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COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

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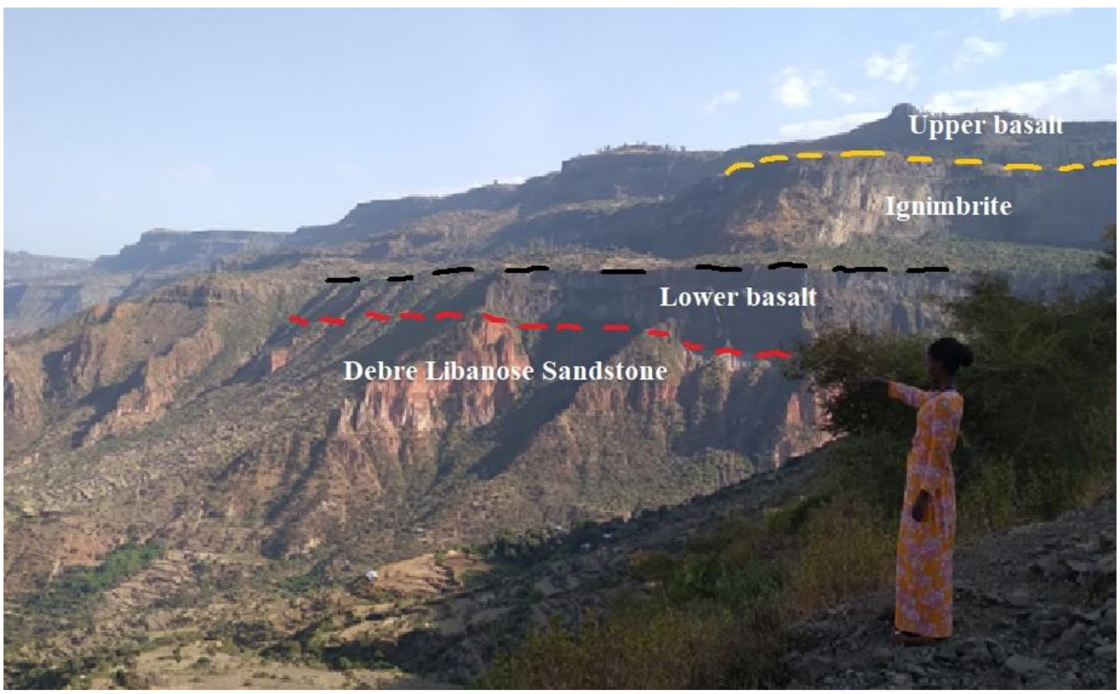
STRATIGRPHY AND PETROGRAPHY OF FLOOD BASALT SUCCESSION AT DEBRE LIBANOS AREA, CENTRAL ETHIOPIA



BY: KURI YIMENU

A thesis submitted to School of Earth Sciences, Addis Ababa University in partial fulfillment of the requirements for the Master of Science degree in Geological Sciences (Petrology)

Feb 2022

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BY:

KURI YIMENU

ADVISOR: Prof. DEREJE AYALEW

A thesis submitted to School of Earth Sciences of Addis Ababa University in partial fulfillment of the requirements for the Master of Science degree in Geological Sciences (Petrology)

Dec 2022

Addis Ababa, Ethiopia

Declaration for Originality

This is to certify that the thesis prepared by Kuri Yimenu, entitled: **Stratigraphy and Petrography of Flood Basalt Succession at Debre Libanos Area, Central Ethiopia** is compiled under supervision of Prof. Dereje Ayalew and submitted in partial fulfillment of the requirements for the Masters of Science degree in Geological Sciences (Petrology). It is complied with Addis Ababa University's rules and regulations and, it satisfies accepted requirements in terms of originality and quality. I further declare that this work is not presented or submitted to any other university or institution. All secondary information sources are properly referenced and acknowledged.

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ABSTRACT

The study area is located in the Northwest Shewa, Oromia Regional State with in NW Ethiopian Plateau, specifically around Debre Libanos, in central Ethiopia, about 105 km, in the northwest of Addis Ababa. The studied stratigraphic successions are cut by Zega wedem River. The main objective of the study is to constrain stratigraphy and Petrography of flood basalt succession at Debre Libanos area. To accomplish the objectives, starting from the beginning various methods have been applied. The methods are; Literature review, field work, and petrographic (thin section) analysis of representative samples. A total of 18 petrographic samples from these stratigraphic units are studied by using a petrographic microscope. From field and petrographic perspective, the area comprises the major lava flows identified in this study are; Aphyric basalt**,** plagioclase-olivine phyric basalt, plagioclase phyric basalt, ignimbrite, plagioclase-olivine-pyroxene phyric basalt and olivine-plagioclase phyric basalt. The volcanic units are underlain by Mesozoic Sandstone formation. The basaltic lava flows are the dominant product with interlayered pyroclastic deposits. The majority of the samples are from Basaltic units and have a variety of textures ranging from aphyric to phyric to mildly porphyritic. Plagioclase and Olivine are the major phenocryst phases with a proportion of pyroxene and Fe-Ti-oxides. In some samples, the groundmass is made of microlites of the same phase with a glassy texture. This distinctive petrographic heterogeneity reveals difference in depth of fractionation and magma flux in the lithosphere. The presence of olivine-plagioclase-pyroxene phyric basalt indicates there is considerable depth of fractionation in the shallow plumbing system. The aphyric basalt flow unit reflects there is no fractionation of any mineral in the shallow crust this indicates that the rate of magma flux to the shallow plumbing system is high.

Key words: *Debre Libanos volcanics, Flood Basalt, stratigraphy, petrography.*

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LIST OF ACRONYMS

CFB – Continental Flood Basalt

Cpx – Clinopyroxene

EARS – East African Rift System

Fig. – Figure

GPS -Geographical Positioning System

HT – High Titanium

KM – Kilometer

LIPs – large igneous provinces

LT – Low Titanium

masl – meters above sea level

MER – Main Ethiopian Rift

mm – Millimeter

MORBs– mid oceanic ridge basalts,

My – Million years

NW – Northwestern

NWEP – North Western Ethiopian Plateau

OIBs – ocean island basalts,

Plag – Plagioclase

PPL – Plane polarized light

Pxn – Pyroxene

SE – Southeastern

SEEP – South Eastern Ethiopian plateau

Wt% – Weight in percent

XPL – Cross polarized light

CHAPTER ONE

INTRODUCTION

1.1 Background

A "Continent Flood Basalt Province" (CFBP) can be defined as a series of volcanic eruptions that affected portions of the continental crust and were many made up of thick basaltic lava flows, which may have affected either the continental (such as the Parana-Etendeka, Deccan, etc.) or oceanic crust (such as Ontong Java) (Jerram and Widdowson, 2005), Ukstins et al., 2002) Continental flood volcanism (CFV) refers to huge eruptions of basaltic lava flows and, in some cases, rhyolitic lavas and pyroclastic materials, frequently with volumes in excess of 1 X $l0^6$ km3 (Rochette et al., 1998). The Ethiopian volcanic province, located at the northern end of the East African Rift System (EARS), is one of the youngest large igneous provinces (LIPs) consisting mainly of flood basalt volcanics with an area of 622,108 km2 and a younger rift volcanics. Estimates of the average lava thickness are widely varied, ranging from 1.6 km on the NW Ethiopian Plateau to 500 m in the SE Ethiopian Plateau and Chew Bahir Basin to 650 m on the Somali/Harar Plateau (Rooney et al., 2017). The rift and plateaus, which can be separated into two main series: the trap series and the rift series, are where these volcanic products are mostly exposed. During the initial stages of the rift, groupings of formations known as trap series are formed before the main Ethiopian rift develops perfectly. They are often referred to as pre-rift sequences or plateau volcanoes. They are the main igneous units revealed in the northwest and southeast Ethiopian plateaus, with a layer of mafic and felsic volcanic rocks occupying a total volume of around 620,147 km3 (Rooney et al., 2017). (Ukstins et al., 2002; Kieffer et al., 2004). The majority of the province crops out in Ethiopia, whereas the rest is located in Yemen on the eastern side of the Red Sea (Pik et al.,1998). It consists mostly of basaltic lavas, rhyolitic ignimbrites, and pyroclastic-fall deposits, as well as less often occurring basaltic pyroclastic rocks and rhyolitic lavas (Dereje Ayalew et al., 2002; Kieffer et al., 2004; Ukstins et al., 2002; Natali et al.,2011;2013). According to Mohr (1983) and Mohr and Zanettin (1988), it has a total area of roughly 600,000 km2 and a volume of about 350,000 km3.

Flood basalts and related felsic pyroclastic rocks, also known as Ethiopian traps, are continental volcanic rocks that erupted before the onset of continental rifting and sea-floor spreading in the Afar, which is believed to be related to the Afar plume activity. The bulk of these volcanic erupted mainly around 30 Ma ago during a relatively short, <5 My period (SeifeMichael Berhe et al., 1987; Hofmann et al., 1997; Kieffer et al., 2004). Large shield volcanoes grew on the surface of the volcanic plateau after this fissural activity peak. In many instances, the major volcanic plateau was created by co-magmatic shield and flood volcanism (Keiffer et al., 2004). There are several different types of basaltic rocks in Ethiopia's volcanic regions, including the alkaline, transitional, and tholeiitic series (Dereje Ayalew et al., 2002; Beccaluva et al., 2009). The Northern Ethiopian plateau mainly consists of tholeiitic to transitional basaltic lavas (Mohr and Zanettin, 1988), which were erupted at 30Ma in a period of 1Myr or less. The basalts cover an area of 210, 000 km2 with a lava pile up to 2000m thick in the central-eastern part, thinning to less than 500m toward the northern and southern boundaries (Hofmann et al., 1997). On the eastern margin of northern Ethiopia, neighboring the Afar escarpment, rhyolites volcanic rocks characterizing the upper part of the sequence have been interpreted as the differentiated products of basaltic magmas that mark the start of continental rifting (Dereje Ayalew et al., 2006).

1.2 Review of previous geological work

Many researches have been undertaken on northwestern Ethiopian plateau basalts. The Ethiopian volcanic plateau is divided into two parts by the main Ethiopian rift 11 Ma. The plateau lying to the west of the rift system is designated the North Western Ethiopian plateau (NWEP), while the other to the east is named the South Eastern Ethiopian plateau (SEEP) Wolfenden et al., (2004). The northwestern Ethiopian plateau does not fit the popular image of a continental flood basalt province in that it is not a thick monotonous, rapidly erupted pile of undeformed flat lying tholeiitic basalts. Instead, it is made up of several distinct volcanic centers with different magmatic character and with a large range of ages (Kieffer et al., 2004). The major volcanic units of the North Western Ethiopian Plateau (NWEP) include the Trap series or the continental flood basalt i.e. (Oligocene –Miocene basalts and rhyolites), Miocene- Pliocene shield volcanoes, and Quaternary volcanic rocks.

Dereje Ayalew and Gibson 2009 study, which used a composite stratigraphic section of the north Shewa volcanic succession at Yite-Koste to show the intercalation of basalt and rhyolite formations, found that the north Shewa succession of basalts and rhyolites is distributed over a large area (>2200 km2), locally exceeds 1000 m in thickness and the volcanic lie uncomfortable on Cretaceous sandstone. The topmost part of the sequence consists of a thick ignimbrite unit that often forms topography typical of plateau morphology. Upper and Lower basalts and Upper and Lower ignimbrites were used to split the succession. The Ethiopian flood basalts is chemical and mineralogical is relatively homogeneous Majority are aphyric to sparsely phyric, and contain phenocrysts of plagioclase and clinopyroxene with or without olivine. Most have tholeiitic to transitional compositions (Mohr, 1983; Mohr & Zanettin, 1988; Pik et al., 1998).

Like the other continental flood basalt provinces, there are no intermediate lavas, and the volcanism is of a clearly bimodal basalt rhyolite type (Dereje Ayalew, 2011). (e.g., Karoo and Parana). Moreover, the majority of the flood basalt contains phenocrysts of plagioclase and clinopyroxene with or without olivine and is mineralogically aphyric to sparsely phyric. Their chemical makeup ranges from tholeiitic to transitional (Mohr, 1983; Pik, et al., 1998; Kieffer et al., 2004; Beccaluva et al., 2009). Low-Ti basalts (LT), high-Ti1 (HT1), and high-Ti2 (HT2) basalts are defined as three separate geochemical groups based on trace element and Ti concentrations by (Pik et al. 1998; 1999), and (Beccaluva et al., 2009) allows a more precise definition of their zonal arrangement. Quantitatively, Low-Ti tholeiites (LT) dominate in the northwest (150000 km3); High-Ti lavas (HT1) dominate in the southeast; and ultratitaniferous transitional basalts and picrites (HT2) are abundant in the Lalibela area, nearer to center of the Afar triangle. The northern portion of the Ethiopian flood basalt sequence in the Western Ethiopian Plateau is composed of up to 2 km thick predominantly mafic lavas with minor felsic pyroclastic (Hofmann et al. (1997); Dereje Ayalew et al., (2002)). Rhyolites are found throughout the strata of the volcano as ash layers between basaltic lava flows or as isolated eruptive units with a volume equivalent to that of a single unit of mafic lava. They thicken as they approach the top of the lava sequences (Kieffer et al. 2004). The mantle xenoliths found in the plateau area's Quaternary alkaline lavas exhibit a wide range of compositions, from spinel lherzolites to harzburgites and olivine-websterites. The dominant lherzolites are protogranular and generally lack modal evidence of metasomatic reaction.

Their modal composition is in the following ranges: olivine 60-61%, orthopyroxene 22%, clinopyroxene 14-15%, spinel 3% (Beccaluva et al., 2009) and characterized by cinder-cone fields, which suggest that the ascent of the magmas may have involved hydraulic fracturing, permitting rapid rise up through the lithosphere without undergoing significant fractional crystallization or crustal contamination (Dereje Ayalew, 2011). The northwest Ethiopian volcanic plateau which represents the so-called ‘Ethiopian flood basalt province’ evolved during at least two major pulses: at 30 Ma in the northern plateau and 20 Ma in the central plateau.

The study by Dereje Ayalew (2011), suggests that volcanism commenced in north-central Ethiopia c. 20 Ma, 10 Ma after initial magmatism in the northern Ethiopian plateau. The isotopic compositions of north Shewa basalts and rhyolites indicate the increasing involvement of crustal materials in the evolution of north Shewa magmas with time, probably as a consequence of thermal weakening of the crust triggered by repeated injections of hot basaltic magmas in the lithosphere during rifting. Three-time periods that are equivalent to the most significant magmatic events each followed by a bimodal or silicic magmatic activity, in East Africa during the Cenozoic are given by the work of Rooney et al., (2017). These periods are (i) Eocene Initial Phase (45 to 34 Ma) focused in Southern Ethiopia and Northern Kenya (Turkana), (ii) Oligocene Traps phase (~33.9 to 27 Ma) observed from Turkana in the south to Yemen in the north, to Sudan in the west, and the margin of the Somali Plateau to the east and (iii) Early Miocene resurgence phase (plume-dominated magmatic activity) (~26.9 to 22 Ma) seen throughout the regions. In this work, a new estimation on the volume, area, and thickness of the 720,000 km3 volume of magmatism in East Africa from ca. 45 to 20 Ma is given. From this, the northwest and southeastern Ethiopian plateaus cover a total volume of about ~620,147 km3.

Krans et al., (2018) provide detailed flow-by-flow petrographic investigations from the beginning to the end of the Ethiopian–Yemen flood basalt province, all within a well-constrained stratigraphy (LT flood basalts around the Lake Tana area). The Ethiopian flood basalt province is divided into three sections: lower flood basalt, which is predominantly Ol-phyric with Cpx-rich cumulates; middle flood basalt, which has Plg-megacrystic flows and oscillations between Plg-phyric and Ol-phyric flows; and upper flood basalt, which is predominantly Plg-phyric and devoid of cumulates.

The lower crust (dominated by the crystallization of clinopyroxene cumulates in the absence of plagioclase) and the mid-to-shallow crust (dominated by the crystallization of clinopyroxene cumulates in the absence of plagioclase) show evidence of two fractionation regimes, according to modal analyses (dominated by plagioclase cumulates).

Rooney et al. (2018) conducted a study on the dikes associated to the LT flood basalts that erupted in western Ethiopia to examine at the region's magmatic plumbing system. These studies showed the identical composition and timing of the western Ethiopian dike swarm and the eruption of the Oligocene flood basalts. They also identified the western Ethiopian dike swarm as a magmatism source for the LT flood basalt lavas.

Based on detailed field logging, Dereje Ayalew et al., (2021) present three formations that are recognized, given names, and linked to documented radiometric ages from the Oligocene in nearby regions. From the bottom to the top of these formations: The Wegeltena Rhyolite, which is composed of silicic ignimbrites dated at 30.2 Ma, is uniformly overlain by Teri Basalt, the main phase of flood basalt emission. A thin bed of conglomerate, sandstone, and mudstone, which represents a 3 Ma period of volcanic quiescence, lays on top of this. The Kon Basalt, which has a 27.8–26.7 Ma dating, is found at the top of the series.

The absolute 40Ar/39Ar age of an Oligocene-Miocene flood volcanics and Miocene -Pliocene volcanoes from the western Ethiopian plateau is determined by Hofmann et al. (1997), Coulie et al. (2001), Ukistins et al. (2002), Kieffer et al., et al. (2004) Summarized in table blew

Table 1.1. Summary of age data on western Ethiopian Plateau

No.	Location	Rock Name	Age	Source
1.	North Addia Ababa	Mio-Pliocene Volcano	10.6-3.2Ma	Ukstine et al., (2002)
2.	Guna Mt.	Mio-Pliocene Volcano	10.7Ma	Kiffer et al., (2004)
3.	Simien Mt.	Mio-Pliocene Volcano	18.7Ma	Kiffer et al., (2004)
4.	Alem Ketema	Mio-Pliocene Volcano	21.6Ma	Coulie, (2001)
5.	Guguftu Mt.	Mio-Pliocene Volcano	22.3 Ma	Coulie, (2001)
6.	Mt. Choke	Mio-Pliocene Volcano	22.4 Ma	Coulie, (2001)
7.	Blue Nile River	Flood Basalt	26.9-29.4 Ma	Hofmann etal., (1997)
8.	WegelTena	Flood Basalt	30.2-28.2 Ma	Hofmann etal., (1997)
9.	Limalimo	Flood Balsalt	29.4-30.8 Ma	Hofmann etal., (1997)
10.	Simen Mt.	Flood Basalt	30.4 Ma	Kiffer et al., (2004)
11.	Lalibela	Flood Basalt	31.0 Ma	Kiffer et al., (2004)

1.3 Location and accessibility of the study area

Debre Libanos area is a part of the Northwestern Ethiopian plateau in the Central Part of the country, located in the North west Shewa, Oromia Regional State. Its geographical coordinates are 9° 43′ 0″ to 9° 42′ 31″ N latitude and 38° 52′ 0″ to 38° 52′ 0″ E longitude and falls in the Ethiopian Mapping Agency topo sheet No. NC 37- 10. The area is accessible with Addis Ababa-Bahr Dar main asphaltic Road travelling from Addis Ababa –Muke Turi – Debre Libanos. The total travel distance from Addis Ababa to Debre Libanos area is about 105 km, in the northwest of Addis Ababa and 16 km away from Fiche, the zone capital city.

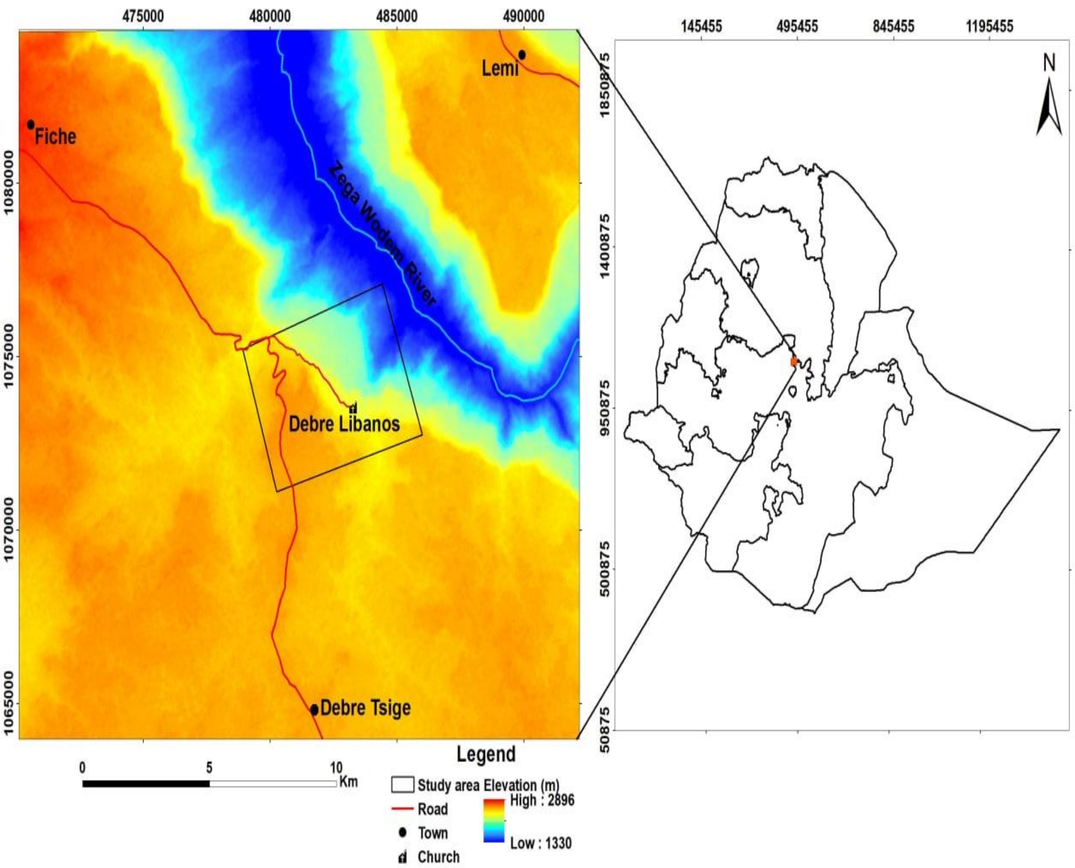

Figure 1.1 Location and accessibility map of study area

Figure 1.2 Location and accessibility map of the study area from google map imagery

1.4 Physiography of the study area

The physiography of Ethiopia is generally grouped in to three geographical sectors due to the geological events that take place in geological history. These are: (1) Main Ethiopian Rift and Afar depression, (2) Northwestern Ethiopian Plateau with adjacent low land and high land areas, and (3) South- eastern (Somali) Plateau. The vast volcanic and tectonic activity that took place after the flood basalt volcanism creates different physiographic features in the Debre Libanos area such as ridge, cliff and plains. The area is a part of northwestern Ethiopian Plateau, which encompasses varied topography ranging from the deeply dissected wide canyon or gorge along the Zega wedem river course to very rugged rocky mountainous terrains forming plateau at the top of the gorge.

