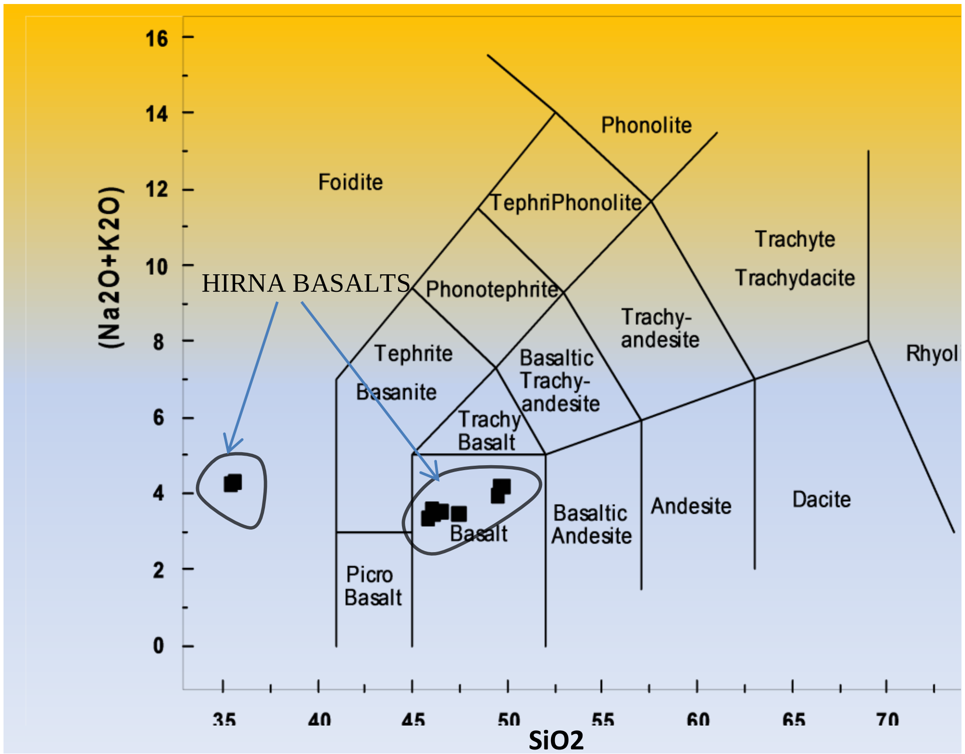
ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL SCIENCES

SCHOOL OF EARTH SCIENCES

PETROGENESIS OF FLOOD BASALTS FROM HIRNA AREA, SOUTH EASTERN ETHIOPIAN PLATEAU

BY: ANDUALEM GETAW



A THESIS SUBMITTED TO THE SCHOOL OF EARTH SCIENCES ADDIS ABABA UNIVERSITY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN GEOCHEMISTRY

JULY 2013

PETROGENESIS OF FLOOD BASALTS FROM HIRNA AREA, SOUTH EASTERN ETHIOPIAN PLATEAU

A THESIS SUBMITTED TO THE SCHOOL OF EARTH SCIENCES ADDIS ABABA UNIVERSITY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN GEOCHEMISTRY

BY ANDUALEM GETAW

ADVISOR Dr. DEREJE AYALEW

JULY 2013

ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL SCIENCES

SCHOOL OF EARTH SCIENCES

PETROGENESIS OF FLOOD BASALTS FROM HIRNA AREA, SOUTH EASTERN ETHIOPIAN PLATEAU

BY ANDUALEM GETAW

APPROVED BY THE EXAMINING BOARD

Dr. SEIFU KEBEDE ------------------------------------

Chairman, Department

Graduate committee

Dr. DEREJE AYALEW ------------------------------------

Advisor

Prof. GEZAHEGN YIRGU ------------------------------------

Examiner

Dr. MULUGETA ALENE ------------------------------------

Examiner

ACKNOWLEDGMENT

I have no words to express my deepest gratitude to my advisor Dr. Dereje Ayalew for his decisive guidance throughout this thesis work. The constructive suggestions he gave me were important to accomplish the work and this final manuscript. Moreover, I would like to thank him for His support in suggesting and providing valuable reference materials and sharing his field and research experiences. Thank you and God bless you.

I am highly indebted to Prof. Tyrone Rooney in Michigan State University (U.S.A) for providing the major and trace element analyses result and for his consistent suggestion and comment over the whole work thank you and God may bless you.

My final deepest gratitude directly goes towards Addis Ababa University for providing the necessary equipment's and finance for the successful accomplishment of this final manuscript.

TABLE OF CONTENT

CHAPTER ONE: INTRODUCTION

CHAPTER TWO: REGIONAL GEOLOGIC SETTING

CHAPTER THREE: GEOLOGY AND PETROGRAPHY OF HIRNA BASALTIC ROCK

CHAPTER FOUR: WHOLE ROCK GEOCHEMISTRY

CHAPTER FIVE: DISCUSSION

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This study presents new petrography, major and trace element data from Hirna basalts, southeastern Ethiopian plateau which directly overlies the Cretaceous Upper sandstone for a maximum thickness of 540m. The study exhibit the presence of variation in geochemical distribution over the area. Major and trace element variation mostly controlled by source region heterogeneity and fractionation history of the primary magma. Generally silica saturated and undersaturated basalts have been recognized. Silica undersaturated basalts characterized by high Fe_2O_3 (17.34-17.54 wt%), and low SiO_2 (34.89-35.02 wt %) and show enrichment in highly incompatible trace elements Sr (806-1198ppm), Zr (323-422), Nb (111-142). Silica saturated basalts on the other hand exhibit SiO_2 (45.45-49.04 wt %) MgO varies between 4.55-6.16wt% and comparatively the concentration of highly incompatible trace element in silica saturated basalts are low Sr (594-72 ppm), Zr (145-171ppm), Nb (17-19ppm). The incompatible trace element ratios between the two basalts form two distinctive groups. Silica saturated basalts exhibit La/Y <1, La/Lu 65-70, La/Yb 9.5-10.61, La/Nb >1 and silica undersaturated basalts show La/Y 2.96-3.12, La/Lu 322-323, La/Yb 44-45, La/Nb <1. This incompatible trace element ratio variation and the crossing pattern on the Chondritic normalized REE (rare earth element) plot between the two groups shows source region heterogeneity. Enrichment of LREE (light rare earth elements) and depletion of HREE (heavy rare earth element) have been observed for both basalts. This signature is indicative of melting in the presence of residual garnet in the source region. The highly compatible trace element concentration of the area is very limited (Ni<45ppm and Cr<60ppm) and have low MgO/ ($MgO+Fe_2O_3$) ratio (0.26-0.33) it is a characteristics of high involved magma spectrum. The basaltic successions of the area's major and trace element data petrogenetic model suggests fractionation of Olivine, pyroxene, Fe-Ti oxide and ±plagioclase are the major factors responsible for the modification of the primary magma.

1.1.PREAMBLE

The Mid-tertiary (~30 Ma) volcanisms cover large areas of the Ethiopian plateau presently, which attain a maximum local thickness of 3000m basaltic lava flows and apparently fed from fissure rather than central vent volcanism, are referred to as continental flood basalt volcanisms. The extensive Ethiopian continental flood basalt province which resulted from mantel plume-head activity associated with the opening of the Red Sea and Gulf of Aden at the Afro Arabian triple junction (Mark et al., 2003), is one of the fewest and youngest igneous provinces in the world and the best examples in which to examine the role of mantle plume, lithospheric mantle and crustal contribution to flood basalts genesis (Conticelli et al., 1999 and Gorge and Rogers, 2002).

Petrogenetic study over different areas of the Ethiopian plateau province reveals the existence of significant chemical diversity within individual volcanic area. Geochemical and petrologic study indicates that the nature and source rock characteristics of the magma, the extent to which the magma have interacted with rock of the continental crust, degree of partial melting and degree of fractional crystallization are the major process which involved in the chemical diversification of the single volcanic province (Pik et al., 1998, 1999; Kiieffer et al., 2004; Beccaluva et al., 2009; Kabeto, 2010).

This study focuses on the petrogenesis of continental flood basalts from Hirna area, southeastern Ethiopia plateau. Depending on field observation, petrography, major and trace element data the geology and petrogenesis of the Hirna area southeastern Ethiopia floods basalts province have been constructed.

1.2. REVIEW OF PREVIOUS GEOLOGICAL WORK

Different study around the world on continental flood basalt confirms significant difference in their major and trace element composition with those of basalts erupted through oceanic lithospheres (MORB and OIB). In general those continental flood basalts (CFB) characterized by low TiO_2, CaO/Al_2O_3, and Fe_2O_3 and relatively high SiO_2 (Simon and Chris, 1995; Piccirillo et al., 1989; Miranda et al., 1997 and Ewart et al., 1998) and this compositional variation have been attributed to difference in their upper mantle source and/or to crustal contamination (Gibson et al., 1995).

For continental flood basalt (CFB) provinces around the world such as the Parana, Etendeka, Karoo Ferrar and Deccan their generation has a relationship with mantle plumes has been widely hypothesized (Hawkesworth et al., 1986, 1988; Macdougall, 1988; Piccirillo and Melfi, 1988; Melluso et al., 1995 and Peate, 1997).

Many studies reveals that mantle plume have been widely invoked in the genesis of continental flood basalts but there actual role remains controversial; dose the plume trigger melting of the lithosphere by supplying heat and/or is the main source of the magma?(Richards et al., 1989; White and McKenzie, 1989; Campbell and Griffiths, 1990).

Chemical variation of basaltic lavas in continental settings is essentially controlled by a number of parameters that include mantle temperature, lithospheric thickness (hence degree of partial melting), source composition, and certain shallow level processes such as crustal contamination and crystal fractionation (McKenzie and Bickle, 1988).

Generally for the geochemical variation of single province three widely advocated hypotheses have been used (i) spatially variable partial melting within upwelling convicting mantle plume (Gibson et al., 1995, Cambell and Griffiths, 1990), followed by variable extent of crustal contamination (Foder, 1987). (ii) Wet melting of laterally heterogeneous sub-continental lithospheric mantle by heat supplied from underlying mantle plume (Gallagher and Hawkesworth, 1992). (iii) Mixing of picritic oceanic island basalt (OIB) type melt derived from a mantle plume with mafic ultrapotassic melts as they rise through the sub-continental lithospheric mantle (SCLM) (Ellam and Cox, 1991).

When Continental flood basalts compared at (8% MgO) with oceanic basalts trends the displacement of many CFB to lower Na_2O, Fe_2O_3 Total, TiO_2 and CaO/Al_2O_3 but higher SiO_2 at similar Mg# (100*Mg/Mg + Fe_{total}) is not readily explicable by crustal contamination rather it is the effect of source composition and/or the effect of melting processes (Simon and Chris, 1995).

In general many of the continental flood basalts have isotope and trace element signature that is differ from those of oceanic basalts derived directly from the convicting upper mantle. While some workers have mentioned that this difference can all be attributed to crustal contamination (E.g. Arndt et al., 1993). Several studies conclude that the effect of crustal contamination can be calculated and that the residual signature reflects difference between the magma source region in continental and oceanic areas (Simon and Chris, 1995).

The Ethiopian Traps occur near the triple junction of the Red Sea, Gulf of Aden and east African rifts and are associated with the Afar hotspot. Most of the province lies over the African plate **(**Poornachandra et al., 2003). Conventional K-Ar ages of basalts, rhyolites and ignimbrites from the plateau north of Addis Ababa range from 14 - 40 Ma (Merla et al., 1979 and Poornachandra et al., 2003). Berhe et al. (1987) noticed prolonged stages of volcanism between 21 and 50 Ma, whereas Ebinger et al. (1993) and Poornachandra et al. (2003) have proposed a main phase of volcanic activity between 35 - 17.5 Ma ago, in the southern part of the Ethiopian rift. Hofmann et al. (1997) and Poornachandra et al. (2003) recently reported a 40Ar/39Ar age of 30 Ma and suggested that the volcanic activity lasted for a period of 1 Ma or less.

The Ethiopian volcanic plateau is not a thick, monotonous, rapidly erupted pile of un-deformed, flat-lying tholeiitic basalts. Instead, it consists of a number of volcanic centers with different magmatic character and with a large range of ages (Kieffer et al., 2004).

Pik et al. (1998; 1999) have classified the north-western Ethiopian flood basalts into three distinct geochemical groups based on trace element and Ti concentrations: low-Ti basalts (LT), high-Ti1 (HT1) basalts and high-Ti2 (HT2) basalts. And they observed a suite of ‘low-Ti’ (LT) basalts restricted to the northwestern part of the province HT1 (High Titanium one) found to the east of the province and HT2 (High Titanium two) found to the flank of the rift margin. Generally Beccaluva et al. (2009) concluded that the Early Oligocene northern Ethiopia and Yemen volcanic province provides an important natural laboratory as it comprises the entire range of CFB magmas from Low-Ti to High-Ti. Very High-Ti basalts and picrites and erupted in a well-defined space and time interval, and overlain by younger alkaline basalts with peridotite xenolites, which provide direct evidence of the nature of the mantle section beneath the plateau.

The north Ethiopian plateau basalts are overlain by huge shield volcanoes mainly composed of alkaline lavas which makes the Ethiopian flood basalts distinctive from the other world’s greatest continental flood basalt areas (E.g. Mt. Choke and Gugugftu, 22Ma; Mt. Guna, 10-7 Ma) (Kieffer et al., 2004). On the eastern margin of the northern Ethiopian plateau, neighboring the Afar escarpment, rhyolitic volcanic rocks characterizing the upper part of the sequence has been interpreted as the differentiated products of basaltic magmas that mark the start of continental rifting (Ayalew et al., 2006).

A work by Kabeto (2010) around Michew area identifies that the Low TiO_2 basalts are characterized by relatively flat REE patterns and lower Ti and incompatible trace element concentrations assumed to be derived from depleted mantle.

And another research that conducted in the southwestern parts of the plateau by Davies et al. (2003) reveal that The LT basalts, which occupy the northwest part of the plateau, show consistently low TiO_2 contents and considerable heterogeneity in their trace element geochemistry. Marked troughs for Th and Ta/Nb, and variable LREE enrichment may suggest that they have undergone extensive lithospheric contamination, and that they are derived from a LREE depleted garnet free source.

According to George and Rogers (2002) the southern Ethiopia flood basalts classified into two eruptive episodes; the pre-rift Amaro and Gamo transitional thoiites (45-35 million years) and followed by the syn-extensional Getera-Keli alkali basalts (19-11 million years) which shows distinctive features in both trace element and isotope ratio. Amaro/Gamo lava shows high Zr/Nb ratio than the Getra-Kele lava whereas the 206Pb/204Pb ratio is higher in Getra-Kele lava and this distinctive variations of the two eruptive phases in the chemistry of the rock is due to the difference in source region. George and Rogers (2002) concluded that the Eocene Amaro and Gamo basalts of southern Ethiopia are products of mantle plume. And the geochemical data confirm that the plume source region was distinct from that feeding the more voluminous Ethiopian-Yemen CFBs further north, and probably associated with the mantle plume situated beneath the east African plateau. Additionally they distinguish the source region of the Amaro/Gamo phase is a mantle plume and the enriched continental mantle lithosphere is the source region of the Getra-Kele phase. On the same paper George and Rogers (2002) explain that isotope and trace element variation with in the Amaro/Gamo lava reflects poly baric fractional crystallization and limited crustal contamination.

According to Berhe et al. (1987), the K-Ar age determination indicates that the oldest rock in the southeastern Ethiopia record 30.0±4.5 Ma in the Lower Stratoid Basalt and the youngest rock record 5.3±1 Ma in the Reira Basalt.

Various regional study over Ethiopian plateau confirm that the southeastern Ethiopian flood basalt province is less voluminous than the northwestern Ethiopian plateau basalt and because of this less attention have been given for the southeastern Ethiopian plateau flood basalts (Zanettin et al., 1980). But in the southeastern plateau approximately 600m basaltic lava succession of pyroxene and plagioclase-aphyric basalt has been recorded in the Reira basaltic lava succession (Berhe et al., 1987). This much volcanic succession can provide a well-defined geochemical data set for the ongoing worldwide petrogenetic study especially for the younger Ethiopian continental flood basalt province. To date in the southeastern Ethiopian plateau continental flood basaltic province detail petrogenetic study have not been conducted in a well-organized manner so, this research intend to come up with a new geochemical data set for Hirna area southeastern Ethiopian plateau basalts.

1.3. OBJECTIVES OF THE STUDY

1.3.1. General objective

The General objective of this research is based on field observation, petrography, major element and available trace element data to study the petrogenesis of the continental flood basalt from Hirna area in south eastern Ethiopian plateau.

1.3.2. Specific objective

The specific objective of the study includes:

- To construct the detail stratigraphic sequence of the flood basalt flows in the study area
- To construct the Geological map of the area at the scale of 1:25,000
- To study the geochemical characteristics of the rocks in the study area
- To study the petrology of the flood basalt in the study area

1.4. METHODOLOGIES

In order to achieve the general and specific objectives of this research the following methodology were followed.

1.4.1. Secondary data collection and review of previous relevant works

Before the field work have been conducted the following activity were done.

- Different previous relevant works on Geology, petrology, Geochemistry, volcanology and tectonic settings that conducted around the study area reviewed from published or unpublished reports, maps, journals, scientific publications, web sites, etc. Books, journals, scientific publications and web sites that conducted in different part of the world specifically that important for this study were reviewed.

- Before the field works were conducted the study area is delineated using Arc GIS software from topographic map of Hirna sheet (0941c3, Edition 1 EMA 1999) 1:50,000 scale.
- Available information’s like temperature, rain fall data, forest coverage and soil coverage, accessibility of the area, topographic set up, and lithological set up of the study area were collected from topographic map, Google Earth Aerial photo and from different existing data.

1.4.2. Field work

The field work was conducted from December 18/2012 to December 29/2012 for a total of 11 Days. At time of field work the traverse sections were selected systematically in order to encounter different lava flows that believed to be appropriate for sampling techniques. Before the actual sample collections were conducted, a total of two days spent to select the appropriate traverse sections and two traverse sections were selected. Along traverse two which is towards Awrasko ridge a total of 540m thick lava flows and 384m thick basaltic lava flows in the first section towards Muleta ridge were recorded which directly overlie on the Cretaceous Upper sand stones unit.

