



ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIS
DEPARTMENT OF EARTH SCIENCES

**VOLCANIC STRATIGRAPHY AND PETROGRAPHY OF THE
NORTHWESTERN ETHIOPIAN FLOOD VOLCANICS IN
UPPER KESEM RIVER SECTION, CENTRAL ETHIOPIA**

A Thesis Submitted To School Of Graduate Studies Of Addis Ababa
University In Partial Fulfillment Of The Requirements For The Master Of
Science In Geological Sciences Degree (Petrology)

BY

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Addis Ababa, Ethiopia

June, 2023

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ADDIS ABABA

June, 2023

Declaration

Declaration

This is to certify that the thesis prepared by Misrak Lemma, entitled: "Volcanic Stratigraphy and Petrography of The Northwestern Ethiopian Flood Volcanics in Upper Kesem River Section, North Shewa, Central Ethiopia" is compiled under supervision of Prof. Gezahegn Yirgu and submitted in partial fulfillment of the requirements for the Masters of Science in Geological Sciences (Petrology). It is complied with Addis Ababa University's rules and regulations and, it satisfies accepted requirement 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.

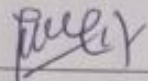
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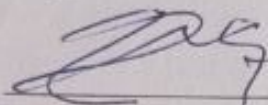
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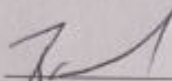
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Abstract

A petro-stratigraphic study of the volcanic sequence exposed in the Upper Kesem river section is presented. The study area is located in central Ethiopia, North Shewa administrative zone, between Koremash and Shola Gebeya localities, about 80 kilometers north-east of Addis Ababa. The study examined a nearly continuous, ~1080-m thick sequence of stratigraphically preserved basalt flows and intervening silicic pyroclastic deposits. The lower contact of the volcanic sequence is not exposed in this river section. Following a comprehensive field investigation, lithostratigraphic logs for various sections are presented. The sequence is dominated by flood basalts (~78%) with significant proportions of felsic lavas and pyroclastic deposits (~22%) towards the top part of the succession. The very top of the volcanic succession comprises of shield-forming basaltic lava flows and scoraceous deposits. Paleosols and clastic sediments are commonly found as thin layers interbedded within the volcanic sequence, indicating time gaps in eruptive activity. This sequence includes the main phase of flood basalt volcanism and the transition to the termination of flood basalt activity. From the constructed composite volcanic stratigraphy, five lithostratigraphic units have been identified, namely 1) Lower Basalt, 2) Lower Rhyolitic Ignimbrite, 3) Upper Basalt, 4) Upper Rhyolitic Ignimbrite, and 5) Shield Basalt. These lithostratigraphic units correlate very well with sequences described in other sections of the Northwestern Ethiopian plateau. A total of 25 representative samples from these stratigraphic units have been studied petrographically. The petrographic studies reveal that only basalts and felsic volcanics have been identified; rocks of intermediate compositions have not been found, indicating a bi-modal petrological distribution for the volcanic sequence. Overall, the basalts exhibit a wide range in their modal mineralogy and phenocryst assemblage. This variation suggests a polybaric plumbing system for the basaltic lavas with several magma chambers developed at various depths within the crust and with each chamber undergoing independent recharge and fractionation processes. Shield volcanism likely represents a decrease in magmatic flux over time. The large-volume silicic pyroclastic deposits further reveal that flood basalt volcanism was accompanied by the development of large and shallow magma chambers, in which basaltic magmas were stored and underwent extensive fractionation and evolution. These deposits further highlight that large and long-lived silicic volcanic complexes with large calderas must have developed on the flood basalts.

Key words: Ethiopian volcanic province, *lithostratigraphy*, *Oligo-Miocene*, *petrography*, *Upper Kesem river*, *volcanics*

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List of Acronyms

Ar-Argon

amsl- Above mean sea level

Ba-Barium

C-Central

CFB – Continental Flood Basalt

Cpx – Clinopyroxene

CSA-Central Statical Agency

DEM-Digital Elevation Model

EARS – East African Rift System

Fig. – Figure

GPS -Geographical Positioning System

GIS- Geographic Information System

HT – High Titanium

K-Potassium

KES-Kesem

KM – Kilometer

LIPs – large igneous provinces

LT – Low Titanium

M-Meter

Ma- Million years ago

MER – Main Ethiopian Rift

mm – Millimeter

MORBs– mid oceanic ridge basalts

N-North

Nb- Niobium

NW – Northwestern

NWEP – North Western Ethiopian Plateau

OIBs – ocean island basalts

Ol-Olivine

Opx-Orthopyroxene

Plg – Plagioclase

PPL – Plane polarized light

Px-Pyroxene

S-South

SE – Southeast

SEEP – South Eastern Ethiopian plateau

SW-Southwest

Ti-Titanium

UTM-

Wt% – Weight in percent

XPL–Cross polarized light

1. Introduction

1.1 Background of the study

Ethiopian Cenozoic volcanic province constitutes a thick succession dominated by fissural basalts and minor silicic products spread over an area measuring several hundred thousand square kilometers (Gezahegn Yirgu, 1997). Ethiopian volcanic province is the latest large igneous provinces (LIPs) that located at the northern end segment of the East African Rift System (EARS). This province is primarily dominated by flood basalt volcanics with a total area of around 622,108 km² and younger rift volcanics (Rooney et al., 2017).

According to Pik et al., (1998) the volcanic products in Ethiopia are mainly exposed within the rift (rift series) and plateaus (trap series). The trap series were developed when the MER is first initiated before the full development of rifts. These units are also named as Pre-rift sequences or plateau volcanoes. The spatial distribution of this volcanic province dominantly exposed in Ethiopia, and some parts are cropped out in Yemen on the eastern part of Red Sea (Pik et al., 1998). According to several studies (Ukstins et al., 2002, Dereje Ayalew et al., 2002, Kieffer et al., 2004 and Natali et al., 2011, 2013), flood Volcanics of Ethiopia composed from dominate basaltic lavas, pyroclastic fall deposits and rhyolitic ignimbrites and minor amount of basaltic pyroclastic rocks.

The Ethiopian volcanic has two major categories; The first one is Continental Flood Basalt, (in several locations covered by the shield forming basalts, spanning huge portions of the country's highland northwest and southeastern plateaus throughout the Tertiary period) where as the second one is Rift series, that still actively ongoing. According to Kieffer et al. (2004), Ethiopia's continental flood basalt is largest, youngest, least deformed, and best preserved volcanic rocks.

The continental flood basalts of Ethiopia is a portion of the Afro Arabian Igneous Province associated to the Afar plume and the Red Sea, Gulf of Aden and Ethiopian Rift triple junction (Kurkura Kabeto, 2010). CFBs are large eruptions of mostly basaltic lava with an area greater than 100,000 km² and a thickness of less than one kilometre that occur during geologically brief time intervals (1–5 Ma, with the majority of the volume erupted over 1 Ma) (Krans et al., 2018).

The rapturing of the lithosphere is frequently linked to continental flood volcanism (CFV). According to Pik et al., (1999) as continental breakup advances towards matured

rifting, Ocean island basalts and mid oceanic ridge basalts are examples of lavas whose geochemical characteristics frequently move towards oceanic lava flows, indicating a gradual involvement of upper mantle elements.

The flood basalts and associated felsic pyroclastic rocks (Ethiopian Traps) are continental volcanic rocks that erupted before the onset of continental rifting and sea-floor spreading in the Afar, It is thought to be connected to the activity of the Afar plume. According to Pik et al. (1998), 1999; Kieffer et al. (2004), melts from an upwelling mantle plume were generated inside the Oligocene CFB in northern Ethiopia.

The NW Ethiopian flood volcanics have been divided into three separate geochemical groups, including low-Ti basalts (LT-type), high-Ti1 (HT1-type), and high-Ti2 (HT2-type) basalts, depending on Ti and trace element concentrations (Pik et al., 1998, 1999). Following CFB are large shield volcanoes covering around 20% of the plateau's surface above the flood basalts (Addise Mekonnen., 2006). These shield volcanoes overlain on the fissural type continental flood basalt eruptions differs from the flood basalt not only in age but also in volume and composition and they are central eruptions.

These shield volcanoes are forming higher relief (1000-2000 m above the plateau), less voluminous (Mohr and Zanettin, 1988, Kiseffer et al., 2004). In the north western Ethiopian Plateau they are different shield forming volcanoes overly the flood basalts. Those shield forming volcanoes includes Guna, Gugufu, Megezez, Simien and Choke volcanoes (Kieffer et al., 2004). This study focused on the upper Kesem river section volcanic rocks on producing sketch map, petrographic description, constructing the stratigraphic section and provides detail geological information about the area.

1.2 Description of the study area

The Upper Kesem river section (study area), which is defined by the geographic coordinates UTM zone 37 easting (522417 to 552417) and northing (1004102 to 1034102), is found in North Shewa Zone, Amhara Regional State, central Ethiopia, about 80 km to the northeast of Addis Ababa (Fig. 2). The area is accessible through Addis Ababa-Debre Birhan main asphaltic road. Specifically the research areas are accessible by Addis Ababa –Aleltu – Hamus Gebeya and then to alternative gravel road to Koremash (Fig1.1) and from Sheno _Kotu Gebeya to Shola Gebeya.

The research area's physiography, combined from DEM and Hill shade is shown in (Fig1.2a) and the topographic profile section of the upper Kesem River section from A to A' as presented in (Fig1.2b).

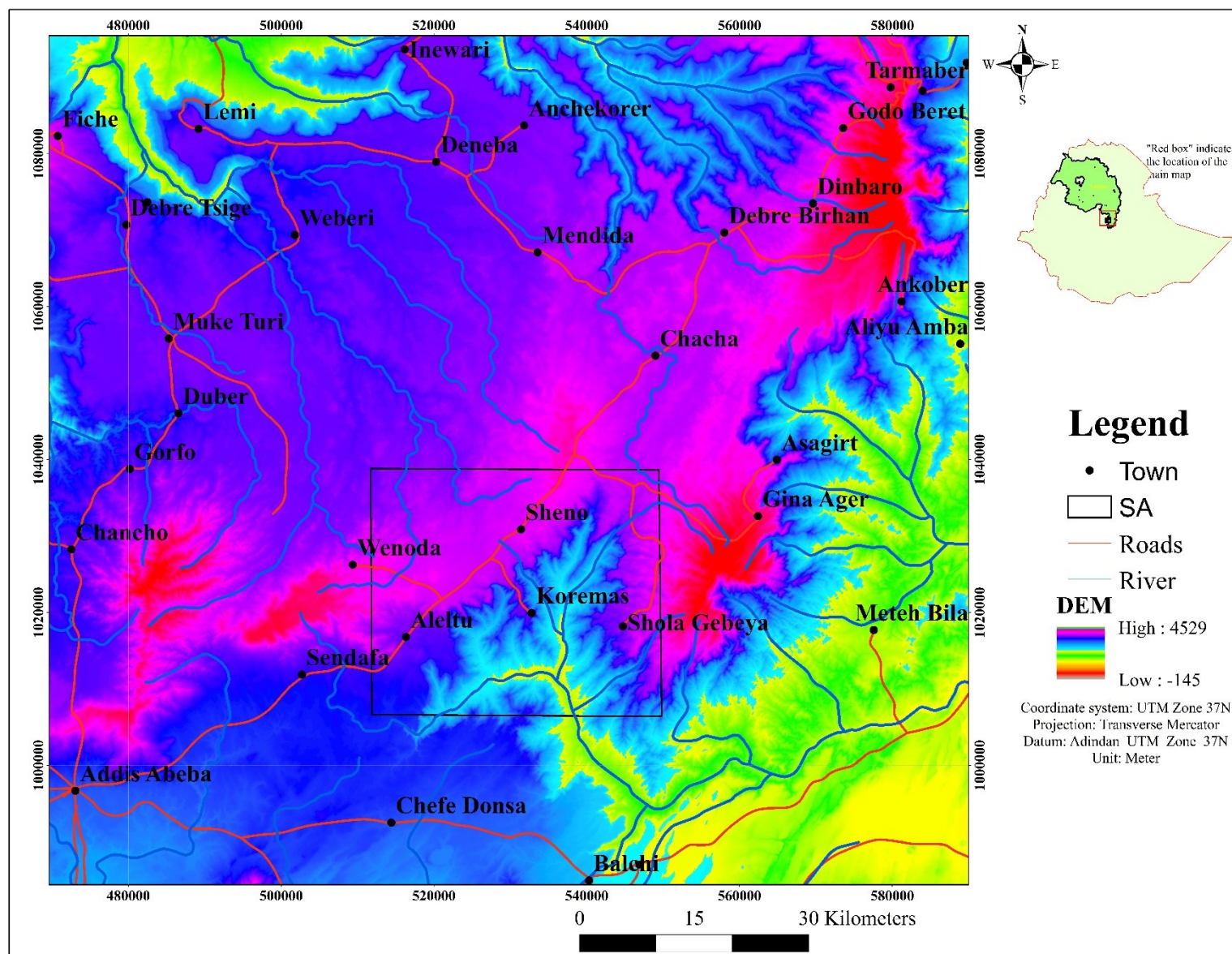
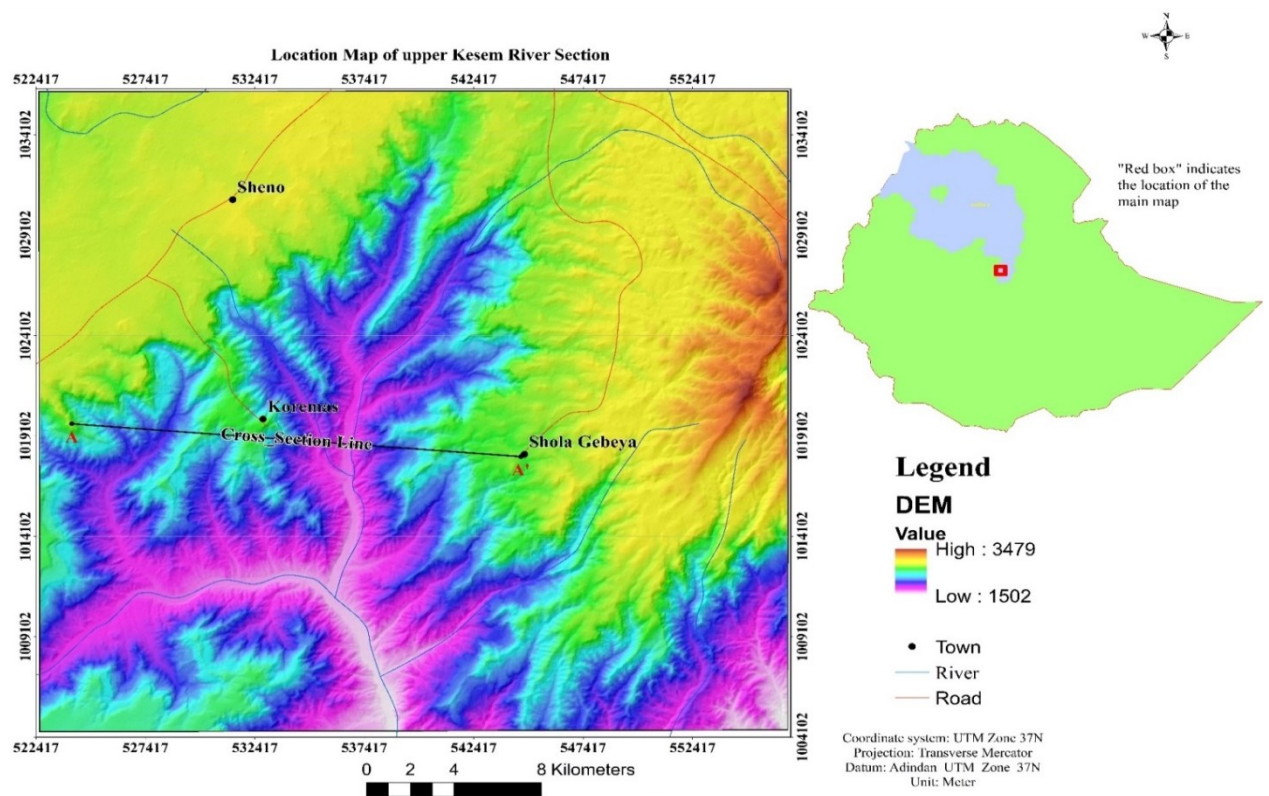


Figure 1.1 Location map Upper Kesem river section (study area).

a)



b)

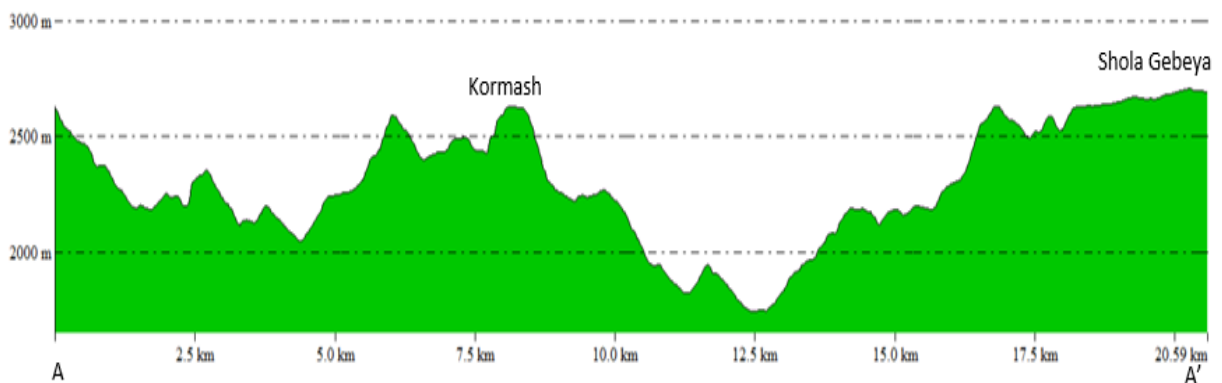


Figure1.2 a) Physiography of the research area, integrated from Hill shade and DEM, b) Topographic profile section of the upper Kesem River section from A to A'.

1.2.1 Physiography

The research area (Upper Kesem river section), is a part of northwest Ethiopian Plateau, is found on the western verge of the Main Ethiopian Rift (MER). Large-scale tectonic activity and volcanic activity throughout the Miocene–Pliocene period resulted in the formation of different physiographic features of the research area, including the mountains, ridges, and escarpments that surround the rift floor. Upper Kesem river section has highest elevation ~2,650 m amsl (Fig1. 3).

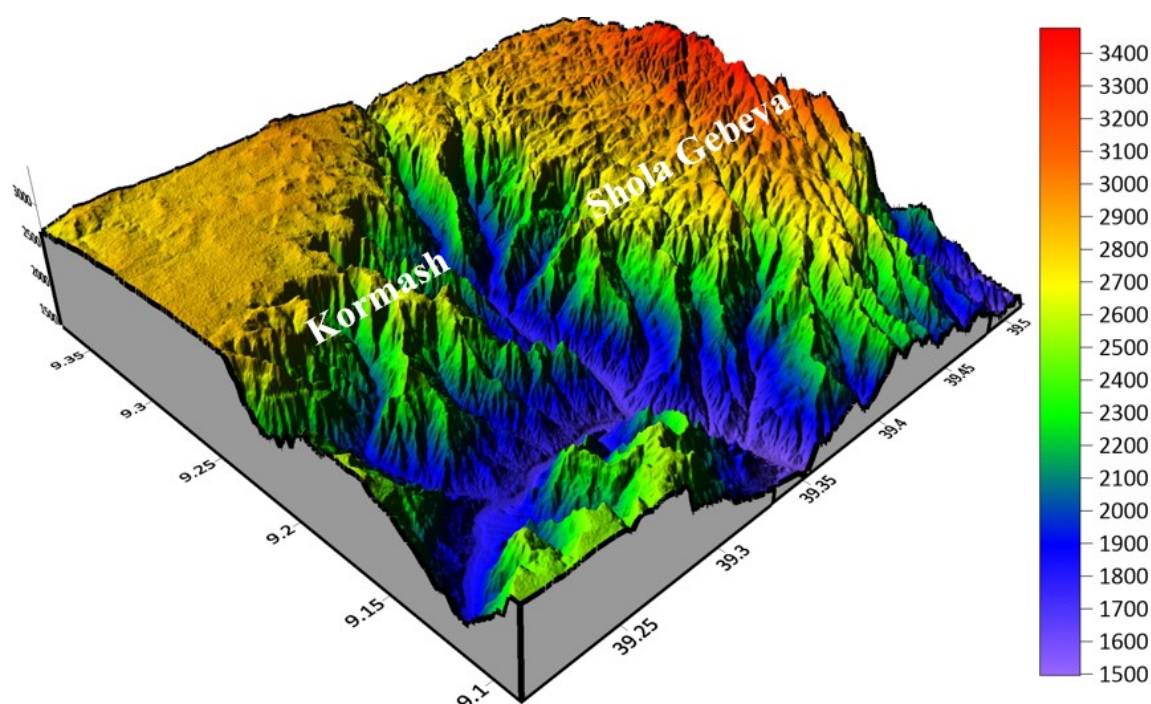


Figure1.3 Three (3D) physiographic view map the study area.

1.2.2 Drainage

Dendritic drainage is the predominant kind of drainage in the studied region. In the Kesem drainage basin, streams and rivers originate from the southern portion of the escarpment and Chanco-Berek ridge and flow southward from north to south to the Kesem River. There are other rivers and streams in the Kesem drainage basin, including the Germame, Inkoy, and Jirany. These rivers and streams create sub parallel dendritic drainage patterns (Fig1.4).

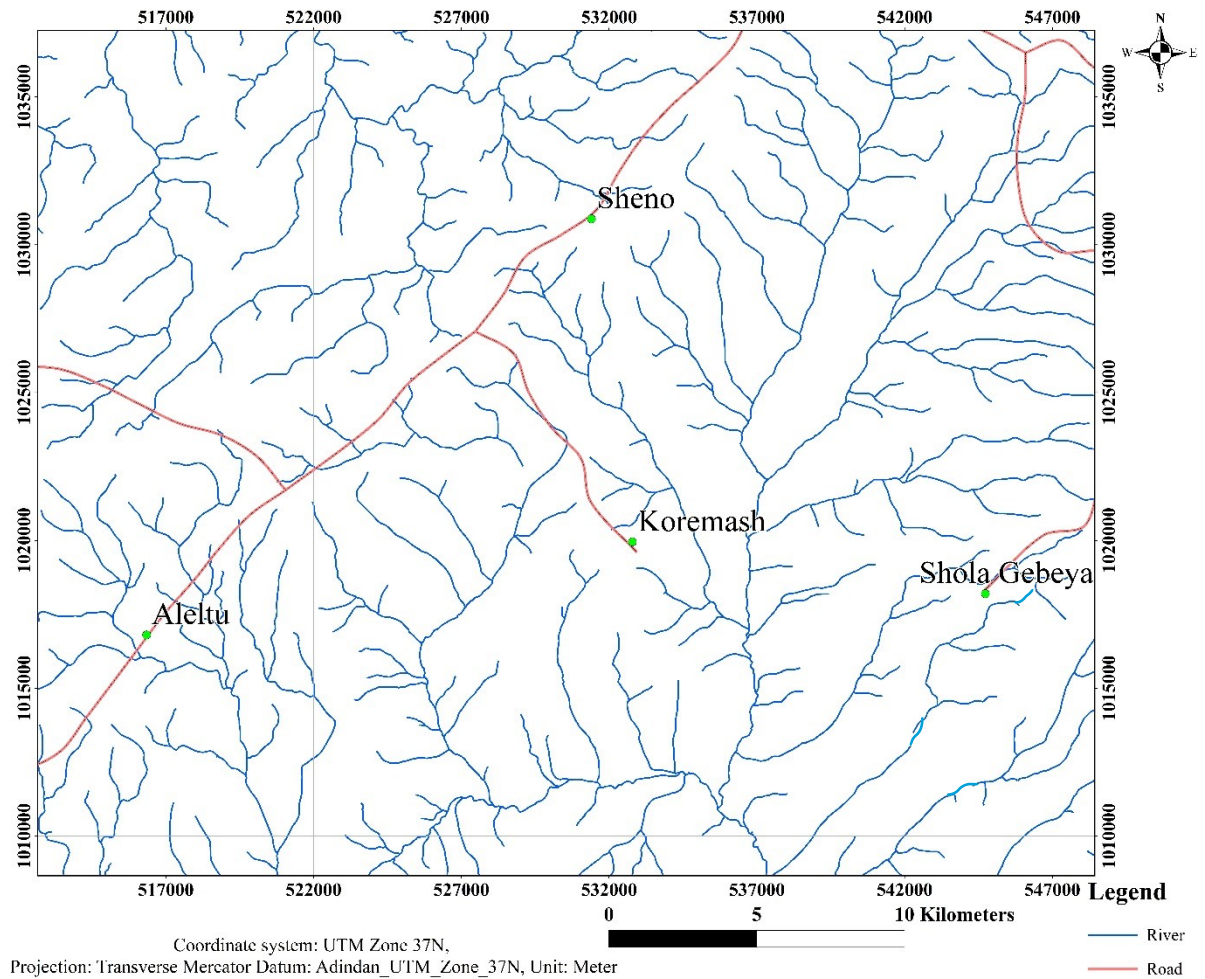


Figure1.4 Drainage map of the Upper Kesem River section

1.3 Population climate and vegetation

1.3.1 Population

According to the Central Statistical Agency of Ethiopia's (CSA) 2007 national census, this woreda has a total population of 55,235, up 20.72% from the 1994 census. Of those, 28,394 men and 26,841 women live there, while 2,187 people, or 3.96% of the population, live in urban areas. Shola Gebeya Kesem has a population density of 80.07 per square kilometer, which is lower than the Zone average of 115. The area is 689.87 square kilometers.