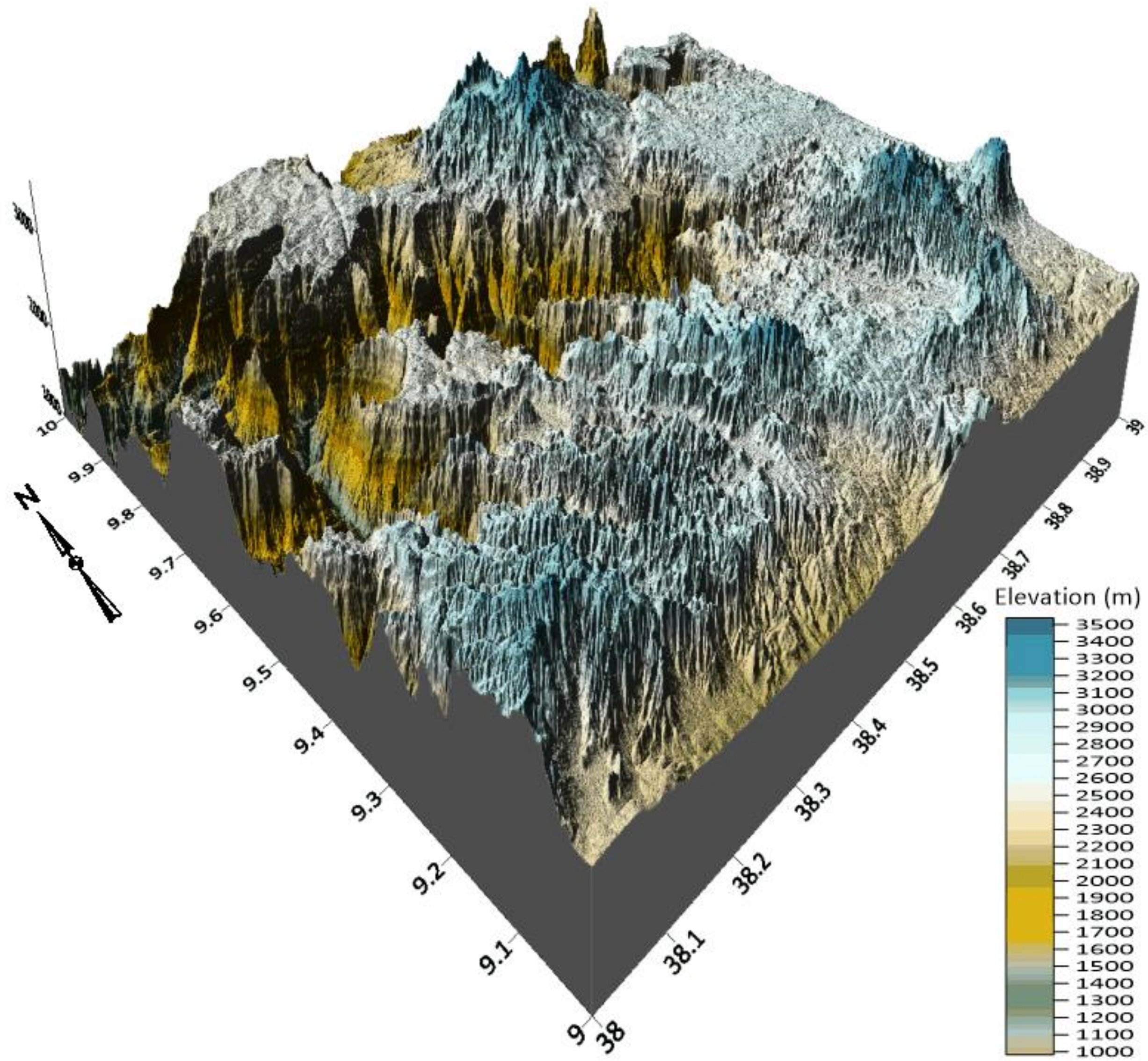

Figure 1.3 Physiographic map of the study area

1.5 Climate and Vegetation

The climate condition within the country is more affected by altitude change (Daniel Gemechu, 1977) has documented as Desert or Bereha (<800 m), Tropical or Kola (800 -1500 m), Subtropical or Weyna Dega (1500-2300 m), Temprate or Dega (2300-3300 m) and Alpine or Kur (>3300 m). The study area has a range of climatic conditions from subtropical or weynadega (1500-2300 m) to Temperate or Dega (2300-3300 m), it categorized on the basis of their elevation variation as noted by Daniel Gemechu (1977).

The hottest month in Debre Libanos, March, has days with highs of 80°F (27°C) and lows of 54°F (12°C). The coldest month, December has days with highs of 74°F (23°C) and lows of 46°F (8°C). The wettest month in Debre Libanos is August with an 82% chance of precipitation on a typical day and gets 0.03 inches (0.7 mm) of precipitation, while the driest month in Debre Libanos is December with a 4.0% chance of precipitation on a typical day and gets 0.03 inches (0.7 mm) of precipitation. (https://wanderlog.com/weather/80070/11/debre-libanos).

Highlands of Debre Libanos areas, are extremely vegetated with Bahir Zaf, this type of tree is very common throughout the plateau. However, in the lowland of Debre Libanos has rarely populated short trees of various type been common along the major river and its feeder streams, especially cedar, Girar, Tinjut and other short trees (which is adapted from Ethiopian name).

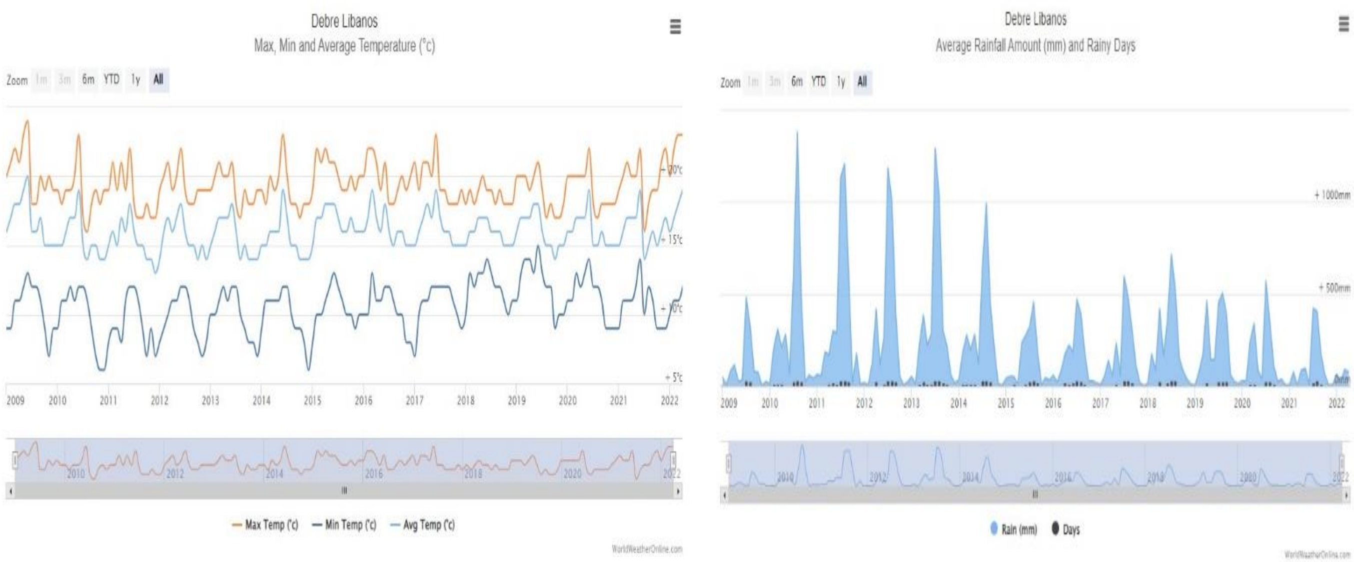

Figure 1.4 Average Temperature and Rainfall from 2014-2021 in Debre Libanos. https://www.worldweatheronline.com/debre-libanos-weather-averages/et.aspx accessed in 23th May 2022 at 9:23 pm).

1.6 Statement of the Problem

Many researches have been conducted on Ethiopian plateau magmatism at a regional scale and detailed investigations on single sections of the plateau are scarce and lack a detailed geological map and Stratigraphy of any particular section of the Ethiopian flood basalt province.

Some previous researchers have worked on regional study on the Plateau of Ethiopian volcanic rocks regarding geology, geochemistry, Stratigraphy and structural geology include (Pik et al., 1998, 1999; Kieffer et al., 2004; Seife Michael Berhe et al., 1987; Dereje Ayalew et al., 2002, 2006; Dereje Ayalew and Gezahegne Yirgu, 2003; Mohr, 1983; Hoffman et al., 1997; Natali et al., 2011; Krans et al., 2018; Dereje Ayalew et al., 2021).

However, these previous works are basically studied at the regional level and there is no detailed Stratigraphic and Petrography study in the Debre Libanos area. Hence, detailed geological mapping, stratigraphic and petrographic study is still needed for complete understanding of the volcanic units, extent, major lava flow morphologies, nature of contact between successive lava flows and stratigraphy of flood basalt provinces.

Thus, the present study focused on detailed petrographic descriptions, stratigraphic logging and geological mapping, for identification of volcanic units, extent, major lava flow morphologies, nature of contacts between each lava flow and determine total thickness.

1.7. Objectives

1.7.1 General objective

The principal objective of this study is to constrain the stratigraphy and Petrography of flood basalt successions at Debre Libanos, Northwestern Shewa, Central Ethiopia.

1.7.2 Specific objectives

- To describe and identify the different rock units, mineralogical and petrographic features of the flood basalt in the study area.
- To assess the major morphologies of lava flow and know the present or absent of interlayering sediment between lava flow.
- To constrain estimated total thickness of volcanic units and identifying the nature of contact between each successive lava flow.
- To Produce detailed geological map and cross section for study area at the scale of 1:25,000.

- To produce a complete stratigraphic log section of the study area and correlate stratigraphic sections with published works in the central Ethiopian plateau.

1.8 Methods and Filed Equipment

1.8.1 Methods

The main methodologies use for this study is revision of previous works**,** field work and petrographic analysis.

1.8.1.1 Literature Review

Before the field work and laboratory analysis, a comprehensive review of relevant literatures including previous works on the geology, tectonic setting, petrology and geochemical nature of the flood basalt succession of the study area and its surrounding, has been done. To understand about the area different previous works which are relevant for this study on the Some of the major activities conducted during the revision of previous works were collecting previous technical reports, journals, textbooks, extracting relevant information from the satellite image and aerial photograph, reviewing and compiling different kinds of literature (published and unpublished reports) related to the study area.

1.8.1.2 Field Work

This is used to know the distribution of the lithological units and lava flow morphologies. The main activities which have been done during the field work include: detailed rock descriptions, creation of geological maps, taking photographs, and sampling. 1:50,000 scaled base map has been used for data collection during the traverse. The samples for this study have been collected from the different volcanic units found in the study area. Latitude and longitude position of the sampling locations is undertaken for mapping the different volcanic units, by using a handheld Global Positioning System (GPS) receiver. Elevation has been also recorded and used as a representation to log stratigraphic sequences over short distances at the outcrop scale, and they have been integrated to construct the complete stratigraphic section.

1.8.1.3 Petrographic Analysis

For this study, 18 thin sections were prepared in Central Laboratory of Geological Survey of Ethiopia, and the subsequent petrographic analysis has been done under petrographic microscope in the Petrographic Laboratory of School of Earth Sciences of Addis Ababa University. A detailed petrographic study (thin section descriptions) including mineral identification, modal proportion, textural descriptions, and rock naming have been performed. Photomicrographs of representative mineral assemblage and textural features have been taken.

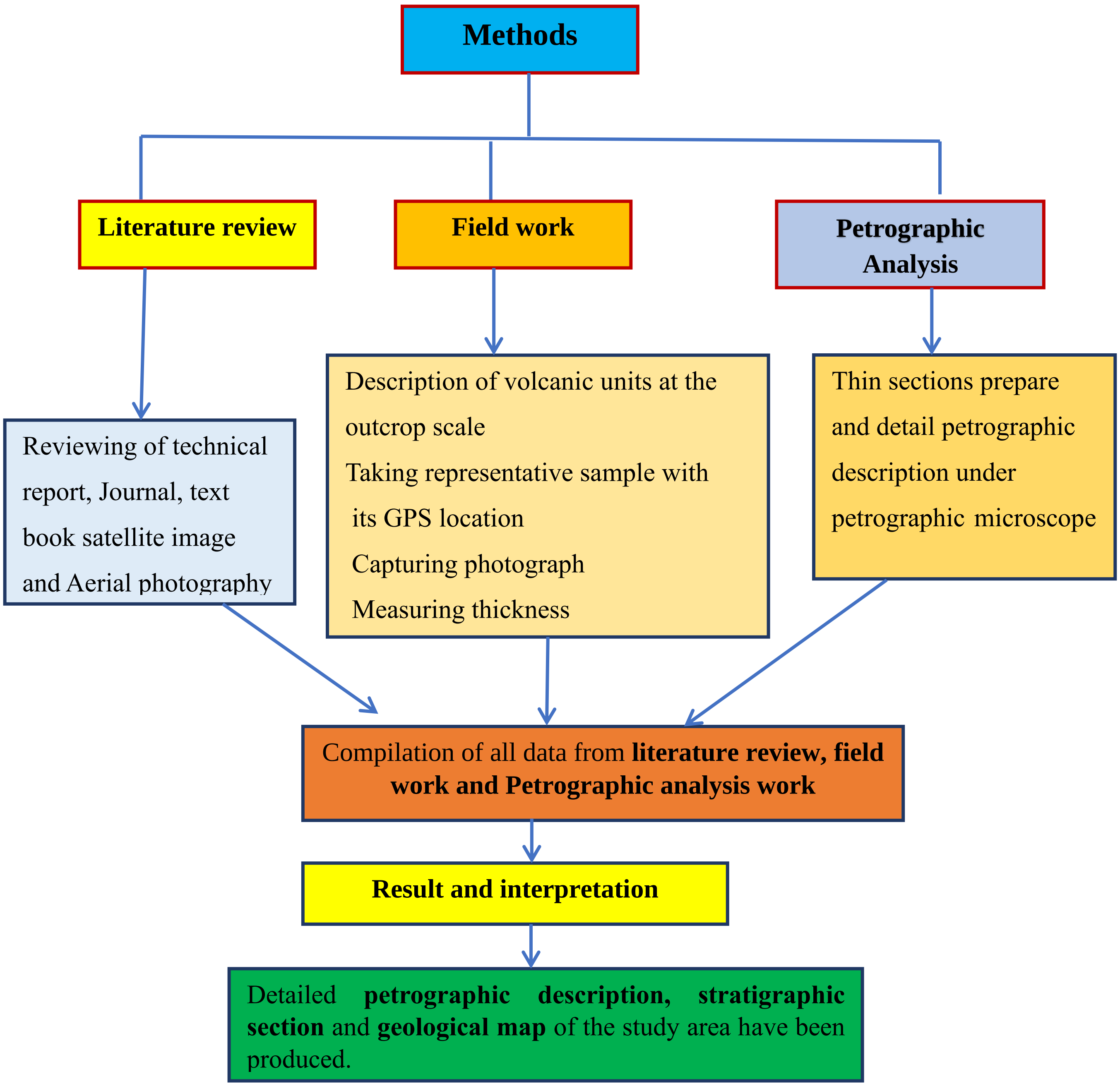

Figure 1.5 General Flow chart of methods

1.8.2 Filed Equipment

Based on the availability and relevance, various kinds of data/ information are be collected from different sources. The equipment's are used before, during and after the geological field works of the present study are: Burton compass, GPS, DEM maps, Topo map, camera, Geological hammer, Handheld lens, Measuring tape, Sample bags. Software such as Global Mapper, Arc GIS, Google Earth Pro, Surfer and strater 5 and different plotting software are used to prepare geological map Stratigraphic log and petrographic data of the analyzed sample.

1.9 Research Outcomes and Significances

As mentioned in the problem statement the Debre Libanos area has not been studied in the aspect of Stratigraphic and Petrography in detail. The main research outputs and significances presented as follow:

- Detail description about Petrology and petrography of the flood basalt.
- Geological map of the study area at a scale of 1:25,000 and geologic cross-section.
- Stratigraphic section of the study area.

This study is used to fill the existing gap in the following:

- This study used to fill the existing gap in the detailed study of continental Flood basalt of the Ethiopian plateau in relation to the petrologic and petrographic investigation.
- Detailed geological map and stratigraphic sections of the study area will be important as a basic source of data for understanding the geological history of the study area, as a part of the northwestern Ethiopian plateau.
- Contributed some data set to the ongoing worldwide studies of continental Flood basalt.

1.10. Thesis frame work

This thesis work is framed into six chapters. The first chapter includes a general background of the study area, the problem of the statement, the objectives of the study, the methodology used, a review of previous works related to this study area, and finally, the main significance and expected outcome of the study. Detailed regional geology in the frame of this study is presented in Chapter 2. This chapter includes general information about continental flood basalt provinces, followed by a review of regional studies about Ethiopian large igneous provinces including the flood basalt provinces. The final portion of this chapter combines details (Stratigraphy and Petrography) of different studies about the North-Western Ethiopian plateau.

Details of field observation about the local geology of the study area are presented in Chapter 3**.** This chapter includes a geologic map of the study area, description of different lithologic units in the study area and lava morphology with representative photographs of exposures and the stratigraphic section of the lithologic units at different localities.

In Chapter 4 petrographic description of representative samples taken from the different lithologic units described in local geology are described in detail with representative images of the samples from the petrographic microscope study are explained. The local data and observations are discussed with the regional previous studies in Chapter 5. The final part of the report includes conclusions and recommendations made in the study in Chapter 6.

CHAPTER TWO

REGIONAL GEOLOGY

2.1 Introduction

The Cenozoic continental flood basalts (CFB) of Ethiopia are located at the junction of the three-rift system: Red Sea, Gulf of Aden and the East Africa continental rift system. The majority of the province crops out in Ethiopia, while the rest of the province is exposed on the eastern side of the Red Sea (Pik et al., 1998). Eocene beginning phase (45–34 Ma), Oligocene trap phase (33.9–27 Ma), and early Miocene resurgence phase (26.9–22 Ma), which is then followed by bimodal lavas and silicic volcanism, are the three time periods that make up the basaltic magmatism (Rooney, 2017 and Krans et al., 2018). Southern Ethiopia and northern Kenya are the only places where basaltic volcanism occurred during the Eocene beginning phase (Furman et al., 2006; Rooney, 2017; Krans et al., 2018). North Ethiopia and Yemen are affected by the eruption of the Ethiopian Arabian plateau flood basalt, which occurs during the Oligocene (Baker et al., 1996; Hofmann et al., 1997; Rooney, 2017). Basaltic activity took the form of shield activity in the northwest Ethiopian plateau, fissure eruption on the southeast plateau, and increasing eruptions in the Turkana region during the Miocene resurgent period (Kieffer et al., 2004; Furman et al., 2006; Rooney, 2017; Krans et al., 2018). The trap basalts of Mohr and Zanettin's (1988) four-type division of the trap basalts of Ethiopia such as Ashange basalt, Aiba fissural basalt, Alaji fissural basalt and rhyolite, and Termaber basalt.

The initiation of the Man Ethiopian Rift comes after the creation of the trap series (MER). The MER, which makes up the northernmost portion of the East African Rift System (EARS) and connects the EARS with the Afar triple junction, is a significant portion of the EARS (Bekele Abebe et al., 2007 and Corti, 2009). A magmatic rift called the MER keeps track of all the many phases of rift development. As a result, it is a great location to study how continental expansion and lithospheric plate rupture have changed through time (Corti, 2009). According to Corti (2009), the main Ethiopian rift can be separated physiographically into three segments: the southern, central, and northern segments. The initiation of the Man Ethiopian Rift comes after the creation of the trap series (MER). The MER, which makes up the northernmost portion of the East African Rift System (EARS) and connects the EARS with the Afar triple junction, is a significant portion of the EARS (Bekele Abebe et al., 2007 and Corti, 2009).

A magmatic rift called the MER keeps track of all the many phases of rift development. As a result, it is a great location to study how continental expansion and lithospheric plate rupture have changed through time (Corti, 2009). According to Corti (2009), the main Ethiopian rift can be separated physiographically into three segments: the southern, central, and northern segments. The first episode of magmatism comprises mainly basaltic flows and scattered silicic centers developed along the rift floor. CFB generation was favored in northern Ethiopia and the conjugate Yemen margin by several factors: 1) lowered solidus temperatures of plume metasomatized mantle sources; 2) heat transfer by the plume buoyancy flux that raised the regional geotherm; and 3) decompression of the upwelling mantle (Beccaluva et al., 2009).The development of the Main Ethiopian and Afar rift systems, plateau uplift, and Cenozoic flood basalt volcanism have all been attributed to the upwelling of a mantle plume that may have been connected to the African Super-plume (Pik et al., 1998, Kieffer et al., 2004).

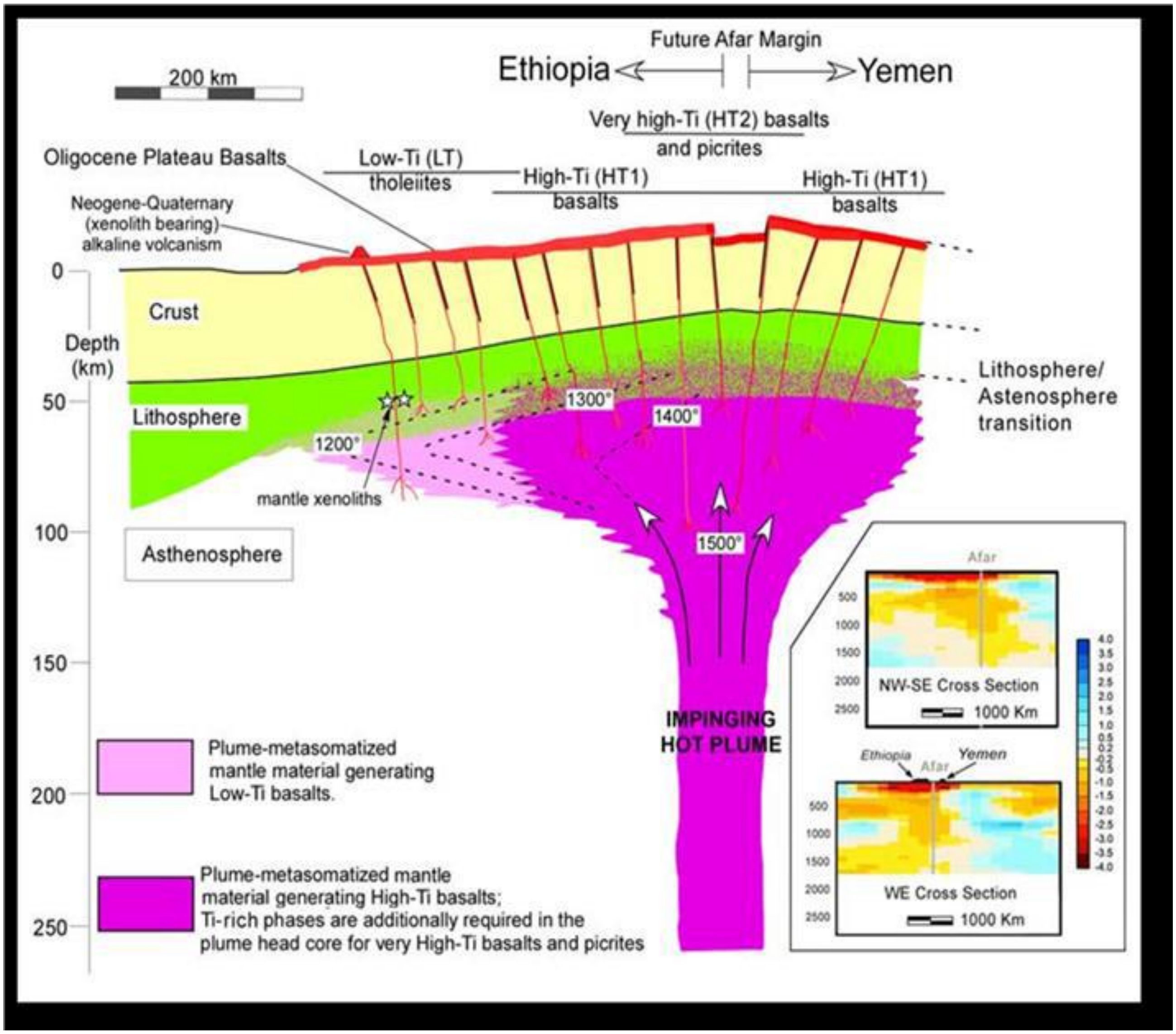

Figure 2.1. Illustration showing the Afar plume impinging on the Afro-Arabian lithosphere and the generation of Oligocene Northern Ethiopia-Yemen CFBs from a thermally and compositionally zoned plume head (Beccaluva et al., 2009). The inset shows mantle tomographic cross-sections beneath Afar, based on models for shear-wave velocity variations (Davaille et al., 2005).