During field investigation an attempt was made to describe the rock and lava flows in detail at the out crop scale. And a total of 18 samples were collected that represents the encountered lithology for both Geochemical and thin-section analysis. Wherever possible an attempt was made to get fresh and representative samples from each basaltic lava type by avoiding the upper and weathered parts of the sampling station. At time of sampling each samples property (color, texture and its relation with the flow successions) were described. Each sampling stations and lithological contacts GPS readings were recorded and photos of different lithological unites were taken during field investigations. Attempts were made to construct detail lithological unit logging during the field work and the closest thickness of each basaltic type were estimated. The sample numbers have a prefix of “**HB**” which stands for **Hirna Basalt**. For example “**HB1A1**” which stands for **Hirna Basalt** along **traverse “1**” from lower parts of the basalt**,** sample number **“1”**

1.4.3. Petrography and Geochemical Data Analysis

After the field work have been completed successfully a total of 12 least altered samples among from 18 samples were selected based on its degree of weathering and sent to USA Michigan State University geological laboratory for Major and Trace element geochemical analysis. 12 samples were selected for thin-sections analysis which believed to be the representative of all basaltic type and its thin-sections preparation were conducted in the Ethiopian Geological survey and the analysis for the thin-sections conducted in the laboratory of Addis Ababa University. Detail geochemical analysis methods for both Major and trace element were described in chapter 4.

- By compiling all information collected during field survey (lithological contact and sampling station GPS readings) a geologic map of the area were prepared with Arc-GIS
- And finally by integrating all information collected in the field with thin-section and geochemical data the petrogenesis of the rock in the study area have been discussed.

1.5. LIMITATIONS OF THE STUDY

The southeastern Ethiopian volcanic province covers a wider areal coverage in that to have a well-organized geochemical data set it needs a large number of data from a well exposed complete out crop section, however because of limited financial and time constraints this work has been concluded over the limited Hirna area.

This paper final output is concluded based on petrography, major and trace element data. To have a well-confined petrogenetic history of the area it needs to conduct isotopic data interpretation.

1.5.LOCATION AND ACCESSIBILITY OF THE STUDY AREA

The study area Hirna is located in the south eastern Ethiopian plateau, which is about 370 km away from Addis Ababa town (the capital city of Ethiopia) in Tulo woreda which is in the Oromia region part of the West Hararghe administrative Zone. The study area is bounded by 9°

9’00’’ to 9°11’30’’N latitude and 41°2’00’’E to 41°4’30’’E longitude is part of Hirna sheet (0941c3, Edition 1 EMA 1999) at 1:50,000 scale. It is bordered on the south by Mesela, on the west by Chiro, on the north by Doba, and on the east by the East Hararghe Zone. The nearest town for the study area is Hirna town about 7 km to the southeast along the main asphalt road which passes Addis Ababa to Deri Dewa.

1.6.1 Physiography, climate and vegetation

Topographically the district is characterized by diversified landforms, i.e., highlands, lowlands and valleys. Attitudinally, it stretches between 1800m and 2500 m.a.s.al. Hirna, Burka, Dabaso and Burka Recha rivers are flowing through the district.

Climatically, the district is classified into woinadega zones. Man-made forests are available in the district. Kara Farsho and Gara Nugus are reserved forest areas. In these reserved forest areas and other parts of the district, Menelik bushbuck, leopard, warthog and birds of different species are available.

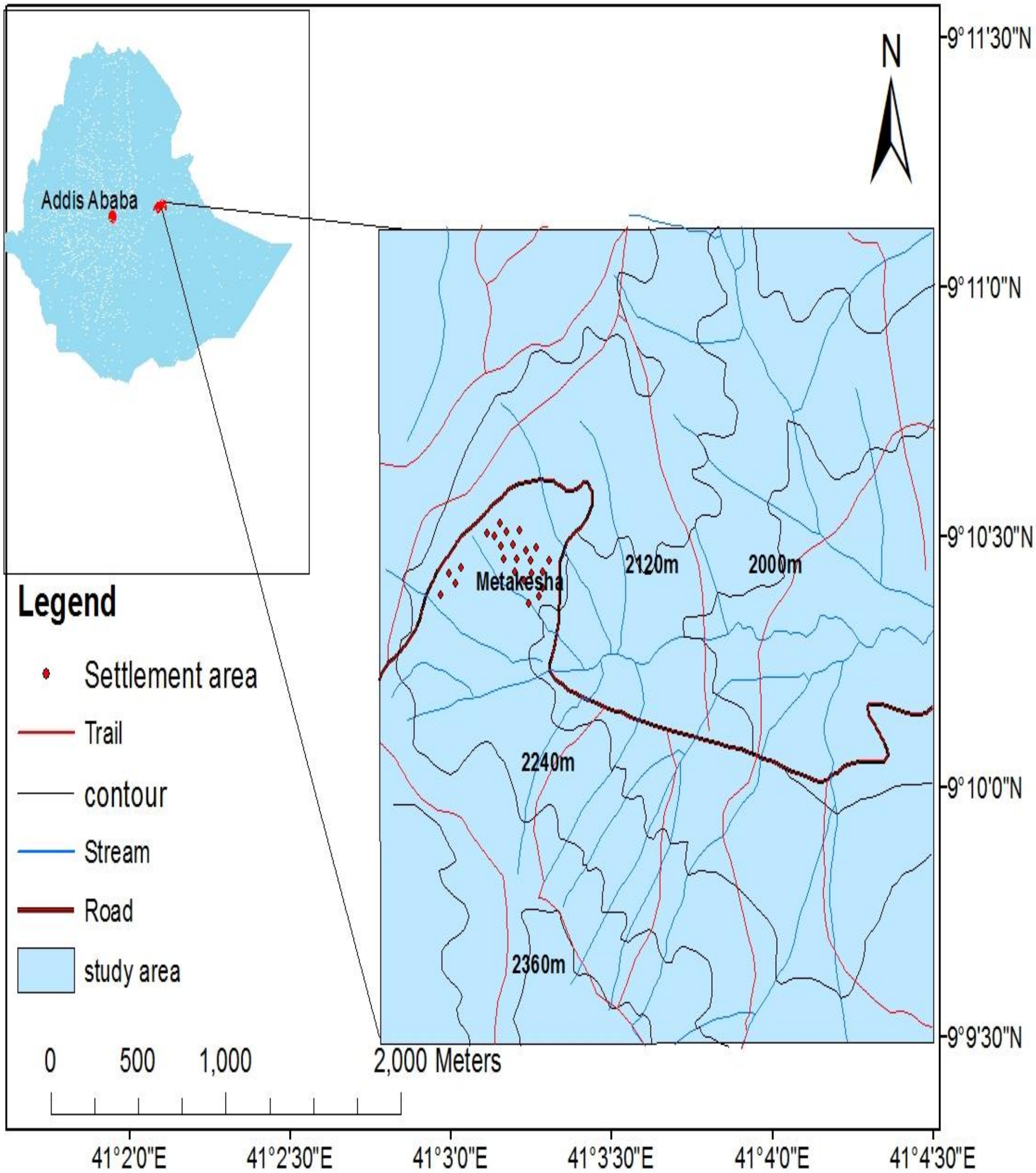


Fig.1.1: Location map of the study area

2.1. INTRODUCTION

The existing geological map of Ethiopia show that the country is covered by 18% Precambrian basement rock, 25% Mesozoic sedimentary rock and 56% Cenozoic volcanic and sediments (Solomon, 2000).

Precambrian basement exposures are found in areas which are not affected by intensive Cenozoic volcanism, rifting process and the place where Mesozoic cover has been eroded away. The Precambrian rocks exposed in four major areas of the country in north (Tigray region); west (Gojam,Wollega, Illibabore and Kefa); east (Harerghe region) and south (Sidamo and Bale). In the Precambrian basement two lithostratigraphic assemblages have been recognized these are gneissic terrains found mostly in the southwestern sector of the country and metamorphosed volcano sedimentary belt mostly dominate in the northern sector of the country.

According to Kazmin (1972), the Ethiopian late Paleozoic to Mesozoic sedimentary Formation was deposited in related to transgression-regression cycle. Mengesha et al. (1996) noticed the first transgression started in the Late Triassic to early Jurassic period and forms the Ogaden region in the southeast towards northwest and reached its maximum extent in Kimeridgian. During this time Adigrat Formation, Hamanilei Formation and Abay Formation were deposited. Regression of the sea started towards the end of Jurassic depositing Lagoonal Facies of Agula Formation. The lower most Cretaceous is represented by the Korahe Formation in the Ogaden region and marks the first regression event. The second regression transgression event took place in Aptian and Turonian depositing Mustahil Formation, Ferefer Formation and Belet Formation. In the late Cretaceous the second regression event took place and depositing continental sediments.

The mid tertiary (~ 30 Ma) Ethiopian continental flood basalt form part of the large Afro-Arabian igneous province, which is related to the Afar plume and Red sea-Gulf of Aden Ethiopian Rift triple junction (Kabeto, 2010).

Mengesha et al. (1996), classifies the Cenozoic volcanic and sedimentary cover into the following units Ashangi Formation, Jima volcanics, Aiba Basalts, Arisi and Bale Basalts, Mekonnen Basalts, Alajae Formations, Tarmaber Gussan and Tarmabar Megezez Formations, Adewa Formation, Teletel and Surma Basalts, Mabla and Arba Guracha Formations, Dalaha Formations, Tulu Wollel Trachyte, Afar series, Nazret series, Danakil Group (Red sea), Chilalo Formation and Mursi and Bofa Basalts.

Ethiopian volcanic province is composed of a Tertiary Basaltic pile, with thickness varying from 700 to 3000m. It covers an area several hundred kilometers across the plateau on either side of the main Ethiopian rift Afar depression (Berhe etal., 1987). Distinctive petrological features of the Ethiopian plateau are 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 (http://sp.lyellcollection.org/ at Addis Ababa University on October 4, 2012).

The Ethiopian flood basalts were erupted in three major stages (Berhe etal., 1987).

Stage1. This is mainly older than 40 Ma

Stage2. 34 to 30 Ma for NW Ethiopia and 40 to 30 Ma for SW.

Stage3. Spans 30 to 26 Ma in NW Ethiopia and 30 to 21 Ma in SW Ethiopia and both are marked by incoming of silicic volcanism.

2.2.THE CENOZOIC ETHIOPIAN PLATEAU VOLCANIC PROVINCE

Mantle plume played a major role in plate tectonic process leading to the breakup of super continents (Poornachandra et al., 2003). The arrival of plume head at the bases of the lithosphere results in the uplift, eruption of continental flood basalt and sometimes continental breakups (Sleep, 1990; 1995 and Poornachandra et al., 2003). In different parts of the world several million cubic kilometer (10^6*km^3) of lava was poured out in a very short period of time over large area during continental flood basalt activity (Poornachndra et al., 2003).

Ethiopian plateau form the largest part of extensive continental flood basalt province which resulted from mantel plume-head activity associated with the opening of the Red Sea and Gulf of Aden at the Afro Arabian triple junction (Mark et al., 2003). The Tertiary volcanism in Ethiopia has persisted for at least 45 million years (Gorge and Rogers, 2002).

Mohr (1962), divide the Cenozoic volcanic rock of Ethiopia in to Trap and Aden series. Trap series used to refer the whole pile of the Tertiary flood basalt sequence with intercalations of felsic lava and pyroclastic rock which forms southwestern and southeastern plateau. The term Aden series used for post rift (middle Miocene to quaternary) volcanic rock of the main Ethiopian rift, Afar Depression and some part of Ethiopian plateau.

The flood basalt and other subordinate volcanism in Ethiopia during Tertiary time has built up a sub areal volcanic pile having a thickness range from 500-1500m and locally attain a thickness of 3000m (Mohr and Zanettin, 1988). The Ethiopian continental flood basalt has an estimated total areal coverage of 600,000km^2 and not less than 750,000km^2 before erosion (Mohr, 1963; Mohr and Zanettin, 1988). And the preserved volume of the Ethiopian volcanic has been estimated to be 350,00km^3 (Baker et al., 1972). Tertiary flood basalt and their intercalated silicic volcanic now uplifted on the western and eastern (Harar) plateau of Ethiopia and cover an estimated volume of about 300,000km^3**.**

2.2.1. Northwestern Ethiopian plateau volcanic province

In western Ethiopia (Wollega and Ilbabor area) the Tertiary volcanism covers more than one third of the Wollega Ilbabor area. Three section where measured which show five volcanic Formations; from the base upward (Berhe et al., 1987).

- The Geba basalt; which form a 100m thick of aphyric basalt which thins westward. Generally the Geba basalt contains olivine phenocrysts in a holocrystalline, fine grained groundmass of Augite plagioclase, olivine and opaque's.
- The lower aphyric basalt; is a succession of aphyric hawaiites forming a thin less than 200m veneer on the basement complex.

- The lower trachytes; form a 50m thick unit overlying the lower aphyric basalt. It is associated with pyroclastic and minor basaltic unit.
- The upper basalt; are separate from the underlying unit by thin succession of lacustrine sediments and form over 300m of aphyric basalt, hawaiite and mugearite intercalated with porphyritic plagioclase, olivine and pyroxene basalt.
- Tulu Wollel basalt; contains mega crysts of plagioclase and there is minor trachytic flow. The youngest volcanic rocks in the area are the shield forming trachyte lava flows of Tulu Wollel and Sayi.

The earliest volcanism in southwestern Ethiopia the Akobo basalt gives an age of 45.4 Ma (Berhe et al., 1987).

Comprehensive major, trace element, and Sr-Nd-Pb-Hf isotopic study of Mid-Tertiary volcanic sequences from the northwestern flood basalt province in Ethiopia around Michew area show the volcanic rocks range in composition from basanites, alkalinebasalts, ankaramites transitional and tholeiitic basalts and picrites and forms 6 volcanic successions (Kabeto, 2010).

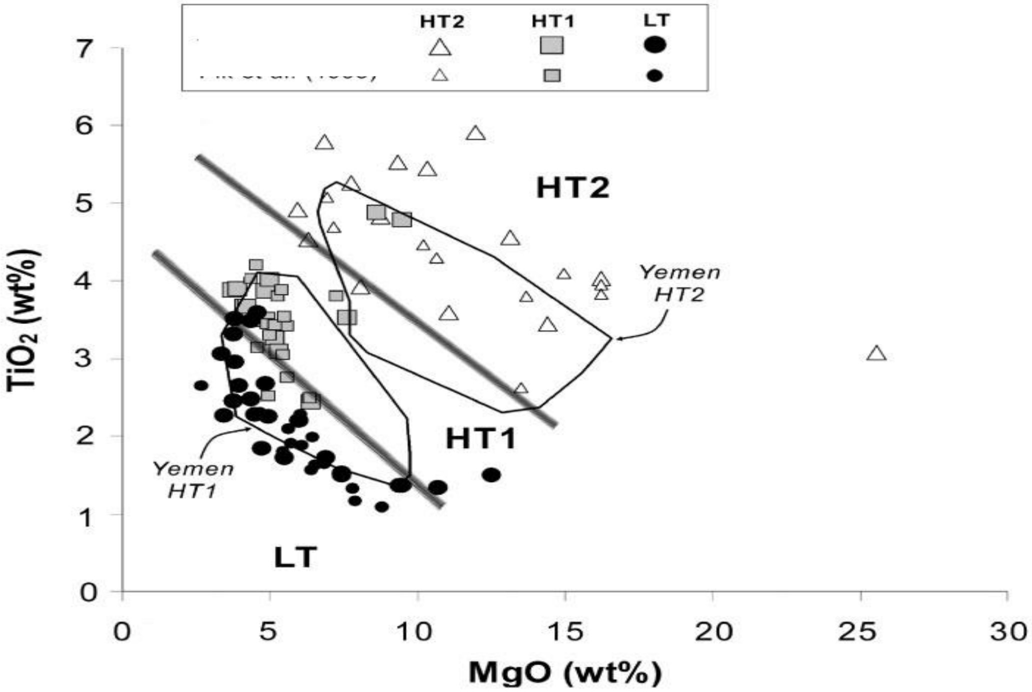


Fig.2.1: TiO_2(wt%) vs MgO (wt %) plot for the northwestern Ethiopian CFBs after Beccaluva et al. (2009) data obtained from study on Continental Flood Basalts and Mantle Plumes: a Case Study of the northern Ethiopian Plateau. LT, Low-Ti tholeiites; HT1, High-Ti tholeiites; HT2, very High-Ti transitional basalts and picrites.

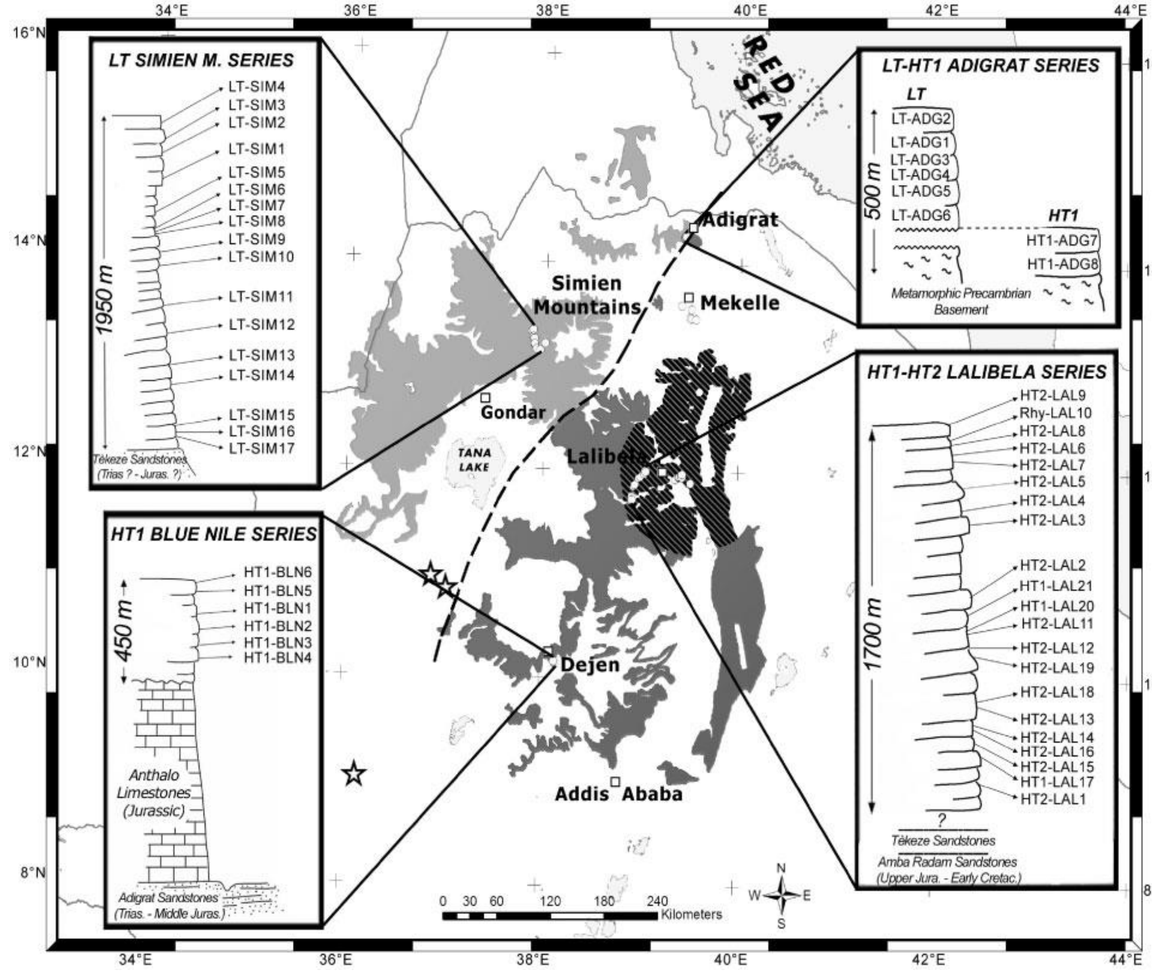


Fig.2.2: Generalized cross-sections and maps of Oligocene CFBs within the northern Ethiopian plateau showing the distribution of the three types of basalt from four selected sections LT, HT1 and HT2 basalts (Beccaluva et al. 2009).

