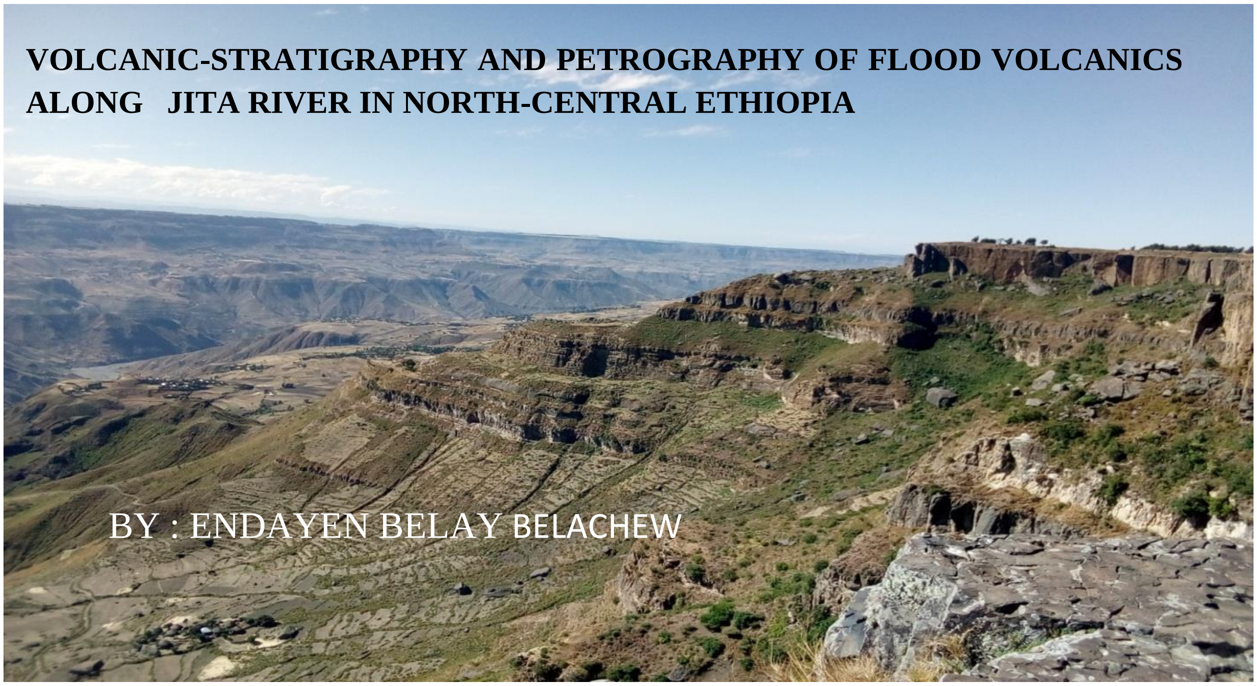
ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCES

VOLCANIC-STRATIGRAPHY AND PETROGRAPHY OF FLOOD VOLCANICS ALONG JITA RIVER IN NORTH-CENTRAL ETHIOPIA



BY : ENDAYEN BELAY BELACHEW

A THESIS SUBMITTED TO THE SCHOOL OF EARTH SCIENCES, GRADUATE PROGRAM, ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCES IN GEOLOGICAL SCIENCES (PETROLOGY)

JUNE, 2020
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ADVISOR: DEREJE AYALEW (Prof.)
CO-ADVISOR: GEZAHEGN YIRGU (Prof.)

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Approved by the examining committee

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Examiner	Signature	Date
_________________________	_____________________	______________________
Examiner	Signature	Date

Declaration of originality

I declare that the thesis entitled“Volcanic stratigraphy and petrography of flood volcanics along Jita River in North central Ethiopia” has been carried out by me under supervision of Prof. Dereje Ayalew and Prof. Gezahegn Yirgu, school of Earth science, Addis Ababa University, during the year 2020 as part of Master of Science in petrology. This work has never been presented in any other university or institution for the award of a master’s degree. All sources and materials used for the thesis have been well referenced and duly acknowledged.

