distribution compare to the modal proportion result from petrographic analysis.

The total alkali –silica diagram is one of the most useful classification schemes available for volcanic rocks and the chemical data,the sum of Na_2O and K_2O content (total alkalis, TA) and the SiO_2 content (S) are taken directly from rock analysis as Wt% Oxides and plotted onto the classification diagram. On the bases of silica content this diagram divides rocks into ultrabasic, basic, intermediate and acidic. The TAS (total alkalis –silica) diagram also used to divide the volcanic rocks into alkaline and subalkaline (originally tholeiitic) series. The general characteristics of the study area basaltic rocks are illustrated in the total alkali- silica (TAS) classification of (Le Bas et al., 1986) (Fig.4.1).The study area lava samples plot in the field of basalt, picro basalt, trachy basalt and cluster around alkaline/ subalkaline boundary displaying transitional character. In the total alkali – silica (TAS) diagram of the previous works around Lalibela area HT2 basalt also cluster around alkaline/subalkaline boundary displaying more alkaline transitional character with respect to LT and HT1 basalts, which mostly plot in the subalkaline field (Piccirillo et al., 1979; Pik et al., 1998, 1999; Beccaluva et al., 2009 and Natali et al., 2016).All the analyzed samples are basalts with SiO_2 concentrations 41.7Wt% to 49.97Wt%.The basaltic rocks in the area shows high concentration of TiO_2(3.81.-6.87 Wt %.) and FeO* ranges from 11.59to 15.71 Wt%.The study area basalts display Mg# (Mg # =100*Mg/(Mg +Fe^{2+})) ranging from 33 to 67, whereas the CaO/ Al_2O_3 ratios vary from 0.890 to 1.989.The studied samples show ranges of Al_2O_3 (5.9-14.77 Wt %),MgO (3.36-16.25 Wt %) and alkalis (Na_2O +K_2O) vary from 2.35-5.19 Wt%. All the analyzed samples of basaltic rocks have low silica contents (< 50Wt %). From the petrographic description that is discussed on chapter three with CIPW norm of each mineral for the study area basalt give some additional information about the type of basalt. The normative minerals of the study area basaltic rocks described in (table4.1) contain olivine norm (0.95-15.66 wt %), hypersthene norm (1.01-20.37 wt %) and quartz norm of 0/85 wt% in one sample. Based on the norm calculation the study area basaltic rocks are olivine normative transitional basalt.

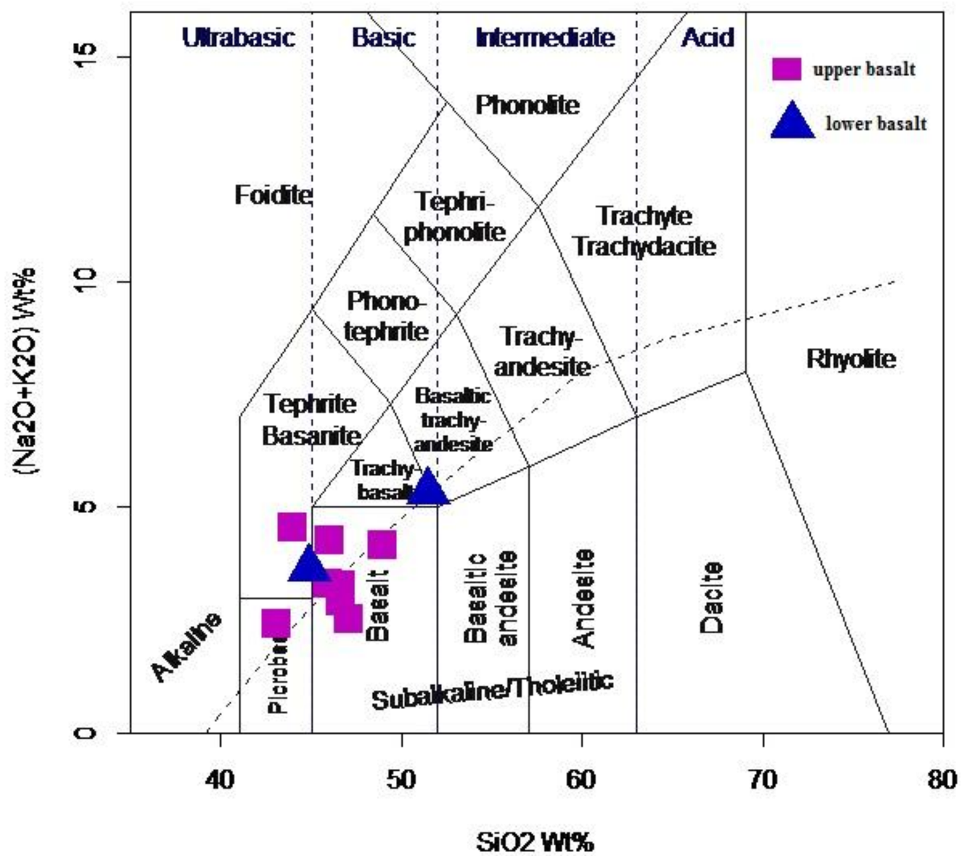


Figure 4.1 total alkalis –silica (TAS) diagram of the study area basaltic rocks to identify alkaline series from subalkaline /tholeiitic series after Le Bas et al. (1986).

Table 3.1 Major & trace elements table of the analyzed samples for both lower basalt (B13 & B16) and upper basalt with their calculated norm from major element oxides

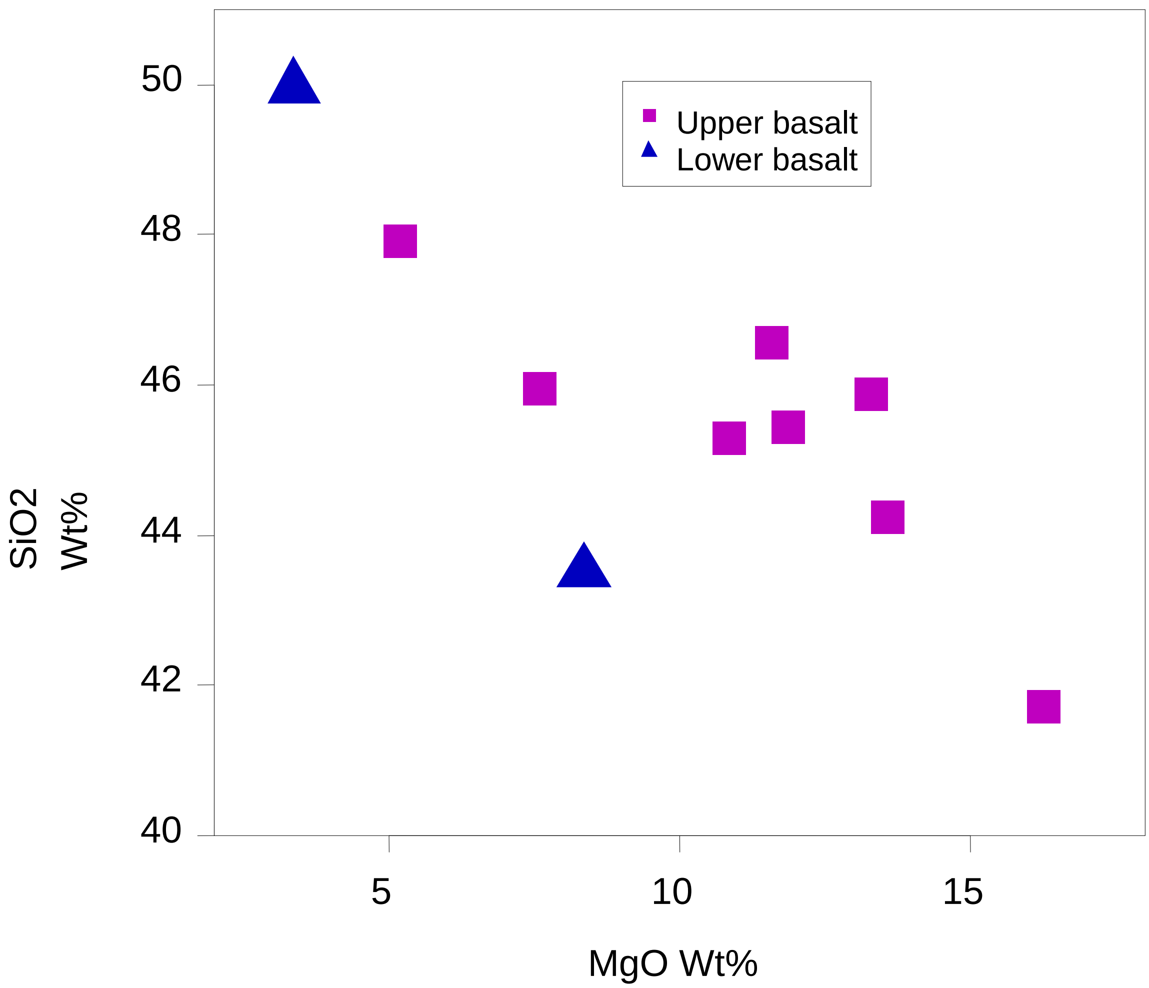
SAMPLES	B3	B4	B7	B11	B13	B14	B15	B16	B18	B20
SiO2	44.24	45.43	41.7	45.87	49.97	45.3	45.95	43.5	46.56	47.92
TiO2	4.52	4.41	5.33	3.81	3.36	4.42	5.28	6.87	3.88	3.92
Al2O3	7.05	7.91	5.9	7.95	14.77	9.48	11.94	8.8	11.37	13.5
FeO*	13.03	12.96	14.04	12.21	11.78	12.51	15.71	13.99	11.59	13.8
MnO	0.19	0.19	0.19	0.19	0.18	0.19	0.22	0.19	0.16	0.22
MgO	13.58	11.86	16.25	13.27	3.36	10.85	7.6	8.35	11.59	5.19
CaO	10.06	11.41	10.6	11.37	7.72	10.8	11.96	10.85	11.36	8.56
Na2O	1.85	1.73	1.55	1.57	3.76	1.93	2.79	2.07	1.7	3.09
K2O	1.32	1.09	0.8	0.87	1.43	1.26	1.95	1.45	2.63	0.97
P2O5	0.52	0.42	0.52	0.38	0.8	0.47	1.05	0.9	0.42	0.72
LOI	1.92	0.88	0.34	0.88	1.31	1.86	1.59	2.16	4.23	0.4
Sum	98.28	98.29	97.22	98.37	98.44	99.07	106.04	99.13	105.49	98.27
Mg#	65	62	67.4	66	33.7	60.7	46.3	51.5	64.1	40.1
CaO/Al2O3	1.427	1.443	1.989	1.43	0.89	1.139	1.002	1.233	0.999	1.01
Norm (Wt%)										
Quartz	0	0	0	0	0	0	0	0.85	0	0.00
Albite	15.654	14.639	13.116	13.285	31.816	16.331	23.608	17.516	14.385	26.147
Anortite	7.034	10.598	6.778	12.075	19.200	13.482	14.296	10.437	15.625	20.101
Orthoclase	7.80	6.44	4.73	5.14	8.45	7.45	11.52	8.57	15.54	5.73
Diopside	19.06	22.30	19.15	22.83	2.24	17.42	16.08	11.16	19.54	3.79
Hypersthene	13.69	17.85	9.25	20.37	7.33	16.47	0	15.63	1.01	11.17
Olivine	7.92	0.95	15.66	1.47	6.83	1.74	8.04	0	13.17	6.23
Ilmenite	0.41	0.41	0.41	0.41	0.39	0.41	0.47	0.41	0.34	0.47