In this woreda, 11,891 households with an average of 5 people per household and 11,499 dwelling units were counted. 99.9% of the recognized population their religion as Ethiopian orthodox Christianity, which was practiced by the majority. (https://en.wikipedia.org/wiki/Hagere_Mariamna_Kesem accessed March 2023). The lowlands have a denser population than the highlands. People mostly engage in farming

and, to a lesser extent, cattle raising. They used a traditional farming system and irrigation to raise cereal crops like teff, wheat, maize, sorghum, and chickpea. They rear domestic animals like horses, donkeys, cattle, sheep, and other farm animals.

1.3.2 Climate

The rift region's mean annual temperature and rainfall range from 37 to 40°C and 800 to 1000 mm, whereas the plateau area's average annual temperature and rainfall range from 20 to 25°C and 500 to 1600 mm (Ethiopian Mapping Agency, 1981). In general, the region experiences climates that range from humid (highland, "Dega to Weina Dega") to desert (low land, "Kola"). The average temperature in April is roughly 21°C, but it seems colder at night, according to the weather averages. There are typically 11 rainy days in April in Shola Gebeya, and the area receives an average rainfall of 65.43mm. It's around 66% humid.

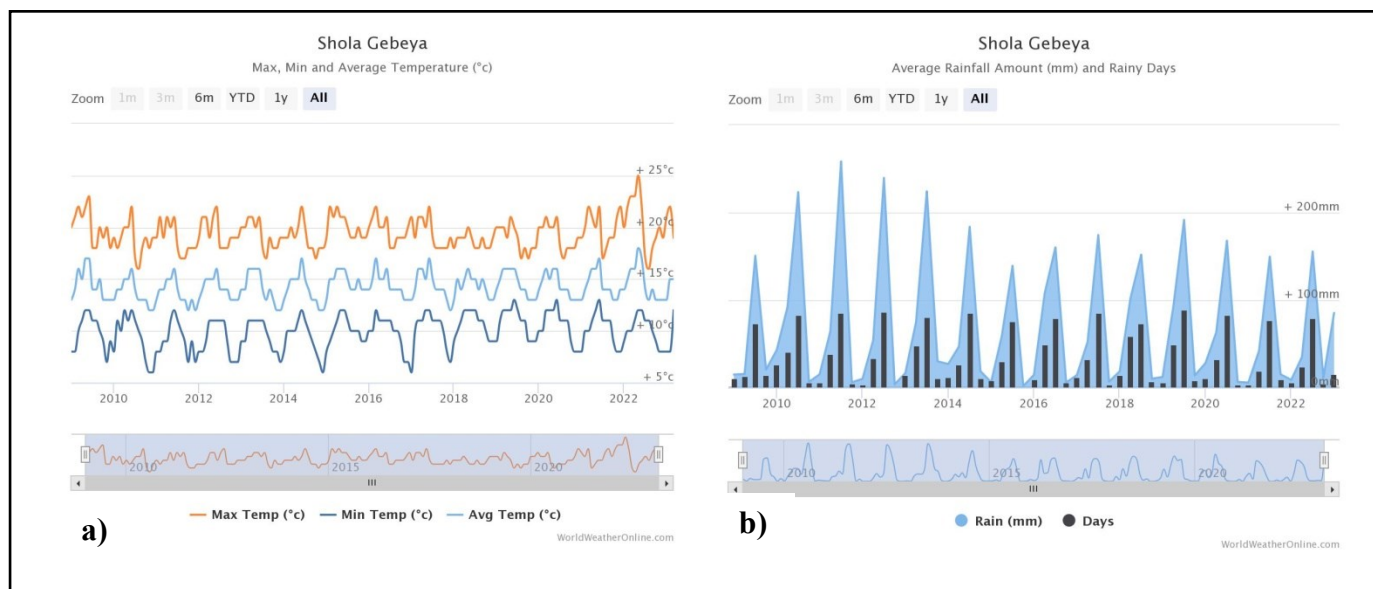


Figure 1. 5 Average Temperatures (a) and Rainfall (b) from 2010-2022 in Shola Gebeya. (<https://www.worldweatheronline.com/shola-gebeya-weather-averages/et.aspx> accessed in 13th January 2023 at 02:05 am)

1.3.3 Vegetation

The research region is distinguished by its diverse vegetation cover. In comparison to the other areas, the northwest portion of the research area has a less dense vegetation cover. Eucalyptus trees, girar, bushes, tiny shrubs, and several undifferentiated evergreen plants

make up the majority of the vegetation types. Northwest of the study region, high altitudes are home to dense eucalyptus trees.

1.4 Statement the Problem

Beginning with early stratigraphic investigations focused on the volcanics of the Ethiopian plateau (Mohr, 1967; Kazmin, 1972; Merla et al., 1979; Zanettin et al., 1980; Berhe et al., 1987; Mohr, 1983) three volcanic units, the Ashange formation, Aiba basalts, Alajae formation, and Tarmaber-Megezez formation (bottom to top chronology), have been identified on the northern and central Ethiopian Plateau. Different studies also employ various stratigraphic categories (upper and lower unit) (Hofmann et al., 1997; Kieffer et al., 2004; Dereje Ayalew and Gibson, 2009; Krans et al., 2018).

No thick, monotonous, frequently erupted volcanic plateau exists in Ethiopia mass of undisturbed, horizontal tholeiitic basalts; rather, it consists of a variety of eruption centers having various magmatic characters and with a wide age range (Kieffer et al. 2004). According to Rooney (2017), the former division of the Ethiopian Trap plateau into the Ashange, Aiba, and Alajae groups is no longer useful for contemporary magmatic studies because of the deep lateral changes in the mineralogical composition of the lavas and the appearance of synchrony in eruption.

According to Beccaluva et al. (2009), flood basalt has varies thickness in the different part of Ethiopian plateau sections. In some locality like north Gonder (Simien Mountain) Mesozoic sedimentary rocks are covered by basaltic lavas having the thickness around 1950m. The other section around north eastern part of Ethiopia around Adigrat area, the Precambrian crystalline basement is covered by 500 meters of basaltic lavas. In addition to the above localities, around Dejen (Abay basin) the Mesozoic sedimentary rocks are coved by 450-meter thick basaltic lavas and around Lalibela area it is also covered by the 1800 m-thick Lalibela layer, which is composed of basaltic lavas with some rhyolitic intercalations at the top. Therefore, the goal of the present research is to discover the thickness of the plateau basalt in the Koremash area's upper Kesem river section.

Dereje Ayalew et al. (2021) assert that Ethiopian flood basalt field mapping and linkage has not been yet undertaken; quite divergent stratigraphic schemes for the volcanic pile have been provided in the literature (Mohr and Zanettin 1988; Hofmann et al., 1997; Krans et al., 2018). Although stratigraphic studies have gotten less attention (Mohr and Zanettin 1988; Krans et al. 2018), they are just as significant for providing the

geographical and temporal characteristics required to limit models of magmato-tectonic evolution. This province is more complicated than previously believed, according to ongoing stratigraphic mapping and investigation. (Mohr 1983; Rooney, 2017; Krans et al., 2018). Accordingly the stratigraphic studies are essential to understand CFB magmato-tectonics condition of the certain areas.

The majority of prior research on the Ethiopian plateau magmatism was done at the regional scale, and in-depth studies of individual plateau parts are rare. Therefore most part of the Ethiopian plateau volcanic rocks require comprehensive study in terms of lithological unit identification, extent, and field relationship description, detailed textural and mineralogical study, and finalized volcanic stratigraphic section establishment, based detailed field mapping and petrographic description of the representative rock sample taken from the study area.

As a result of incomplete exploration in terms of petrographic and petrologic characteristics of the volcanic rocks of the upper Kesem river section area volcanic units, the aim here is to establish the complete petro stratigraphic section to fill the existing gap in the detailed study of volcanic rocks of an area along the upper Kesem river section, as part of a single section within Northern Shewa of the northwestern Ethiopian plateau.

Furthermore, it is challenging to correlate a large amount of the existing, high-quality geochemical data from diverse section of the Ethiopian flood basalt province due to the absence of a complete geological map that shows the geology of any specific flood basalt province in Ethiopian. One of the least explored sections is the upper Kesem river area in Ethiopia in terms of geological characteristics and there are limited research works or geological investigation related to geology, and other aspects of geological works. In the current proposed study, detail geological and petrographic study conducted to understand the stratigraphic and mineralogical characteristics of the flood volcanic rocks in upper Kesem river section.

1.5 Objectives

1.5.1 General objective

The general objective of this research work is to establish a complete volcanic stratigraphic section based on the lithologic, and petrographic characteristics of the exposed volcanic rocks in the upper Kesem river section, North Shewa, Central Ethiopia.

1.5.2 Specific Objectives:

The specific objectives of this study are;

- ❖ To identify the distribution of major lithological units and major lava flow morphologies within the stratigraphic section.
- ❖ To establish a stratigraphic sequence of the upper Kesem river volcanic pile.
- ❖ To characterize the petrography and petrology of the volcanic units in the study area and interpret based on regionally set geochemical and geochronological data to flood basalt magmatism in Ethiopia.
- ❖ To produce a sketch geological map and geological cross section of the study area
- ❖ Correlate the lithostratigraphic succession in the mapped area, with volcanic successions in other studied sections of the Ethiopian volcanic province and
- ❖ Infer the magma storage and eruptive conditions

1.6 Methods

In order to successfully accomplish the objectives of this research, the following methods have been utilized: Field observation and description of lithostratigraphic units, stratigraphic sampling, and petrographic analysis. On the basis of geologic mapping and descriptions of stratigraphic sections, the main volcanic stratigraphy was developed during many traverses of the flood basalt sequence. The study consisted of three stages of methods as field and laboratory studies.

1. Remote sensing and GIS studies
2. Field investigation and sampling
3. Petrographic studies

Different softwares are used to produce the final geological sketch map, geological profile (cross section) and stratigraphic log section of the area from field data using ArcGIS, Global mapper, Strater, and Surfer and G-micro vision software to analysis the modal proportion of minerals during petrographic description.

1.6.1 Field description of lithological units

This is used to identify the kind of volcanic lithologies and distribution of the lithologic units and lava flow morphologies. Activities include during this stage: detailed rock descriptions, preparation of sketch geological maps, taking measurement of geological structures, taking photographs, and sampling. 1:50,000 scale base map was used for data collection during the traverse.

1.6.2 Sampling

During the field work in addition to field description and mapping standard sampling was a component of this research. In this section of the research standard and representative rock samples were collected in each and every traverses when certain variations were noted. While samples were taken from a certain location, detail field description of lithology, geomorphology, contact relationship, degree of alteration, thickness and lateral continuity as well as sampling location (Latitude, longitude and elevation) using a hand-held GPS, Global Positioning System were recorded.

1.6.3 Petrographic analysis

After the filed mapping and sampling process were completed, 25 representative samples selected based on lithological variation, physical property of rock areal distribution for petrographic analysis. Thin sections were prepared at the Central Geoscience Laboratory of the Geological Survey of Ethiopia. 25 thin-sections were examined under a polarizing microscope to characterize their textures, modal proportions, and mineral compositions. Overall methodological framework is presented in (Fig1. 6).

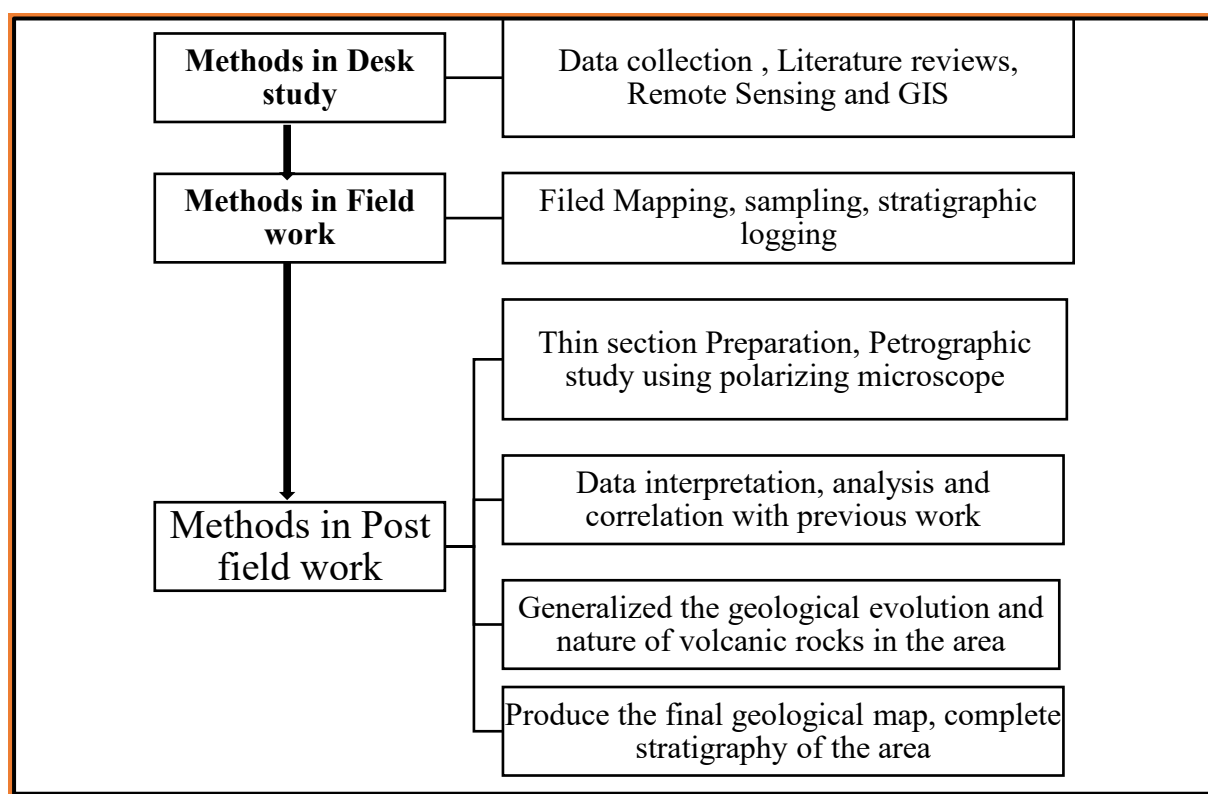


Figure 1.6 General flow chart of the research methods.

1.7 Review of previous geological work

The Ethiopian continental flood basalt province is found at the junction of Red sea Gulf of Aden (oceanic rift) and East Africa (continental rift). The majority of the province is exposed in Ethiopia, with the remaining portion situated in Yemen on the eastern bank of the Red Sea. These Oligocene basalts on the northwest Ethiopian Plateau, according to Pik et al. (1998), are covered by less dense Miocene lavas that erupted from huge central vent volcanoes. However, thick Eocene-Miocene acidic lavas and ignimbrites dominate the volcanic sequence in southern Ethiopia, where Eocene-Oligocene basalts are uncommon. According to Pik et al. (1998, 1999), the northwestern Ethiopian flood basalts are classified based on trace element and Ti concentration into three different geochemical categories, those are low-Ti basalts (LT-type), high-Ti1 (HT1-type) basalts, and high-Ti2 (HT2-type) basalts. The low-Ti (LT) basalt group is exposed at the northern part of Ethiopian plateau, whereas the entire high-Ti (HT1 and HT2) basalts group is exposed in the eastern and southern parts of the plateau (Fig.1.7).

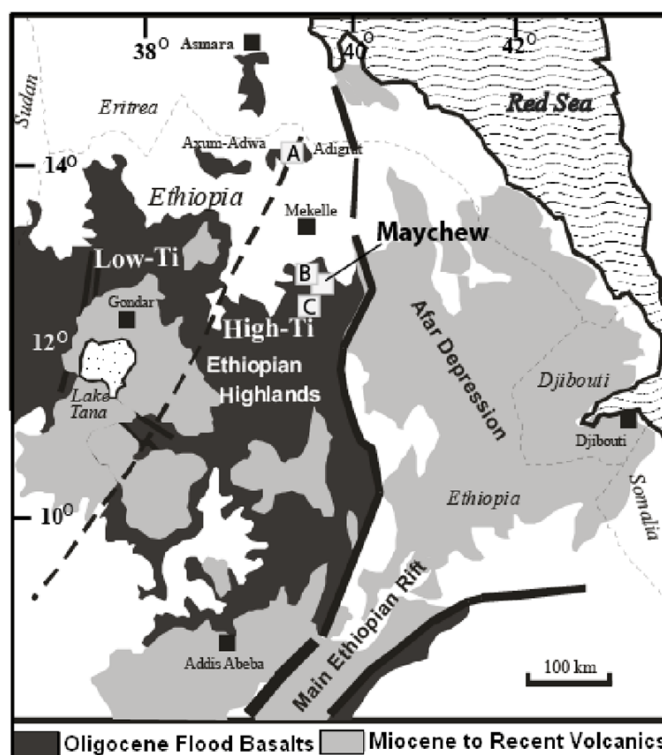


Figure 1.7 A map shows the low-Ti and High-Ti flood basalt province which is separated by the broken line (Pik et al., 1998).

Ethiopian Cenozoic volcanic province consist the largest intercontinental magmatic provenance. It developed entirely during Cenozoic with emission huge amount of flood basalts and inter-bedded ignimbrite (Gezahegn Yirgu, 1997). According to Zanettin et al., (1980) stratigraphic studies conducted in the northeastern part of Ethiopia plateau, the flood basalts are divided into four divisions as Ashange basalt, Aiba fissure basalt, Alajae basalts and rhyolites, and Termaber basalts from oldest to youngest.

The Ashange is characterised by thin slightly dipping basaltic lava flows that are only a few km in length. These flows are locally zeolitized and are unconformably overlain by flat-lying flows (Aiba Formation). Massive flows that can reach heights of up to 100 metres when ponded and are typically composed of olivine basalt with common columnar jointing define the Aiba Formation. Locally, sparse interbedded pyroclastic deposits of varying thickness are observed in this formation at Amba Aiba.

This formation is overlain by the Alajae Formation, characterized by ignimbrites with sparsely interbedded basalt flows and Termaber formations which are shield volcanism (Mohr and Zanettin, 1988). Hofmann et al. (1997) used 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.

According to (Kieffer et al. 2004), the Simien shield volcano's lower and upper stratigraphic divisions, as well as the flood basalts beneath them, are also used. The Cenozoic volcanic rock associations consist of Aiba, Alaji (Alaji Sirro and Alaji Molale) and Tarmaber (Tarmaber-Gussa and Tarmaber-Megezez) formations. Zanettin et al. (1974) and Justin-Visentin et al. (1974) dated (using K-Ar dating method) few rocks collected from Mendida (15.8 Ma), Debre Birhan-Tarmaber road (15.4 Ma), Kesam (Cassem) gorge (23.4-13.2 Ma), Mt. Megezez (13.0 Ma) and ignimbrite cover near Sheno (11.3-7.8 Ma) (GSE, 2009)

According to Dereje Ayalew et al., (2021) the north Shewa sequence of basalts and rhyolites is spread out across a wide region ($>2200 \text{ km}^2$) and reaches 1000 m in thickness and overlies on Cretaceous sandstone. On the north Shewa volcanic sequence upper and lower basalts and upper and lower ignimbrites were used to split the succession (Dereje Ayalew et al., 2021).

Dereje Ayalew et al., (2021) suggests north Shewa basalts and rhyolites indicate that crustal materials have become increasingly involved in the evolution of north Shewa magmas over time, most likely as a result of thinning of the crust due to heat caused by repeated injections of hot basaltic magmas into the lithosphere during rifting.

The plateau basalts from Sheno (Sheno-Megezez locality in Ethiopia) area display significant variation in Rb/Nb and Rb/Ba ratio and indicates that the magma is interact dominantly with the upper crust and having the compositional similar to Alaji acidic rock and the rock from the Megezez area range in composition from basalt to trachy-andesite. The compositional range is caused by Assimilation Fractional Crystallization (AFC) process (Gezahegn Yirgu, 1997).

1.8 Significance of the study

From this research work it is expected that, the complete lithostratigraphic section and petrographic descriptions of upper Kesem river section volcanic rocks will completed through the methods described in the method section. In short the following points will the expected out puts of this research works

- ✓ Detail sketch geological map and geological cross-section of the area which comprise the lithological units, geological structure and geomorphology of the area.
- ✓ Complete lithostratigraphic section of the upper Kesem river section.
- ✓ This study used to fill the existing gap in the detailed study of continental flood volcanics of the Ethiopian plateau in relation to the petrologic and petrographic investigation.
- ✓ The detailed geological map and the stratigraphic section of the upper Kesem river section will serve as a basic source of data for understanding the geological history of the study area, which is a portion of the plateau in northwest Ethiopia.
- ✓ Contribute a data set to the ongoing research on continental flood volcanics worldwide.

1.9 Organization of the thesis

The thesis is organized into six chapters. Chapter one is introduction with general background about Ethiopian Volcanics province and of the upper Kesem river section, the problem of the statement, the objective of the study, the methods used, a review of previous works related to this study area, and finally, the main significance of the study is incorporated.

Detailed regional geology from the world to the specific study area of this research is presented in Chapter two of the thesis report. This chapter includes general information about continental flood basalt and its province, followed by a review of regional studies about east African, specifically Ethiopian huge volcanic provinces including the flood basalt and rift related volcanic rocks. Details of field observation about the local geology of the research area are presented in chapter three.

This chapter includes a geologic map of the research area, field extent, and their field relationship of the different lithologic units in the upper Kesem river section with representative photographs of exposures and the stratigraphic section of the lithologic units at different localities. The last part of the chapter encompasses data about flow characteristics of these basaltic flow products and geologic formations (primary and secondary) seen in the research area.

In chapter four 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 five. The final part of the report includes conclusions and recommendations chapter six.

2. Regional Geological Setting

2.1 Continental flood volcanism

Continental flood basalt provinces (CFBP) can be defined as a series of volcanic outpourings erupted onto areas of continental crust and which are comprised predominantly of great thicknesses flows of basaltic lava (Jerram, and Widdowson, 2005). (CFBPs) are commonly associated with spatially constrained melting anomalies located within the upper mantle (e.g., Ernst and Buchan, 2003). According to Rooney et al., (2007) the continental flood basalt (CFB) province and associated continental break-up related to the outpouring of mantle plume.

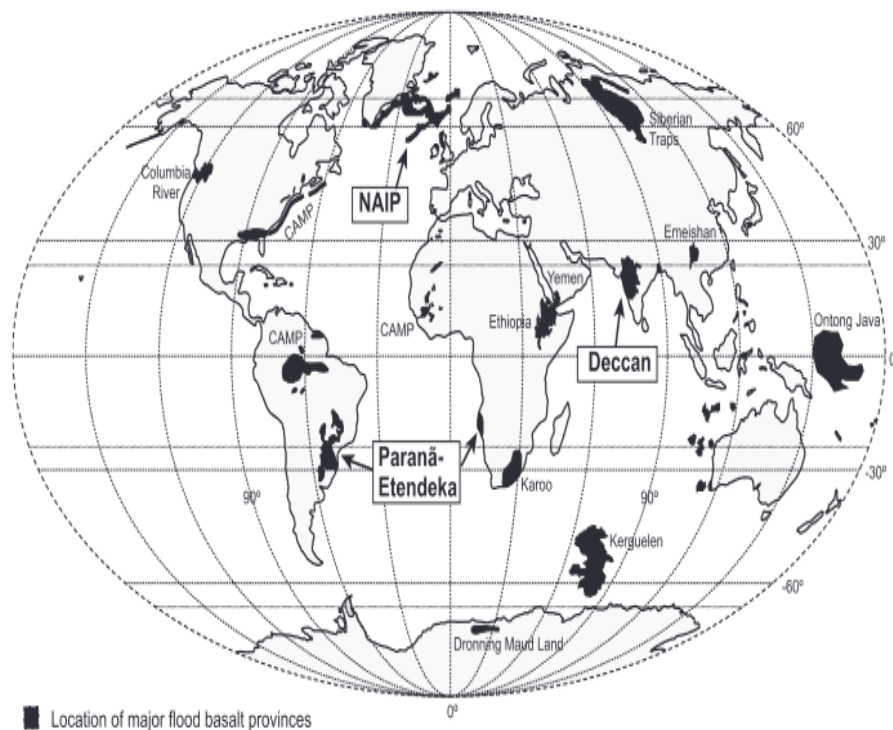


Figure 2.1 The Continental Flood Basalt Provinces (Jerram, and Widdowso., 2004)

CFBP are dominated by tholeiitic mafic lavas consisting of plagioclase, clinopyroxene (augite and often pigeonite) and iron titanium oxides, usually with olivine and (less frequently) orthopyroxene (Self et.al 2015). The dominant phenocryst having large crystals up to several cm in length in the flood basalt is plagioclase. According to Pike et.al, (1998), petrogenesis of continental basaltic flood volcanic provides more information about the relationships between mantle domains at the beginning of continental break-up.

The igneous province which is characterized by large in size contain abundant flood basalt piles; erupted over huge areas the flood basalt includes basaltic lava flows, tuffs, rhyolitic ignimbrite, trachytic and phonolitic products (Mohr and Zanettin, 1988). In addition to mafic volcanics (basalts), the flood volcanics contains significant volumes of rhyolitic extrusive rocks (which are consist of friable tuffs, rhyolites and ignimbrites) typically in the top parts of the sequence ((Mohr and Zanettin; 1988; Pik, et al., 1998, Dereje Ayalew and Gezahegn Yirgu, 2003).

According to the previous studies the continental flood consists of mafic (basaltic) and felsic (rhyolitic) extrusive rocks. Hence the andesitic lavas are lacking and the volcanism is of a distinctly bimodal basalt rhyolite type (Dereje Ayalew.,2011) similar with (Karoo and Parana) continental flood basalt provinces. The mineralogical composition of most flood basalt are aphyric to slightly phyric and contain different phenocrysts such as plagioclase, pyroxene (clinopyroxene) and olivine (with or without). They have tholeiitic to transitional chemical composition (Mohr, 1983; Pik et al., 1998; Kieffer et al., 2004; Beccaluva et al., 2009).