2.2 Continental Flood Basalts

Continental flood volcanism (CFV) represents massive eruptions of basaltic lava flows and, in some cases, rhyolitic lavas and pyroclastic rocks, (Baker et al.,1996; Dereje Ayalew et al., 2002; Kieffer et al., 2004; Ukstins et al., 2002), often with volumes in excess of 1 X l0 6 km3(Rochette et al., 1998). The upwelling of mantle plume impinged on the base of the lithosphere is assumed to be related to the continental flood basalt (CFB) province and accompanying continental break-up (Storey,1995; Rooney et al.,2007). Nearly all CFB provinces contain significant volumes (up to 20% of the total volcanics) of acidic eruptive, usually in the upper part of the sequence capping the basalts (Dereje Ayalew, 2011).

In addition, almost all continental flood basalt regions' volcanic suites are bimodal basalt–rhyolite, with a marked paucity of intermediate compositions (Dereje Ayalew and Gezahegne Yirgu, 2003; Dereje Ayalew, 2011). According to Pik et al. (1999), the majority of lavas from major CFB provinces (Parana', Deccan, Siberia, Karoo, etc.) show isotopic and trace element signatures that are not typical of OIB, implying that they are not produced straight from the deep mantle. Instead, magmatism in most continental-flood-basalt (CFB) provinces comprises a mix of melts produced from lithospheric and convicting mantle sources, as well as readily-fusible crust (Baker et al., 1996; Hawkesworth et al., 1999).

Further, Dereje Ayalew et al. (2006) found that, at least within the last 200 Ma, the beginning of continental flood basalt (CFB) magmatism is spatially and temporally associated to continental break-up, which leads to the creation of oceanic crust. Furthermore, the relationships between the timing of CFB formation and rifting leading to ocean-floor formation are complex, and can vary in time and space (Courtillot et al., 1999; Hawkesworth et al., 1999). Magmatism can predate continental extension by several million years (e.g., Ethiopia-Yemen), magmatism and break-up can be synchronous (e.g., Parana-Etendeka, North Atlantic Tertiary volcanic province/ Greenland-UK), or magmatism can postdate break-up by several million years (e.g., Australia- India).

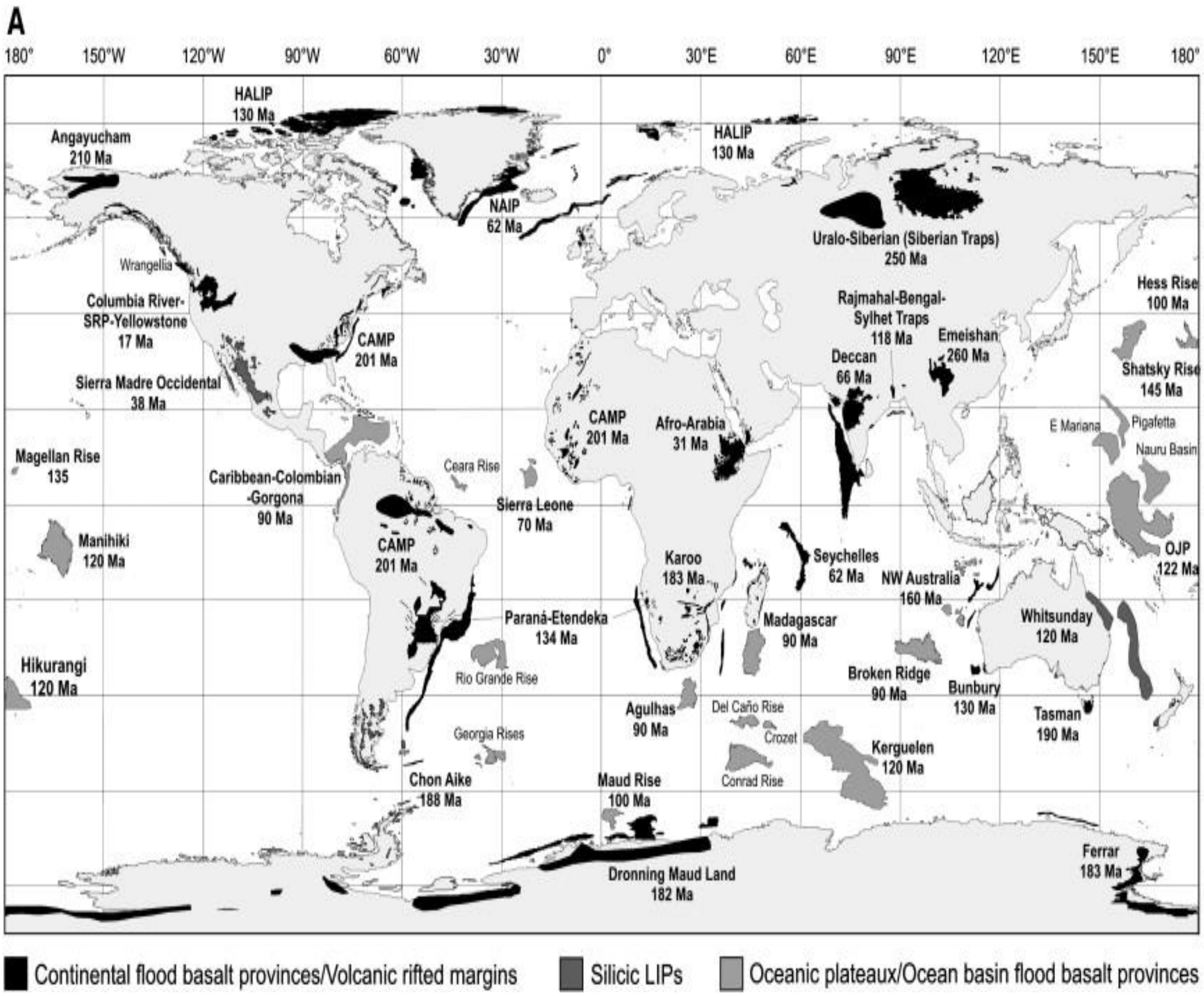

Figure 2.2 Location map of Large igneous provinces (LIPs) of the world, ages are those of the main phase or pulse of volcanism; (NAIP stands for North Atlantic Igneous Province and CAMP for Central Atlantic Magmatic Province (Adopted from Self et al., 2014).

2.3 Ethiopian Continental Flood Basalts

The Ethiopian continental flood basalt (CFB) province is one of the youngest (30 Myr) significant igneous provinces, and is associated with continental break-up and ocean basin formation (Dereje Ayalew and Gezahegne Yirgu, 2003; Kieffer et al., 2004; (Dereje Ayalew et al., 1999; Baker et al., 1996). Further, this flood basalt province is located near the Afar triple junction (Dereje Ayalew et al., 2002; Mohr and Zanettin, 1988; Pik et.,1998;1999).

The province's primary portion is in Ethiopia, while the remainder is in Yemen on the eastern side of the Red Sea (Pik et al., 1998). According to Rochette et al., (1998) the trap volcanics (western and eastern plateaus) encompass at least 600000 km2 with a total volume of at least 350000 km3 (Mohr, 1983; Mohr and Zanettin, 1988) and probably more than 1200000 km3.

The thickness of the lava pile varies greatly, reaching up to 2000 m in northwestern Ethiopia and thinning to 500 m towards both north and south (Furman, 2007). Basaltic lavas, rhyolitic ignimbrites, pyroclastic-fall deposits, and less frequent basaltic pyroclastic rocks and rhyolitic lavas make up the majority of the flood volcanism (Dereje Ayalew et al., 2002, 2011; Kieffer et al., 2004; Peccerillo et al., 2007). According to Kieffer et al. (2004), the Oligocene Ethiopian flood basalt has a reasonably consistent mineralogical and chemical composition. The majority of the rocks are aphyric to sparsely phyric and contain phenocrysts of plagioclase and clinopyroxene with little to no olivine. Further, the chemical compositions of Ethiopian continental flood basalts range from tholeiitic to transitional (Pik et al., 1998; Mohr and Zanettin, 1988; Mohr, 1983). Furthermore, the paucity of intermediate lavas and the volcanism's bimodal basalt-rhyolite nature (Mohr & Zanettin, 1988; Dereje Ayalew, 2011) are characteristics shared by the majority of continental flood basalt provinces, such as the Karoo and Parana. Additionally, the Ethiopian Plateau lavas are defined by a distinctive zonal organization, with extremely high-Ti transitional basalts and picrites (HT2, TiO2.4-6.5 wt.%) near to the Afar triple junction and low-Ti tholeiites (LT) to the west, high-Ti tholeiites (HT1) to the east (Beccaluva et al., 2009; Kieffer et al., 2004). The majority of these basalts and accompanying felsic rocks appear to have erupted within a relatively short time (5 Ma), with the highest rates happening between 31 and 28 Ma (Hoffmann et al., 1997; Pik et al., 1998; Ukstins et al., 2002; Coulié et al., 2003).

This strong eruption was concomitant with the onset of continental rifting in the Red Sea–Gulf of Aden systems by 29 Ma (Wolfenden et al., 2005), but predates the main rifting phases associated to the development of the MER (Corti, 2009). According to Mohr and Zanettin (1988) the eruptive process for the Ethiopian continental flood basalt (CFB) province was particularly active during mid-Tertiary, and was renewed in Afar some 5 My ago. Furthermore, Mohr and Zanettin (1988) found that Eruption rates on the Ethiopian plateaus were much lower than in other flood basalt regions over the 43 My of activity, possibly reflecting a slower rate of lithospheric thinning. This slow eruption rate in Ethiopia is consistent with the volcanic province's extremely long active period, 43 My, compared to only a few million years for the quickly built Columbia River and Deccan Plateau piles (Hooper, 1982; Cox and Hawkesworth, 1985 as cited in Mohr and Zanettin, 1988). The Ethiopian flood basalts have been credited with melting associated with the activity of one (Afar plume) or two (Afar and East African or Kenyan plumes) mantle plumes impinging on the continental lithosphere (Rogers et al., 2000; Ebinger and Sleep, 1998; George et al., 1998). Likewise, it has been suggested that the flood basalts of Ethiopia are the result of several plume stems erupting from a single, wide, and deeply buried mantle upwelling (the African super plume; Furman et al., (2006). Additionally, the heterogeneity of the flood basalts that produced the Ethiopian plateau supports the idea that magma originated from a large area of mantle upwelling that is different in terms of temperature and composition Kieffer et al., (2004).

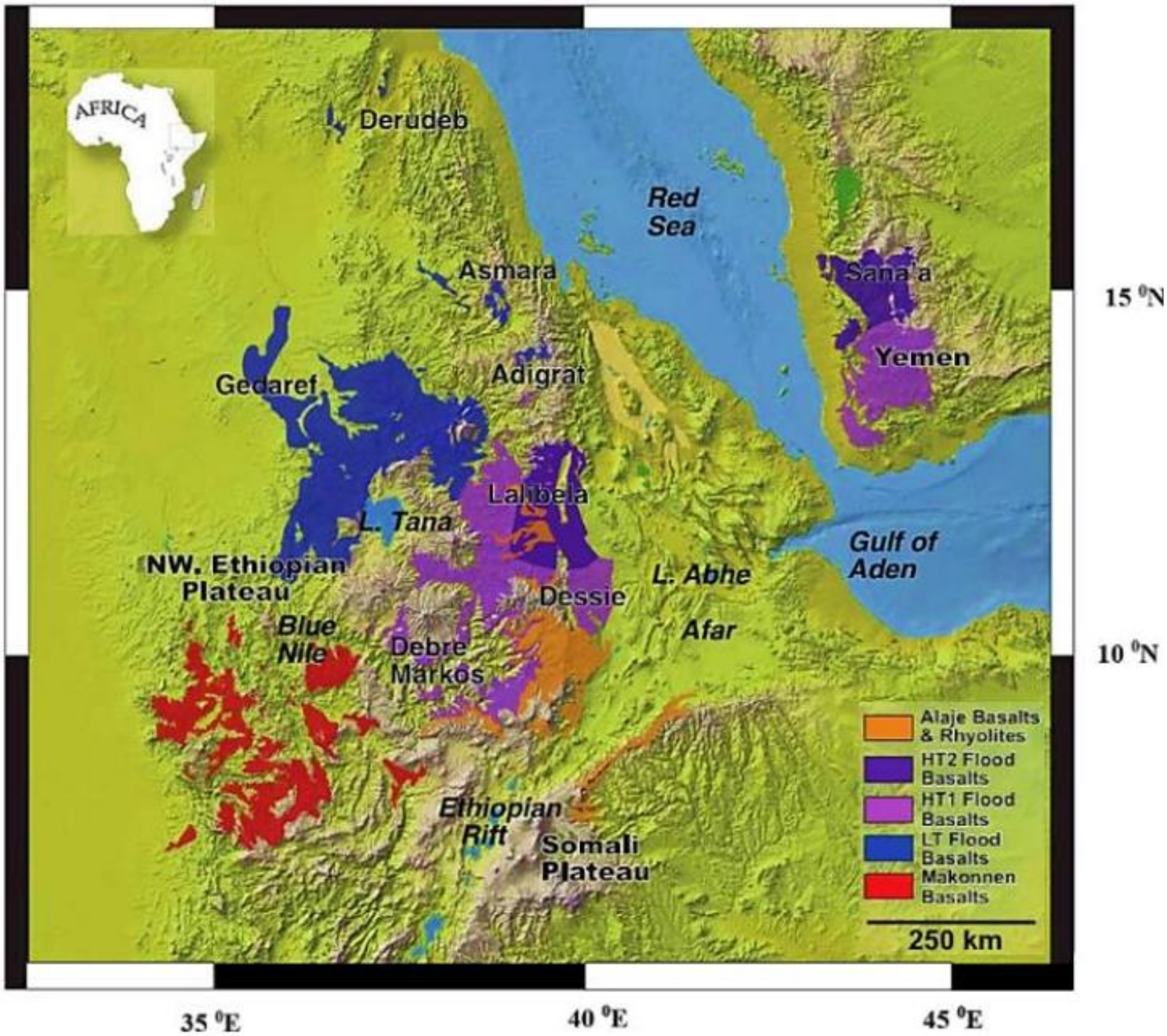

Figure 2.3 Map of Oligocene basalts in Ethiopia and Yemen (after Rooney, 2017)

2.4 Northwestern Ethiopian Plateau Volcanism

The volcanic succession of Ethiopia is cut into two major sectors as northwestern (Ethiopian) and southeastern (Somalia) plateau by the Ethiopian Rift. The western plateau includes the northern, central, and southwestern sectors, whereas the southeastern plateau comprises the eastern, southeastern and southernmost part of the Ethiopian flood volcanic province (Corti, 2009). The volcanic succession in the northwestern Ethiopian plateau is emplaced on the horizontal to sub-horizontal transgressive and regressive sedimentary strata of Mesozoic age. However, this volcanic plateau does not fit the popular image of a continental flood basalt province in that it is not a thick, monotonous, quickly erupted pile of flat – laying tholeiitic basalt. Instead, it consists of a number of volcanic centers with different age and magmatic character (Kieffer et al., 2004). The northwestern traps comprise a series of late Eocene and Oligocene fissure basalts, covered by Miocene shield volcanoes. It has a conventional K/Ar age range of 14 to 140 Ma which is measured from basalts, rhyolites and ignimbrites from the plateau to the north of Addis Ababa (Hofmann et al., 1997). According to Kieffer et al., (2004) the northwestern Ethiopian plateau volcanic units have mainly classified as the Oligocene flood volcanics (trap series) comprised of Oligocene – Miocene basalts and rhyolites, the Miocene –Pliocene shield volcanoes, volcanic plugs and domes, and Quaternary volcanics. The occurrence of Cenozoic volcanism in the northwest Ethiopian flood basalts started the eruption of Ashange basalt during Eocene/Oligocene followed by extrusion of Aiba basalts and Alajae formation during the Oligocene-Miocene (Mohr and Zanettin, 1988). These volcanic eruptions are characterized by flood basalts with interbeds of pyroclastic rocks with rhyolitic or less trachytic compositions (SeifeMichael Berhe et al., 1987; Pik et al., 1998, 1999). The WEP's flood volcanic sequence comprises rhyolitic, trachytic, and phonolitic products in addition to basaltic lava flows and basaltic tuffs (Mohr and Zenettin, 1988). The flood volcanics (Trap series) contain substantial amounts of felsic volcanic rocks despite the dominance of basalts, usually in the upper parts of the sequence (Dereje Ayalew et al., 2002; Dereje Ayalew and Gezahegn Yirgu, 2003). Particularly in the upper parts of the sequence the felsic volcanic rocks, which are primarily friable tuffs, rhyolites, and ignimbrites, are interlayered with the flood basalt(Dereje Ayalew et al., 1999; Mohr & Zanettin, 1988; Pik, et al., 1998). Simen, Mt. Choke, Guguftu, and Mt. Guna are a few examples of low-angle shield volcanoes that erupted from larege central vent volcanoes that are similar magmatic composition to the underlying flood basalt, i.e., tholeiitic shields overlie tholeiitic flood basalts, and alkaline shields overlie alkaline flood basalts (Kieffer et al., 2004). The volume of the shields is about 20% of that of the flood basalt (that is about 4x104km3) (Kieffer et al., 2004). All Quaternary alkaline basalts and trachyte deposited south of Lake Tana in the northwest plateaus are Quaternary plateau basalts and volcanics (Kieffer et al., 2004), which occur due to local rift structures north-south trending extensional faults (Chorowicz et al., 1998). In the Lake Tana graben, scoriaceous basalt flows and volcanic cones are well preserved. The volcanic rocks of the Lake Tana area are usually described as olivine alkaline basalts (Merla et al., 1979).

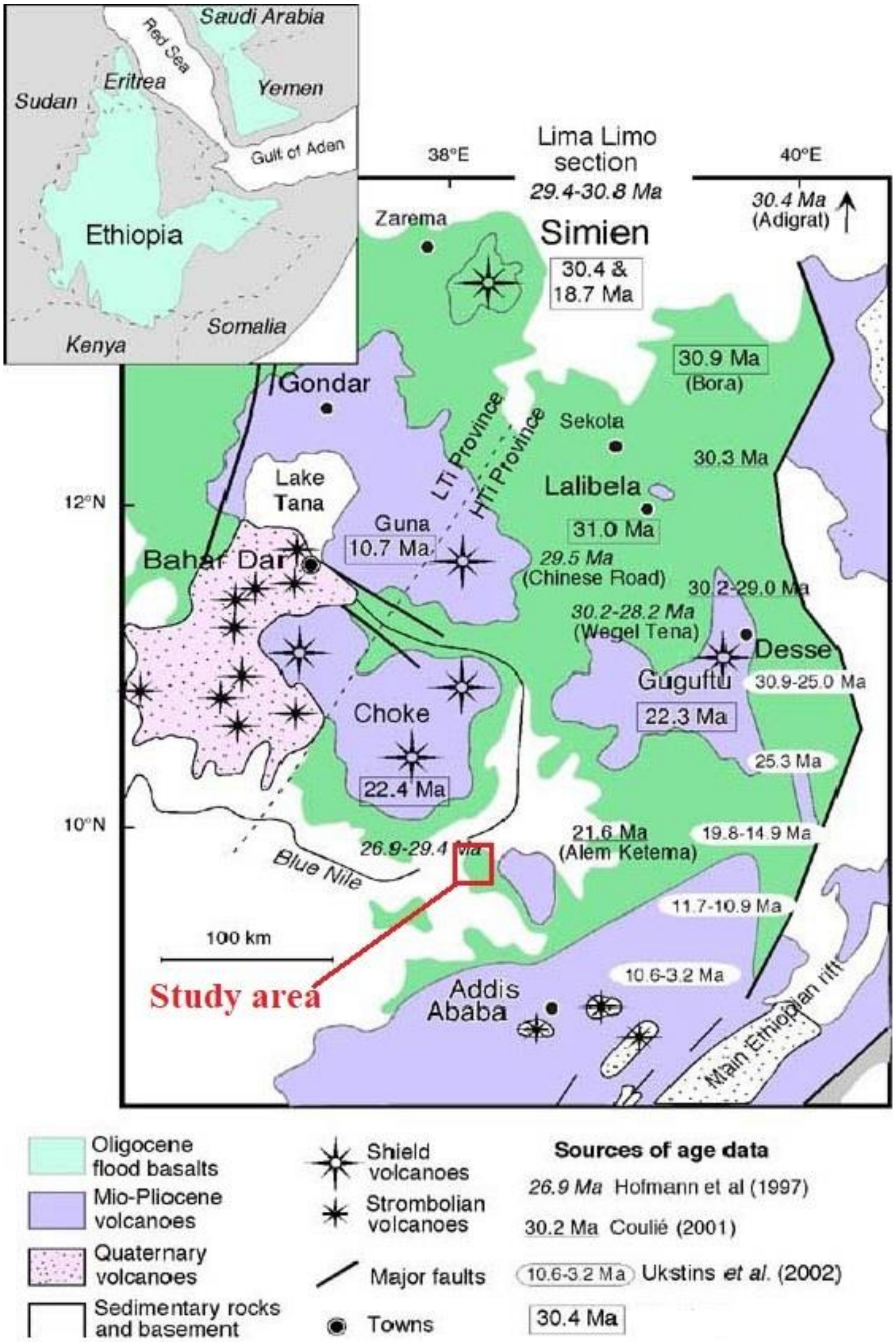

Figure 2.4 Map of the northern part of the Ethiopian plateau showing the extent of the flood Volcanism, location and age of major shield volcanoes (Modified from Zanettin,1992; pik et al.,1999), with additional age data from Kieffer et al. (2004), Hoffmann et al. (1997), Coulie et al. (2003) and Ukstins et al. (1999).