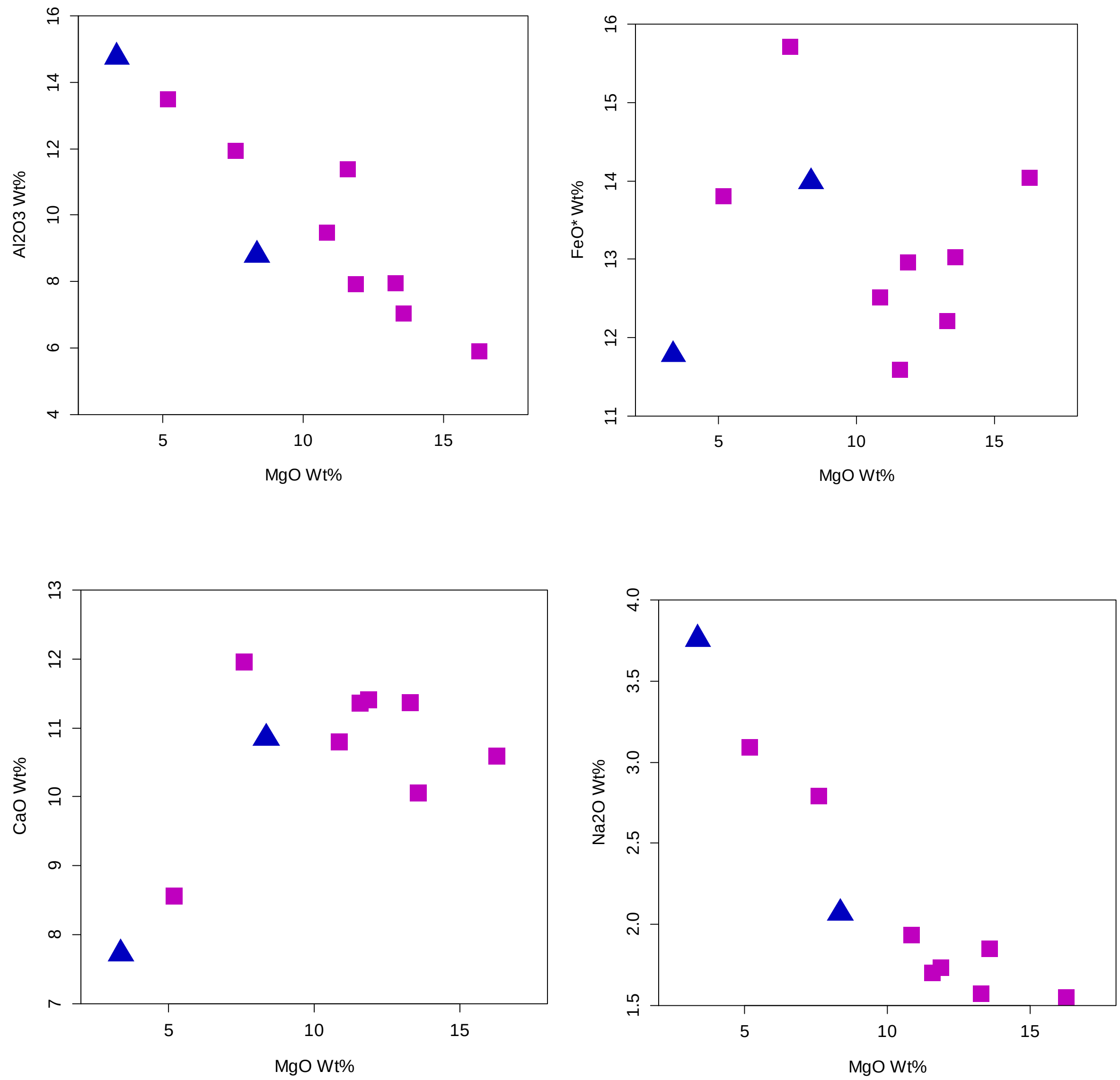
Hematite	13.03	12.96	15.60	12.21	11.78	13.90	17.45	15.55	12.88	13.80
Apatite	1.20	0.97	1.20	0.88	1.85	1.09	2.43	2.09	0.97	1.67
Perovskite	0	0	0	0	0	0	0.13	0	0	0
Sphene	10.57	10.30	12.55	8.82	7.75	10.32	12.16	16.33	9.08	9.01
Total	96.37	97.42	98.44	97.49	97.14	98.61	106.18	98.54	102.54	97.89
TE(ppm)	**B3**	**B4**	**B7**	**B11**	**B13**	**B14**	**B15**	**B16**	**B18**	**B20**
Ba	240.0	311.2	633	223.4	460.3	282	407.5	289	665.5	482.5
Co	73.31	70.34	88	66.06	38.04	58	56.43	57	69.71	46.98
Cr	979.63	774.07	1120	908.16	23.54	630	9.54	410	358.99	45.38
Nb	57.38	43.228	42.2	38.07	64.60	44.7	74.52	71.3	42.59	25.48
Ni	444.89	174.39	553	176.24	17.39	143	18.54	227	99.99	34.70
Pb	3.541	2.778	2.857	1.783	4.063	3.864	3.167	2.475	2.023	2.306
Rb	33.01	23.44	18.8	20.53	26.12	20	31.49	32.2	66.55	20.06
Sc	33.09	43.15	31	45.92	19.72	34	32.77	29	49.18	31.11
Sr	316.7	490.5	526	907.8	1019.9	500	964.4	668	680.0	521.7
Th	5.343	3.513	3.07	3.206	6.304	3.74	6.878	5.27	4.421	2.691
U	1.559	0.983	0.99	0.875	1.712	1.08	1.649	1.52	0.978	0.771
V	367.2	388.6	358	370.6	254.2	364	424.7	444	405.7	393.9
Zr	412.7	365.8	377	288.1	569.5	355	336.2	699	225.6	218.1
Cs	0.659	0.191	0.25	0.112	0.468	0.19	0.667	0.25	0.670	0.431
Hf	10.369	8.764	9.2	7.982	13.288	8.5	8.772	15.6	5.707	5.862
Ta	6.944	3.535	6.2	3.818	5.732	3.8	7.948	10	4.985	2.952
La	49.26	36.80	31.6	33.50	60.78	36.2	61.89	53.8	41.90	29.28
Ce	119.19	89.10	77	82.99	139.99	82.3	137.40	128	91.19	69.02
Pr	15.49	11.67	10.7	11.14	18.87	11.4	17.10	18.65	11.21	9.55
Nd	65.31	50.49	50.9	48.91	82.17	48	70.11	80.8	45.36	43.99
Sm	13.61	10.74	11.55	10.73	17.41	10.3	13.65	18.45	8.70	10.07

Eu	3.935	3.082	3.79	3.241	5.093	3.12	4.099	5.69	2.553	3.487
Gd	11.368	9.330	11.55	9.159	14.99	8.79	11.081	16	7.086	10.05
Tb	1.484	1.258	1.46	1.248	2.003	1.22	1.422	2.19	0.906	1.438
Dy	7.431	6.651	7.35	6.438	10.383	5.97	7.224	10.65	4.643	7.962
Ho	1.198	1.099	1.28	1.097	1.719	1.11	1.170	1.81	0.764	1.480
Er	2.904	2.790	3.19	2.716	4.270	2.57	2.845	4.03	1.865	3.886
Tm	0.360	0.347	0.39	0.355	0.551	0.39	0.350	0.57	0.233	0.519
Yb	2.095	2.175	2.01	2.074	3.293	2.08	2.093	2.65	1.423	3.300
Lu	0.293	0.306	0.25	0.286	0.446	0.29	0.286	0.35	0.207	0.471
Y	32.61	30.74	28.9	29.60	47.19	27.2	31.70	46	20.93	40.22

The Harker variation diagram is a binary graph on which two selected variables are plotted and this variation diagrams have condensed and rationalized a large volume of numerical information and show qualitatively that there is an excellent correlation (either positive or negative) between each of the major elements displayed with silica or magnesium oxides as differentiation index. Harker variation diagrams for the study area flood basalts were constructed using MgO as differentiation index because it shows wide range of variations and the other major oxides plotted in vertical axis. The plots of MgO versus other major oxides are illustrated bellowon Fig. 4.2 and the illustrated trends of the oxides indicate fractionation of the mineral olivine, clinopyroxene and plagioclase. Due to the accumulations of phenocrysts in the study area flood basalts the variation diagrams show scattered trends. In addition to this Cox(1980), suggested that the marked scatter in variation diagrams plot is a natural consequence of the effect of polybaric crystal fractionation with source heterogeneity, variable degrees of partial melting and crustal contamination, In the major oxide bivaraite plots of the study area the overall data trends can be explain by olivine and clinopyroxene fractionation, consistent with the observed phenocrysts assemblage. In the binary variation diagrams of the major oxides /(SiO_2, Al_2O_3, FeO*, CaO) versus MgO results due to fractionations of olivine – clinopyroxene mineral assemblages from the source. From the diagram bellow the plots of SiO_2, Al_2O_3 and Na_2O versus

MgO nearly show good negative trends, whereas the other plots show scatter patterns due to element mobility or alteration results.




