



Addis Ababa University  
College of Natural Sciences  
School of Earth Sciences

COMPOSITIONAL VARIATION OF ERTA'ALE BASALTIC  
ERUPTION WITH TIME

By  
**Edelawit Lemma**

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



June 2017

Addis Ababa University

Addis Ababa, Ethiopia

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SCHOOL OF GRADUATE STUDIES  
SCHOOL OF EARTH SCIENCES**

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## **Declaration of Originality**

I hereby declare that the thesis is my original master's degree work under the supervision of Prof. Dereje Ayalew, School of Earth Sciences, Addis Ababa University during the year 2017. This work has not been presented or submitted to any other university or institution for the award of any degree. All sources and materials used for the thesis have been duly acknowledged.

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## Abstract

Erta'Ale lava lake is located at the center of the Erta'Ale volcanic range in the northern afar depression. Erta'Ale is known by its two active lava lake situated at northern and central part of the caldera. The thesis generally considered the compositional variation of the Erta'Ale lava through time. Field investigation, petrographic and whole rock geochemical studies have been applied to meet the objectives. The lava of Erta'Ale volcano has MgO content ranging from (4.56-6.36 wt%) and SiO<sub>2</sub> content (47-52 wt%) which decrease with increasing of MgO. The Al<sub>2</sub>O<sub>3</sub> and CaO contents slightly increase with decreasing MgO down to ~6 wt%, and then decrease with decreasing of MgO a general positive trend for Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>. The variations diagram of the Erta'Ale lava show fractionation of mineral phase. In most of the Erta'Ale lava (Ce/Pb > 20) crustal contamination is not major process. However there are some samples which have low value of Ce/Pb ratio (<20) because of their high value of Pb . The Erta'Ale lava is characterized by low La/Nb (<1) and Ba/Nb (<5) which is the characteristics of mantle plume derived melts. Trace element data of the Erta'Ale basalt show that the source of the Erta'Ale basalt is Afar Mantle plume. The La/Nb, La/Sm and Ce/Pb versus time diagram indicate that the source, depth and degree of melting of the Erta'Ale basalt don't have a significant change with time. The geochemical results show that there is no significant compositional variation in the Erta'Ale basaltic rock. However, there is a slight chemical variation between the 2017, 2010 and the others older lava. This variation is a result of the difference in degree of fractionation.

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## **List of Acronyms**

a.s.l above sea level

CFB Continental Flood Basalt

EARS East African Rift System

GPS Global Positioning System

HREE Heavy Rare Earth Element

ICP-MS Inductively Coupled Plasma Mass Spectroscopy

ICP-AES Inductively Coupled Plasma Atomic Emission Spectroscopy

INNA Instrumental Neutron Activation Analysis

LILE Large Ion Lithophile Element

LOI Loss of Ignition

LREE Light Rare Earth Element

MER Main Ethiopian Rift

MORB Mid oceanic ridge basalt

OIB oceanic island basalt

PPL Plane Polarized Light

PREMA Prevalent mantle

REE Rare Earth Element

TAS Total Alkali Silica

XPL Cross Polarized Light

XRF X-ray Fluorescence Spectrometry

# Chapter one

## 1. Introduction

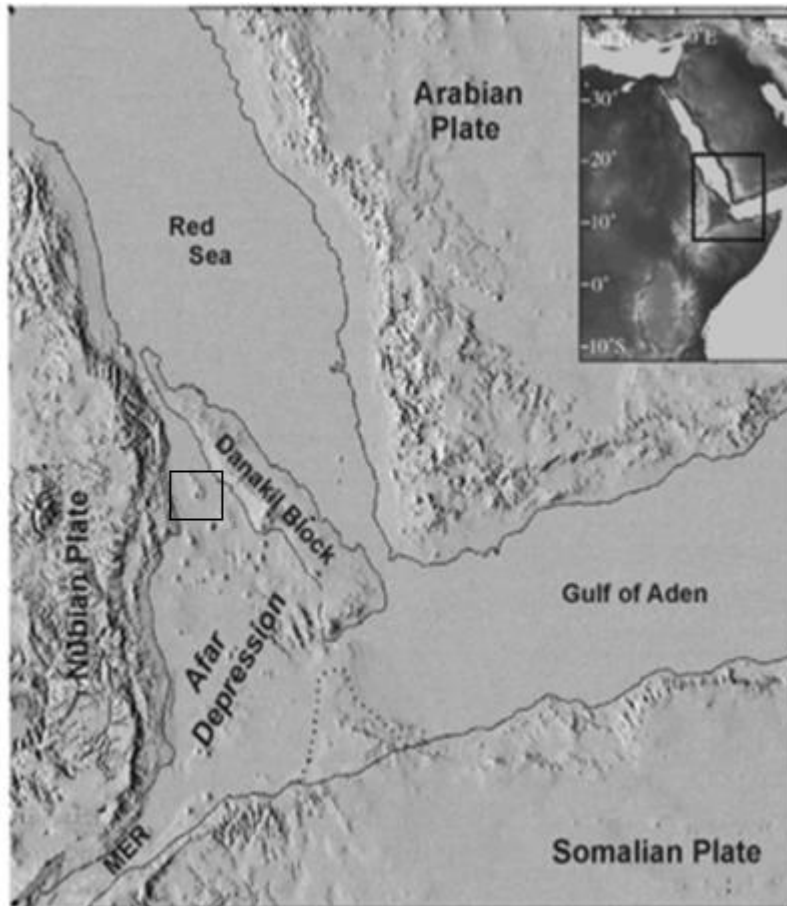
### 1.1 Background

The Afar Depression is the product of a tectonic triple-rifts junction where the spreading ridges forming the Red Sea, Gulf of Aden emerge on land and meet the East African Rift (Beyene Alebachew and Abdelsalam, 2005). The Afar Triple Junction is located along a divergent plate boundary dividing the Nubian, Somalian, and Arabian plates. This area is an example of continental rifting leading to seafloor spreading which leads to the production of an oceanic basin (Chorowicz, 2005). The region constitutes the three arms of the spreading centers (the Red Sea, Gulf of Aden and the MER) which are not uniformly evolved (Miruth Hagoes et al., 2010).

Beyene Alebachew and Abdelsalam, (2005) stated that high heat and mass ascent underneath an anomalous upper mantle caused the raise of the Afar Dome, volcanism, and rifting. Gezahegne Yirgu et al. (2006) imply that Afar volcanic province has experienced a long and complex history of basaltic and felsic volcanism since 45 Ma. According to Barrat et al. (1998) the northern part of the Afar depression (Danakil depression) is characterized by intense tectonic and volcanic activity. Volcanism is bimodal in the southern and central Afar it is either fissure fed basalt or silicic central volcano (Lahitte et al., 2003).

In about 1 Ma. ago the formation of new oceanic crust become obvious in Afar because of this there is a development of a series of basaltic volcanic range built along an active axis (Barberi et al., 1974). The Erta'Ale Range is one of the volcano-tectonically active segments of the East African rift system (EARS) and the range is composed of seven volcanic centers that are aligned NNW-SSE Gada Ale, Alu, Dalaffilla, Borale Ale, Erta'Ale, Ale Bagu and Hayli Gub. (Miruth Hagos et al., 2016). Erta'Ale is a basaltic shield volcano located at the center of the Erta'Ale range within the Danakil Depression (Field et al., 2012). It rises 700m above the Danakil depression (Oppenheimer and Francis, 1997). Erta'Ale is known for its active lava lakes situated in the northern and southern pits within a main 0.7×1.6-km elliptical summit crater which have both contained lava lake (Field et al., 2012). The Erta'Ale lava lake is one of the four long lived lava lake in the world which are Erebus of Antarctica, Nyiragongo of DR. Congo

and Ambrym of Vanuatu (Field et al., 2012). However Erta'Ale lacks extensive investigation because of its difficult climate condition and political problems that prevented almost any access to the area before 1960s this shows a clear discontinuity in the literature and most of the published work was based on the remote sensing data rather than field work (Harris et al., 2005).



*Figure 1.1 Regional view of Afar depression (after Collet et al., 2000 and Miruth Hagoes et al., 2010) the small rectangle in the Afar depression represent Erta'Ale.*

## **1.2. Location and Accessibility of the study area**

The research project is conducted in the northeastern Ethiopia, in Zone two administration of Afar Regional State. Specifically the study area is located in the northern part of the Afar depression in the Erta'Ale volcano. The study area is located 779 km from Addis Abeba city and 200 km from the Samera town which is the center of the Afar region. The Afar region is a remote and challenging area to do field work, it is known by its inhospitable climate condition. The study areas is a difficult place to access before but know with help of the Afar region administration and the local people the area become accessible to the tourist and for the researchers.

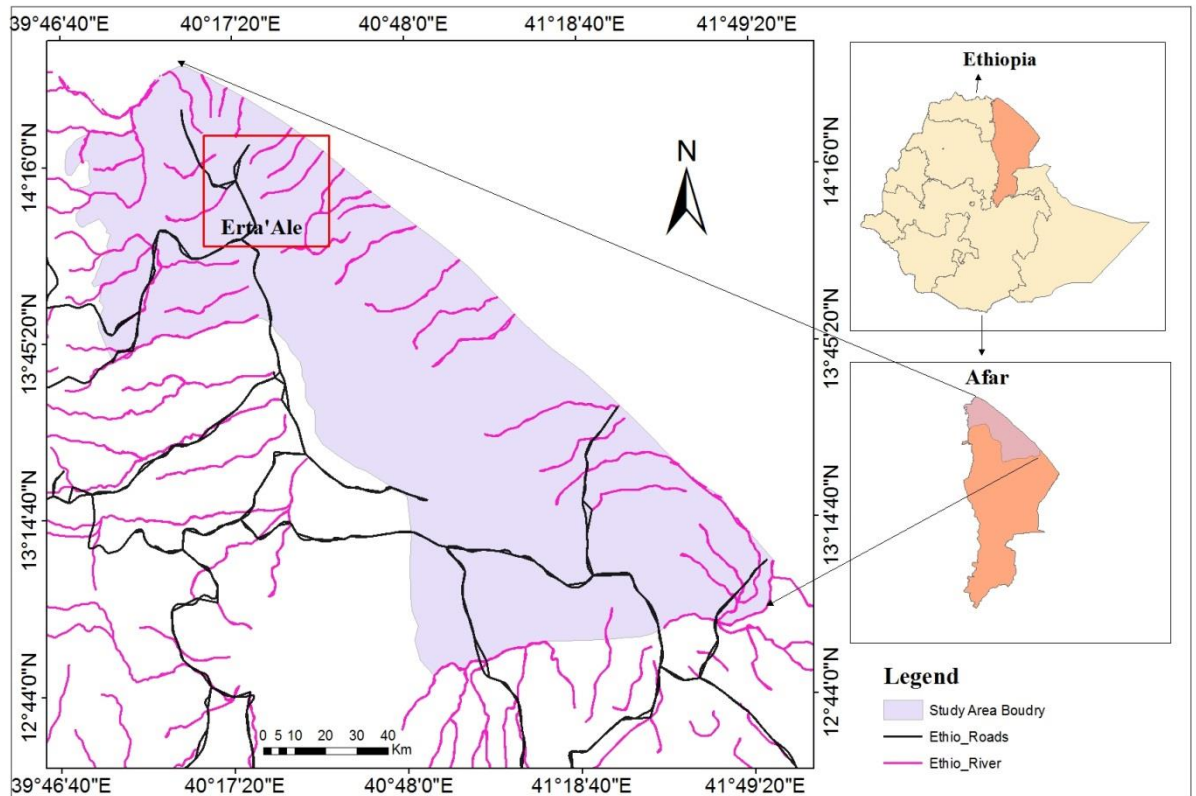


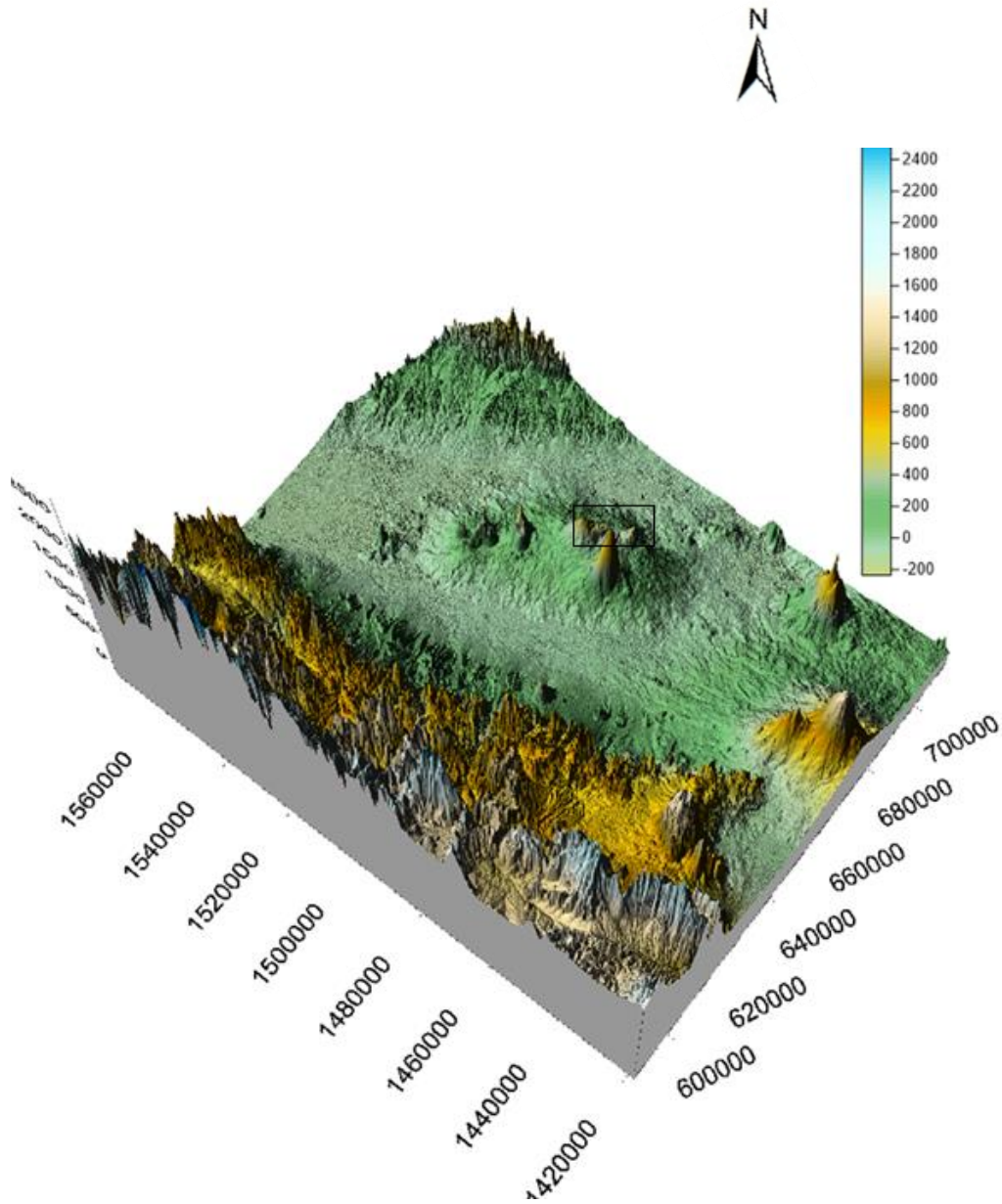
Figure 1.2 Location map of the study area

### 1.2.2 Climatic condition and Vegetation

The study area is climatically categorized as arid with temperatures vary from 30<sup>0</sup>c in highlands to 48<sup>0</sup>c in lowlands. The area receives an annual rain fall of less than 500mm. Even though not much, significant vegetation types are found comprising of riverain wood land, bush land, shrub land, grass land, seasonal marshes and swamps.

### 1.2.3 Physiographic and Drainage

The Afar depression covers an area of 200,000 km<sup>2</sup> (Beyene Alebachew and Abdelselam, 2005) and it is bordered on the west by the Ethiopian escarpment on the east and north east by the Danakil Microplate and on the south by the Somalian plateau (Miruth Hagos et al., 2010).



*Figure 1.3 Physiographic map of the Ert'a Ale volcano and its surrounding. The rectangle is the study area*

#### **1.2.4 Population and settlement**

The 2007 Ethiopia census reports suggest that 1,276,374 Afar people live in Ethiopia (Geological survey of Ethiopia, 2015). They are nomadic or transhumance (moving from highland to lowlands with the seasons and rise and fall of the flood waters of the rivers). They carry their houses with them and reassemble them when they make temporary settlement. The volcano erupted many times in the last century and killed hundreds of livestock and forced evacuation of the local people.

### **1.3. Statement of the problem**

As it is known Erta'Ale is one of the persistent lava lakes in the world and because of this it continues attracting the attention of volcanologists and petrologiest. However Erta'Ale lacks extensive investigation because of its difficult climate condition and political problems that prevented almost any access to the area before 1960s this shows a clear discontinuity in the literature and most of the published work was based on the remote sensing data rather than field work (Harris et al., 2005). After 1960s the published chemical analysis of basalt from Erta'Ale volcano for example are Barberi et al. (1974), Bizouard et al. (1980) and Barrat et al. (1998) and they suggest that the main product of the Erta'Ale volcano is a transitional basalt which is in neither tholeiitic nor alkali (Field et al., 2012). Erta'Ale volcano is one of rift related volcano in the area. The Erta'Ale range volcanoes are mostly studied regionally by different authors (e.g. Bizouard et al., 1980, Barrat et al., 1998 and Barberi and Varet, 1970). However, detail studies on the Erta'Ale shield volcano are rare. In this study the Erta'Ale volcano product at different time will be studied. The major goal of this research project is to understand the compositional variation of the Erta'Ale basaltic eruption with time by analyzing the different kind of lava flows that is found in the area.

### **1.4. Objective of the study**

#### **1.4.1. General objective**

The general objective of this research is to understand the compositional variation of Erta'Ale basaltic eruption through time.

#### **1.4.2. Specific objective**

- To characterize the petrography and geochemistry of the rock
- To distinguish the petrogenic process involved in the generation of this rock
- To trace the mantle source of the rock

### **1.5 Methodology**

#### **1.5.1 Introduction**

The study will be conducted through several different consecutive steps to achieve the final set goals. The methodology that will be followed throughout the whole research work can be divided into three steps; pre fieldwork, field work and post field work. In the pre field work relevant literatures have been reviewed in order to have a general overview

about the geology of the study area and surrounding regions. This part provides important and solid information about the area what other authors did and recommended to be done earlier. In this pre field work activity most of the material, instrument and data that are used during the field work are gathered. During field work collection of appropriate, type of data and sample size of rock for petrographic and geochemical analysis is done. The data that area collected during the field work are analyzed, synthesized, interpreted and presented in the post field work.

For this research work two types of data are collected primary and secondary data. For the primary data that are collected during the field work which is in this case the rock sample are analyzed for both geochemical and petrography study. The secondary data that are collected from different literature which are specifically work on the area is used for comparison. All the data that are collected during the field work and from the literature reviews are analyzed, interpreted and presented together.

### **1.5.2 Field Work**

Field work is one of the main ways for collecting data. The field work is done in January 2017. The main aim of this field work is to collect different representative sample of the Erta'Ale basaltic eruption product at different time for laboratory analysis (Petrographic and Geochemical analysis). During the field work the sample collected are from the major lava flows found within the crater therefore, minor lava flows which are difficult to differentiate in the field are not include or sampled.

### **1.5.3. Laboratory analysis**

#### **1.5.3.1 Petrographic analysis**

For petrographic analysis six samples are selected and prepare in the geological survey of Ethiopia. The petrographic examinations were conducted at petrology laboratory of school of earth science, Addis Abeba University. Each rock sample is studied under thin section for its mineralogical make up based on the optical properties of the minerals. The main output of the thin section is the modal proportion of mineral. The information from the petrographic analysis is correlated with the geochemical analysis result of sample of its type.