2.2 East African continental flood volcanism

The continental flood basalts volcanic (CFB) which are large in size in East African rift (EAR) system is erupted associated with regional uplift Fig 2.2 (Ethiopian and Kenyan domes) Peccerillo et al., (2003) revealed that magmatic evolution in Ethiopia has commenced as three main stages. The first stages which form Ethiopian plateau, recorded about 50-10 Ma, characterized by eruptions of tholeiitic to transitional flood basalt lava flows intercalated with slightly alkaline trachytic and rhyolitic-ignimbrites (Mohr and Zanettin, 1988). A second stages of volcanic activity originated around 10-5 Ma and were developed several shield forming volcanic centers originated from transitional to sodium rich alkaline basaltic rocks and minor trachytes (Peccerillo et al., 1979). The last stages are ranging from Pliocene to present, characterized by the expansion of the Main Ethiopian Rift (MER) and Afar depression.

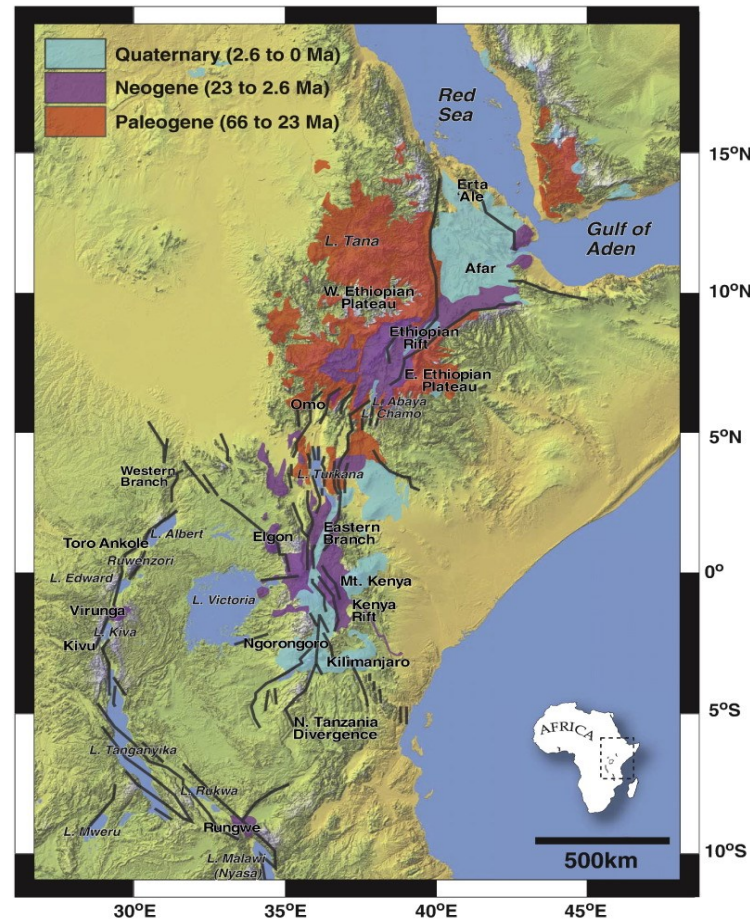


Figure 2.2 East African rift system tectonic setting in the Horn of Africa (after Kieffer et al., 2004)

2.3 Ethiopian continental flood volcanism

The continental flood basalt in Ethiopian (which was erupted during Cenozoic era) province is located at the junction of two oceanic rifts (Gulf of Aden and Red Sea), and one continental rift (East African continental rift). This province expressed as largest intercontinental magmatic provinces developed during Cenozoic era due to the eruption of large amount of flood basalts and inter-bedded ignimbrite (Gezahegn Yirgu, 1997). The Ethiopian flood basalts (or traps) cover an area of about $720,000 \text{ km}^2$ with an estimated volume of $720,000 \text{ km}^3$ (Rooney 2017 cited in Dereje Ayalew, 2021), forming a layer of mafic and felsic volcanic rocks.

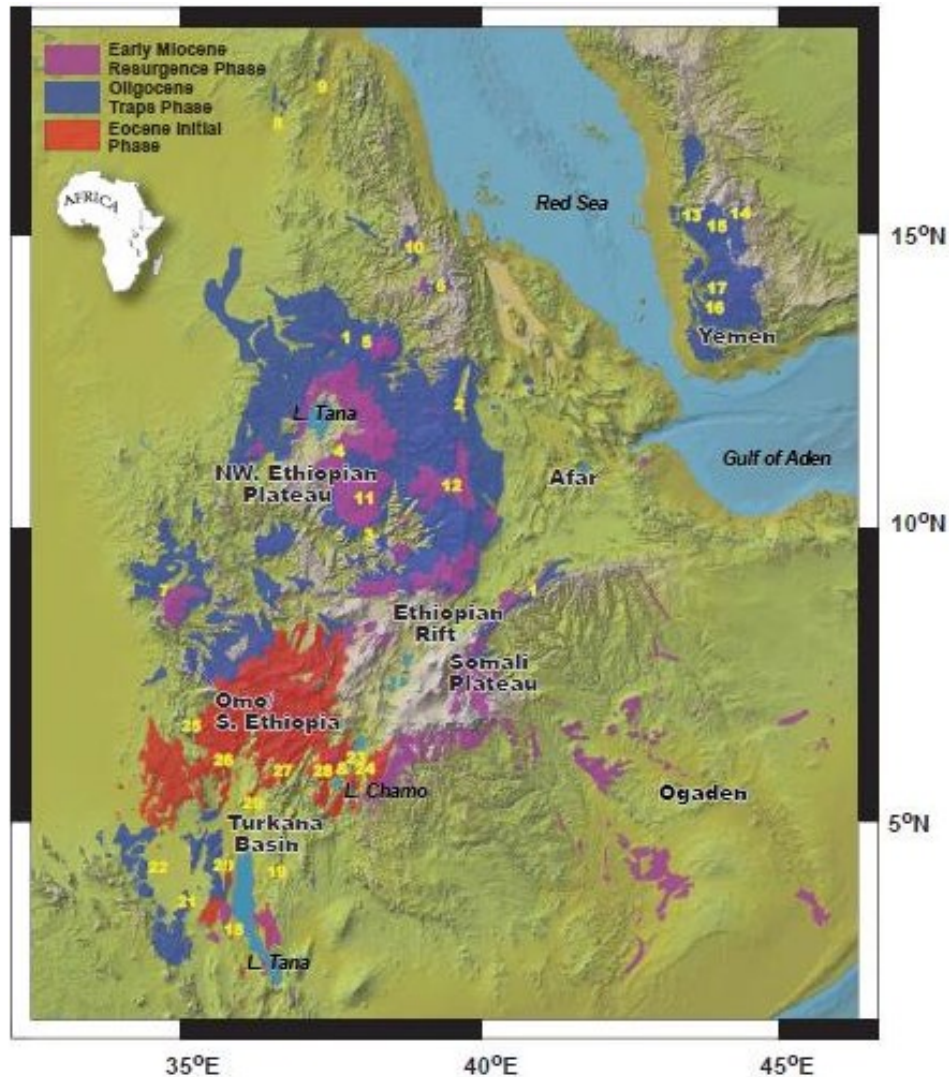


Figure 2.3 Map of topographic relief displaying the regional extent of Ethiopian and Yemeni platform flood basalts (blue) (after Rooney, 2017).

According to Kieffer et al. (2004) the Ethiopian flood volcanics unit covered by mafic (basaltic) and felsic (rhyolitic) volcanic rocks with variable thickness up to 2 km. According to Zanettin et al. (1978, 1980) the volcanic stratigraphy of Ethiopia have been grouped into three major class, those are; Pre-oligocene, Oligo-Miocene and Mio-Pliocene. Based on eruption the above-mentioned groups divided in to four categories those are; Pre-Oligocene (Ashengi), Oligocen (Aiba formation and Alaji Termaber Guassa), Miocene (Alaji Molale and Termaber Megezez) and Miocene-Pliocene (Bishoftu Formation) stages (Zanettin et al. 1980).

The other scholars Abbate and Sagri, (1980), based on volcanic activity, frequency of volcanic centers, their lithological development and age of effusion the extrusive (volcanic) rocks in Ethiopia are categorized in to five major provinces. These are

volcanics of the, Northern plateau, Southern plateau, Somalian plateau, Afar volcanites, and Main Ethiopian Rift (MER) volcanics.

The great East African rift at the north end (Afar and MER) split the Ethiopian flood basalt plateau volcanics into two main parts as north western and south eastern plateau during 11 Ma. The plateau lying in the west side of the rift system is known as the North Western Ethiopian plateau (northern, central and south western plateau), while the other to the east is named the South Eastern Ethiopian plateau (southern, eastern and south eastern (Wolfenden et al., 2004 and Corti, 2009).

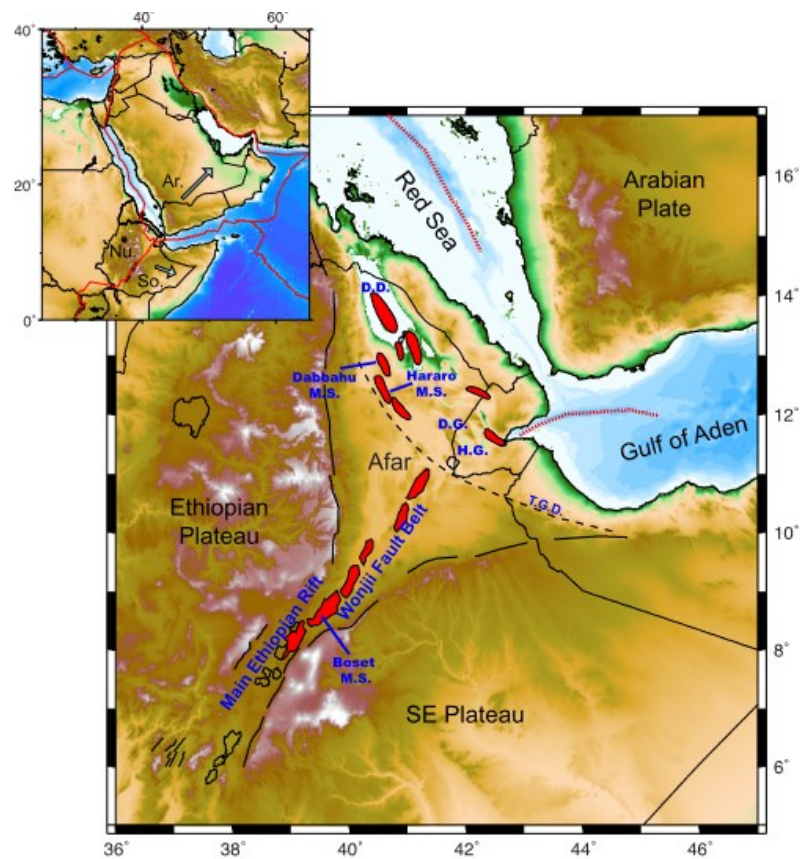


Figure 2.4 Map shows the MER and Afar, splitting of northwestern and southeast Ethiopian plateau, Corti, (2009).

2.4 Volcanics of northwestern Ethiopian plateau

As it described above among the two plateau the upper Kesem river section located on the Ethiopian plateau which found in the northwestern part of the country. From the previous research done by Kieffer et al. (2004) the flood volcanic in this plateau section is classified as: The Trap Series also known as Oligocene flood volcanics which includes (rhyolites and Oligocene-Miocene basalt), Miocene-Pliocene shield volcanoes, Volcanic

plugs and domes and Quaternary volcanics. The northwestern Ethiopian plateau made up of numerous different eruption centers with diverse magmatic character and with a large range of ages (Kieffer et al., 2004).

The flood volcanism was followed by emplacement of huge shield volcanic eruption and by continental rifting (Hoffmann et al., 1997 and Kieffer et al., 2004). According to Kieffer et al. (2004) shield volcanics formed after the flood volcanism have different mineralogical and geochemical characteristics and magma flux of lavas having the variation from 30-10 Ma.

According to Zanettin et al (1980) as cited in Krans et al (2018) the Ethiopian flood basalts were initially divided into four divisions, from oldest to youngest, by stratigraphic studies centered on the northeastern region of the Ethiopian plateau, those are: Ashange basalt, Aiba fissure basalt, Alajae basalts and rhyolites, and Termaber basalts.

2.5 Volcanic stages in Northwestern Ethiopian plateau

Numerous studies have looked at the volcanic succession in central Ethiopia (Zanettin et al., 1974, 1978; Justin Visentin et al., 1974; Mengesha Teffera et al., 1996). The Tertiary volcanics of the Ethiopian plateau were split into two main cycles by Zanettin et al. (1974): First, Ashangi basalts; second, Aiba basalts +Alaji rhyolites+ Termaber basalts.

The two volcanics were distinguished by unconformities and differential tectonics. Zanettin et al. (1978) have also classified the volcanic succession of central Ethiopia in to three main stages. 1) The pre-Oligocene stage (Ashangi Formation), 2) The Oligo-Miocene stage and 3) Mio-Pleistocene stage. Each stage can be divided into one or more volcanic 'Formations'. Other authors, though, such as Dereje Ayalew et al. (2002) added certain volcanic stages, such as the Wegel Tena Oligocene rhyolitic-ignimbrite.

2.5.1 Pre-Oligocene stage

Ashangi Formation

Ashangi formation named after Ashange in northern Ethiopia. This formation represents earliest fissure-fed flood basalt volcanism on northwestern Ethiopian plateau (Mengesha Tefera et al., 1996). The Ashangi Formation consists of basalts of transitional tholeiitic and/ or alkaline basalts and consists of rift of pre-Oligocene age in the Amba Alaji area.

According to Mengesha Tefera et al. (1996), this trap lava flow is primarily characterized by heavy weathering, crashing, and tilting. The Ashangi Formation is made up primarily of slightly alkaline basalts with interbedded pyroclastic and infrequently rhyolitic lava flow. Doleritic sills and dykes frequently inject this lava flow. More tuffaceous and interbedded lacustrine deposits with lignite coal seams are seen in the upper portion of the unit. According to Zanettin and Jusetin Visentin (1975) and Merla et al. (1973), both of which were mentioned by Mengesha Tefera et al. (1996), it was thought that these early flood basalt flows were only present in the volcanic regions of northwest Ethiopia.

Ashangi formation (having several hundreds of m to Km thick and with a number of flows (5-6 number of flows)) in the northwestern plateau (Zanettin et al., 1980) and it is found unconformably under the major Oligocene (Aiba) basalt, (Zanettin et al., 1980). Zanettin et al. (1980) state that K/Ar dating of the Ashangi formation (tilted and crushed basaltic flows) demonstrates that it is older than the subordinate Aiba basalts. This K/Ar dating, however, could not be sufficient to establish the region's volcanic succession without additional field and geochemical data (Mengesha Tefera et al., 1996).

2.5.2 Oligocene stage

The Oligo-Miocene stage is divided into two sub stages: the Oligocene and Miocene. The Oligocene sub stage consists of Aiba, Alaji-Sirro and Termaber Guassa Formations (Zanettin et al., 1978; B. Zanettin and E. Justin Visentin, 1974).

Aiba transitional basalt

According to Mengesha Tefera and colleagues (1996), the Aiba transitional basalt is the second significant pulse of the fissural basalt flow in the northern Ethiopian plateau. According to Zanettin et al. (1974a; 1975 as referenced in Zanettin et al., 1978; Zanettin et al., 1980), it has a composition that is halfway between tholeiitic and moderately alkaline. Aiba basalt has aphyric and compacted nature, fresh, at places showing stratification with interflow acidic layers/mainly tuff (Mengesha Tefera et al., 1996).

This continental basalt flow has an average thickness of between 200 and 600 meters and is unconformably overlain on the Ashangi Formation. The Aiba basalts are said to be composed of huge transitional flood-basalt flows with well-developed vertical to sub-vertical columnar joints, but locally intercalating with some agglomerate beds, according to Hofmann et al. (1997) and Ukstins et al. (2002). Late Oligo-Early Miocene dating

ranges from 34 to 28 Ma (Zanettin et al., 1980). This unit is equivalent to Arsi and Bale Basalt in SE Mekonnen Basalt in SW Wollega Basalt in Western Ethiopia.

2.5.3 Oligocene-Miocene stage

Alaji Formation

On the plateau in northwest Ethiopia, the Alaje formation is located above of the Aiba basalts and comprises basalts that are transitional to tholeiitic in character. Aged between 32 and 15 Ma, the Alaje formation is predominantly made up of aphyric flood basalts related to rhyolites (ignimbrites) and subordinate trachytes (Mohr and Zanettin, 1988; Mengesha Tefera et al., 1996).

Alaje basalts are very similar to Aiba basalts in terms of chemical composition and mineralogy, but are overall a little less silica-saturated (Mohr, 1983). Conformably overlay Ashange and Aiba, in the absence directly overlay the Mesozoic.

2.5.4 Miocene stage

The Miocene sub stage includes Alaji Molale and Termaber Meghezez Formations.

Termaber Megezez Formation

Named after Tarmaber, Represents the Shield forming Volcanoes in Plateau Group. The fissural volcanism was followed by a central volcanism with alkaline affinities, quite comparable to that of Termaber Guassa. The Tarmaber shield forming (are Early and Middle Miocene) volcanoes has the age range from 23 to 11 Ma (Kieffer et al., 2004), on the northwest and southeast plateaus basaltic shield volcanism from the Oligocene to Miocene is represented by the Tarmaber Formation, which dates from 30 to 13 million years ago (Mohr and Zanettin, 1988).

This formation characterized by basaltic rocks with alkaline chemistry. Age range 26-16 Ma in the north and 16-13 Ma in the south. Sela Dingay-Debre Berhan-Gorgo ignimbrites which is equivalent to Alaje formations are covered by Tarmaber-Megezez basalts (Dejene Hailemariam et al., 2017). On the flexural boundary of the Adama basin, flood basalts are overlain by trachytic flows (formed at the base of Megezez) frequently contain feldspar phenocrysts that resemble lathes and that originated from the Megezez volcano and it was dated at 10.4 $\pm$ 0.2 Ma and 10.5 $\pm$ 0.2 Ma, respectively, using whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar (Wolfenden et al., 2004).

2.5.5 Quaternary volcanics (after 2 Ma)

According to Mengesha Tefera et al., (1996) they studied in the NW portion of Ethiopian plateau which is the Quaternary basalts exposed near Lake Tana graben and Injibara area. These volcanic units having a Quaternary alkaline chemical affinity of basaltic lava flows with some trachytes and they are grouped in a Pleistocene age. Hofmann et al. (1997) noted that the host lavas are basanitic in composition and its age around 0.39 ± 0.03 Ma.

Table 1 Cenozoic volcanic successions of central Ethiopia

According to Zanettin et al. (1974)	Mengesha Tefera et al. (1996)	Age
Quaternary rhyolite and basalts of the MER	Undifferentiated alluvium, lacustrine and beach sediments	Quaternary
	Rhyolitic volcanic centers, obsidian pitchstone, pumice, ignimbrite, tuff, subordinate trachytic lava	
	Basalt flows, spatter cones and hyaloclastics	
	Dino formation; ignimbrite, tuff, coarse pumice, waterlain pyroclastics with intercalations of lacustrine sediments	
	Nazret series; ignimbrites, unwelded tuffs, ash flows, rhyolitic flows, domes and trachyte	Tertiary
	Afar series; basalts with subordinate rhyolitic domes and flows and ignimbrite	
Balchi rhyolite	Bishoftu formation; basalts and trachyte	
Tarnaber basalts and intermediate volcanics	Tarnaber-Megezez formation; basalts	
Alaji rhyolite and basalts	Alaji formations; basalts with minor rhyolite and trachyte eruptives	
Aiba basalts	Aiba basalts; flood basalts with rare basic tuffs	
	Ashangi formations; basalt flows with tuffs	

3. Geology of the Upper Kesem River area

The present study area, which is found in the north western Ethiopian plateau ,consist the lito-stratigraphic section of upper Kesem river and with an overall thickness of 1080m from (1700 to 2780 masl elevation) shown in (Fig3.1). The study emphasis to construct a complete litho-stratigraphic section of Koremash section and along Shola Gebeya section. In this chapter it is try to describe the general geology of the study area based on field observation, mapping and sample description.

3.1 Descriptions of lithologic units

The geology of the area encompasses Lower basalt, Lower rhyolitic ignimbrite and tefacious sediment, Upper basalt, Upper ignimbrite & rhyolite and Quaternary river deposit (Qrd) as shown in (Fig3.1). In addition to the lithological variation of the study area is characterized by different tectonic events which are revealed by the existence joints and faults having the general orientation of NNE to SSW and E to. The detail description of each lithological unit presented as follows from bottom to top stratigraphic successions.

The Litho-stratigraphic units of the study area are;

1. Lower Basalt Unit
2. Lower Rhyolitic Ignimbrite Unit
3. Upper Basalt Unit
4. Upper Rhyolitic Ignimbrite Unit
5. Shield-forming Basalt Unit, In the following sections, field observations in the different areas, from where representative samples were collected will be summarized from bottom to top for each litho-stratigraphic unit.

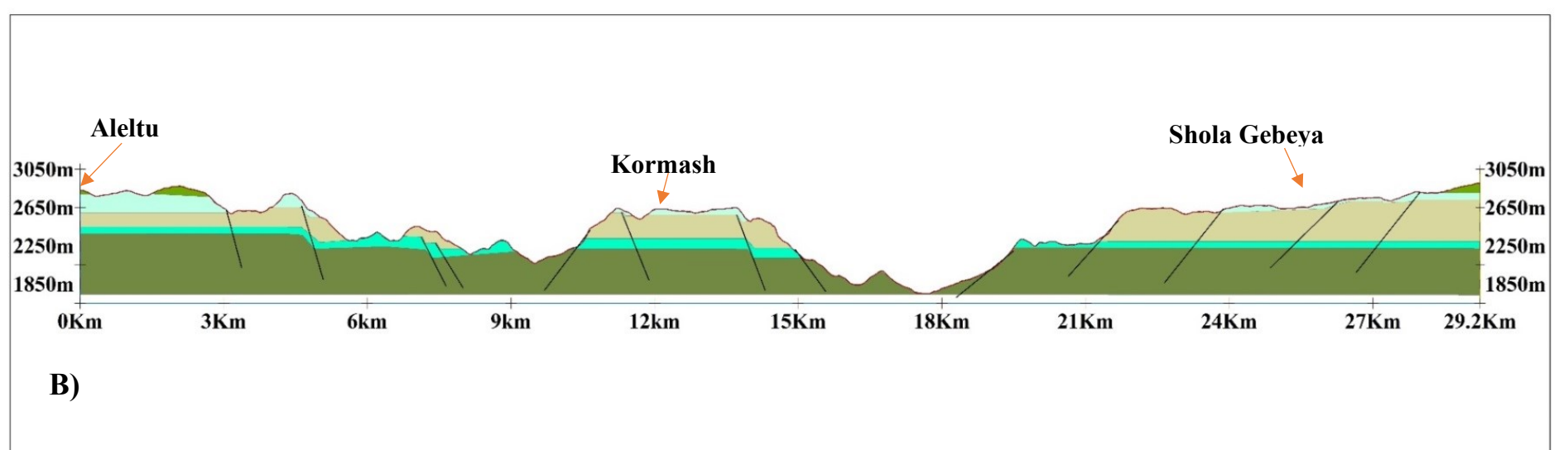
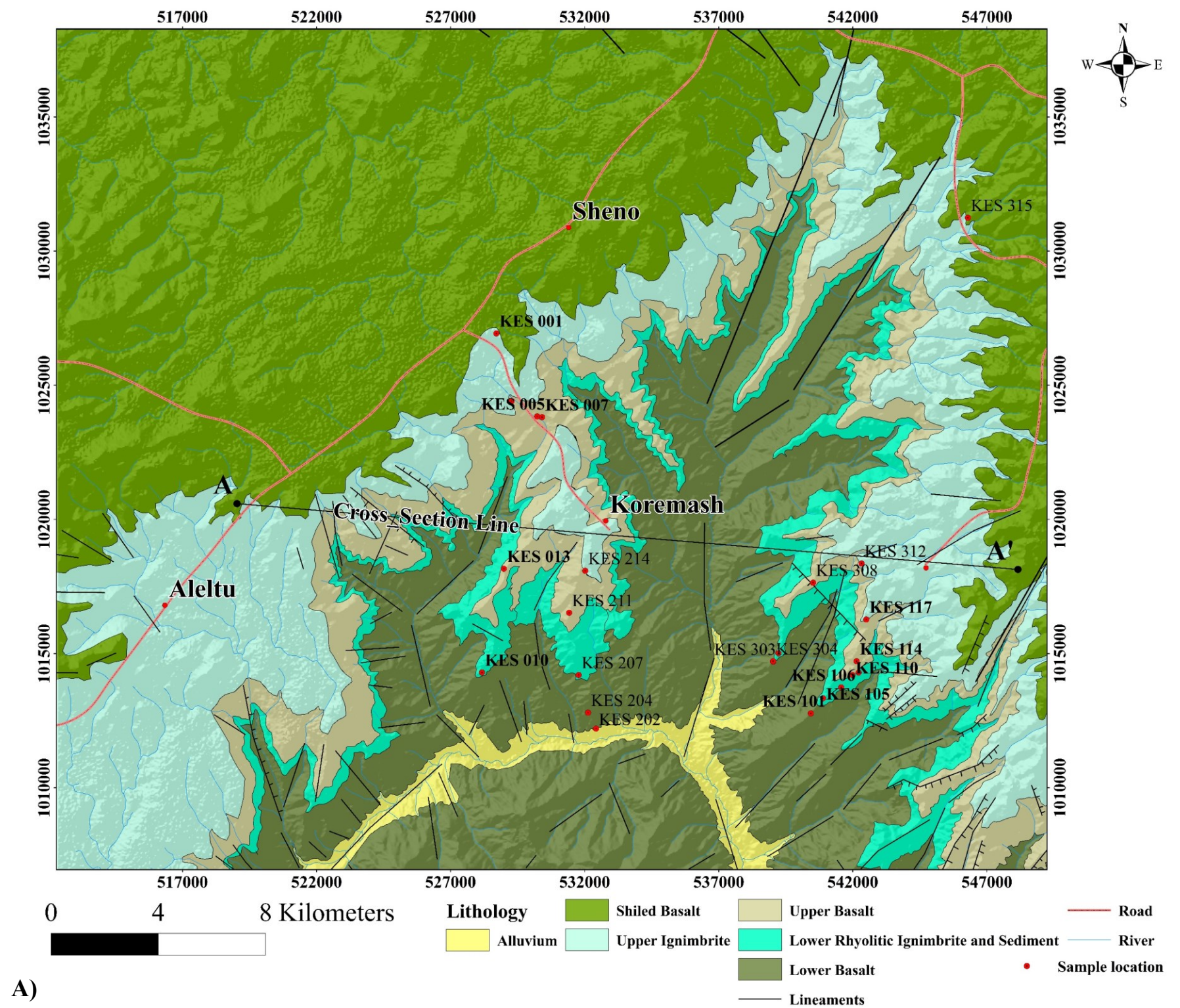