Al2O3 Wt%
MgO Wt%
FeO* Wt%
MgO Wt%
CaO Wt%
MgO Wt%
Na2O Wt%
MgO Wt%

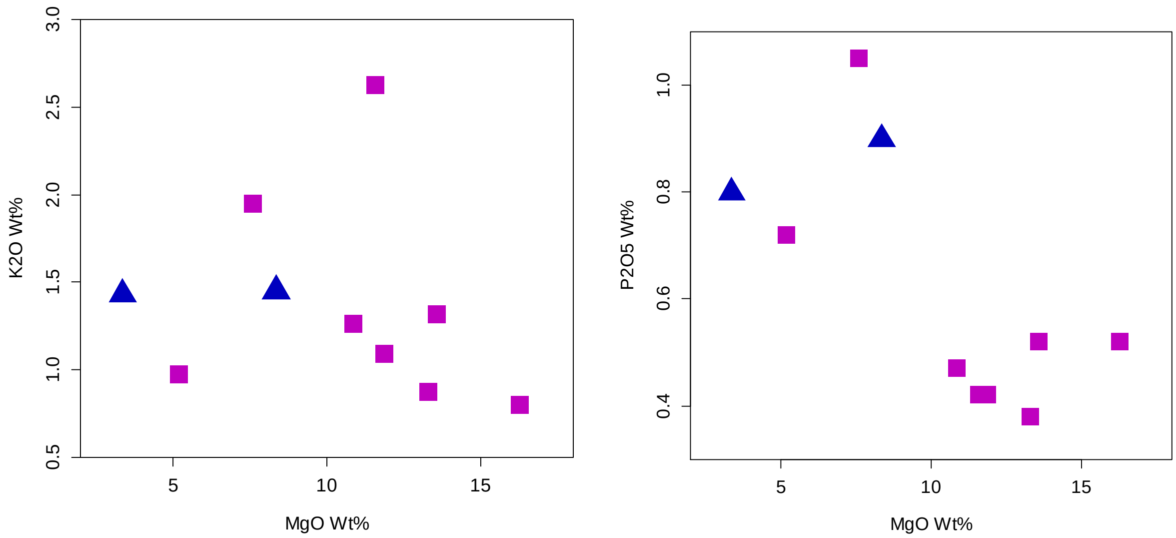


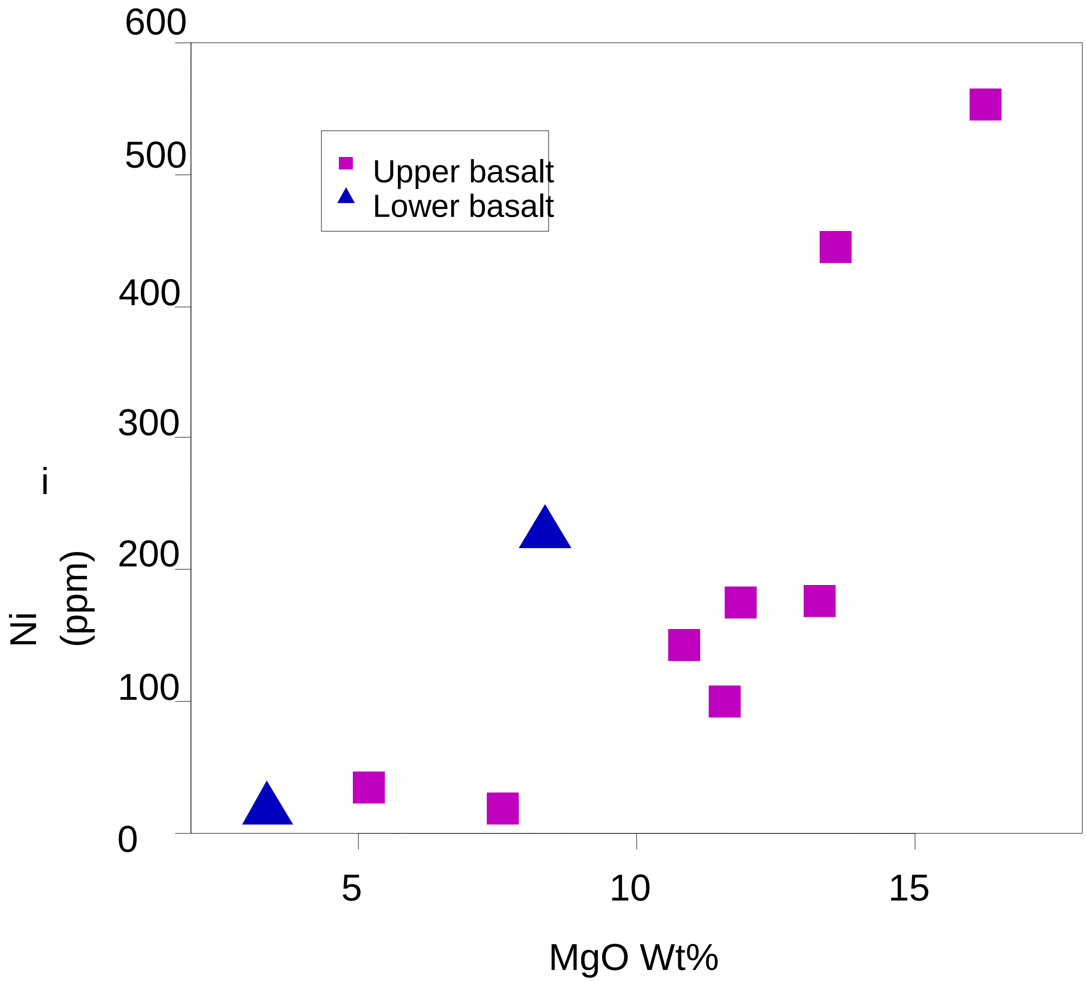
Figure 4.2.Harker (1909) variation diagrams of the study area basaltic rocks and all the major oxides are characterized by their trends.

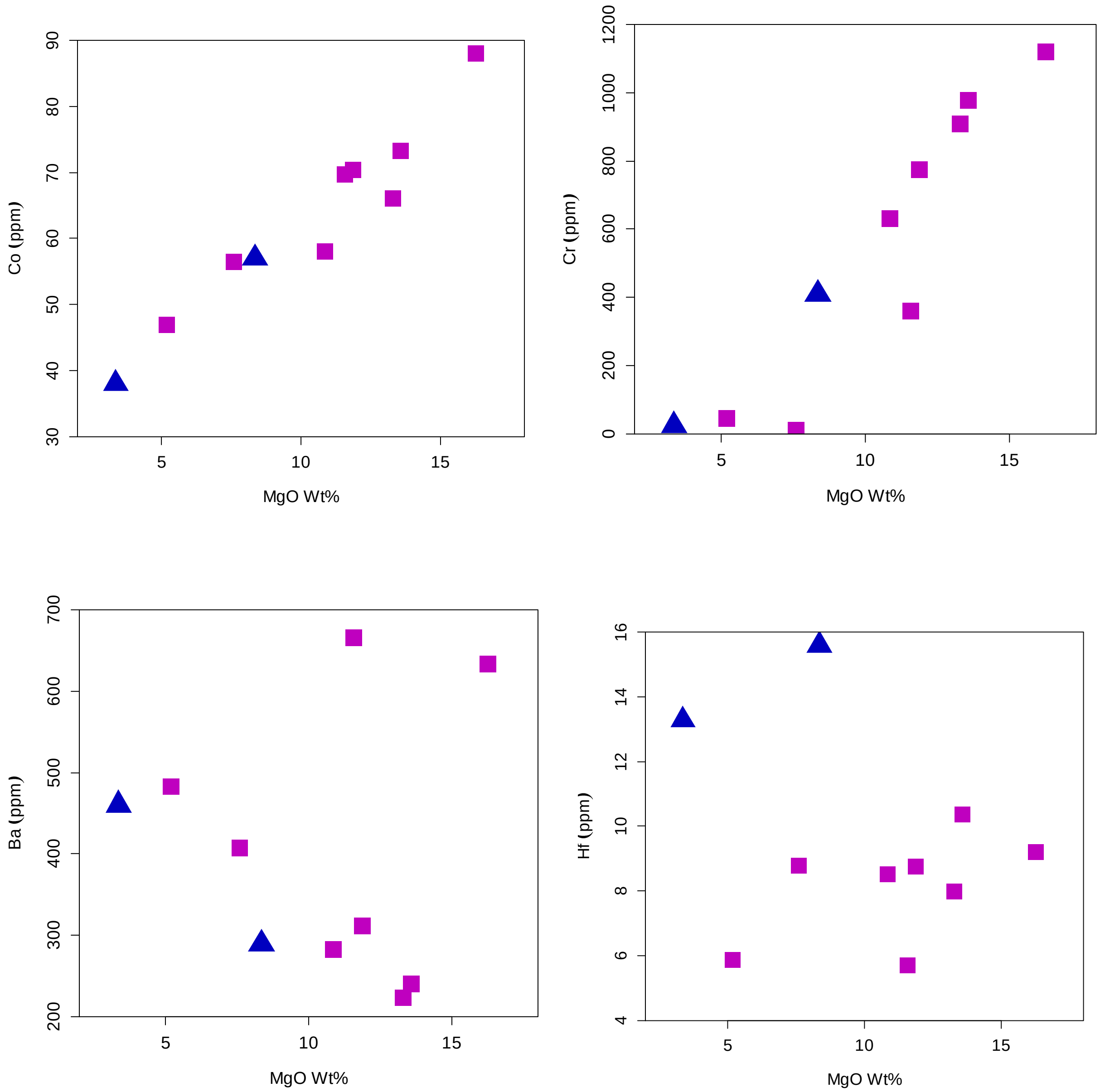
4.3. Trace Elements Geochemistry

In addition to major elements variation of trace elements also provides insight into the source and major processes that controlled the nature of these lavas. Trace elements, by definition, constitute only a small fraction of a system of interest; they provide geochemical and geological information out of proportion to their abundance. According to Rollinson, (1993), trace elements are elements which present at less than 0.1wt. % level and their concentrations are expressed in parts per million (ppm) or more rarely by parts per billion (ppb). It can also be defined as elements that are not stoichiometric constituents of phases in the system of interest (White, 2013). In the current study the relative abundances of trace elements with some trace element ratios are used to identify the minerals or processes involved in the formation of the study area basaltic rocks. Trace element data for the study area are presented in Tables 4.1.

The studied samples trace element concentrations show highly variable values and incompatible elements enrichment. The concentrations of Sr and V is high in the analyzed samples (316.7-1019.9ppm & 254.2-444ppm respectively).These elements concentrations reflect the lack of significant plagioclase and Fe- Ti oxides fractionations in the early stages of differentiations Ayalew et al., et al. (2009). The studied sample show variable ranges of mobile elements (Rb, Cs, U, Pb, Ba, Sr) concentrations, this may suggest that modification of the original composition.

From trace elements analysis result Ba, Cr, Ni, Sr and V show slightly high concentration compared to other elements. The compatible elements (Co, Cr, Ni, Sc) in the study area basaltic rocks have low to high concentrations. i.e Co (38.04 -88,), Cr(9.54 -1120.), Ni (17.39 -553,), and Sc (19.72 -49.18,).Compared to the primary magma the study area basaltic lavas except one sample (B7) show low concentrations of compatible elements (Wilson, 1989). The B7 sample from the area have significantly high higher MgO (16.25Wt %), Ni (553ppm) and Cr (1120ppm) concentrations. this may result from the presence of micro olivine and clinopyroxene phenocrysts in the analyzed bulk rock sample. The moderately variable Rb (18.8-66.56 ppm) and Ba (223.4-665.5) concentrations in the studied samples is likely to be caused by small post crystallization alteration processes or crustal contamination. Higher Sr (316.7-1019.9 ppm) content and Rb (18.8-66.56 ppm contents compared to OIB (Rb: 31 ppm; Sr: 660 ppm) (Sun and McDonough, 1989) are noticeable in these rocks. In comparison with the Nb and Ta concentrations of OIB (Nb; 48 ppm; Ta: 2.7 ppm) (Sun and McDonough, 1989; Iwamori and Nakamura, 2015), the Nb (25.48-74.52 ppm and Ta (2.952-10 ppm) contents of the studied samples exhibit relatively the same values. The low Ni and Cr concentrations compared to primary mantle melts (Ni: >400-500 ppm, Cr: >1000 ppm) (Wilson, 19890) (table4.1) negate their primary magma signature suggesting that magma modification might have taken place. Some compatible and incompatible trace elements concentrations of the studied samples are plotted against MgO on (fig 4.3) bellow. Plots of these trace elements versus MgO indicate different trends or correlations. The compatible elements such as Ni, Co and Cr (Fig.4.3) below show somewhat linear relationship with some scatter with MgO andthis correlation may be related to fractional crystallization of olivine and clinopyroxene. The other trace elements (Ba, , Nb, Ta, Hf) show somewhat scattered patterns versus MgO concentrations.


Upper basalt
Lower basalt
600
500
400
300
200
100
0
5
10
15
MgO Wt%
Ni (ppm)


Co (ppm)
MgO Wt%
Cr (ppm)
MgO Wt%
Ba (ppm)
MgO Wt%
Hf (ppm)
MgO Wt%

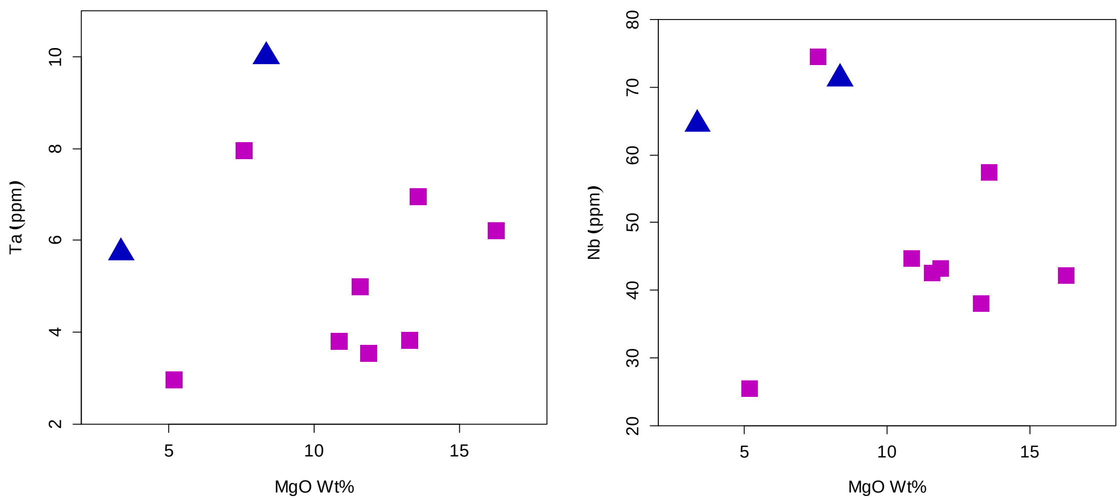


Figure 4.3. Variation diagrams of selected incompatible trace elements of this study with MgO.