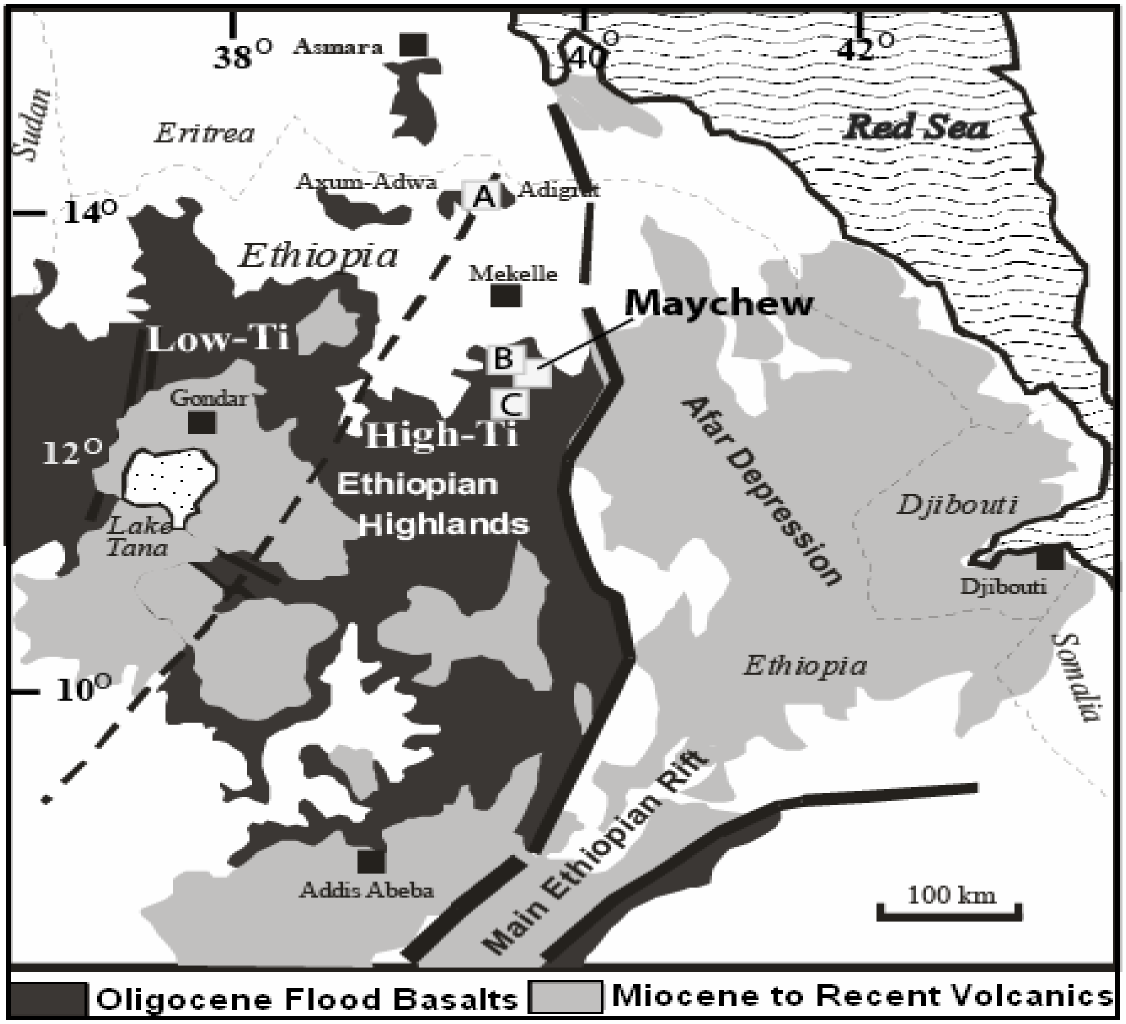


Fig.2.3: Location map of NW Ethiopian Plateau, Afar Rift and Main Ethiopian Rift from Kabeto (2010). The approximate broken line separates the low-Ti and High-Ti flood basalt province of Pik et al. (1998).

2.2.2. Southeastern Ethiopian plateau volcanic province

Except some petrologic, geochronology and regional geologic study, detail petrogenetic studies are lack in the southeastern Ethiopian plateau volcanic province particularly in the area of the present study.

Within the southern Harar plateau the regionally extensive late Oligocene to Miocene flood basalts are only a few hundred Meters thick and the thickness increase towards the rift valley whose major evolution began in mid-Miocene time (Mohr and Zanettin, 1988).

Berhe et al. (1987) classified the Bale (southeastern Ethiopia) Cenozoic volcanics in to four major groups: the Lower Stratoid Basalts, the Reira Basalts, the Dodola and Aroresa Trachyte and the Senta Basalt and Batu Trachytes. These early flood basalts are overlain in the eastern Btu Mountains around 150 km east of the rift valley by about 200m of localized rhyolitic ignimbrites (Berhe et al., 1987; Mohr and Zanettin, 1988). These silicic rock are significantly older than the 13.5-11 Ma silicic volcanism of the northern of Harar plateau which latter appear to find no equivalent in the south. Mohr and Zanettin (1988) determine as much as 600m upper Miocene flood basalts (Reira Basalts 15-5.3Ma) cover the Batu Mountains region where they rest directly on the older flood basalts. In contrast with this older aphyric basalts the younger one include both plagioclase and pyroxene phyric type and the flow are frequently scoriaceous and separated by paleosol (Berhe et al., 1987; Mohr and Zanettin, 1988).

Mohr and Zanitten (1988), confirms the northern rim of the Harar plateau Formation comprises transitional basalt with theoliitic tendency, similar to Aiba and Alaji Formation basalts of the northern Ethiopia plateau. The northeastern Harar plateau basalts are usually aphyric but further west porphyritic flow become more common, phenocrysts in this lava are labradorites, less common augite and rare FO85-80 olivine; micro phenocrysts of titaniferous magnetite occur. Subordinate more alkaline transitional basalts are characterized by potassic oligoclase in the groundmass and carry rare titanaugite phenocrysts.

Berhe, et al. (1987), concluded that the Cenozoic volcanisms of the Bale (southeastern Ethiopia) area occur as four major groups forming a succession of about 2000-2300m thick basalt and trachytes.

- Lower stratoid basalt; 10-150m thick of weathered ahpyric basalt which directly rest on the protrozoic basement
- The Reira basalt; which form 600m succession of ahpyric, pyroxene and plagioclase-aphyric basalt. The Reira basalt is unconformably overlain by the Aroresa trachytes and Dodola ignimbrites which is restricted to the North West.
- The Dodola and Aroresa trachytes; the Dodola ignimbrites primarily composed of rhyolitc ignimbrites trachytes and ashflow tuffs.

- And the Senta basalt and Batu trachytes; which form the second highest volcanic edifices in Ethiopia. This volcanic were erupted from different centers and display rapid lateral thickness variations. The age of the southeastern Ethiopia flood basalt range from 30 to 22 Ma (Berhe et al., 1987). The oldest flood basalt in southeastern Ethiopia is about 30 Ma (Berhe et al., 1987).

Rock type and name of formation	***Age ma***
Hawiite, lower Aphyric basalt	10.6±1.6
Hawiite, lower Aphyric basalt	11.22±.2
Aphyric basalt, Saneta basalt	2.1 0±.5
Olivine basalt, Riera basalt	5.3±1
Porphyritic Olivine basalt, lower stratoid basalt	23.5±4.5
Micro-porphyritic feldspar basalt lower stratoid basalt	22.0±3.5

Table.2.1 K-Ar age determination of volcanic rocks from southeastern Ethiopian plateau after the work of Berhe et al. (1987).

CHAPTER THREE GEOLOGY AND PETROGRAPHY OF HIRNA BASALTS

3.1. INTRODUCTION

A detail geochemical and petrological examination of flood basalt of Hirna area, southeastern Ethiopian plateau has not been attempted prior to this work. During regional scale study as part of the construction of the geological map of Ethiopia at the scale of 1:2,000,000 the Hirna flood basalts are considered part of the Tertiary Ethiopian continental flood basalts.

On the geological map of Dire Dawa area at the scale of 1:250,000 geology of Hirna area basalts belonged in to Alaji basalts which are transitional in composition. In general Alaji Formation mainly consists of aphyric flood basalts associated with rhyolite and subordinate trachyte. According to Mangesha et al. (1996) Alaji Formation makes up the bulk of volcanic succession on the northwestern and southeastern Ethiopian plateaus. On the northwestern plateau Alaji Formation rests conformably on Aiba basalts but in most outcrops in southeastern plateau it directly overlies on Mesozoic sediments as do Hirna basalts. The Alaji Formation contains basalts that are transitional to tholeiitic in nature and increase in alkalinity is observed in younger member of the Formation.

The studied Hirna area flood basalts attain a maximum thickness of 540m which is directly overlain on the Cretaceous Upper sandstone unit. The aim of this thesis is to identify processes that are responsible for the chemical diversification and to study geochemical characteristics of Hirna flood basalts.

3.1. STRATIGRAPHIC SEQUENCES, SAMPLING TECHNIQUES AND PETROGRAPHIC DESCRIPTION.

The basalt samples obtained for this study are from two selected traverse sections. The first section is towards Muleta ridge has a total of 384m thick basaltic lava flows. In the second section towards Awrasko ridge 540m of basaltic lava flows were mapped. Wherever possible, samples were taken from the appropriate position of most lava flows to obtain least altered basalt. A total of 18 samples were collected from the two selected sections and from among these 12 least altered samples were prepared for major and trace element analysis. 12 possible representative samples for the whole flow succession were prepared for thin-section analysis.

The geology of Hirna area, which is covered in this work, has shown no much variety of basaltic lava. Flood basalts of the area exposed between 1919m-2462 m a. s. l for a total thickness varies 384-540m along selected sections. Based on field observation and petrographic study basaltic flows of the area represented Aphyric to sub-porphyritic textural nature. The impact of weathering on each basaltic type is profound and it is very difficult to get a fresh samples. The lower parts of lava sequence characterized by sub-porphyritic textural nature display gentle undulating morphological topography which directly overlie on Cretaceous Upper sandstone unit. Petrographically lower parts of the lava flows are sub-porphyritic texture and much of the groundmass is dominated by brownish glassy material. Next to the sup-porphyritic basaltic flows between 2037-2166m a .s .l, predominantly aphyric textural basaltic type were exposed and the groundmass phase in this flows are dominantly a matrix of opaque mineral, olivine and trace amount of pyroxene. Whereas upper parts of the basaltic lava succession of the area comprise aphyric to sub-porphyritic lava flows that form cliff along the sections.

Modal proportion of plagioclase is decreasing from sub-porphyritic basalt to aphyric but olivine proportion is increase. Similarly, the proportion of glassy material in the groundmass is much dominant in the sub-porphyritic basalts. Secondary filled minerals are very common in sub-porphyritic and mineral alteration is also intense this property is not extensive in aphyric basalts. Petrographic characteristics of some representative samples are summarized in Table 3.1 and 3.2 below. Most of the samples are hypocrystalline to microcrystalline, the majority samples used in this study are non vesicular and nearly aphanitic, with <25 vol. % phenocrysts of olivine, plagioclase and, less commonly, clinopyroxene in a fine-grained matrix of olivine, plagioclase, clinopyroxene and opaque oxides. Phenocrysts mainly consist of dominant plagioclase and rare olivine in almost all basaltic type. The groundmass is locally sub-ophitic with plagioclase laths, interstitial clinopyroxene and abundant opaque minerals; brownish interstitial glass is the dominant one on the groundmass of the sub-porphyritic lava flows. Detailed petrologic description of each basaltic types of the area is described below.

3.1.1. Sup-porphyritic basalts

This basalt exposed between (1919-2037 and 2166-2267m a. s. l) having a maximum thickness of 118m and 116m respectively along selected sections.

The petrographic characteristic of this basalt is mostly sub-porphyritic and it contains a moderate proportion of phenocrysts of plagioclase. Randomly arranged elongate crystals of plagioclase (14-15 vol %), (<4 vol %) warped around olivine crystals in the phenocrysts is dominated and it is surrounded by a film of glass, an aggregate of equate granular augite crystals and small proportion of opaque minerals. In groundmass phase abundant plagioclase with subordinate amount of augite and olivine occurs together with abundant opaque minerals. Brownish interstitial glasses and occasional occurrence of alkali feldspars dominate the groundmass phase. In the microscopic scale pale yellow altered minerals are available in this rock type and even within a single hand samples rim of olivine's are commonly replaced by (orange-brown generally iddingsitized) a complex mixture of clay minerals.

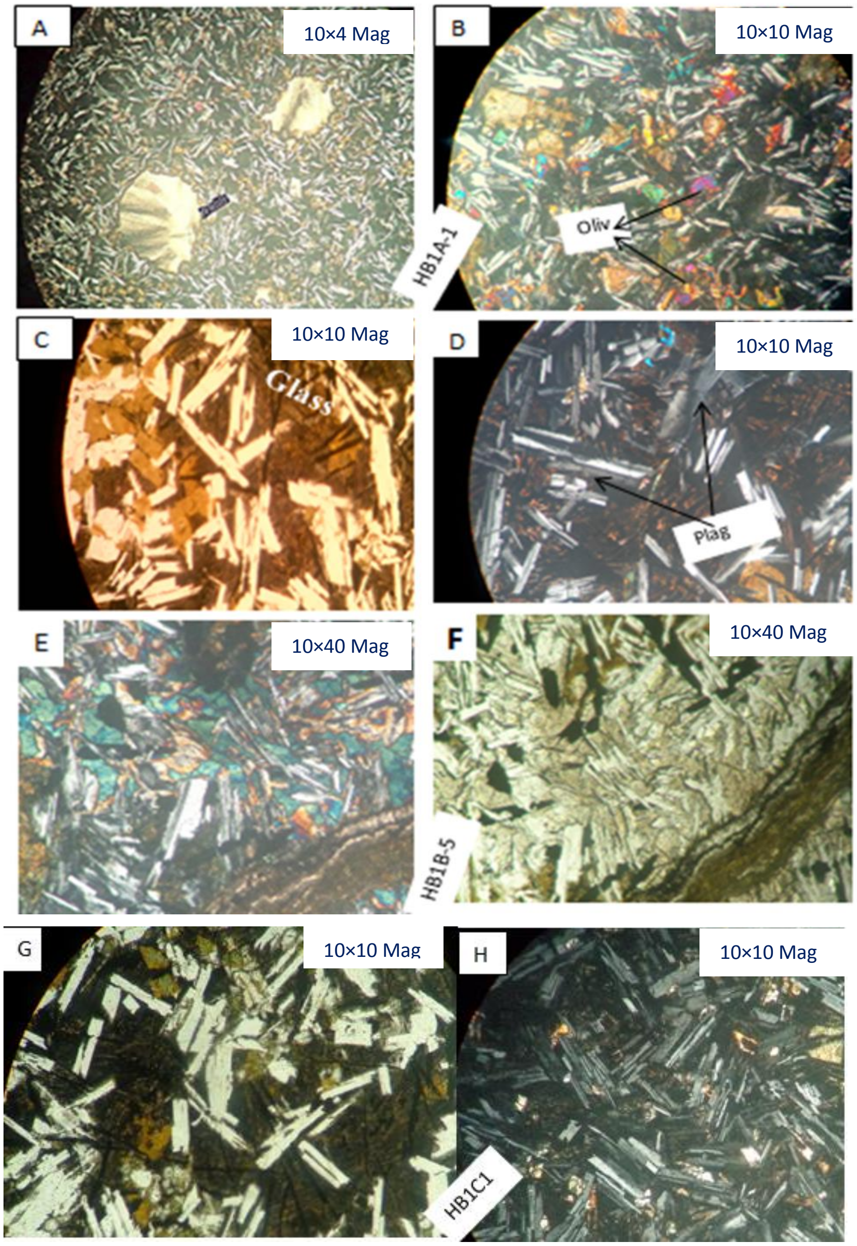


Fig.3.1: Petrography of the volcanic rocks of Hirna area showing various mineralogical and textural features. Microphotograph, (b), (d), (e) and (h) were taken under crossed polarizers, whereas (a), (c), (f) and (g) were taken under plane polarized light. (a) and (b) sub porphyritic, plagioclase rich basalts with medium - large phenocrysts of olivine and clinopyroxenes; the plagioclase are lath-like but randomly aligned of varying size. (c) and (d) plagioclase sub porphyritic basalts. Brownish color glassy material fills the interstices of other grains. (e) and (f) shows plagioclase rich opaque mineral dominated microcrystalline aphyric basalts.

3.1.2. Aphanitic basalts

This basaltic lava succession exposed between 2037-2166 and between 2256-2480m a. s. l attain a local maximum thickness of 129m and 169m respectively along the selected sections.

The rocks are rich in plagioclase towards the bottom and poorer in olivine relative to the top. Aphyric elongate crystal of plagioclase, olivine and trace proportion of clinopyroxene (augite) and large crystals of opaque minerals form the frame work of the rock. In these rock units glassy material is absent and some amount of clinopyroxene, very fine grained plagioclase crystals, opaque minerals and olivine dominate the rock unit.