Figure 3.1 A) Geological sketch map of upper Kesem River area at the scale of 1:50,000; (B) Geological cross section of the study area A to A' with vertical exaggeration (2X)

3.1.1 Lower Basalt Unit

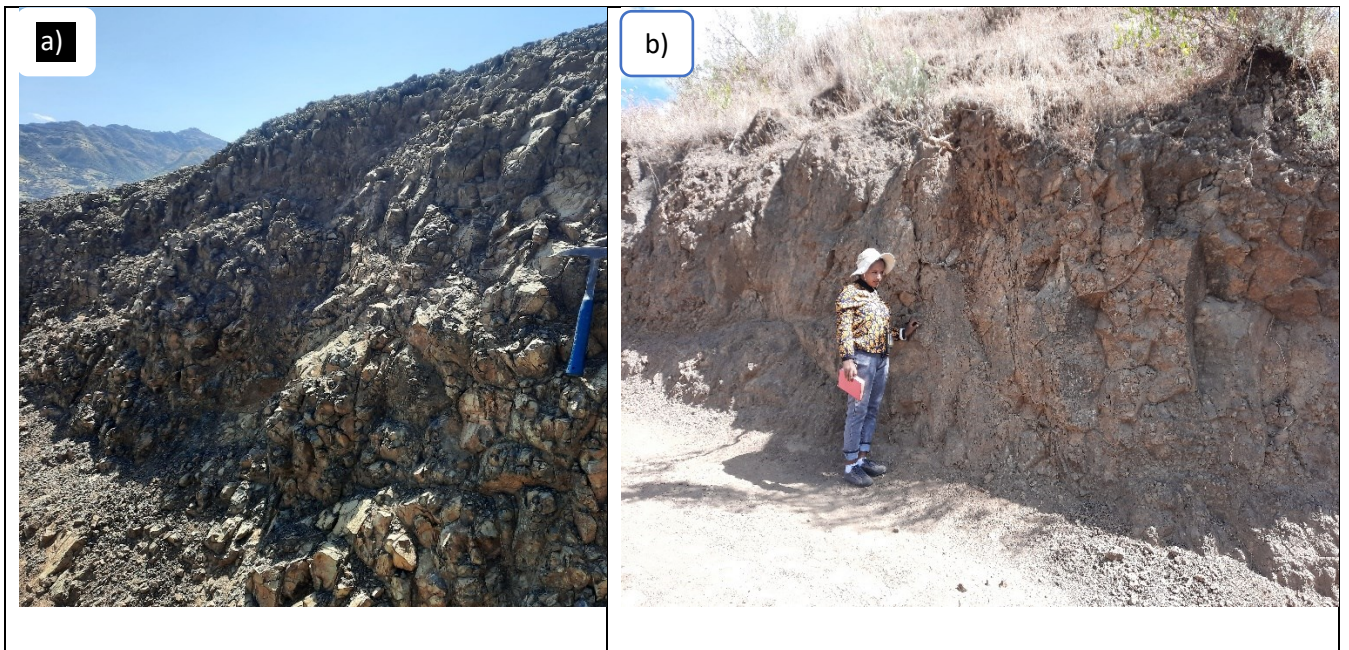
This unit consists of aphanitic basalt intercalated with plagioclase phyric basalts. Most of the basalt flows consist of poorly to moderately porphyritic basalt and some vesicular basalt. It is strongly fractured, irregularly jointed, spheroidally weathered, and shows sheet like structure. In this basaltic rock it is difficult to determine the number of flows since it is intensively weathered and highly fractured.

This unit shows relatively gentle topography. The power contact of this basaltic sequence is not exposed making it difficult to determine the overall unit thickness. The observed thickness of this unit within the study area is between 300-450m. The photographs taken from this unit are presented as follows. Fig 3.2 (a and b) shows the general geomorphology of the exposures, (Fig 3.3) Outcrops of the lower basalt unit show (a) highly fractured, (b) high degree of weathering (c) spheroidal weathering (d) columnar jointed and in some part paleosols are found separating lava flows.





Figure 3.2 (a) The photograph shows the rugged topography of lower basalt unit (b) Panoramic view of Lower basalt from Shola Gebeya section.



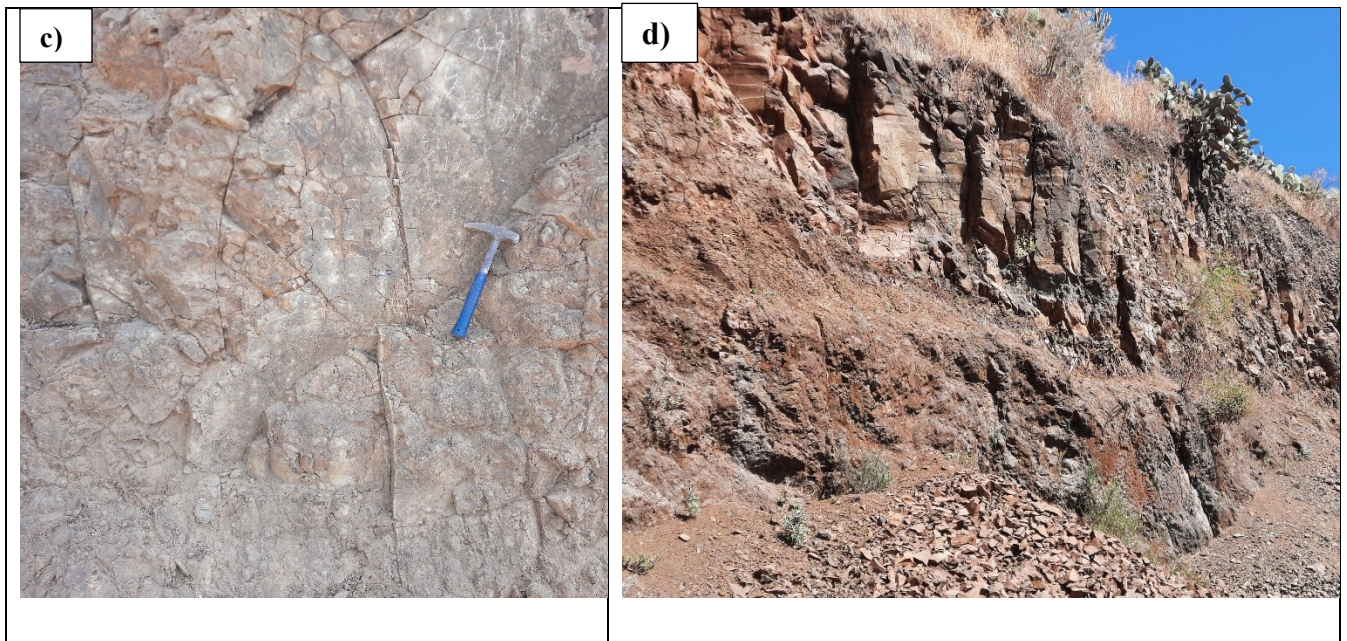


Figure 3.3 a) Highly fractured basalt flows of the Lower Basalt Unit exposed along Koremash section near Germamea River, b) Highly weathered Lower basalt flows from Shola Gebeya section Kidusge area c) Lower basalt, shows spheroidal weathering Shola Gebeya section in Kidusge area, d) Lower basalt, shows columnar joint and paleo soil between different lava flow Shola Gebeya section in Zala Zenbaba area.

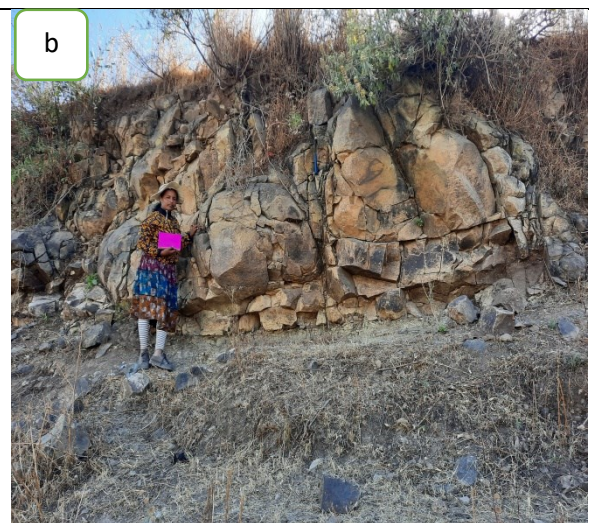
3.1.2 Lower Rhyolitic Ignimbrite Unit

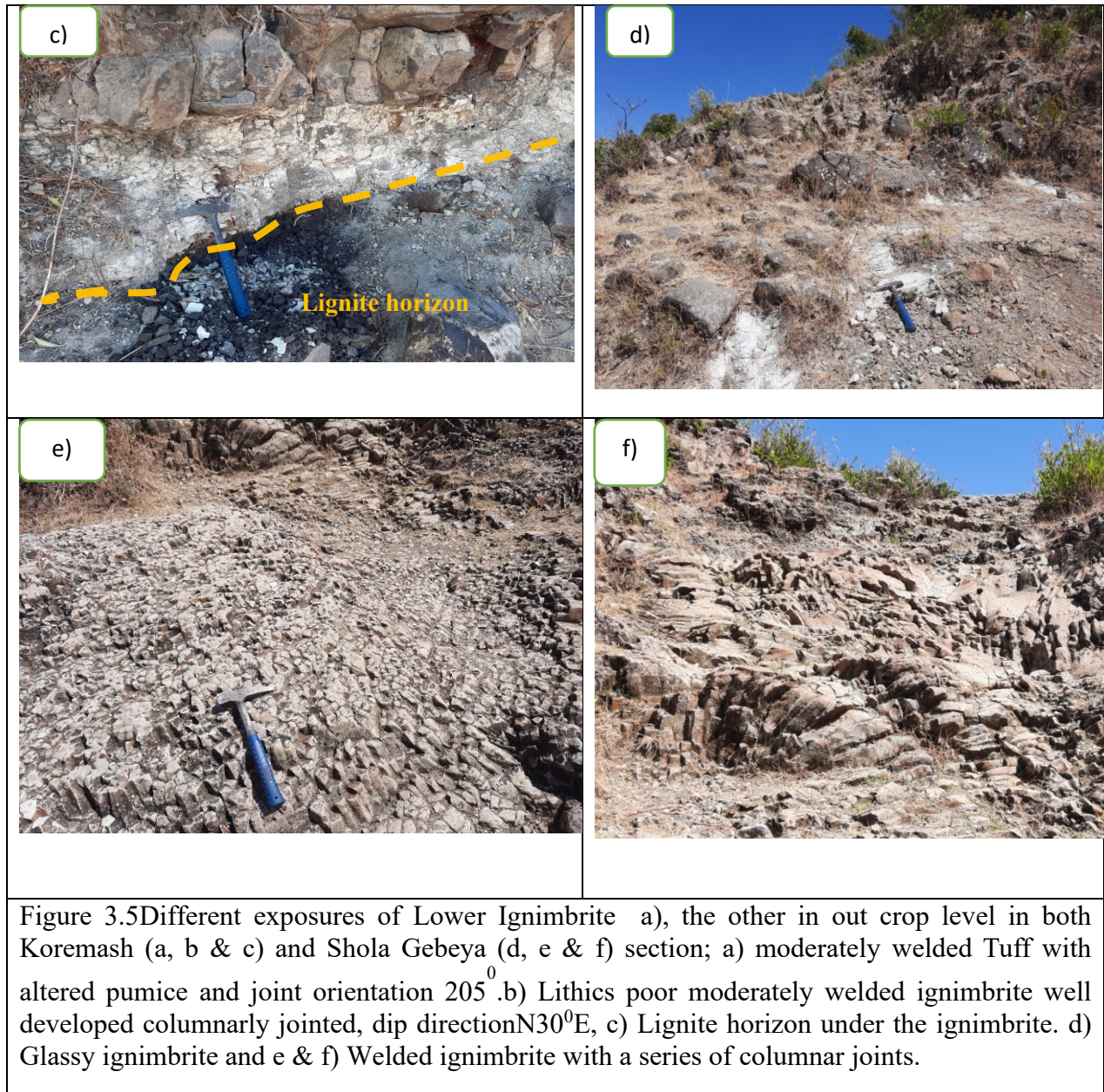
This pyroclastic unit is well exposed in Koremash and Shola Gebeya sections; it is very limited in its overall thickness compared to the Lower Basalt unit. This pyroclastic unit consists of several pyroclastic deposits and is broadly characterized by greenish gray to light gray color. The unit is massive, slightly fractured, dominantly lithics-poor, contains poor to moderate amounts of crystals, shows well developed columnar joints and forms cliffs. The overall thickness of this unit varies in different sections and ranges from 50 m (along Shola Gebeya section, Kidus Gee area, and Zala Zenbaba area) to 150 m (along Koremash section, Sosit Amba and Weyn Amba area) (Fig 3.4).

The Ignimbrite unit has various degree of welding in different localities. Around Weyn Amba area the ignimbrite unit is less welded and highly weathered (Fig.3.5 b), and in the same location lower part of the ignimbrite is highly welded and contains moderate amounts of crystals. The Ignimbrite unit from Shola Gebeya section around Zala Zenbaba area shows highly glassy texture with some minerals (Fig 3.5d) and the middle part of the ignimbrite units from the same area shows highly columnarly jointed structure (Fig3.5 e and f).



Figure 3.4 Photograph taken from Sosit Amba area, which shows the topographic expression of the ignimbrite unit.





3.1.2.1 Intra-volcanic Tuffaceous Sediments

This layer consists of tuffaceous sediments and is found in the eastern part of the study area intercalated between Lower basalt and Lower Ignimbrite units in Shola Gebeya section. This clastic sedimentary layer is characterized by light gray to pinkish gray color, coarse to very coarse grained with basaltic rock fragments. In exposures from Shola Gebeya to Kidus Gae and from Shola Gebeya to Zala-Zenbaba, approximate thickness is around 15 m. Its lateral extent is not easily traceable at the surface because of poor exposure. The tuffaceous sediments in these localities are characterized by light grey color (Fig 3.6 c and d) and coarse

clasts and crystals with visible minerals and rock fragments. The layer shows graded bedding and gentle tilting (Fig 3.6 a and b).

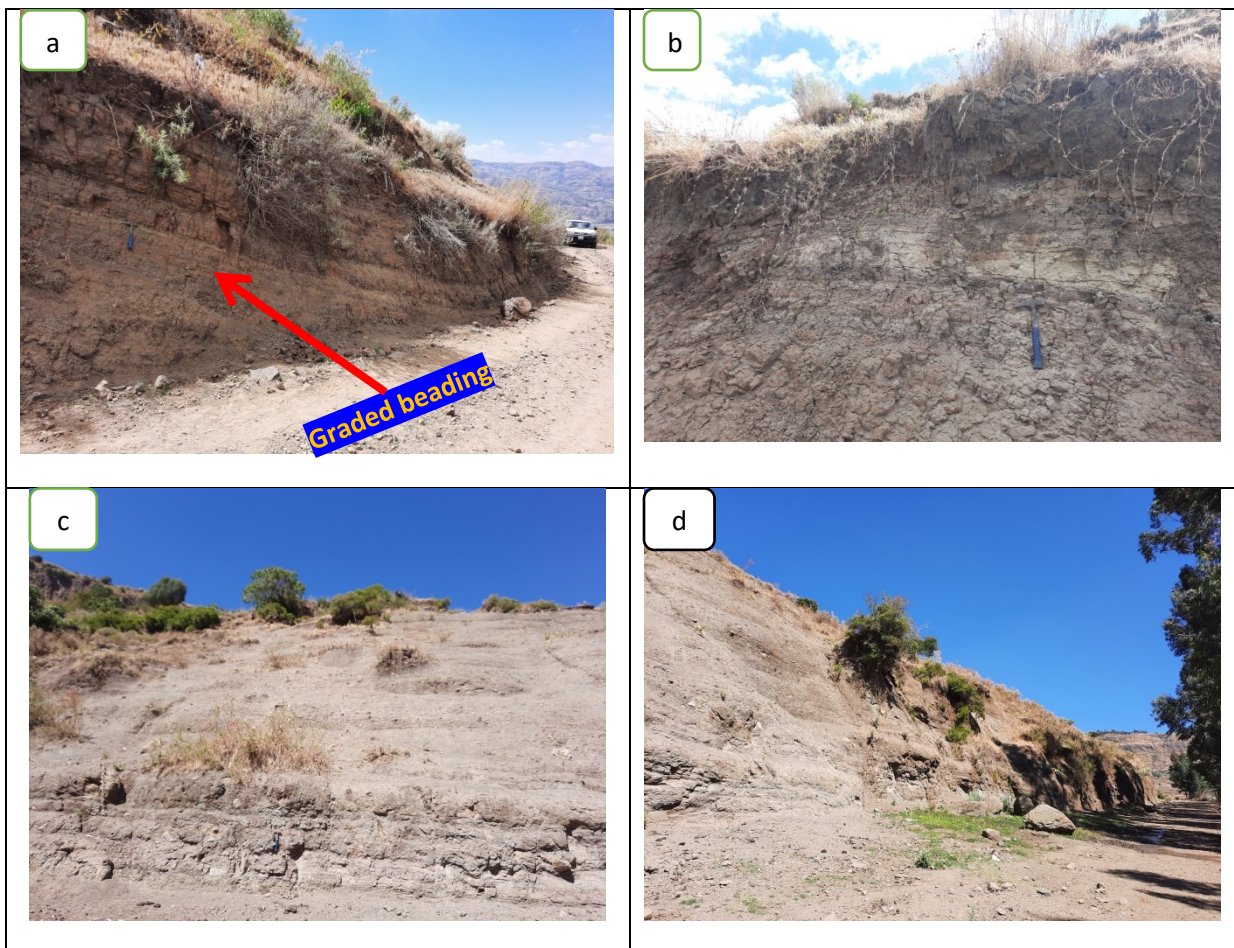




Figure 3.6 Exposures of tuffaceous sediments at different localities; a, b and e) graded bedded tuffacios sediments around Kidus Ge area with dip direction 115 SE; c and d) around Zala Zenbaba area.

3.1.3 Upper Basalt Unit

This basaltic unit is well exposed both at Koremash and Shola Gebeya sections and unconformably overlies the Lower Ignimbrite unit. The unconformity surface is expressed by sedimentary layers and paleosol horizons. This unit consists of a thick pile of horizontal basaltic lavas, subordinate pyroclastic layers and lava domes (in Shola Gebeya section). The overall estimated thickness of this unit at the different sections ranges between 300 and 400 m. The thickness of individual basaltic lava flows ranges between 20 and 55 m and there are at least 7 to 10 continuous flows in some cliff sections.

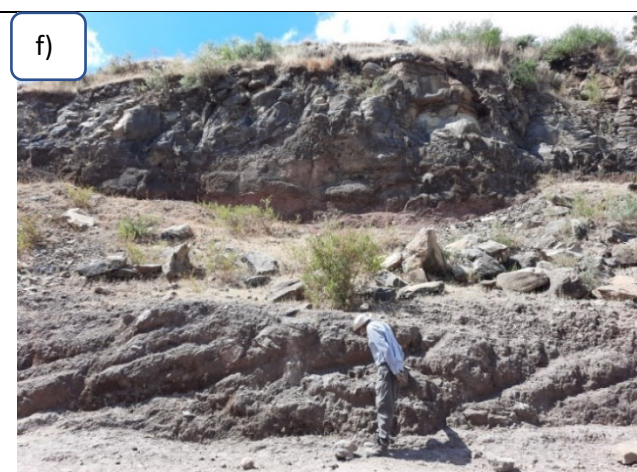
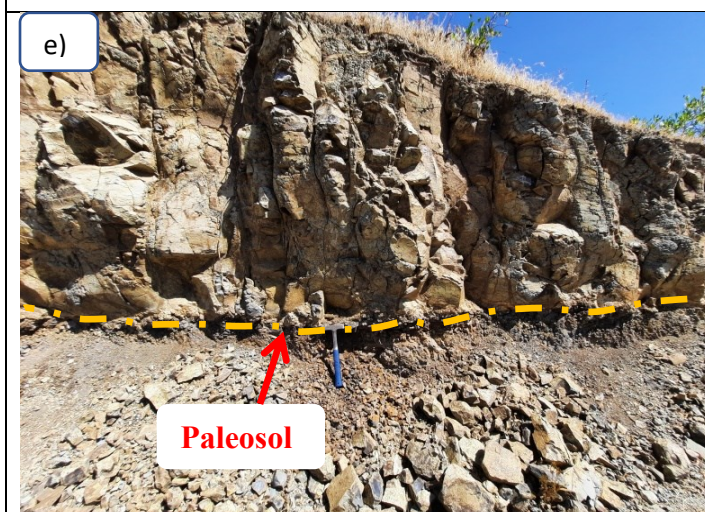
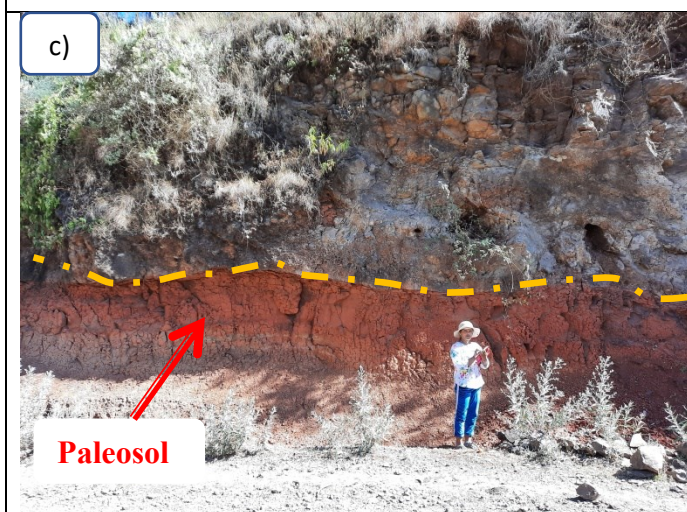
The basalt lavas are dominantly characterized by porphyritic textures. Phenocryst assemblages include plagioclase plagioclase + olivine, plagioclase + pyroxene, plagioclase + pyroxene + olivine Aphanitic, scoraceous and vesicular basalts are also present in smaller abundance. (Fig 3.8 f). In the vesicular basalt, some vesicles are filled by secondary minerals like calcite. Some of the flows are columnar jointed (Fig 3.8 b,e,h) while others are massive and fractured.

The unit as a whole forms steep cliff as shown in the panoramic view (Fig 3.7).

This basalt flows weather spheroidally to dull gray, reddish brown (weathered color), light gray and dark gray colors. The different basaltic flows and the subordinate felsic volcanics are commonly separated by paleosols. .



Figure 3.7 Panoramic view of the Upper Basalt unit (Shola Gebeya section)



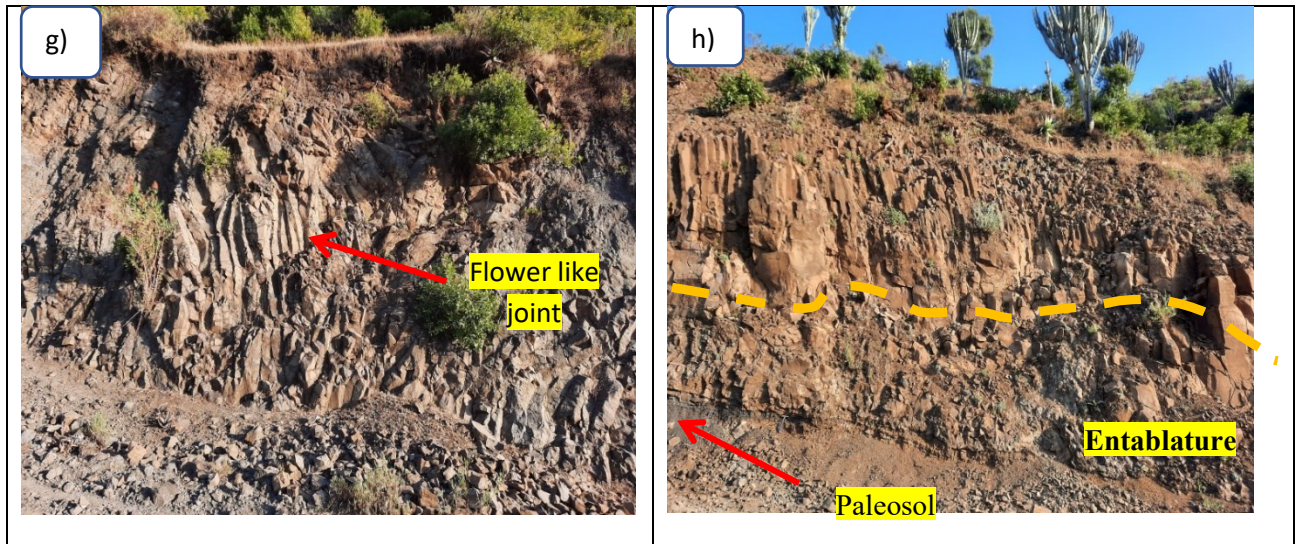


Figure 3.8 Exposures of basalt flows belonging to the Upper Basalt unit. a and b: Koremash section; c,d,e,f,g and h: Shola Gebeya section. a) columnar jointed and fractured flow, b) irregular jointed columnar basalt, c) Highly weathered aphyric basalt d and e) Columnar jointed aphyric basalt, f) scoracious lava flow above the lower ignimbrite f, g) flower like columnar jointing in basalt; and h) strait columnar joint at the middle and entablature at the bottom

3.1.3.1 Basaltic Lava flow and dome

This exposure of what looks like a lava dome is found in the eastern part of the study area Shola Gebeya section around Kidus-Gee. This volcanic feature is medium grey in color, poorly porphyritic, finely crystalline and moderately weathered lava and exhibits flow banding and vertical sheeting as shown in Fig 3.9 a and b. Approximate observed thickness is around 7m.