4.3.1 Normalized Multielement (Spider) Diagrams

According to Thomson et al. (1983,1984), studies of trace element geochemistry of continental flood basalts have tended to focus on the incompatible elements, i.e. those elements which are strongly partitioned into the liquid phase during partial melting or fractional crystallization of mantle materials. Primitive mantle normalized trace element variation diagrams (spidergrams) of the study area basaltic rocks illustrated on Figure 4.4and the investigated basalts are characterised by the large ion lithophile incompatible elements (Rb, Ba) enrichiment over high field strength incompatible elements(Zr, Y, Dy, Yb, LU).This enrichment of incompatible elements of the study area basaltic lava might results due to the source enrichment and or lower degrees of partial melting. The primitive mantle normalized diagrams of basaltic lava in the study area show peak at Ta, Pr, and trough at Pb and Sr in the diagram. The trough at Sr suggests that fractionation of plagioclase minerals in the studied samples.From the diagram the different anomaleous behaviour of the elements might results due to different mineral phases involvment and insignificant crustal contamination in the processes of this basaltic lava formations. This thesis work results of primitive mantle normalized diagram havenearly the same properties with the HT2 basalts of previous works around Lalibela(Pik et al.,1998, 1999; Beccaluva et al.,2009).The primitive mantle normalized diagrams of the studied samples plotpattern display intersection among different magmatic segments, implying that the basalts might not be cogenetic.

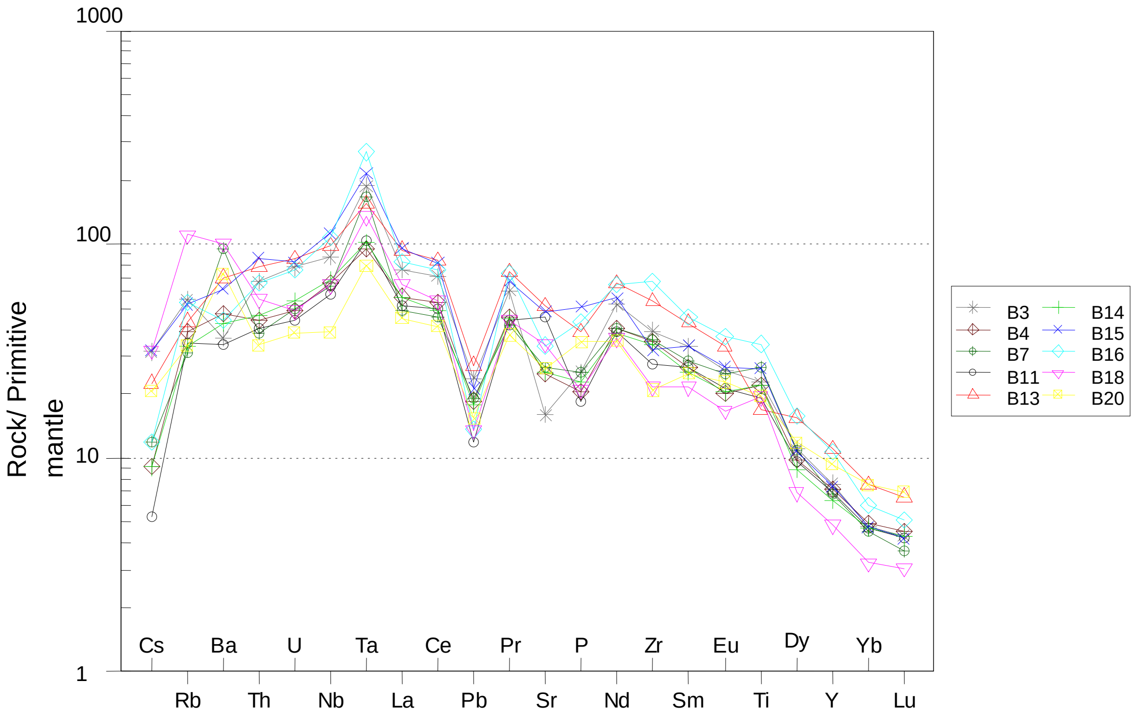


Figure 4.4. Primitive mantle normalized Spider plot of the studied samples afterMcDonough and Sun, (1995).

4.3.2. Rare Earth Elements (REE) Geochemistry

The concentrations of rare earth elements in rocks are normalized to a common reference standard, which most commonly comprises the value for chondritic meteorites, because these chondritic meteorites are thought to be relatively unfractionated samples of the solar system dating from the original nucleosynthesis. According to Rollinson, (1993) Chondritic normalization of rare earth elements has different functions. Firstly it eliminates the abundance variation between odd and even atomic number. It allows any fractionation of the rare earth elements group relative chondritic meteorites to be identified and secondly in the graph below rare earth elements are given in an order according to increasing ordering numbers, i.e. decreasing ionic radius and concentration values are normalized. The light rare earth elements are highly incompatible, while the heavy rare earth elements are moderately incompatible. The chondrite normalized rare earth element patterns of the studied samples is illustrated on fig. 4.5below, and from chondrite normalized rare earth elements patterns, this work result shows light REE enrichment and heavy REE depletion. The previous works such as (Beccaluva et al., 2009; Pik et al..; 1998, 1998; Kiefer et al., 2004), suggests that this LREE enrichment and HREE depletion indicates the presence of garnet in the source. Light rare earth elements enrichment and heavy rare earth elements depletion shows similar pattern with OIB (oceanic island basalts) in chondrite normalized diagram. From the diagram below none of the lavas show anomalies in Eu (Eu/Eu* 0.92-1.04). The enrichment of LREE in the studied samples range in terms (La/Yb) N, between 9.52 – 17.92. The REE diagram (La/Yb) N shows negative slope. The enrichment of the light rare earth element in the chodrite normalized diagram may either be a consequence of crustal contamination or their duration from enriched subcontinental mantle source. The REE plot pattern shows intersection among different magmatic segments, this indicates basalts in the study area lower basalt and upper basalt samples are not cogenetic.

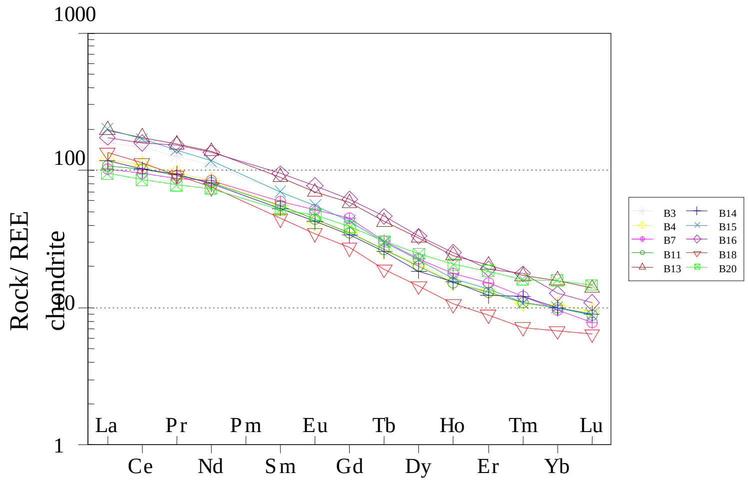


Figure4.5. Spider plot of chondrite normalized REE diagram after Boynton, (1984) for this study.

CHAPTER FIVE

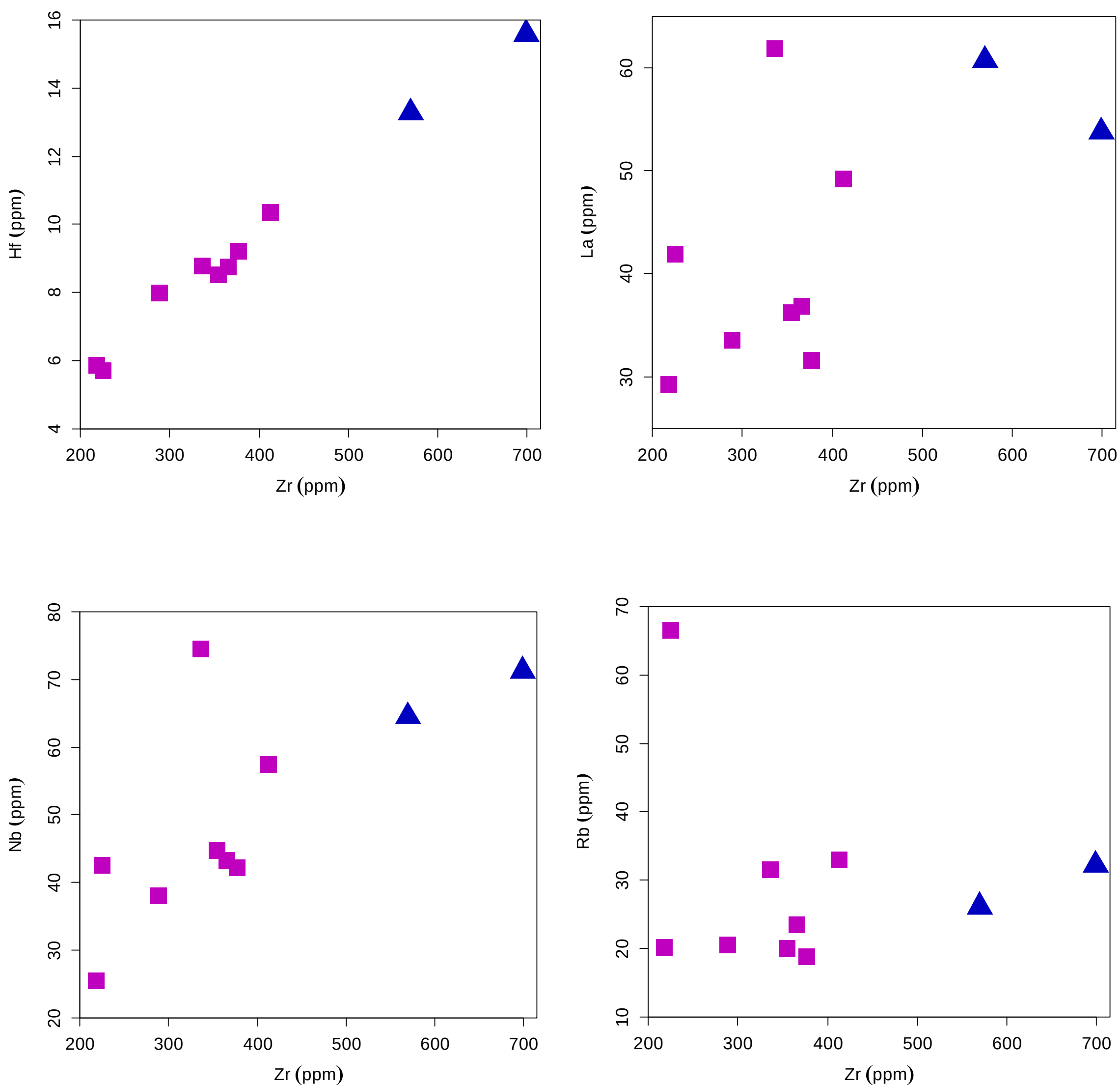
5. DISCUSSION

The formation and evolution of the Ethiopian continental flood basalt mostly related with the Afar mantle plume (Pik et al., 1999; Kieffer et al., 2004; Beccaluva et al., 2009; Natali et al., 2011, 2016). Petrographic, whole rock geochemical and isotopic analysis has been done in northwestern and northeastern Ethiopian Oligocene flood basalt, to know the source characteristics of this area. This thesis work is conducted in the northwestern Ethiopian Oligocene flood basalt and petrographic with geochemical (major & trace elements) data analysis was used to characterize the process involved in the petrogenesis of this crystal rich volcanic rock.