2.4.1 Stratigraphy of NW Ethiopian Plateau Volcanism

According to SeifeMichael Berhe et al. (1987), the northwest Ethiopian plateau's Oligocene volcanism was divided into three stages: the Ashenge (Pre-Oligocene), Aiba (34–30 Ma), and Alaje (30 to 26 Ma). Further, stratigraphic studies (Zanettin et al., 1980, as cited in Krans et al., 2018), focusing on the northeastern region of the Ethiopian plateau, initially divided the northwest Ethiopian flood basalts into four divisions, from oldest to youngest: Ashange basalt, Aiba fissure basalt, Alajae basalts and rhyolites, and Termaber basalts. The Ashange is distinguished by thin (5 m) dipping flows that are restricted to a few kilometers in extent. These fluxes are unconformably layered over by locally zeolitized flows (the Aiba Formation). Massive olivine flows that can reach 100 meters when ponded the Aiba Formation is distinguished by basalt with columnar jointing. At Amba Aiba, thin interbedded pyroclastic deposits of varied thickness are seen locally in this formation. Overlying this formation are the shield-volcanic Termaber Formation and the ignimbrites-and-sparsely-interbedded-basalt-flows-characterized Alajae Formation (Mohr and Zanettin, 1988).

Hofmann et al. (1997) study the Lima-Limo section north of Lake Tana, which is 1950 m thick, to divide the province into upper and lower units based on morphological boundaries. The lower and upper stratigraphic divisions on the Simien shield volcano and underlying flood basalts are also study by Kieffer et al. (2004). The characteristics used by Mohr and Zanettin (1988) to define the upper and lower units of the initial stratigraphic classification were based on local observations that were not consistent throughout the flood basalt province (Krans et al., 2018).

Krans et al. (2018) applied stratigraphic divisions as lower, middle, and upper flood basalts based on petrographic differences observed in North-western LT flood basalts. In this study, three divisions within the Ethiopian flood basalt province defined broadly as the lower flood basalt (consists of 400 m of flows), which is dominantly Ol-phyric with Cpx-rich cumulates, the middle flood basalt (nearly 1000 m of flows), which exhibits Plg-megacrystic flows and oscillation between Plg-phyric and Ol-phyric flows, and the upper flood basalt (~ 330 m of flows), which is dominantly Plg-phyric and devoid of cumulates.

Based on detailed field logging, Dereje Ayalew et al., (2021) present the stratigraphy of the flood basalt succession in eastern Wollo province, northern Ethiopian plateau. Three formations are recognized, given names, and linked to documented radiometric ages from the Oligocene in nearby regions. From the bottom to the top of these formations: The Wegeltena Rhyolite, which is composed of silicic ignimbrites dated at 30.2 Ma, is uniformly overlain by Teri Basalt, the main phase of flood basalt emission. A thin bed of conglomerate, sandstone, and mudstone, which represents a 3 Ma period of volcanic quiescence, lays on top of this. The Kon Basalt, which has a 27.8–26.7 Ma dating, is found at the top of the series. Significant differences in lithology and age range are shown when this new stratigraphy is compared to previous Oligocene sequences on the northern plateau. These differences have implications for how the Ethiopian flood basalt province was constructed.

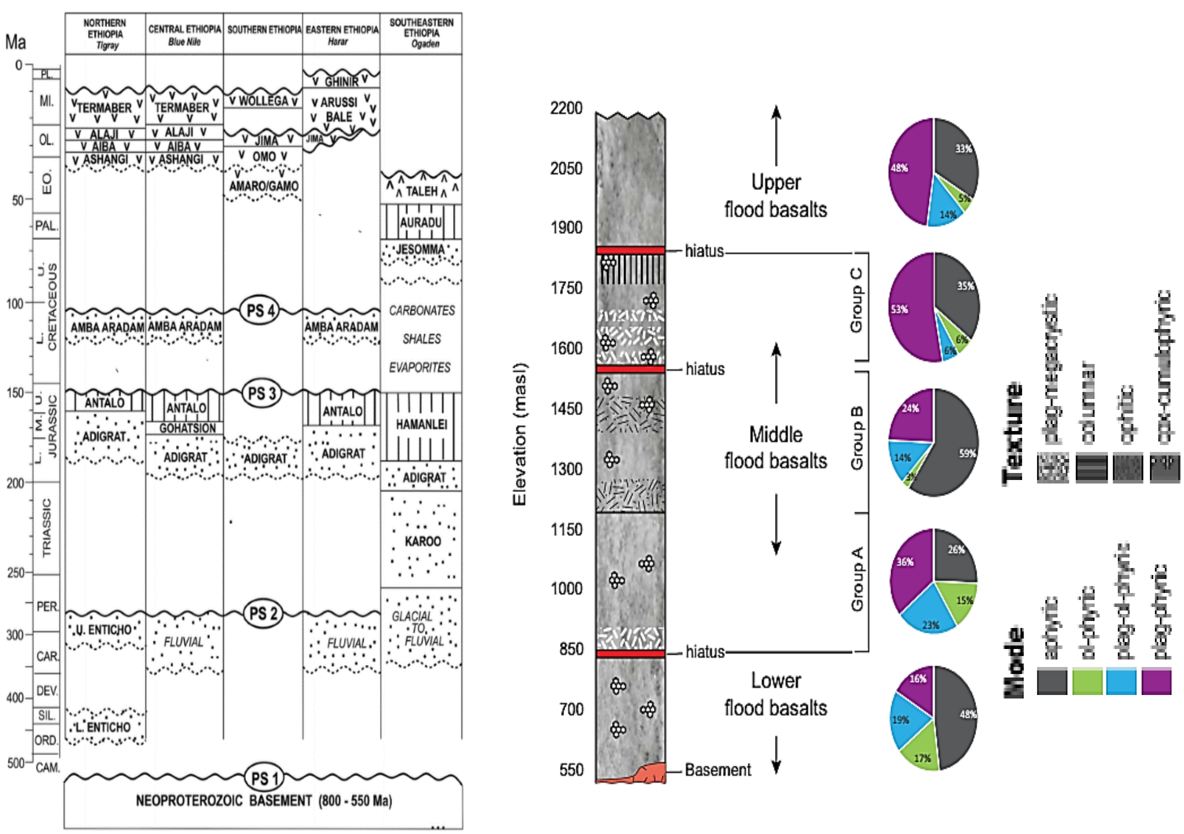

Figure 2.5 A) Schematic stratigraphic chart of Ethiopia (from Abbate et al., 2015) with the major planation surfaces (PS) of Coltorti et al (2007) and B) Simplified petrostratigraphic column of the Ethiopian NW plateau LT flood basalts. Relative percentages of modal phases for each unit and group are shown on the right (From Krans et al., 2018).

2.4.2 Petrographic and Geochemical Characteristics of NW Ethiopian Plateau Volcanism

The geochemical and petrographic properties of the Ethiopian Plateau Basalts vary, as does their spatial distribution. The three main types of magma are geographically delimited according to the amount of TiO2 they contain (Pik et al., 1998). Extremely high-Ti (ultra-titaniferous) transitional basalts and picrites (HT2) are discovered close to the Afar triple junction, while low-Ti (LT) and high-Ti (HT1) tholeiites are found in the west, east, and respectively (Pik et al., 1998; Kieffer et al., 2004; Beccaluva et al., 2009). Three geochemical divisions have been made based on the titanium and trace element differences in the various lava types from the northwest Ethiopian continental flood volcanic regions, such as low-Ti (LT) provinces in the west around Simen Gonder, high-Ti (HT1) provinces in the east that were the subject of this study, and an eastern high-ti (HT2) province that is located closer to Lalibela (Pik et al.,1998). The LT basalts are tholeiitic, with higher SiO2 (47–51 wt%), lower Nb/La (0.55-0.85) ratios, lower TiO2 (1–2.6 wt%), and lower SiO2 concentrations. The major plagioclase phenocrysts in this low-TiO2 suit feature aphyric-intergranular and aphyric-ophitic textures, and petrographic examination can also reveal the presence or lack of olivine phenocrysts (Beccaluva et al., 2009; Natali et al., 2016).

The matrix is composed of plagioclase, interstitial clinopyroxene, and Fe-Ti oxides; these minerals have properties typical of tholeiitic magmas (Pik et al., 1998). The LT and HT2 magma compositions are primarily characterized by aphyric to ol-phyric that span from microcrystalline to coarser-grained textures, and the HT basalts show a continuous range between these compositions. Rarely occurring as a phenocryst phase, plagioclase has a sieve-like texture (Pik et al., 1998). According to Pik et al. (1998), olivine is frequently found in the groundmass and is linked to rich Fe-Ti oxides and clinopyroxene phenocrysts, which are consistent with more alkaline magmatic compositions. Transitional to alkaline basalts and picrite compositions with higher TiO2 (2.6-5 wt%), higher Nb/La (1.1-1.4), and lower SiO2 (44-48.3 wt%) values are characteristics of HT2 flood lavas. The matrix is composed of plagioclase, interstitial clinopyroxene, and Fe-Ti oxides; these minerals have properties typical of tholeiitic magmas (Pik et al., 1998). The LT and HT2 magma compositions are primarily characterized by aphyric to ol-phyric that span from microcrystalline to coarser-grained textures, and the HT basalts show a continuous range between these compositions. Rarely occurring as a phenocryst phase, plagioclase has a sieve-like texture (Pik et al., 1998).

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CHAPTER THREE

LOCAL GEOLOGY

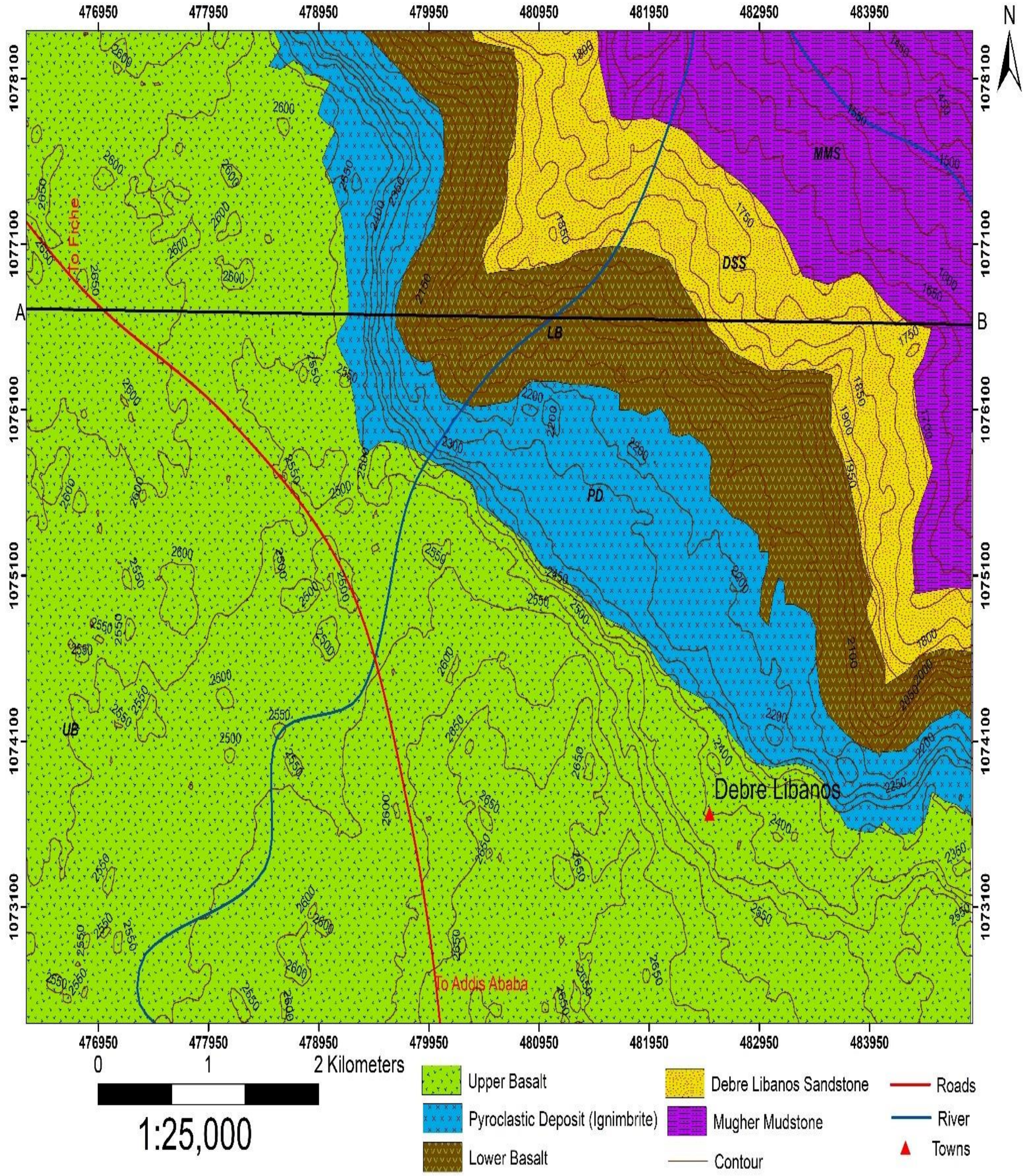
3.1 Introduction

The study area is located in the Northwestern Ethiopian plateau which covers the stratigraphic study of the Debre Libanos area it has a 715 m-thick sequence (from 1946 to 2661 masl elevation). The area is mostly covered with flood basalt volcanism. It is characterized by gentle slope around the town of Debre Tige and moderately to cliff forming in the south, south east and South west part of the town. From field observation, lava flows are generally exposed as stratigraphic positions of Lower basalt, Ignimbrite and upper basaltic lava flows. And also, they exposed an extensive area along with erosional escarpments, flat laying plateau and undulating places. They are generally variable in mineral assemblages, color, textures and thickness. The study mainly shows that the area comprises mafic lava of different field characteristics.

3.2 Lithological Descriptions

From the combination of studies in the field observation, petrographic investigation and geological mapping the Debre Libanos locality volcanic products comprise; Lower basalt, Pyroclastic Deposit (Ignimbrite) and Upper basalt. Geomorphologically, the area is extensively eroded and dissected by deep gorges of Zega Wedem. In this case, the area was investigated along with selected traverses which accounted for several in number that have been devised to encounter different exposures in the area. Some of these traverses are river cutting and also cross-cutting of the erosional escarpment along the human footpath were commonly used during field work. During field observation, identification of rocks and stratigraphic sampling were conducted in detail. In the area, various volcanic flows have been conducted and henceforth they have differentiated based on their field relations and petrographic characteristics. The field descriptions in outcrop scale, lithologic units with a geological map, geological cross-section and complete stratigraphic log section of the study area are presented in this chapter. From field and petrographic perspective, the area comprises 7 intermittent flows. The composite volcanic-stratigraphy is established based on these different flow exposures with marker contacts. The major volcanic flows identified in this study are; Aphyric basalt**,** plagioclase-olivine-pxn phyric basalt, ignimbrite, plagioclase-olivine phyric basalt, olivine-plagioclase pyhric basalt, plagioclase-phyric basalt and Aphyric basalt.

A)



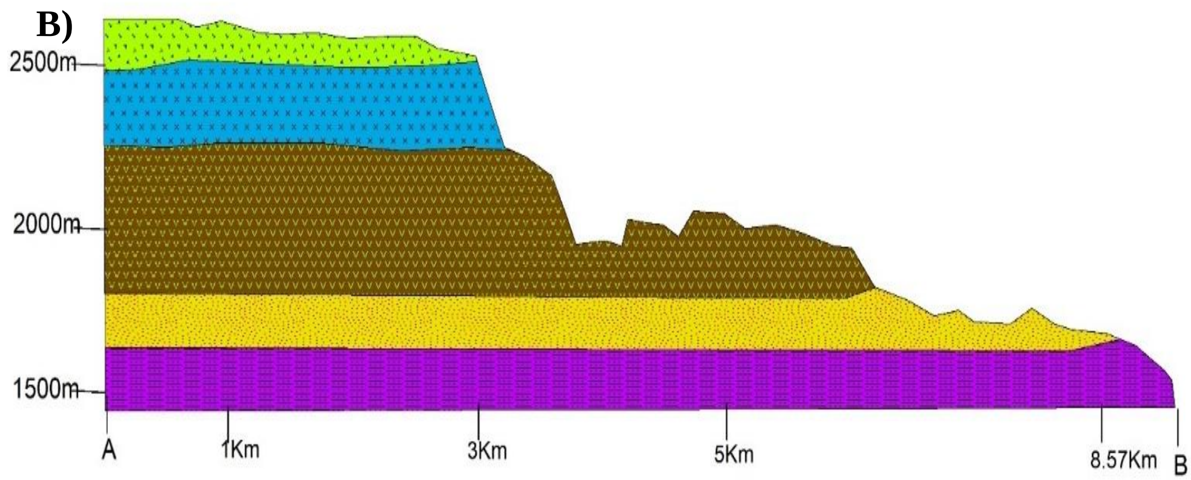


Figure 3.1 Geological map of Debre Libanos area flood basalt volcanism (A) and cross section from A-B (B).

3.2.1 Mesozoic Sandstone Formation

This unit is the oldest rock unit exposed in the area at the deep gorges made by an intersection of Zega Wedem River locally the area called Zegamel, in the Southwestern and Southeastern end of the study area at the base of Debre Libanos and Chagel section. The exposed unit has a thickness of 200 m (approximately from 1745 to 1946 masl elevation). The unit is overlain unconformably by lower basalt; the unconformity surface is characterized by the unevenly eroded irregular surface over which unconsolidated sediments are deposited. The sandstone is redish, light grey, and pale pink colored, fine to medium-grained at the exposed base and the top part of the unit composed of intercalation of conglomerate and silty sediment with the sandstone along the contact area to the overlying unit.

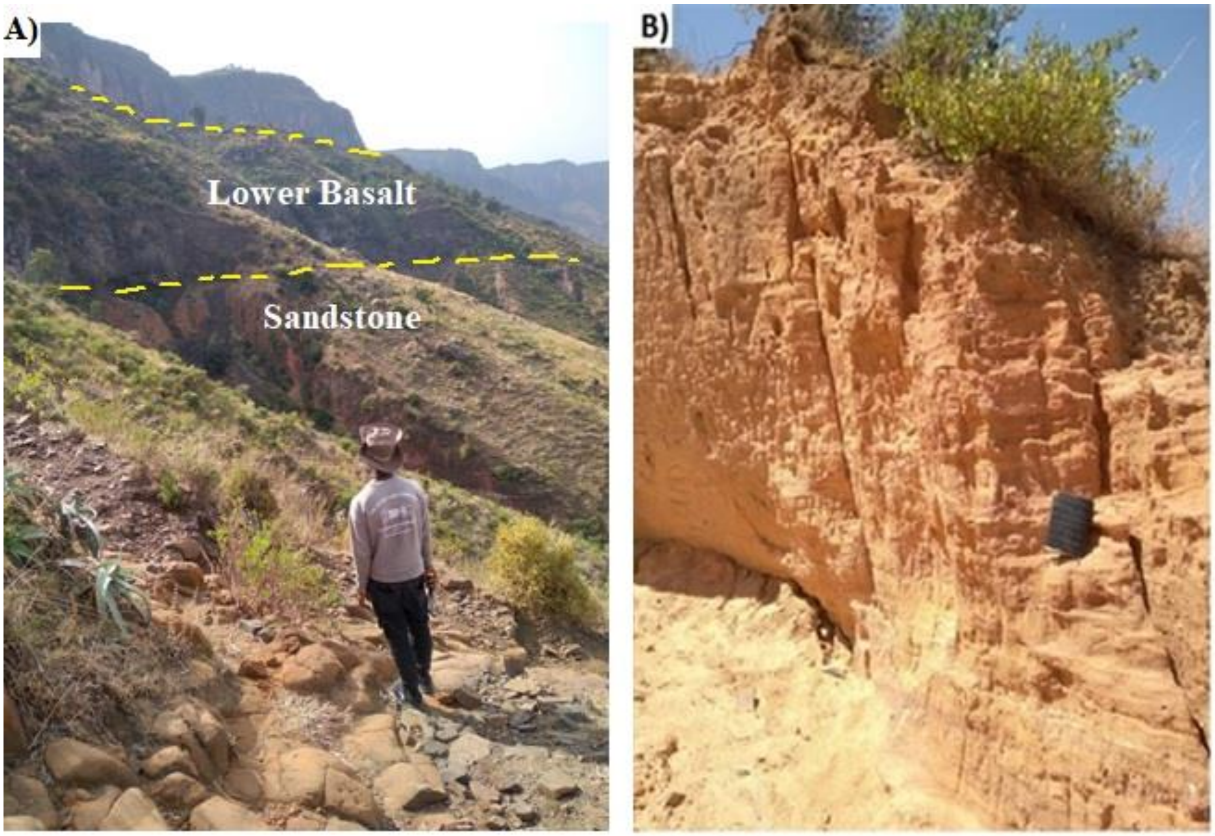
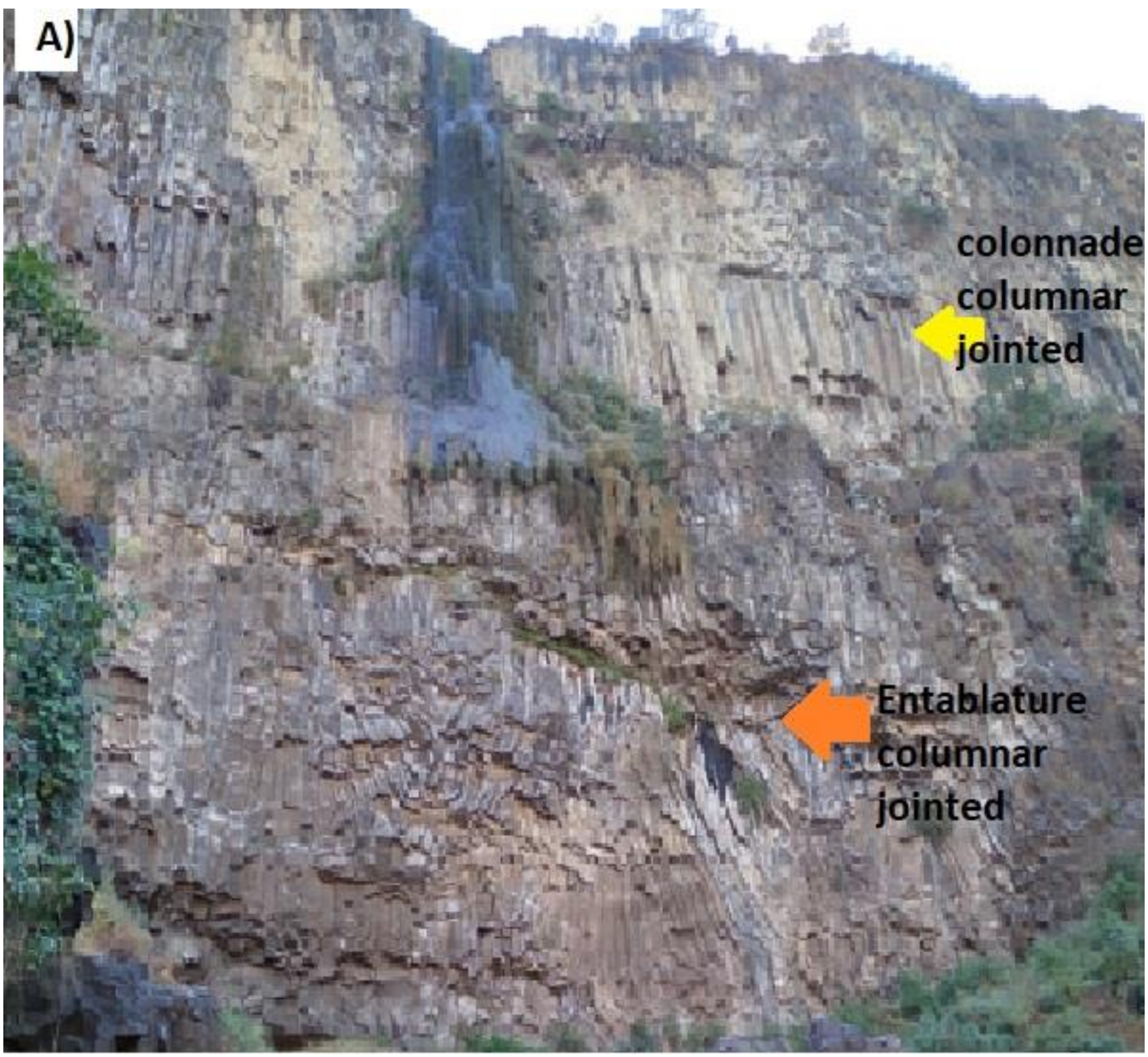


Figure 3.2 Exposure of Mesozoic sandstone unit at the base of the stratigraphic section of the study area. A) Unconformable contact between sandstone and lower basalt. B) Redish Conglomeratic sandstone unit on the top part of sandstone formation.