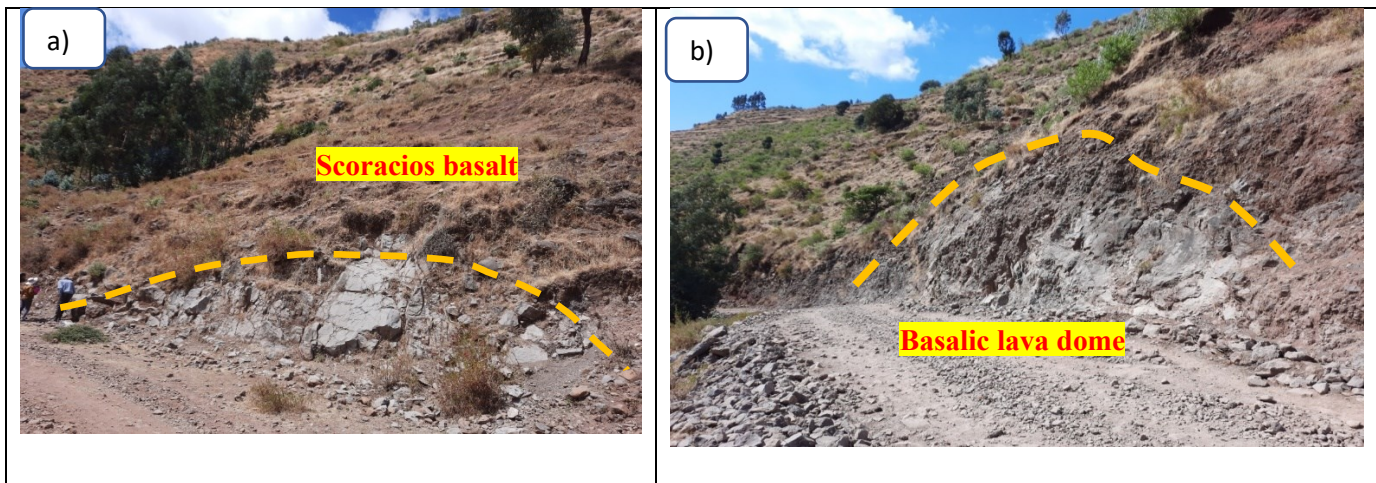
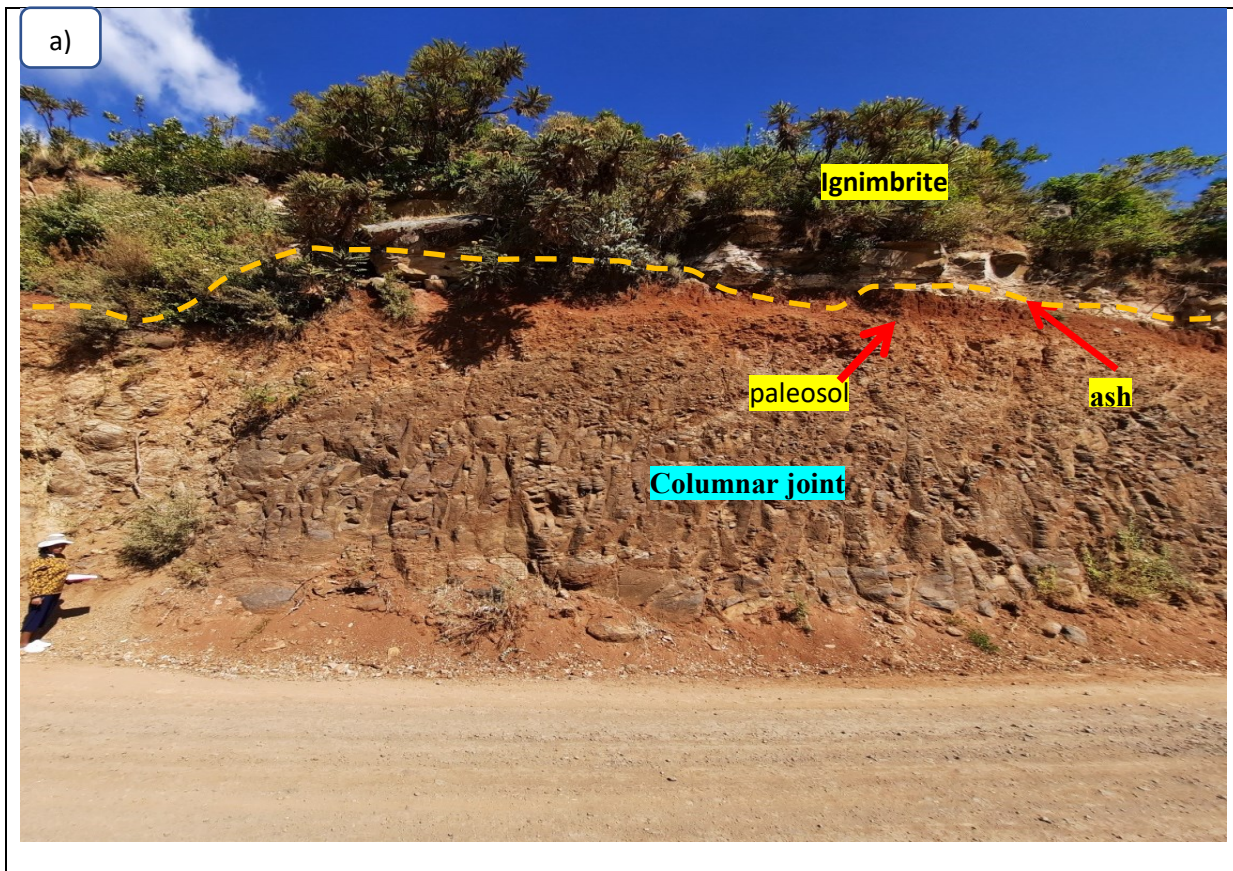


Figure 3.9 a and b) Basaltic lava flow/dome overlain by scoracious basalt lava.

3.1.4 Upper Rhyolitic Ignimbrite Unit

This felsic deposit dominating the topmost flood basalt succession of the study area is referred to as Upper ignimbrite Unit. This unit is exposed in the upper parts of Koremash and Shola Gebeya sections overlying the Upper basalt unit. It is constituted of dominantly massive pyroclastic deposits and has an approximate thickness of up to 80 m (from 2780 to 2700 m amsl). The pyroclastic deposits in both Koremash and Shola Gebeya sections are light to medium gray in color, moderately weathered and fractured. The deposits are, are horizontally layered and slightly columnar jointed. The deposits are massive, fine-grained, lithic poor and contain moderate amounts of alkali feldspar crystals. Visible crystals are light-color (Fig3.10).





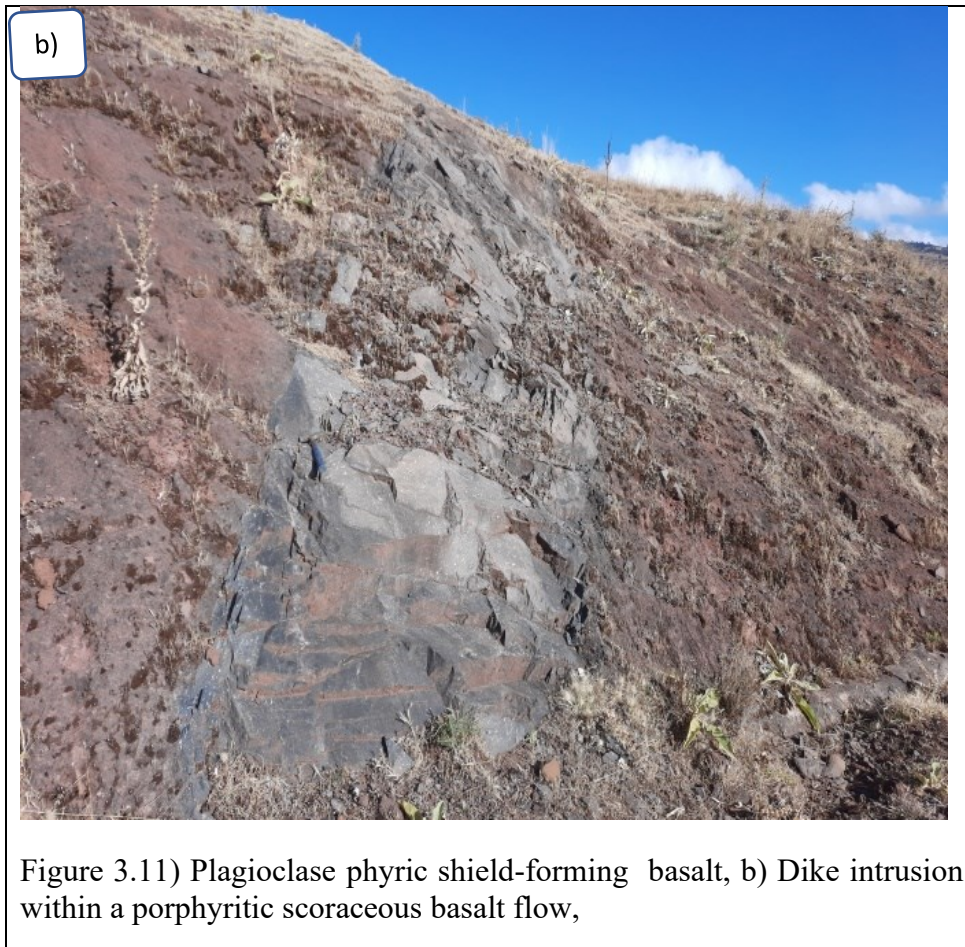
3.1.5 Shield-forming Basalt Unit

Megezez mountain is one of the Mid-Miocene shield volcanoes on the north-western Ethiopian (part of Tarmaber formation). Extensive outcrops of basalt lavas are encountered on the road between Sheno area and Shola Gebeya this dominantly basaltic unit overlies the Upper ignimbrite deposit with a contact at an altitude of ~2830 m. The series of basaltic flows continues up to the summit of Megezez at an altitude of 3509 m with an estimated

overall thickness of 521 m. The basaltic flows here are thinner and less continuous than the underlying basalts of the Lower and Upper basaltic units.

They also are more porphyritic, containing abundant and often large phenocrysts of plagioclase and olivine (Birhanie Girum, 2022). The fresh color of the basalt lavas is commonly dark gray and the weathered color is light gray. They exhibit porphyritic, vesicular (Fig3.11a) and aphanitic textures. The typical characteristic observed on this basaltic unit is the presence of large size phenocrysts of plagioclase at the top part and aphanitic at the bottom. There are some dike intrusions that cut the basaltic flows (Fig 3.11b).





3.2 Morphology of Lava Flow Products

The following terms are crucial when discussing the morphology of lava flows. Lava flows are the result of a single outpouring of lava that can be made of one or more flow lobes that are often separated by weathering surface and/or clastic lithologies. A flow lobe is used to define an individual set of lavas surrounded by a cooled lava crust. If the lava flow consist one flow lobe or more than one we call it simple lava flow and compound flow respectively, A flow field is the aggregate product of a single eruption, which comprises one or more lava flows (Self et al., 1997; Walker, 1971)

The basaltic lava flow types in this study area have distinct unit flow structures that resemble sheets or tabular structures. A thin layer of sediment (paliosol), a weathering surface, and pyroclastic deposits (ash tuff) separate the various flow units. Top flows in exposed flow field vesicular surfaces are observed. Middle flows are characterized by massive, vesicle

poor columnar jointed flow lobes. (Well-developed columnar jointing Colonnade jointing from Reidel et al., 2013) The columnar joints are mainly blocky columnar joints that are vertically orientated. (Entablature type from Reidel et al., 2013) In some flow lobes, the middle section exhibits patterns ranging from numerous, irregularly joined tiny columns to arbitrarily arranged cooling joints. The bottom flows are observed to be a thin planar surface. The morphology of the bottom flow observed in different flow fields is highly dependent on the underlying unit.



Flow lobe in a flow field

Figure 3.12 a) Panoramic view of thin layers of different lava flow, b flow lobe in a flow field, c) show Upper flow Columnar joint and entablature the bottom flow.

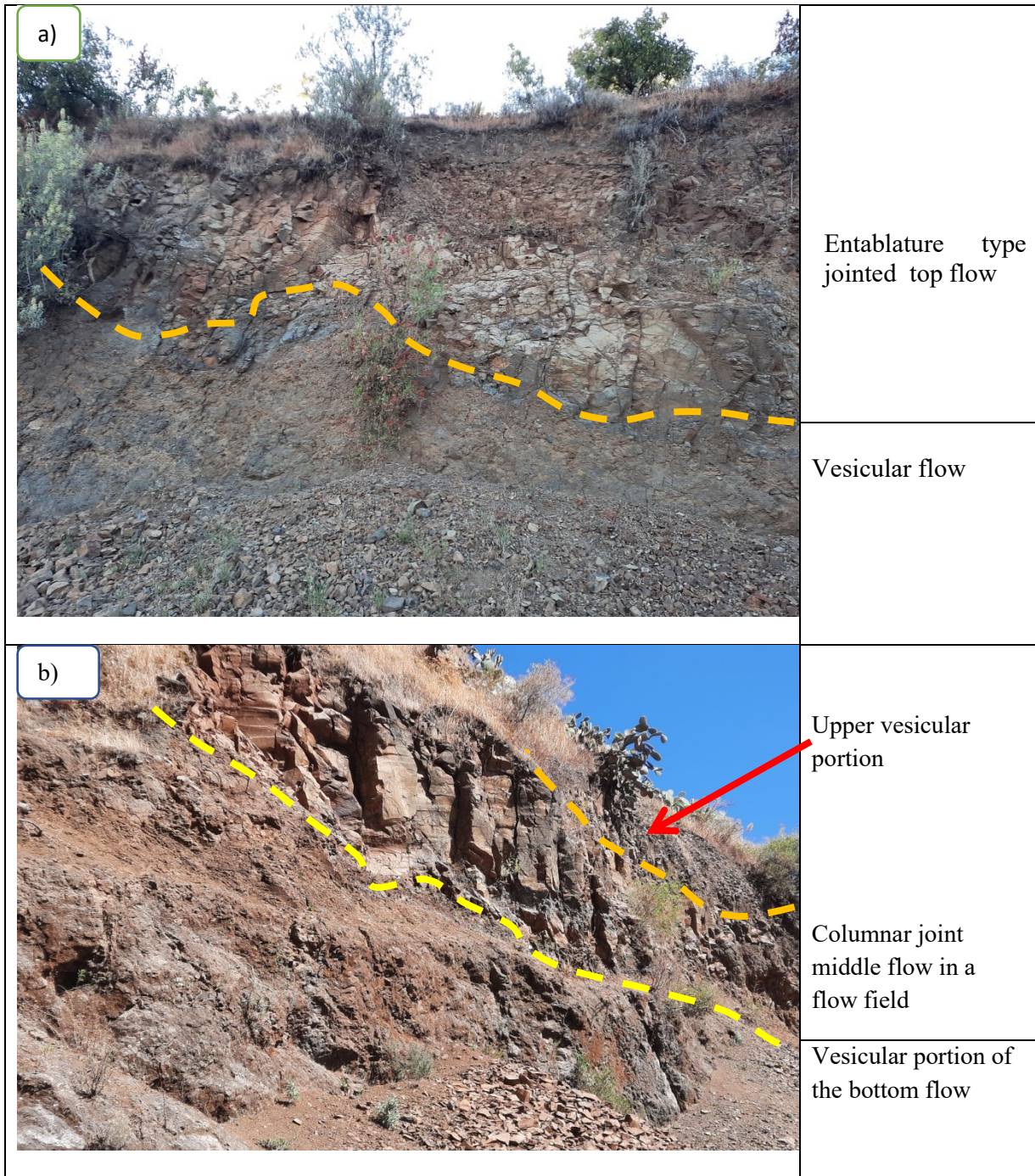


Figure3.13 Photographs of different basaltic exposures demonstrating the typical features of lava flow morphologies of flood basalts in the study area; a) at Koremash section b) locate at Shola Gebeya section.

3.3 Geologic Structures

In the study area different geological structures are observed. These geological structures are divided into primary and secondary structures. The primary geological structures are formed during the outpouring of lava flows to reach on the earth surface. In contrast, geological structures which are formed after the deposition of the rocks as a result of the tectonic activities to which the rock is subjected are called secondary structures. The most observed structures in the study area are primary structures which include lava flows, different types of columnar joints (Colonnade which is more regular and a coarser pattern often found at the base of the flow and Entablature is more irregular, and often found near the top of flows Reidel et al., 2013). The most top part of the geologic succession in the area forms three-dimensional topography.

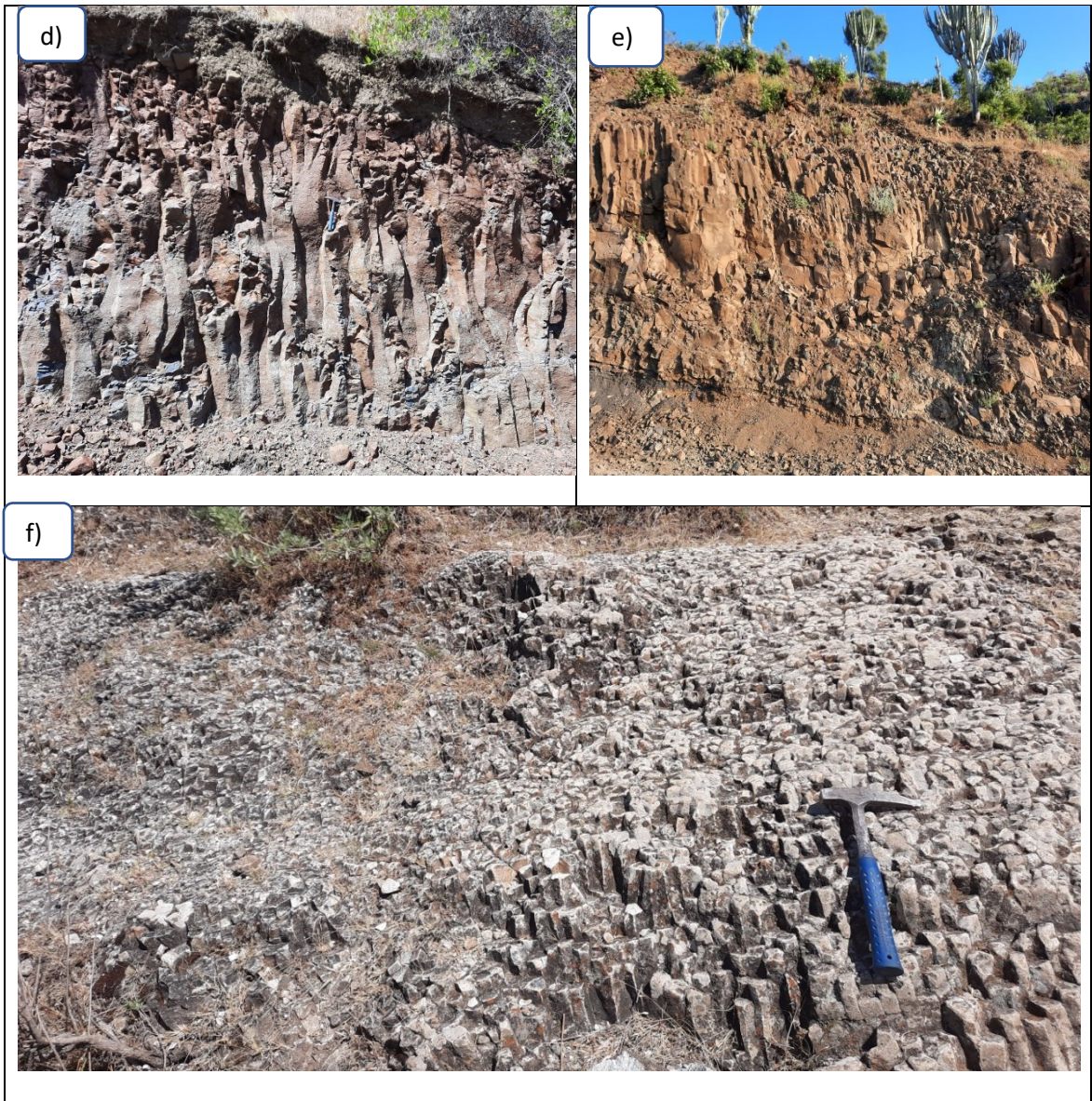


b)



c)





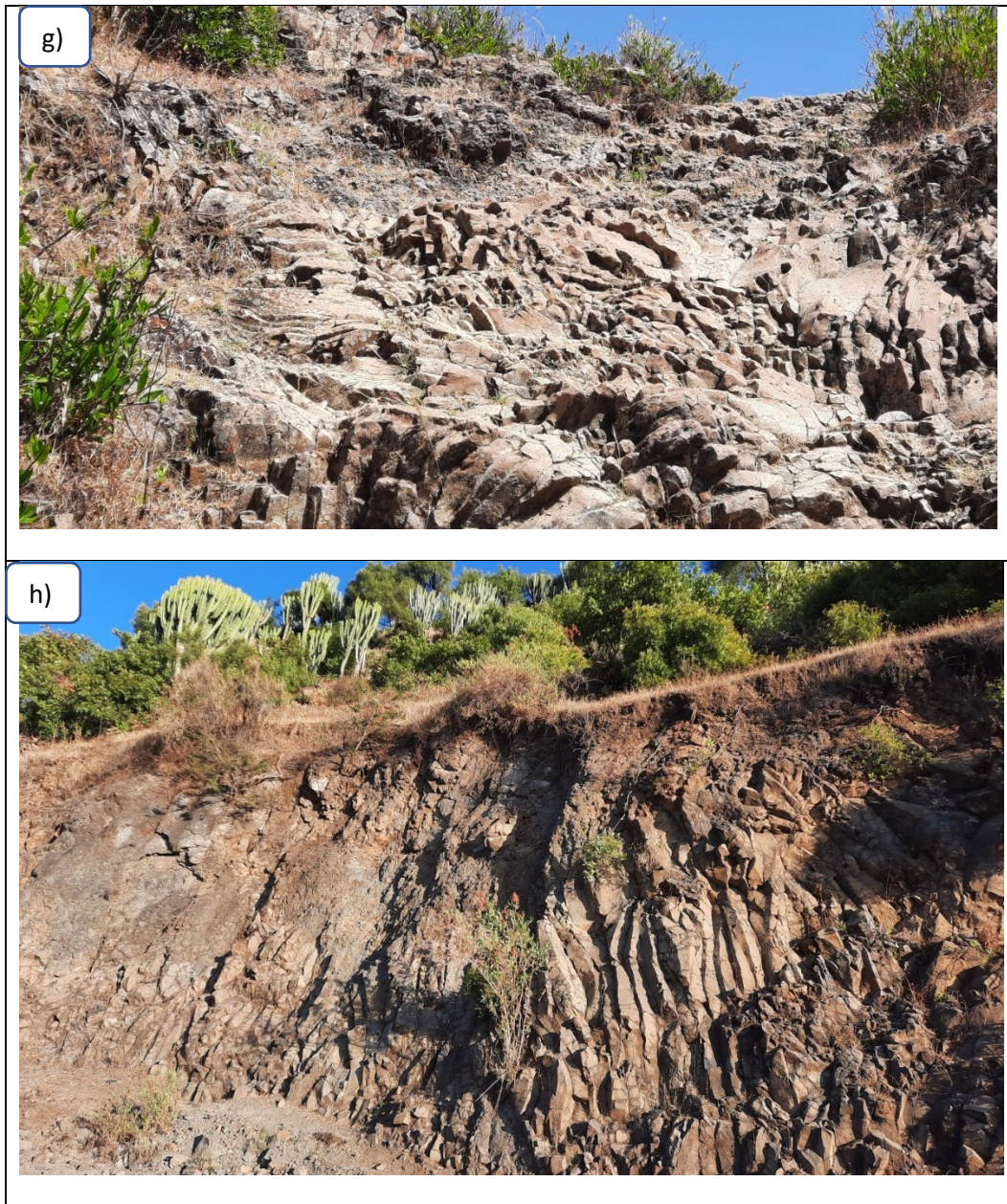


Figure 3.14 Panoramic view of morphological topographies formed by the different lava flow products (a, b and c); a) Panoramic view of different lava flow with normal fault, b) panorama of a basaltic plateau formed by upper basalt, c) pyramidal topography formed by upper basalt. Different types of columnar jointing in Koremash and Shola Gebeya section; d, e and h) columnar joints formed by upper basalt, entablature at e and flower structure joint at h. Thinly columnar ignimbrite(f) and sub-vertical joint of ignimbrite at Zala Zenbaba area (g).

4. Petrography

4.1 Introduction

In this chapter the detail description of representative samples that are taken from different lithological unit identified in chapter three are examined under polarizing microscope. Twenty five(25) samples were prepared for petrographic description, from those 4 samples from Lower basalt, 11 samples from upper basalt, 4 samples from lower Ignimbrite, 3 samples from upper Ignimbrite, 2 samples are from volcanic bombs and 1 sample from shield.

These 25 volcanic rock samples are described in detail based on mineralogical and textural features, such as crystallinity, granularity and degree of alteration. The different nomenclatures; like Plg_phyric, Plg_Cpx_Ol_phyric, intergranlar and Aphyric_sub-ophitic, these descriptions of these textural and modal terms are given in Krans et al., (2018) in regional study.