#### **1.5.3.2 Geochemistry analysis**

The rock samples that were selected for geochemical analysis were prepared in the geological survey of Ethiopia. The pulverized samples were shipped to ALS Services,

Loughrea located at Dublin road, Louhrea, Co. Galway, Ireland for whole rock analysis using complete characterization package that include both ICP- MS and ICP-AES. ICP MS was used to analyse trace elements and ICP AES is used for major element analysis in their oxide form with LOI. The final result is interpreted to understand the petrogenic process, the source of the mantle and finally to understand the compositional variation of Erta'Ale basaltic eruption through time.

### **1.6. Significance of the research**

This research project is particularly design to see the compositional variation of the Erta'Ale basaltic eruption with time by using the product of the eruption basalt based on their petrography and geochemical properties. To do this different literature will be reviewed and used to compare the result of the composition of the product of the basaltic eruption with this research result and see the change in composition through time.

The main expected researches out puts are will be as follows:

- A clear understanding on the recent lava flow in the area based on petrography and geochemistry.
- An interpretation based on the geochemical analysis to understand the petrogenic process involved in the generation of this rock and to trace the source of the mantle.
- Characterize the 2017 and 2010 lava based on their geochemical and petrographic study from the other lava flows.

Once this research is done there will be a clear understanding of the compositional change on the basaltic eruption that occurs in the area in different eruption time. This research can fill the gap in the study of the Erta'Ale basaltic eruption and also help us to understand the source of the mantle and petrogenic process.

### **1.7. Previous work**

The Afar depression in Ethiopia marks the intersection between the Red Sea, Gulf of Aden and East African Rift systems (Barberi and Varet, 1970). Quaternary magmatism is largely confined in Afar Depression, and axial zones of MER (Vidal et al., 1999). The Erta'Ale Range is one of the volcano-tectonically active segments of the East African rift system (EARS) and it is a host of seven shield volcanoes and Erta'Ale is one of them. Erta'Ale volcano is one of the persistent lava lakes in the world however; it lacks investigation because of its inhospitable climate condition and political problem before 1960s (Harris et al., 2005). After 1960s the published chemical analysis of basalt from

Erta'Ale volcano suggest that the most abundant product of the Erta'Ale volcanic rock is a transitional type of basalt which is neither typically tholeiitic nor alkali and fall within transitional field between the two main magma series (Barberi et al., 1974 ; Bizouard et al., 1980 ). On the other hand according to Miruth Hagos et al. (2010) basalts from the Danakil Depression are entirely transitional alkali to tholeiitic and are resemble the Oligocene flood basalt of northwestern Ethiopia.

As already stated in Barberi and Varet, (1970) the Erta'Ale volcanic rocks form a complete differentiation series from basalts to alkaline and peralkaline rhyolites. The Erta'Ale volcanic rock sequence is produced by fractional crystallization of the parental magma in shallow magma chamber (Barberi et al., 1974). During fractional crystallization we see variation in solid phase (olivine, plagioclase, pyroxene) with transition from calcium rich to sodium rich and from magnesium rich to iron rich crystals when evolution of the coexisting liquids from basalt to alkali rich rhyolite (Bizouard et al., 1980). Petrographic study of Erta'Ale as already stated in Bizouard et al. (1980) show us plagioclase is the dominant mineral in the crystallization sequence, olivine separates mainly at the early stage, opaque minerals separate at the intermediate stage and rhyolites can be obtained by crystal fractionation of the associated basalts.

Field et al. (2012) imply that the 2010 lavas are olivine-normative, whereas the older underlying lava most likely from the 1973 eruption is quartz normative. The mineral assemblage in the 2010 samples is plagioclase, clinopyroxene and olivine (Field et al., 2012). The parent magma of the Erta'Ale volcanic rock is the most abundant product of the series which is transitional basalt (Barberi and Varat, 1970). Barberi and Varat, (1970) imply that magma fractionation has been realized at relatively shallow depth and time is an important factor in the differentiation process. The petrological and isotopic data show that the volcanic products of the Erta'Ale ranges have been considered to be of sub crustal origin, without any appreciable contamination with crustal material (Barberi and Varet, 1970). The study of the isotope and incompatible trace element ratio of the basalt suggest that there is a difference in their mantle source (Barrat et al., 1998). Volker et al. (1997) imply that isotopic compositions of Afar volcanic rocks data, indicating mantle source areas with small-scale isotopic heterogeneities and/or contamination with continental crust. Afar Petrogenetic modeling shows that melts are predominantly generated at depths greater than 80 km, indicating the existence of a thick upper thermo-mechanical boundary layer in a rift system approaching the point of plate rupture (Ferguson et al., 2013).

Different authors have examined lava lake dynamics focusing on gas and thermal budgets, seismicity, description of surface features, and eruptive style at Erta'Ale (Le Guern et al., 1979; Oppenheimer and Francis, 1997; 1998). The high heat flux and exogenous growth rate are indicative of a volcano that grows largely by magmatic intrusion which is consistent with the formation of new crust in the extensional tectonic environment of northern Afar (Oppenheimer and Francis, 1997).

# Chapter two

## 2. Regional geologic setting

### 2.1. The Afar depression

The Afar depression and Main Ethiopian rift are part of the East African Rift System (EARS) (Miruth Hagos et al., 2010). The East African Rift System (EARS) a place where the earth's internal (active and passive) forces are currently trying to create new plates (e.g., the Somalian and Danakil Microplates) by splitting apart the old African plate (Miruth Hagos et al., 2010). The East African Rift System (EARS) is extended from southern Tanzania and Lake Malawi, where the African continent begins to break apart, northward to the Afar Triple Junction, where the on-land Danakil Depression meets the oceanic spreading ridges of the Red Sea and Gulf of Aden (Castillo et al., 2014).

The Afar Depression is an incipient region of continental to oceanic transitional crust situated at the junction of two new oceanic rifts (Gulf of Aden and Red Sea Rifts) and continental rift (Main Ethiopian Rift) (Atalay Ayele et al., 2009). The Afar depression is the youngest magmatic margin in the world (Hammond et al., 2011). It is triangular in shape and covers an area of 200,000 km<sup>2</sup> (Beyene Alebachew and Abdelsalam, 2005) and it is separated from the elevated areas of the Ethiopian Plateau to the west, the Southeast Plateau and Ogaden to the south, and the Danakil Horst to the east by fault controlled escarpments (Makris and Ginzburg, 1987). Age determination for the initiation of the Afar rift indicates that it is probably around a period of Lower Miocene (i.e., 25 my) (Barberi et al., 1972). According to Hofstetter and Beyth, (2003) the fault plane of the Afar depression is strike-slip and normal originating from fault planes striking NW–SE which indicate a clockwise block rotation or bookshelf model in central Afar depression.

The nature of the Afar Depression lithosphere is a debatable issue and several authors have described the lithosphere of the Afar Depression to be oceanic, continental, and transitional and even a new continental lithosphere (Beyene Alebachew and Abdelsalam, 2005). Geophysical data reveal that the crust of the depression is an oceanic-type, whereas geochemical data confirms that the nature of the Danakil Depression crust is not yet an oceanic crust type (Miruth Hagos et al., 2010). According to Miruth Hagos et al. (2010) the Danakil depression is not a full stage of oceanic crust because the contents of

highly incompatible trace elements, REE, and their ratios are much higher than the contents of the Red Sea and Gulf of Aden basalts.

The Afar crust has an intermediate thickness between normal continental and oceanic crusts. However, it maintains the characteristic seismic velocities of a continental crust (Makris and Ginzburg, 1987). The lithospheric thickness is not uniform throughout the Afar depression (Miruth Hagos et al., 2010). Stuart et al. (2006) estimated the thickness of the lithosphere to be ~26 km in the southern and central Afar and gradually decreases towards the north reaching a minimum of 14 km in the Dallol area. Hammond et al. (2011) estimated that beneath rift-rift-rift triple junction there is a thin crust ~26 km in the south to ~16 km in the north and it is bounded by thick crust, ~40–45 km beneath the western plateau and ~35 km beneath the southeastern plateau.

The geology of the Afar Depression and its margins is of great interest because it may represent the complete sequence of rocks from the late Proterozoic to the present and it is also an excellent site of depositional environment (Miruth Hagos et al., 2010). The basaltic rock of the Afar are not homogeneous chemical differences may result because of the variation in stage of rifting, magmatic sources, and possibly the degree and depth of melting (Miruth Hagos et al., 2010). According to Beyene Alebachew and Abdelsalam, (2005) the geological units of the Afar Depression and marginal areas can be divided into four broad groups.

### **2.1.1. Neoproterozoic basement, Mesozoic sedimentary rocks, and Eocene-Miocene basalts**

The pre rift group Neoproterozoic basement is part of the Arabian Nubian Shield and Mesozoic sedimentary rocks which get younger towards the south and south west of the Ethiopian and Somalian plateau (Beyene Alebachew and Abdelsalam, 2005). However, these pre rift groups are either doesn't exist or covered by the Pliocene quaternary volcanic and sediment (Beyene Alebachew and Abdelsalam, 2005).

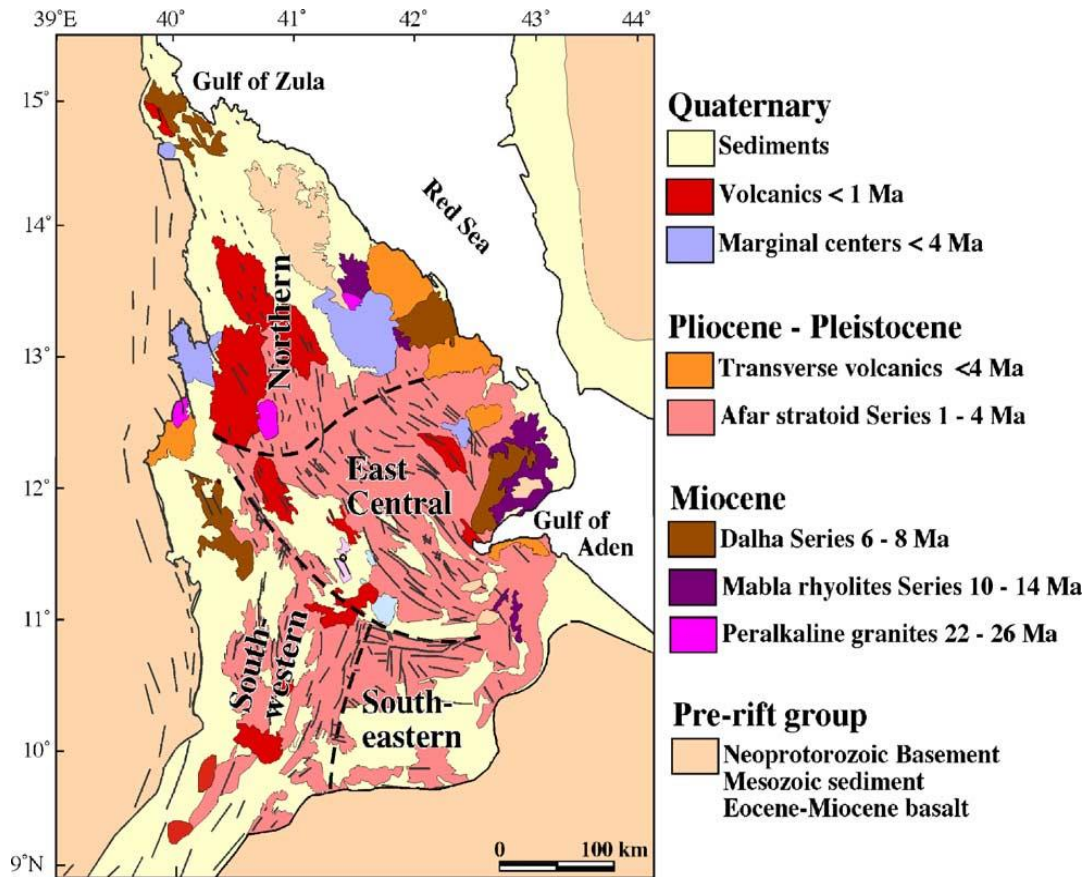


Figure 2.1: Geological map of the Afar depression and the geologic units found in the area are described with their age adopted from Beyene Alebachew and Abdelsalam, (2005)

### 2.1.2 Miocene igneous rocks

Eocene–Miocene flood basalts cover the Mesozoic sedimentary rocks on both the Ethiopian and the Somalian Plateau and the flood basalt found in the afar depression is ~25-15 Ma and the Alkaline to per alkaline intrusive rocks are found along eastern and western margin and in the northern part of the Afar depression (Beyene Alebachew and Abdelsalam, 2005). Beyene Alebachew and Abdelsalam, (2005) imply that Mabla and Dalha Series are the younger Miocene igneous rock with in the Afar Depression

### 2.1.3. Pliocene volcanic rocks

Pliocene – Pleistocene volcanic rock are the most important geologic unit which cover most of the Afar depression and the most important series of the rock is the Afar Stratoid series which cover more than two third of the Afar depression (Beyene Alebachew and Abdelsalam, 2005). Barberi et al., (1974) suggest that about 2/5 of these volcanic rocks

are basalts frequently found to be porphyritic, vesicular, and tholeiitic in their geochemical nature.

#### **2.1.4. Quaternary volcanic and sedimentary rocks**

The shield volcanoes of the northern Afar are belonging to the quaternary volcanic rocks of the Afar depression and Quaternary sedimentary rocks in the Afar Depression are dominated by lacustrine deposits (Beyene Alebachew and Abdelsalam, 2005). Barberi and Varat, (1970) imply that the northern part of the Afar depression is covered by sedimentary detrital rocks, evaporites and extensive lava field.

Despite the difference in tectonic environment Afar and Iceland are the two places in the world to study Mid Oceanic ridge on land and there are distinct similarities in the volcanic rock produced (Betton and Civetta, 1984).

#### **2.2 Afar volcanism**

In Afar three types of volcanism can be distinguished and Peralkaline silicic rocks have been found in each of them (Barberi et al., 1974; 1972). The first one is volcanism of oceanic nature this type of volcanism is found in the rift axes of the Red sea and Gulf of Aden and the peralkaline rock in this case are formed from the fractionation of basaltic magma (Barberi et al., 1972). The second one is continental volcanisms which are formed along the margin of the rift and the peralkaline rocks found in this margin show contamination by sialic crust (Barberi et al., 1974; 1972). According to Barberi et al. (1972) the other group of volcanism developed in central and southern Afar rifts is stratoid volcanism which has the petrological sequence of mainly transitional basalt and rhyolite. Their similarities with the sequence of the Main Ethiopian rift are the result of widespread fissural activity (Lahitte et al., 2003).

According to Vellutini, (1990) the major episodes of volcanism in the Afar depression can be summarized as follows: 1) the oldest volcanic units older than 25 Ma are formed by fissure flood basalts overlying a Mesozoic sedimentary sequence; 2) two periods of extensive rhyolite volcanism occurred between 25 -19 Ma and ~14 - 9.5 Ma; 3) The thick basaltic Dalha series erupted between 9-4 Ma partly cover the rhyolitic series; 4) the stratoid series which cover the Dalha series and 5) the recent fissure basalt outcrops in linear narrow zones.

#### **2.3. The Erta'Ale Range**

All the shield volcanoes and fissure basalts in the Danakil Depression erupted in a very short time period (late Quaternary/Holocene) and are emplaced very close to each other in

a single and tectonically homogeneous segment, the Erta'Ale Range (Miruth Hagos et al., 2010). The Erta'Ale volcanic range is elliptical in shape which covers an area of 2350 km<sup>2</sup> from the Salt plain in the north up to Lake Giulietti in the south (Barberi and Varat, 1970). Erta'Ale axial range is found to the east of the Ethiopian plateau which is ~2500m above sea level and the west of Danakil Alps which is ~ 1000m a.s.l (Acocella, 2006). The Range has a mean elevation of several hundred meters a.s.l, rising above a plain of evaporite and lacustrine deposit (Acocella, 2006). The Range is located in the south of the Dallol Depression; the thickness of the continental crust in the range is < 15 km (Miruth Hagos et al., 2010).

Betton and Civetta, (1984) stated that volcanism in Afar has been focused in to discrete axial and transverse ranges during the last 1Ma. The axial ranges are short oceanic type spreading segment which are produced by fissure eruption of theolitic basalt and represent the accreting plate margin within Afar and transverse ranges are lineaments marked by the alignment of basaltic flows and scoria cones, transverse to the main tectonic trend of the Afar depression (Betton and Civetta, 1984). The Sr isotopic compositions of the basalts from the Afar axial are enriched in LILE and transverse are relatively depleted (Barberi et al., 1980).

The axial rang which is the zone of the quaternary extension and magmatism is marked by cluster of voluminous fissure basalt and basaltic shield volcanoes of transitional in composition (Hayward and Ebinger, 1996). The entire surface of the range is covered by volcanic product which form a complete differentiation from basalt to alkaline and peralkaline rhyolite (Barberi and Varat, 1970). According to Miruth Hagos et al. (2010) throughout the Erta'Ale Range the basaltic outcrops are younger than 100 ka, fresh, and hypocrySTALLINE.

In the Danakil depression volcanism has been important since Pliocene (Miruth Hagos et al., 2016). Now most of the volcanic activity is localized to the axial zone forming three spectacular volcanic chains the Erta'Ale, Alayta and Tat'Ali (Barrat et al., 1998). The Erta'Ale range volcanic centers are found ~10 km intervals in the NNW-SSE direction and linked by a 10-km-wide zone of short sub vertical faults (Hayward and Ebinger, 1996). Active normal faulting and volcanism which is mainly basaltic in composition are common in the axis of the Erta'Ale range (Acocella, 2006). Hayward and Ebinger, (1996) state that the range in Afar is an excellent place to study the transition of continental rifting to sea floor spreading.

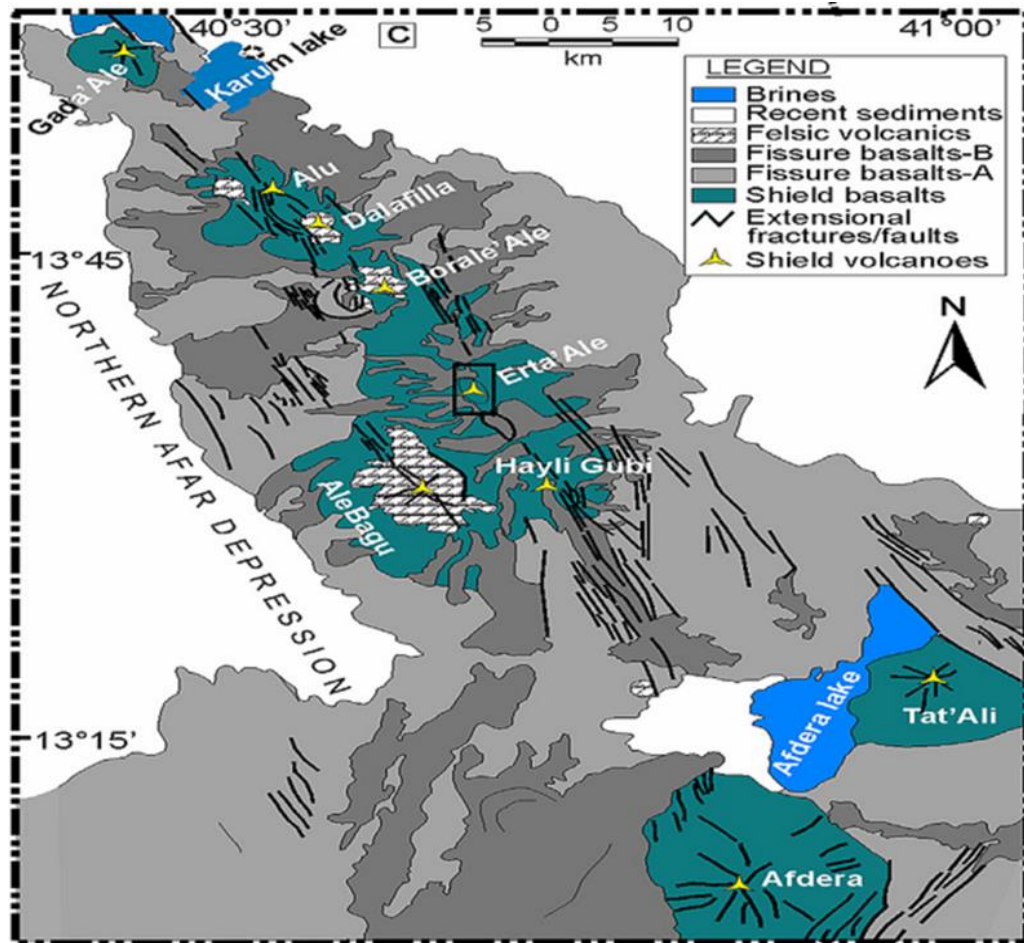


Figure 2.2: Geological map of the northern Afar/Danakil Depression which also show the seven Erta'Ale range volcanoes including Erta'Ale volcano which is the study area (after Miruth Hagos et al., 2016 pp. 30).