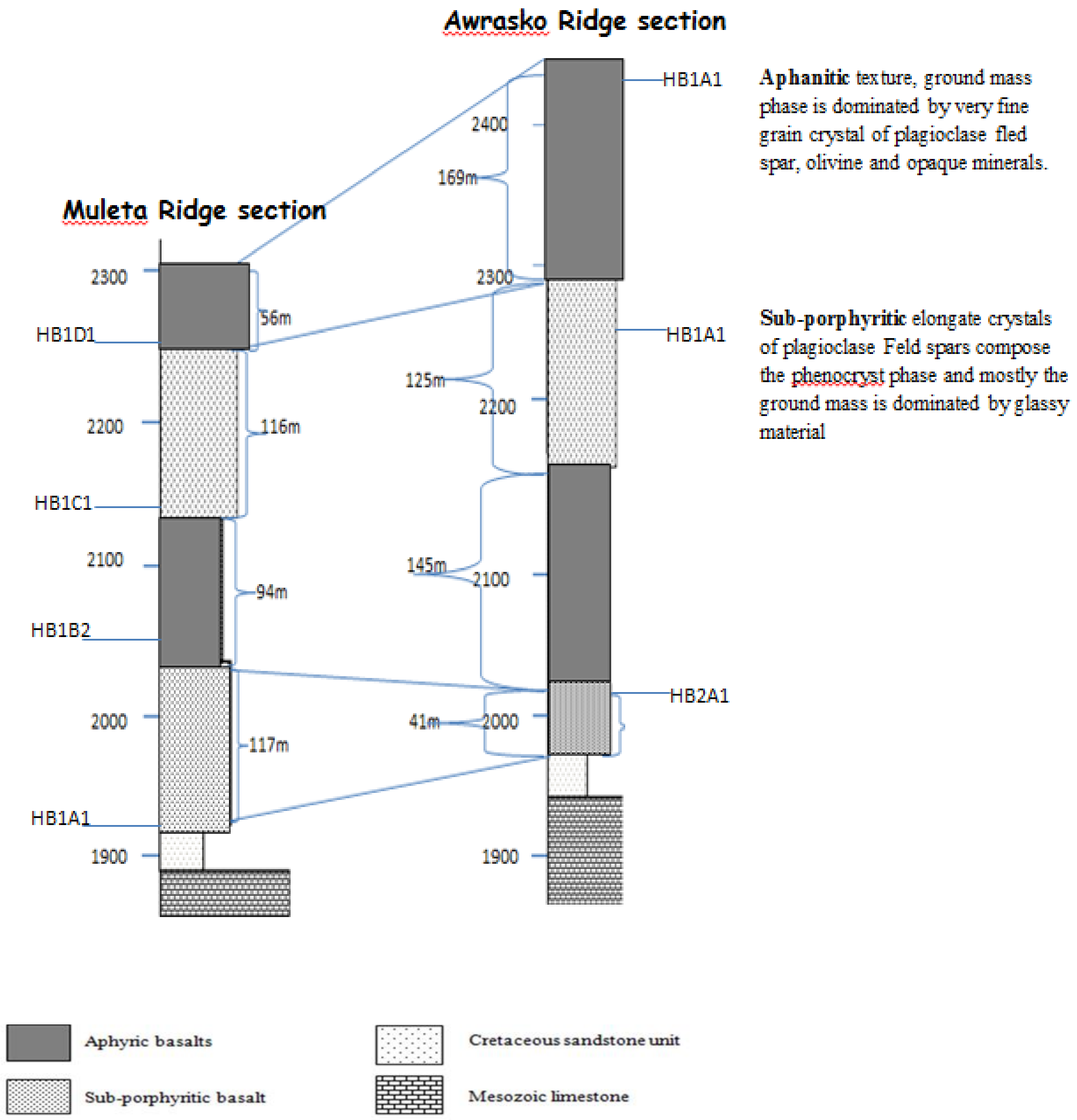
Sample no.	Rock texture	**Rock name**	**Phenocryst and microphenocryst**	**Groundmass phase**
HB1A1	Sub-porphyritic	Basalt	Pl, Ol, Opaque, Cpx	Pl, Cpx, Opaque, Gl
HB1A2	Sub-porphyritic			
HB2A1	Sub-Porphyritic	Basalt	Pl, Ol, Opaque, Cpx	Pl, Cpx, Opaque, Gl
HB1B2	Aphyric	Basalt	Pl, Ol, Cpx, opaque	Cpx, Ol, pl
HB1C1	Sub-porphyritic	Basalt	Ol, Cpx, Pl	Cpx, Pl, Opaque, Gl
HB2C2	Sub-porphyritic			
HB1D1	Aphyric	Foidite	Pl, Ol, Cpx, opaque	Gl, Pl, Opaque
HB2D1	Aphyric	Basalt		

Table.3.1 Show petrographic characteristics of representative samples of Hirna basalts which indicate the dominant phenocrysts and ground mass phases. Olv, olivine; Cpx, clinopyroxene; Pl, plagioclase; Gl, Glass. On the table some samples has been rejected which show similar petrographic characteristics with other described samples.

Sample No	Phase	Modal proportion of phenocryst phase	Petrographic summery
HB1A1	Plagioclase Olivine Clino-Pyroxene	16 vol % <3 vol% <2 vol %	Sub-porphyritic randomly arranged elongated phenocrysts of plagioclase, a very small proportion of olivine, clinopyroxene and glassy material form the frame work of this rock. The interstices of which are filled with smaller size plagioclase, wrapped around olivine, augite crystals and a large proportion of brownish interstitial glass.
HB2A1	Plagioclase Olivine Clino-pyroxene	14 vol% 2 vol% <2 vol%	Sub–porphyritic, plagioclase rich basalts with medium to coarse-grained phenocrysts of olivine and clinopyroxenes; the plagioclase are lath-like but randomly aligned, whereas the Olv and Cpx are rounded to angular of varying size. The groundmass phase is mainly composed of glassy material.
HB1A2	Plagioclase Olivine Clino-pyroxene	14 vol% 2 vol% Trace amount	Sub–porphyritic, plagioclase rich basalts within hypocrystalline groundmass. The plagioclases are lath-like but randomly aligned, whereas the Olv and Cpx are rounded to angular of varying size.
HB2B3	Plagioclase Olivine Clino-pyroxene Opaque minerals	Around 6 vol% 3 vol % Trace amount 5 vol %	Large anhedral opaque minerals elongated flat aphyric plagioclase and small proportion of olivine crystals form this rock sample.
HB1C1	Plagioclase Olivine Clino-pyroxene	15 Vol% <2 vol% Trace amount	Small elongate crystal of plagioclase is the dominant phenocryst. Unlike the other this sample lack opaque mineral and dominated by brownish interstitial glassy material.
HB2C2	Plagioclase Olivine Clino-	15 vol% <2 vol% Trace amount	Elongate and randomly arranged crystals of plagioclase are the dominant phase in the phenocrysts phase. The proportion of unaltered

	pyroxene		olivine in the phenocrysts phase is very small, and most of the altered minerals are result from olivine and most of the observed olivine crystal show altered from the rime and the core remain unaltered.
HB1D1	Plagioclase Opaque minerals Olivine Clino-pyroxene	8 vol% 8 vol% 5 vol% Trace amount	Aphyric texture of plagioclase, olivine and opaque minerals dominates and glassy material is absent and composed of very fine plagioclase and large proportion of opaque minerals.
HB2D1	Plagioclase Opaque minerals Olivine Clino-pyroxene	10 vol% 8 vol% 5 vo% Trace amount	Aphyric texture of plagioclase, olivine and opaque minerals dominate the rock. Unhedral Opaque mineral proportion is dominant throughout the sample.

Table.3.2: Petrographic description of representative samples for the whole Hirna basalts which show variation in there modal composition from both sub-porphyritic and aphanitic basalts of the area. On the table some samples has been rejected which show similar petrographic characteristics with other described samples.



Aphanitic texture, ground mass phase is dominated by very fine grain crystal of plagioclase fled spar, olivine and opaque minerals.

Sub-porphyritic elongate crystals of plagioclase Feld spars compose the phenocryst phase and mostly the ground mass is dominated by glassy material

Fig.3.2: Stratigraphic log of Hirna continental flood basalt along selected sections. Numbers on the left side shown on the vertical axis represents heights above sea level and numbers shown by arrow represents thickness of each basaltic type. The sample numbers on the section is there position on the stratigraphy of the area.

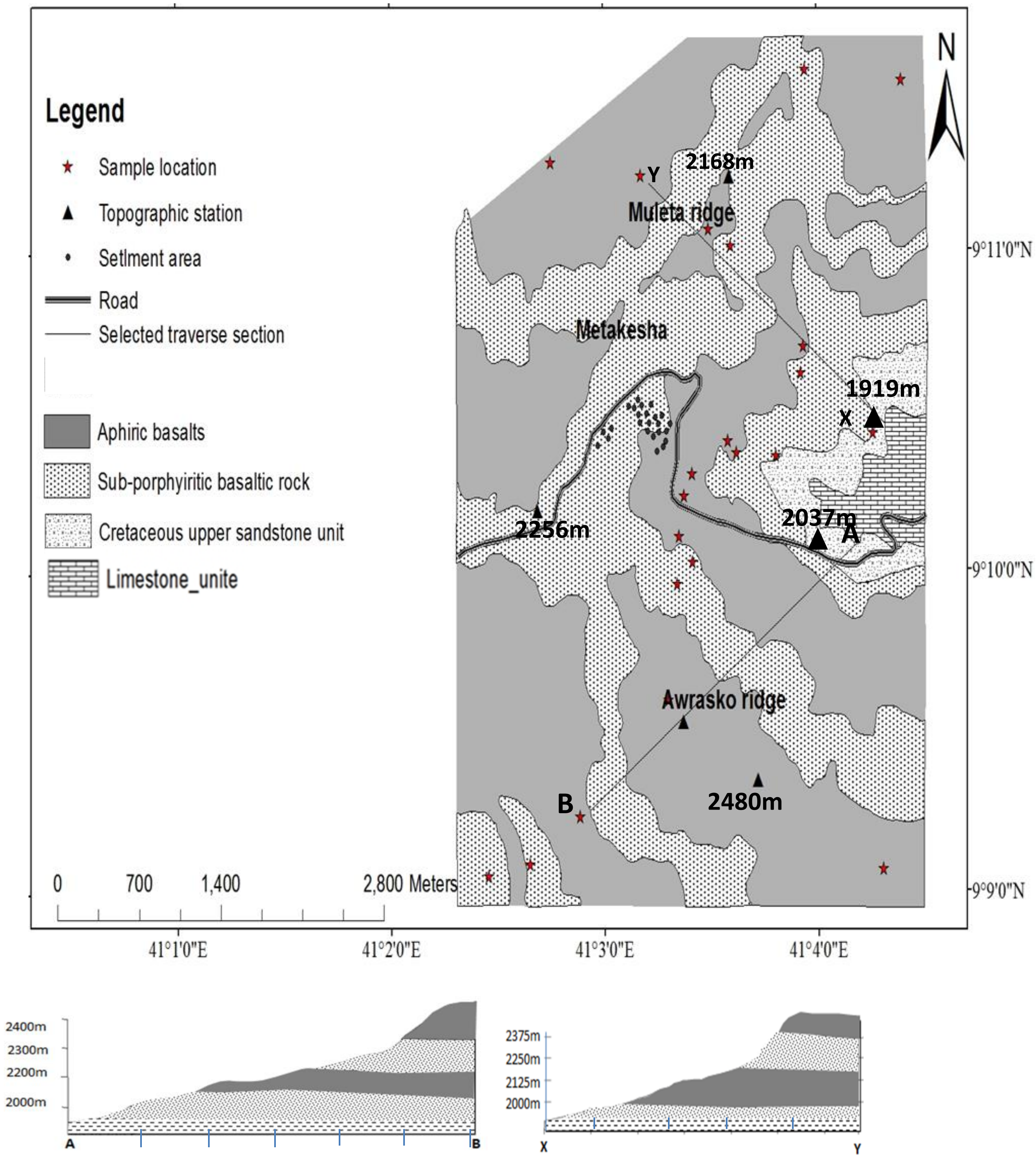


Fig.3.3: Simplified geological map and Cross sectional view of Hirna basalts from A to B and X to Y which shown in the geological map. Stars on the map show location of the samples.

4.1.ANALYTICAL METHOD

Based on their degree of alteration 12 of the least altered representative samples were sent to Michigan State University for whole rock geochemical analysis. During sample preparation for analysis samples were carefully cut to avoid all obvious signs of alteration. Major elements were analyzed by X-ray fluorescence (XRF) on powder pellets, using a wavelength-dispersive automated ARL Advant'X spectrometer. Accuracy and precision for major elements are estimated as better than 3% for Si, Ti, Fe, Ca and K, and 7% for Mg, Al, Mn, Na; and trace elements were analyzed by IC-PMS Accuracy and precision, based on replicated analyses of samples and standards, are estimated as better than 10% for all elements well above the detection limit.

4.2.MAJOR AND TRACE ELEMENT GEOCHEMISTRY OF HIRNA BASALTS

4.2.1. Major element

The geochemical data-set from Hirna basalts shows that the samples fall within the basalts and foidite fields based on total alkali silica (TAS) classification diagram after Le Bas et al. (1986) (Fig5.1). Excepting one sample (HB1A2) loss of ignition (LOI) for all samples is < 2 Wt %. During classification of rock and major element data set interpretation using variation diagram, samples are normalized to 100 % on a volatiles free basis. Sample HB1-D1 and HB2-B1 fall in the field of foidite on TAS classification diagram. These two samples have SiO_2 content of 35.02 and 34.89 Wt% respectively. CIPW normative calculation after Johannsen A. (1931) indicates these samples are silica undersaturated nephiline normative (13.7 and 13.1 % respectively). The rest of the rocks from this study exhibit consistent range in SiO_2, ranges from 45.45 to 49.04 Wt% (Table4.1). These foidite samples are characterized by relatively high amounts of MgO, TiO_2, CaO and extremely high Fe_2O_3 (17.54 and 17.34 respectively) and low Al_2O_3 content than the rest of the rocks from the area.

Almost all samples are moderately fractionated mafic rocks with MgO values between 4.66 and 10.67 Wt%. The distribution of TiO_2 in the basaltic, rocks of the area covers a range between (3.46 – 4.76 Wt %) and have a similar chemical distribution with the high Ti one basalt on classification of Pik et al. (1998) northwestern Ethiopian plateau basalt.

On MgO vs TiO_2 and Fe_2O_3 variation diagrams, the Hirna basalts show a general positive correlation trend between, which is interpreted as the fractionation of titanomagnetite from the melt. In addition to this, the Hirna basalts display significantly higher CaO and K_2O Wt% at a given range of TiO_2 content than do the northwestern Ethiopian plateau basalt (comparison made from the data obtained from Beccaluvai et al. (2009).

Sample no **Wt%**	**HB1 A1**	**HB1 A2**	**HB1B 2-1**	**HB1B 2-2**	**HB1 C1**	**HB1 D1**	**HB2 B1**	**HB2 B2**	**HB2 B3**	**HB2 C1**	**HB2 C2**	**HB2 D1**
SiO_2	48.77	48.71	45.93	46.18	49.04	35.02	34.89	45.99	46	47.04	47.24	45.45
TiO_2	3.4	3.38	3.98	3.97	3.43	4.67	4.67	4.09	4.08	3.79	3.77	3.88
Al_2O_3	13.97	13.96	13.9	14.07	14.12	10.55	10.5	13.8	14.19	13.49	13.69	13.9
Fe_2O_3	13.32	13.05	15.41	15.34	13.7	17.54	17.34	15.41	14.44	14.78	14.56	15.7
MnO	0.21	0.21	0.2	0.21	0.21	0.25	0.21	0.2	0.16	0.22	0.2	0.21
MgO	4.72	4.55	6.07	5.89	4.85	8.59	10.67	5.89	5.43	5.67	5.53	6.16
CaO	8.98	8.93	9.9	10.13	8.97	15.62	14.69	10.01	10.15	9.92	9.94	9.78
Na_2O	2.94	2.9	2.8	2.73	2.94	3.02	2.81	2.82	2.74	2.76	2.8	2.66
K_2O	1.12	1.17	0.7	0.67	0.96	1.16	1.33	0.73	0.7	0.67	0.63	0.64
P_2O_5	0.85	0.85	0.74	0.78	0.85	1.63	1.25	0.76	0.73	0.91	0.92	0.75
LOI	1.52	2.11	0.21	0	0.74	1.65	1.4	0.13	1.22	0.53	0.51	0.71
Sum	100	100	100	100.14	100	100	100	100	100	100	100	100

CIPW normative minerals calculations were performed using the norm-calculating program based on Johannsen A, 1931. In the course of CIPW, norm calculations 10 quartz + hypersthene normative (silica saturated) and 2 nepheline normative (silica under saturated) rocks are encountered.