3.2.2 Lower Basalt Unit

This rock unit is found relatively at a lower elevation, which is the lower basalt of the study area. It is mainly exposed along the deep gorge in the southern, southwestern and southeastern part of Debre Libanos Monastery. It lies unconformably on the sandstone this unit is dominantly consists of different sub-units include massive basalt, columnar basalt, intensely fractured and weathered basalt and scoriaceous basalt. The nature of contact or boundary between lower basalt and pyroclastic deposit (Ignimbrite) unit is sharp contact. The total thickness of this formation within the study area is about ~ 258 m (1946 to 2204 masl). At elevated of 2060-2091 meter above mean sea level, about 31-meter-thick pyroclastic deposit (ignimbrite) unit is found interbedded with lower basalt flows unit.

This rock unit commonly forms moderately steep to gentle topographic features have majorly light-black to dark-gray fresh color and light-gray weathered color, aphanitic to vesicular texture in hand specimen. The vesicles are sub-round to elliptical and elongated vesicles, the vesicles are partially filled by calcite. Lower Basalt flows frequently contain numerous columnar Joint /cooling joints that are composed of mainly entablature types jointing displays numerous randomly oriented columns and colonnade columnar joint types include numerous regularly or vertically oriented columns. Sample collected from this unit show clearly identifiable plagioclase which is colorless in physical observation. Representative samples were collected from this unit for petrographic analysis.



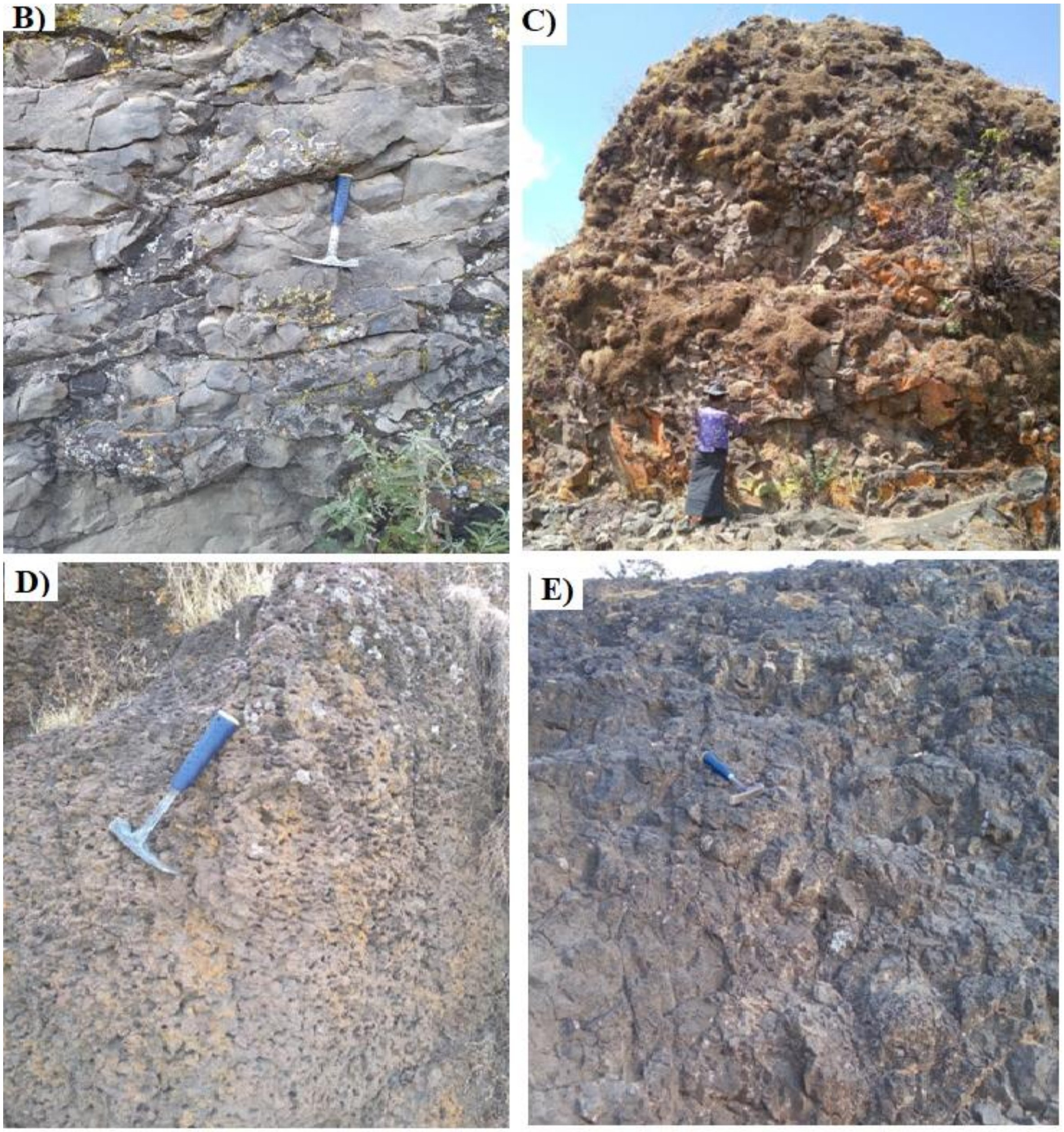


Figure 3.3 Different exposures of lower basalt from Debre Libanos and Chagel Section in SW and SE part of the study area. A) Cliff forming exposure of lower basalt at the bottom part is irregular (entablature types) columnar joint, at the middle massive fracture flow and at the top part colonnade types of columnar joint. B) Close up view of massive basalt. C) Strongly fracture and weathered basalt. (D) and (E) exposure of scorious and vesicular basalt.

3.2.3 Pyroclastic Deposit (Ignimbrite Unit)

The pyroclastic deposit (ignimbrite unit) is one of the lithological units found in the study area and is exposed in both the Debre Libanos and Chagel sections. It forms a steep to gentle slope. These exposures are continuing along the south-west and south-east directions of Debre Libanos monastery. It is overlain by upper basalt and underlain by lower basalt. The contact between lower basalt and ignimbrite is a sharp contact. The approximate thickness of this unit is estimated at 245 m (220–2450 m amsl). The rock unit is light gray to gray in color, slightly weathered massive ignimbrite. It contains glass and rock fragments. The rock fragment has a light gray color and shows layering. The remaining part of the rock is composed of fine-grained and visible crystals. The groundmass is made up of fine material that ranges from gray to white. Visible crystals are light-colored. At the base of this ignimbrite unit, about 0.9 cm (2204–2205 m) of volcanic ash is interlayering between the lower basalt flow unit and pyroclastic deposit (ignimbrite) unit, but laterally the volcanic ash is changed into one of a more friable nature and is much thinner.


A)
Ignimbrite
Volcanic ash

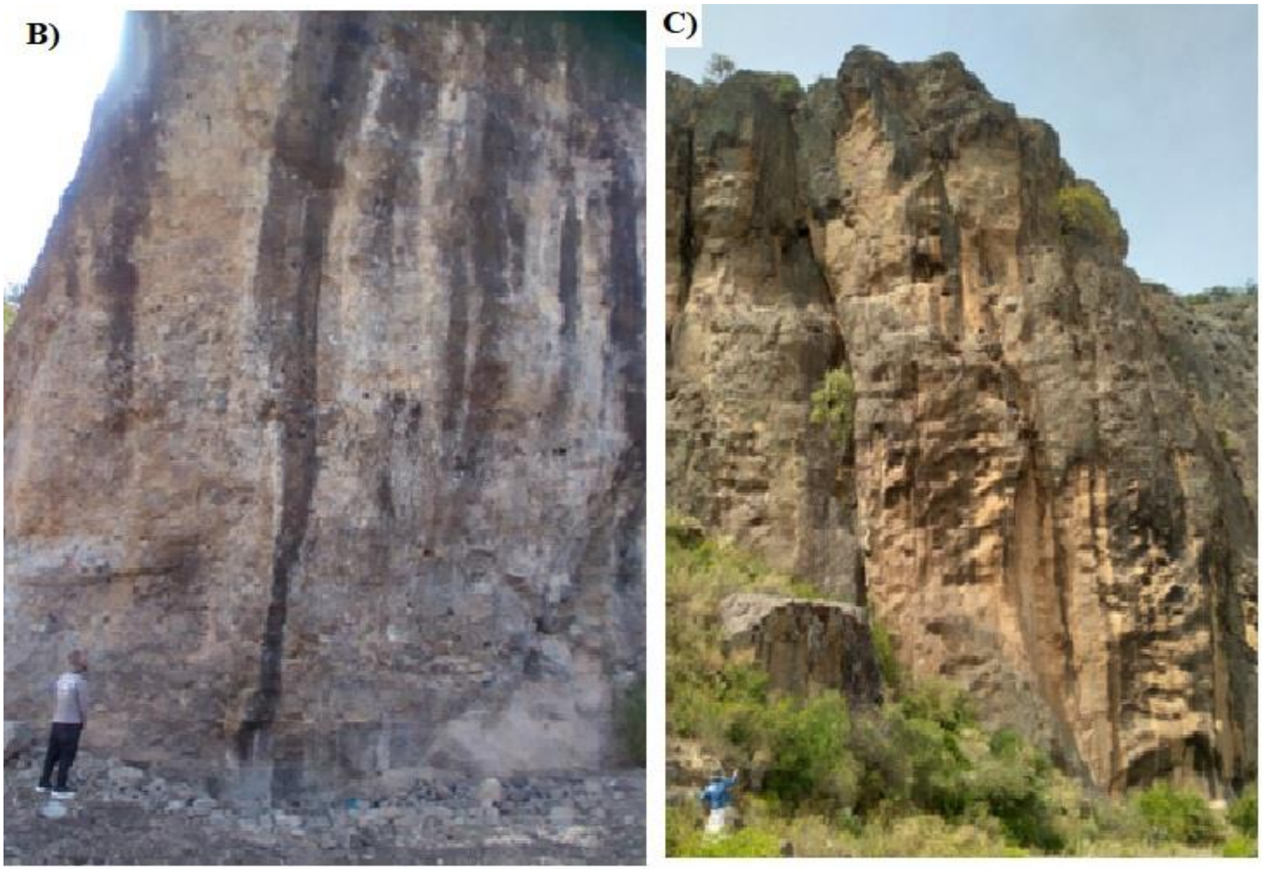
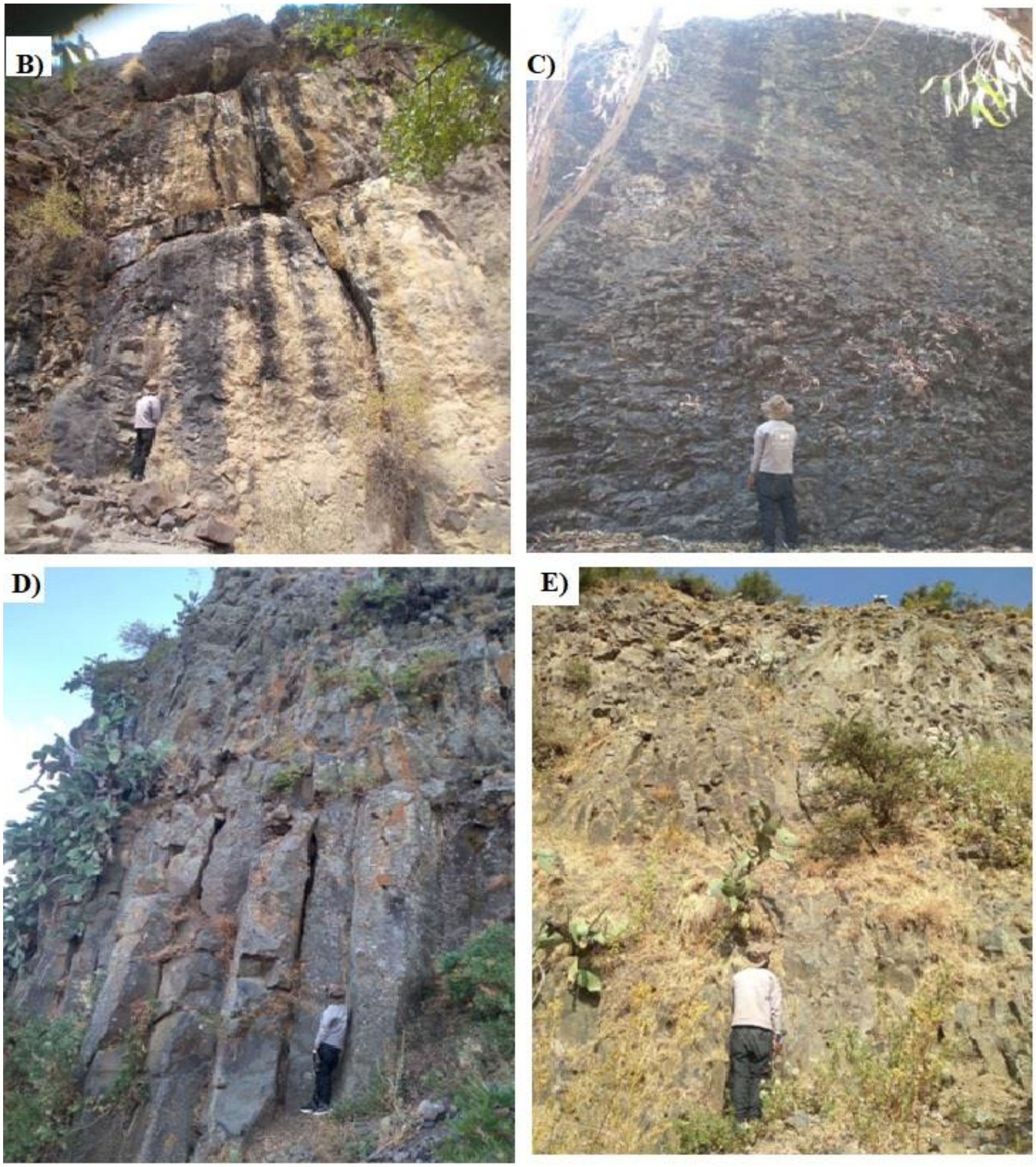


Figure 3.4 A) Outcrop scale exposure of different ignimbrite unit overlay by Volcanic sediment. B) massive ignimbrite unit from Debre Libanos section hora area. C) cliff forming exposure of ignimbrite unit from chagel section.

3.2.4 Upper Basalt Unit

Upper Basaltic units exposed along the Debre Libanos section and in the Chagel (Abbaro) section are underlain by the Ignimbrite unit. It forms a relatively flat-topped cliff that forms plateau topography. An estimated thickness of this unit reaches up to 211 m (from 2450 to 2661 m amsl). Lithologically, this basaltic unit is dominantly represented by the association of different basaltic lavas and subordinate pyroclastic rocks. The basalts consist of aphyric-phyric varieties, columnar basalt, and massively fractured basalts. The exposure of this unit shows a black to dark gray color that changes to a yellowish gray to green color upon weathering. The contact between the ignimbrite unit and the upper basalt is a sharp contact. The basaltic unit of this formation is composed of successive lava flows with a dominant flow thickness of 20–60 m. At an elevation of 2540-2575 meters above mean sea level, at the top of the Chagel section on the upper basalt flows unit, about 35 meters thick of slightly welded to unwelded volcanic ash can be found.

The different basaltic units and the subordinate felsic products at Chagel stratigraphic section are the other main lithological units that cover the study area forming a flat topography.


B)
C)
D)
E)

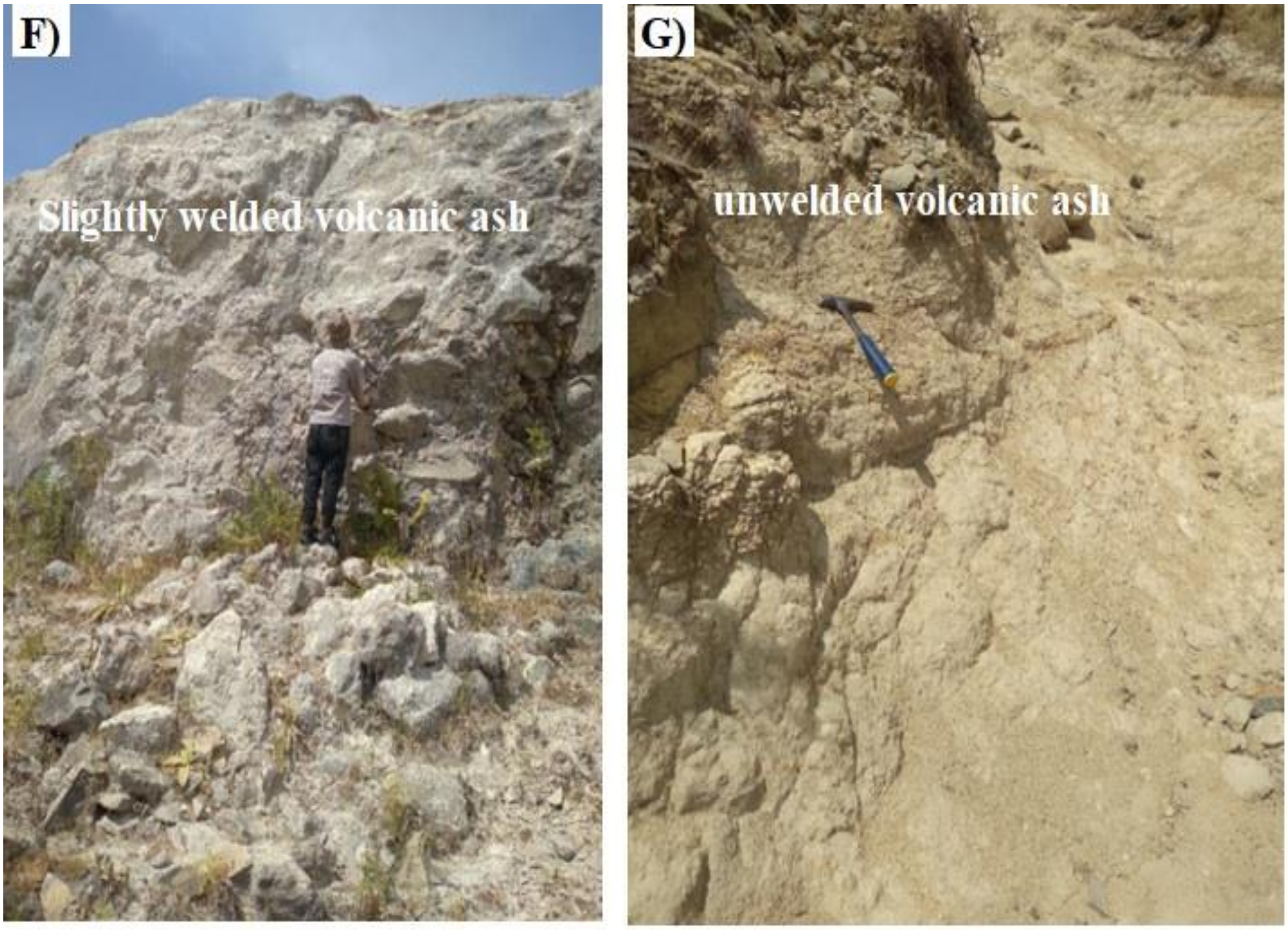


Figure 3.5 Outcrop scale exposure of different unit with in the upper basalt part of stratigraphic units. A) panoramic view of thick massive basalt on the top part of upper basalt exposure B) massive jointed basaltic unit c) closeup view of black fractured basalt. (D) and (E) steep slope forming exposure of irregulars jointed columns and massive regular (colonnade type) jointed thicker basalt flow unit. (F) and (G) Close up view of Slightly welded and un welded volcanic ash.