The central part of the range is a host of the active lava lake (Erta'Ale lava lake) which is characterized by intense tectonic and volcanic activity (Miruth Hagos et al., 2010). Miruth Hagos et al. (2010) propose that the Erta'Ale and Ale Bagu basalts with contrasting petrological and geochemical characters they have similar  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, which indicates that the Danakil Depression basalts are derived from a single reservoir, prevalent mantle (PREMA), which is commonly called the hot mantle plume source. In According to Miruth Hagos et al. (2010) based on  $\text{TiO}_2$  and incompatible trace element contents, the basaltic suites of the northern Afar depression can be broadly divided into three magma groups: (1) Low-  $\text{TiO}_2$  tholeiitic basalt characterizes the Erta'Ale and Alu-Dalaffilla shield basalts. (2) High- $\text{TiO}_2$  transitional alkali basalt characterizes the AleBagu and Afdera shield basalts. (3) Erta'Ale fissure-fed basalt lies in between the

above two magma group. Depend on mineralogy and morphology according to Miruth Hagos et al., (2016) the volcanic rock of Erta'Ale range is divided in to three major series: The Fissural basalt series, Erta'Ale–Alu Shield Volcanoes and AleBagu–Afdera Shield Volcanoes.

#### **2.4. Erta'Ale Lava Lake**

The Erta'Ale lava lake lies at the center of the Erta'Ale axial volcanic range in the northern part of the Afar depression. The summit of the Erta'Ale caldera is 1600m \* 700m in dimension (Oppenheimer and Francis, 1997). The caldera wall is completely visible and it entirely covered by a homogeneous pile of sub horizontal basaltic lava flows and it is characterized by along-rim and across-rim structures, which result from the local and regional stress fields (Acocella, 2006). The flanks of the volcano are gently sloping and fresh, whereas the inner walls of the caldera form ~30-m-high cliff made of different layers of basalt lava (Miruth Hagos et al., 2016).

The lava lakes of Erta'Ale have been erupting continuously since 1967 making it one of the world's most active volcanic regions (Thurmond et al., 2006). According to Oppenheimer and Francis, (1997) one or more of the Erta'Ale lava lakes has probably existed for the last century. The volcano erupted many times since and killed hundreds of live stocks and forced evacuation of the local people. Persistent lava lake like Erta'Ale lava lake are connected to a deeper source region, the resupply of heat prevents continuous propagation of a solidification front downwards from the lake surface (Oppenheimer and Gezahegne Yirgu, 2002). Spampinato et al. (2008) imply that persistent lava lake such as Erta'Ale shows us the upper most part of an active magmatic system at surface. The longevity of the lava lake provides evidence for convective circulation between the lake and a deeper magma reservoir (Oppenheimer and Francis, 1997).

Watson et al., (2004) suggest that different and large amount of gas can be produced from eruption of volcano (H<sub>2</sub>O, SO<sub>2</sub>, CO<sub>2</sub>, HCl, HF, and HS). According to Oppenheimer and Gezahegne Yirgu, (2002) the heat loss from Erta'Ale lava lake differ from 100-400 and 14-17 MW, respectively and it is supported by crystallization and drive convection between the lake and a deeper and larger magma reservoir. The Erta'Ale shield basalts along the rift axis are derived from a shallower magma chamber (Pagli, C et al., 2012; Miruth Hagos et al., 2010). Concurrent with the geodynamic setting of the area, the low frequency of effusive eruptions (beyond the lava lake pits) suggests that the volcano

growth is mainly due to endogenous processes (magmatic intrusion) as suggested by Oppenheimer and Francis, (1997).

#### **2.4.1 Synthesis of Erta'Ale activity**

According to Barnie et al. (2016) Franco-Italian field campaigns were the first to visit Erta'Ale by ground observation between 1968 and 1973, during which both the lava lakes were exist. The geologist Pastori.T is attracted by a red glow on Erta'Ale in 1906 and he tried to reach the summit but it was unsuccessful however, since 1940 occasional flights over the volcano have exposed activity in the lake (Le Guern et al., 1979). As already stated in Le Guern et al., (1979) two active lava lake are found in the caldera, one in the north and the other near its center and the southern part of the lake is covered by lava flows.

In December 1969 a red glow was observed without active lava fountain through open fissures (Le Guern et al., 1979). The lake level of the northern lava lake was 30m higher than in 1969 and the red color of the lava could be seen in daylight in December 1970 (Le Guern et al., 1979). Le Guern et al., (1979) imply that the lake level had risen further in January 1973 with both lava lakes overflowing several times.

In 1973 both the northern and central lava lakes were substantially infilling the north central and southern caldera lobes (Oppenheimer and Francis, 1997). According to Oppenheimer and Francis, (1997) there is no any lava flow between 1984-1995 the lake level appear to have a steady state around 100 m below the caldera floor. Fluctuation of the lake level from the year 1968 up to 1974 is described by Le Guren et al. (1979), the 1994/1995 lake level fluctuation is described by Oppenheimer and Francis, (1997) and the 2009/2010 lake level fluctuation is Field et al. (2012) are described in the figure below. Because of the new basaltic lava flow which was not cold enough there was no any chance to go near and see the 2017 lake level.

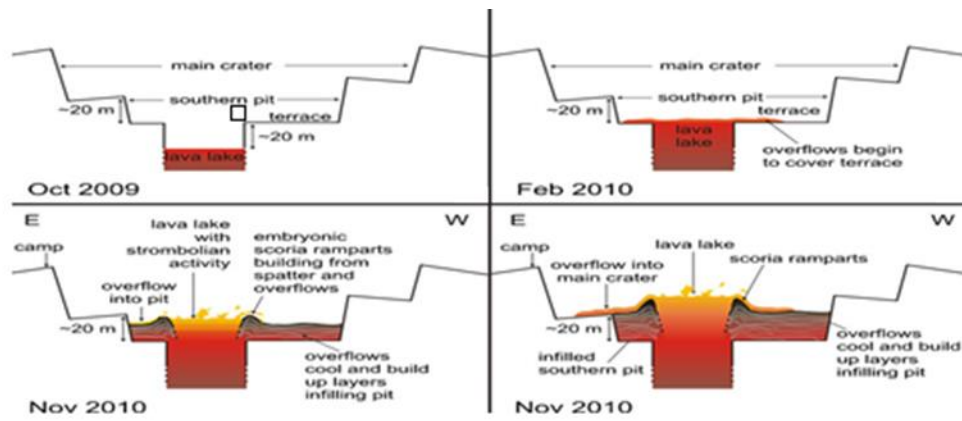


Figure 2.3 Fluctuation of the central pit lava lake level in the 2009/2010 year adopted from Field et al. (2012)

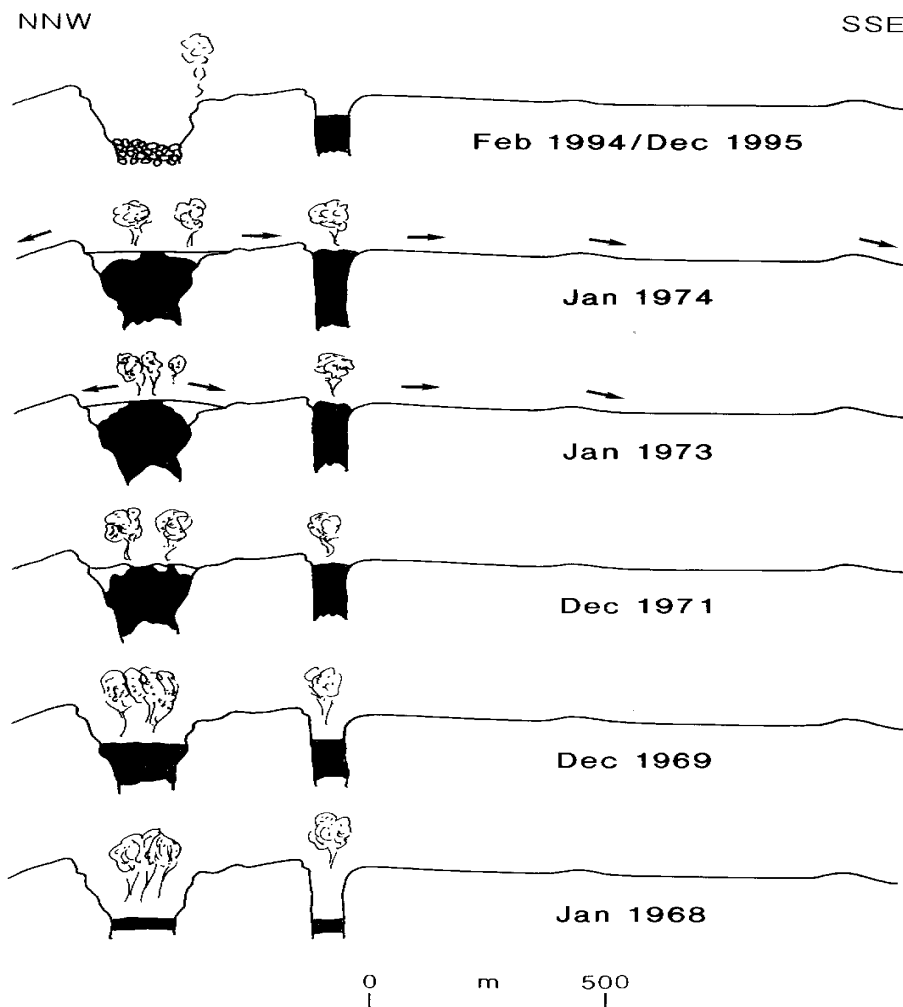


Figure 2.4: Fluctuation of the lake level of the Erta' Ale lava lakes from in the year 1968 up to 1974 by Le Guren et al. (1979) and the 1994/1995 lake level fluctuation by Oppenheimer and Francis, (1997)

# Chapter Three

## 3. Lithology and Petrography

### 3.1. Introduction

Erta'Ale shield volcano is located at the center of the Erta'Ale range and rises 613m above sea level. The summit caldera of Erta'Ale volcano is a host of two active lava lakes (the northern and central pits) which have both contained lava lakes. Despite the two lava lakes in the area there is another active volcano formed in the area during the field visit. The rock units described here are the result of the Erta'Ale shield volcano. The major lithological units are; 2017 lava, 2010 lava, Basalt 3, Basalt 4, Basalt 5 and Basalt 6. The volcano is erupted many times in the last century as a result the lava that cover the whole area is produced. Overspills of lava with in the summit caldera forms eventually flowing of lava for a short distance down the volcano flank which are responsible for the formation of the different lava in the area.

In this research we have the 2017 lava, the 2010 lava and others which age are not exactly known but older than both the 2017 and 2010 lava flow are included. But for some of the lavas depending on their position their relative age are known.

The observation of the lava lake was made days after a new lava flow occur which is responsible for the formation of the 2017 lava. According to the local people there was a fluctuation of the lake level and once the lake level was high enough there was a small lava flow once awhile. The basalts are slightly to highly vesicular but massive basalts are also abundant.



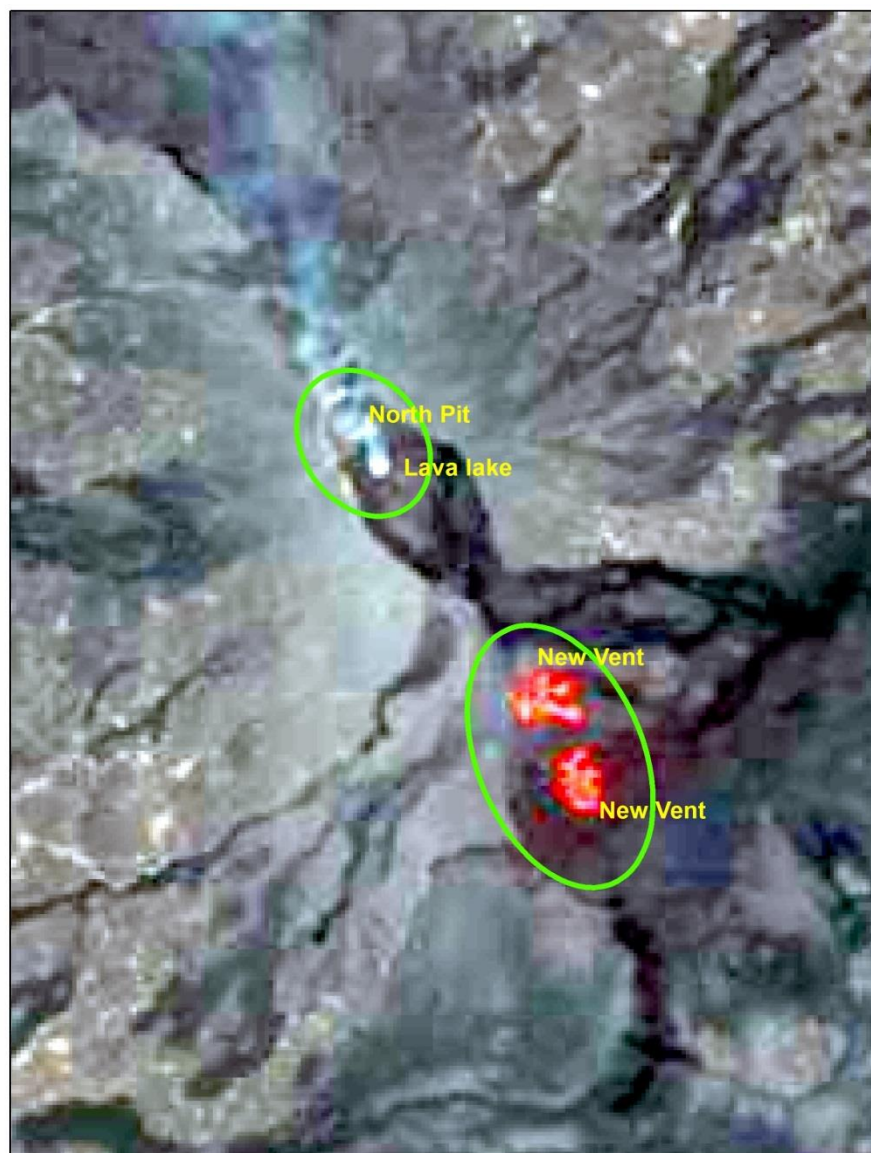
*Figure: 3.1 Filed photograph of the extent of the November–December 2010 eruption lavas*



*Figure 3.2: Satellite image of Erta'Ale volcano. The satellite image of the 2017 lava (March 10, 2017)*

### 3.1.1 The new erupted active volcano

The Erta'Ale lava lake is one of the persistent lava lake in the world. During the field work there is another volcano discovered days before the field visit which is ~3km far from the lava lake. This active volcano is first discovered by the local people and it approximately covers 1.5 km<sup>2</sup> and found south of the Erta'Ale lava lake. According to the local people there was no change on the Erta'Ale lava lake in lake level or other things which can be used as an indicator for the formation of the new active volcano. However, after the eruption of the new volcano there is only smoke on the Erta'Ale lava lake and because of the new basaltic lava flow which was not cold enough there was no any chance to go near and see the lake level.



*Figure 3.3 Satellite images of location of Erta'Ale volcano and the other active volcanoes in the area on (January 26, 2017)*



*Figure 3.4 Photograph of the new erupted active volcano at night from distance which is found south of the Erta’Ale lava lake. Photographed on (February 02/017)*



*Figure 3.5 Photograph of the locations of the Erta’Ale lava lake and the new erupted active volcano. Photographed on (February 02/017)*

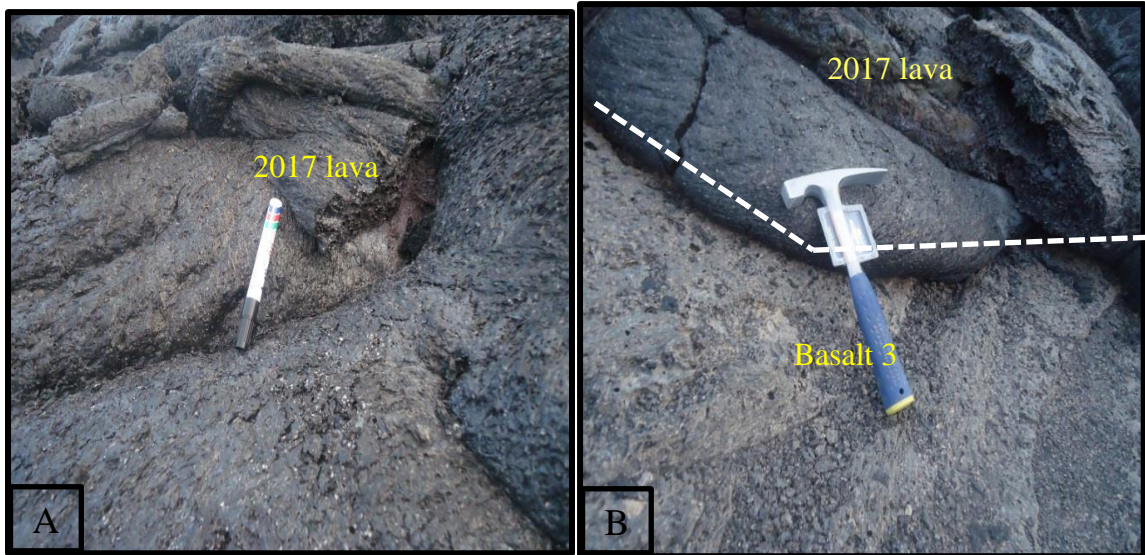
### **3.2. Lithology and Petrography Description**

#### **3.2.1. The 2017 lava flow**

The lava flow occurs in January 2017 and covers most of the southern part of the caldera. The youngest basaltic lava flows of the Erta’Ale volcano are the one that are found on the top of the other lava flows. The sample from 2017 lava flow was fresh and appears in black color than the other sample. The vesicles of the rock can give us an idea about the

time of the formation of the different units found in the area. As the vesicles of the rock decreases the age of that rock increases. The 2017 basalt is highly vesicular basalt which is also the youngest one.