Apatite	**2.05**	**2.06**	**1.76**	**1.85**	**2.03**	**3.94**	**3.01**	**1.81**	**1.75**	**2.17**	**2.19**	**1.79**
Ilmenite	0.46	0.46	0.43	0.45	0.45	0.55	0.46	0.43	0.35	0.47	0.43	0.45
Sphene	7.9	7.9	9.25	9.17	7.91	10.99	11.06	9.52	9.71	8.76	8.76	9.02
Orthoclase	6.74	7.08	4.15	3.96	5.73	6.99	3.89	4.33	4.19	3.99	3.75	3.82
Albite	25.32	25.11	23.78	23.11	25.11	0.77	0	23.93	23.51	23.53	23.86	22.71
Anorthite	22	22.13	23.38	24.17	22.71	12.04	12.31	22.91	24.69	22.61	23.09	24.31

Hametite	13.56	13.36	15.47	15.34	13.83	17.89	17.63	15.46	14.64	14.89	14.67	15.84
Diopside	5.05	4.93	6.18	6.23	4.19	31.56	29.41	6.55	6.04	6.66	6.3	5.37
Hyperstene	9.63	9.31	12.31	11.79	10.25	0	0	11.67	10.91	11.14	10.95	12.99
Nephelene	0	0	0	0	0	13.7	13.1	0	0	0	0	0
Quartz	7.39	7.72	3.34	3.99	7.84	0	0	3.44	4.24	5.82	6.04	3.75
Olivine	0	0	0	0	0	5.04	9.38	0	0	0	0	0
Wt %	100.1	100	100	100	100	111.1	111.1	100	100	100.1	100.1	100

PPm

Sc	29.48	28.75	29.07	25.75	30.32	28.89	32.47	28.54	27.33	29.36	27.76	27.10
V	358.40	336.79	407.08	398.25	362.79	385.97	413.67	403.67	409.00	386.95	378.06	403.00
Cr	52.31	49.07	54.11	48.89	53.21	40.71	58.02	51.72	50.05	46.45	45.09	49.84
Co	37.06	34.42	46.53	46.10	36.98	54.91	59.66	46.84	45.81	41.64	43.40	46.41
Ni	20.53	19.53	42.71	40.80	23.60	33.07	44.04	42.63	41.60	32.56	34.94	41.16
Rb	21.42	20.58	14.38	13.93	19.51	27.38	36.75	13.63	11.07	14.15	14.04	13.29
Sr	594.15	594.74	702.64	721.54	602.00	1198.42	806.75	695.93	710.72	675.53	668.56	666.04
Y	36.85	36.63	29.60	27.21	37.87	35.07	27.44	29.15	28.06	32.31	30.77	28.07
Zr	165.08	164.16	155.91	145.32	171.38	422.16	323.23	155.02	150.05	164.09	156.36	148.45
Nb	18.38	18.51	18.17	18.80	18.92	142.50	111.31	19.14	18.57	18.86	19.13	17.86
Cs	0.38	0.36	0.22	0.37	0.35	0.19	0.37	0.13	0.15	0.35	0.24	0.27
Ba	712.96	712.36	459.94	477.98	677.76	701.27	608.77	476.90	453.55	734.06	701.06	438.15
La	27.51	27.65	21.08	20.74	28.25	109.39	81.32	21.57	20.75	24.61	24.40	20.67
Ce	61.53	62.29	46.05	49.20	62.78	200.09	159.65	48.82	46.62	55.80	57.31	46.73
Pr	9.06	9.15	6.76	6.92	9.26	23.54	18.34	7.05	6.69	8.05	8.10	6.71

	HB1 A1	HB1 A2	HB1 B2-1	HB1 B2-2	HB1 C1	HB1 D1	HB2 B1	HB2 B2	HB2 B3	HB2 C1	HB2 C2	HB2 D1
Nd	44.38	44.40	32.98	32.79	45.41	88.98	68.74	33.67	32.18	38.99	38.38	32.40
Sm	10.17	10.16	7.70	7.63	10.44	15.21	11.88	7.89	7.54	9.01	8.76	7.57
Eu	3.78	3.83	2.63	2.65	3.88	4.17	3.40	2.71	2.72	3.11	3.08	2.59
Gd	9.88	9.90	7.63	7.20	10.16	11.75	9.08	7.75	7.36	8.69	8.32	7.36
Tb	1.36	1.34	1.06	0.99	1.41	1.48	1.15	1.06	1.02	1.19	1.14	1.02
Dy	7.50	7.45	5.83	5.39	7.69	7.55	5.81	5.88	5.62	6.54	6.21	5.57
Ho	1.42	1.42	1.12	1.03	1.46	1.33	1.03	1.12	1.07	1.24	1.17	1.07
Er	3.57	3.54	2.80	2.59	3.66	3.23	2.46	2.84	2.70	3.11	2.93	2.68
Tm	0.47	0.47	0.37	0.33	0.49	0.41	0.30	0.37	0.35	0.41	0.39	0.35
Yb	2.74	2.75	2.22	2.08	2.82	2.40	1.84	2.24	2.12	2.42	2.31	2.15
Lu	0.40	0.40	0.32	0.30	0.42	0.34	0.25	0.33	0.31	0.35	0.34	0.31
Hf	4.16	4.13	3.91	3.63	4.32	9.37	7.33	3.97	3.82	4.13	3.91	3.74
Ta	1.27	1.28	1.30	1.28	1.32	8.98	6.73	1.34	1.30	1.33	1.31	1.25
Pb	3.01	2.92	2.06	2.25	2.84	2.02	2.39	2.30	2.16	2.30	2.48	2.25
Th	2.09	2.09	1.75	1.69	2.14	12.22	8.59	1.79	1.68	1.95	1.86	1.67
U	0.67	0.67	0.52	0.57	0.67	2.82	2.24	0.56	0.52	0.60	0.62	0.52

Table4.1 Major and trace element concentration of all rock samples from Hirna, south eastern Ethiopia.

Fe_2O_3 content show a range from 13.05 to 15.7 Wt % and MgO content varies 4.55 to 6.16 Wt % for silica saturated basalts and (Fe2O3 17.54 and 17.34 wt %) and (MgO 8.59 and 10.67 wt %) for the silica undersaturated basalts although this much variation of MgO suggests that they may have undergone variable degree of fractionation.

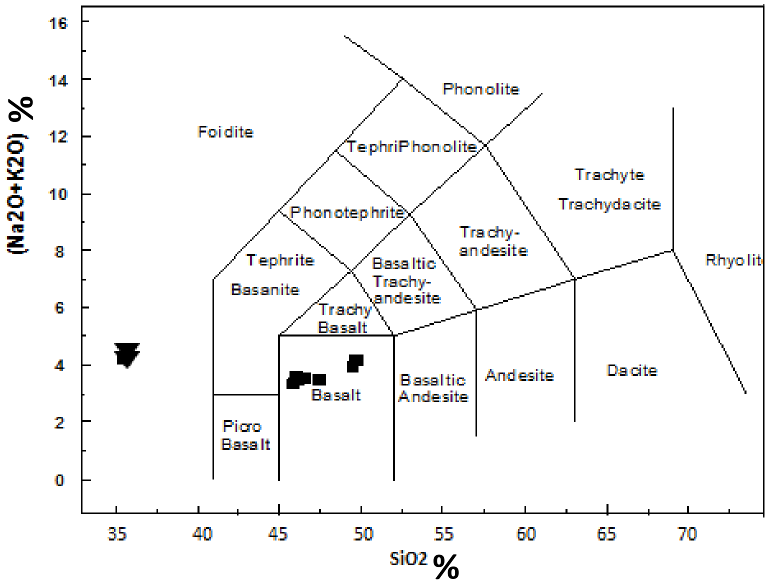


Fig. 4.1: Classification of Hirna Basalts southeastern Ethiopia plateau based on the total alkalis versus silica (TAS) classification diagram after Le Bas et al. (1986).

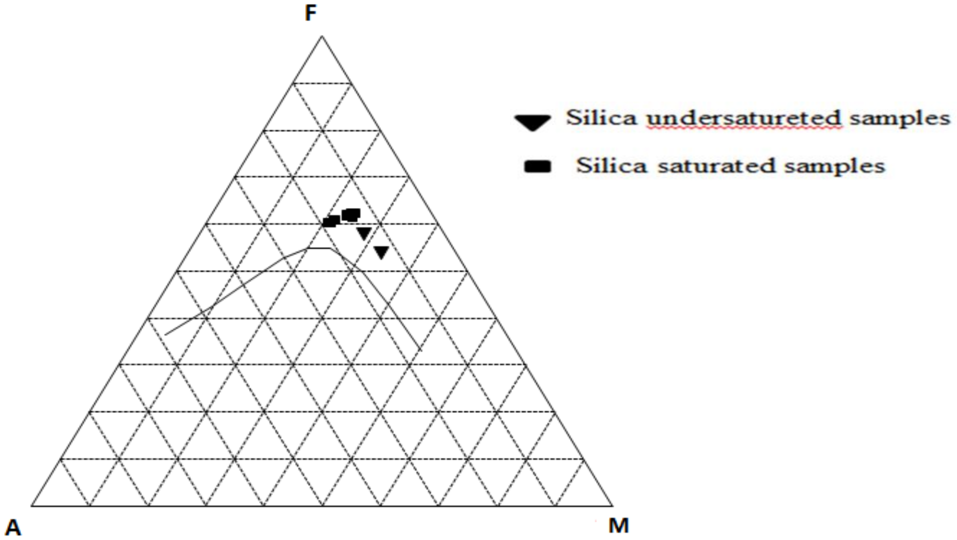
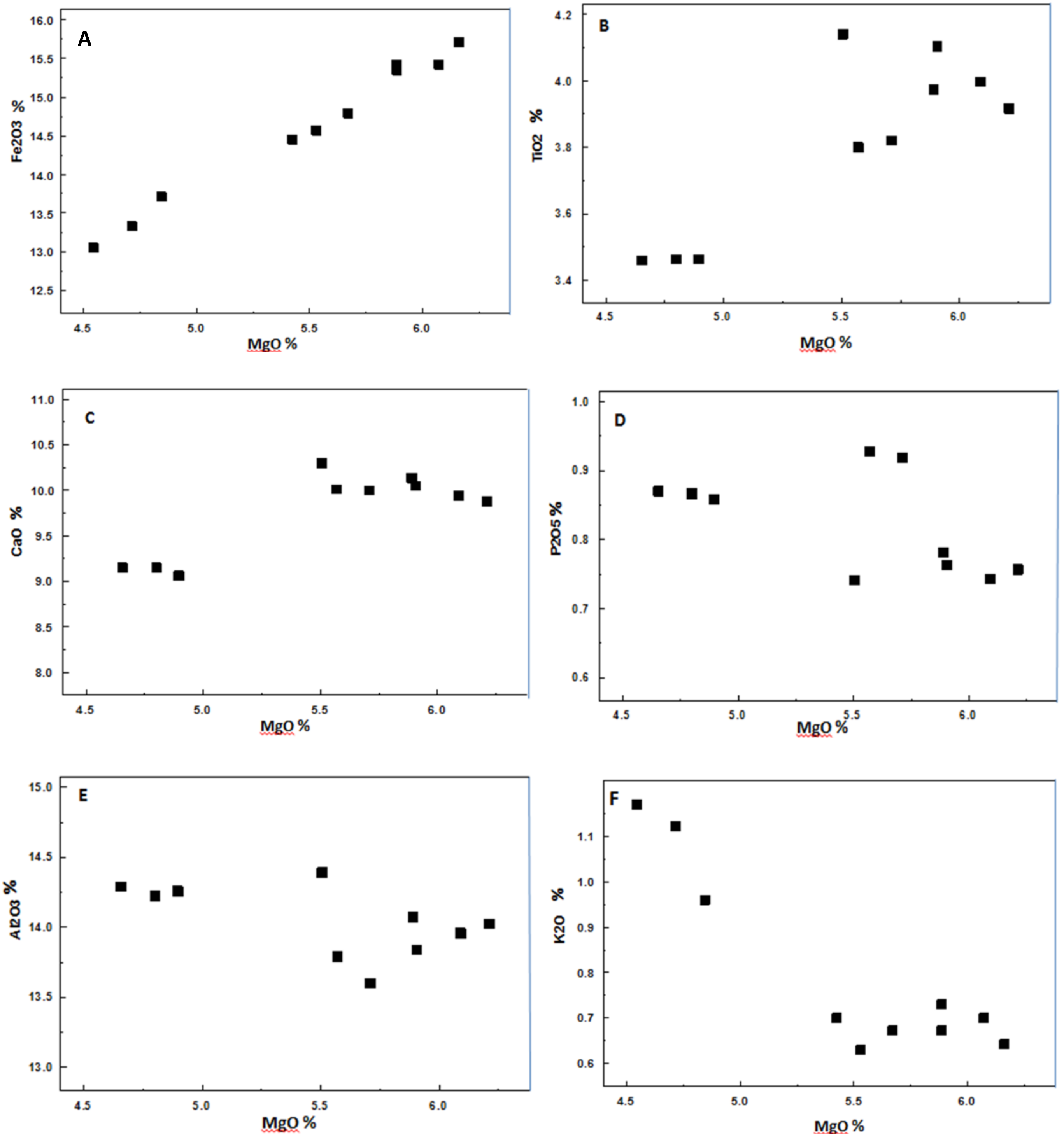


Fig. 4.2: AFM Classification of Hirna Basalts southeastern Ethiopia plateau all samples fall under tholeiitic rock category after Kuno (1968).

Major element data can be used in reconstruction of variation diagrams, which reveal interrelationship between elements in the data set. On this basis, several variation diagrams have been constructed for major element oxides choosing MgO wt% as the X-axis (differentiation index). MgO is chosen as differentiation index because it has reasonably wide range of values and continuously decreases during crystal liquid fractionation. The variation diagrams for major elements with MgO are indicated below in Figure 4.2 A-H


A
Fe2O3 %
16.0
15.5
15.0
14.5
14.0
13.5
13.0
12.5
4.5
5.0
5.5
6.0
MgO %
B
TiO2 %
4.2
4.0
3.8
3.6
3.4
4.5
5.0
5.5
6.0
MgO %
C
CaO %
11.0
10.5
10.0
9.5
9.0
8.5
8.0
4.5
5.0
5.5
6.0
MgO %
D
P2O5 %
1.0
0.9
0.8
0.7
0.6
4.5
5.0
5.5
6.0
MgO %
E
Al2O3 %
15.0
14.5
14.0
13.5
13.0
4.5
5.0
5.5
6.0
MgO %
F
K2O %
1.1
1.0
0.9
0.8
0.7
0.6
4.5
5.0
5.5
6.0
MgO %

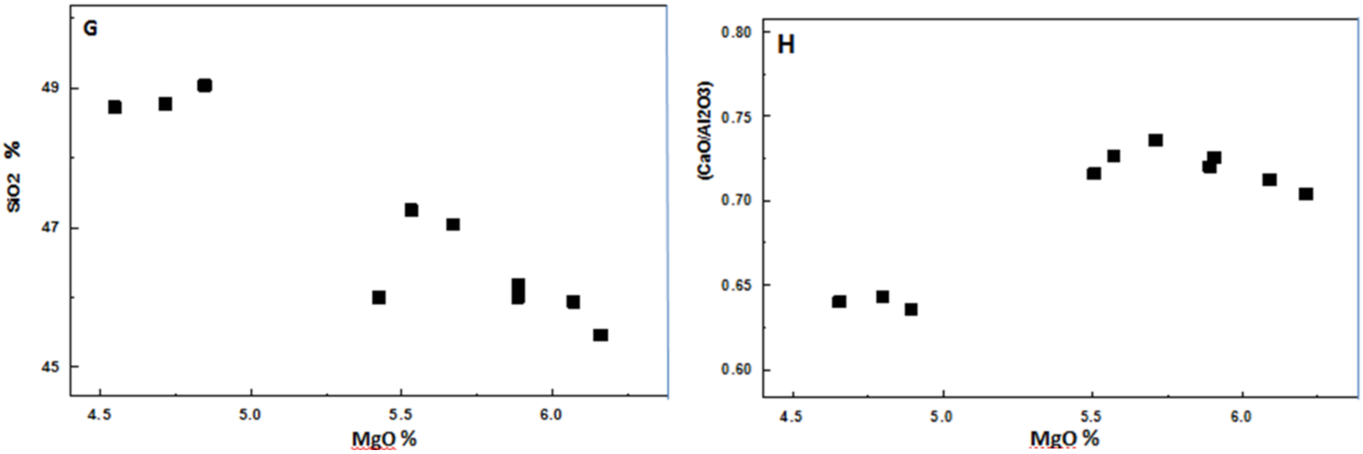


Fig. 4.2: MgO (wt %) versus selected major element data (wt %) and (H) MgO wt% Vs (CaO/Al2O3) ratio plots of Hirna basalts southeastern Ethiopia plateau. Data are recalculated on volatile-free basis. The two silica undersatureted samples have been rejected from the plot (These two samples have extremely anomalous geochemical data from the rest sample)

From the diagram we observe that there is a strong negative correlation between MgO versus SiO_2 and K_2O. On the basis of the above plots we suggest the differentiation of the melt is controlled by the addition or subtraction of olivine from the system. MgO drop rapidly with little variation of SiO_2 which support the fractionation of olivine crystal from the melt. On the other hand the diagram shows positive correlation with MgO Vs Fe_2O_3 and TiO_2 plot.

MgO wt% vs CaO wt% plot show very slight negative correlation trend up to 5.8 Wt% of MgO which is controlled by the removal of olivine and after wards they show positive trend on the liquid line of descent. This positive correlation is a suggestive of crystal liquid control by the fractionation of clinopyroxene from the melt. The inflection in the crystallization trend on 5.8 Wt% of MgO value on MgO versus CaO plot supports the onset of fractionation of clinopyroxene (together with plagioclase and olivine) (see Fig 4.2 C).

Variation of CaO/Al_2O_3 with MgO is particularly given sensitivity to the proportion of olivine, clinopyroxene and plagioclase fractionation. It is obvious that clinopyroxene has a high CaO/Al_2O_3 ratio and MgO content and therefore fractionation of clinopyroxene rapidly drive the residual melt to lower CaO/Al_2O_3 and MgO. And conversely the removal of plagioclase from the magma increase both CaO/Al_2O_3 and MgO in the residual melt. And olivine fractionation decrease MgO rapidly but lives CaO/Al_2O_3 unchanged.

Hirna basalt reflects similar trend on the above explanation (Fig 4.2.H) fractionation of olivine up to ~5.8 Wt% of MgO and then dominated by the removal of clinopyroxene from the melt. The absence of clinopyroxene phenocryst in Hirna basalt may support that fractionation of clinopyroxene is the primary feature of this liquid magma. The existence of large proportion of plagioclase in the phenocryst phase of the lava also might be consistent with plagioclase removal not play prominent role in the crystal liquid fractionation. Generally major element chemical variations within the whole basaltic rock of Hirna can be largely explained by crystal fractionation involving olivine, clinopyroxene, iron-titanium oxides, and ± plagioclase, However, difference in TiO_2, CaO, K_2O, Al_2O_3 and to some extent in SiO_2 and Fe_2O_3 with in this restricted province reflect variable degrees of partial melting and/or crustal contribution to the melt.

4.2.2. **Trace element**

The compatible trace element Ni and Cr shows limited value throughout the area that is <45 ppm and 60 ppm respectively. These trace elements in several samples have undergone large fractionation since initially forming as partial melts from the mantle. Almost all samples contain Ni<45 ppm, Cr <60 ppm indicating the major fractionation of olivine and/or clinopyroxene from primary mantle melts. Crystal fractionation is the preferred mechanism for such Cr and Ni depletion as its abundance is not expected to vary under conditions of increasing partial melting.