5.1 Crystal Fractionation

The study area basaltic rock display large compositional variations due to magma source heterogeneity, extent of melting and crystal fractionations. The Bilbala area basaltic rocks around Lalibela contain variable proportions of olivine, clinopyroxene and plagioclase phenocrysts which indicate fractional crystallization of the parental magma before eruption. Magnesium number in the studied samples is intermediate (33-67) suggests a slightly evolved magmatic character (Reichow et al. (2005). In the binary plot of the analyzed samples SiO_2 and Al_2O_3 correlate negatively with MgO, while CaO, Ni, Cr and Co have positive correlation with MgO (Fig.4.2 & Fig. 4.3). The binary plots of CaO/Al_2O_3 versus MgO bellow display a positive correlation in the studied samples. These systematic behaviors of these elements in the studied samples of the area indicate olivine and clinopyroxene dominant liquidus minerals during cooling and crystal fractionations (Green, 1980; Wooden et al., 1993). The positive correlation of Ni with MgO suggests fractional crystallization of olivine minerals. The positive correlations between Cr and CaO/ Al_2O_3 with MgO indicate fractional crystallization of clinopyroxene (Green, 1980). From the Harker variation diagram Al_2O_3 increases as MgO decreases (Figure 4.2), which together with the lack of marked Eu anomaly in the studied samples rare earth element chondrite normalized diagram suggests that plagioclase was not a major phase during fractionation. This feature visualized through the plots of major element variation diagrams of the studied samples (Fig.4.2). The involvement of clinopyroxene and olivine fractional crystallization in HT2 basaltic rocks around the study area is characterized by different authors

(Pik et al., 1999; Kieffer et al., 2004; Beccaluva et al., 2009; Natali et al., 2016).Pik et al. (1999) in his work the more differentiated HT1 group in northwestern Ethiopian plateau basalt displays a high scatter in the (Nb, La, Ta and Hf vs. Zr) diagram, while the LT and HT2 suits exhibit distinct correlations that pass through the origin. He also recognized that for the LT basalts display a higher scatter in the (Pb, Th, Rb, U and Ba vs Zr) plots suggest that the involvement of processes other than alteration and fractional crystallization in the petrogenesis of this LT lavas. The plots of these incompatible elements (Nb, La, Ta, Hf, Pb, Th, Rb, U and Ba vs.Zr) as shown bellow for the studied samples display the HT2 basalts character.



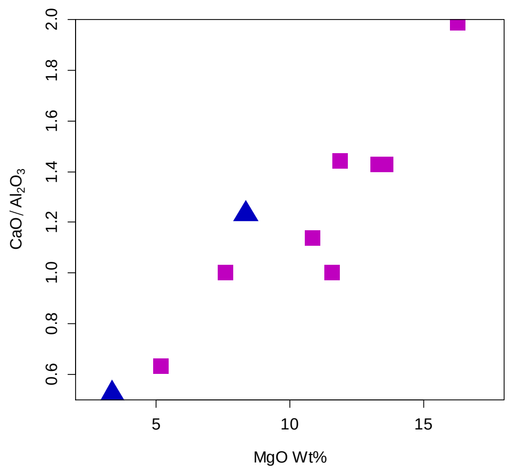


Figure 5.1 binary plots of CaO/Al2O3 versus MgO and selected incompatible trace elements versus Zr for the studied samples. Symbols as fig. 4.1

5.2 Crustal contaminations

Magmatic contamination during magma ascent to the surface through continental crust attributes compositional variation of mantle derived magma (Arndt and Christensen, 1992; Saunder et al., 1992; Song et al., 2001, 2008). Incompatible elements (Th, La & U) in the studied samples are correlated negatively with MgO (Fig. 5.2), implying insignificant interaction with continental crust (Zhang et al., 2009).In the study area Nb/U ratio ranges from 33.1 to 45.2 (Appendix 1), significantly higher than the average Nb/U ratios of 6-12 for continental crust (Sun and McDonough, 1989).In the studied samples primitive mantle normalized diagram (Fig. 4.4) Nb and Ta does not show negative anomalies. According to Cox (1980) the negative Nb and Ta anomalies are relatively common in continental flood basalts and these anomalies are accounted for mixing by crustal materials. The absence of negative Nb and Ta anomalies in the studied samples might indicate insignificant mixing or negligible mixing with crustal materials during the genesis of this basaltic lava. The interaction between subcontinental lithospheric mantle and asthenospheric melts is responsible for the depletion of high field strength elements (HFSE), especially Nb and Ta, in continental crust lavas (Arndt and Christensen, 1992; Van der Wal and Bodinier, 1996). Such types of properties are not observed in the studied samples. The ratio of highly incompatible elements such as Zr/Nb (4.5-9.8), Hf/La (0.14-0.29) and Zr/Ce (2.5-5.5) vary in the study area basaltic rocks. These ratio variations reflect heterogeneity in the source

Sun and McDonough, (1989), Weaver, (1991). Enrichment in LREE and highly incompatible elements is observed in the studied samples chondrite normalized rare earth element diagram. According to Thompson, (1984) enrichments in LREE and highly incompatible elements may either be a consequence of crustal contamination or derivation from enriched mantle source. The Ce/Pb, Nb/Th and Nb /U ratios of the study area basaltic rocks display 21.3-51.7, 9.5-13.8 and 33.1-45.2 respectively. These elemental ratios have nearly OIB type character as reported by Hofmann et al. (1986), (Nb/U = 37-57), Hofmann (2003), (Nb/Th =10-20). In contrast crustal contaminated basalts show low ratios of these elements. The concentration of thorium and its ratios i.e. Th/Ta is low in the analyzed samples, but the high thorium content with high Th/Ta ratio is the characteristics of contamination with crustal material (Wooden et al.,1993). In general the Nb –Ta positive anomalies with slightly higher values of (Ta/U) N =1.81-3.56, (Nb/Th)N =1.15-1.67 and low Th/Ta (0.5-1.1)character in the studied area indicates negligible crustal contamination during magma ascent. The analyzed samples display La/Nb ratio (0.8-1.2) and According to Thompson et al. (1984) La/Nb ratio is a suitable index of crustal contamination in magma and suggested that La/Nb < 1 for OIB, continental alkali basalts whereas continental flood basalt magmas range from 0.5 to 7. The La/Nb ratio of the study area basalts are show the same range withrespect to that of CFB and this reflects limited crustal contamination of parent magma (Peate et al., 1999; Song et al., 2001). Based on trace element and isotopic data of the previous works in northwestern Ethiopian plateau indicates insignificant crustal contribution for the genesis of HT2 basalts and LT basalts show observable crustal contamination during magma ascent (Pik et al., 1999; Kieffer et al., 2004; Beccaluva et al, 2009; Natali et al., 2016).

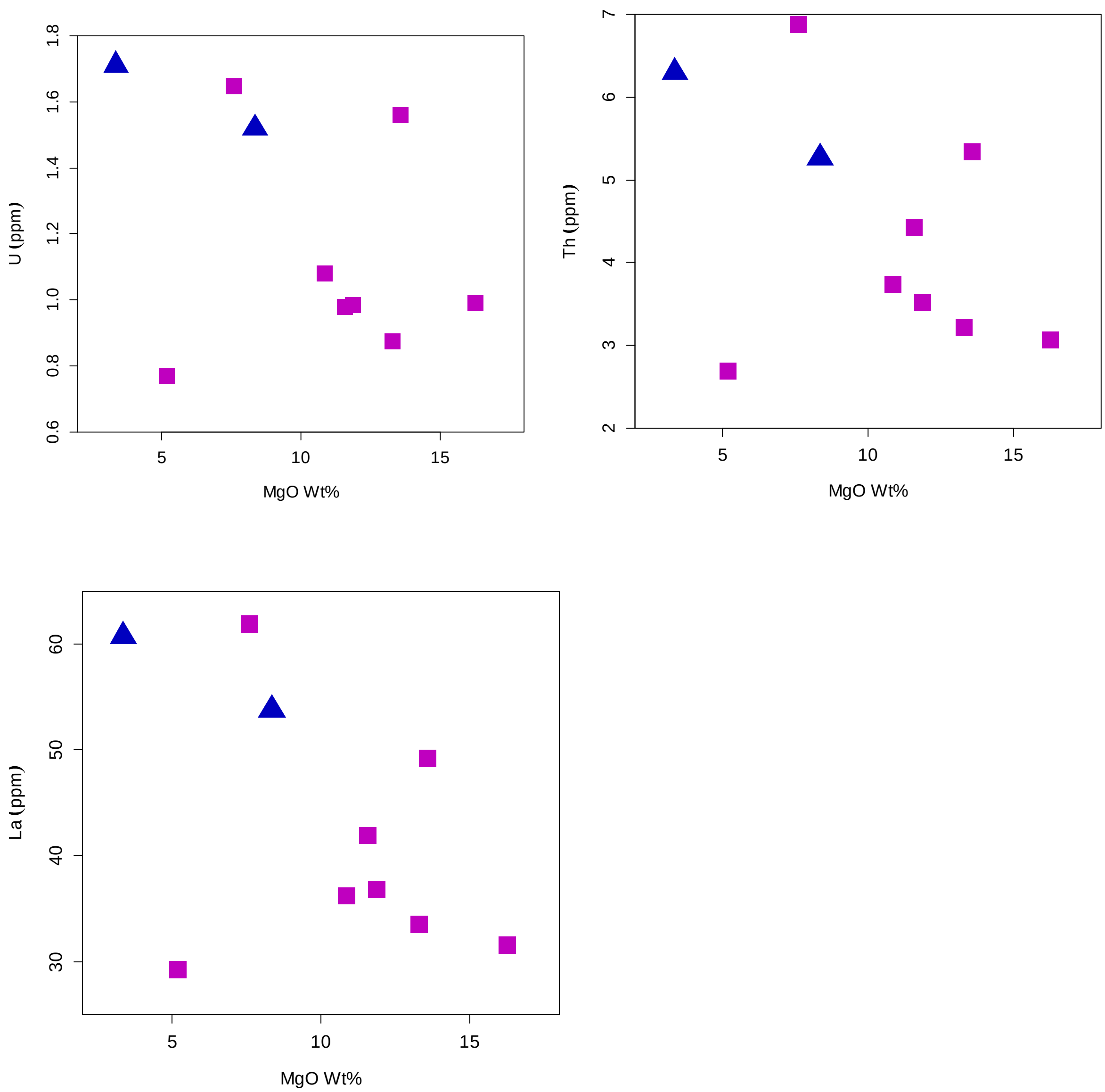


Figure5.2 selected incompatible elements vs. MgO diagrams for the study area basaltic rocks. Symbols as in fig. 4.1

5.3 Mantle source characteristics

In the studied samples the CIPW normative calculations show the presence of the normative hypersthene + quartz in one sample and the normative olivine or normative olivine + hypersthene (Table 4.1) as reported by Hirose and Kushiro, (1993) & DePaolo and Daley, (2000) small degrees of melting at higher pressure produces alkali magmas with normative olivine +hypersthene whereas larger degrees of melting at shallow depths generates tholeiitic magmas with normative hypersthene and quartz. According to works of (Lassiter et al., 1995; Reichow et al., 2005; He et al., 2010) rare earth compositions in basaltic magma provide important constraints in understanding the mantle melting conditions because their relative abundances in mantle derived melts are strongly dependent on the degree of partial melting and the nature of aluminous phase (spinel or garnet) in the mantle source. La/Yb and Sm/Yb are strongly fractionated when melting occur in the garnet stability field as suggested by Rollinson (1993). He also indicates the Gd/Yb and Sm/Yb as distinct indicators of the presence of residual garnet during partial melting. The REE signatures of the studied basaltic samples marked by (La/Yb)N = 9.5- 17.9, (Sm/Yb)N = 3.31- 7.56 and relatively low HREE contents and thus suggest that the parental magmas were derived by partial melting of a mantle source (Safonova et al., 2008; Buslov et al., 2010).