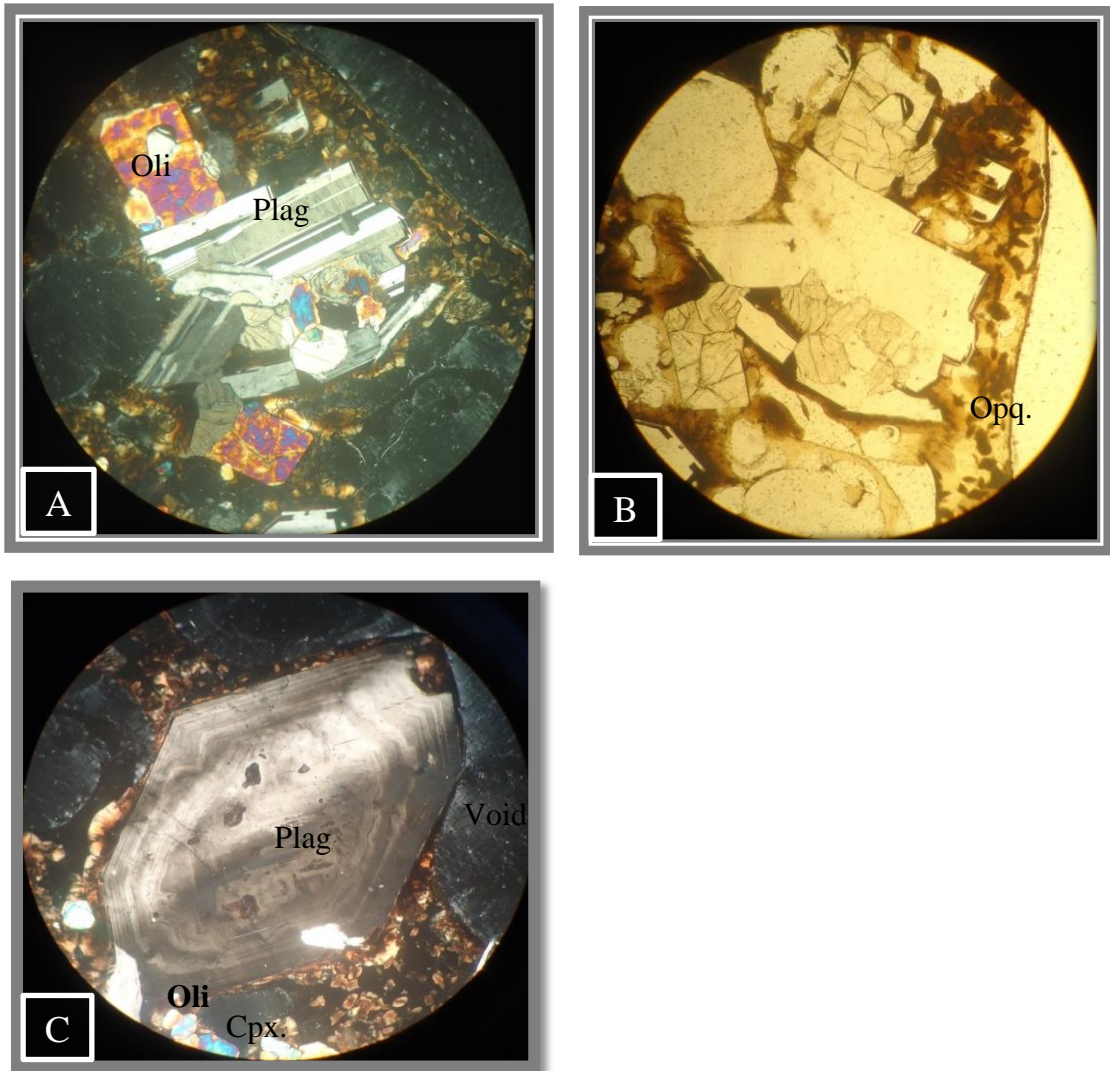
This rock unit has smooth surface and the thickness of the flow reach up to 10 cm. It is phoehoe type of lava and Plagioclases are the visible mineral.



*Figure 3.6 Field photo graph of the 2017 basaltic lava flow (A) Basaltic lava flow of the 2017 Basalt which is found on the north western of the Erta'Ale lava lake. (B) Stratigraphic position 2017 lava flow and the underlying lava flow Basalt 3*

### Petrography

The 2017 lava has porphyritic texture with phenocryst of plagioclase, olivine and clinopyroxene set in groundmass constitute of plagioclase, opaque oxide, olivine and clinopyroxene. The phenocryst of plagioclase show zoning texture and have anhedral to subhedral shape. The phenocryst constitutes about 34% with in which the plagioclase represents 24%, olivine 5% and clinopyroxene 3%. Olivine has euhedral shape but plagioclase and clinopyroxene have anhedral to subhedrl shape. The groundmass constitutes 18 % opaque oxide and the rest is covered by void space.



*Figure 3.7: Micro photo picture of 2017 lava flow under 10X magnification under XPL (A), PPL (B) view and (C) micro Photo of phenocryst of zoned plagioclase embedded in groundmass of opaque oxide, olivine and clinopyroxene under 10X magnification under XPL view. The labels are (Plag-Plagioclase, Oli- Olivine, Cpx – Clinopyroxene, Opq.- Fe-Ti oxide and Void- Void space).*

### **3.2.2. The 2010 lava flow**

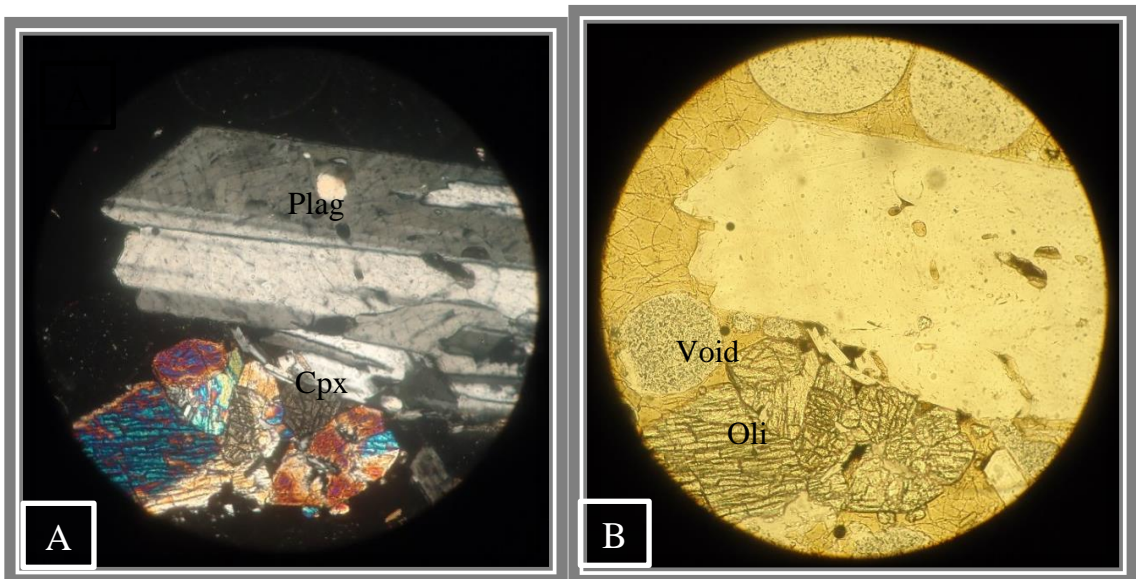
The eruption occurs in December 2010 and covers the entire caldera floor and overflowed the southern crater rim. The flows have phaohoe type. The lavas are vesicular and porphyritic with abundant plagioclase and some olivine.



*Figure 3.8: Field photograph of the Erta 'Ale lava lake and the extent of the 2010 lava flow*

#### Petrography

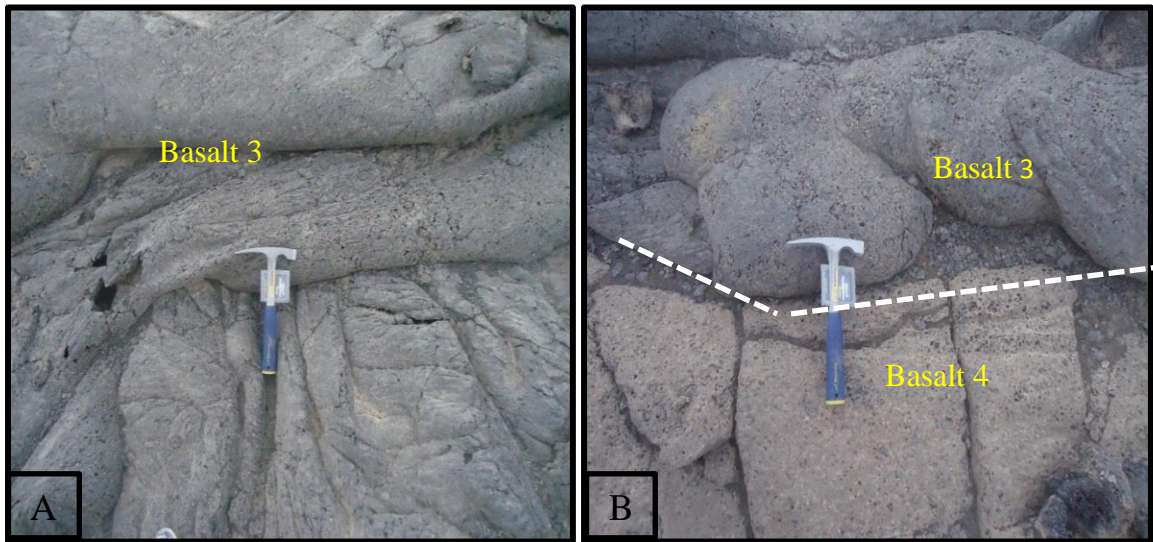
The 2010 lava is vesicular with phenocryst of plagioclase clinopyroxene and olivine. The phenocryst of plagioclase is characterized by its zoning texture and its anhedral to subhedral shape. The phenocryst constitutes about 18% from which plagioclases represent 15%, olivine 2% and clinopyroxene 1%. Anhedral to subhedral micro phenocryst of clinopyroxene and olivine are found. The rest of the thin section is covered by void space with some Opaque oxide.



*Figure 3.9 Micro photo picture of the 2010 lava flow under 10X magnification under XPL (A) and PPL (B). The labels are (Plag-Plagioclase feldspar, Oli-Olivine, Cpx-Clinopyroxene and Void- Void space).*

### 3.2.3. Basalt 3

Basalt 3 is a result of another lava flow from the lava lake before the flow of the latest lava flow. The unit has grey color which is a result of weathering and plagioclase is visible in the fresh sample. Most of the lava flow is covered by the later coming lava. The vesicles of the lava are less than the 2017 lava flow. Based on the relationship between vesicles and time of formation and also the position of the rock unit it is obvious that this unit is older than the new lava flow and younger than lava flow beneath them.



*Figure 3.10: Field photograph of basaltic lava flow of Erta'Ale Basalt (A) lava flow from Erta'Ale volcano which is described as basalt 3 (B) stratigraphic position of lava flow of Basalt 4 overlain by Basalt 3*

#### *Petrography*

The lava flow has porphyritic texture with phenocryst of plagioclase set in a ground mass of plagioclase feldspar, opaque oxides and to a lesser extent, clinopyroxene and olivine. The phenocrysts of plagioclase are euhedral to subhedral and show polysynthetic twinning. Not all but some of the phenocryst of plagioclase shows zoning. The phenocryst constitutes about 34% within the plagioclase represent 26%, olivine 3% and clinopyroxene 5%. The phenocryst of clinopyroxene and olivine has subhedral shape. The rest of the rock is covered by opaque oxide and void space.

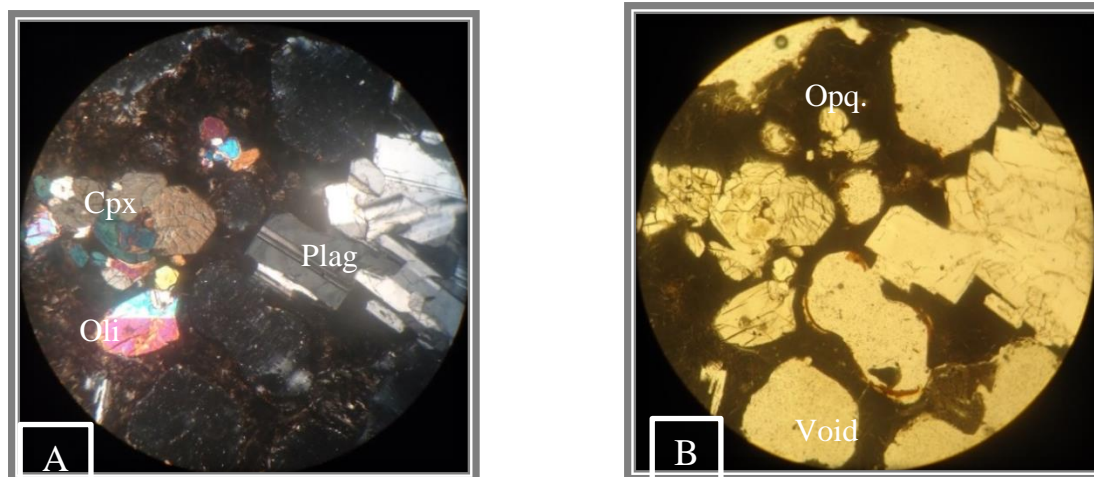


Figure 3.11: Micro photo picture of basalt 3 under 10X magnification under XPL (A) and PPL (B). The labels are (Plag-Plagioclase feldspar, Oli- Olivine, Cpx – Clino pyroxene and Void- Void space).

### 3.2.4. Basalt 4

This basalt is found under basalt two and it is more affected by weathering process. Vesicular basalts exhibit brown to reddish color when altered. The lava flow of this unit is found north of the Erta’Ale lava lake. The lava flow of this unit did not cover much of the area this is because of the basaltic eruption that form this basalt was erupted many times ago its product are covered by the other young basaltic lavas.

The vesicles in this basalt are less than the vesicles that are found in 2017 and in Basalt 3. Depending on the vesicles and position of this unit and degree of weathering of this basalt we can say that this lava flow is older than the above three lava flows.

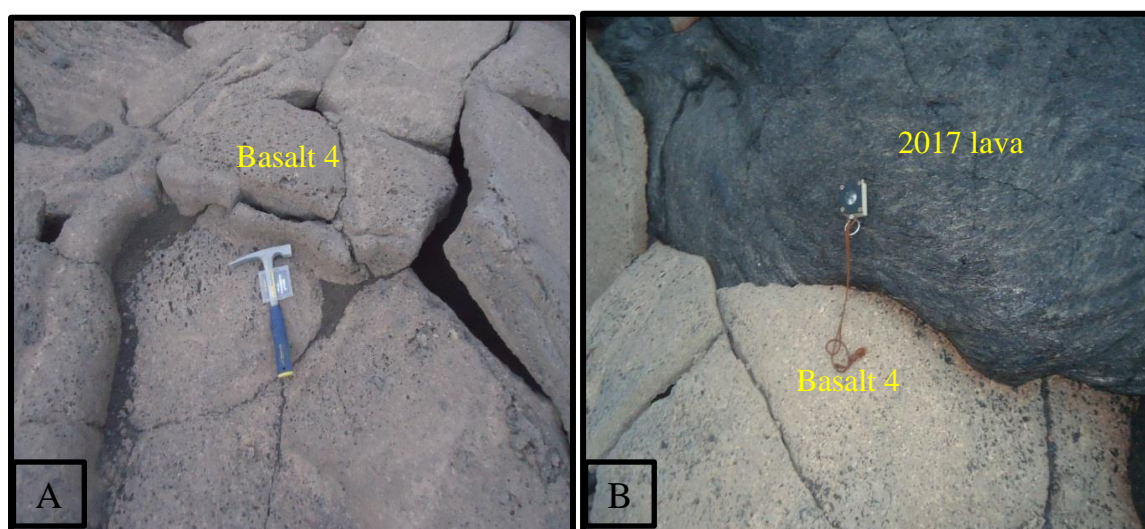
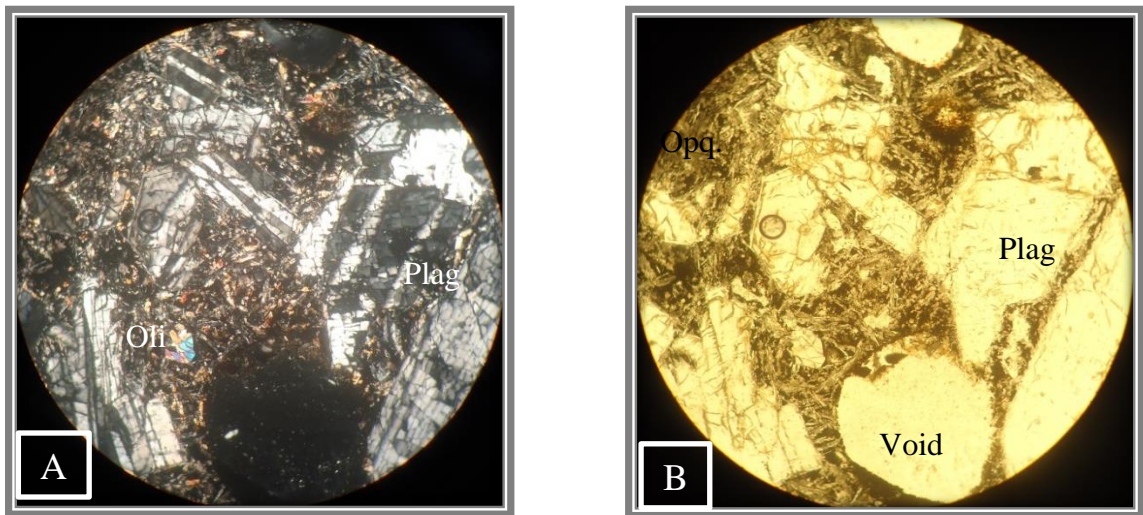


Figure 3.12: Field photographs of the Erta’Ale basaltic rocks. (A) Lava flow which is responsible for the formation of Basalt 4 and (B) The flow of 2017 lava flow on Basalt 4 which is relatively older

## Petrography

The lava has porphyritic texture with phenocryst of plagioclase, set in groundmass of olivine, clinopyroxene and opaque oxide. The phenocrysts constitute about 43%. From the total phenocryst percentage plagioclase represent 36%, olivine 5% and clinopyroxene 2%. The phenocryst of plagioclase has anhedral to subhedral shape. In the ground mass opaque is the dominant mineral with some anhedral shape olivine and clinopyroxene. The void space of this rock is less than the above all basalts.



*Figure 3.13 Micro photo picture of lava flow of Basalt 4 under 10X magnification under XPL (A) and PPL (B). The labels are (Plag-Plagioclase feldspar, Oli- Olivine, , Opq.- Fe oxide and Void- Void space*

### 3.2.5. Basalt 5

This rock unit is a result of a basaltic lava which flow towards south of the lava lake. This basalt is vesicular basalt which the vesicles are small in size than both 2017 and 2010 lavas. The vesicles seen on this basalt are almost similar with basalt 3. There is no a clear contact between the other basalt on the area with this basalt. During the field visit it was very difficult to step on this basalt.



Figure 3.14: Field photo graph of Erta'Ale basaltic eruption product which flows towards south of the lava lake.

### Petrography

Unlike the other basalt the plagioclase content of this basalt is very small which is less than 5% and the olivine is less commonly found but the ground mass of this basalt is covered with opaque which is almost half of the mineral constitute of the rock. The less commonly found phenocryst is plagioclase which show zoning and have euhedral to anhedral shape.