4.2 Lower Basalt

Four samples are selected from lower basalt, this unit show variety of grain size texture, poorly phyric (KES 202, KES 204) and Phyric (KES 101, KES 302). The poorly phyric basalt contains plagioclase, clinopyroxene(Augite) and opaque oxides. The ground mass are microcrystalline lath of plagioclase, opaque-oxide. In KES 202 there is the abundance of glass whereas the other is not.

KES 101 and KES 302 are phyric intergranular the abundance of phenocrysts in sample is 15% with Clinopyroxne 31.2% and plagioclase 37% in sample KES 101 and Clinopyroxene 6.6% and plagioclase 42.5% in KES 302. The groundmass in these samples shows pilotaxitic texture formed by intergranular randomly oriented large laths of plagioclase and clinopyroxene crystals are surrounded by groundmass off microcrystalline plagioclase, ferromagnesian minerals and opaque.

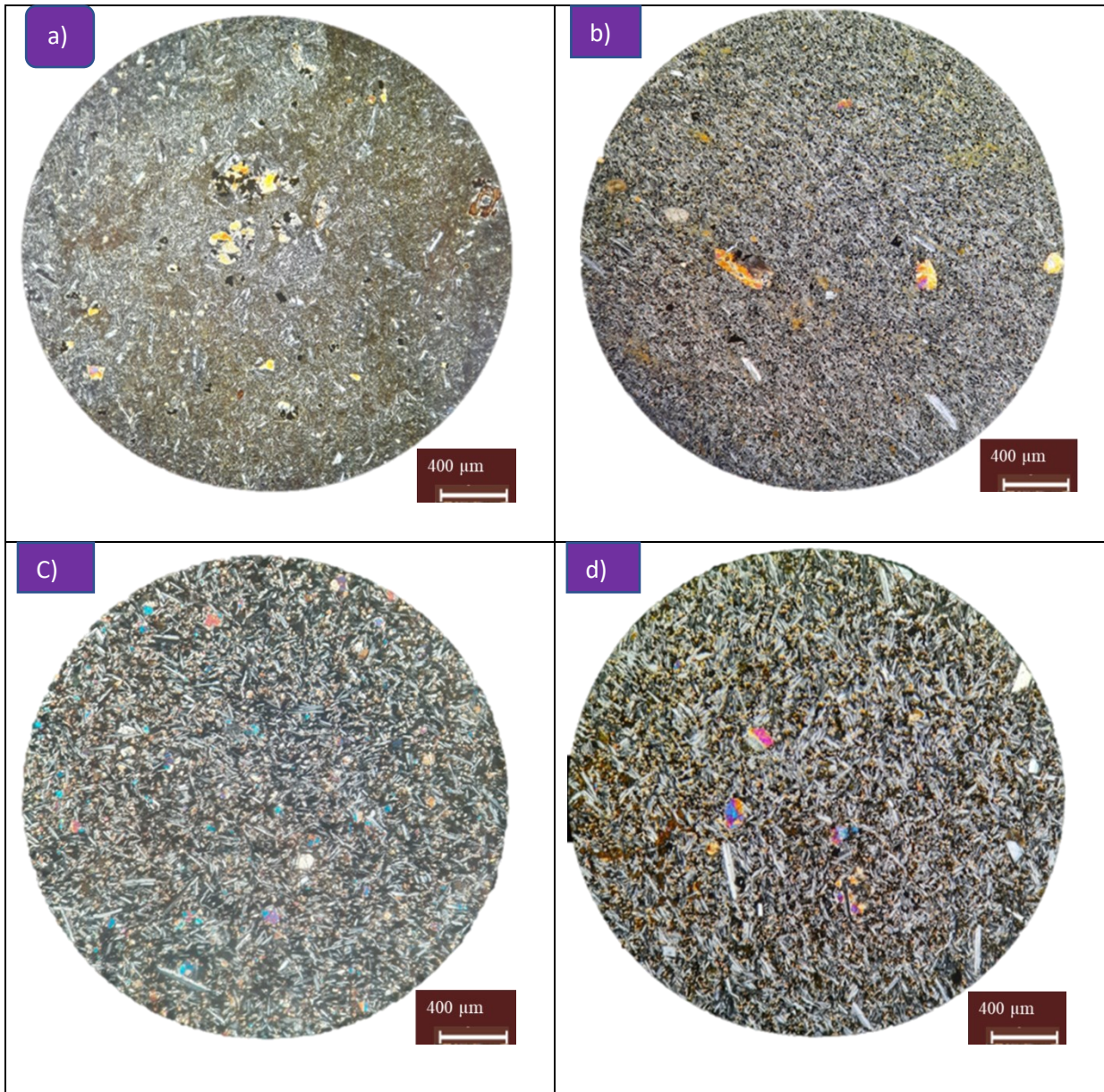


Figure 4.1 Representative thin section photomicrographs of basaltic sample from Lower basalt unit, (a) KES 202 and (b) KES 204: aphric to microporphyritic with groundmass dominated by laths of plagioclase, (c) KES 101 and (d) KES 302 microcrystalline-intergranular texture formed by plagioclase and clinopyroxene microphenocrysts. (All photomicrographs are taken with 4X magnification in cross-polarized light).

4.3 Volcanic bombs

KES 105 and KES 106 are taken from volcanic bombs, KES 105 shows sub ophitic texture with plagioclase laths only partially enclosed by clinopyroxene, (Fig.4.2a). KES 106 shows plagioclase laths (67%), clinopyroxene (22%) and opaque oxides (10.5%). The plagioclases are coarser and have subhedral to euhedral crystal forms and show intergranular texture (Fig.4.2b). The groundmass shows holocrystalline texture.

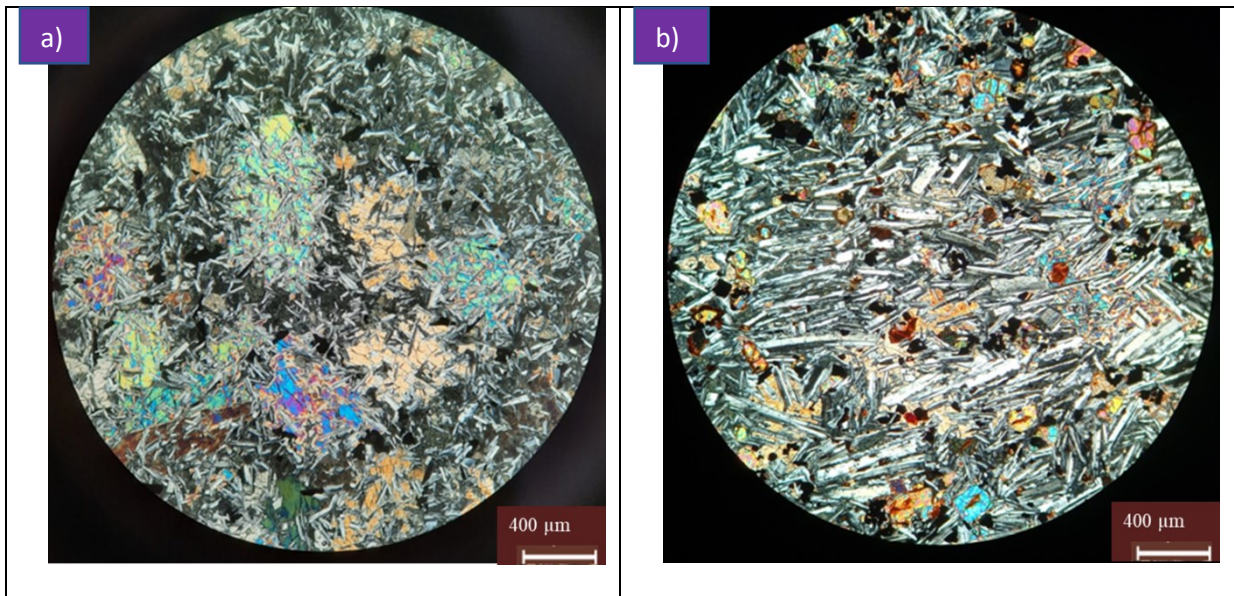
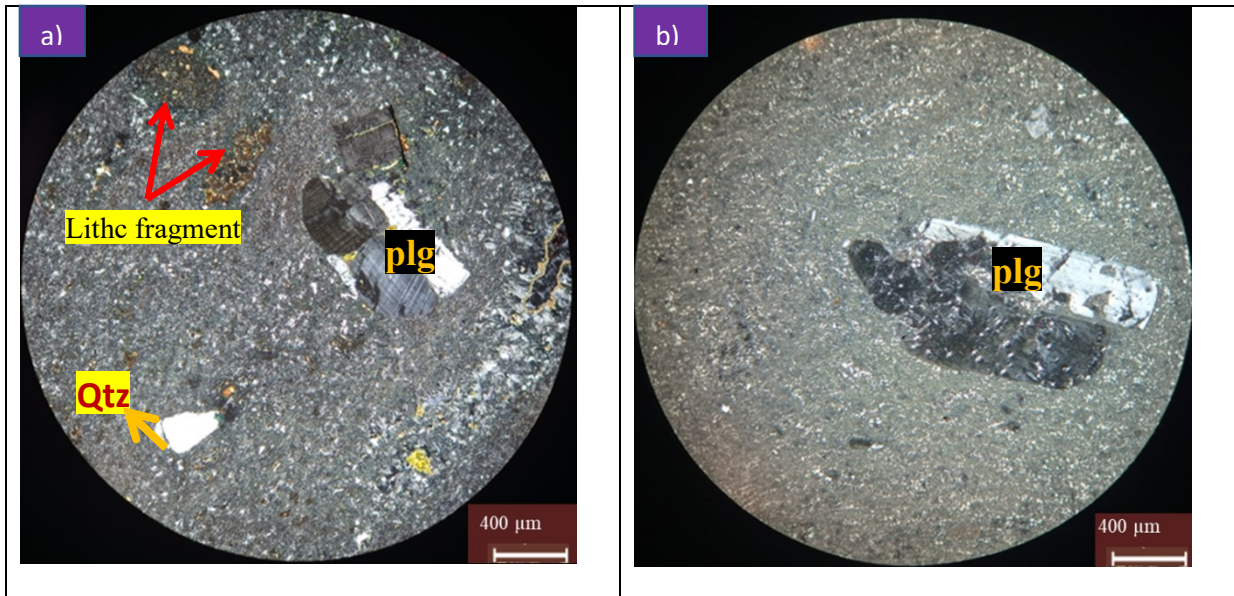


Figure 4.2 Thin section photomicrographs of samples from the volcanic bombs, photomicrograph taken in 4 X magnifications in cross-polarized light

4.4 Lower Rhyolitic Ignimbrite

From this unit 4 samples are selected, KES 010, KES 207, KES 303 and KES 304. KES 010 is a fine-grained lithic-poor pyroclastic rock with crystal components of alkali feldspar and quartz, embedded in microcrystalline quartz and volcanic glass. KES 207 is similar to KES 010 and shows with a larger alkali feldspar crystal embedded in microcrystalline quartz and glass (Fig. 4.3 b). KES 303 shows crystals of alkali feldspar and quartz together with a lithic fragment within vitric groundmass (Fig. 4.3 c). KES 304 has quartz and sanidine as well as lithic fragments (Fig. 4.3 d). In these samples, alkali-feldspars (mostly sanidine) are subhedral to anhedral while the quartz grains are anhedral. Most of the crystals contain inclusions of glass.



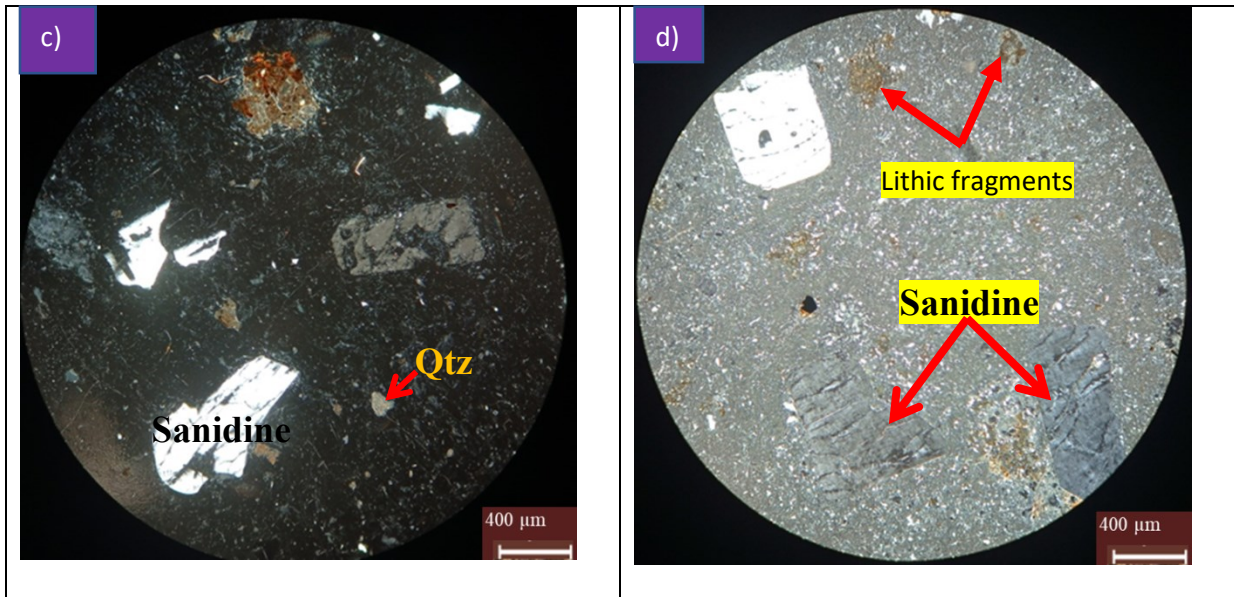
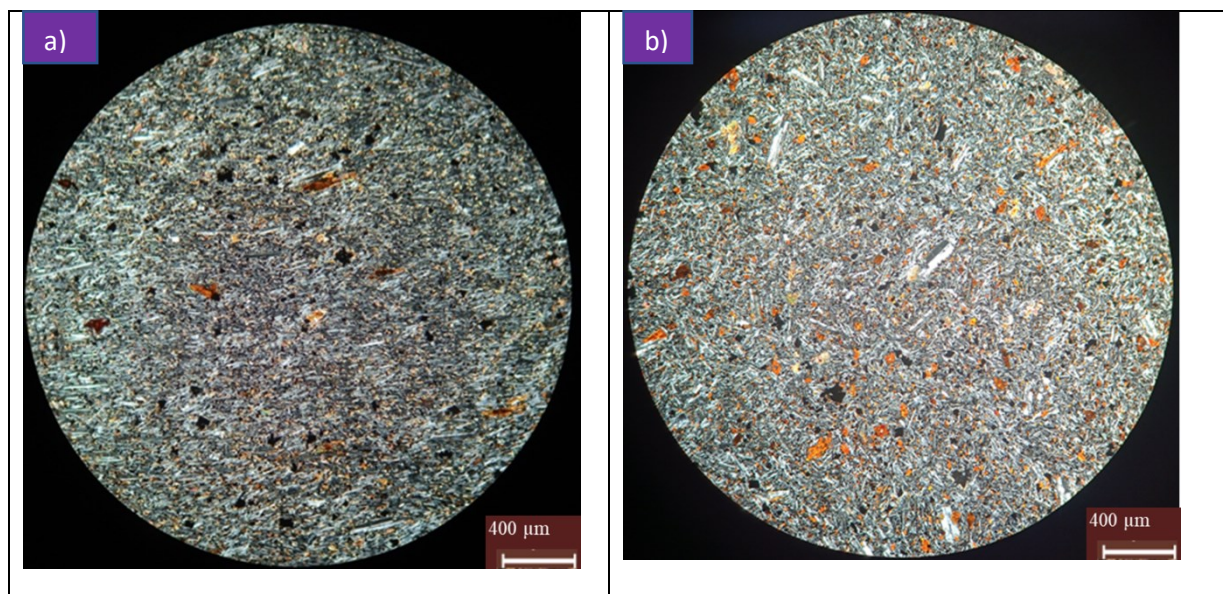


Figure 4.3 Representative thin section photomicrographs of rhyolitic ignimbrite samples, sanidine, and quartz are the dominant crystal phases within a glassy groundmass; (a) KES 010, (b) KES 207, (c) KES 303 and (d) KES 304. Photomicrograph taken in 4 X magnifications in cross-polarized light.

4.5 Upper Basalt

From upper basalt unit, 11 samples are selected and described, KES108, KES 310, KES110 and KES114 are poorly phyric basalts which consisting of <3% phenocrysts of plagioclase minerals and microlites of various minerals occupying the fine groundmass. The groundmass consists dominantly of microlites of plagioclase to sub-intergranular texture with subordinate opaque oxides.



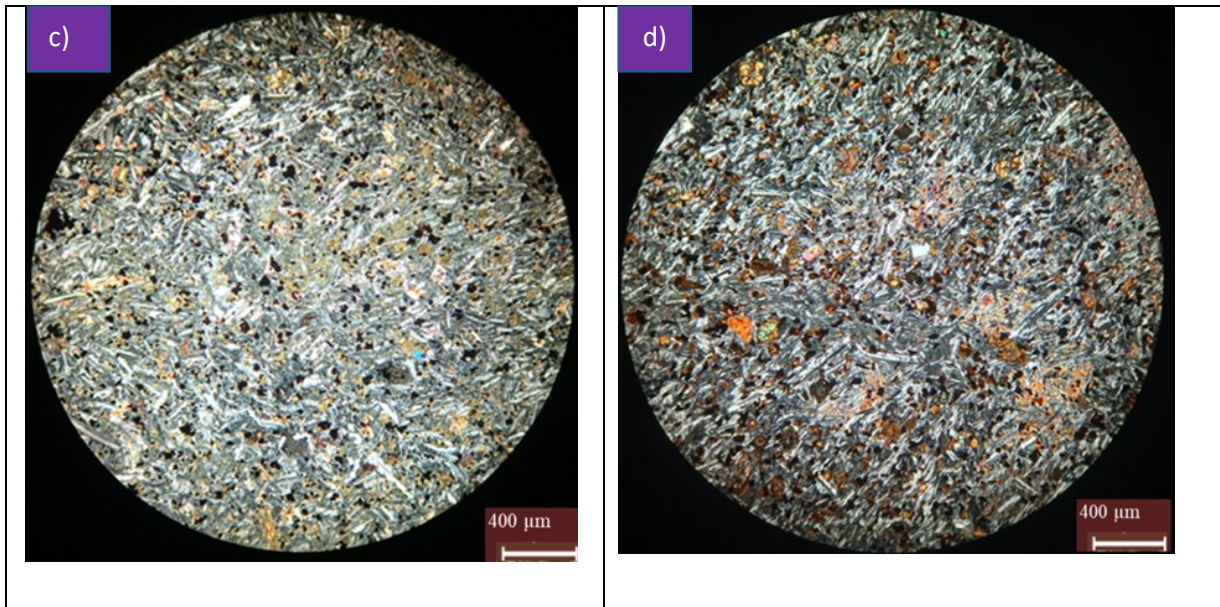


Figure 4.4 Representative thin section photomicrographs of aphyric basalt samples a) KES108, b) KES 310 c) KES110 and KES114 from the Upper Basalt unit: photomicrograph taken in 4 X magnifications in cross-polarized light.

Porphyritic samples from the upper basalt unit show different assemblages of phenocryst mineral phases (plagioclase, olivine, and pyroxene) and opaque minerals and secondary alteration minerals. In addition to the presence of plagioclase as a phenocryst phase, it is the dominant mineral phase within the groundmass forming subhedral to anhedral twinned crystals. Based on the relative proportions of the phenocryst phases these basalts are classified as Plg-phyric, and Plg-Px-Ol-phyric basalts.

Plg-phyric Basalts (KES 007 and KES 117; Fig. 4.5): These are porphyritic basalts with plagioclase as the dominant phenocryst phase. In KES 007, % plagioclase constitutes 80% of the total phenocrysts present, opaque oxides cover 5% and there are altered pyroxenes. Euhedral-subhedral grains of plagioclase show cumulo-phyric texture (clusters of plagioclase mineral only). In KES 117, phenocrysts of plagioclase are found along with secondary minerals (calcite) and altered pyroxene.

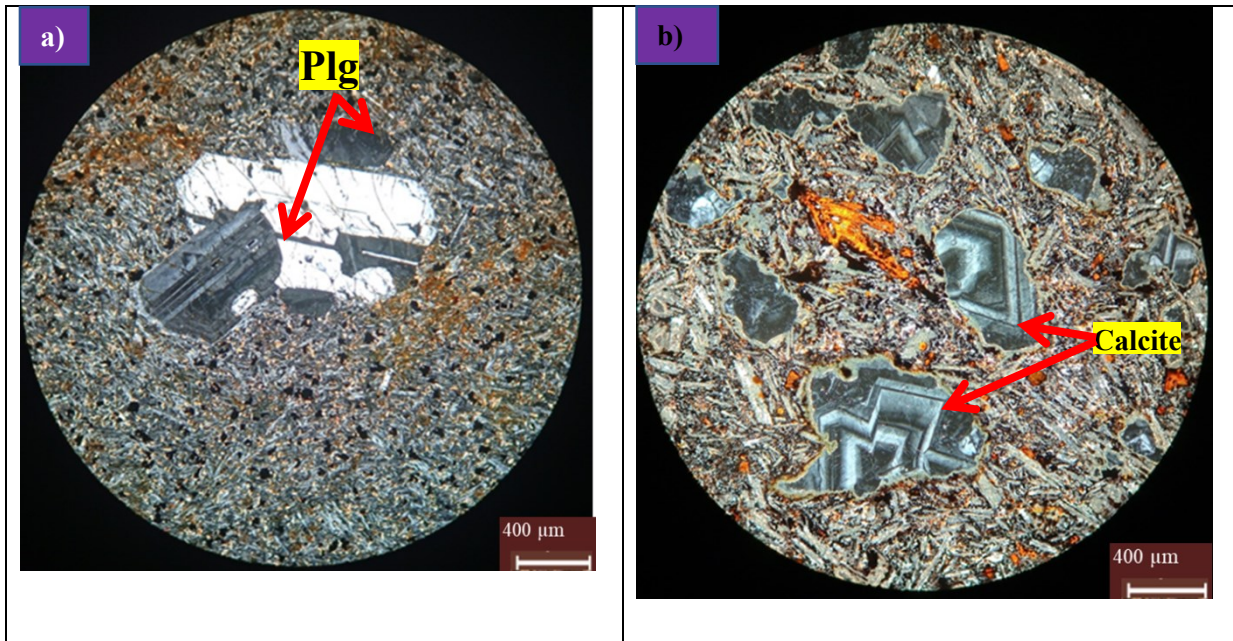


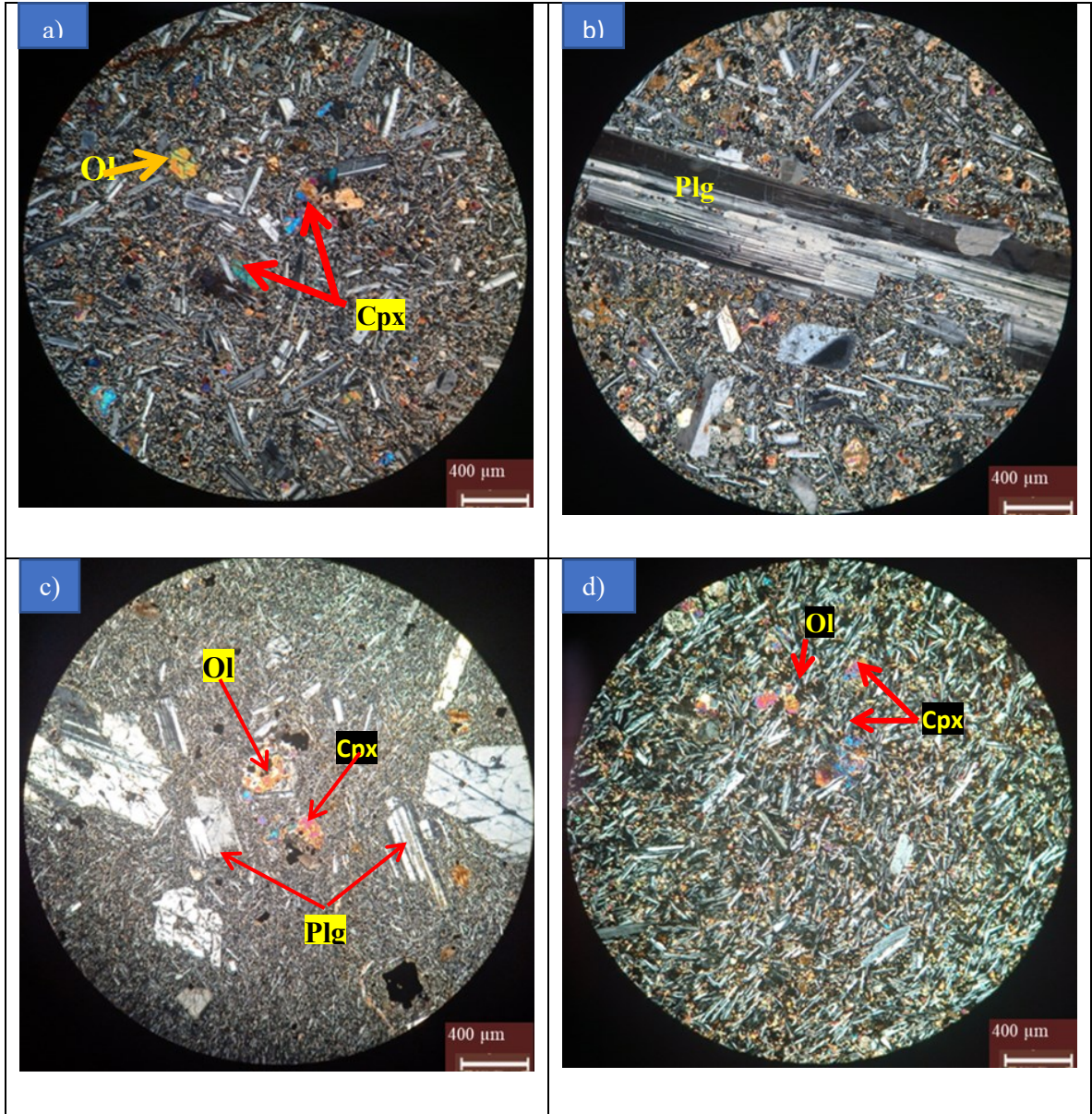
Figure 4.5 Photomicrographs showing certain textural features of Plg-phyric basalt samples from the Upper Basalt unit: (a) large plagioclase phenocrysts within groundmass dominated by finer plagioclase (microcrystalline to intergranular), altered pyroxene, (b) plg- phyric basalt with secondary calcite. photomicrograph taken in 4 X magnifications in cross-polarized light.