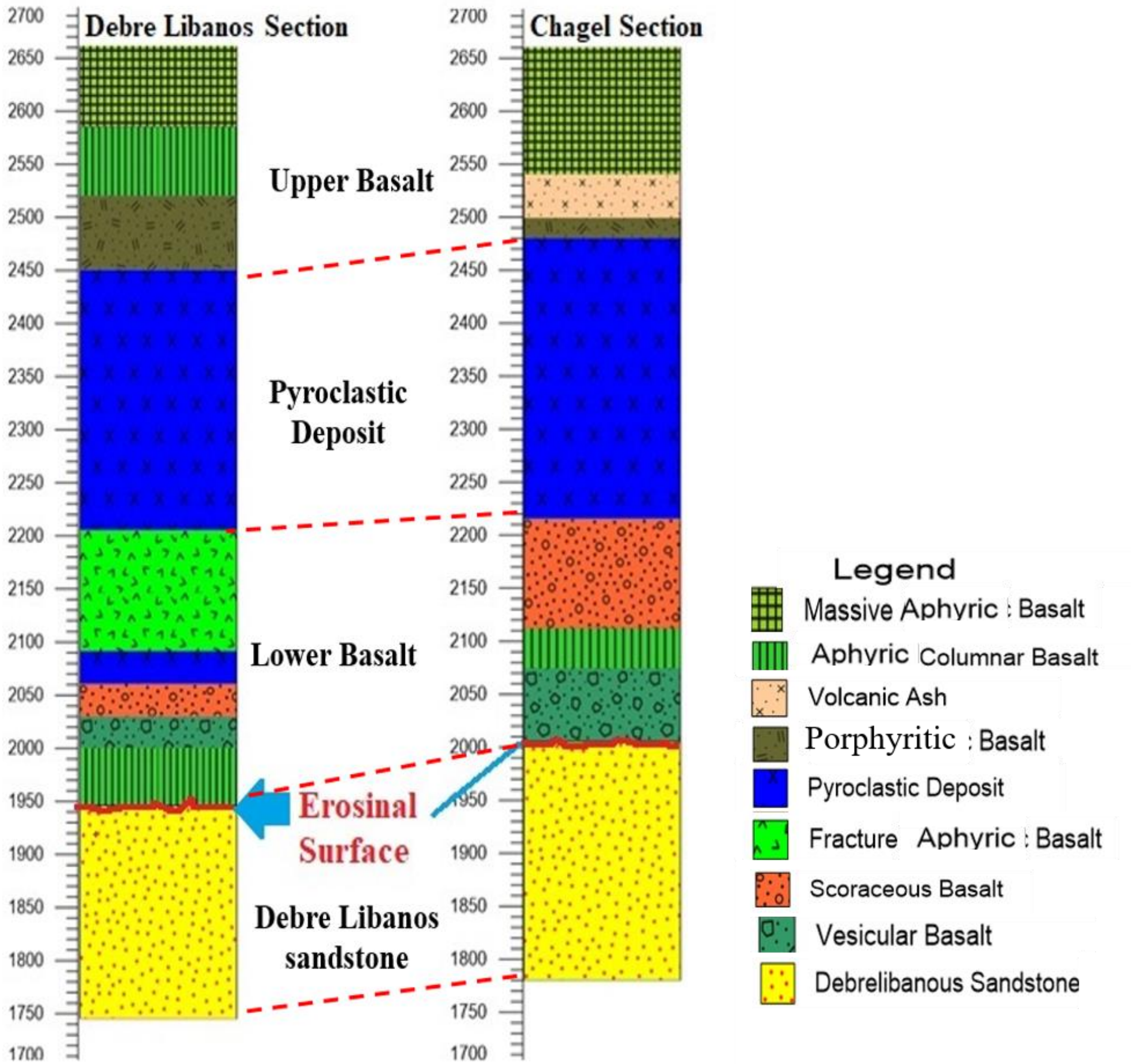
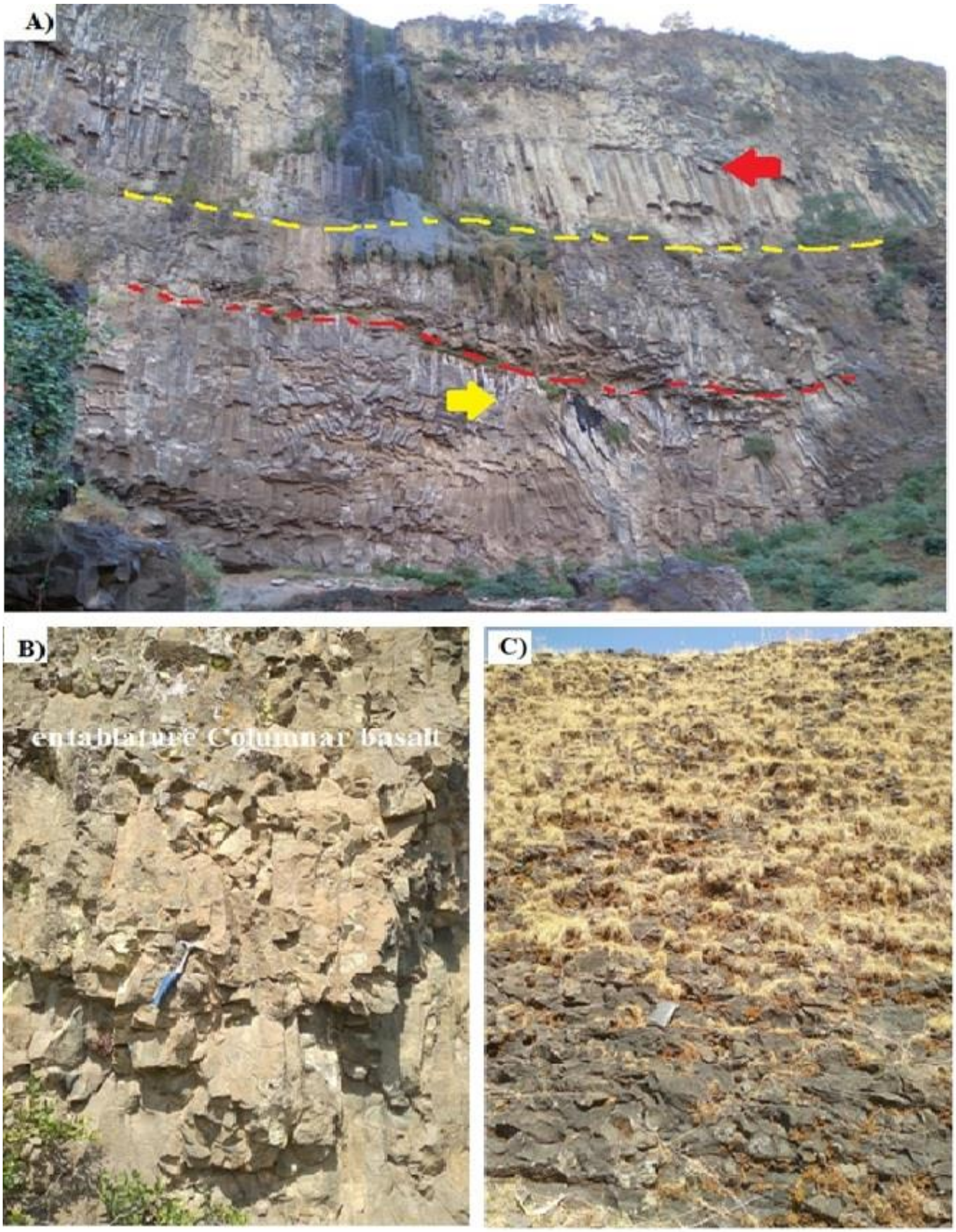


Figure 3.6 Stratigraphic section of the various lithologic units in the study area in two different sections (Debre Libanos and Chagel).

3.3 Morphology of Lava Flow

Morphology of Flood basaltic lava flows in the study area includes; pahoehoe lava flow, ‘a’ā type vesicular lava flow, columnar jointed and massive lava flow. The morphology of columnar jointed flow base at the lower basalt are irregular jointed small columns to randomly oriented cooling joint (Entablatures) types lava flow and flow tops are regularly oriented cooling columnar joints (colonnade) type lava flow. The basaltic lava flow types consist of sheet-like or tabular flow structures of individual units. The different flow units are separated by a thin layer of sediment, weathering surface, and pyroclastic deposits (Ignimbrite). Flow tops in exposed flow fields at upper basalt are characterized by pahoehoe flow surface or smooth and in some flow ‘a’ā type vesicular surfaces are observed. The morphology of the flow base observed in different flow fields is highly depend on the underlaying units.


A)
B)
entablature Columnar basalt
C)

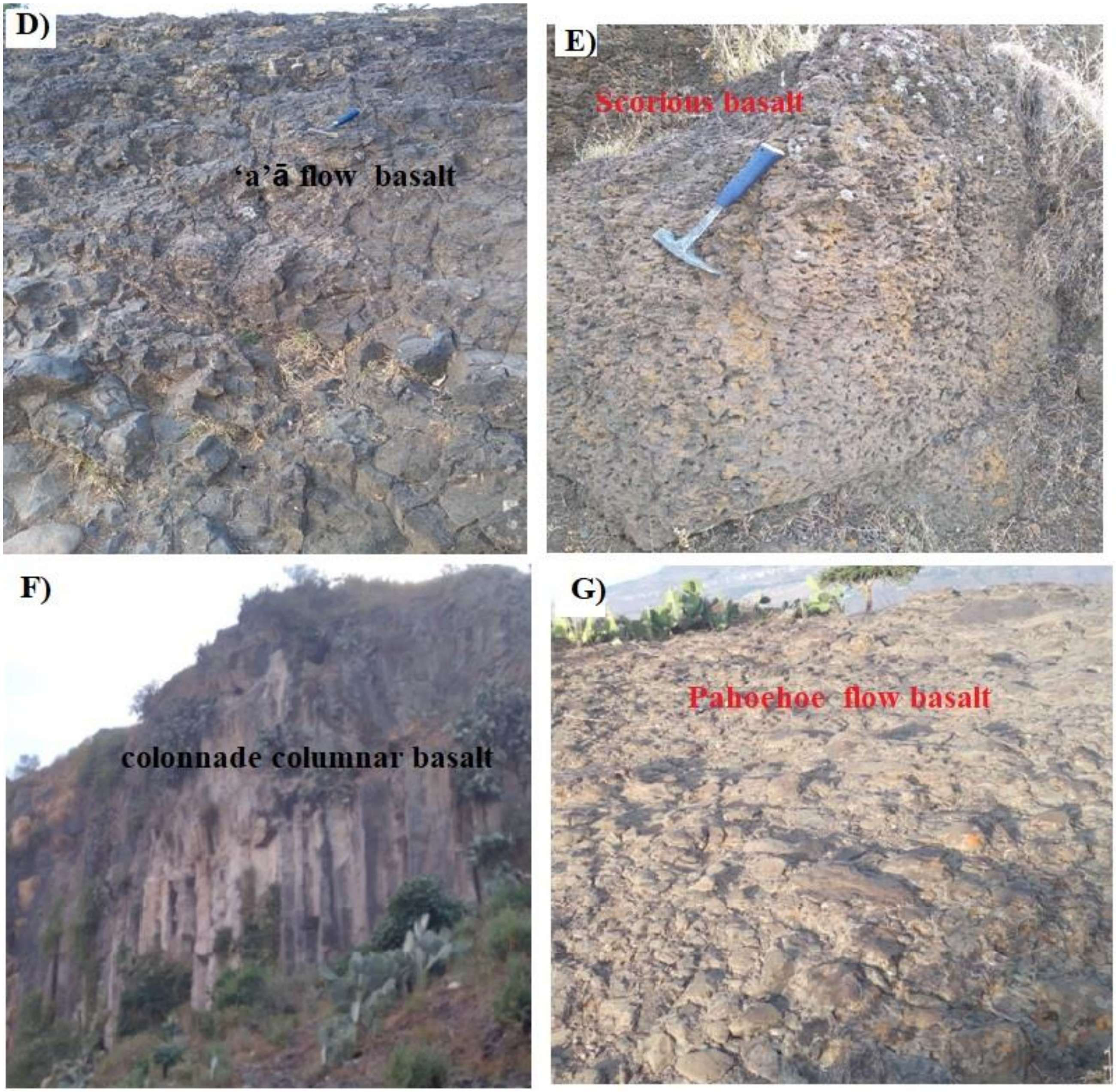


Figure 5.7 Different exposures of typical features of lava flow morphologies flood basalts in the study area; Location of the section where photographs taken is from Debre Libanos area: A) Lower basalt exposure of Columnar basalt of entablature types of flow at the base and colonnade types of flow at the top part of lower basalt. (B) and (C) are Fracture and weathered sheet lava flow basalt from Debre Libanos section part of lower basaltic flow. (D) and (E) ‘a’ā and Scorious flow type vesicular basalt from chagel section. F) Thick and massive regular (colonnade) columnar flow types of basalt. G) Pahoehoe type basaltic flow morphology from chagel section part of upper basalt.

CHAPTER FOUR

PETROGRAPHY

4.1 Introduction

In this chapter details of representative samples taken from different lithological units identified in Chapter three are examined under a polarizing microscope and presented with an illustrative microphotograph. A total of 18 samples are analyzed for petrographic purposes. Among them, 13 samples are from basaltic units, 4 ignimbrite sample, and 1 from the Mesozoic sandstone. The 17 volcanic rock samples are described in detail based on mineralogical and textural features, such as crystallinity, granularity, and degree of alteration. The various nomenclatures, such as plg-phyric, plg-Ol-phyric, plg-Px-phyric, plg-Ol-Px-phyric, intergranular, aphyric-ophitic, etc., used in regional studies for other CFB are used to basaltic samples. Descriptions of these textural and modal names are applied in Krans et al., (2018). Samples from flood basalt are described in the first portion followed by interlayered pyroclastic products and finally samples from the upper basalt. The summary of each petrographically analyzed sample is attached in the last part in table format.

4.2 Petrographic Character of Lower Basalt units

Samples from Lower flood basalt unit show different ranges of grain size texture; (DL02) and (CL03) are collected from aphyric basaltic texture unit in hand specimen sample. It is aphyric and microcrystalline from petrographic observation. This aphyric samples consist identifiable plagioclase, olivine, and Fe-Ti oxides in a Felty and vitrophyric groundmass with <2% phenocrysts of plagioclase mineral. Equigranular aphyric grains show an intergranular texture in the groundmass. (DL03) and (CL 02) Samples are collected from aphyric-vesicular texture basaltic units in hand specimen sample. It is dark gray and aphanitic-vesicular texture from hand sample. From petrographic observation plagioclase and olivine are dominant. It is composed of identifiable plagioclase, olivine, pyroxene and ground mass. The thin section shows aphyric vesicular texture in which microphenocrysts of plagioclase are dominated with lath shaped and they exhibit randomly oriented intergranular texture.

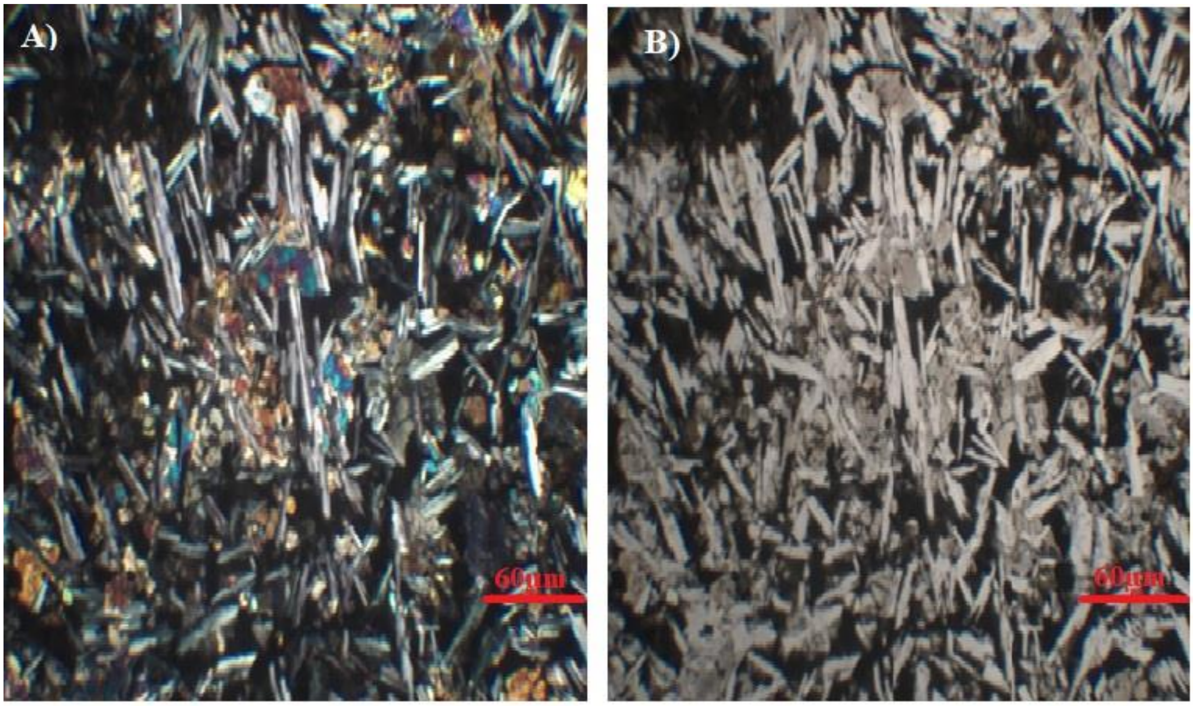


Figure 4.1 Microphotographs of samples from the Lower basalt: (A) and (B) show microphotographs of aphyric-intergranular basalt under the XPL and PPL view of DL02 respectively, groundmass dominated by finer plagioclase, altered olivine and opaque minerals.

(DL05) and (DL06) samples were collected from a porphyritic lower flood basalt unit. The porphyritic sample is dominated by phenocrysts of plagioclase, olivine, and pyrite minerals (Plg-Ol-Cpx phyric basalt) embedded in a glassy and finer groundmass consisting of plagioclase, olivine, pyrite, and opaque minerals (Fe-Ti oxides). The abundance of phenocrysts in sample DL-05 is 5% with dominant plagioclase. The groundmass in these samples shows cumulophyric texture formed by intergranular, randomly oriented plagioclase microlites and felty groundmasses as observed in sample DL-05. The maximum size of the phenocryst mineral grains is plagioclase, typically 0.2 mm in DL-05 sample thin section. The abundance of phenocrysts in sample DL-06 is 20%, with dominant plagioclase and olivine. Euhedral-subhedral grains of olivine display cumulophyric texture (only clusters of olivine mineral) in some of the samples. The maximum size of the phenocryst mineral grains is olivine, typically 0.4 mm in DL-06 thin section.

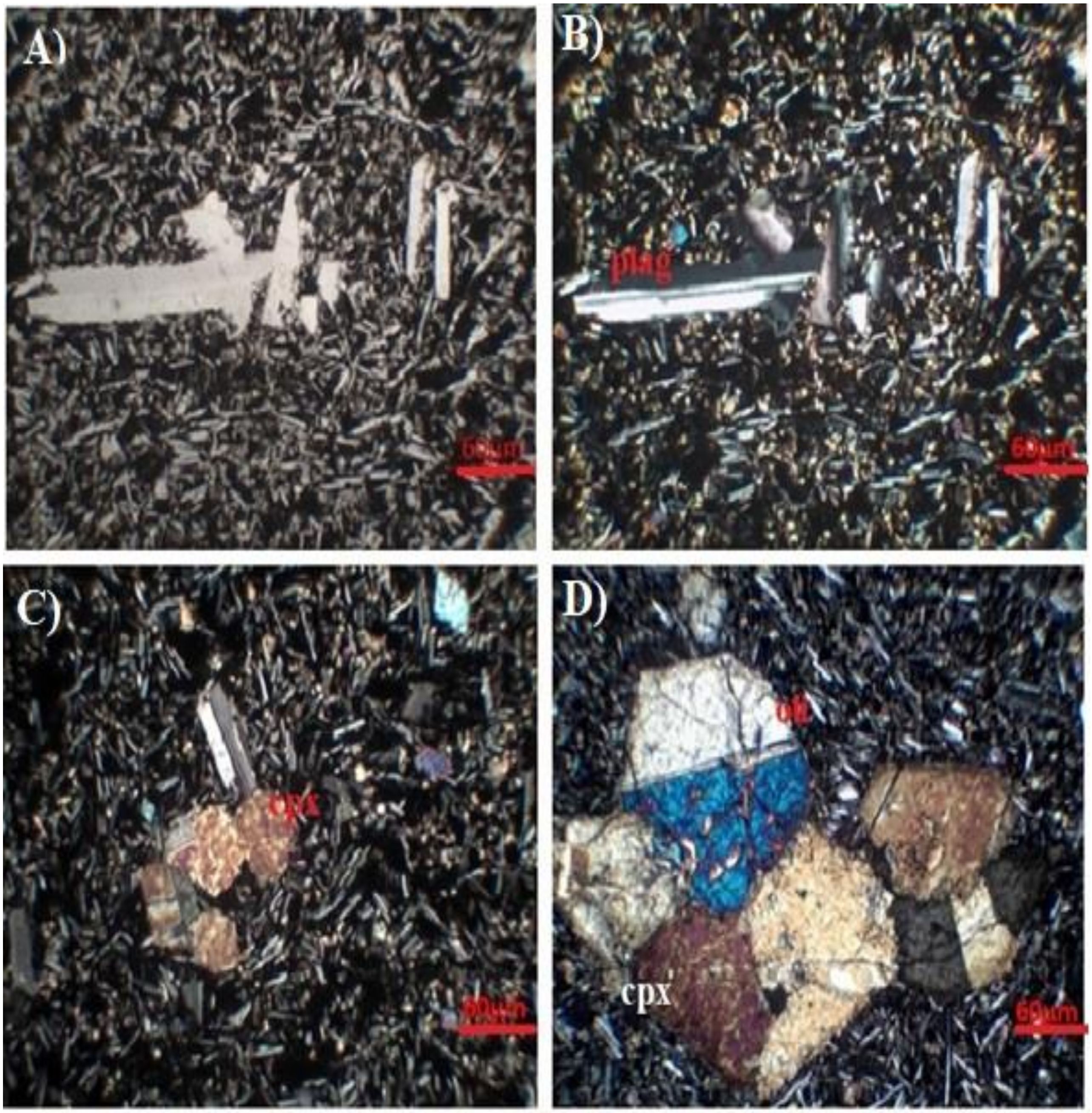


Figure 4.2 Microphotographs of representative textures and modal mineralogy in the lower flood basalts. (A) and (B) plagioclase lath and opaque minerals (Fe-Ti- oxide) poikilitic plagioclase texture of thin section photo under PPL and XPL respectively from DL-05 sample. C) Euhedral to sub-hederal shape of plag and cpx thin section photo under XPL. D) Cumulophyric phenocrysts texture of euhedral to sub-hederal shape olivine and cpx from thin section under XPL from sample DL-06.

4.3 Petrographic Characteristics of Pyroclastic Deposit (Ignimbrite unit)

Sample DL-04, DL-07 and CL-05 are an ignimbrite unit in a hand specimen it is composed of different rock fragment with flattened glass within a vitric groundmass. In the thin section, it is observed that it is composed of basaltic rock and crystal fragments which are dominantly composed of mafic minerals (alkali feldspar, plagioclase, pyroxene, and opaque minerals). The groundmass of the sample is dominated by the flattened vitric textured glass with finer lithic and crystal fragments.

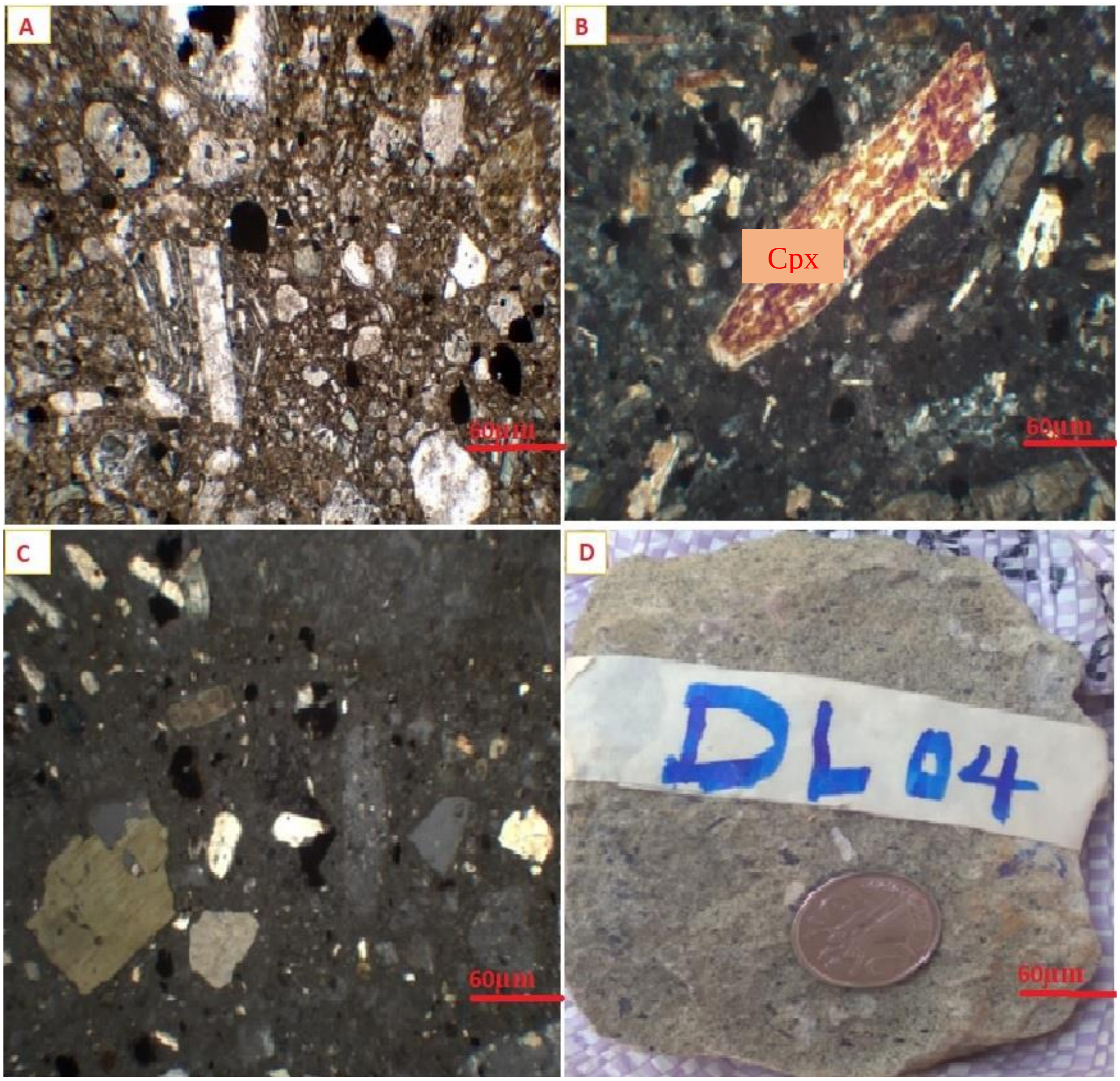


Figure 4.3 Microphotographs of Ignimbrite sample (A, B, C) and Hand-sample photograph (D) (DL-04); the sample is composed of abundant crystal (pyroxene (Cpx), and opaque minerals and rock fragment), (All photomicrographs are taken in 10X magnification in A) Plane polarized and cross-polarized light B and C.