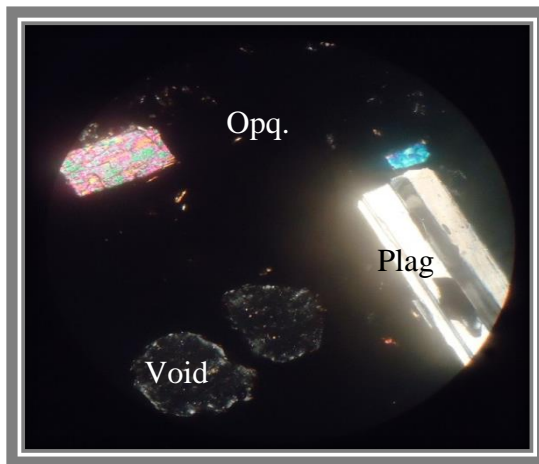


Figure 3.15: Micro photo picture of lava flow of Basalt 5 under 10X magnification under XPL (A) The labels are (Plag-Plagioclase feldspar, Oli- Olivine, Opq.- Fe oxide and Void- Void space

### 3.2.6. Basalt 6

Basalt 6 is the most dominate unit in the study area. It is found on the south east of Ert'Ale lava lake. It is brown to dark grey unit mainly composed of feldspar and it can be considered as massive or not vesicular compared to the above basalt depending on the vesicularity of the unit. There is no a clear flow of basalt 5 on basalt 6 but depending on the vesicles basalt 5 is flow before basalt 6.

As already said there is an inverse relation between vesicularity and age. The vesicles of the basalt are decreasing from youngest basalt up to this unit. Depending on the vesicularity of this unit it can be considered as the oldest lava flow. Therefore this unit is overlain by all of the other basalt found in the area.

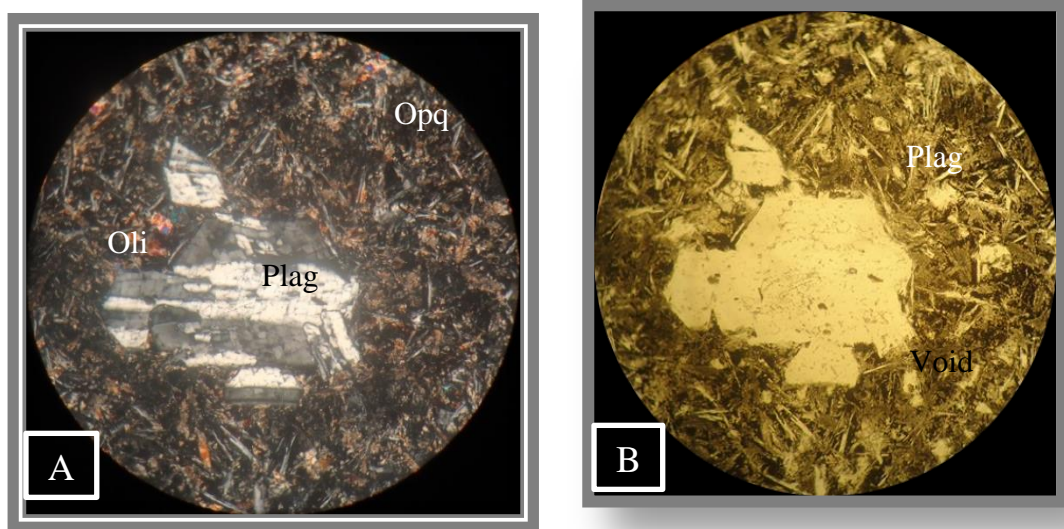
The out crop of this unit is easily differentiated because of the smooth and rope like surface. This rope like surface is forms as the surface lava cools while the molten material beneath is still moving as a result the surface cools in a series of overlapping ropy lobes which is an indicator of the pahoehoe lava which flows slowly.



*Figure 3.16 Field photograph of Ertá'Alé basaltic eruption products. (A) rope like structure of Pahoehoe type of lava which is found on basalt 6 (B) exposure of basaltic lava flow of basalt 6*

### Petrography

The lava has porphyritic texture with phenocryst of plagioclase, set in groundmass of olivine, clinopyroxene and opaque oxide. The phenocrysts of plagioclase show some slight zoning. The plagioclases form a dense network of elongate plagioclase microphenocrysts in the ground mass and have anhedral to subhedral shape. Microphenocryst of olivine has anhedral shape. The phenocryst constitutes about 58% within the plagioclase represent 40%, olivine 13% and clinopyroxene 5%. The ground mass is covered with olivine and opaque. The void space of coverage of this rock is decrease to 25%.



*Figure 3.17: Micro photo picture of lava flow of Basalt 6 under 10X magnification under XPL (A) and PPL (B). The labels are (Plag-Plagioclase feldspar, Oli- Olivine , Cpx- Clinopyroxene, Opq.- Fe oxide and Void- Void space).*

The percentage of the void space is decrease to 25%. The percentage of the void space is decrease from 2017 and 2010 lava up to this one which is true because the vesicularity of the rock in hand specimen is decrease from 2017 and 2010 up to this basalt. This is an indicator of the time of formation of the basalts, 2017 lava which have higher vesicles is the younger and basalt six which has low or small vesicles are the older and the other will fall between them according to the percentage of the void space.

*Table 3.1 Petrographic description of the Erta 'Ale samples and the dominate mineral found in the thin section with their modal proportion*

Sample code	Mineral phase	Modal Proportion (%)	Petrographic characteristics
2017 lava	Plagioclase Olivine Clino pyroxene Opaque	24 5 3 18	The 2017 lava has porphyritic texture with Phenocryst plagioclases which show zoning. They are set in a ground mass of olivine, pyroxene and opaque. Half of the rock is covered with void space (54%)
2010 lava	Plagioclase Olivine Clino pyroxene Opaque	15 2 1 35	Plagioclase with zoning texture is the dominant mineral. Phenocryst of plagioclase, olivine and clino pyroxene are set in the ground mass of the same mineral with opaque. The phenocrysts have anhedral to subhedral shape. The rest of the rock is covered by void space (47%).
Basalt 3	Plagioclase Olivine Clino pyroxene Opaque	26 3 5 23	The phenocryst plagioclase has euhedral to subhedral shape and set in a fine-grained matrix of plagioclase, opaque, clinopyroxene and olivine. 43 % of the thin section is covered with void space
Basalt 4	Plagioclase Olivine Clino pyroxene Opaque	36 5 2 22	The olivine in this basalt is appeared as fine grained in the ground mass with opaque. The phenocrysts of plagioclase have anhedral shape and 35% of the thin section is covered by void space
Basalt 5	Plagioclase Olivine Clino pyroxene Opaque	4 1 - 52	Plagioclase, olivine clino pyroxene content of this basalt is very low and most of the rock composition is covered with opaque and the rest is by void space (43%).

Basalt 6	Plagioclase	40	The dominate mineral are plagioclase, olivine and clinopyroxene which are embedded with the same mineral (plagioclase, olivine and clino pyroxene). The phenocryst of plagioclase show zoning and 25% of void space found in this rock.
	Olivine	13	
	Clino pyroxene	5	
	Opaque	17	

# Chapter Four

## 4. Geochemistry

### 4.1. Introduction

The sample analyzed for this study come from the Erta'Ale basaltic shield volcano. Inside the magma chamber there are processes which modify the chemical composition of the primary magma produced by partial melting of the source through fractional crystallization, magma mixing, contamination or the mixture of these process (Rollinson, 1993). Rollinson, (1993) suggest that to resolve the chemical effect of these processes the use of the geochemical tools, trace and major element studies coupled with isotope composition are needed. In this research both major and trace element studies are used. Major and trace element analysis of the samples are plotted in the variation diagram, and as chondrite and primodal mantle normalized patterns. The purpose of the plot is to display the abundances and variation pattern of the element and to know the distribution pattern of the element that help to understand and to trace the source of the mantle and the petrogenic process.

#### 4.1.2 Methodology

The samples are prepared in geological survey of Ethiopia. The powdered sample is analyzed by analytical method of Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) for major element with LOI analysis and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) for trace element at ALS Services, Ireland.

The results of the geochemical analysis are major and trace element concentration data. This data has to be integrated by different software package like Microsoft excel 2010 and petrograph version 2 beta. The final outputs from the software are in the form of graph. In order to assess the compositional variation of Erta'Ale shield volcano we incorporate studies of Erta'Ale lavas from (Miruth Hagos et al., 2016; Field et al., 2012) for comparison.

Major elements were analyzed using Multi element Inductively Coupled Plasma (ME-ICP06) whereas trace element analyzed Multi element Mass Spectrometer (ME-MS81) techniques. The detection capacity of the methodology's between 0.01and100% for major element and generally 0.01 to 10,000ppm for trace element except for Cr (10-10,000ppm) and V (5-10,000ppm). In addition the instrument are also sensitive for lose of Ignition

ranging between 0.01 and 100%. The used standards are lithium borate fusion for resistive elements, four acid digestions for base metals, and aqua regia for volatiles.

The sample from Barrat et al. (1998) were analyzed by XRF analysis for major and some trace-element abundances and the Rare earth elements (REE) by isotope dilution method (ID) using a Cameca TSN-206 single collector mass spectrometer and other elements like for example U, Th, Hf, Ta, La, Ce, Sm, Tb and Yb were determined by instrumental neutron activation analysis (INAA). The sample from Field et al. (2012) are analyzed by X-ray fluorescence (XRF) for whole rock major and trace elements. The other sample from Miruth Hagos et al. (2016) are analyzed by XRF spectrometry for major oxides, minor and trace element abundances and the contents of the rare earth elements (REE) and other trace elements were analyzed by INAA.



*Figure 4.1 Distribution and location of samples that are collected from Erta' Ale for geochemical analysis*

Table 4.1: Geochemical analysis result of Erta 'Ale shield volcano samples. On the table the notation LD stands for – Less than Detection Limit. The major element (including LOI) is expressed by wt. % and trace element value by ppm respectively. The geochemical data is normalized in volatile free base.

Sample	2017 lava	2010 lava	Basalt 3	Basalt 4	Basalt 5	Basalt 6
E(m)	0403940		0403941	0404018	0403946	0403913
N(m)	0133613		0133614	0133506	0133514	0133454
<b>Major element (ICP -AES) (wt %)</b>						
SiO <sub>2</sub>	49.11	49.06	49.63	42.27	52.62	47.68
TiO <sub>2</sub>	2.03	1.93	1.91	5.37	2.45	2.20
Al <sub>2</sub> O <sub>3</sub>	16.10	16.74	16.31	5.93	13.81	14.01
Fe <sub>2</sub> O <sub>3</sub>	11.36	10.76	10.60	15.75	12.40	12.12
MnO	0.17	0.17	0.18	0.19	0.19	0.18
MgO	5.88	6.08	5.91	16.55	4.56	6.36
CaO	12.12	12.16	11.98	10.72	8.37	12.58
Na <sub>2</sub> O	2.71	2.73	2.58	1.54	3.36	2.48
K <sub>2</sub> O	0.53	0.51	0.53	0.80	1.57	0.36
P <sub>2</sub> O <sub>5</sub>	0.30	0.28	0.28	0.53	0.51	0.30
Total	100.31	100.42	99.90	99.65	99.84	98.27
LOI	-0.30	-0.42	0.10	0.35	0.16	1.70
<b>Trace Elements (ICP-MS) (ppm)</b>						
Li	10	–	10	10	10	10
Sc	33	–	33	31	29	36
V	307	284.2	295	372	307	321
Cr	90	113.7	120	1170	70	170
Co	39	38.17	94	88	32	39
Ni	48	56.98	52	590	37	59
Cu	146	113.4	125	115	162	151
Zn	84	87.19	80	137	107	88
Ga	19	18.9	16.2	16	19.8	17.9
Ge	<5	<5	<5	<5	<5	<5
Rb	11.7	10.74	11.5	19.8	35.1	12.8

Sr	308	310.8	306	547	277	305
Y	26.1	24.7	23.1	30.3	43	26
Zr	162	140.4	154	378	388	170
Nb	27.9	24.46	24.9	44.3	56.1	29.1
Mo	2	1.045	2	2	4	1
Cd	0.7	0.152	0.5	1.2	0.7	0.8
Sn	4	1.402	3	3	5	3
Cs	0.14	<L.D.	0.18	0.36	0.46	0.13
Ba	122.5	123.2	122.5	663	267	142.5
La	21.3	20.02	20.1	33.2	47.3	22.7
Hf	4	3.549	3.6	9.5	8.8	4.5
Ta	1.6	1.827	1.5	5.2	4.7	1.5
Tl	<0.02	–	0.03	<0.02	0.02	<0.02
Pb	2	1.4049	3	9	9	13
Ce	46.3	41.97	43.2	80.4	98.2	47.7
Pr	5.82	5.404	5.28	11.05	11.15	6.08
Nd	24.4	22.6	22.6	53	47	26
Sm	5.12	4.986	4.98	12.1	9.34	5.5
Eu	1.64	1.736	1.62	3.64	2.6	1.82
Gd	5.66	5.031	5.39	11.35	9.48	6.15
Tb	0.82	0.774	0.79	1.52	1.41	0.92
Dy	4.87	4.613	4.58	7.58	8.39	5.28
Ho	1.01	0.871	0.89	1.23	1.61	0.96
Er	2.63	2.369	2.51	2.93	4.73	2.91
Tm	0.39	0.346	0.35	0.37	0.69	0.39
Yb	2.44	2.181	2.03	1.98	4.17	2.4
Lu	0.33	0.338	0.31	0.24	0.63	0.36
Th	2.39	2.236	2.37	3.17	6.85	2.66
U	0.67	0.615	0.6	0.93	1.97	0.76

## 4.2 Major element Geochemistry

The major elements like (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and P) with LOI are analyzed and the analytical data is used in oxide form. The raw analytical data readjusted to volatile free bases to use for the interpretation and to draw the graphs. The volatile free base is calculated by normalizing the major element concentration value to 100%.

### 4.2.1 Classification diagram

The entire samples analyzed are plotted on the diagrams of LeBas et al. (1986) which use the relationship of Alkalis ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) versus silica ( $\text{SiO}_2$ ) for classification purpose. The rocks of the Erta'Ale show a range of  $\text{SiO}_2$  contents from 47.68 to 52.63 wt%. The general characteristics of the volcanic rocks of the shield volcano of this research with data from Field et al. (2012) and Miruth Hagos et al. (2016) has plotted together for comparison in the total alkalis-silica (TAS after Le Bas et al., 1986, see Fig.4.1).

The Erta'Ale shield volcano lava flows are clustered in a narrow region in the diagram. All the samples including the 2017, 2010 lavas and the other samples of different authors are predominately basaltic with except one of the sample which falls in the basaltic andesite range. This sample has high silica 52 wt% and alkali content with average of 5 wt %. Most of the Erta'Ale samples are dominantly transitional.

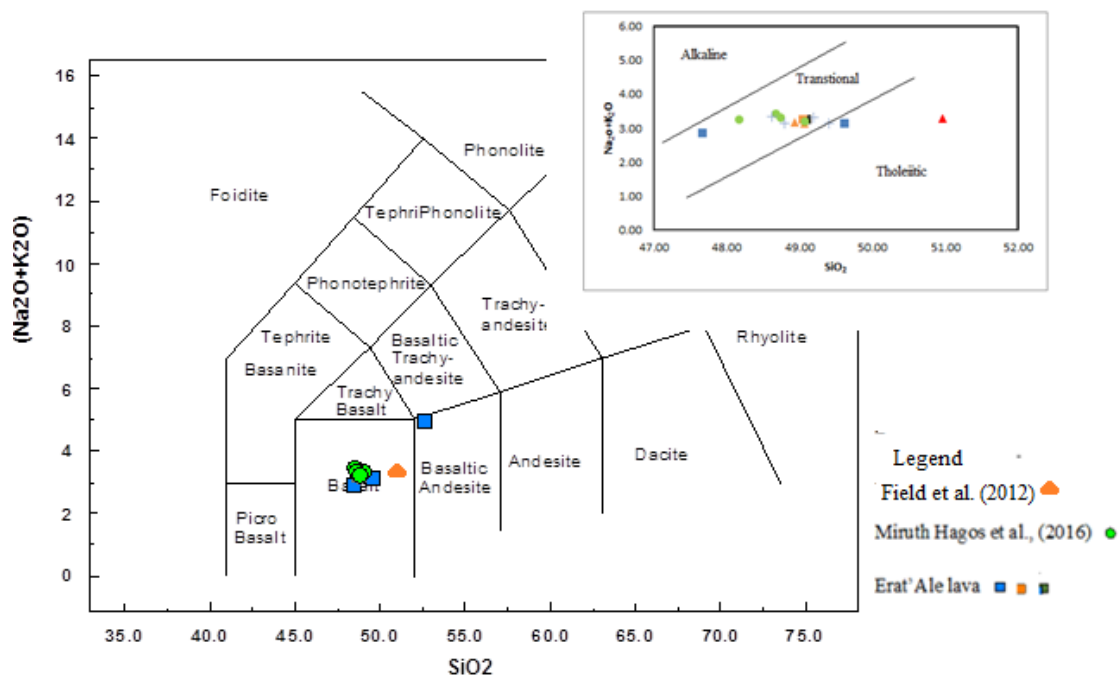


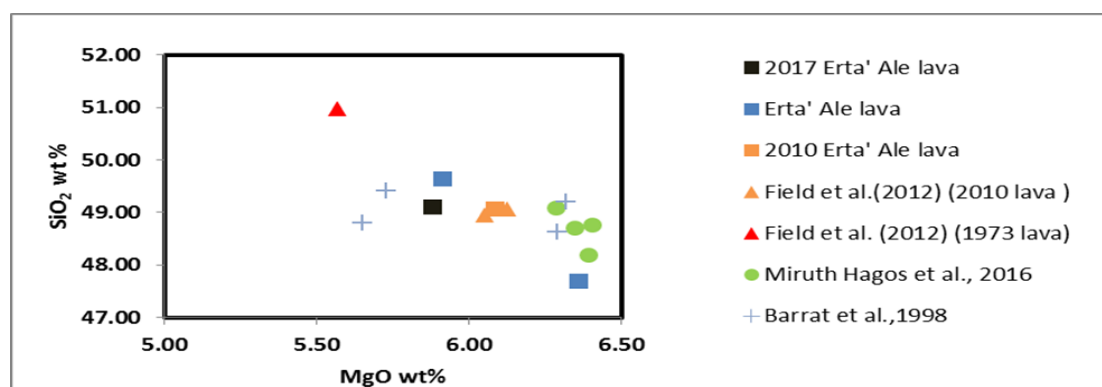
Figure 4.2: TAS diagram after Le Bas et al. (1986) of the collected samples for classification of the rock and magma series. The major element geochemistry data is volatile free base in wt. %. Data from Field et al. (2012) and Miruth Hagos et al. (2016) has been included for comparison.

## 4.2.2 Major element Variation diagrams

It is known that major element data are significantly used in construction of variation diagrams by choosing MgO wt% as the X-axis (differentiation index). MgO is chosen as differentiation index because it continuously decreases during crystal liquid fractionation and there is no any significant variation in the SiO<sub>2</sub> content.

From major element variation diagram different trends can be observed. The plot is prepared for some selected major elements. In the diagram the analysis of the rock show a general positive trend for Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>, negative correlation for SiO<sub>2</sub> and an inflected trend for Al<sub>2</sub>O<sub>3</sub> and CaO.

The lava of Erta' Ale volcano has MgO content ranging from 4.56-6.36wt%. The variation diagrams for major elements with MgO are indicated below in (Fig 4.3). SiO<sub>2</sub> in the range of ~ (47-52) wt% show generally negative correlation with MgO. The Al<sub>2</sub>O<sub>3</sub> contents slightly increase with decreasing MgO down to ~6 wt%, and then decrease with decreasing of MgO. This kind of bimodal trend is also observed in CaO which also show an increment up to 6.0 wt% for MgO then start to decrease. The abundance of TiO<sub>2</sub> varies between (1.93-2.45) wt % and Fe<sub>2</sub>O<sub>3</sub> is in the range of (10.6-12.4) wt% with both oxides showing enrichment with increasing of MgO. The variation diagram of the other major oxide (Na<sub>2</sub>O, K<sub>2</sub>O, MnO and P<sub>2</sub>O<sub>5</sub>) doesn't show a clear trend. Therefore, they are not included in the variation diagram. Basalt 4 is not taken under consideration because of contamination and the other sample Basalt 5 is an evolved sample with low value of MgO (4.56) and high value of SiO<sub>2</sub> (52) wt% and it is not taken under consideration in the major and trace element variation diagrams.