Endayen Belay Belachew ____________ ________________

Signature Date

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

Prof. Dereje Ayalew (Advisor) _______________ ________________

Signature Date

Prof. Gezahegn Yirgu (Co-Advisor) ________________ ________________

Signature Date

Abstract

The study area is located in the North Wollo zone within the NW Ethiopian volcanic plateau. The area provides a well-preserved volcano-stratigraphic sequence from lower basalt initiation to upper lava flow termination. The main objective of this study is to establish the petrovolcanic stratigraphy of the area and then finally to put the petrographic observations within the context of magmatic evolution or depositional history of volcanic products. To accomplish the research objectives, actual field observation, stratigraphic sampling and petrographic analysis methods were applied. The major volcanic units from bottom to top are aphyric-intergranular basalt, aphyric-trachy flow basalt, augite cumulophyric basalt, olivine-augite phyric basalt, Kfs vitrophiric rhyolite, augite phyric basalt, basaltic tuff, columnar-aphyric basalt, non-columnar-aphyric basalt, moderately welded rhyolitic tuff, Kfs phyric rhyolitic-ignimbrite, Kfs phyric rhyolite, columnar-aphyric basalt, thin layer basaltic agglomerate and slightly vesicular aphyric basalt. Petrographyically, these volcanic rocks have different mineral compositions and textures; this heterogeneity reveals that there is a variation in depth of mineral fractionation and magma flux in the lithosphere. The presence of Cpx cumulophyric, Ol-Cpx and Cpx phyric basalt flows in the lower flow pile suggests that there is a considerable depth of fractionation in the deeper crustal level. The ol-megacryst composition and iddingsite alterations also reflect a constant replenishing of new primitive magma recharging the deeper plumbing system. Similarly, the presence of paleosoils, Kfs vitrophyric rhyolite and basaltic tuffs are also indications of cyclicity of magma eruptive phases in both shallow and deeper crust plumbing system with variable magma influx rate. However, the upper basaltic groups are extremely dominated with plagioclase microphenocrysts marked by agglomeratic deposit and capped with vesicular aphyric basalt. These observations indicate that the plumbing system was fed by shallow reservoir with decreasing rate of magma flux. Furthermore, the felsic units have dominant Kfs phenocrysts implying that the rate of magma flux was decreased and crystallized at shallow crustal level. The flows have broad changes in mineralogy and eruptive cyclicity and this suggests that they were pulsed with a fluctuating magmatic influx along with complex plumbing systems and overtime fed by shallower magmatic plumbing reservoirs. Overall, the petrovolcanic- stratigraphy findings in this study provide a new insight into the magmatic evolution of the Ethiopian CFB provinces.

Keywords: Cpx-cumulophyric, Megacrystic olivine, Magma plumbing system, Petrography, Volcanic Stratigraphy.

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First and for most, I would like to provide my heartfelt thanks to almightily God who strengthened me in all the ways which I have travelled to reach this point. My deepest and special gratitude goes to my advisor Prof. Dereje Ayalew for his follow up, invaluable advices, constructive comments and suggestions, encouragement, systematic discussions and limitless financial support at various times throughout the entire thesis. Further, he provided me with moral support which really meant a lot to me.

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List of Acronyms

Aug	Augite
AFC	Assimilation and Fractional crystallization
Akf	Alkali feldspar
ca.	circa (around)
C°	degree Celsius
Cpx	Clinopyroxene
DEM	Digital Elevation Model
GPS	Global Positioning System
GSE	Geological survey of Ethiopia
ERDAS	Earth Resources Data Analysis System
Fig.	Figure
Kfs	K-feldspar
Km	Kilometer
Km^2	Kilometer square
Ma	Millions of years
masl	meters above sea level
mm	millimeter
NE	Northeast
NW	Northwest
Ol	Olivine
Opq	Opaque
Opx	Orthopyroxene
Plag	Plagioclase
PPL	Plane Polarized Light
Qtz	Quartz
Sa	Sanidine
SE	Southeast
SW	Southwest
Vol.%	Volumetric percentage
Wt.%	Weight percent
XPL	Cross Polarized Light