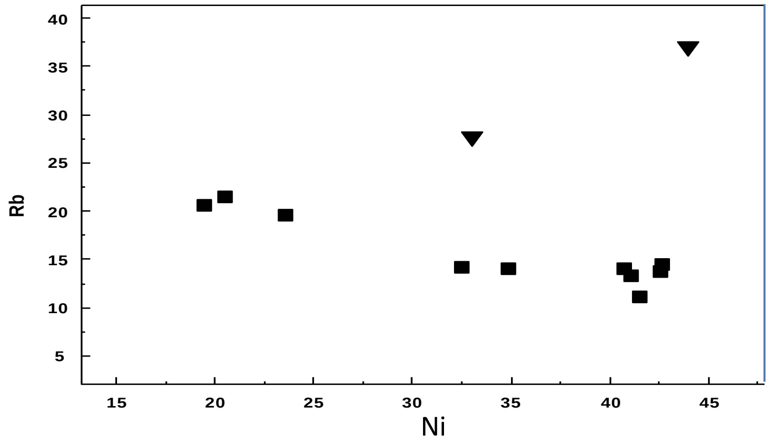
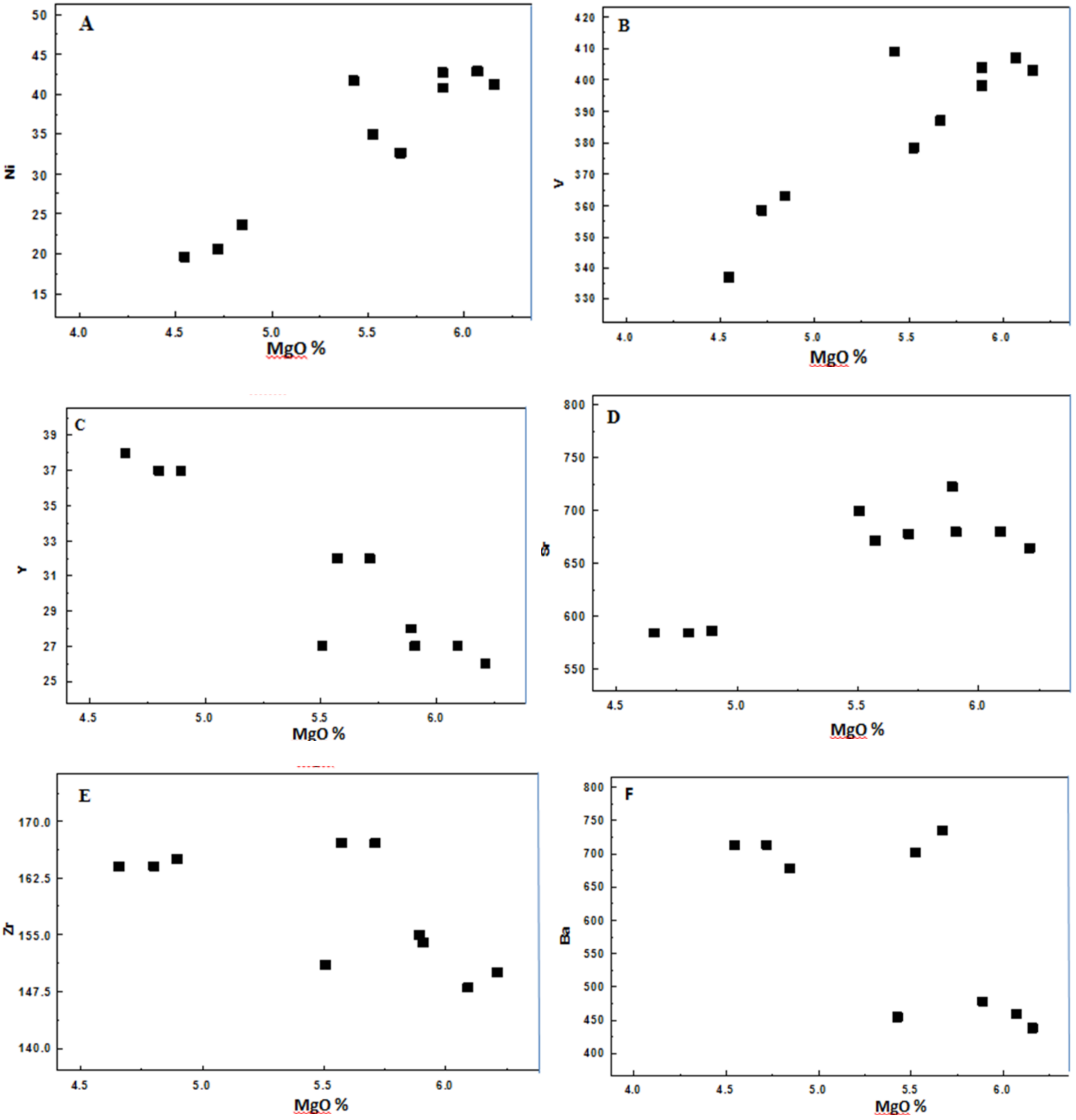


Fig 4.3 Ni (ppm) vs Rb (ppm) variation diagram shows the impact of the petrogenetic process is more pronounced on the compatible elements, which reflect fractional crystallization is the major process in the magma modification process.

In comparison with northwestern Ethiopian plateau HT1 basalt (high Ti1 basalt) the Hirna basalt reflects depletion in highly compatible trace element. Ni and V show a coherent positive correlation trend against MgO plot (Fig.4.4), whereas Cr and Sc show no correlation with MgO (not plotted).



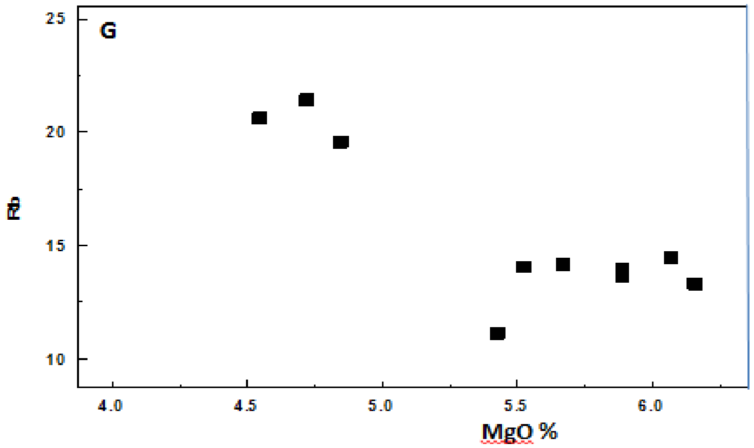


Fig.4.4: MgO (wt %) versus trace element (ppm) variation diagram for basalt samples of Hirna southeastern Ethiopia plateau. The silica undersaturated samples have not been plotted on the variation diagram (This two samples have extremely anomalous geochemical data from the rest samplein both major and trace element data)

The incompatible trace elements Ba, Zr and Rb with some scatter increase with decreasing MgO. Several incompatible trace element correlates with MgO content negatively suggesting that they are a feature of the mantle source region and/or the result of fractionation history of the magma. The whole rock sequence reflects enrichment in highly incompatible trace elements for the majority samples (LREE and LIL) (Fig.4.6.A and B). The variation of Nb within the whole lava sequence is very limited ranging between 17.86-19.14ppm with the exception of silica undersaturated nephline normative samples (HB1D1 and HB2B1). This sample shows high enrichment of the highly incompatible traces elements La (109.39 and 81.32ppm), Nb (142 and 111 ppm), Sr (1198 and 806 ppm) and Zr (422 and 323 ppm) value respectively which deviate abnormally from the majority samples. Rocks of this kind are very unusual in the Ethiopian volcanic province. In northwestern Ethiopian plateau around Gebre Guracha area similar anomalous samples have been observed Rooney et al. (2010). Interpretation of rocks from Gabra Guracha continues, however preliminary data suggests the source of these rocks is distinct from much of the flood basalt province and may be an anomalous component in the Afar plume or an enriched domain with in the sub-continental lithospheric mantle.

The extreme enrichment in highly incompatible trace element of these samples is probably associated with the source region enrichment history. Chondrite-normalized rare earth element (REE) pattern of these two samples are not parallel with the rest samples of the area. Highly variable MREE content of this sample leads to crossing pattern with the others that require derivation of the magma from different mantle source. These samples also exhibit very higher La/Sm (6.84 and 7.19) and La/Lu ratio.

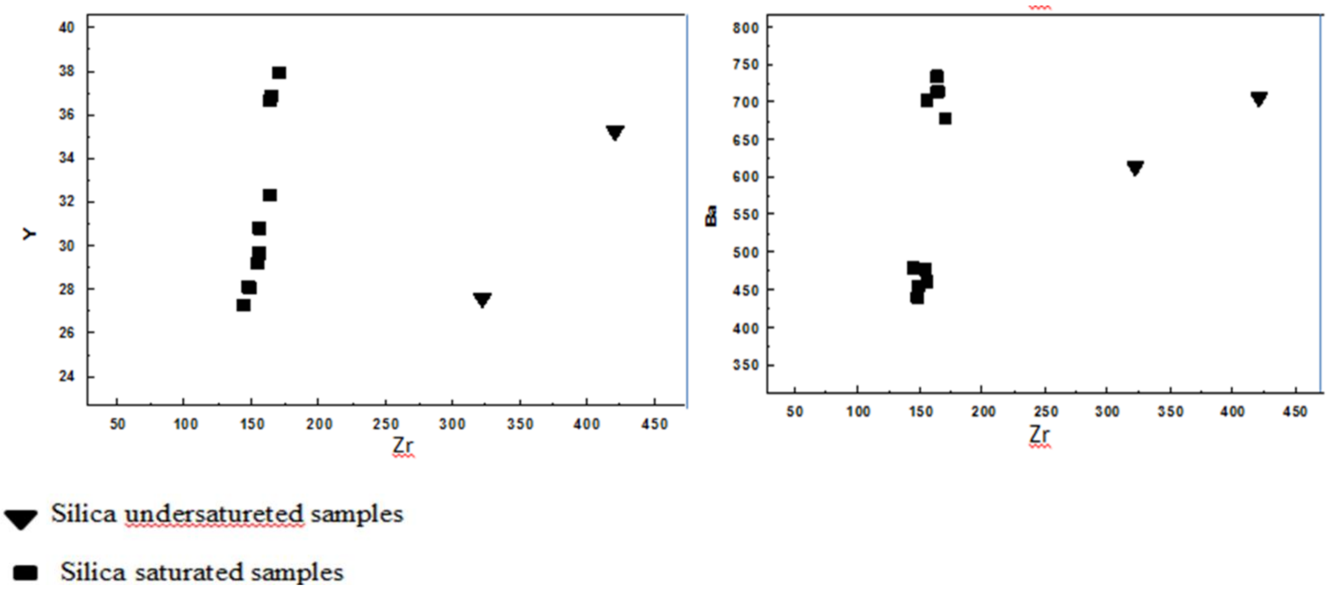


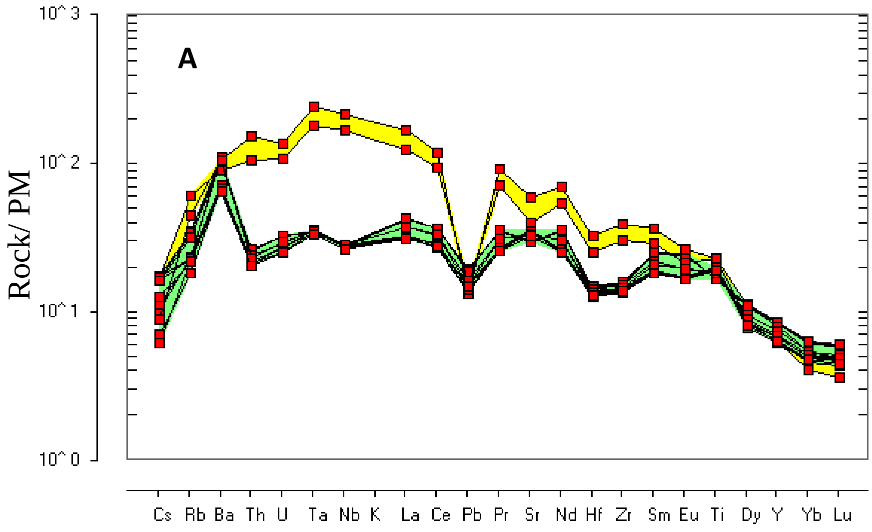
Fig.4.5: Zr (ppm) vs Y (ppm) and Ba (ppm) variation diagram of Hirna basalt samples southeastern Ethiopia plateau.

Ratio	HB1-A1	HB1 A2	HB1 B2-1	HB1B2-2	HB1C1	HB1D1	HB2B1	HB2B2	HB2B3	HB2C1	HB2C2	HB2D1
Zr/Yb	60.14	59.66	70.29	69.99	60.74	175.96	175.85	69.09	70.63	67.72	67.69	69.01
Ba/Nb	38.8	38.49	25.32	25.43	35.82	4.92	5.47	24.92	24.43	38.92	36.64	24.53
La/Nb	1.5	1.49	1.16	1.1	1.49	0.77	0.73	1.13	1.12	1.31	1.28	1.16
Tb/Yb	0.5	0.49	0.48	0.48	0.5	0.62	0.63	0.47	0.48	0.49	0.49	0.47
La/Yb	10.02	10.05	9.5	9.99	10.01	45.59	44.24	9.61	9.77	10.16	10.56	9.61
Zr/Nb	8.98	8.87	8.58	7.73	9.06	2.96	2.9	8.1	8.08	8.7	8.17	8.31

Ba/Rb	33.28	34.62	31.98	34.32	34.75	25.61	16.57	34.99	40.97	51.87	49.93	32.97
Rb/Sr	0.04	0.03	0.02	0.02	0.03	0.02	0.05	0.02	0.02	0.02	0.02	0.02
La/Lu	67.94	68.75	65.44	69.57	67.75	323.64	322.5	65.06	66.03	69.92	72.65	67.1
Nb/Y	0.5	0.51	0.61	0.69	0.5	4.06	4.06	0.66	0.66	0.58	0.62	0.64
La/Y	0.75	0.75	0.71	0.76	0.75	3.12	2.96	0.74	0.74	0.76	0.79	0.74
Zr/Y	4.48	4.48	5.27	5.34	4.53	12.04	11.78	5.32	5.35	5.08	5.08	5.29
Ti/Zr	123.47	123.44	153.04	163.77	119.99	66.32	86.62	158.17	163.01	138.47	144.55	156.69
Rb/Nb	1.17	1.11	0.79	0.74	1.03	0.19	0.33	0.71	0.6	0.75	0.73	0.74

Table 4.2 Selected trace element ratios of Hirna basalts, southeastern Ethiopia plateau.

The trace element profiles are all convex upward although enrichment of the more incompatible element over the HREE (heavy rear earth element) is more pronounced in the silica undersaturated nephline normative samples (Fig. 4.6). LILI (large ion lithophile element) abundance for example Ba varies between10-100X the primitive mantle and Rb varies between10-15X the primitive mantle).



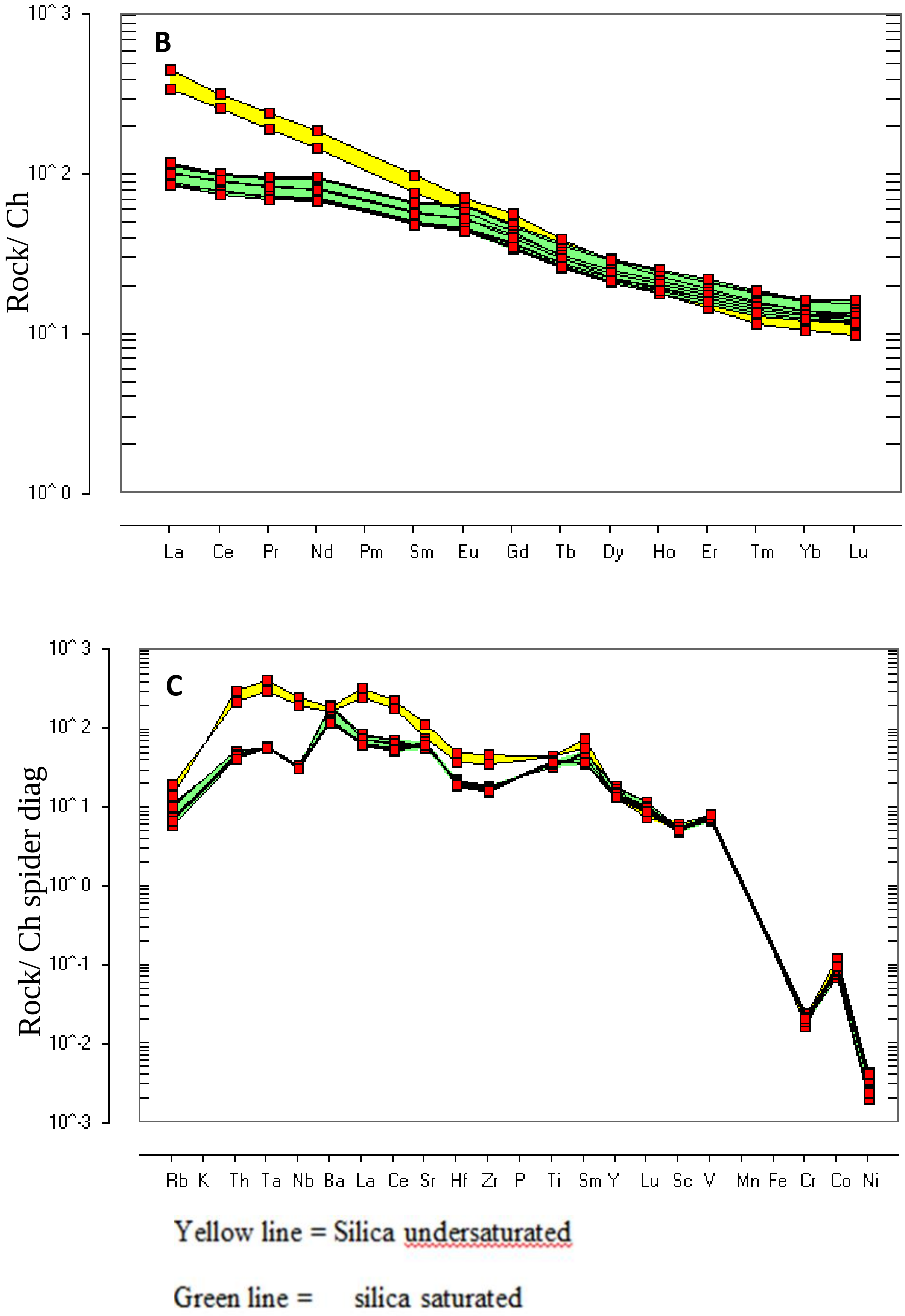


Fig 4.6: A) Primordial mantle normalized plot after McDonough and Sun (1995). B) COND normalized plot after McDonough and Sun (1989). C) Chondrite normalized spider diagram after wood et al. (1979b) plot for Hirna basalt.