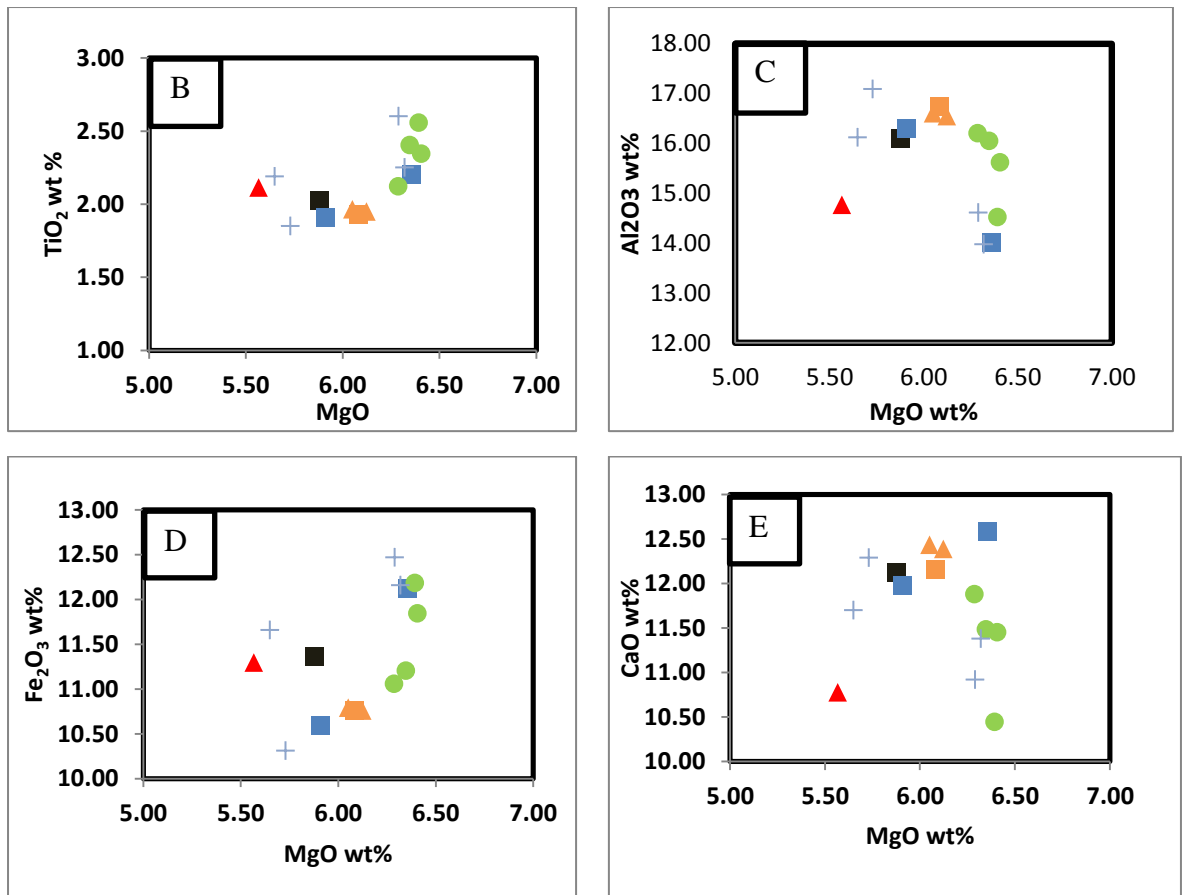


Figure 4.3 variation diagram of whole rock composition for all representative rock samples collected. The major element concentration is volatile free base and expressed by wt. %. Data from Field et al. (2012), Barrat et al. (1998) and Miruth Hagos et al. (2016) has been included for comparison

### 4.3. Trace elements geochemistry

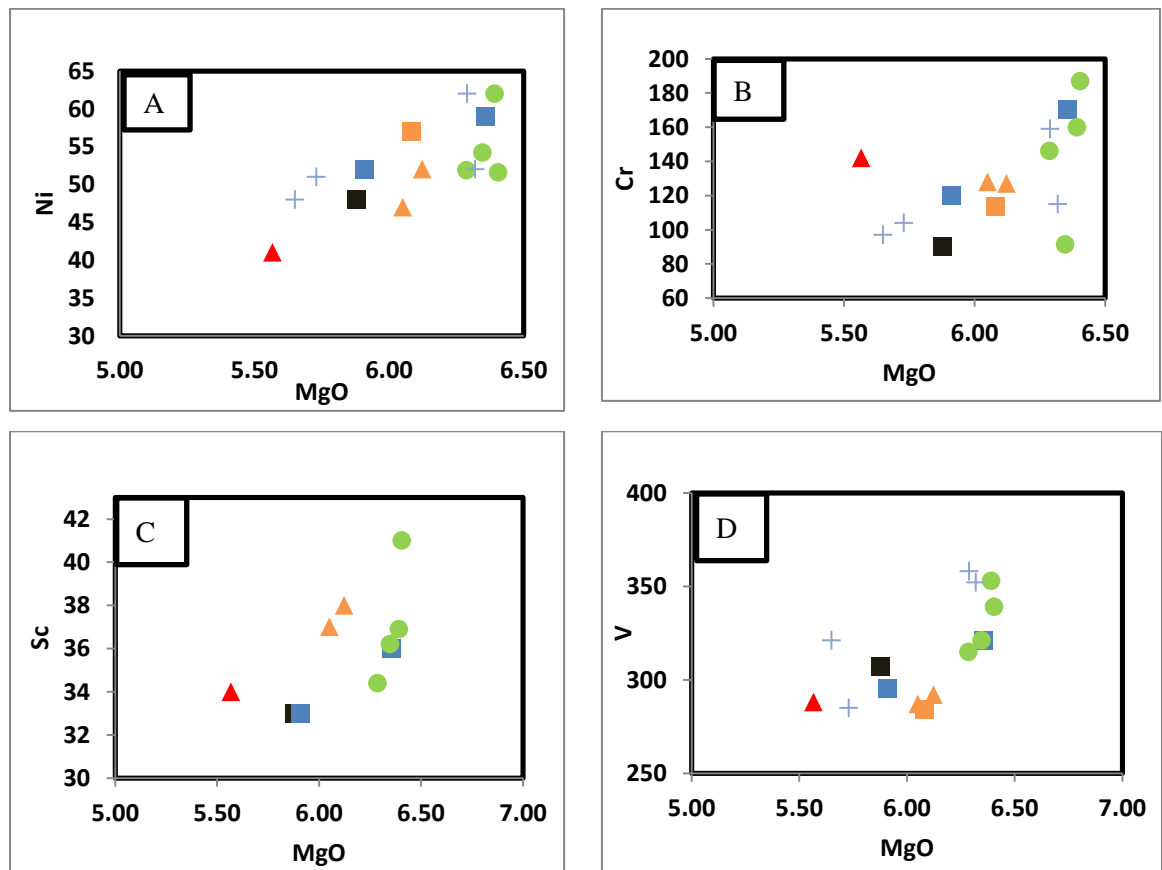
Trace elements are elements which are found less than 0.1% and their concentration expressed in parts per million (ppm) or by parts per billion (ppb). Despite their abundance they provide important geochemical and geologic information. Variations of trace elements also provides additional insight into the sources and major processes that controlled the nature of the volcanic products. The relative abundances of trace elements are used to identify the minerals that were present during melting or fractional crystallization. Various bivariate variation diagrams i.e. trace elements vs. MgO wt %, trace vs. trace and trace element ratios against trace are plotted.

Unlike major elements (Si, Al, Ca, etc.), whose variations are mostly limited to a factor of <100, trace element concentrations can vary by as much as a factor of 1000 (three orders of magnitude). This fact, together with the way trace elements are distributed between

coexisting minerals and liquids in geologic systems, qualify them as highly significant indicators of petrologic processes (Best, 2003)

### 4.3.1 Trace element variation diagram

The plot in Fig 4.4 shows the variation between trace element and MgO. The compatible trace elements especially Cr and Ni form a positive correlation. The incompatible trace elements (Nb, Zn, Rb, Y and Zr) against MgO are plotted. The plots show a clear positive trend line. The Erta’Ale lava has low value in compatible element Ni 37-59 ppm and Cr 125-162 ppm. V varies in the range of (284-353) has positive correlation with MgO but Ba start to decrease with increasing of MgO.



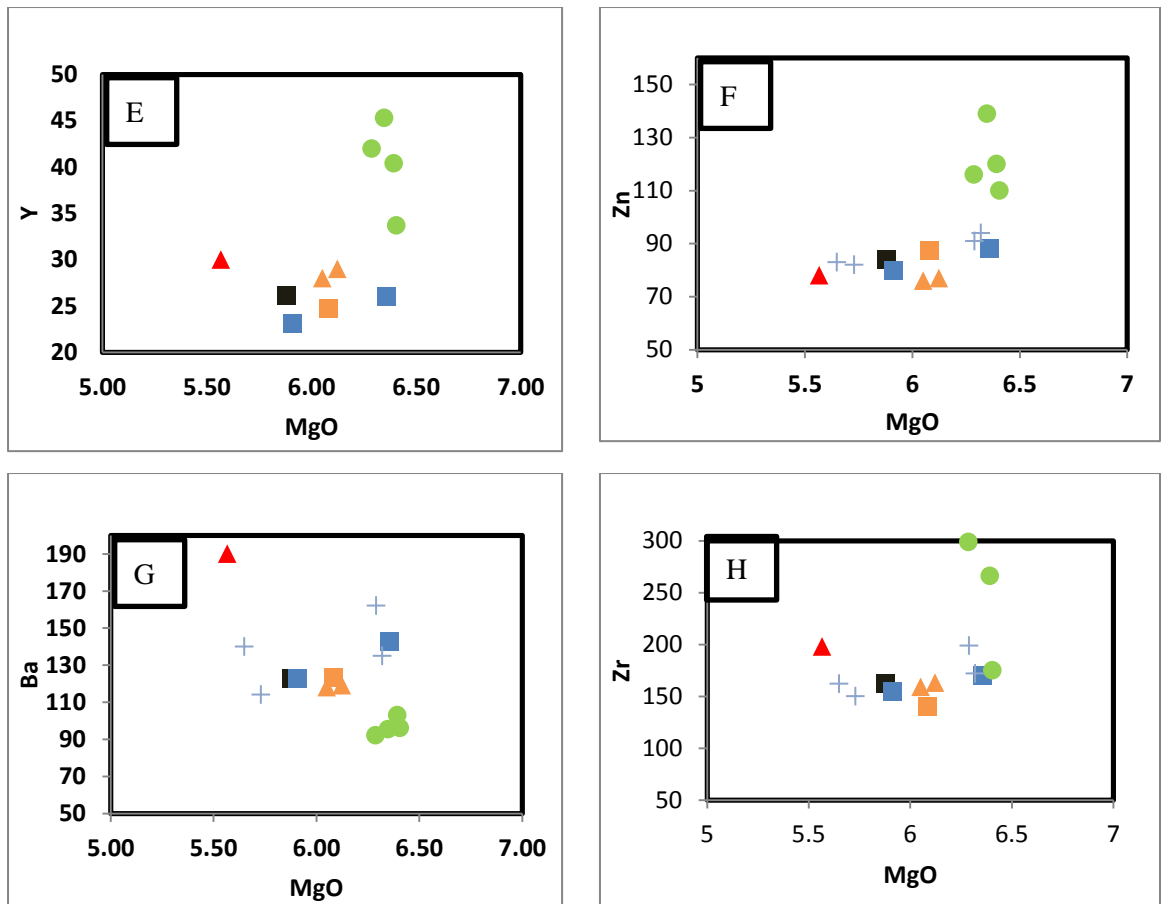


Figure 4.4 Trace element versus MgO variation diagrams. Data from Field et al. (2012), Barrat et al. (1998) and Miruth Hagos et al. (2016) has been included for comparison. The symbols are the same as shown in the figure 4.3.

Zr does not enter into the major crystalline phase. Because of this, Zr prefers the liquid phase so it's very important to study behavior of elements in magmatic evolution by taking Zr as an index. Zr has a low bulk distribution coefficient between appropriate crystallising phases and magma (Bizouard et al., 1980). The incompatible trace element (Zn, Y, Nb and Rb) against Zr are plotted (Fig 4.5) and show a positive correlation. The trace ratio versus trace plots of the Erta'Ale lavas in (Fig 4.5 G and H) shows Th/La and Nb/Y versus Rb show a positive linear correlation. The plot of La/Nb and Ba/Nb in the (Fig 4.5 E and F) show that the both La and Ba increased with increasing of Nb.

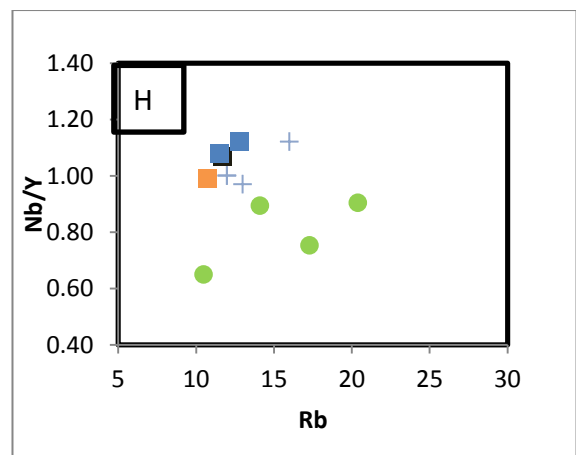
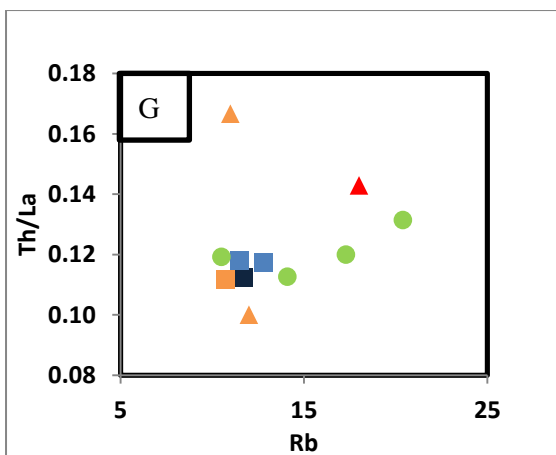
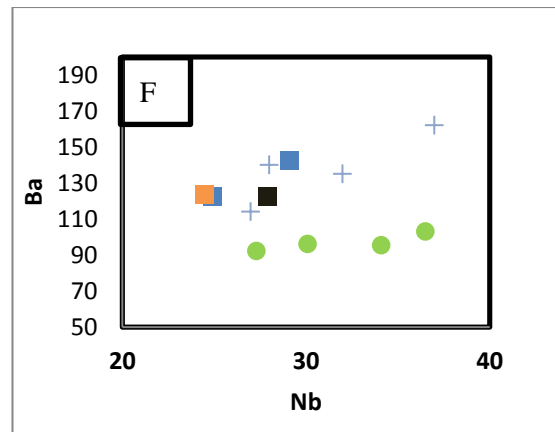
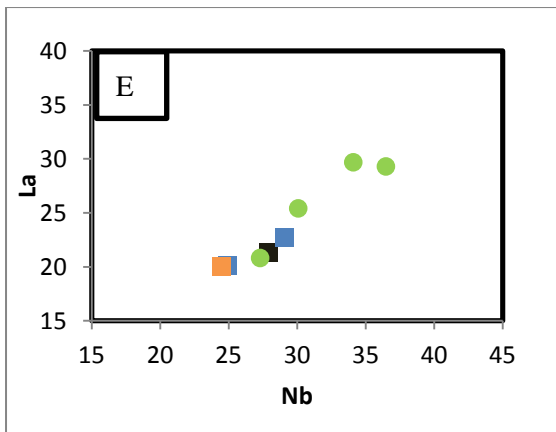
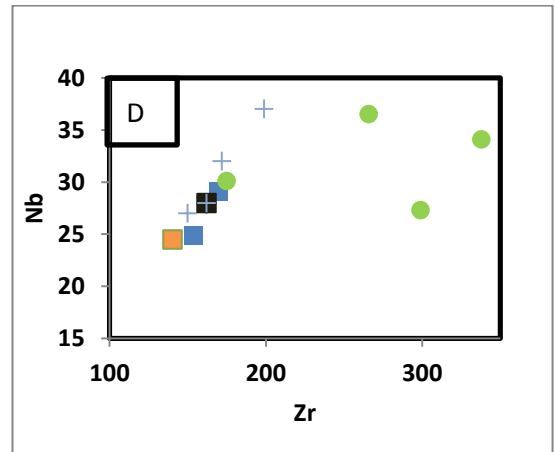
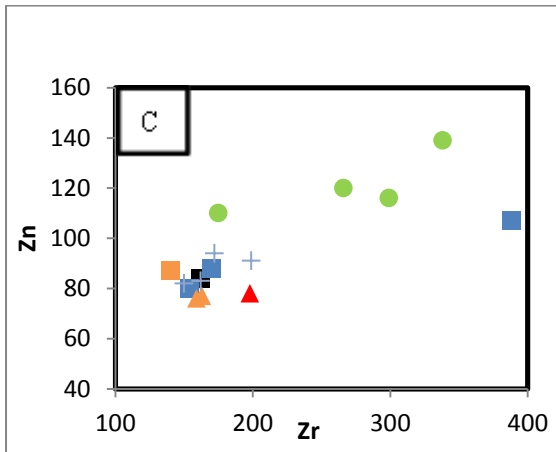
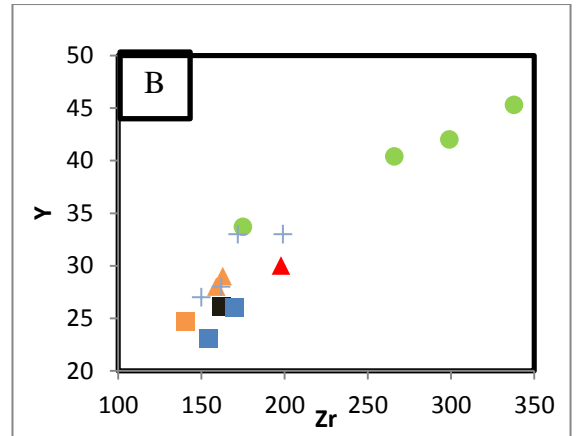
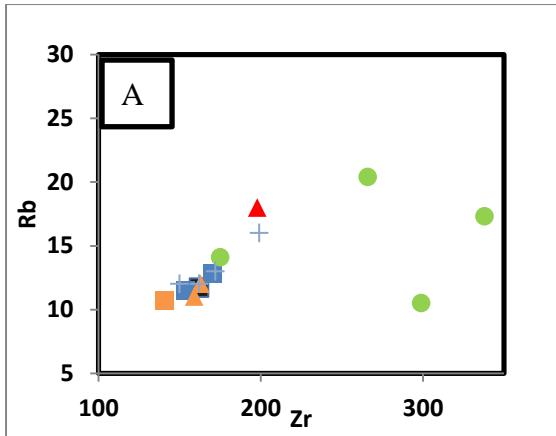


Figure 4.5 Plots for selected trace element with trace element and trace element ratio with trace element Data from Field et al. (2012), Barrat et al. (1998) and Miruth Hagos et al. (2016) has been included for comparison. The symbols are the same as shown in the figure 4.3.