CHAPTER ONE

1. Introduction

1.1. Background

The project is conducted in the southeastern part of NW Ethiopian volcanic province along Jita River, which is located about 160 km NW of Dessie town. The main aim of this thesis work is to establish the petrovolcanic stratigraphy of the area. In addition, this study constrains the petrogenetic evolution and depositional history of the volcanic suits. The Cenozoic Ethiopian continental flood volcanic province is found at the junction of three rifts: two of oceanic rifts (Red Sea and Gulf of Aden), and the East African continental rift (see inset map in Fig.2.2). The main part of the province outcrops in Ethiopia, whereas the rest is located in Eritrea and the eastern part of the Red Sea within Yemen plateau. In the part of Ethiopia, the huge volume of lava flow is preserved, which has an estimated volume of about 350,000 km^3 that forms a pile up encountered with 2000 m thickness, and also covered an estimated areal extent accounted for 600,000 km^2 (Mohr,1983; Mohr & Zanettin,1988) that erupted around 30 Ma ago. This Ethiopian intracontinental Cenozoic volcanic province constitutes a thick volcanic succession, which are dominated by fissural basalts and subordinate felsic products that spread over an area covering several hundred-thousand square kilometers (Yirgu, 1997).

This study is supposed to be part of northwestern plateau, in which the Oligocene fissural basalts are overlain by the less voluminous Miocene lavas, which erupted from large central vent volcanoes (Mohr and Zanettin, 1988; Kieffer et al., 2004). Some authors agreed with the idea of Mohr and Zanettin (1988) that this voluminous flood basalt magmatic activity in Ethiopia was commenced by the Oligocene time (~30-35 Ma) and then followed by a complex shield volcanic activity (Kieffer et al., 2004; Yirgu et al., 2006). These Ethiopian plateau regions comprise different dated shield volcanoes. From these plateau regions, the most common shield centers are Semien (18.7 Ma), Choke (22.4 Ma), Guguftu (22.3 Ma), Guna (10.7 Ma), Tarmaber-Megezez formation (21.6 Ma), which have been conducted by Kieffer et al. (2004) who also estimated their total areal coverage, which accounted for 20 % of the surface of the plateau and have an estimated thickness around 2000 m that rests on the fissural feed flood basalt and the total volume also encountered to be about $4x10^4$

km^3. From the petrological, geochemical and isotopical investigation, these large shield volcanic centers have different compositional magma flux of lavas from the peak of flood volcanism to the onset of major rifting in the northern part of the volcanic plateau (Kieffer et al.,2004). Similarly, this northwestern Ethiopian plateau volcanic region has been studied and mapped well with small scale by many other authors (e.g., Pik et al., 1999; Ayalew et al., 2002; Dereje Ayalew and Gezahegn Yirgu, 2003; Beccaluva et al., 2009; Natalli etal., 2016), Jita flood volcanic sequence is missing. Therefore, the present large scale study focused on this gap in order to have full scientific information about the area.

Furthermore, Pik et al. (1998) have studied the magma types of these regions on the basis of geochemical studies and classified them spatially into three distinct volcanic provinces in terms of their titanium and trace element concentration and also delineated their boundary as of low Ti (LT), High Ti-1, (HT1) and high Ti -2 (HT2) (see Figs. 2.2 and 2.3). In this classification system, the LT rocks are restricted in the western part of the northwestern Ethiopian province, but the HT1 and HT2 rocks are situated in the south- eastern and north-eastern part of the plateau, respectively. Based on this geochemical variation, the current study area falls in the region of HT1 suite, which is closest to the Main Ethiopian rift margin. Temporally, the early part of the Jita volcanic section has been dated by Ayalew et al. (2002) with Rb-Sr isochrons on the whole rocks and mineral separates (ca.30.1±0.4 Ma) implying that the silicic volcanism commenced during the Oligocene eruptions within ~2 Ma and was named as Wegel Tena rhyolitic-ignimbrite units. Overall, most studies of the northwestern Ethiopian plateau have been focused on a regional study with respect to geochemical analysis, and very little attention was given to detailed stratigraphic analysis with petrographic investigation. Therefore, the present study focuses on a petrographic analysis in detail flow- by -flow with large scale in terms of stratigraphic framework to fill the previous scientific gaps.