Plg-Px-Ol-phyric Basalt: In this category, KES 004, KES005, KES013, KES 211 and KES308 are found (Fig. 4.6). In sample KES 004 elongated plagioclase having 3 to 8 mm long, about 45%, the groundmass minerals are fine plagioclases and opaque oxides. Olivine mineral having the alteration along the boundaries, it is about (6%), Clinopyroxene having inclined extinction around (6%).

Sample KES 005, Elongated plagioclase having 3 to 5mm length (having some alteration along the edges), the groundmass minerals are laths of plagioclases and granules of opaque oxides. The dominant phenocrysts are plagioclase (57%) and clinopyroxene (4.4%), olivine 3% and opaque minerals (6%). These three phenocryst phases constitute the holocrystalline groundmass. KES 013 which is contain micro phenocrysts of plagioclase ~80% with a considerable proportion of olivine. Phenocryst assemblage contains Plg (40.3%), Ol (18.7%), Cpx (10%) and opaque oxides (15.3%). The groundmass is nearly holocrystalline.

KES 211 the phenocrysts are plagioclase (52.9%), clinopyroxene (15.9%), olivine (10%) and opaque minerals are (20%), the dominant groundmass are microlites plagioclase.

These samples have sub- intergranular to intergranular texture. In KES 308 there are equigranular plagioclases with olivine 6%; cpx 4% and 10% covers opaque oxides. The groundmass texture it holocrystalline. It have olivine megacryst.



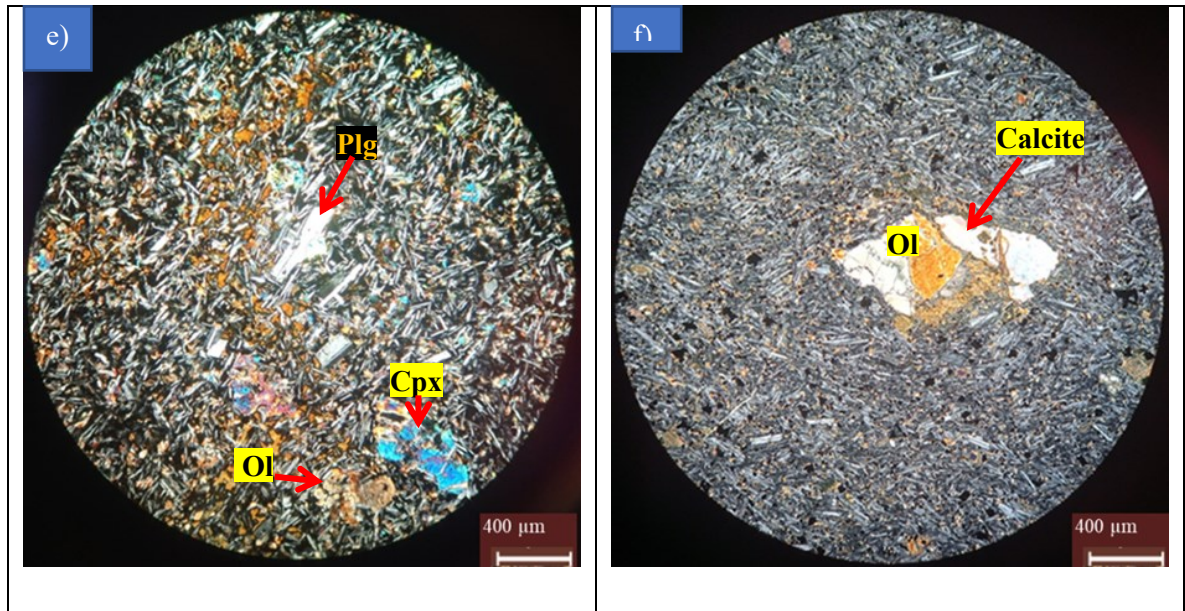


Figure 4.6 Photomicrographs showing certain textural features in a Plg-Px-Ol phyric basalt sample from the Upper Basalt unit: a) KES004, b) KES004, c) KES005, d) KES013, e) KES211 and f) KES308 (photomicrographs are taken from the same sample in 4X magnification in cross-polarized light; Plg: plagioclase; Ox-oxides (opaque minerals)).

4.6 Upper Rhyolitic Ignimbrite

The pyroclastic rock samples taken from the upper rhyolitic ignimbrite unit have the following petrographic properties: the deposits are fine-grained, lithic and crystal-poor with generally scarce crystals of sanidine and quartz set in a cryptocrystalline ground mass. Crystals are generally fractured. Sanidine is commonly euhedral while quartz is often resorbed with rounded margins and embayed edges. The fine-grained groundmasses show devitrified and eutaxitic texture.

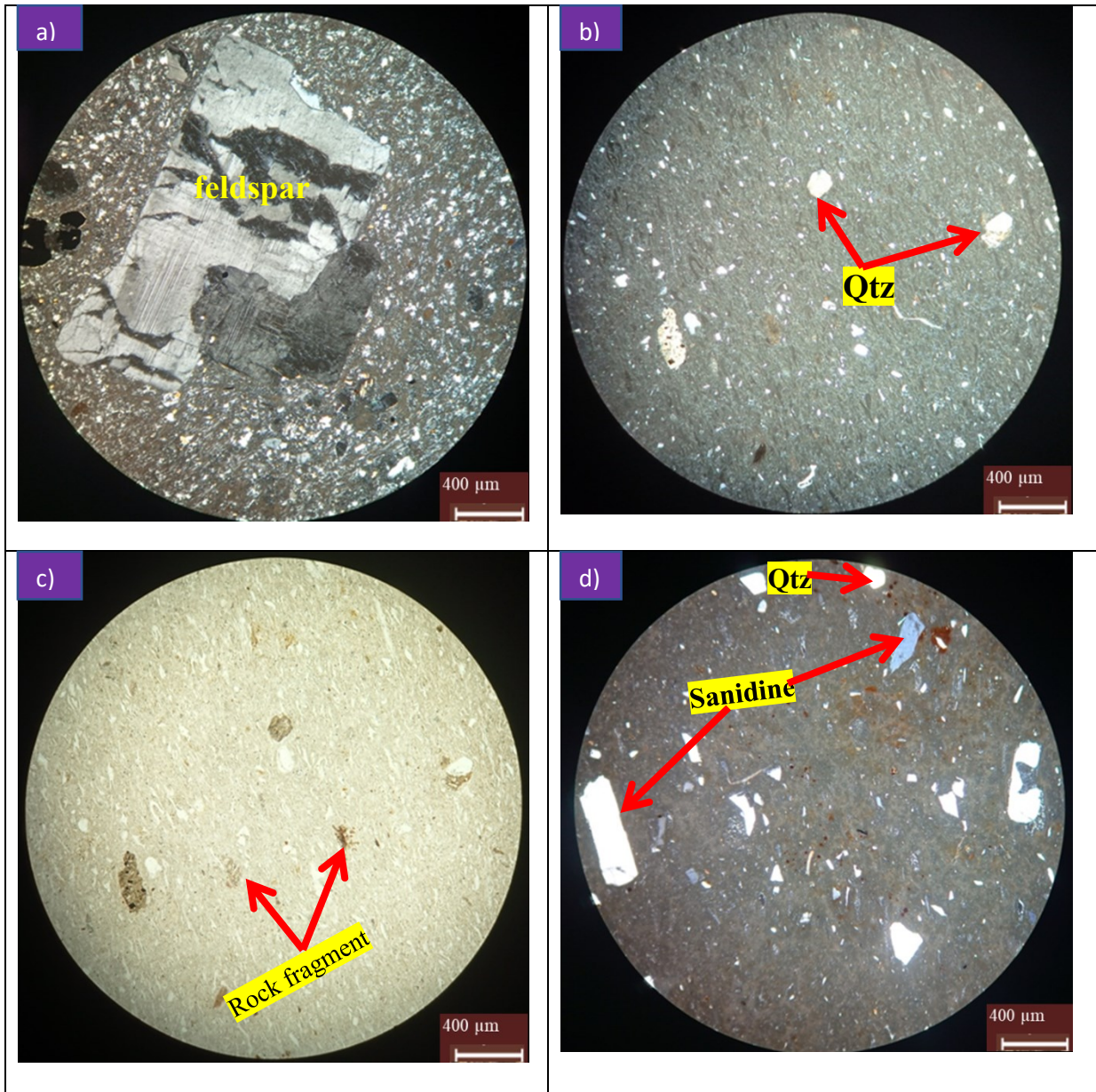


Figure 4.7 Representative thin section photomicrographs of Rhyolitic ignimbrite samples: sanidine, and quartz are the dominant crystal components within a glassy groundmass; (a) KES 001 (b) KES 214 (c) KES 214 PPL and (d) KES 312; (All photomicrographs are taken in 4X magnification in cross-polarized light, except c which is in Plane polarized light).

4.7 Shield basalt unit

From the shield basalt unit, one sample is prepared and described: this sample is dominated by microphenocrysts of plagioclase and opaque oxides.

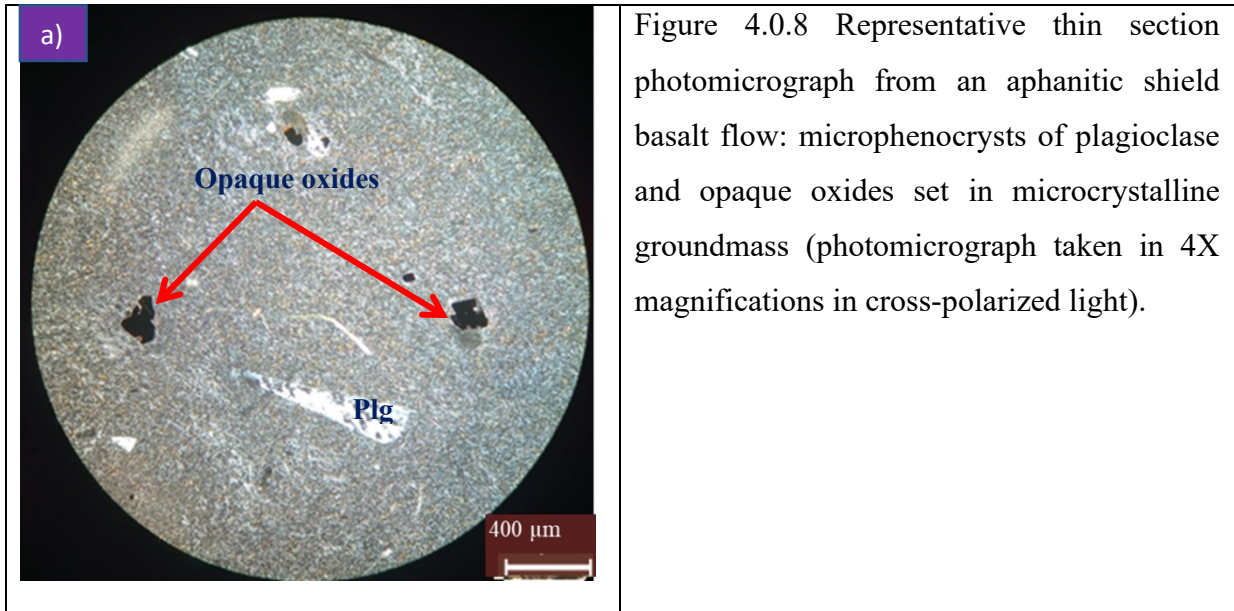


Table 2 Summary of textural features and mineralogy of the petrographically examined rock samples in order of their stratigraphic position (elevation).

S.No	Sample code	Elevation (m)	Lithostratigraphic unit	Texture	Phenocryst assemblage	% of phenocrysts	Dominant mineral phases in phenocrysts	Ground mass texture	Petrographic rock Name
1	KES 202	1710	Lower basalt	Aphanitic	Cpx, plg, oxides	<1%	Plg	Vitric, Felty	aphyric basalt
2	KES 204	1820	Lower basalt	Aphyric–microcrystalline	Plg, Cpx	<1%	Plg	Holocrystalline,	aphyric basalt
3	KES 101	2172	Lower Basalt	Aphyric intergranular	Plg, Cpx and Opaque minerals	37 %	Plg (50%), Cpx (48%)	Felty	Plg-cpx-phyric basalt
4	KES 105	2243	Lower Basalt	Sub ophitic	Cpx, Opx, plg	>50%	Cpx,Opx, Plg	Holocrystalline, Intergranular	Plg-cpx-phyric basalt
5	KES 302	2270	Lower Basalt	Aphyric intergranular	Larger plag,cpx,	43%	Plg (55%), Cpx (30%)	Holocrystalline, Intergranular	Plg-cpx-phyric basalt
6	KES 207	2115	Lower Rhyolitic Ignimbrite	Hypocrystalline	Qtz, Microcrystalline Qtz, , Lithic fragments		Alkali feldspar, qtz, Lithic fragments	Microcrystalline qtz, glass	Ignimbrite

7	KES 303	2251	Lower Ignimbrite	Hypocrystalline	A. feldspar, Qtz, lithic fragments		Alkali feldspar, Qtz, Lithic fragments	glass	Glassy Ignimbrite
8	KES 304	2260	Lower Ignimbrite	Hypocrystalline	A. feldspar, Qtz, Lithic fragments		Alkali feldspar, Lithic fragments	Felty, vitric	Ignimbrite
9	KES 010	2262	Lower Rhyolitic Ignimbrite	Hypocrystalline	A.feldspar, Microcline, Qtz, Plag, Rock fragments, Oxides		Alkali feldspar and qtz, Lithic fragments	Vitric, Microcrystalline qtz,	Ignimbrite
10	KES 106	2301	Upper basalt	Intergranular	Plg, Cpx and Opaque mineral	80%	Plg (67%), Cpx (22%) and Opaque mineral (10.5%)	Holocrystalline	Plg-Cpx-phyric basalt
11	KES 108	2357	Upper basalt	Aphyric–microcrystalline	px, plag and opaque mineral	>3%	px, plg	Holocrystalline, Intergranular	Aphyric basalt
12	KES 211	2389	Upper Basalt	Intergranular	Plag, Cpx and Opaque mineral	>50%	Plg (53%), Cpx (18%), Ol (15%)	Holocrystalline, plagioclase Intergranular	Plg-Cpx-Ol-phyric basalt

13	KES110	2421	Upper basalt	Intergranular	Plagioclase, Cpx and Opaque mineral		Plg, Cpx and Opaque mineral	Holocrystalline	Aphyric basalt
14	KES 308	2432	Upper Basalt	Microcrystalline to intergranular basalt	plg, Ol, Afeldspar, Opx, and opaque mineral	>20	plg, Ol, ,Opx, and opaque mineral	Holocrystalline Plagioclase	Plg-CpPx-Ol-phyric Basalt
15	KES 013	2468	Upper basalt	Intergranular basalt	Plg,Ol, and opaque mineral	30%	Plg (50%), Ol (25%) Cpx (15%)	Holocrystalline Intergranular	Plg-Cpx-Ol-phyric Basalt
16	KES 310	2541	Upper Basalt	Aphanitic, Intergranular	Plg,Ol, and opaque mineral		Plg, Ol	Holocrystalline	Aphyric basalt
17	KES 117	2569	Upper basalt	Porphyritic, Amygdaloidal	Plg,Ol	10%	Plg	Holocrystalline, Microlites	Plg-phyric Basalt
18	KES 007	2684	Upper basalt	Glomeroporphyritic	Plg, opaque minerals	<5%	Plg (80%)	Holocrystalline, Microlites	Plg-phyric Basalt
19	KES 005	2708	Upper basalt	Microcrystalline - Plagioclase intergranular basalt	(>5mm)Plag,Cpx and opaque minerals	20%	Plg (60%), Cpx (20%) Ol (10%)	Microcrystalline plagioclase.	Plg-Cpx-Ol-phyric Basalt
20	KES	2742	Upper basalt	intergranular	>5mm Plg, Ol, Opx, Cpx, and	~30%	Plg (65%), Cpx	Holocrystalline	Plg-Cpx-Ol-phyric

	004A			basalt	opaque minerals		(15%), Ol (10%)	Microcrystalline plagioclase.	Basalt
21	KES 114	2504	Upper basalt	intergranular basalt	Plg, Cpx and Opaque mineral		Plg Cpx	Holocrystalline	Aphyric Basalt
22	KES 214	2535	Upper Ignimbrite	Hypocrystalline	Qtz, Lithic fragment		Qtz, Lithic fragments	Vitric,	Rhyolitic Ignimbrite
23	KES 312B	2649	Ignimbrite	Hypocrystalline	Qtz, Afeldspar, Lithic fragment		Alkali feldspar, Qtz, Lithic fragments	Vitric,	Rhyolitic Ignimbrite
24	KES 001	2822	Upper Rhyolitic ignimbrite	Hypocrystalline	Qtz, Afeldspar, Microcline, Microcrystalline quartz, lithic fragment		Qtz, Alkali feldspar, Lithic fragments	Vitric, Felty	Rhyolitic Ignimbrite
25	KES 315A	2926	Shield Basalt	Aphanitic	Plg, Opaque Minerals	<1	Plag	Trachytic	Aphyric basalt

5. Discussion

5.1 Introduction

This chapter discusses the stratigraphy and petrography of the volcanic sequence in the Upper Kesem river section of the North-Western Ethiopian plateau. For the construction of the composite stratigraphy two representative sections were selected, one is from Hamus Gebeya-Koremash-Kesem River and the second is Koto-Shola Gebeya-Kesem River. In this section, all the result obtained from, remote sensing image interpretation, field investigation and petrographic data are integrated with the pervious works and discussed to understand and construct the complete volcanic stratigraphy and the petrographic evolution of the study area.

This part also contains the correlation of each stratigraphic unit from the different section of the study area (Four stratigraphic section) two section from Hamus Gebeya-Koremash-Kesem section and two sections from Koto-Shola Gebeya-Kesem section. And the final composite stratigraphy of the study area is presented with the correlation of the regional geology from the North Western plateau from the different published works at the different areas.

5.2 Lithological comparisons and correlation of the Northern Kesem (upper) river section with the others studied sections

Lower Basalt (Ashange basalt, a 1700 to 2150): The Upper Kesem River Section which the present study conducted is a part of North-Western Ethiopian Plateau which is the escarpment of the Western part of the main Ethiopian rift. In this area the bottom lithological units exposed are lower basalt which is regionally called Ashange basalt having the thickness ranges from a 300 to 450m thick. These lithological units are the oldest basaltic formation exposed in the lower section of the study area near Keseme/Germame River in the Koremash and Shola Gebeya Section.

The flows in this basalt are generally horizontally bedded, sometimes it forms sheeting in some localities. The lower basalt is characterized by the raged morphology and relatively gentle than the upper basalt and the rock units are extensively affected by fractures and weathering which ranges from slightly to completely rate of weathering. The other geological information observed from this unit is the existence of dikes. Previously this lithological units which contain lower

basalt of the study area, lower ignimbrite and Tuffaceous sediments, and upper basalts are considered as a single unit and named as Kesme Basalt (Dejene H/Maryam, 2017 et.al) and unpublished thesis (Birhani Girum, et.al 2021). In the present study those three different lithological units are clearly separated, described and mapped. The other studies by (Dereje Ayalew and Gibson, 2009) around Northwestern Ethiopian plateau around North Shewa Yita Koste, section they describe this lithological units have the thickness of 320m.

Recently two studies were conducted by Masters student from Addis Ababa University (Feyesel Sefa, 2021 and Kuri Yemenu, 2022) unpublished thesis in the North western Plateau the lower basalt around Sela-dngay area is 330m thick and at Debrelibnos section has the thickness of 258m. Accordingly the lower basaltic unit has the minimum thickness around 250m. The field descriptions provided by different studies are correlated with the current studies which are highly fractured and highly weathered.

For the petrographic study from the lower basalt samples taken from the different elevation with sample code KES202-from 1710m (having the minerals with the dominant of Plg, and Cpx and opaque oxides) and the texture of this samples shows that the lower section of this unit is aphanitic texture. The other samples having the code of KES204-from 1820m (have the dominate minerals of Plg and with small amount of Cpx) and the texture of this unit in the middle part shows aphyric microcrystalline.

The third sample from the top part of this having the code of KES101-from 2150m (have the dominate minerals of Plg, and Cpx, oxides) and the texture of this sample shows Aphyric intergranular textures. The petrographic studies by others around Yita Koste by (Dereje Ayalew and Gibson, 2009), and others unpublished research by (Feyesel Sefa, 2021 and Kuri Yemenu, 2022) shows similar composition with current studies.

Lower Rhyolitic Ignimbrite which is ~100 to 150 m thick is consisting of ignimbrite with various degrees of welding and crystals. In Shola Gebeya section the contact between the lower basalt and the beginning of ignimbrite is characterized by glassy ignimbrite which indicates that the fast cooling of pyroclastic flows. From the petrographic study these rock units have quartz and sanidine minerals. The composition of this glassy textured unit is dominantly rhyolitic as inferred from thin section study. Near instantaneous melt solidification (glass-forming) process

results from two major mechanisms (Hefferan and O'Brien, 2010): quenching and rapid gas loss. Quenching occurs when melts of any composition come into contact with liquid water or air; mostly basic (low SiO₂) glasses quench when volcanoes erupt on the ocean floor or as massive flood basalts.

The second mechanism limited to silicic melts occurs by rapid loss of dissolved gas. The porphyritic varieties (Vitrophyric textures) in this lava product represent the partial crystallization of the magma before its rapid solidification. Since the glassy unit in this study area is rhyolitic, the possible formation relates to a rapid loss in gas by viscous lava fluxing at a higher rate to a cooler surface air condition. When it goes from the contact to the center part of a rhyolitic Ignimbrite unit, it shows the tightly columnar jointed ignimbrite.

The tiny columnar jointed nature of these rocks indicates that the Rhyolitic ignimbrite units are formed at high temperatures. In the Koremash section this unit also shows that the columnar joint ignimbrite. Generally, this lower Rhyolitic Ignimbrite is the marker felsic rock units which separates the Lower and the Upper Basaltic flows of the area. As it is mentioned above the basalt unit in the study area are mapped as a single basaltic flows, but from the current study it is clearly observed that in between the different basaltic lava flow, the lower rhyolitic ignimbrite is observed in all of the Travers having the ranges of 100 to 150m.

The thickness of this unit varies from area to area due to paleogeography and this unit also found at different elevation in the Koremash area and in the Shola Gebeya area, the elevations variation is probably due to faulting as the area is the margin of the MER.

Upper Basalt (Aiba Basalt 2300 to 2700mas): above the lower ignimbrite and sediments, the upper basalt unit is exposed in all section through Koremash to Kesem and Shola Gebeya to Kesem sections. This unit consists of several lava flows up to ten different basaltic flows separated by paleosols. The thickness of flows ranges from 20 to 55m and nearly each lava flow is separated by 2 to 3m thick paleosol . Generally, the overall thickness of this upper basalt unit ranges from ~300m to 400m. According to Dereje Ayalew, and Gibson, (2009), the estimated thickness of this unit is >280m.

From the field observation the Upper basalt shows that at the bottom part of the flows it has some scoracious basalt, at the middle it shows columnar jointed structures and at the top of the

flow vesicular basalts. From upper basalt 11 samples are selected for petrographic study. Among those samples, the lower part of the sample from this unit shows poorly phyric microcrystalline texture and the others samples are intergranular texture. The mineralogical composition of the units are plg, px, ol and oxides. Most of the samples from this unit have holocrystalline groundmass.

The upper basalt unit is dominated by plagioclase phenocrysts having 3 to 8mm diameters. The modal percentage of the minerals from this unit shows plagioclase 50 to 75%, Clinopyroxene 4 to 22%, Olivine 10 to 25%. The petrography studies for this unit from the different area shows intergranular texture with dominant constituent of plagioclase minerals (Dereje Ayalew and Gibson, 2009, Feyesl Sefa, 2021).

Upper Rhyolitic Ignimbrite (Alaje Formation 2700 to 2800masl):- At the top of the basaltic flows, this silicic unit is exposed around Koremash, HamusGebeya and SholaGebeya areas. This pyroclastic unit has approximately 80m thick. From the field observation this lithological unit forms the gentle topography at the top of flood volcanic flows. In some area this unit has columnar joint structure with lithic poor to moderately amount of crystal. The petrographic study of from this sample shows that glassy /hyaline texture with the presence of feldspar, quartz crystals and lithic fragment components. Since the quartz and feldspar crystals are the dominate minerals from the petrographic study the pyroclastic deposits are derived from felsic lava.