#### 4.4 The Rare earth element (REE) and Multi element Variation Diagram

In the Rare earth element (REE) and multi element variation diagram the data from Miruth Hagos et al. (2016) has been included for comparison. Rare Earth Element (REE) value of the element concentration is normalized to chondrite according to values of Sun and McDonough (1989). Generally, the rare earth elements pattern indicates enriched light rare earth element (LREE) and almost flat heavy rare earth element (HREE) pattern. Chondrite-normalized REE diagram appear as smooth and Eu anomalies are absent in the Erta'Ale basalts. There is no extreme depletion in the HREE. The pattern of the REE diagram show parallel for all of the samples. The enrichment of LREE range in terms of  $(La/Yb)_N$ , is 5.29 - 6.87. In the rare earth element diagram the most of the REE patterns are sub parallel to each other. The 2017 lava is not visible because of overlapping of some samples.

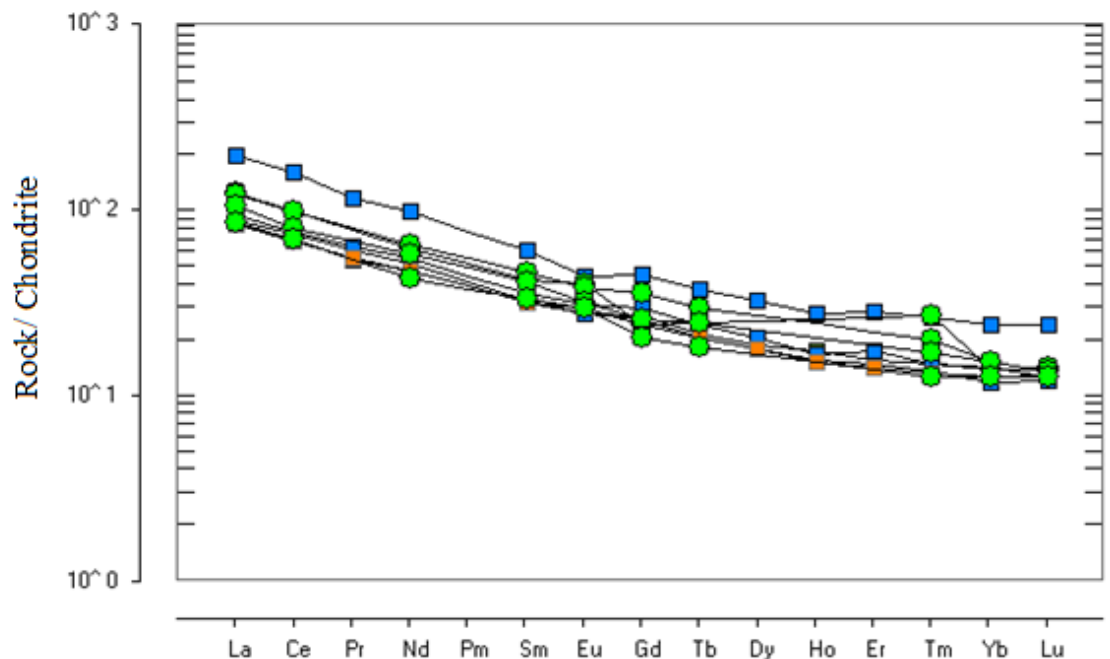


Figure 4.6: REE variation diagram of samples from Erta'Ale volcano. The concentration value of the rock sample is normalized to chondrite value determined by Sun and McDonough, (1989). Data from Miruth Hagos et al. (2016) has been included for comparison. The symbols are the same as shown in the figure 4.3.

Multi element variation diagram is plotted on (Fig 4.7) the diagram is prepared based on McDonough and Sun (1995); normalized to primordial mantle plot. The pattern shows negative spike or slight depletions in Ba, Sr, and K concentrations but enrichment in Rb, Th, U, and Zr. Basalt 5 sample however, exhibit some differences, such as positive U and Pb anomalies. Ta and Nb show a positive spike. Ta and Nb show a positive spike.

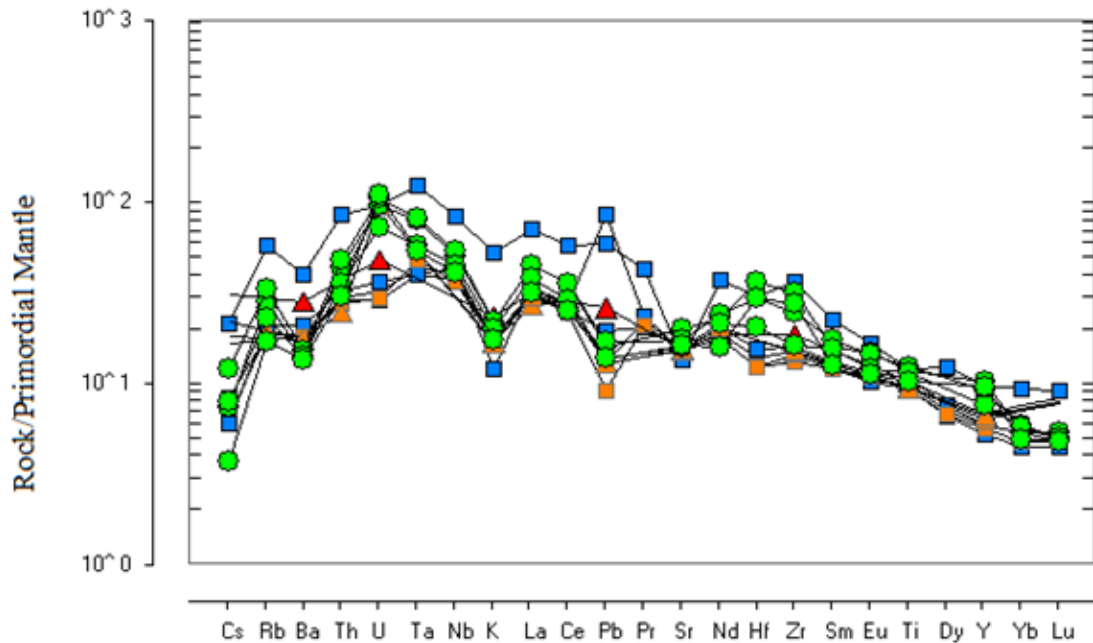


Figure 4.7: Multi-element variation diagram of representative rocks of Erta' Ale. The samples are normalized to primordial mantle of value determined by McDonough and Sun (1995). Data from Miruth Hagos et al. (2016) has been plotted for comparison. The symbols are similar as shown in the figure 4.3.

# Chapter Five

## 5. Discussion

Erta'Ale shield volcano is one of the world persistent lava lakes and it is known by its two active lava lake. It lies at the center of the Erta'Ale axial volcanic range in the northern part of the Afar depression. The area is characterized by different kind of product but transitional type of basalt is the dominant one (Beberri and Varat, 1970).

In order to evaluate the petrogenic process of Erta'Ale shield volcano we incorporate studies of Erta' Ale lavas from (Miruth Hagos et al., 2016; Field et al., 2012 and Barrat et al., 1998) for comparison. All the samples from Field et al. (2012), Barrat et al. (1998) and Miruth Hagos et al. (2016) with this research result are plot together in the major element variation diagram trace element modeling, REE variation diagram and multi element variation diagram. To trace the mantle source of the Erta'Ale shield volcano in addition to the above listed secondary data the studies of Oligocene continental flood basalts from Pik et al. (1999) is also included.

### 5.1 Petrogenetic Evolution of Erta'Ale Basalt

The parent magma of the Erta'Ale volcanic rock is the most abundant product of the series which is transitional basalt (Barberri and Varat, 1970). In the rare earth element diagram the REE pattern shoes almost sub parallelity this kind of pattern is an indication of the derivation of the samples from a single parent melt. In the Rare earth element (REE) diagram the parallelity of the relative enrichment shows a systematic accumulation or removal of mineral phases.

The low MgO content of the Erta'Ale lavas (< 7 wt. %) show that the rocks of Erta'Ale volcano are evolved magma. The trend of major and trace element variation diagrams has characteristics to show the evolving process for the rocks is fractional crystallization. Barberri et al. (1974) which imply that the Erta'Ale volcanic rock sequence is produced by fractional crystallization of the parental magma in shallow magma chamber. The incompatible trace element (Zn, Y, Nb and Rb) against Zr show a positive correlation. This show the rocks have a similar evolution history.

The lava of Erta'Ale volcano has MgO content ranging from 4.56-6.36 wt% and has low value in compatible element Ni 37-59 ppm and Cr 125-162 ppm. Magmas with such

chemical characteristics could not be primary melts and thus they underwent variable degrees of olivine fractionation.

The Erta'Ale lava shows a major and trace element variation that mainly affected by fractionation of mineral phases. From negative correlation of  $\text{SiO}_2$  and positive correlation  $\text{Fe}_2\text{O}_3$  with  $\text{MgO}$  the first phase of crystallizing minerals are Fe and Mg bearing mineral phases (e.g. Olivine and Pyroxenes). Fractionation of olivine is also seen in the Ni versus  $\text{MgO}$  relationships (Fig. 4.4 A)

The next phase that fractionate from the system is plagioclase and pyroxene that evidently indicated by the late dropping of  $\text{CaO}$  and  $\text{Al}_2\text{O}_3$  trend line after some concentration of  $\text{MgO}$ . On major element variation diagram the trend of  $\text{Fe}_2\text{O}_3$  and  $\text{TiO}_2$  with  $\text{MgO}$  indicate fractionation of Fe -Ti oxide. The fractionation process is also shown by the trace element geochemistry. The positive correlation of incompatible element like Ni and Cr indicate the fractionation of olivine. The positive trend of V with  $\text{MgO}$  is also another indicator for fractionation of Fe - Ti oxide.

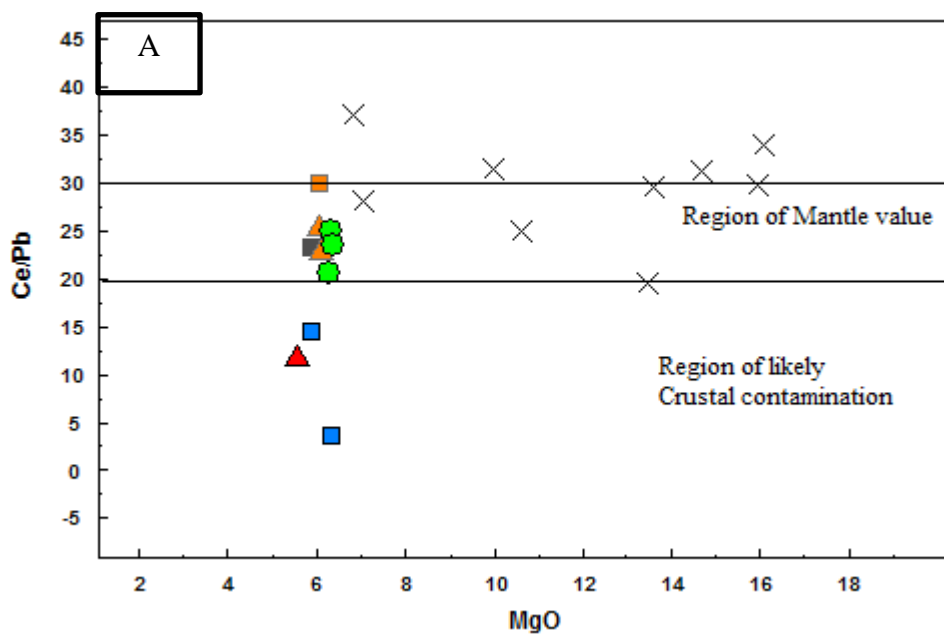
The trends of the compatible and incompatible elements show the differentiation and fractionation of Mg and Fe bearing minerals; like olivine and pyroxenes. The trend of Ba indicates the removal of feldspar. V similar to  $\text{TiO}_2$  its fall is related to Fe -Ti oxide fractionation. In the Rare earth element variation diagram there is absence of Eu anomaly and the lavas shows a  $(\text{Eu}/\text{Eu}^* \sim 1)$  that likely comes from accumulation of plagioclase feldspar. The negative anomaly of Ba and Sr in the multi element variation diagram shows the removal of plagioclase feldspar from the magma and the slight trough of Ti suggests fractional removal of Fe-Ti oxides. The distribution of the samples and the trend in the diagrams suggest early crystallization controlled by olivine followed by pyroxene, plagioclase and Fe-Ti oxides. The Erta'Ale basaltic rock has low value of La/Nb ratio in the range of (0.75-0.84), Rb/Nb (0.42-0.63) and Ce/Pb value in the range of mantle derived melts

During partial melting process the magma are enriched in incompatible element and depleted in compatible element. In contrast, fractional crystallization is much more efficient in producing compatible element depletion than incompatible element enrichment. Therefore, models of incompatible against compatible trace elements are potentially powerful tools to further discriminate between fractional crystallization and melting processes.

## 5.2 Source of the mantle

### 5.2.1 Crustal contamination

Crustal contamination is high where crustal thicknesses are considerably large and magma supply rates are low, resulting in greater residence times for individual magma batches within the lithospheric crust (Furman, 2007). Values of Ce/Pb measured in mafic lavas are thus sensitive to contamination, and this ratio is well-defined for primary mantle derived liquids ( $25 \pm 5$ , Hofmann et al., 1986). (Fig 5.1) show Ce/Pb versus MgO diagram.



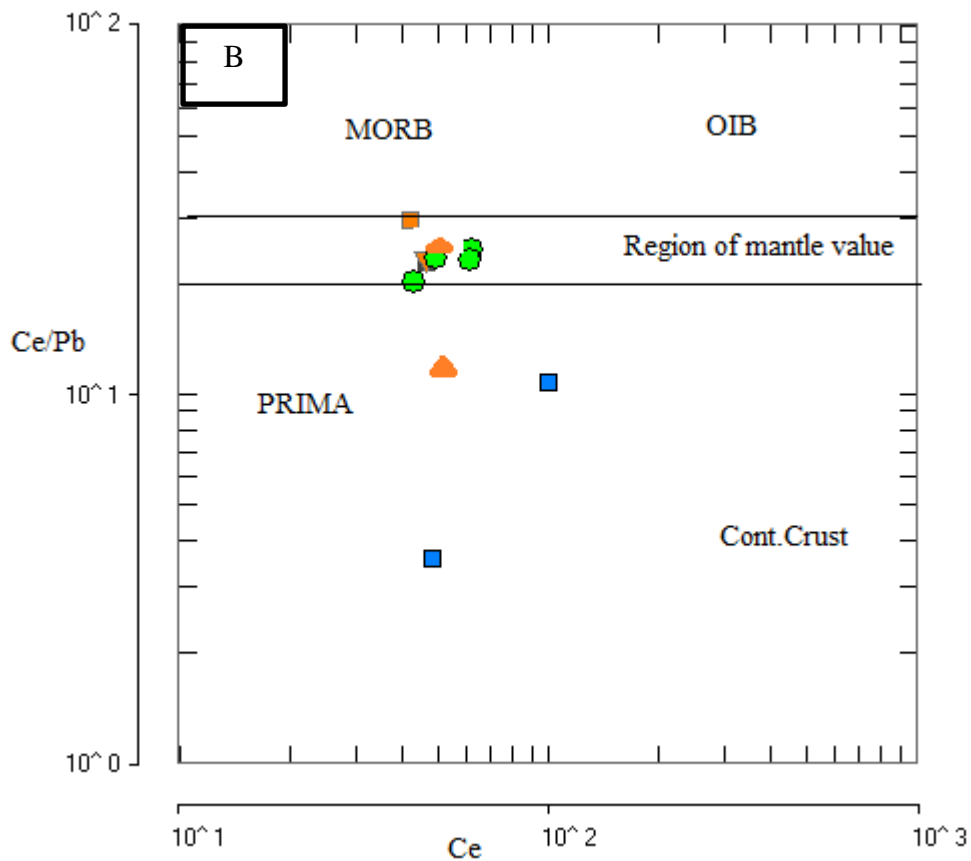


Figure 5.1: Ce/Pb vs Mgo diagram of the Erta'Ale lava (A) and Ce/Pb versus Ce diagram (B) which shows the boundary between mantle derived melt and crustal involvement. Data from Field et al. (2012) and Miruth Hagos and Oligocene flood basalt from northwestern Ethiopia data from Pik et al. (1999) are plotted together for comparison. The fields for mantle value and crust and the others are from Hofmann et al. (1986). The symbols are similar as shown in the figure 4.3.

Most lavas from the Erta'Ale have Ce/Pb values within the range of mantle derived melts (20-30; Hofmann et al., 1986). However, there are few exceptions (ER03, ER06 and the 1973 lava from Field et al. (2012)) which have slightly lower Ce/Pb ratios (<20) than mantle values. The positive anomalies of Nb and Ta in the multi element variation diagram also reveal the absence of crustal contamination. According to Dereje Ayalew et al. (1999) high trace element ratio such as La/Nb and Th/Nb are sensitive to crustal contamination. The Erta'Ale lava has low La/Nb ratio with average value of 0.81 and Th/Nb 0.09. In the Erta'Ale lava in (Fig 4.5 E and F) both La and Ba has positive

correlation with Nb which reveals the involvement of crustal material. Crust has low Ce/Pb values but lithosphere has higher (Dereje Ayalew et al., 2006).

The strong enrichment of Pb in multi element variation diagram for basalt 5 and 6 cause the low Ce/Pb ratio. These samples are fall in the region of crust this is because of their high concentration of Pb which results in low concentration in Ce/Pb ratio. The petrological and isotopic data show that the volcanic products of the Erta'Ale ranges have been considered to be of sub crustal origin, without any appreciable contamination with crustal material (Barberi and Varet, 1970). Most of the lava from Erta'Ale reveals the absence of crustal contamination. However, there are some lavas which shows a minor crustal material involvements. This can be explained by anomalously high Pb content.

### **5.2.2 Source region of Erta'Ale lava**

Mantle plumes are a result of a focused transfer of mass from mantle to core and are agents of outgassing from the mantle (Sonnenfeld, 1981). Tadewos Chernet and Hart, (1999) suggest that Mantle source input vary spatially and temporally throughout the Horn of Africa. Two compositionally distinct mantle plumes are found beneath East African rift system one beneath the present Ethio-Afar dome and the other beneath the Kenya Plateau (Rogers et al., 2000). However, according to Ebinger and Sleep, (1998) there is only a single large plume beneath the Ethiopian plateau which is initiated the oldest basaltic volcanism in southern Ethiopia at ~45 Ma. Ethio-Kenya volcanic province has experienced a complex and long episode of basaltic and felsic volcanism since late Eocene (Gezahagne Yirgu et al., 2006). The region, therefore, records the complete sequence of volcano tectonic activities from the plume head to tail and from incipient intra continental rifting to seafloor spreading (Miruth Hagos et al., 2010).

In order to trace the mantle source of the Erta'Ale shield volcano we incorporate studies of Erta'Ale lavas from Miruth Hagos et al., (2016); Field et al., (2012) and Barrat et al., (1998) and to evaluate possible mantle source we compare these Erta'Ale basalts with well-documented Oligocene continental flood basalts from Pik et al. (1999). The Ethiopian CFB contains sub-aerial alkaline tholeiitic basalts and they are supposed to be associated with the Afar hot mantle plume (Dereje Ayalew et al., 2002). Behind all CFB volcanism and the related continental rifting, there is a driving force called mantle plume, which normally originate at the core-mantle boundary and rises upwards (Miruth Hagos et al., 2010).

Dereje Ayalew et al. (2016) imply that the Afar samples were derived from a source more depleted than the source that produced the MER basalts. Hart et al. (1989) also suggest that basalts from northern Afar have characteristics more similar with depleted normal mid-ocean ridge basalts (N-MORBs). Many of the Ethiopian rift basalts plot within the field defined by recent lavas derived from the Afar plume (Furman et al., 2006). The Ethiopian rift basalts have Ce/Pb ratios between 20 and 34 similar to those observed in modern OIB and MORB (Dereje Ayalew et al., 2016).