1.2. Geographic setting of the study area

1.2.1. Location and Accessibility

The study area is situated in the western part of North Wollo Zone, Amhara National Regional State of Ethiopia. Geographyically, the area is bounded by a grid of easting, which ranging from 490449 (min) to 524603 (max) m and Northing of 1274533 (min) to 1300741 (max) m in UTM (Universal Transverse Mercator) coordinate system. The map covers an approximate area of 742.4 km^2. The area is highly rugged and devoid of rural feeder roads (see Fig.1.1). The major road adjoining Addis Ababa-Woldia to Gashena is a principal road to arrive at the study area with an estimated distance about 621 km. And also there is another alternative road that runs from Addis Ababa-Dessie-Kutaber to Wegel Tena (ca.561 km) which is partly gravel. The road running from Gashena -Kon-Wegel Tena to Dessie town which is under construction gave major access since it bisects the major study of Jita volcanic terrain.

There are also minor dry weather roads, especially on the flat plateau. Much of the area is deeply dissected by Jita, and many other small and deep non-perennial streams (e.g., Gazo River) that feed the Jita River.

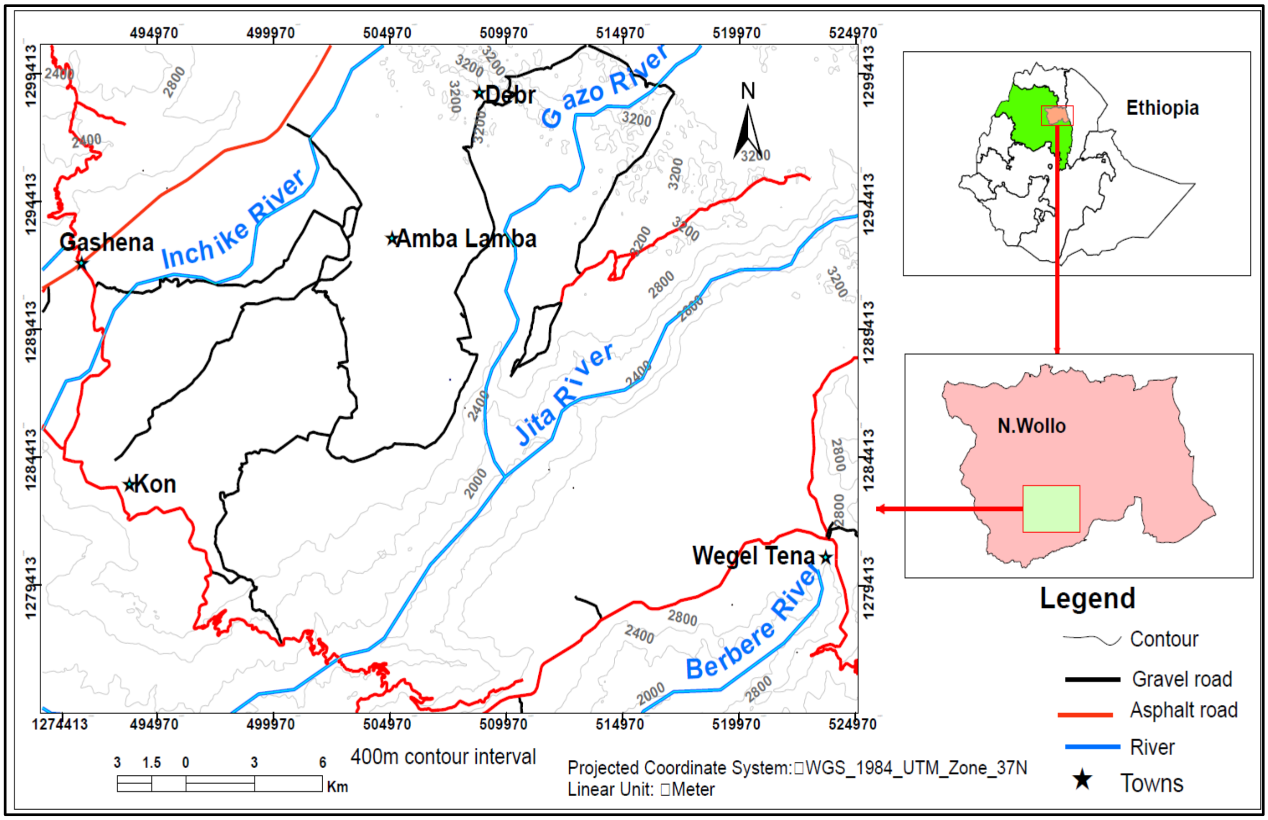

Figure 1.1: Location map of the study area.

1.2.2. Physiography and Drainage Characteristics

1.2.2.1. Physiography

Physiographically, the study area belongs to the northwestern highlands of Ethiopia. The area can be classified into two major physiographic regions. These are the plateau area, especially Gashena-Kon-Gazo have flat highlands. Part of the area are characterized by non- uniform flat highlands, especially the Debr and east of Kon area which have minor patchy hills with high elevation and some depressions. The other physciographic unit is the rugged and deeply dissected terrain of Jita plateau. These rugged terrains are the dissected erosional remnant surface and slopes which are gentle to very steep. Generally, the study area has variable in relief. The highest morphologies are exposed on the east of the Gazo flat plateau, which have an estimated elevation around 3250 m above sea level. In addition, the higher plateau surfaces are also found around Gashena and north of Kon areas, with a range of elevation from 2920 to 2880 m above sea level.

On the contrary, the lower rugged places in the study area lie at the confluence of Jita feeder streams, which records about 1700 meters above mean sea level. The undulating surface found around the town of Gashena and northeast of Kon area lies in between 2860 to 2910 m. These highlands and rugged terrains are erosional remnant, which have worn down many volcanic successions of the region. The remnant plateau areas are all covered by plateau volcanic rocks.