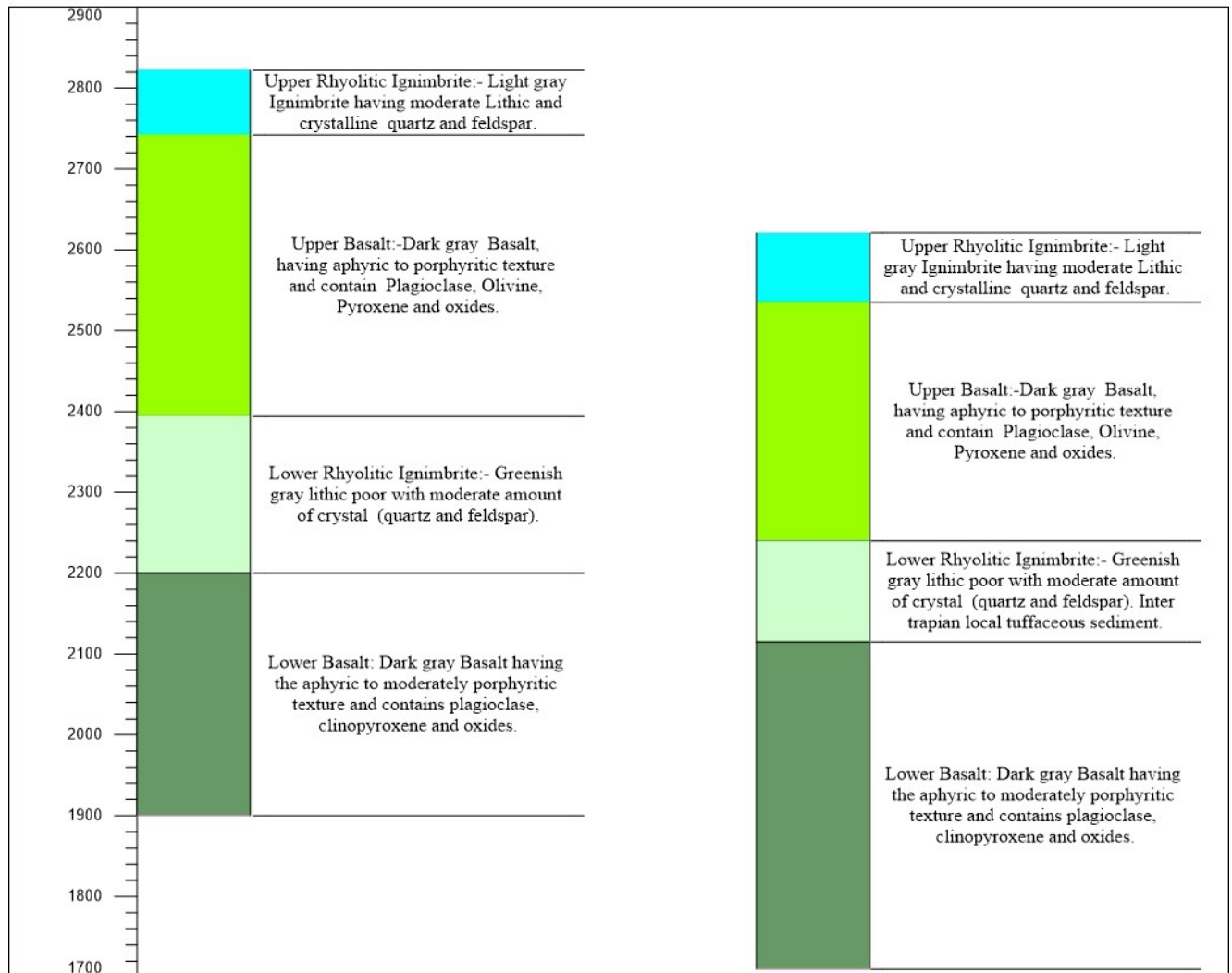
Shield volcanics (Megezez Formation above, 2800masl);

Shield-forming basalt lavas are found on top of the upper ignimbrite unit which is known by short fissural type of volcanic eruption (Megezez formation). From field observation, this rock unit is characterized by the presence of aphyric and porphyritic basalt flows together with volcanic agglomerate, basaltic scoria. Only one sample is was considered for petrographic analysis of the shield basalts. This sample shows that the bottom part of the Megezez flows are characterized by aphanitic texture with the presence of minor plagioclase and oxide minerals. The groundmass of this sample shows trachytic texture.

Lower Basalt and Upper Basalt are separated by a layer of clastic sediments which indicates a time gap between the two flood basaltic units (the Lower basalt and Upper basalt units) also differ in their geomorphological manifestations: the lower basalt unit shows relatively gentle

topography whereas the Upper basalts form steep cliffs and are frequently separated by paleosol horizons.

From the Upper Kesem River section four stratigraphic sections are produced as shown in Fig 5.1 and 5.2 below.



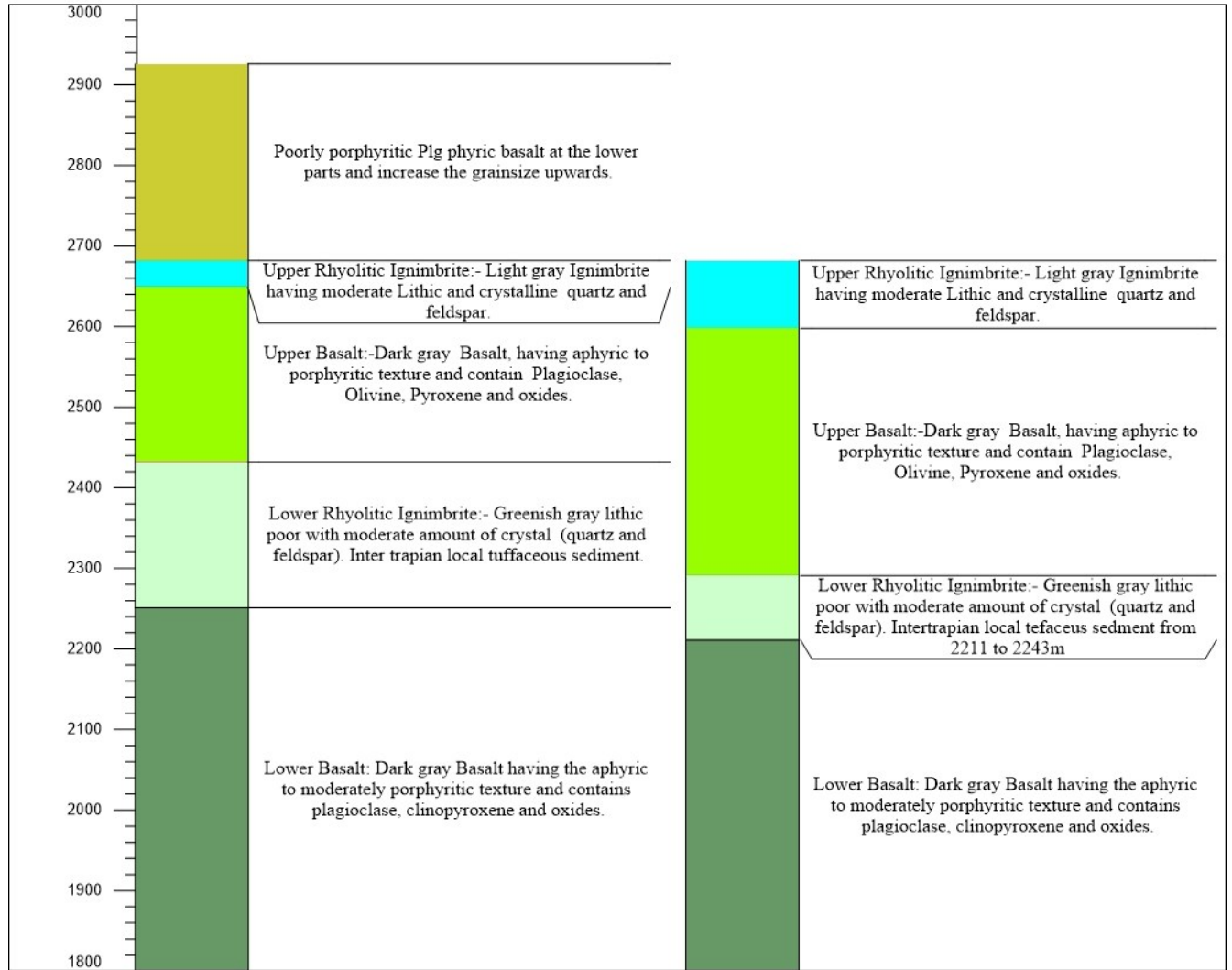


Figure5.1 Volcanic stratigraphic log section of the Upper Kesem river section (a) the two sections are from Hamus Gebeya -Kore mash Germama river section and (b) the two sections are from Shola Gebeya Kesem section.

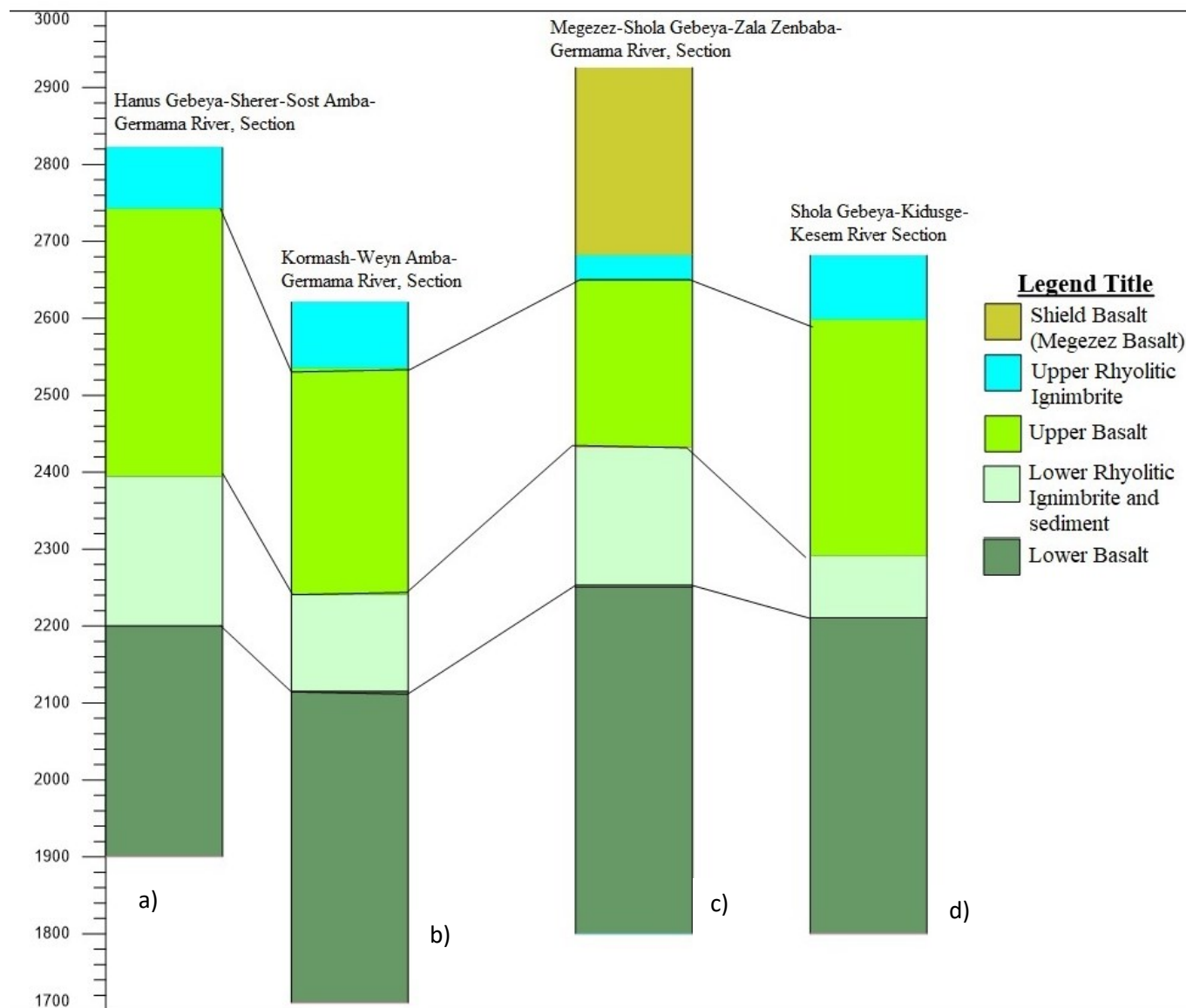


Figure 5.2 Correlation of local volcanic stratigraphic sections of the study are (a and b) from Koremash section and (c and d) from Shola Gebeya section.

5.3 Composite stratigraphic section and Correlation

Table 3 Composite volcanic stratigraphy of the Upper Kesem River section with summary note.

	Litho-stratigraphic Unit with approximate thickness	Summary description of litho-stratigraphic units
	Shield basalt (Megezez basalt) (>400m);	The unit consists of tens of basalt lava flows and interbedded scoraceous layers. The lower flows are largely poorly porphyritic to sparsely Plg phyric and degree of porphyricity increases upwards.
	Upper rhyolitic ignimbrite (~80m);	This felsic unit consists of several separate pyroclastic flow and fall deposits. The overall color varies from light to medium grey, is massive, and contains moderate amounts of lithics and crystals (quartz and feldspar).
	Upper flood basalt (~400m)	The unit consists of tens of thin (~37.5m) basalt flows. Basaltic lava flows are intercalated with minor felsic-pyroclastic layers. Most individual basalt flows typically show flow top, flow core and flow bottom features. They are aphyric to porphyritic in texture and contain phenocrysts of plagioclase, olivine, clinopyroxene and opaque oxides in various proportions.
	Lower rhyolitic ignimbrite (~150m)	This pyroclastic unit consists of several separate pyroclastic flow and fall layers. It varies in color from light grey to greenish gray, is massive, welded, lithic poor, contains moderate amounts of crystals (quartz and feldspar) and includes thin tuffaceous sediment layers.
	Lower flood basalt (~450m) Lower contact with Mesozoic sediments is not exposed	This consists of three of thick (~150m) basalt flows are highly fractured and weathered; aphyric to moderately porphyritic with plagioclase, clinopyroxene and opaque oxides in to holocrystalline groundmass.

Table 4 Lithostratigraphy correlation of the local volcanic stratigraphic units to the previous works in north western Ethiopian flood Volcanics.

Thicknes s	Evolution of the northern Main Ethiopian rift: Birth of a triple junction (Wolfenden et al., 2004).	North Shewa volcanic succession at Yite-Koste (Dereje Ayalew and Gibson, 2009); Locally exceeds 1000 m (~2300->3000)	Stratigraphy of Sela Dingay area (Fisel Sefa, 2021); ~ 1700 m (~1620-3315 masl)	Stratigraphy And Petrography Of Flood Basalt Succession At Debre Libanos Area 715m (1946-2661 masl) (Kuri Yimenu, 2022).	Volcanic Stratigraphy And Petrography Of The Northwestern Ethiopian Flood Volcanics In Upper Kesem River Section (this study), 1050m (1700-2750 masl)
Volcanic lithostratigraphy	The stratigraphically lowest sequences in the Kessem gorge and the most heavily dissected are fine-grained basalts and interbedded ignimbrites. • Lower basalt unit (extremely altered basalt) having a thickness > 250 m • Ignimbrite overlies the altered basalt • Scoria cones overlie the widespread felsic unit near Meteh Bila.	Lower unit consists of basaltic lava flows with a prominent layer of Rhyolitic ignimbrites in the middle part of the sequence. The topmost part of the sequence consists of a thick ignimbrite unit forming plateau morphology. • Lower Basalt Formation (320 m thick) with thin rhyolite layers • Lower Ignimbrite (80 - 120 m thick) with no interbedding of basalts • Upper Basalt Formation (>280 m thick) with thin rhyolite layers • Upper Ignimbrite Formation (>230 m thick) with no interbedding of basalts	The bimodal basalt-rhyolite stratigraphic succession is mainly basaltic with layers of minor Rhyolitic-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 Rhyolitic lava products in the middle and the top of the succession. The central type shield basalt ends the stratigraphy. • Lower Flood Basalt (330m) • Sela Dingay Rhyolitic Lava (400 m) • Upper Flood Basalt (440 m) • Sela Dingay Rhyolite-	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. • Lower basaltic lava flows 258 m thick • Pyroclastic Deposit (ignimbrite) 245 m. • Upper Basalt Lava Flows 211 m	The stratigraphic sequence is composed of basalt with layer of subordinate Rhyolitic ignimbrite deposits • Lower Basalt ~450m thick • Lower Rhyolitic Ignimbrite ~150m thick • Upper Basalt ~ 400m • Upper Rhyolitic Ignimbrite ~80m thick • Shield Volcanics 521m from (Birhan Girum, 2022)

			Ignimbrite (118 m) Termaber Shield Basalt (407 m)		
Petrography		✓ The mafic lavas vary from aphyric to porphyritic with phenocrysts (up to 7 vol. %) of plagioclase (bytownite and labradorite), olivine, and clinopyroxene. ✓ The rhyolites are sparsely porphyritic (with up to 10 vol. % phenocrysts) and are comprised of alkali feldspar (sanidine and anorthoclase), quartz, and minor ilmenite.	- The basaltic lavas are dominantly composed of plagioclase (bytownite and labradorite) phenocrysts and microlites with olivine, pyroxene, and abundant Fe-Ti oxides. - The Rhyolitic rocks (with up to 10-30% phenocrysts) are compositionally dominated by alkali feldspar (sanidine and orthoclase), quartz, and minor plagioclase and micas. - Ignimbrite interlayering within the upper basalt is composed of mafic lithic and crystal fragments	- The basaltic units are dominantly composed of plagioclase phenocrysts with Olivine, pyroxene and opaque minerals. - The Ignimbrite units 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.	✓ The basaltic lavas are dominantly composed of plagioclase with pyroxenes, olivine, biotitic and opaque mineral. ✓ The Rhyolitic Ignimbrite is sparsely porphyritic (up to 15% phenocrysts) and this unit is composed of dominantly alkali feldspar (sanidine), quartz and minor plagioclase.

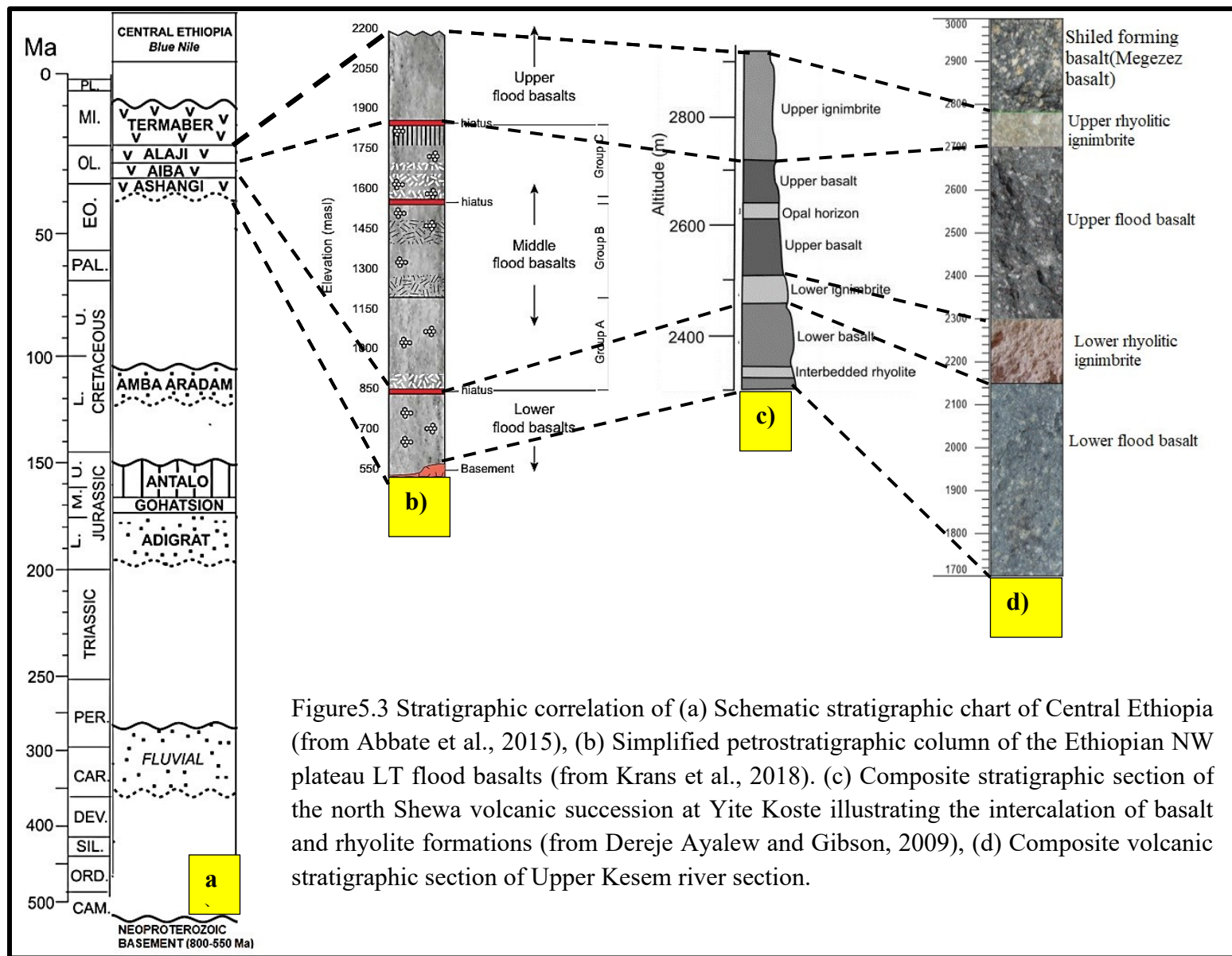


Figure 5.3 Stratigraphic correlation of (a) Schematic stratigraphic chart of Central Ethiopia (from Abbate et al., 2015), (b) Simplified petrostratigraphic column of the Ethiopian NW plateau LT flood basalts (from Krans et al., 2018). (c) Composite stratigraphic section of the north Shewa volcanic succession at Yite Koste illustrating the intercalation of basalt and rhyolite formations (from Dereje Ayalew and Gibson, 2009), (d) Composite volcanic stratigraphic section of Upper Kesem river section.

6. Conclusions and Recommendation

6.1 Conclusion

The present study which was conducted in the North western plateau, with the main aim of producing volcanic stratigraphy in Upper Kesem River section, Central part of Ethiopia.

From the literature review, remote sensing image interpretation, filed mapping and petrographic analysis for the flood volcanic sequence in the Upper Kesem River section the following conclusions are drawn.

- The exposed volcanic pile in the Upper Kesem river section reaches an overall thickness of ~1080 meters. The lower contact of the volcanic sequence with the underlying Mesozoic sedimentary formations is not exposed. Rift margin faults with moderate displacements have affected the sequence. The normal faults are broadly oriented NNE- SSW; ENE-WSW trending faults also occur.
- The volcanic strata are essentially flat lying and laterally continuous; limited low-angle tilting due to faulting is present in some places.
- The volcanic sequence is dominated by flood basalts (~850m thick; ~78%) with significantly thick felsic pyroclastic deposits and lavas (~230m thick; ~22%). Thin intra-volcanic clastic sediments of lacustrine and fluvial origin as well as paleosol horizons are also present.
- The thick volcanic pile has been subdivided on stratigraphic and lithological bases into the following units or formations: 1) Lower basalt (Ashenghe Formation), 2) Lower Rhyolitic ignimbrite, 3) Upper basalt (Aiba formation), 4) Upper rhyolitic ignimbrite (Alaji formation) and 5) Shield basalt (Tarmaber formation). The above units or formations are separated by clear contacts: either contrasting lithologies (magma composition) and/or occurrence of sedimentary beds and paleosol horizons that signify significant hiatus in volcanic activity and hence in magma supply rate/flux.
- In previous studies, the Upper Kesem River section was described as consisting a single flood basalt succession (Kesem basalt unit). The present study has identified the occurrence of a felsic formation of significant thickness (here referred to as the Lower rhyolitic ignimbrite Unit) separating two distinct flood basalt series,(the

Lower and Upper flood basalt units), The Lower basalt unit consists of at least three different flows separated by the paleosol). In contrast, the Upper basalt unit consists of tens of lava flows having thicknesses of 20 to 55m separated by 2 to 3m thick paleosols.

- The two felsic units (Lower and Upper ignimbrite units) within the volcanic pile comprise of extensive sheets of pyroclastic deposits and lavas. These large-volume volcanic products indicate that flood basalt volcanism was accompanied by the development of large and shallow magma chambers in which basaltic magmas were stored and underwent extensive fractionation and evolution. These deposits further highlight that large and long-lived silicic volcanic complexes with large calderas must have developed on the flood basalts, erupting both effusively and explosively. As relatively younger basaltic lavas have buried the entire felsic units, the locations of such volcanic centers have not been identified so far.
- Temporal constraints for changes in plumbing system dynamics are recorded in the petrography and stratigraphy of the erupted lava flows. Shield volcanism represents a decrease in magmatic flux over time
- The petrographic analysis from the different units of the study area, from the Lower basalt shows (aphyric and aphyric inter granular texture and modals of aphyric and Plg-Cpx-pyric basalt) whereas Upper basalt shows (aphyric microcrystalline and Intergranular, glomeroporpyritic and the modal name of Plg- pyric, Plg-Cpx-Ol-pyric, basalt), reveals that most of the samples are aphyric to phyrlic, representing HT1 characteristics.
- A polybaric plumbing system for the lavas may be suggested on the basis of modal mineralogy. From broad variations in modal mineral assemblage in the basalt flows, it is reasonable to suggest that several chambers developed at various depths within the crust, with each chamber undergoing independent recharge and fractionation processes.
- Petrographic studies of samples representing the litho-stratigraphic units of the volcanic pile reveal the occurrence of basalts and felsic volcanics only. Rocks of intermediate compositions have not been found, indicating a bi-modal petrological distribution.

- From the Upper Kesem Volcanic sequence, it is concluded that the Ethiopian volcanic plateau consists of a number of volcanic centers with different magmatic character and variable thickness of lava products with a large range of age of eruption observed from the existing paleosols.
- The overall geometry and petrological characteristics of the volcanic pile are broadly similar to those described in other exposed sections of the Northwestern Ethiopian plateau (Sela Dingay).
- The Upper Kesem River volcanic pile may, therefore, be considered as the southernmost continuation of the Ethiopian north-western volcanic sub-province.

6.2 Recommendations

- Detailed geochemical study from the different lava flows of the area is recommended to understand the clear relationship between the different basaltic and felsic lava products.
- The complexities in the structural set up of the area made the mapping complicated in some localities. This is due to down throwing of the younger formations over the older ones; therefore, it requires age dating of rocks in this area.
- Since the study area is part of the escarpment and the Ethiopian Rift, it consists of a number of local and regional structures. Hence detail study is needed to develop a simplified structural model of the area

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