5.1. PETROGENESIS

5.1.1 Fractionation History

Rock geochemistry of the area reveals that fractional crystallization is the dominant factor in the modification of the primary magma spectrum. MgO/ (MaO+Fe_2O_3) ratio shows a range between 0.26-0.33 and represents highly evolved magma series. MgO vs CaO/Al_2O_3 ratio and MgO vs CaO plot (Fig.4.2 C and H) show a negative correlation trend up to 5.8 wt% of MgO concentration beyond this point the liquid line of dissent (LLD) tends to correlate both positively which support the fractionation of olivine in the first phase and then clinopyroxene, magnetite and ± plagioclase feldspar.

Based on the major element data, Olivine, clinopyroxene, ± magnetite or titanomagnetite and ± plagioclase were major fractionating phases in the petrogenetic history of the magma spectrum which is supported by compatible trace element depletion Ni<45 ppm, Cr <60ppm for all rock samples indicating the removal of olivine and/or clinopyroxene from primary mantle melts.

The different and often high incompatible element ratio of Zr/Yb and Ba/Nb of the Hirna basalt are not easily explained by different degree of partial melting or fractional crystallization therefore it seems like that these difference trace element ratio are the product of crustal contamination. It is supported by the evident that strong fractionated Zr/Nb ratio indicate that contamination with crustal material with high Zr/Nb ratio and low Nb concentration. Except the silica undersaturated samples all basalts have La/Nb ratio (1.1-1.5). The high La/Nb ratio of this sample with very low Mg/MgO+Fe_2O_3 is potentially consistent with crustal contribution to the melt.

5.1.2 Source rock characteristics

Chondrite-normalized rare earth element (REE) diagrams for all basalts show light rare earth element (LREE) enrichment relative to heavy rare earth element (HREE) (Fig 4.6 B). Rare earth element (REE) pattern indicate that garnet influenced the variation in HREE and LREE, suggesting that the basalt originated from a garnet peridotite source. Zr and Y have 2.17 and 5.42 partition coefficient respectively for the mineral garnet White (2001). As a result high Zr/Y ratio in the Hirna basalt suggests that this basaltic magma may derived from garnet bearing mantle source region. The LREE/HREE ratio of the Hirna basalt also confirms the presence of mineral garnet residue in the source region (La/Sm 2.7-2.78 for silica saturated basalts and 6.84- 7.19 for the silica undersaturated samples) and La/Lu ratio 322.5- 323.04 for the nephline normative samples. The high concentration of incompatible element combined with high LREE/HREE ratio and steeper slopping of the chondrite normalized rare earth element pattern of the silica undersaturated samples indicate partial melting under a condition that left a large amount of garnet in the residue. Relatively the high content of MgO and Fe_2O_3 of these rocks suggest melting at considerable depth. On the contrary the silica saturated basaltic samples show less fractionated pattern than the silica undersaturated basalts (La/Lu ratio varies between 65.06 and 72.65). The silica saturated basaltic rocks have relatively flat REE and moderately sloping HREE.

The major difference between the two types of basalt in a level of incompatible trace element which differ by a factor of >5 for La, Nb, Zr and Ta there are two obvious way of explaining such differences in the level of partial melting varied widely or the magma were generated from the source with different trace element composition.

Variations of trace element ratio within rock have been largely explained as a result of source rock heterogeneity. Patterns of variation in La/ Yb-Tb/Yb ratio and Ba/Nb-La/Nb ratio suggest the involvement of two source region with distinctive enrichment histories (see Fig 5.1). The silica undersaturated samples has Ba/Nb ratios 4.92-5.47 whereas the silica saturated samples have 24.43-.38.8 and La/Nb ratio of 0.73-0.77 and 1.1-1.5 respectively.

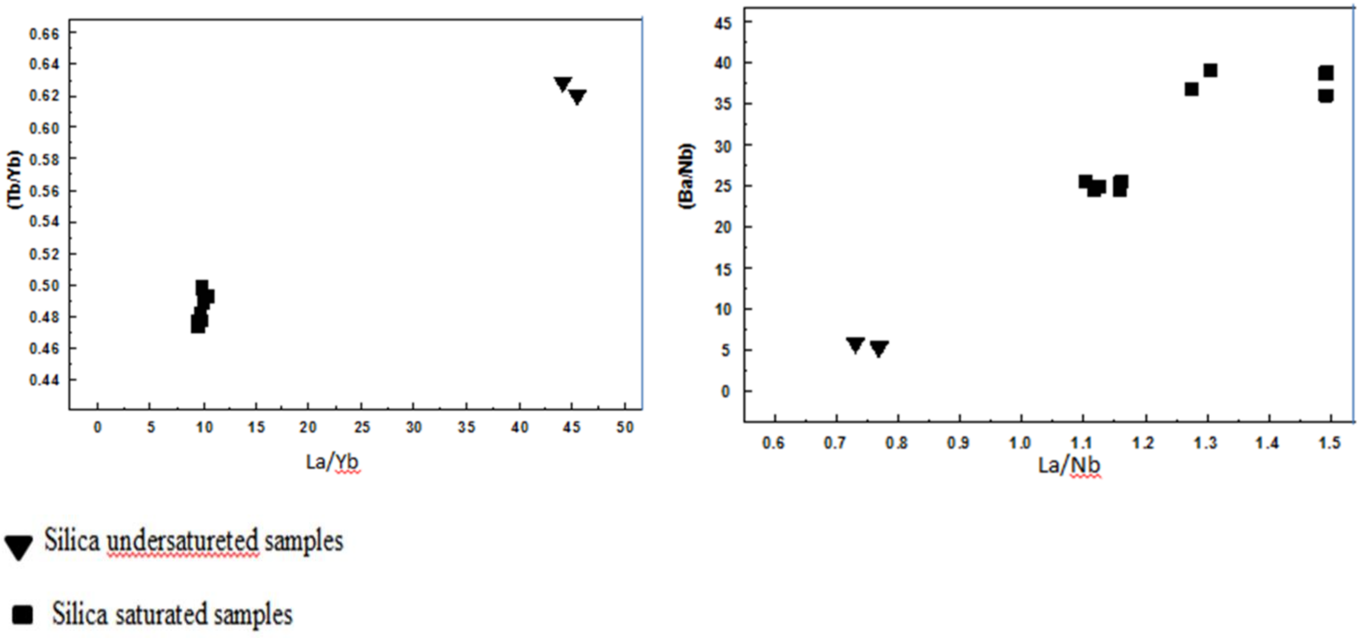


Fig 5.1 La/Yb Vs Tb/Yb ratio and La/Nb Vs Ba/Nb ratio plot showing two distinctive groups of Hirna basaltic rocks.

Incompatible trace element ratio can be affected by source region variation instead of degree of fractional crystallization and/or partial melting. The presence of two distinctive groups based on the incompatible trace element ratio combined with the crossing pattern in the chondritic normalized REE patterns (see Fig 4.6 B) between the two groups explaining the involvement of two mantle source region in the area.

Rb and Ba are compatible with phlogophite while Sr, Rb and Ba are moderately compatible with amphibole. Melts in equilibrium with phlogophite are expected to have significantly higher Rb/Sr and lower Ba/Rb values whereas melt in equilibrium with an amphibole-bearing source are expected to have a higher Ba and Ba/Rb value. Furman et al. (1999) presented lava from many volcanic areas that have low K_2O/Na_2O (<0.75) and low Rb/Sr values (<0.06) and interpreted these result as consistent with the melting of amphibole bearing source, the Hirna basaltic lava succession characterized by higher Ba content, except the silica undersaturated samples (Ba/Rb value >28) and low K_2O/Na_2O (0.23-0.47) and Rb/Sr value (< 0.06), this trace element ratio distribution consistent with the melting of an amphibole bearing-source region.

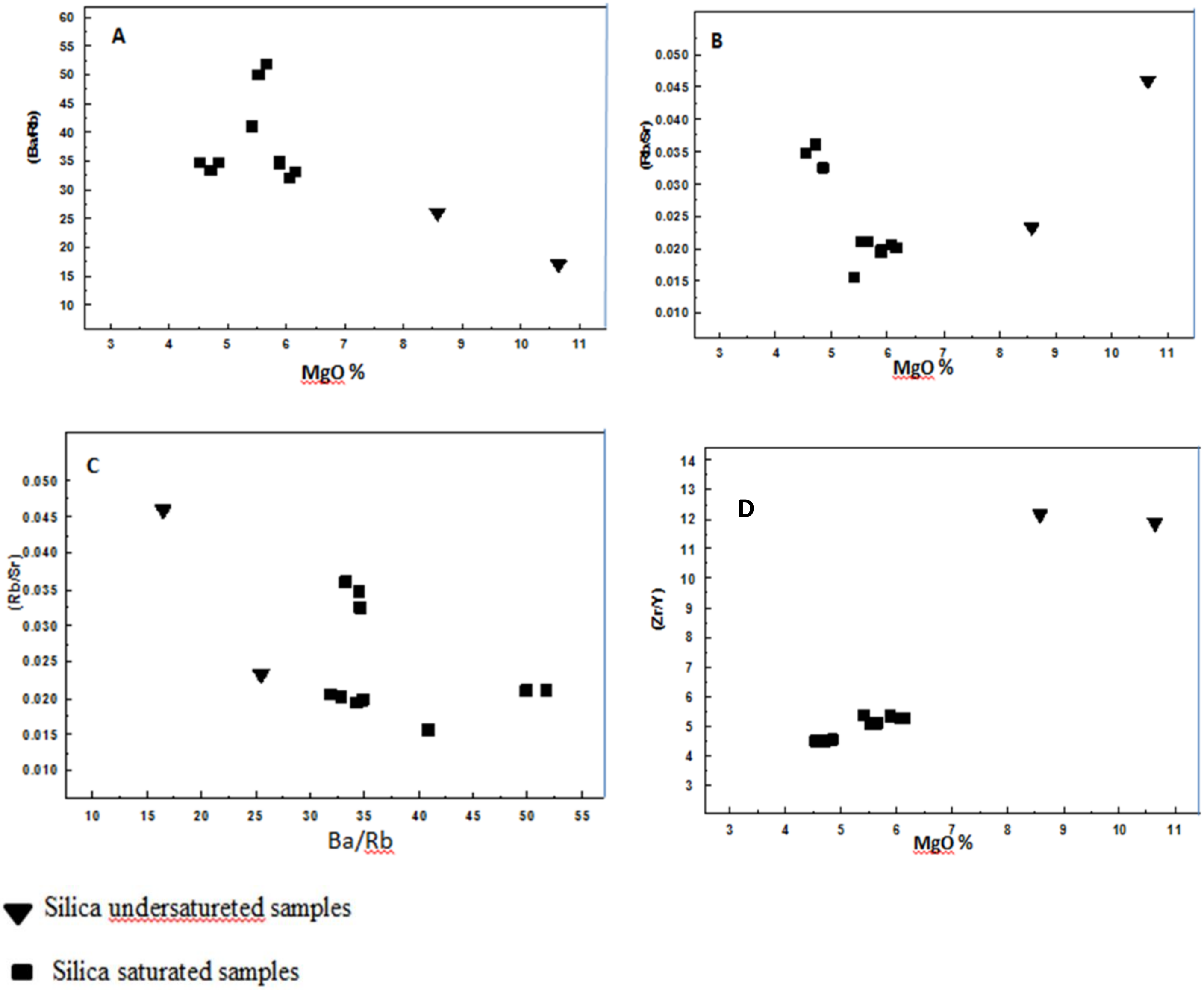


Fig. 5.2: A)MgO wt% Vs Ba/Rb, B) MgO wt% Vs Rb/Sr and C)Ba/Rb Vs Rb/Sr D) MgO wt% Vs Zr/Y ratio variation diagram showing distinctive variation of the Hirna basalt (southeastern Ethiopia plateau flood basalt) elevate amount of Ba/Rb ratio value indicate the amphibole-bearing source region was in equilibrium with the melt.

6.3. DATA COMPARISON WITH THE NORTHWESTERN ETHIOPIAN PLATEAU CFB

On the basis of TiO_2 content, basalts from northwestern plateau of Ethiopian continental basalt province can be arranged zonally (Pik et al., 1998 and Beccaluva et al., 2009). TiO_2, and other major element and trace element characteristics confirm the existence of three main magma types (Pik et al., 1998, Kabato, 2010, Beccaluva et al., 2009 and Kieffer et al., 2004). **1**)Low-Ti tholeiites (LT), in the NW which is mostly plot in the subalkaline field, showing the widest differentiation range with MgO 3-12 wt %, coupled with the lowest TiO_2 contents (1.0-3.5 wt %. **2**)High Ti one lavas (HT1) predominate southeastwards and this group is mainly composed of tholeiitic basalts with MgO 4-9 wt % and TiO_2 2.5-4.8 wt %; **3**) ultratitaniferous transitional basalts and picrites (HT2) that are concentrated in the Lalibela area, and are characterized by transitional basalts and picrites that cluster around the alkaline-subalkaline boundary with MgO 5-12 wt % and TiO_2 3.5-5.9 wt % for basalts, and MgO 13-16 wt % and TiO_2 2.6-4.5 wt % for picrites Beccaluva et al. (2009).

With some minor exceptions the Hirna flood basalts (south eastern Ethiopian plateau) resemble Pik et al. (1998) HT1 type of flood basalt in both major and trace element distribution. In particular, MgO varies between 4.55and 10.67 wt% and TiO_2 between 3.4 and 4.67 wt%. These rocks share tholeiitic magmatic character with relatively high concentrations of incompatible trace elements and moderately fractionated trace element patterns. These similarities support the idea that the two provinces may have been generated from the mantle source having similar geochemical signature at similar degree of partial melting, therefore this result further support the hypothesis that this volcanic province would have been the south ward extension of the zonally arranged Ethiopian flood basalt from the Afar plume.

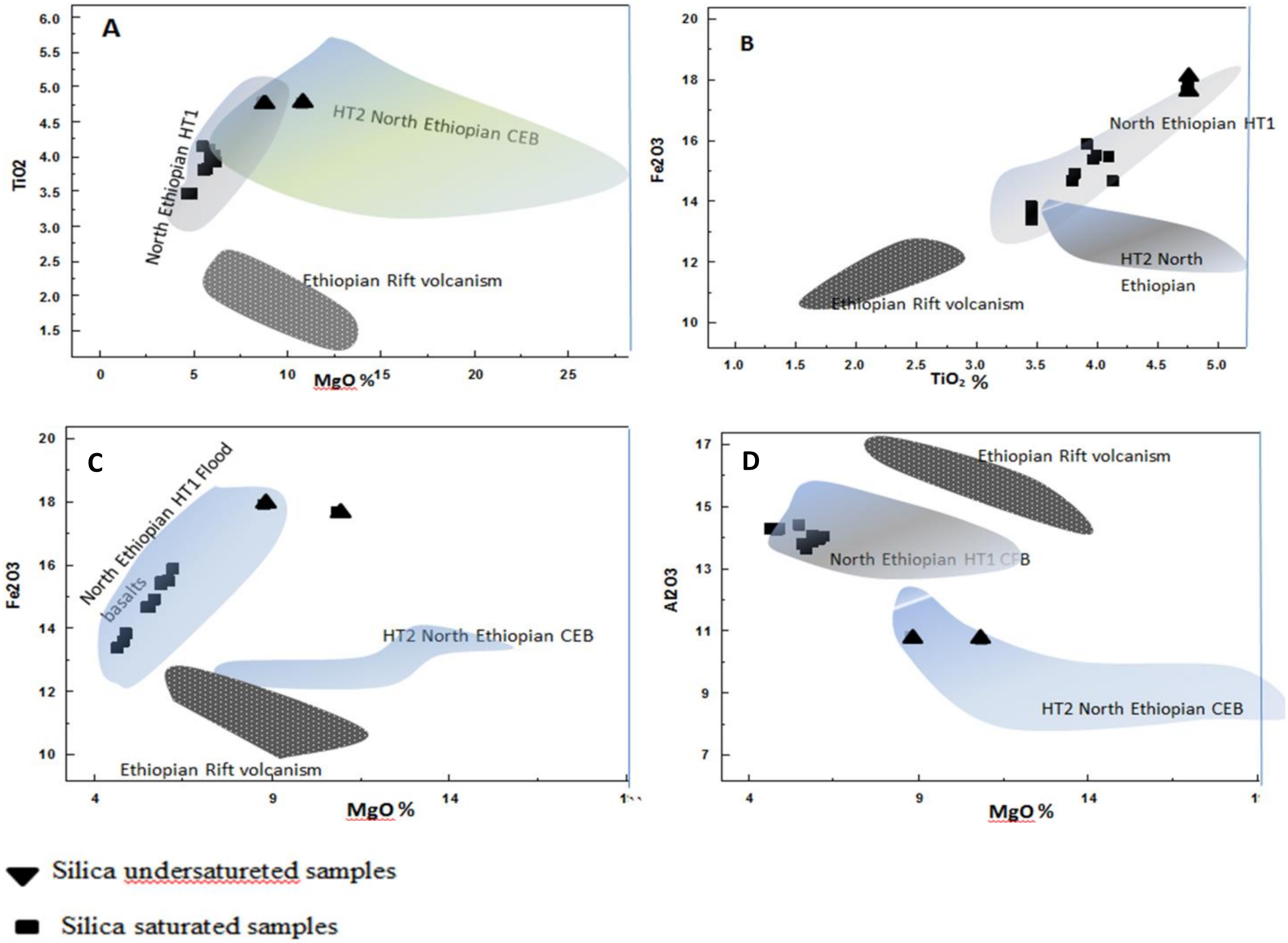


Fig. 5.3: MgO wt% Vs TiO_2, TiO_2 Vs Fe_2O_3, MgO Vs Fe_2O_3 and MgO Vs Al_2O_3 variation diagram showing similarity in geochemical distribution between HT1 and Hirna basalts. HT1 and HT2 basalts from northwestern Ethiopia plateau flood basalt Data obtained from Beccaluva et al. (2009), Ethiopian rift volcanism Data from Furman et al. (2006) and Hirna basalt (Southeastern Ethiopian plateau) Data from this study.

The observation that was mad by Beccaluva et al. (2009) the clinopyrxene in the northwestern Ethiopian HT characterized by enrichment of light rare earth element (LREE) and depletion in heavy rare earth element (HREE) this compositional distribution is resulted in initial melting in the presence of residual garnet in the source region.

The high Ba content, Ba/Rb ratio >28, low K_2O/Na_2O (0.23-0.47) and Rb/Sr value (< 0.06), in the Hirna basalt consistent with the melting of an amphibole bearing-source region. And similarly high LREE/HREE ratios of the Hirna basalt confirm the existence of residual garnet in the mantle source region; therefore this similarity in geochemical distribution pattern between the two province may suggest that the two (HT1 and Hirna basalt) generated at the same degree of partial melting from the mantle source region which have similar geochemical signature.