4.4 Petrographic Character of Upper Basalt

Cl-08 and DL-09 are Porphyritic samples from the upper basalt show different types of mafic phenocrysts, dominant plagioclase with a variable proportion of cpx, olivine, and Fe-Ti oxides (opaque minerals), and secondary alteration minerals. The total proportion of phenocryst abundances is 5-20% in a holocrystalline to hypocrystalline groundmass with a felty texture. In addition to its presence as a phenocryst phase, plagioclase is the dominant mineral phase within the groundmass, forming subhedral to anhedral twinned crystals. The rock is a pyrophyric basalt based on the dominant phase in the phenocryst. It contains 20% phenocrysts, including plagioclase phenocrysts (80% and 0.48-mm max. size), with a considerable proportion of other minerals. The groundmass varies from microcrystalline to intergranular, forming a poorly intergranular to cumulophyric texture.

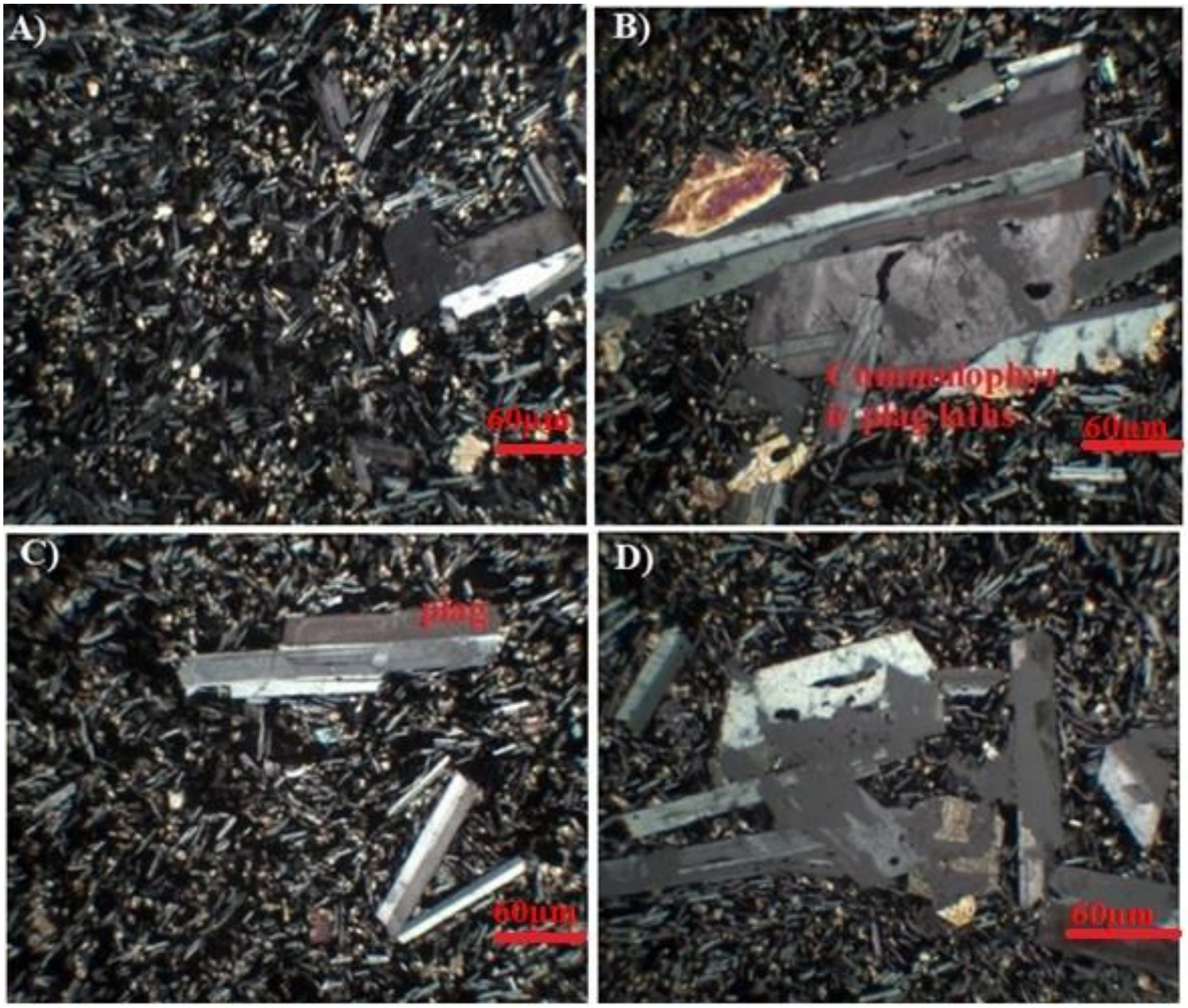


Figure 4.4 Microphotographs of plagioclase (cumulophric texture) in plag-phyric basalt from upper basalt unit. (A) showing plagioclase phenocrysts with fine-grained olivine and opaque minerals; sample DL-09 (B) showing Cumulophyric plagioclase phenocryst texture. (C) and (D) Also plagioclase laths with ground mass and opaque mineral.

DL-10 is ol-plag phyric basaltic samples consist of 10% phenocrysts (commonly olivine and rare plagoclase) minerals and microlites of various minerals occupy the fine groundmass. The groundmass is microcrystalline in most samples with felty texture. The microlites show an intergranular texture consisting of olivine (dominant distinguishable phase), plagioclase, and large proportions of Fe-Ti oxides. Its phenocrysts phase including dominantly Olivine phenocrysts (~75 % and 0.09mm max. size) with a considerable proportion of plagioclase minerals.

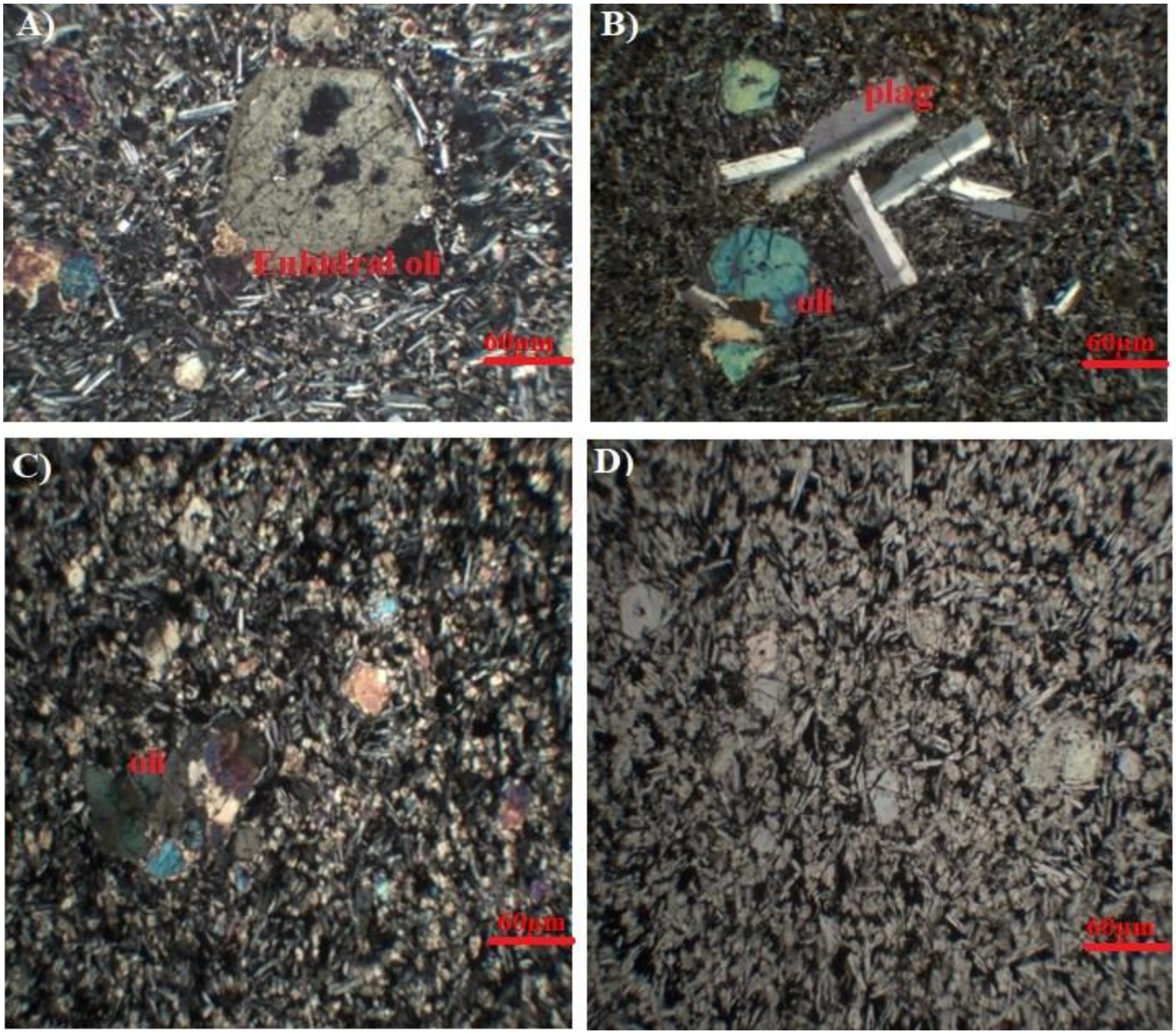


Figure 4.5 Representative thin section microphotographs of ol-plag phyric basalt samples from the Upper Basalts: (A) and (B) Olivine and intergranular plagioclase microlites forming the groundmass and opaque minerals DL-10.

(CL 08) and (DL12) collected from porphyritic upper flood basalt unit. The porphyritic sample is dominated by phenocrysts of plagioclase and olivine minerals (Plg-Ol- phyric basalt) embedded in a glassy and finer groundmass consists of plagioclase, olivine and Opaque Minerals (Fe-Ti oxides). The abundance of phenocrysts in sample CL-08 is 5-8% with dominant plagioclase. The groundmass in these samples shows cumulophyric texture formed by intergranular randomly oriented plagioclase microlites and felty groundmass observed in sample DL-12.

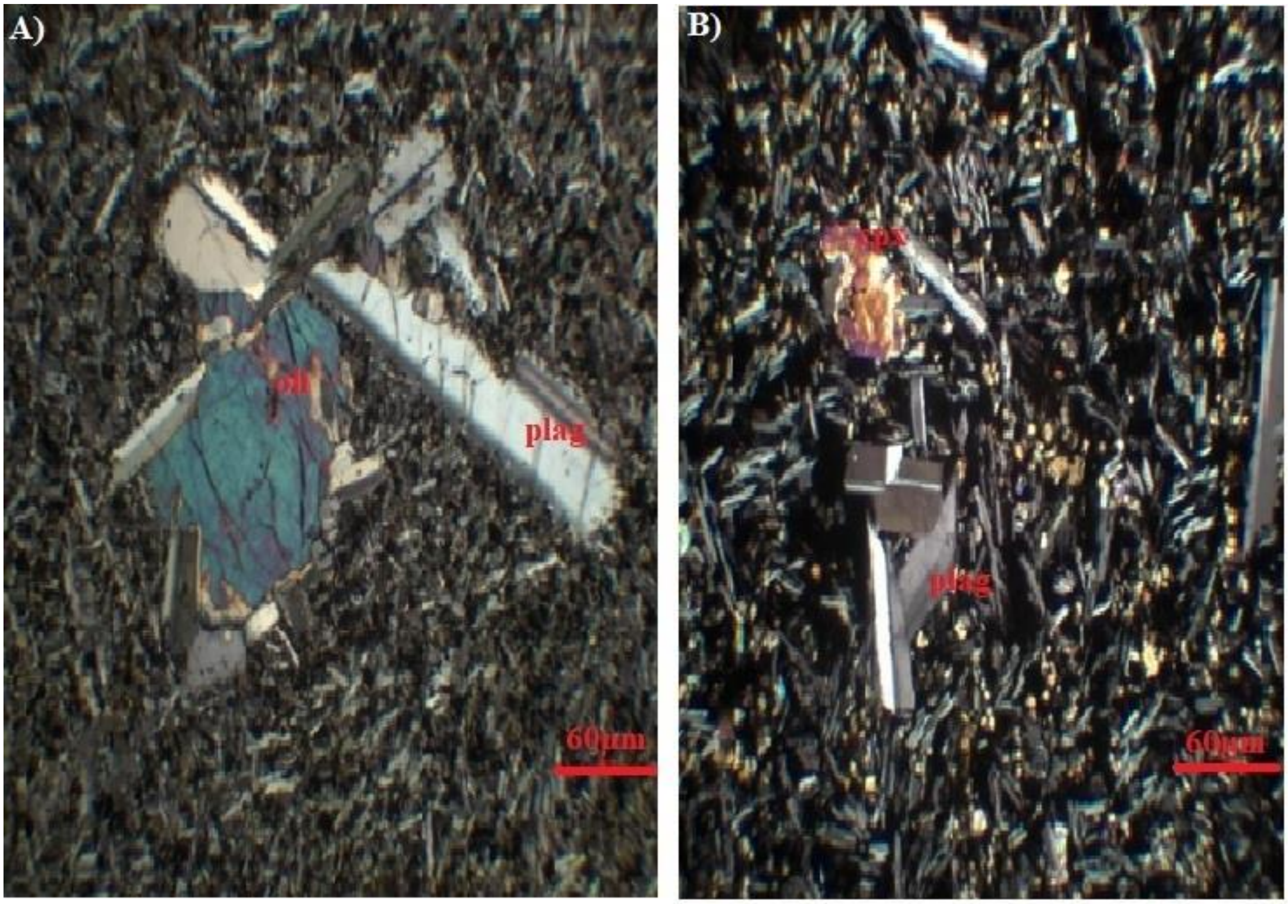


Figure 4.6 Photomicrographs showing clusters of plagioclases, olivine in Plg-Ol-phyric basalt samples from the Upper Basalt. A) Cumulophyric phenocrysts texture of euhedral to sub-hederal shape olivine and plag from thin section under XPL from sample CL-08 and B) Sub-hederal Plag lath of thin section photo under XPL. D).

Sample DL-11 collected from the aphyric upper basalt unit. It is composed of identifiable fine-grained plagioclase, Fe-Ti oxides (opaque mineral) and groundmass. The groundmass assemblage consists of fine grain materials with trachytic flow texture.

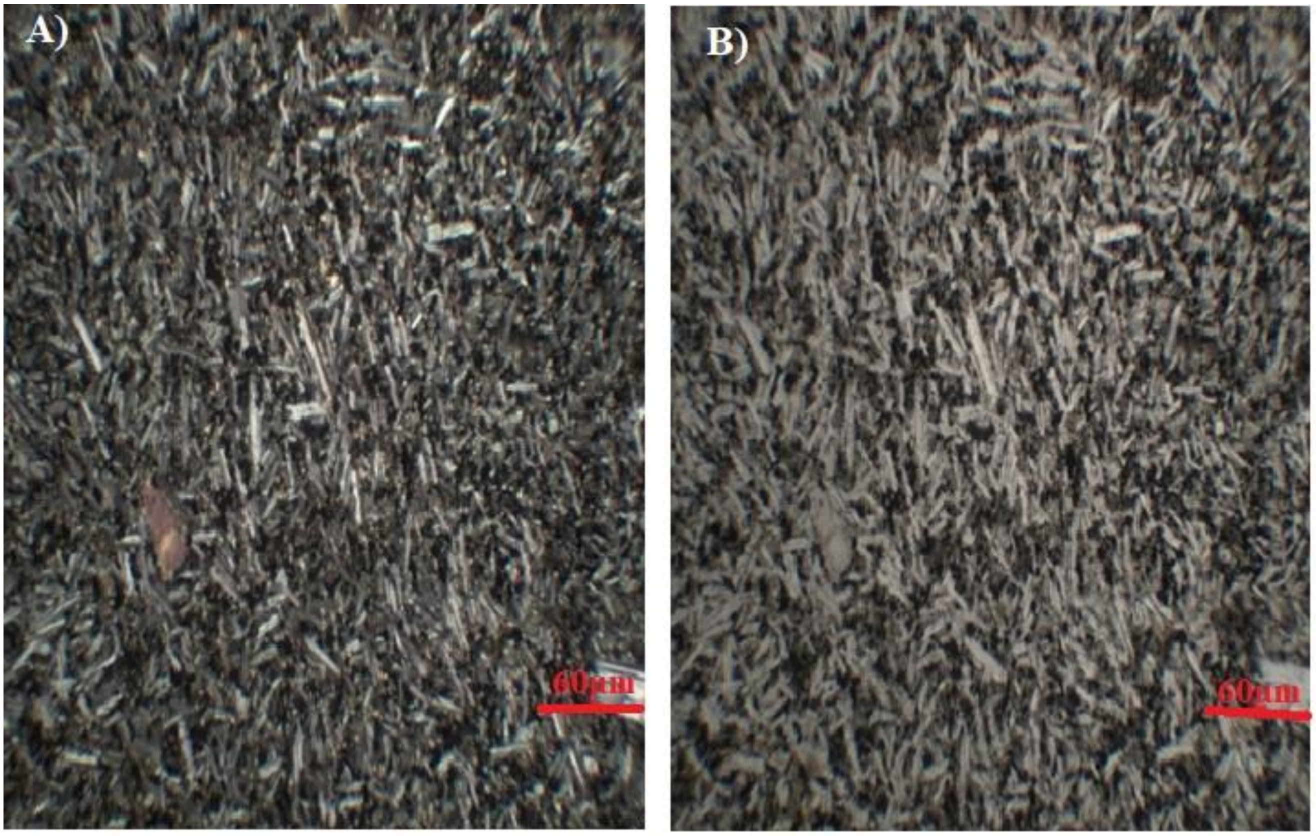


Figure 4.7 Microphotographs of aphyric upper basaltic flow unit. Sample DL-11 (A) and (B) showing plagioclase laths and opaque with fine-grained groundmass under XPL and PPL respectively.

Table 4.1. Summary of the petrographically analyzed rock samples in order of their elevation.

Sample code and elevation	Location UTM (Zone 37P)	Litho stratigra phic unit	Texture	Distinguishable Mineral Constituent	Dominant phase in phenocryst	% Of Pheno crysts	Modal Name
DL-01, **1933 M**	482395 E 1076290N	Mesozoic Sandstone	Equigranular, grain supported, sandy grains	A-Feldspar, Quartz and fine cement material	Feldspar ~ (75%), Quartz (20%)	-	Arkosic-Arenite
DL-02, **1947 M**	483145 E 1076278N	Lower Basalt	Aphanitic, Intergranular	Plagioclase, olivine , and Opaque Minerals	Plag	<1 %	Aphyric basalt
DL-03, **2030 M**	483264E 1076278N	Lower Basalt	Aphanitic, Vesicular	Plagioclase, olivine , and Opaque Minerals	Plag	1 %	Aphyric basalt
DL-04, **2090 M**	483220E 1076098N	Pyroclastic product	Porphyritic, cumulophyric, hypocrystalline,	Alkali-Feldspar, Opaque Minerals(glass) Basaltic Rock Fragment	Alkali-Feldspar Basaltic Rock Fragment (Px, Plg,)	25%	Ignimbrite
DL-05, **2151 M**	483043E 1075828N	Lower Basalt	Porphyritic	Plagioclase, olivine , and Opaque Minerals	Olivine ~ 30%, plag ~ 60%,	8%	Plag-Ol-phyric basalt
DL-06, **2204 M**	482740E 107466N	Lower Basalt	Porphyritic, cumulophyric,	Plagioclase, olivine	plag ~ 45%, olivine ~ 35%,	30%	Plag-Ol-Pxn-phyric basalt

				, Clinopyroxene and Opaque Minerals	cpx ~ 20%		
DL-07, **2337 M**	482195E 1074524N	Pyroclastic deposit	Porphyritic, vitrophyric	Alkali-Feldspar, Quartz, glass and Rock fragment (Plag and oli)	Opaque mineral ~50% and Basaltic Rock Fragment (Px, Plg,) (35%)	25%	Ignimbrite
DL-08, **2395 M**	482164E 1075531N	Pyroclastic product	Porphyritic, Vitrophyric	Alkali-Feldspar, Glass and Basaltic Rock Fragment (Px, Plg,)	Alkali-Feldspar ~ (35 %), Basaltic Rock Fragment (Pxn, Plg,) ~ (30%)	35%	Ignimbrite
DL-09, **2456 M**	482107E 1074539N	Upper Basalt	Porphyritic, ophitic	Plagioclase, olivine , pxn and Opaque Minerals	Plag ~ (75%), olivine ~ (20%)	(14%)	Plg-phyric basalt
DL-10, **2592 M**	481595E 1074478N	Upper Basalt	Porphyritic	Plagioclase, olivine , pxn and Opaque Minerals	Olivine ~ (60%), plag ~ (35%)	(15%)	Ol-Plg-phyric basalt
DL-11, **2608 M**	481590E 1074135N	Upper Basalt	Aphanitic, Intergranular	Plagioclase and Opaque Minerals	Plag	(2%)	Aphyric basalt
DL-12, **2661 M**	481458E 1074392N	Upper Basalt	Porphyritic	Plagioclase, olivine	Plag ~ (55%), Olivine ~ (40%)	(10%)	Plag-Oli-Phyric basalt

				, and Opaque Minerals			
CL-2, **2074 M**	480146E 1078201N	Lower Basalt	Aphanitic, Vesicular	Plagioclase and Opaque Minerals	Plag	(2%)	Aphyric basalt
CL-03, **2113 M**	480116E 1078176N	Lower Basalt	Aphanitic, Intergranular	Plagioclase and Opaque Minerals	Plag	(2-3%)	Aphyric basalt
CL-05, **2439 M**	478562E 1077457N	Pyroclastic deposit	Porphyritic, hypocrystalline ,	A-Feldspar, pxn Rock fragment and Glass	A-Feldspar (30%), Rock fragment (55%)	(35%)	Ignimbrite
CL-06, **2469 M**	479463E 1077342N	Upper Basalt	Aphanitic	Plagioclase and Opaque Minerals	plag	(2%)	Aphyric basalt
CL-07, **2471 M**		Upper Basalt	Porphyritic, Amygdaloidal	Plagioclase, Calcite , and Opaque Minerals	Plag and Opaque Minerals	(3%)	Amygdaloidal Basalt
CL-08, **2530 M**	479396E 1076918N	Upper Basalt	Porphyritic	Plagioclase, olivine , pxn and Opaque Minerals	Plag ~ (55%), Olivine ~ (30%),	(5-8%)	Plg-Ol-phyric basalt

CHAPTER FIVE

DISCUSSION

5.1 Introduction

This chapter discusses the stratigraphic construction of flood basalt products in the Zega Wedem River section of the north-western Ethiopian plateau, starting from the underlying sedimentary unit up to the topmost part of the succession (upper basalt) overlaying these units. The data from chapters three (local geology) and four (petrographic data) are integrated for discussion with regional studies in terms of field geological relationships, petrography, petrology, and the magmatic system. The discussion also includes the correlation of each stratigraphic unit with its respective previous stratigraphic names given by the different researchers. Finally, the composite stratigraphy of lithologic units with modal percentages in the study area is presented with a summary of each unit. This study examined 18 fresh samples for mineralogical assemblage (both phenocryst and microphenocryst phases) and microtextures, as well as field observations. Based on these petrographic analysis and field observation methods, the study area comprises different volcanic flows such as aphyric basalt**,** plagioclase-olivine phyric basalt, ignimbrite, plagioclase-olivine pyroxene-phyric basalt, olivine-plagioclase phyric basalt, and plagioclase-phyric basalt.