From the primitive mantle normalized patterns and chondrite normalized rare earth element patterns of the studied samples display large ion lithophile element and light rare earth element abundance, suggesting that their parent magma had a mantle source which had experienced sufficient enrichment in these elements. These basalts have Nb (25.48-74.52 ppm) and Zr (218.1-699 ppm) contents higher than those of N-MORB (Nb = 2.33 ppm, Zr = 74 ppm) and nearly similar to that of OIB (Nb = 48 ppm, Zr= 280 ppm) implying their generation from an enriched mantle source (Sun and McDonough, 1989). The Ba/Th (45-206), Ba/La (4.9- 20) and Th/Nb (0.073-0.11) ratios of the study area basalts are consistent with a source carrying signatures of enriched mantle (Weaver, 1991; Song et al., 2001). The Zr/Ba ratios of the study area basalts ranging from 0.5 to 2.42 and Zr/Hf ratios varying from 36- 44.8, indicate involvement of asthenospheric mantle source in the melting process, because the lithospheric sources Zr/Ba ratios vary between 0.3-0.5, while asthenospheric sources of parent melts have greater than 0.5 Zr/Ba ratios (Menzies et al., 1991; Kurkcuoglu, 2010). Trace element ratios of Zr/Nb in the studied samples vary from4.5 to 9.8. According to Sun and McDonough, (1989) plume derived basalts have lower ratios of Zr/Nb (<10) in comparison with N-MORB (Zr/Nb: >301). A relatively lower range of Zr/Nb ratios of the study area basaltic samples suggest a plume origin for the parental magma.

The (Th/Ta) N ratios in the analyzed samples range from 0.2 to 0.5. This result is near unity implying an asthenospheric or plume origin of basaltic rocks of the area. In addition to this the diagram of Ba/Nb versus La/Nb bellow shows the data plots closely OIB trend i.e. Ba/Nb = >4 & La/Nb =0.7-1 in OIB& Ba/Nb =<4, La/Nb =1-1.3 for MORB (Weaver, 1991; Sun and McDonough, 1989; Ben Othman et al., 1989). This type of trend indicates that the study area basaltic rocks originated from parental sources in which essentially no continental lithosphere was involved). The Nb/La ratio in the study area ranges from 1 to 1.17, which indicates melt of the basaltic lavas in the study area is not lithospheric origin because melts of lithospheric mantle origin have less than one (<1) Nb/La ratio Smith et al. (1999). From this observation the study area basaltic rocks formation corresponds to partial melting of Afar mantle plume (C1 component) as concluded by previous works for HT2 basalts formations. In the plots (Th/Yb)N versus (La/Sm)N of the studied samples show garnet involvement in its source.

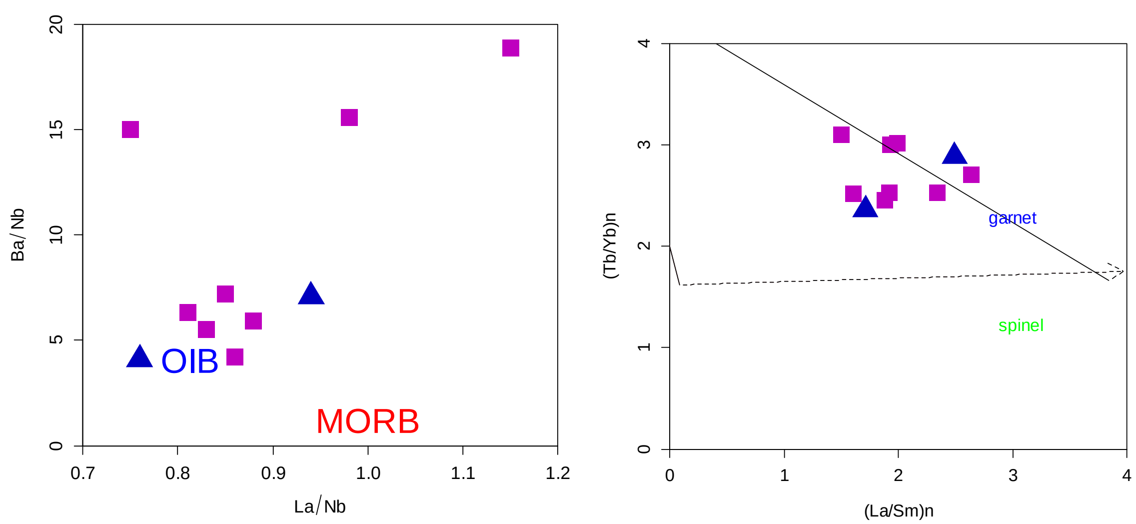


Figure 5.3 selected trace element ratio diagram for the studied basaltic rocks after (Weaver, 1991; Sun and McDonough, 1989; Ben Othman et al., 1989). Symbols as in fig. 4.1.

5.4 comparison of this work with previous work

According to Pik et al. (1998), the northwestern Ethiopian plateau continental flood basalts are classified into LT (Low –Ti basalt) and HT (High-Ti basalt) based on the concentrations of high field strength elements (HFSE), incompatible trace element ratios and major element composition. In the TAS classification diagrams basaltic rocks of the northern Ethiopian plateau are transitional i.e. clustered alkaline / subalkaline field Piccirillo et al. (1979). This idea also supported by Piket al. (1998, 1999) and Beccaluva et al. (2009). Most of the LT and HT2 basalts of northwestern Ethiopian plateau are olivine tholeiites, however quartz tholeiite tendency is observed for LT group and an alkaline tendency for HT2 group. The Mg# (Mg# =100*Mg/ (Mg + Fe2+)) have variable ranges for the different magma type of the northwestern Ethiopia plateau. It ranges from 39 to 52 for HT1 basalts and 32 to 64 for LT basalts and from 52 to 74 for HT2 basalts. The LT basalts display the lowest TiO_2, P2O_5, Fe_2O_{3*}, CaO/Al_2O_3 and relatively high SiO_2 contents and correspond to low –Ti magma type, commonly described in continental flood basalt provinces, in contrast the two other basalts groups (HT1 & HT2) display higher TiO_2, P_2O_5, Fe_2O_3*, CaO/Al2O3 and relatively low SiO2 contents. The MgO concentration is high in HT2 and low in HT1 and LT basalts. The distributions of these three-magma type in northwestern Ethiopian plateau is variable (Pik et al., 1998, 1999; Beccaluva et al., 2009). The major element concentrations of the studied samples display slightly the HT2 character with high contents of TiO2 (3,81-6.87Wt%, FeO* (11.59-15.71 Wt%), CaO/Al2O3 (0.890-1.989) and low SiO2 (41.7-49.97 Wt.%) with intermediate magnesium number (table 4.1) of the previous work mentioned above. According to Pik et al. (1998), northwestern Ethiopian plateau basalt classifications in the Al_2O_3 versus Mg # diagram the HT2 trend has negative slope but HT1 and LT trends positive slope. The studied samples Al_2O_3 versus Mg # diagram as shown below display negative trend like HT2 basalts of previous work. This is one criterion to say the study area basaltic lavas included under the HT2 basalts of the northwestern Ethiopian plateau basalt classification of previous works. In the work of Piket al., (9198, 1999) and Beccaluva et al. (2009) the HT2 basalts of the northwestern Ethiopia plateau display incompatible elements enrichments, high rare earth element contents and strong high field strength elements enrichment with Rb and Sr depletion but the LT basalts in the area show depletion in Rb, Th, U, Ta, Nb and peaks at Ba, K, Pb and Sr. In the primitive mantle normalized diagram of the study area basaltic rocks show trough at Pb, Sr and peaks at Rb,Ba ,Ta, Pr and nearly similar Nd anomalies. In addition to these, the high field strength elements (Nb, Ta, Zr, Ce, U & Th) in the studied samples show enrichment compared to large ion lithophile elements (Pb, Cs, Sr). These depletion and enrichment of the different elements in the study area basaltic lavas also supports to say the area is dominated by HT2 basalts. The analyzed samples result shows the high contents of Sm/Yb (3.05- 6.96) and CaO/Al_20_3 ratios (0.89- 1.99). Pik et al., (1998) indicates that the higher values of Sm/Yb, CaO/Al_2O_3 ratios and FeO* with low SiO_2 and Al_2O_3 displayed in HT2 basalts which derived from Afar plume melts suggests high pressure melting.

According to Pik et al. (1998) the low –Ti suite displays the lowest incompatible trace element contents, but the HT2 basalts are the most enriched and also the LT basalts have low rare earth element contents, whereas HT1 and HT2 basalts higher rare earth element contents and strong LREE/HREE fractionation, in addition the HT2 basalts with their high LREE contents exhibit OIB type mantle normalized incompatible trace element patterns. The HT basalts of northwestern Ethiopian plateau display moderate LILE and strong HFSE enrichment compared to primitive mantle and MORB (Pik et al. 1998, 1999). The study area flood basalts trace element characteristics on primitive mantle normalized diagram also show enrichment of HFSE and moderate LILE as HT2 basalts which reported previously. In the plots of Nb/Y vs. Ti/Y for the studied samples except one sample all the analyzed samples display HT2 basalts character.

In general, the geochemical and petrographic results of the studied samples fit the properties of HT2 basalts of the northwestern Ethiopian plateau. The overall results of the crystal rich volcanic rocks display nearly similar behavior of the HT2 group’s basalt.

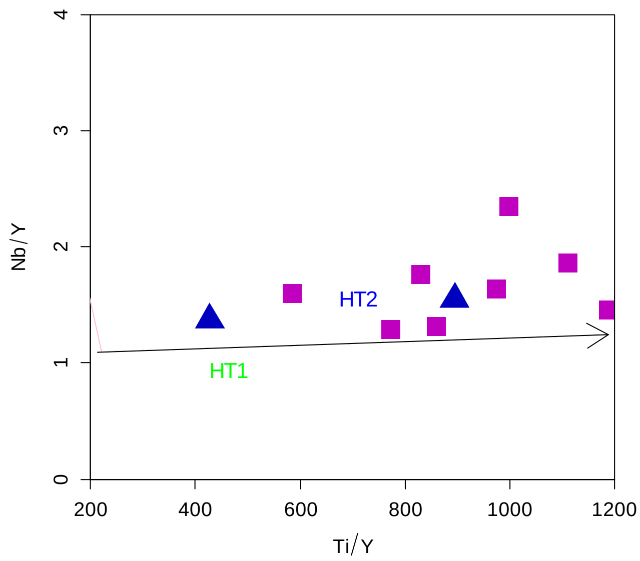


Figure 5.4 binary plots of Ti/Y vs. Nb/Y ratios for the study area basaltic rocks. Symbols as in fig. 4.1

CHAPTER SIX

6. CONCLUSION AND RECOMENDATIONS

6.1. Conclusion

This thesis is conducted in northwestern Ethiopia Oligocene flood basalt around Lalibela specifically in Bilbala area. Based on the field observations, petrography, and whole rock geochemical (major and trace element) studies of this work it is concluded that:

- The study area basaltic rock is classified into two units based on field observation and petrographic results. These are lower basalt, which characterized by fine grained texture with different degree of weathering effect and it has interstitial texture with ground mass of fine grained interstitial pyroxene, plagioclase and opaque minerals in petrographic thin section. The second type of basaltic rock in the study area is the upper basalt that covers most of the area with abundant crystals. In microscopic thin section the upper basalt is characterized by porphyritic texture, with phenocryst of pyroxene, plagioclase and olivine and ground mass of fine grained interstitial pyroxene, plagioclase and opaque minerals.
- Major and trace element data of the study area basaltic rocks with their normative minerals shows that all the studied samples are basalt. In the total alkali (Na2O + K2O) – Silica (TAS) diagram the analyzed samples ranges from alkaline to sub alkaline field and show transition behavior in character. The major elements binary plot (Harker variation diagrams) of the studied sample shows scatter pattern that indicates fractionations of different minerals in their differentiation. Clinopyroxene and olivine are the main minerals that involved in the fractionation process. Plots of MgO with some incompatible and compatible elements show heterogeneity in their source. The basaltic rocks analysis of the study area shows low concentration of SiO_2 and high contents of TiO_2, Al_2O_3, FeO*, MgO with intermediate magnesium number.
- In the binary plot of the analyzed samples SiO_2 and Al_2O_3 correlate negatively with MgO, while CaO, Ni, Cr and Co have positive correlation with MgO. These systematic behaviors of these elements in the studied samples of the area indicate olivine and clinopyroxene dominant liquidus minerals during cooling and crystal fractionations.