7.1. CONCLUSION

Depending on field observation, petrography, major and trace element data study throughout the Hirna basalts (southeastern Ethiopia plateau) the following points have been concluded.

1. The Hirna basalts exposed b/n 1919m-2462m a. s. l. for a Max thickness of 540m which directly overlies on the Cretaceous Upper sandstone unit. The rock of the area represented by aphyric to sub-porphyritic textural nature within hypocrystalline to microcrystalline groundmass of Olv+ Plag ± Cpx and opaque oxides. Phenocrysts mainly consist of dominant Plag (<25 vol. %) and lack Olv crystals in almost all samples.
2. The geochemical data-set from Hirna basalts shows that the samples fall within the basalts and foidite (2 samples) fields based on TAS classification diagram. The foidite samples are silica undersaturated nephline normative which show enrichment of Fe_2O_3, TiO_2, MgO, CaO and depletion of SiO_2 (35.02 and 34.89 wt%) and Al_2O_3. The rest of the basaltic samples are hypersthene normative (silica saturated) rocks.
3. Major element chemical variation and compatible trace element depletion (E.g Ni<45 ppm and Cr<60ppm) with in the area largely explain involvement of crystal fractionation of Olivine, clinopyroxene, iron titanium oxide and ±plagioclase from the primary mantle melt.
4. Two main types of magma have been distinguished by their trace element composition and there ratio distribution over the area (see Fig 5.1). Large difference in the content of incompatible trace element ratio between is explained in terms of difference in source composition. Exclusively the silica undersaturated basalt samples are characterized by enrichment in highly incompatible trace element, high LREE/HREE ratio and steep slope chondrite normalized trace element pattern relative to the rest samples which is explaining the two groups are originated from two different mantle source regions. This much deviation of the two samples from the majority sample with in the restricted province have not been observed in Ethiopian flood basalt except the one which is described around Gebre Gurach northwestern Ethiopian plateau Rooney et al. (2010).

The extreme enrichment of incompatible element of those samples is probably associated with the source region enrichment history in the Ethiopian mantle plume. Generally the presence of two distinctive groups based on the incompatible trace element ratio combined with the crossing pattern in the chondritic normalized REE patterns explain the involvement of two mantle source region in the area.

5. Chondrite-normalized rare earth element (REE) diagrams for all basalts show light rare earth element (LREE) enrichment relative to heavy rare earth element (HREE). These patterns indicate that garnet influenced the variation in HREE and LREE, suggesting that the basalt originated from a garnet peridotite source. . The LREE/HREE ratio of the Hirna basalt also confirms the presence of mineral garnet residue in the source region (Silica saturated (La/Sm 2.7-2.78) and (La/Lu 322.5- 323.04) for the silica undersaturated samples).

6. Major and trace element data set distribution pattern confirm that the Hirna basalt have a very similar geochemical pattern with High Titanium one basalt (HT1) of the North western Ethiopian continental flood basalt province after the work of Pik et al., 1998. These similarities support the idea that the two provinces may have the same source region and generated at the same degree of partial melting and this result further support the hypothesis that this volcanic province would have been the south ward extension of the zonally arranged Ethiopian flood basalt province from the Afar plume.

7.2. RECOMMENDATIONS

Various regional study over Ethiopian plateau confirm that the south eastern Ethiopian flood basalt province is less voluminous than the northwestern Ethiopian plateau basalt and that is why less attention have been given for the southeastern Ethiopian plateau flood basalts. But in the Hirna area approximately 540m basaltic lava succession were recorded in this study. This much volcanic succession can provide a well-defined geochemical data set for the ongoing worldwide petrogenetic study especially for the younger Ethiopian continental flood basalt province. To date in the southeastern Ethiopian plateau continental flood basaltic province detail petrogenetic study have not been conducted in a well-defined manner so, instead of giving more attention for the northern part of the plateau it is better to give for the unstudied southeastern part to have better data for the whole Ethiopian volcanic province.

This paper final conclusion is drowned based on petrography, major and trace element data. To have a well-organized petrogenetic history of the area it needs to conduct Sr-Nd-Pb-Hf isotopic data interpretation. Therefore for the future intended researcher or organization highly advise to include this geochemical data to come up with a well-organized petrogenetic history of this area.

In this research work two silica under saturated and nephline normative samples have been recognized. These kinds of rock are very unusual in the Ethiopian flood basalt province so detail study on these rocks including all geochemical data can provide detail information on the difference of the Ethiopian flood basalt source region.

REFERENCES

Adam, J.D., Green, T.H. and Sie, S.H. (1993). Proton microscope determine partitioning of Rb, Sr, Ba, Y, Zr, Nb and Ta between experimentally produced amphibole and silicate Melts with variable F content. *Chem. Geol.* **109**: 29-49.

Addis Mekonnen. (2006). Geology and Geochemistry of Guna Volcanic Massif North Western Ethiopian plateau. Unpublished MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia, 144pp.

Arndt, N.T., Czamanske, G.K., Wooden, J.L., Fedorenko, V.A. (1993). Mantle and crustal contributions to continental flood volcanism. *Tectono physics* **223**: 39–52.

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

Ayalew, D., Ebinger, C., Bourdon, E., Wolfenden, E., Yirgu, G.and Grassineau, N. (2006). Temporal compositional variation of early syn-rift rhyolites along the western Red Sea margin and northern Main Ethiopian rift. *Geological Society, London, Special Publications.* **259**: 121 -130.

Ayalew, D., Yirgu, G., Barrey, P., Marty, B., Reisberg, L. and Pik, R. (2002). Source genesis and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts. *Geochemica et Cosmochimica Acta.* **66**: 1429-1448.

Baker, B. H., Mohr, P.A. and Williams, L.A.J. (1972). Geology of the east Africa. *Geological society of America special publication*. **36.**

Berhe, S.M., Desta, B., Nicoletti, M. and Teferra, M. (1987). Geology, geochronology and geodynamics implications of the Cenozoic magmatic province in western and Southeastern Ethiopia. *J.Geol. Soc. London.* **144**: 213-226.

Campbell, I.H., Griffiths, R.W. (1990). Implications of mantle plume structure for the evolution of flood basalts. *Earth Planet. Sci. Lett*. **99**: 79–93.

Conticelli, S., Sintoni, M. F., Abebe, T., Mazzarini, F. & Manetti, P. (1999). Petrology and geochemistry of ultramafic xenoliths and host lavas from the Ethiopian Volcanic Province: An insight into the upper mantle under eastern Africa. *Acta Vulcanologica* **11**: 143-159.

Davies, M., Parkinson, I. and Rogers, N. (2003). The origin of High-Ti picrites from the Ethiopian floods basalt province. *The department of Earth Science, The Open University, Walton Hall, Milton Keynes MK 6AA.*

Ebinger, C.J., Yemane, T., Woldegabrieal, G., Aronson, J.L. & Walter, R. (1993*)*. Late Eocene-Recent volcanism and faulting in the southern main Ethiopian rift. *J. Geol. Soc. London.* **150***:* 99-108.

Ellam, R.M., Cox, K. (1991). An interpretation of Karoo picrate basalts in terms of interaction between asthenospheric magmas and the mantle lithosphere. *Earth Planet. Sci. Lett*. **105**: 330– 342.

Ewart, A., Miner, S.C., Armstrong, R.A. (1998). Etendaka volcanism of the Goboboseb mountains and Messum igneous complex, Namibia. Part 1: Geochemical evidence of early Cretaceous Tristan plume melt and role of crustal contamination in the Parana-Etendaka CFB. *Journal of petrology*. **39**: 191-25.

Fodor, R.V. (1987). Low- and high-TiO2 flood basalts of southern Brazil: origin from picritic parentage and a common mantle source. *Earth Planet. Sci. Lett*. **84**: 423–430.

Furman, T. and Graham, D. (1999). Erosion of lithospheric mantle beneath the east African rift system: geochemical evidence from the Kivu volcanic province, *LITHOS.* **48:** 237-262.

Furman, T. Brayce, T. Rooney, B. Hanan, G. Yirgu and D. Ayalew. Head and tails: 30 million years of the Afar plume. From: Yirgu, G., Ebinger, C.J. and Magucres, P.K.H. (2006). The structure and evolution of the east African rift system in the afar volcanic province. *Geoogical society, London, special publication.* **259**: 97-121.

Gallagher, K., Hawkesworth, C.J. (1992). Dehydration melting and the generation of continental flood basalts. *Nature*. **358**: 57–59.

George, R.M. and Rogers, N.W. (2002). Plume Dynamics beneath the African plate inferred from Geochemistry of the Tertiary Basalts of Southern Ethiopia. *Contrib mineral petrol.* **144**: 286-304.

Gibson, S.A., Thompson, R.N., Dickin, A.P. and Leonardos, O.H. (1995). Mafic potassic magmatic key to plume-lithospheric interaction and continental flood-basalt.

Hawkesworth, C. J., Mantovani, M. S. M. & Peate, D. W. (1988). Lithosphere remobilisation during Parana CFB magmatism. In: Menzies, M. A. & Cox, K. (eds) Oceanic and Continental Lithosphere; Similarities and Differences. *Journal of Petrology, Special Issue*. 205-223.

Hawkesworth, C. J., Mantovani, M. S. M., Taylor, P. N. & Palacz, Z. (1986). Evidence from the Parana of south Brazil for a continental contribution to DUPAL basalts. *Nature* **322**: 356-359.

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

Hugh R. Rollinson. (1993). *Using Geochemical data: evaluation, interpretation and presentation.* PEARSON prentice Hall. 380pp.

Juch, D. (1987). Tectonics of the southeastern escarpment of Ethiopia. *Science special publication.* **15**: 445-503.

Kazmin,K. (1975). Exploration of Geological map of Ethiopia, Bulletin 1. Minister of mines, Energy, Water resource and Geological Survey of Ethiopia, Ethiopia, 18pp.

Kazmin, V. (1972). The Geology of Ethiopia Unpublished report , EIGS, Addis Ababa, Ethiopia.

Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Yirgu, G., Ayalew, D., Weis, D., Jerram, D. A., Keller, F. & Meugniot, C. (2004). Flood and shield basalts from Ethiopia: magmas from the African Super swell. *Journal of Petrology*.

45: 793-834.

LaTourette, T., Herving, R.L. and Holloway, J.R. (1995). Trace element partitioning between amphibole, phlogopite and basanite melt. *Earth planet.sci.Lett.* **135:** 13-30.

Luigi, B., Gianluca, B., Claudio, N. and Franca, S. (2009). Continental Flood Basalts and Mantle Plumes: a Case Study of the Northern Ethiopian Plateau. *Journal of Petrology*. **50:** 1377-1403.

MacDougall, J. D. (1988). Continental Flood Basalts. Dordrecht: *Kluwer*. 356 pp.

Mengesha, T., Tadiwos, C. and Workineh, H. (1996). *Exploration of the Geological map of Ethiopia*, 2nd ed., institute of mine and energy, Ethiopia, 83pp.

Melluso, L., Beccaluva, L., Brotzu, P., Gregnanin, A., Gupta, A. K., Morbidelli, L. & Traversa, G. (1995). Constraints on the mantle sources of the Deccan Traps from the petrology and geochemistry of the basalts of Gujarat State (western India). *Journal of Petrology* **36**. 1393-1432.

Merla, G., Abbate, E., Azzaroli, A., Bruni, P., Fazzuoli, M., Sagri, M. and Tacconi, P. (1979). Geological Map of Ethiopia and Somalia. *Comment, Pergamon*. 95 pp.

McKenzie, D.P. and Bickle, M.J. (1988). The volume and composition of melt generated by extension of the lithosphere. *J. Petrol.* **29:** 625–679.

Miranda, s. and Charles, E. (1997). Generation and polybaric differentiation of east Greenland early tertiary flood basalts. *Journal of petrology*. **38 (2):** 235-275.

Miruts Hagos, Christian Koeberl, Kurkura Kabato and Friedrich Koller. (2010). Geochemical characteristics of the alkaline basalts and the phonolite –trachyte plugs of the Axum area, northern Ethiopia. *Austrian Journal of Earth Sciences.* **103 (2)**: 153-170.

Mohr, P. and Zanettin, B. (1988). The Ethiopian flood basalt province. In: Macdougall, J.D. (ed.), Continental flood basalts, *Kluwer Academic Publishers, Dordrecht*. 63 – 110.

Mohr,P.A.(1963). The Geological map of the Horn of Africa, 2,000,000 scale. *Philip and Jaccy, London.*

Mohr,P.A. (1962). The Geology of Ethiopia. *University. Coll of Addis Ababa press*. (reprinted in 1971 Haileselassie University press), Asmera , Ethiopia. 268pp.

Pearce, J. A. and Norry, M. J. (1979). Petrogenetic implications of Ti, Zr, Y, and Nb variations in Volcanic rocks. *Contributions to Mineralogy and Petrology*. **69:** 33–47.

Peate, D.W.(1997). The Parana-Etendeka Province. In: Mahoney, Ž. J., Coffin, B. (Eds)., Large Igneous Provinces: Continental, Oceanic and Planetary Flood Volcanism. *AGU Geophys. Monogr*. **100**: 217–246.

Piccirilo, E.M., Civetta, L., Petrini, R., Longinelli, A., Bellieni, G., Comin, P., Marques, L.S. and Melfi, A.J. (1989). Regional variation within the Paraná flood basalts (southern Brazil); Evidence for sub-continental mantle Heterogeneity and crustal contamination. *chemical geology, Elsevier science publisher.* **75**: 103-122.

Piccirillo, E. M and Melfi, .J. (1988). The Mesozoic Flood volcanism of Parana basin: Petrogenetic and Geophysical Aspect Sao Paulo: *University of Sao Paulo*, 600pp.

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

Poornchandra, G.V.S., Venkateswarlu, M., Srinivasa, B. and Raviprakash,S. (2003). Mantle plumes, continental flood basalt volcanisms and paleomagnaetism. *J. Ind. Geophs. Union.* **7**: 135-144.

Richards, M.A., Duncan, R.A., Courtillot, V.E. (1989). Flood basalts and hot-spot tracks: plume heads and tails. *Science*. **246**: 103– 107.

Rochette, E., Tamrat, E., Fraud, G., Pik, R., Courtillot, V. and Ketefo, E. (1998). Magneto stratigraphy and timing of the Oligocene Ethiopian traps. *Earth and Planetary*

Science letter. **164**: 497-510.

Rooney, T.O., Hart, W.K., Hall, C.M., Ayalew, D., Ghiorso, M.S., Hidalgo, P. and Yirgu, G. (2012). Per-alkaline magma evolution and the tephra record in the Ethiopian Rift Contributions to Mineralogy and Petrology. *Contrib Mineral Petrol.* **164:** 407-426.

Simon, T. and Chris, H. (1995). The nature of the sub-continental mantle; constraints from the Major element composition of continental flood basalts. *Chemical Geology, Walton Hall, Milton Keynes.* **120**: 295-314.

Sleep, N.H. (1990). Hotspot and mantle plumes: Some phenomenology. *J. Geophy. Res.* **95 (B5)**: 6715-6736.

Sleep, N.H. (1995). A way ward plume? *Nature*. **378**: 19-20.

Solomon Gerra. (2000). A short introduction to the geology of Ethiopia, *Chronique de la Recherche minieral Na.* **540**: 2000, 3-10.

White, R. S. & McKenzie, D. (1989). Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research*. **94**: 7685---7729.

White, W.M. (2001). *Geochemistry.*700pp.

Wilson, M. (1989). *Igneous petrogenesis.* Springer, Netherlands, 466pp.

Geological Society, London, Special Publications 2006; 259. Geochemical constraints on flood basalts and rift processes retrieved from http://sp.lyellcollection.org/ at Addis Ababa University on October 4, 2012, p73-75.

Yigang Xu, Sun-Lin Chung, Bor-ming Jahn and Genyao Wud. (2001). Petrologic and geochemical constraints on the petrogenesis of Permian–Triassic Emeishan flood basalts in southwestern China. *Lithos.* **58**: 145–168.

Zanettin B, Justin Visentin E, Nicoletti M, Piccirillo EM, Carrelli, A. (1980) Correlations among Ethiopian volcanic formations with special references to the chronological and stratigraphical problems of the ‘‘Trap Series’’. Geodynamic evolution of the Afro-Arabian Rift System. *Atti dei convegni lincei*. **47**: 231–252.

APPENDIX

Table 1 and 2 Longitude, Latitude and altitudes of the sample location along section one and two respectively.

No	Sample no	Rock Name	Location	Altitude
1	HB1A1	Basalt	41^{0}03’48’’ 9^{0}10’29’’	1919m
2	HB1B1	Basalt	41^{0}03’40’’ 9^{0}10’28’’	2037m
3	HB1B2	Basalt	41^{0}03’38’’ 9^{0}10’31’’	2054m
4	HB1B3	Basalt	41^{0}03’52’’ 9^{0}10’28’’	2021m
5	HB2B3	Basalt	41^{0}03’26’’ 9^{0}10’21’’	2166m
6	HB1C1	Basalt	41^{0}03’27’’ 9^{0}10’43’’	2131m
7	HB1C2	Basalt	41^{0}03’28’’ 9^{0}10’8’’	2228m
8	HB1D1	Basalt	41^{0}03’39’’ 9^{0}11’8’’	2247m
9	HB1D2	Basalt	41^{0}03’24’’ 9^{0}10’4’’	2291m
10	Top of the flow		_	2383m

Table 1

No	Sample no	Rock name	location	Altitude
1	HB2A1	Basalt	41^{0}0352’’ 9^{0}10’28’’	2037m
2	HB2B2	Basalt	41^{0}03’28’’ 9^{0}10’25’’	2114m
3	HB2B3	Basalt	41^{0}03’26’’ 9^{0}10’21’’	2166m
4	HB2C1	Basalt	41^{0}03’24’’ 9^{0}10’13’’	2240m
5	HB2C3	Basalt	41^{0}03’23’’ 9^{0}10’4’’	2260m
6	HB2D3	basalt	41^{0}03’21’’ 9^{0}09’43’’	2420m

Table 2

DECLARATION

This Thesis is my original work and has not been presented for a degree in any other University and that all sources of material used for the thesis have been accordingly acknowledged.

Andualem Getaw

Signature ________________ date ________________

This thesis has been submitted for examination with my approval as a university advisor.

Dr. Dereje Ayalew

Signature ___________________ date _____________

Date and place of submission: July 27/ 2013, Addis Ababa Ethiopia