5.2 Overall Thickness, Volcanic stratigraphy and Magmatic Evolution

Flood basalt eruptions have contributed to the building up of the Ethiopian high plateau. Both basalts and pyroclastic deposit form typical plateau (platform) topography, which is often extensively eroded and dissected by deep gorges. Thickness estimation normally requires know elevation of both the bottom and top of the flood basalt succession. To estimate the total thickness of the volcanic units considered the maximum thickness of each unit at selected sections. The overall thickness of volcanic rock unit in the study area is about 715 m thick.

Lower basaltic lava flows (1946-2204 masl)

The lower lava flow basalt sequences are totally accounted about 258 m thickness, which comprise the Aphyric basaltic flow, Ignimbrite flow, plag-ol-phyric basaltic flow and plag-ol-cpx-phyric basaltic flow. The precise numbers of flows in lower basaltic lava flows are four and these separated flows have variable mineral assemblages and textures. At the bottom of this lava sequence, there is visible exposures of sedimentary units (Debre Libanos sandstone) and the contact between lower basalt and upper sandstone is represented by read zigzag line.

The first aphyric lava flow is found between (1946 - 2060 masl) a thickness of 114m. A thick of 31 m (2060-2091 masl) ignimbrite is also observed. The basaltic flow above this is plag-ol-phyric basaltic flow 60 m (2091-2151 masl) thick and plag-ol-cpx-phyric basaltic flow (2151-2204 masl) 53 m thick.

Pyroclastic Deposit (ignimbrite) (2205-2450 masl)

The pyroclastic deposit is found in the middle portion of the volcanic stratigraphy sequence in the area, which overlain on the texturally different lower basaltic units. This pyroclastic deposit a total thickness reached around 245 m. These dominantly composed of basaltic rock and crystal fragments which are dominantly composed of mafic minerals (alkali feldspar, plagioclase, pyroxene), Quartz and opaque minerals.

Upper Basalt Lava Flows (2450-2661 masl)

The upper basaltic region has three basaltic lava flow sequences, they estimated about 211 m thick and are exposed in both cliff forming and flat topography at the top of the plateau where the termination of volcano stratigraphic setting. These flows are plag-phyric basaltic lava flow (2450-2470 masl) 20 m thick, ol-plag-phyric basaltic lava flow (2470-2595 masl) about 125m thick and aphyric basaltic lava flow (2595-2661 masl) about 66m thick. The characterized by Aphyric-phyric textural varieties, columnated structure and massive fractured basaltic lava flow.

The stratigraphy column is established using the petrographic characteristics on the basis of mineral phenocryst phases and textures which described in the presiding chapter. The earlier stratigraphic study of northwestern Ethiopian plateau did not clearly put the volcanic suites and distinctions between the Ashange, Aiba, Alaji, and Termaber Guasa and Megezez shield flood volcanism (such as Mohr and Zanettin,1988), because they were simply characterized as upper and lower units, which relied only on the basis of local morphology (not consistent with the entire volcanic province in terms of petrography).

Furtherly, Hofmann et al. (1997) have been tried to improve these morphological distinctions found in between upper and lower flood basalts, but lack of a detailed petrological constraints also. Therefore, based on the petrographic differences, this study established three major volcano stratigraphic classification schemes which have been investigated by the characterization of individual lava flow mineral assemblages and textures such as lower basaltic lava flow, Pyroclastic deposit (ignimbrite) unit and upper flood basaltic lava flow. However, these large flows comprise different texturally and mineralogically different lava flows within it (eight in number) as describe above.

For evaluating the magmatic processes associated with the volcanic sequence on the basis of their stratigraphic position, an assessment is required of certain parameters that control the crystallization of mineral phases in both basaltic and felsic rocks during eruption. These parameters are: (1) composition of the parental magma, (2) pressure or depth of crystallization, and (3) the number of volatiles in the magma (Feig et al., 2006; Krans et al.,2018). The mineral assemblages of ol + cpx in basaltic lavas indicate that crystal fractionation happened at a deeper level in the crust or at the crustmantle boundary, whereas the mineral assemblages of plag + cpx + ol minerals indicate that fractionation occurred at a shallow level in the crust in the upper crust (Pik et al.,1998; Krans et al.,2018 and references therein). These crystallization phases of different minerals within lava flows play important role to understand the behavior of the magmatic plumbing system in the study area. It is also known that increasing of water concentration in liquid magma changes the mineral crystallization sequence or delays the order of crystallization (Feig et al.,2006). Under this circumstances, a relatively hydrated magma that contains water (>3wt %) clinopyroxene is crystallized over plagioclase at shallow crustal depths/pressure (Feig et al., 2006). On the other hand, in a relatively dry magma, crystallization of clinopyroxene and olivine minerals are favored at high pressure (10-20 kbar) at the expense of plagioclase, whereas the plagioclase minerals preferably crystalize over clinopyroxene crystals at lower pressures (<5kbar) in the same magma (Morse 1980; cited in Krans et al., 2018). In addition, from the work of Bartels et al., (1991) as cited in Krans et al., (2018) have noted the composition of the parental magma controls the mode and order of crystallization along the liquid line of descent. This observation is supported by Natali et al., (2016) who have described ol + plag in Low Ti lavas, and ol + cpx phenocrysts in High Ti 1 and High Ti 2 lavas. The analyzed volcanic rocks in the study area composed of minerals having different petrographic characteristics.

The lower and upper basalt unit of the study area is plagioclase-Olivine-pyroxene phyric and olivine-plagioclase phyric basalt that shows twining in plagioclase and alteration effect in plagioclase, olivine and clinopyroxene, euhedral- subhedral- anhedral shapes are very common in the samples analyzed. The shape of the crystals implies the order of magma crystallization as euhedral to subhedral assumed to be crystallized first and anhedral crystalized later.

The plagioclase-Olivine- pyroxene phyric basalt unit shows the mineral composition of phenocryst with a modal percentage of 15%-30% phenocrysts of plagioclase as the leading phase and followed by olivine and minor pyroxene. It is characterized by euhedral to subhedral shape, tabular and elongated phenocrysts are observed from the analyzed samples with intergranular to microcrystalline groundmass. The pyroxene phenocrysts show subhedral shape, alteration effects are also observed. The groundmass constitutes of mafic minerals such as plagioclase laths, pyroxene, olivine and opaque minerals with intergranular texture. The most distinguishing feature observed in the lower flood basalt and upper flood basalt unit is the presence of plagioclase – olivine- pyroxene phyric flows. The mineral assemblage and the presence of plagioclase, olivine and clinopyroxene together suggest that they crystallized at relatively considerable in the shallow crust with low pressure rather than the mid-deep crust at considerable depth.

The aphyric basalt unit shows lava flows of different texture and field characteristics. The groundmass shows intergranular and trachytic flow texture. In addition, some samples show glomerocrysts of plagioclase in the microcrystalline groundmass. The modal mineralogical and textural observation of lava flows in this unit indicates that different fractionation nature than the overlain and the underlain basaltic units. The flows in this units are thick with columnar jointed, and aphyric texture suggests an influx of magma into the plumbing system is high and the extrusion rate is high. The texture of this flood basalt unit is aphyric due to its high extrusion rate which could not allow the magma to settle in the shallow crust. This flood basalt unit indicates that there is no fractionation of different minerals in the shallow plumbing system.

At the end of the aphyric basalt extrusion, there may be fractionation or melting of the crust due to the shallow magma chamber, which results in the formation of pyroclastic material. This indicates that at the end of the extrusion of the aphyric basalt there is a decrease in the influx of magma from the deeper staging chamber.

Ash may form due to shallow fractionation of magma or it may be from melt generated from the crust due to the magma chamber in the shallow crust, when there is a decrease in the flux of magma in to the magma chamber and if there are long residence time in the crust. The longer residence time of magma results in the fractionation of mafic minerals and resulted in the formation of the felsic volcanic product.

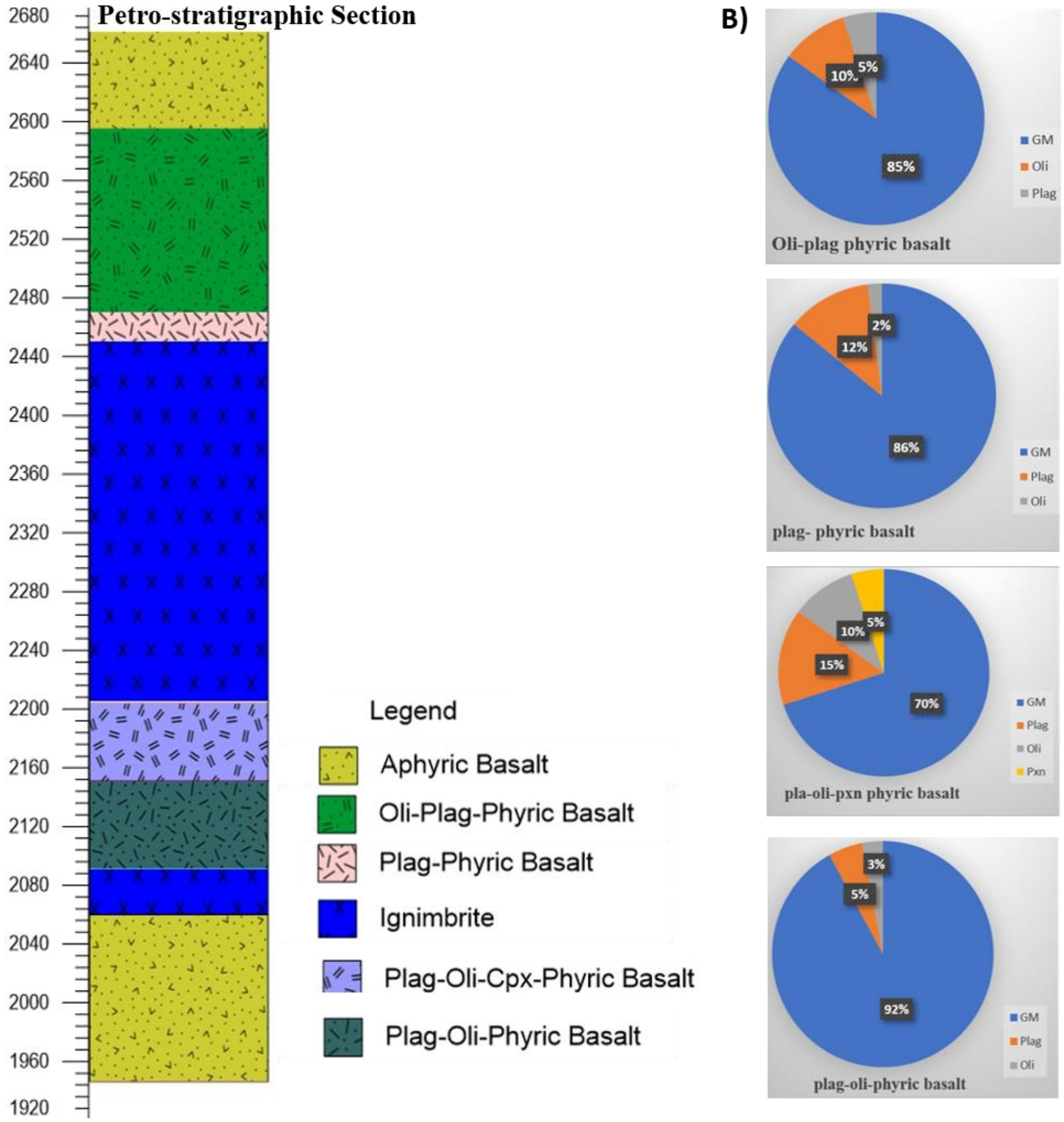


Figure 5.1.A) Petro-stratigraphic Section of the study area. B) Modal variation of phenocryst in these stratigraphic sections.

5.3 Local Volcano stratigraphic Correlation

The majority of stratigraphic correlations are based on broad lithological and geochronological similarities (Getaneh Assefa 1991). The following factors limit the type-formations' extension to Ethiopia's entire plateau region: local/areal field mapping is still pending, stratigraphy of the volcanic succession is poorly studied, accurate radiometric ages are scarce or non-existent and the lithology of the eruptive is unusually varied. As a result, it's possible that a linkage of flood basalts and contained ignimbrites across the Ethiopian plateau is premature at this time. Rather, a comparison is made with previous stratigraphic schemes created elsewhere on the Ethiopian plateau's northern side. The total Thickness of Stratigraphy section of Debre Libanos area is ~ 715m (1946-2661 masl) thick. The stratigraphic sequence is composed of Basalt-Pyroclastic deposit which is predominantly basaltic with layers of subordinate pyroclastic deposits. Silicic-explosive lava products increase significantly from the bottom to the top part of the succession with no interlayering of basaltic flows within the pyroclastic products in the middle and the top of the succession. The massive upper basalt is ending the stratigraphy. Volcanic lithostratigraphy of the area are; Lower Flood Basalt (258m), Pyroclastic deposit (Ignimbrite) (245m) and Upper Flood Basalt (211 m). The petrographic characteristics of basaltic lavas are dominantly composed of plagioclase, olivine and pyroxene phenocrysts and microlites with olivine, pyroxene, and abundant Fe-Ti oxides. The Ignimbrite are composed of alkali feldspar, plagioclase, mafic lithic and crystal fragments. These flows have intergranular textures with plagioclase as a dominant constituent, pyroxene, and abundant Fe–Ti oxides. They are also composed of phenocryst and finer grains of plagioclase, olivine and pyroxene are common in Groundmass.

Between 2120 m and 2260 m, a lower mafic-dominated sedimentary succession and an upper felsic-dominated sedimentary succession distinguish the Volcanic Sedimentary Sequence in the Lemi section (between 2260 m and 2350 m). The coarse volcaniclastic sandstones and thick (> 30 m) conglomerates that make up the lower mafic-dominated VSS. Typically, the polymodal, unstructured, and poorly sorted volcaniclastic conglomerate u nits are found. Aphyric basalt, pyroxene porphyritic basalt, subordinate intermediate volcanic clasts, volcaniclastic sandstone, and wood fragments make up the clasts that make up these units, which range in size from 50 cm to 100 cm (Simon et al., 2021).

Derba section there is an 8 m thick interlava unit comprised of a clean siliciclastic sandstone. The thickest lava flows are found in the LVS due to their ponding in the pre-existing palaeotopography. The number of ponded flows, considered to be >65 m thick, decreases upwards as the topography is levelled leading to the formation of the volcanic plateau. This sequence is overlain by the Volcanic Sedimentary Sequence (VSS). At the Lemi section the VSS is composed of a prominent ~230 m thick sedimentary succession, which is overlain by alternating basalt lava flows and intravolcanic sedimentary units. South of the Lemi section, in the Derba section, there are no sedimentary units within the VSS. Instead, a ~100 m thick pillow lava delta correlates to the VSS at the Lemi section (Simon et al., 2021).

Blue Nile Formation is dominated by tabular (simple) subaerial basalt lava flows, which commonly (but not exclusively) consist of lower colonnade and upper entablature tiers. The lava flow thicknesses generally vary from ~10 m to ~65 m thick. The Trap Series basalts are interbedded with a series of volcaniclastic sedimentary units, comprising thick sequences (>250 m) of conglomerates, sandstones, diatomaceous mudstones, and primary pyroclastic deposits (felsic and mafic) (Simon et al., 2021). The age of the Trap Series in the Blue Nile is estimated to be between 27-20 Ma, based on probable correlation with lava flows dated by the K-Ar method in the Muger and Gohatsion-Dejen areas (Jones & Rex 1974; McDougall et al. 1975; Jones 1976; Coulié et al., 2003 as site in Simon et al., 2021). The eruption of the Trap Series between 27-20 Ma is further supported by more precise 40Ar-39Ar dates of the basal lava flow and several inter lava tuffs near Alem Ketema, dated to 23.4-20.5 Ma (Coulié et al., 2003 as site in Simon et al., 2021).

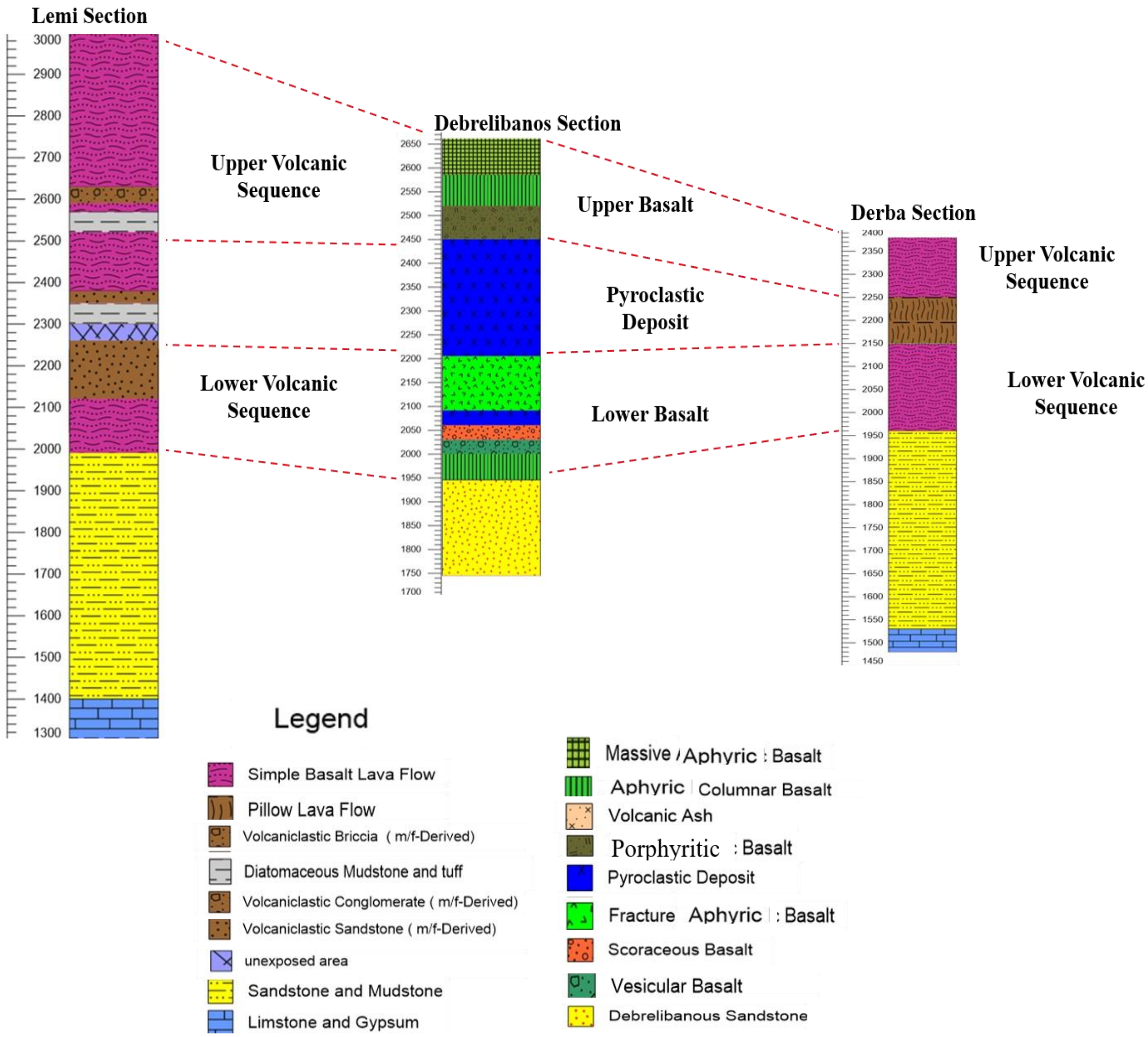


Figure 5.2 Correlation Between Lemi, and Derba Section (Simon et al., 2021) with Debre Libanos section based on morphological distinctions.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Based on Petrographic and Petrologic studies of stratigraphic units along the Zegawedem River section in parts of Northwestern plateau -Central Ethiopia, the following conclusions are made.

- The rock-units in the studied areas are composed of different Lithostratigraphic units mentioned as: Lower basalt, Pyroclastic flow (Ignimbrite Units), the Upper Basalt which represent the Oligocene-Miocene Volcanic Complex as a part of North-western Ethiopian plateau. These volcanic rocks are underlain by Sandstone Formation (Debre Libanos Sandstone).
- From the detailed volcanic-stratigraphic investigation having around 715 m-thick total thickness, the area comprises seven (7) intermittent volcanic flows such as Aphyric basalt**,** plagioclase-olivine phyric basalt, ignimbrite, plagioclase-olivine-pyroxene- phyric basalt, olivine-plagioclase phyric basalt and Aphyric basalt.
- Morphology of Flood basaltic lava flows in the study area includes; pahoehoe lava flow, ‘a’ā type vesicular lava flow, columnar jointed and massive lava flow. It is characterized by the presence of both tabular-classic and compound-braided flow facies.
- The flood basalt sequence in the study area is composed of Basalt-Ignimbrite unit volcanism. These lithostratigraphic successions are deposited as fissural type lava flows in the flood basalts and layers of silicic-explosive products.

6.2. Recommendation

- Detailed geochemical study of the area is recommended to understand the clear relationship between the different basaltic and felsic lava products.
- Isotopic geochemistry is also recommended for the better understanding of the evolution and geochronologic history of the flood basalt of Debre Libanos area.
- Further studies with increased number of sections and samples are recommended to confirm the Petrostratigraphic succession of the flood basalt of the area.

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