- The ratio of highly incompatible elements such as Zr/Nb (4.5-9.8), Hf/La (0.14-0.29) and Zr/Ce (2.5-5.5) vary in the study area basalts. These ratio variations reflect heterogeneity in the source. The basalts from the study area have relatively high Ta and nearly similar Nb abundances and low trace element ratios (Rb/Nb: 0.4-1.6 and Th/Ta: 0.5-1.1), which overlap or are close to those of OIB. The light rare earth element enriched patterns and lack of negative Nb and Ta in the studied sample indicates insignificant crustal contamination during the ascent of magma in the study area.
- Magnesium number in the studied samples is intermediate (33-67) suggests a slightly evolved magmatic character.
- The studied samples have depleted Zr/Nb ratios (< 10). The Zr/Nb depleted character of this mafic lava might imply a dominant mantle plume contribution during the genesis of these lavas.

6.2. Recommendations

- Additional whole rock and mineral chemistry analysis are recommended to adequately understand the magma source characteristics, petrological and geochemical processes involved to produce the rock suites of these crystal rich volcanic rocks of the area.
- Isotopic study is recommended to put further constraints on the origin and location of the source of basaltic rocks of the area.

REFERENCE

Arndt, N.T. and Christensen, U. (1992). The role of lithospheric mantle in continental flood basalt volcanism: thermal and geochemical constraints.J.Geophys.Res.**97**, 10967-10981.

Ayalew, D., Marty, B., Yirgu, G. and Pik, R. (1999). Geochemical and isotopic (Sr, Nd and Pd) characteristics of volcanic rocks from south western Ethiopia. Journal of African Earth Sciences **29,** 381-391.

Ayalew, D., Pierre, B., Bernand. M., Laurie, R., Yirgu, G. and Pik, R. (2002). Source, genesis, and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts. Geochemical et CosmochemicaActa**66**(8), 1429-1448.

Ayalew, D., and Yirgu, G. (2003). Crustal contribution to the genesis of Ethiopian Plateau rhyolitic ignimbrites, basalt and rhyolite geochemical provinciality Journal of the Geological society, **160**, 47-56.

Ayalew, D. and Gibson, S.A. (2009). Head to tail transition of the Afar mantle plume: geochemical evidence from Miocene bimodal basalt rhyolite succession in the Ethiopian large igneous province. Lithos. **112**, 461-476.

Baker,J., Thirlwall, M. and Menzies, M.A. (1996a). Sr-Nd-Pb and trace element evidence for crustal contamination of plume-derived flood basalts: Oligocene flood volcanism in western Yemen.Geochemicacosmochemica, Act **60**, 2559-2581.

Baker, J., Snee, L and Menzies, M. (1996). A brief Oligocene period of flood volcanism in Yemen: implications for the duration and rate of continental flood volcanism at the Afro- Arabian triple junction. Earth and Planetary Science Letters, **138**, 39-55.

Baker, J.A., Macpherson, C.G., Menzies, M.A., Thirlwall, M.F., Al-Kadasi, M. and Mattey, D.P. (2000). Resolving crustal and mantle contributions to continental flood volcanism, Yemen: constraints from mineral Oxygen isotope data. Journal of petrology, **41**, 1805-1820.

Barberi, F., Treuil, M. and Varet.J. (1975). A transitional Basalt- Pantellerite sequence of fractional crystallization, the Boinacentre (Afar Rift, Ethiopia). Journal of petrology, **16**, 22-56.

Beccaluva, L., Bianchini, G., Natali, C. and Siena, F. (2009). Continental flood basalts and Mantle plumes: a case study of the northern Ethiopian Plateau. J. Petrol. **50** (7), 1377-1403.

Ben Othman D., White W.M. and Patchett J. (1989). The geochemistry of marine sediments, island arc magma genesis and crust –mantle recycling. Earth planet. Sci. Lett. **94**, 1-21.

Berhe, S.M., Desta, B., Nicoletti, M. and Teferra, M. (1987). Geology, geochronology and geodynamic implication of the Cenozoic magmatic province in W and SE Ethiopia. J. Geol. Soc. London, **144**, 213-226.

Buslov, M.M., Salfonova, I. Yu, Fedoseev, G.S., Reichow, M., Davies, C. and Babin, G.A.(2010). Permo – Triassic plume magmatism of the kuznetsk Basin, central Asia:geology, geochronology and geochemistry. Russian Geology and Geophysics **51**, 901-916.

Chazot, G. and Bertrand, H. (9193). Mantle sources and magma continental crust interactions during early Red Sea- Aden rifting in southern Yemene: elemental and Sr, Nd, Pb isotope evidence. J. Geophys. Res. **98**, 1818-1835.

Chernet, T., Hart, W.K., Aronson, J.L. and Walter, R.C. (1998). New age constraints on the timing of volcanism and tectonism in the northern Main Ethiopian Rift- southern Afar transition zone (Ethiopia).J.Volvanol. Geotherm. Res. **80**, 267- 280.

Chorowicz. J., Collet. B., Bonavia. F.F., Mohr. P., Parrot.J.-F. and Korme.T.(1998). The Tana basin Ethiopia: Intra plateau uplift. Rifting and subsidence. Tectono physics **295**. 351-367.

Coffin, M.F. and Eldholm, O. (1994). Large igneous provinces: crustal structure, dimensions and external consequences. Rev. Geophys. **32**, 1-36.

Coulie, E., Quideleur, X., Gillot, P-Y., Courtillot, V., Lefevre, J-C. andchiesa, S. (2003). Comparative K-Ar and Ar/Ar dating of Ethiopian and Yemenite Oligocenevolcanism implications for timing and duration of the Ethiopian traps. Earth andplanetary science Letters **206**,477-492.

Cox, K.G., (1980). A model for flood basalt volcanism. J.Petrol. **21**, 629-650.

Davidson, A. and Rex, D.C. (1980). Age of volcanism and rifting in southern Ethiopia. Nature, **283**, 65-66.

DePaolo, D.J. and Daley, E.E., (2000). Neodymium isotopes in basalts of the Southwest Basin and Range and lithospheric thinning during continental extension. Chemical Geology **169**, 157–185.

Dercq, M., Arndt,N.,Lapierre, H. and Yirgu, G. (2001). Les pitons trachytiquesd'Ethiopiene sont pas les conduits d'alimentation des trapps.C.R.Acad. Sci. paris**332**:609-615.

Ebinger C.J., Yemane T. WeldeGabriel G., Aronson J. L., and Walter R.C.(1993). Late Eocene-Recent volcanism and faulting in the Southern main Ethiopian Rift, Journal of the Geological Society, London, V. **150**, P.99-108.

Ebinger, C.J. and Sleep, N.H. (1998). Cenozoic magmatism throughout East Africa resulting from impact of a single plume. Nature, **395**, 788-791.

Furman, T., Bryce, J.G., Rooney, T., Hanan, B.B., Yirgu, G. and Ayalew, D. (2006).Heads and tails: 30 million years of the Afar plume. In: Yirgu, G., Ebinger, C.J., Maguire. P.K.H. (Eds.). The structure and evolution of the east African rift system in the afar volcanic province. Geological Society of London. Special publication, vol. **259**, pp. 123-132.

Gasparon, M., Innocenti, F., Manetti, P., Peccerillo, A., and Tsegaye, A. (1993). Genesis of the Pliocene to recent bimodal mafic- felsic volcanism in the Debre Zeyt area, central Ethiopia: volcanological and geochemical constraints. J.Afr. Earth Sc. **17**, 145-165.

George, R., Rogers, N. and Kelley, S. (1998). Earliest magmatism in Ethiopia: evidence for two mantle plumes in one flood basalt province. Geology **26**, 923-926.

Green, T.H. (1980). Island arc and continent-building magmatism; a review of petrogenetic models based on experimental petrology and geochemistry. Tectonophysics **63**, 367–385.

Harker, A. (1909). *The Natural History of Igneous Rocks*. Macmillan. New York.

Hart, W.K., Weldegabriel, G., Walte, R.C. andMartzman, S.A. (1989). Basaltic volcanism in Ethiopia: constraints on continental rifting and mantle interactions. J. Geophys. Res. **94**, 7731-7748.

He, Q., Xiao, L., Balta, B., Gao, R., Chen, J. (2010). Variety and complexity of the Late Permian Emeishan basalts: Reappraisal of plume-lithospher interaction process. Lithos **119**, 91- 107.

Hirose, K. and Kushiro, I. (1993). Partial melting of dry peridotites at high pressures: determinations of compositions of melts segregated from peridotite using aggregates of diamond. Earth and Planetary Science Letters
14,477-489.

Hofmann, A.W., Jochum, K.P., Seufert, M.,and White, W.M. (1986). Nb and Pb in oceanic basalts: new constraints on mantle evolution. Earth and Planetary Science Letters **79**, 33-45.

Hofmann, C., Courtillot, V., Feraud, G.,Rochette, P., Yirgu, G. and Pik, R. (1997).Timing of the Ethiopian flood basalt event and implications for plume birth and global Change. *Nature*,**389**: 838-841.

Ingrid A., Ukstins, P. R., Renne, P.R., Wolfenden,E.., Joel, B., Ayalew, D., Martin, M. (2002). Matching Conjugate Volcanic Rift Margins: $^{40}Ar/^{39}Ar$ chrono- stratigraphy of pre- and syn-rift bimodal flood volcanism in Ethiopia and Yemen. Earth and planetary science letters **198**, 289-306.

Iwamori,H. and Nakamura, H.(2015). Isotopic heterogeneity oceanic, arc and continental basalts and its implications for mantle dynamics. Gondwana Res. **27(30**, 1131-1152.

Kieffer, B., Arndt, N., Lapierre, H., Basitien, F., Bosch, D., Pecher, A., Yirgu, G., Ayalew, D.,Weis, D, Gerram, D.A., Keller, F.,Meugniot, C. (2004). Flood and shield basalts from Ethiopia: Magmas from the African Superswell. *J. Petrology*,**45**:793-834.

Kurkcuoglu, B. (2010). Geochemistry and petrogenesis of basaltic rocks from the Develidag volcanic complex, central Anatolia, Turkey. Journal of Asian Earth Sciences**37**, 42-51.

Lassiter, J.C., DePaolo, D.J., Mahoney, J.J.(1995). Geochemistry of the Wrangellia flood basalt province: implication for the role of continental and oceanic lithosphere in flood basalt genesis. Journal of petrology **36**. 983-1009.

Mackenzeie, G.D., Thybo, H. and Maguire, P.K.H. (2005). Crustal velocity structure across the main Ethiopian Rift; results from two dimensional wide- angle seismic modeling. Geophys. J.Int**. 162**, 994-1006.

McDonough, W.F. and Sun, S.S. (1995). Composition of the Earth. Chem. Geol. **120,** 223-253. doi: 10.1016/0009-2541(94)00140-4.

Menzies, M.A., Kyle, P.R., Jones, M., Ingram. (1991). Enriched and depleted source components for the tholeiitic and alkaline lavas from Zuni-Bandera, New Mexico: inferences about intraplate processes and stratified lithosphere. Journal of Geophysical Research **96**, 13645-13671.