All the analysed lavas from Erta' Ale and from Oligocene flood basalt from northwestern Ethiopia exhibit trace element ratios such as Ce/Pb (12-37), Ba/La (3.52-9.05), La/Nb (0.75 – 1.05) and Ba/Nb (2.8-9.12). Zr/Nb ratio of original volcanic rocks from OIB is quite low, normally 2–4, while the Zr/Nb ratio of continental crust is very high (Liu et al., 2015). Erta' Ale lava has an average 6.5 Zr/Nb ratio.

Ratios of certain trace elements (e.g., Ce/Pb vs. Nb/U) considered as tracers of mantle sources, plot within the field of mantle derived basalts (Dereje Ayalew et al., 2016). The basalt and basaltic andesite from the Erta' Ale lava has a restricted range of incompatible trace element ratios that indicates derivation from a sub-lithospheric mantle source region (Furman et al., 2006). The linear enrichments of incompatible element ratios plotted against traces in (Fig 4.5 G and H) shows Th/La and Nb/Y versus Rb that show a positive linear correlation interpreted as the lavas are from same magmatic source and related by differentiation. The low CaO/Al<sub>2</sub>O<sub>3</sub> ratios (0.61–0.77) and relatively flat HREE pattern in the Rare earth element (REE) diagram with no extreme depletion is an indicator of a mantle source free of garnet.

The Erta' Ale lava is characterized by low La/Nb (<1) and Ba/Nb (<5) values. Low La/Nb and Ba/Nb ratios are also observed among the younger post-rift basalts from southern Ethiopia. Pik et al. (1999) inferred such low values as mantle plume-derived melts. Oligocene flood basalts throughout Ethiopia (Pik et al., 1999) have lower overall abundances and consistently flatter rare earth element patterns. These subalkaline basalts have high TiO<sub>2</sub>, P<sub>2</sub>O<sub>5</sub>, Fe<sub>2</sub>O<sub>3</sub> and Nb/La and low SiO<sub>2</sub> (Pik et al., 1998). Miruth Hagos et al. (2010) stated that Afar Depression volcanic, particularly the Erta' Ale Range lavas are evolved from the last phase of the Afar mantle plume. The Erta' Ale basalt has average trace element ratios such as: La/Nb (0.79), Ba/Nb (6.49), Zr/Nb (6.5) and Ba/La (8.31). These average values are comparable with the HT2 lavas of the Ethiopian province. Pik et al. (1999) stated that this HT2 lava most likely represents the composition of the Afar mantle plume during the Oligocene.

The variation in isotopic composition from Miruth Hagos et al, (2016) is  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70370 - 0.70531$ ;  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51287 - 0.51289$ ; from Barrat et al. (1998) is  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70354 - 0.70371$ ;  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51290 - 0.51292$  and from Pik et al. (1999) is  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70389 - 0.70407$ ;  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51285 - 0.51296$ . Rogers et al., (2000) suggest that a value close to a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of  $\sim 0.5129$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $\sim 0.7035$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio of  $\sim 19.0$  is now widely accepted as the isotopic composition of the Afar mantle plume. From isotopic composition of the Erta'Ale lavas from Barrat et al. (1998) and Miruth Hagos et al. (2016) and Oligocene flood basalt from Pik et al. (1999) and different trace element value we know that the source of the mantle for the Erta'Ale lava is Afar mantle plume.

According to Pik et al. (1999) the HT2 lava have ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.70400$ ;  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51295$ ) close the average value of OIB. Miruth Hagos et al., (2016) suggest that HT2 basalts of the northwestern plateau are the sole volcanic suite in the Ethiopian volcanic province that represents the geochemical signature of the Afar mantle plume head composition. Furman et al. (2004) imply that the plume-tail lavas from Erta'Ale Range have slightly lower  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios than the plume-head lavas although the  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of these two series overlap. According to Furman et al. (2004) the portion of the plume that melted at  $\sim 30$  Ma was compositionally different from the portion undergoing melting now.

In general, the isotope ratios of the Erta'Ale lavas from Barrat et al. (1998) and Miruth Hagos et al. (2016) and Oligocene flood basalt from Pik et al. (1999) lie within the ranges defined by ocean island basalts (OIB), with  $^{143}\text{Nd}/^{144}\text{Nd}$  ranging from 0.51300 to 0.51255,  $^{87}\text{Sr}/^{86}\text{Sr}$  from 0.7030 to 0.7055 and  $^{206}\text{Pb}/^{204}\text{Pb}$  from  $< 18$  to  $> 20$  (Rogers et al., 2000). The Sr and Nd isotopic composition ranges observed among the Danakil Depression mafic lavas ( $^{87}\text{Sr}/^{86}\text{Sr}$  0.7036–0.7041,  $^{143}\text{Nd}/^{144}\text{Nd}$  0.51286–0.51289) is comparable to that of proposed common source values for mantle plume magmas, termed FOZO (Hart et al., 1992).

The Ethiopian flood basalt province is the only continental flood basalt on the world that records the complete period of volcanism starting from the plume head to the plume tail (Miruth Hagos et al., 2010).

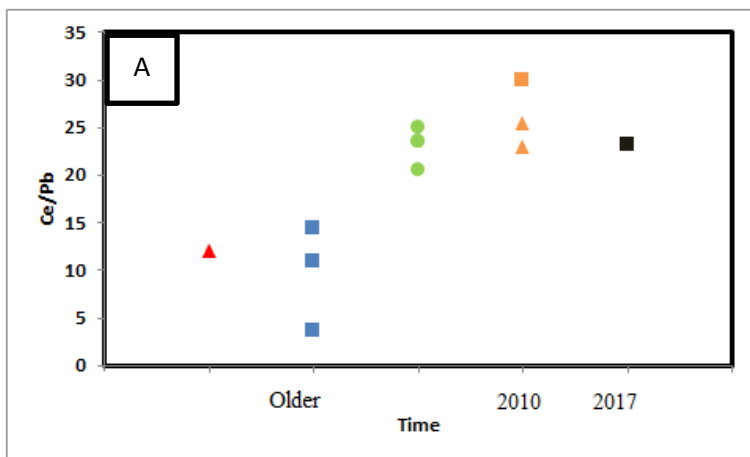
### **5.3 Compositional variation of Erta'Ale Basaltic eruption with time.**

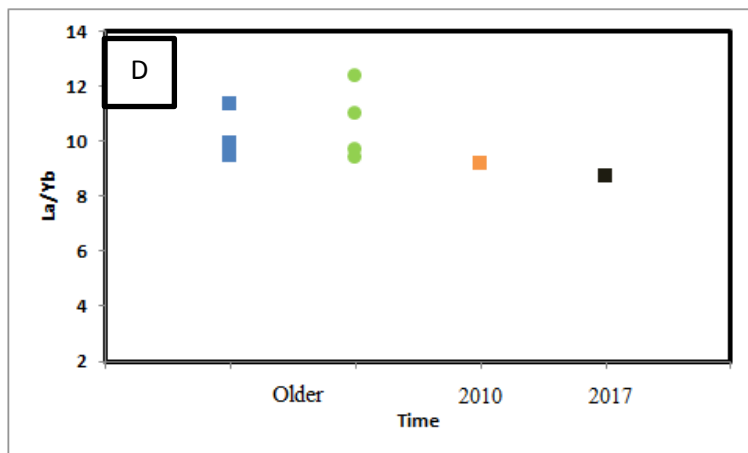
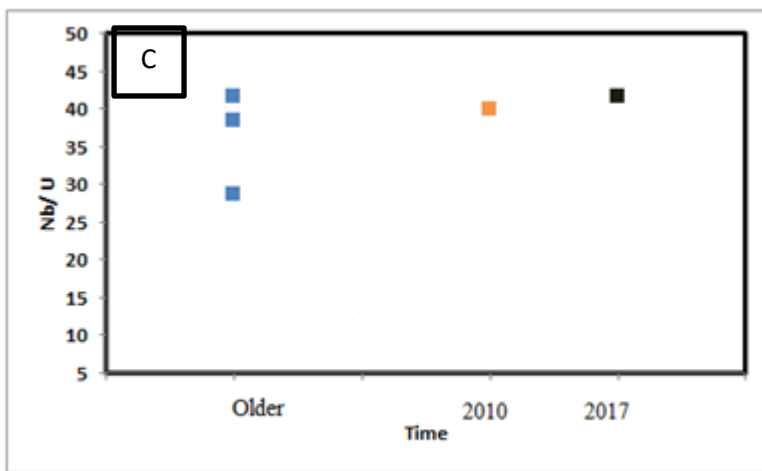
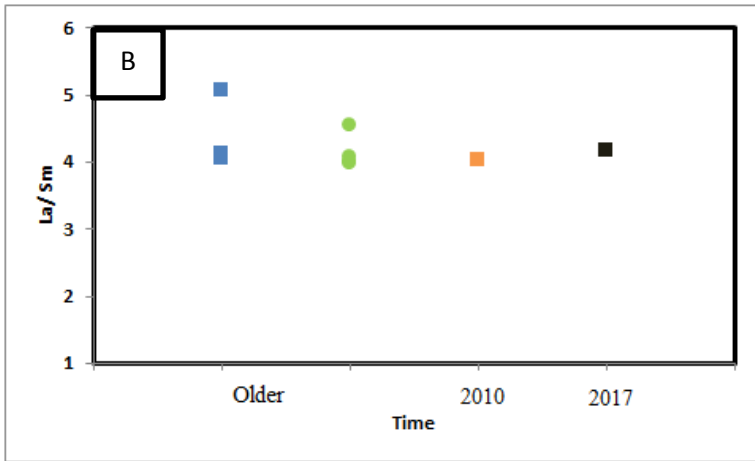
The main question is whether the composition of Erta'Ale basaltic eruption is varying with time or not. In the 2010 and 2017 lava there is no any significant difference in

petrographic and geochemistry. In the diagram below in order to see the compositional variation of Erta’Ale basaltic rock with time the plot of some trace element ratios with time are important. In this study there are a 2017, 2010 lavas and other lava whose age are not exactly known but they generally considered as older lava. The samples from other researchers are taken in to consideration to understand the variation and they are also considered as older lava.

In the figure below (Fig 5.2 A) the ratio of Ce/Pb versus time are plotted and there is a slight chemical variation with time. The high Pb anomaly of basalt 5 and basalt 6 is one reason for the low value of Ce/Pb value of the samples. The La/Nb and Nb/U ratio versus time ratio in the diagram suggests the Erta’Ale basalt have the same source. They have La/Nb ratio (0.75-0.84) and Nb/U value in the range of (28-48) which shows most of the sample of the Erta’Ale basalt are in the range of mantle values with minor contamination. The entire samples of the Erta’Ale lava have a similar source region which is the Afar plume. In the La/Sm versus time diagram below (Fig 5.2 B) there is no any change in the La/Sm ratio of the Erta’Ale lava with time. This can tell us that the depth and degree of melting of the Erta’Ale doesn’t change with time.

However there is a slight chemical difference between the 2010, 2017 lava and the other older lava. However the slight chemical difference is because of the change in degree of fractionation. According to Field et al. (2012) the 1973 lavas appear to be texturally and chemically distinct from those of 2010 these differences can be readily reconciled with a slightly increased degree of fractionation of 1973 lava , as evinced by higher contents of incompatible elements, and lower temperatures. Field et al. (2012) suggest that the sub-volcanic reservoir was refilled by hotter, compositionally similar basaltic magma subsequent to 1973.





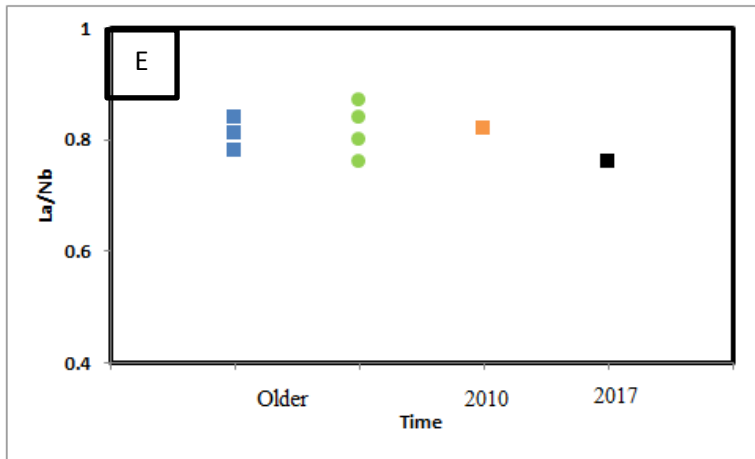


Figure 5.2: Trace element ratio diagrams versus time to understand the compositional variation of Erta Ale basaltic rock with time. The 2017, 2010 and other samples with unknown age with data from Miruth Hagos et al. (2016), and Field et al. (2012) are plotted together for comparison. The symbols are the same as shown in the figure 4.3.

# Chapter Six

## 6. Conclusion and Recommendation

### 6.1. Conclusion

To accomplish the general and specific objective of the research, field and petrographic evidences were utilized in combination with geochemical data. For comparison the result of this research are presented and interpreted with the result of different authors. The main outcomes of this study are;

1. The geochemistry and petrography of the sample from Erta'Ale and the geochemical data from other researchers show us that most of the rocks are basalts except one which is basaltic andesite.
2. The major element variation diagram, trace element variation diagram, REE and multi element variation diagram of the rock groups imply the rocks are linked by a fractional crystallization process. The distribution of the samples and the trend in the diagrams suggest early crystallization controlled by olivine followed by pyroxene, plagioclase and Fe-Ti oxides.
3. Most of the Erta'Ale basalts are the result of mantle derived melts without any crustal material involvement. The absence of negative anomaly of Nb and Ta in the multi element variation diagram and the fall of most of the sample in the region of mantle values  $Ce/Pb \pm 25$  (Hofmann, 1986) is an indicator of crustal contamination is not a major process in the genesis of this rocks. However, there are samples which have  $Ce/Pb < 20$  which likely represent the region of crust in the Ce/Pb versus MgO graph. Therefore, most of the Erta'Ale basalt indicates the absence of crustal contamination. However, there are samples which show crustal involvement which is because of the anomalously high content of Pb.
4. Afar mantle plume is the source of the Erta'Ale volcanic range and the Oligocene continental flood basalt of northwestern Ethiopia (Pik et al., 1999). The Erta'Ale basalt have comparable value of trace element ratio with the continental flood basalt of Pik et al. (1999) which is inferred as the result of Afar mantle plume. The source of the Erta'Ale basalt.
5. All the 2017, 2010 and other older lava have almost similar pattern in the major element, trace element modeling, REE variation diagram and multi element variation diagram of the samples which shows that there is no change in the composition of the

Erta'Ale basalts with time. The trace element ratio (La/Nb, Ce/Pb, Nb/U, La/Yb and La/Sm) versus time diagram also shows that the compositions of the Erta'Ale basalt don't show a significant variation. They display a parallel pattern in the trace element ratio versus time diagram. This parallelism is an indicator of the absence of change in compositional variation with time. Therefore, the composition of Erta'Ale basaltic eruption doesn't show variation with time.

## **6.2 Recommendation**

This study mainly focused on the compositional variation of Erta'Ale basaltic eruption through time it involved both petrographic and whole rock geochemical analysis. For better understanding of compositional variation of the Erta'Ale basaltic eruption with time isotope analysis are very important. Isotope analysis is a strong tool to understand magma evolution. So isotope geochemistry is suggested for further understanding of the source and petrogenesis of the Erta'Ale rocks. Most of the work on Erta 'Ale lava lake are based on remote sensing rather than field work. Detail study on the Erta'Ale lava lake are rare and most of the work on Erta'Ale are regional therefore detail work on the shield volcano is necessary. Geologic maps of greater scales have to be produced so that the structural and lithological features are better understood. The current study only targeted very narrow area for sampling. Therefore, larger areas with various type of lava flow have to be included to better understand the variation. There are different future research opportunities in the Erta'Ale lava lake includes detail work on the reason for persistent of the lava lake, feeding system or magma recharge of the magma chamber.

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**APPENDIX I**  
**Petrographic Analysis**

2017 lava			
Mineral	Modal proportion (%)	Phenocryst average grain shape	Rock name
Plagioclase	24	Subhedral	Basalt
Olivine	5	Euhedral	
Clino pyroxene	3	Subhedral	
Opaque	18	Anhedral	
Void space	50		

2010 lava			
Mineral	Modal proportion (%)	Phenocryst average grain shape	Rock name
Plagioclase	15	Subhedral	Basalt
Olivine	2	Subhedral	
Clino pyroxene	1	Anhedral	
Opaque	35	Anhedral	
Void space	47		

Basalt 3			
Mineral	Modal proportion (%)	Phenocryst average grain shape	Rock name
Plagioclase	26	Subhedral	Basalt
Olivine	3	Subhedral	
Clino pyroxene	5	Subhedral	
Opaque	23	Anhedral	
Void space	43		

Basalt 4			
Mineral	Modal proportion (%)	Phenocryst average grain shape	
Plagioclase	36	Subhedral	Basalt
Olivine	5	Anhedral	
Clino pyroxene	2	Anhedral	
Opaque	22	Anhedral	
Void space	35		

Basalt 5			
Mineral	Modal proportion (%)	Phenocryst average grain shape	Rock name
Plagioclase	4	Subhedral	Basalt
Olivine	1	Subhedral	
Clino pyroxene	-		
Opaque	52	Anhedral	
Void space	43		

Basalt 6			
Mineral	Modal proportion (%)	Phenocryst average grain shape	
Plagioclase	40	Anhedral	Basalt
Olivine	13	Anhedral	
Clino pyroxene	5	Anhedral	
Opaque	17	Anhedral	
Void space	25		

## APPENDIX II

### Geochemistry data

Trace element ratio

Sample	La/Nb	Rb/Nb	Ce/Pb	Th/ Nb	Ba/N b	Zr/N b	Nb/U	Th/La
2017 lava	0.76	0.42	23.15	0.09	4.39	5.81	41.64	0.11
2010 lava	0.82	0.44	29.87	0.09	5.04	5.74	39.77	0.11
Basalt 3	0.81	0.46	14.40	0.10	4.92	6.18	41.50	0.12
Basalt 4	0.75	0.45	8.93	0.07	14.97	8.53	47.63	0.10
Basalt 5	0.84	0.63	10.91	0.12	4.76	6.92	28.48	0.14
Basalt 6	0.78	0.44	3.67	0.09	4.90	5.84	38.29	0.12

Sample	La/Sm	La/Yb	(La/Yb) <sub>n</sub>	Ba/La	Nb/Y
2017 lava	4.16	8.73	5.29	5.75	1.07
2010 lava	4.02	9.18	5.56	6.15	0.99
Basalt 3	4.04	9.90	6	6.09	1.08
Basalt 4	2.74	16.77	10.16	19.97	1.46
Basalt 5	5.06	11.34	6.87	5.64	1.30
Basalt 6	4.13	9.46	5.73	6.28	1.12

**Appendix III**  
**Trace element**

Sample	2017 lava	2010 lava	Basalt 3	Basalt 4	Basalt 5	Basalt 6
<i>Trace element (ICP -MS) (ppm)</i>						
As	0.4	< L.D.	0.1	0.4	1.1	0.8
Se	0.5	–	1.1	0.8	1	0.5
Ag	<0.5	–	<0.5	<0.5	<0.5	<0.5
In	0.018	< L.D.	0.039	0.021	0.032	0.021
Sb	0.13	< L.D.	0.07	0.05	0.2	0.22
Te	<0.01	–	0.03	<0.01	0.02	0.02
W	2	0.32	222	42	2	1
Re	<0.001	–	0.001	0.001	<0.001	<0.001
Hg	<0.005	–	<0.005	<0.005	0.005	<0.005
Bi	0.01	< L.D.	0.03	0.03	0.03	0.02