Merla, G., Abbate, E., Azzaroli, A., Bruni, P., Fazzuoli, M., Sargi, M.,Tacconi, P. (1979). A geological map of Ethiopian and Somalia: Comment. Petgamon, 95p.

Mohr, P. (1967). Review of the geology of the semien mountains. Bulletin of the Geophysical observatory of Addis Ababa **10**, 7993.

Mohr, P. (1983). Ethiopian flood basalt province. Nature **303**, 177-584.

Mohr, P. and Zanettin, B. (1988). The Ethiopian flood basalt province. In: MacDougall, J. D. Continental Flood basalts. Dordrecht: Kluwer Academic, 63-110.

Natali, C., Beccaluva, L., Bianchini, G., Siena, F. (2011). Rhyolites associated to Ethiopian CFB. Clues for intial rifting at the Afar plume axis. Earth and Planetary Science Letters, **312**. 59-68.

Natali, C., Beccaliva, L., Bianchini, G., Ellam, M.R., Savo, A., Siena, F., Staurt, M.F. (2016). High – MgO lavas associated to CFB as indicators of plume - related thermochemical effects: The case of ultra –titaniferouspicrite – basalts from the Northern Ethiopian – Yemeni Plateau. Gondwana Research, **34**, 29-48.

Peate, D.W., Hawkesworth, C.J., Marta,M.S.M., Nick, W.R., Turner,S.P.(1999). Petrogenesis and stratigraphy of the high Ti/Y Urubici magma type in the Parana flood basalt: province and implications for the nature of Dupal-type mantle in the South Atlantic Region. Journal of Petrology **40**, 451-473.

Piccirillo, E.M., Justin-Visentin, E., Zanettin, B., Joron, J.L.,Treuil, M. (1979). Geodynamic evolution from plateau to rift: major and trace element geochemistry of the central-eastern Ethiopian plateau volcanics. NeuesJahrbuch fur Geologie and Plaontologie Abhandlungen, **158**, 139 – 179.

Pik, R., Daniel, C., Coulon, C., Yirgu, G., Hoffmann, C., Ayalew, D. (1998). The northwestern Ethiopian Plateau flood basalts: classification and spatial distribution of magma types. Journal of Volcanology and Geothermal Research **81**, 91-111.

Pik, R., Daniel, C., Coulon, C., Yirgu, G., Marty, B. (1999). Isotopic and trace element signatures of Ethiopian flood basalts: Evidence for plume lithosphere interactions. *Geochim.Cosmochim Acta*,**63**: 2263-2279.

Reichow, M.K., Saunders, A.D., White, R.V. (2005). Geochemistry and petrogenesis of basalts from the west Siberian basin: an extension of the Permo- Triassic Siberian Traps, Russia. Lithos. **79**, 435-452.

Rochette, P., Tamrat, E., Feraud, G., Pik, R., Courtillot, V., Ketefo, E., Coulon, C., Hofmann, C., Vandamme, D. and Yirgu, G. (1998). Magnetostratigraphyand timing of the Oligocene Ethiopian traps. Earth and Planetary Science Letters **164**, 497-510.

Rollinson, H.R. (1993). Using Geochemical Data: Evaluation, Presentation and Interpretation. Longman Group, London, 352p.

Safonova, L.Yu, Simonov, V.A., Buslov, M.M., Ota, T., Maruyama, Sh. (2008). Neo-proterozoic basalts of the Paleo-Asian Ocean (Kurai accretion zone, Gorny Altai, Russia): geochemistry, petrogenesis, geodynamics. Russian Geology and Geophysics **49**, 254-271.

Saunders, A.D., Storey, M., Kent, R.W., Norry, M.J. (1992). Consequences of plume lithosphere interactions. In: Storey, B.C., Alabaster, T., Pankhurst, R.J. (Eds), Magmatism and the cause of continental Breakup. Geological Society of London Special Publication **68**, PP. 41-60.

Smith, E.I., Sanchez, A., Walker, J.D., Wang, K. (1999). Geochemistry of mafic magmas in the Hurricane Volcanic Field, Utah: implications for small and large scale chemical variability of the lithospheric mantle. Journal of geology **107**.433-448.

Stewart, K., and Rogers, N.(1996).Mantle plume and lithosphere contributions to basalts from southern Ethiopia. Earth and Planetary Science Letter **139**, 195-211.

Song, X.-Y., Zhou, M.-F., Hou, Z.-Q., Cao, Z.-M., Wang, Y.-L., Li, Y.(2001). Geochemical constraints on the mantle source of the upper Permian Emeishan Continental flood basalts, Southwestern China. International Geology Review **43**, 213-225.

Song, X.-Y., Qi, H.-W., Robinson,P.T., Zou, M.-F., Cao, Z.,-M., Chen, L.-M.(2008). Melting of the subcontinental lithospheric mantle by the Emeishan mantle plume: evidence from the basal alkaline basalts in Dongchuan, Yunan, Southwestern china. Lithos **100**, 93-111.

Sun, S.S. and McDonough, W.F.(1989). Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes.Geological Society, London, **42**: 313-345.

Tefera, M., Chernet, T. and Haro, W. (1996). Geological map of Ethiopia, scale 1:2,000,000. Ethiopian institute of geological surveys, Addis Ababa, Ethiopia.

Teferi, M., Ayalew, D., Ishiwatari, A., Arai, S., Tamura, A. (2014).Ferropicrite from the Lalibela area in the Ethiopian large igneous province, Journal of Mineralogical and Petrological Sciences. **109:**191-207.

Thompson, R.N., Morrison, M.A., Dickin, A.P .and Hendry, G.L. (1983). Continental flood basalts…arachnids rule OK? In continental basalts and Mantle Xenoliths (Hawkesworth, C.J. and Norry, M.J. Eds). Shiva Pub., Cambridge, USA. 158-185.

Thompson,R.N., Morrison, M.A., Hendry, G.L., Parry, S.J. (1984). An assessment of the relative role of crust and mantle in magma genesis: an elemental approach. Philosophical Transactions of the Royal Society of London **A310,** 549-590.

Van der Wal, D., and Bodinier, J.L. (1996). Origin of the recrystalization front in the Ronda peridotite by Km-scale pervasive potous melt flow. Contrib. Mineral. Petrol. 122, 387-405.

Ukstin,I.A., Renne,P.R., Wolfenden,E., Baker, J., Ayalew, D.. and Menzies,M. (2002).Matching conjugate volcanic refted margins:^{40}Ar/^{39}Ar chrono-stratigraphyrpre- and syn-rift bimodal flood volcanism in ethiopia and yemen .earth and planetary science letters **198**,289-306

Walter, (1998). Melting of garnet peridotite and the origin of komatite and depleted lithosphere. Journal of petrology **39**, 29-60.

Weaver, B.L., (1991). The origin of ocean island basalt end member compositions: trace and isotope constraints. Earth and Planetary Science Letter **104**. 381-397.

Wilson, M. (1989). Igneous petrogenesis. Springer, Netherland, 480p.

Wooden, J.L., Czamanske, G.K., Fedorenko,V.A., Arndt, N.T., Chauvel, C.,Bouse, R.M., King, B.S.W.,Fnight, R.J., and Siems, D.F. (1993). Isotope and trace element constraints on mantle and crustal contributions to Siberian continental flood basalts, Norilsk area, Siberia.Geochim. Cosmochim. Acta. **57**, 3677-3704.

Yang, H.-J., Frey, F.A. and Clague, D.A., (2003). Constraints on the source components of lavas forming the Hawaiian North Arch and Honolulu volcanics. Journal of Petrology **44**, 603–627.

Zanettin, B., Justin-Visentin, E., Nicolrtti, M.,Piccirillo, E.M. (1980). Correlations among. Ethiopian volcanic formations with special references to the chronological and stratigraphical problems of the "Trap Series"' AttideiConvegniLincei, **47**, 231-252.

Zhang J.J., Zheng, Y.F. and, Zi-Fu Zhao, Z.F. (2009). Geochemical evidence for interaction between oceanic crust and lithospheric mantle in the origin of Cenozoic continental basalts in east-central China. Lithos.**110**, 305–326

Appendix

Geochemistry Data

Major elements in elemental form (Wt %)
Calculated by a formula, conversion Number*W_i; where w_i is the Wt. percentages of oxide.
Conversion Number = MW_i*A_i/MW_g; where MW_i molecular weight of cations, A_i is number of cations in the oxide formula and MW_g is the molecular weight of oxide.

Sample #	Ti	P	K	Ti/K	P/K
B3	2.71	0.23	1.1	2.46	0.21
B4	2.64	0.18	0.91	2.90	0.20
B7	3.2	0.23	0.66	4.85	0.35
B11	2.28	0.17	0.72	3.17	0.24
B13	2.01	0.35	1.19	1.69	0.29
B14	2.65	0.21	1.05	2.52	0.20
B15	3.17	0.46	1.62	2.00	0.28
B16	4.12	0.39	1.20	3.43	0.33
B18	2.33	0.18	2.18	1.07	0.10
B20	2.35	0.31	0.81	2.90	0.38
Conversion Number	0.599508	0.436421	0.830147		

Trace element ratio

Sample #	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3
(La/Yb)N	16.0	14.3	10.3	9.5	9.8	11.2	10.6	17.9	12.3	17.9
(Nb/Th)N	1.3	1.5	1.8	1.4	1.3	1.5	1.3	1.7	1.2	1.2
(Ta/U)N	2.4	1.9	3.4	2.4	1.8	1.9	2.6	3.6	2.8	2.1
(Th/Ta)N	0.4	0.5	0.2	0.4	0.5	0.5	0.4	0.2	0.4	0.5
Zr/Hf	39.8	41.7	41	36.1	42.9	41.8	38.3	44.8	39.5	37.2
Th/Ta	0.8	1.0	0.5	0.8	1.1	1.0	0.9	0.5	0.9	0.9
Rb/Nb	0.6	0.5	0.5	0.5	0.4	0.5	0.4	0.5	1.6	0.8
Hf/La	0.2	0.2	0.3	0.2	0.2	0.2	0.1	0.3	0.1	0.2
Zr/Ce	3.5	4.1	4.9	3.5	4.1	4.3	2.5	5.5	2.5	3.2
Sm/Yb	6.54	4.94	5.75	5.17	5.29	4.95	6.52	6.96	6.11	3.05
Ba/La	4.9	8.5	20.0	6.7	7.6	7.8	6.6	5.4	15.9	16.5
Ba/Nb	4.2	7.2	15	5.9	7.1	6.3	5.5	4.1	15.6	18.9
La/Nb	0.9	0.9	0.8	0.9	0.9	0.8	0.8	0.8	1.0	1.2
Ce/Pb	33.7	32.1	27.0	47.2	34.5	21.3	43.4	51.7	45.1	29.6
Nb/La	1.17	1.17	1.34	1.14	1.03	1.24	1.2	1.33	1.02	0.87
Th/Nb	0.09	0.08	0.07	0.08	0.1	0.08	0.09	0.07	0.1	0.11
Zr/Nb	7.2	8.5	8.9	7.6	8.8	7.9	4.5	9.8	5.3	8.6
Nb/Th	10.7	12.3	13.8	11.9	10.3	12	10.8	13.5	9.6	9.5

Nb/U	36.8	44	42.6	43.5	37.7	41.4	45.2	44.8	43.6	33.1
Ti/Y	831	860	1188	772	427	974	999	895	1111	584
(La/Lu)N	17.4	12.5	13.1	12.2	14.2	13	22.4	16	21	6.5
(Sm/Yb)N	7.06	5.37	6.24	5.62	5.74	5.34	7.08	7.56	6.64	3.31
Ba/Th	45.28	88.91	206.19	69.6	73.06	75.4	59.23	54.84	150.57	180.77