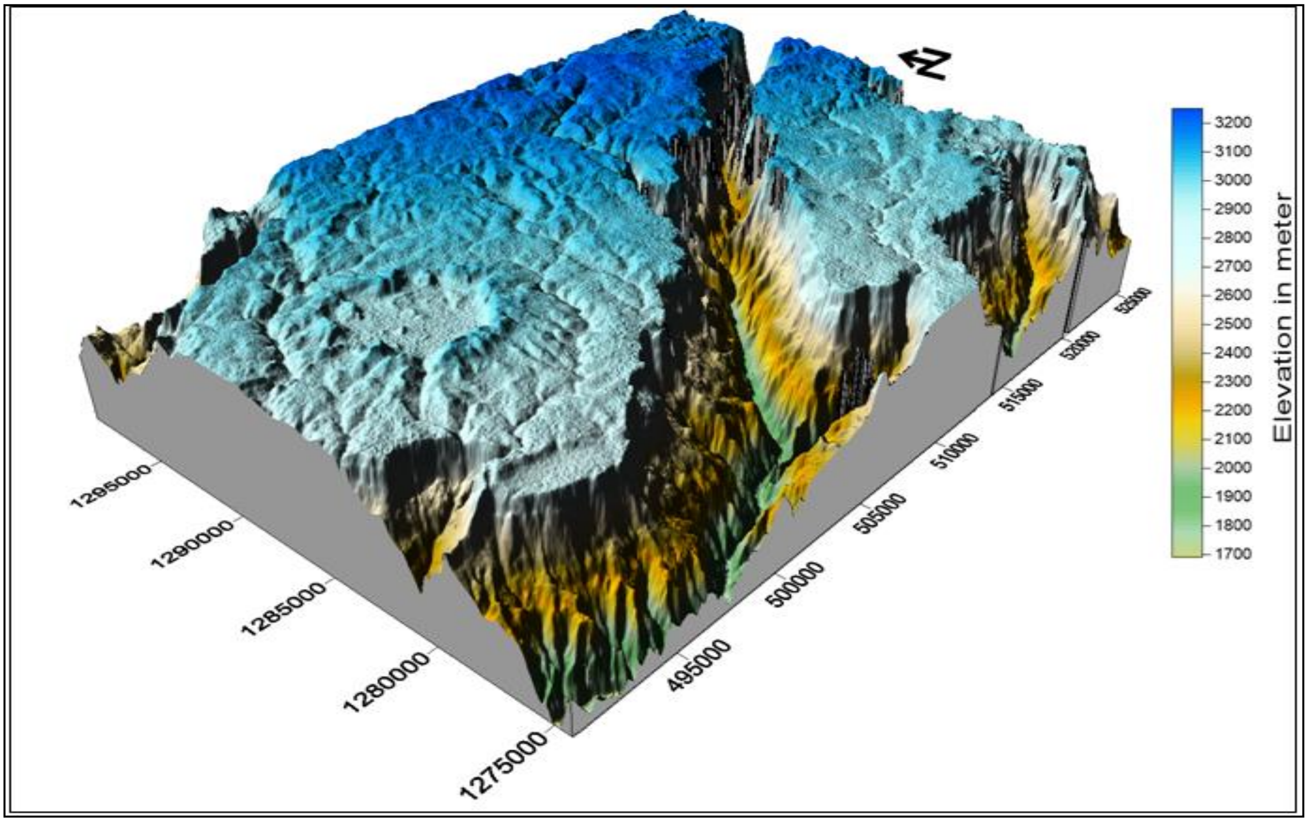

Figure 1.2: Physiographic map of the study area (3D view).

1.2.2.2. Drainage

The major stream in the study area is Jita River with NE-SW trending flow direction on slightly tilted and deeply weathered aphyric-intergranular basalt. All other minor streams are tributaries to this main perennial river (see Fig.1.1). The small tributaries run from the steep slopes, have dendritic character and are non-perennial flows. Most of them are flowing from the highlands of the plateau, which are located in the northern and eastern part of the study area such as highlands of Kon, Wegel Tena and Gazo plateau escarpments. The drainage density is high in most places. High drainage densities together with high rainfall (see Fig.1.3) resulted in deep dissection. As a result, the major stream course lies in the deep gorge of Jita locality.

1.2.3. Climate and vegetation

The climate condition within the country is more affected by altitude change (Daniel Gemechu, 1977) who classified the terrain as Desert or Bereha (<800 m), Tropical or Kola (800 -1500 m), Subtropical or Weyna Dega (1500-2300 m), Temprate or Dega (2300-3300 m) and Alpine or Kur (>3300 m). Based on this, the study area has a range of climatic conditions from Subtropical or Weyna Dega (1500-2300 m) to Temperate or Dega (2300-3300 m). The flat highlands of Kon, Gashena, Hamusit and north of Gazo areas are relatively cold, especially during the night and belong to Temperate or Dega type. In these areas, air humidity is also high. However, south of Kon and Robit areas are categorized in the subtropical classification scheme.

In addition, the study area is included within the Debot metrological station accessed from https://en.climatedata.org/africa/ethiopia/amhara/debot-564611/28/3/2019.

The maximum temperature registered in the study area is around 18.6 °C on the month of June and the minimum temperature is accounted for 6 °C during December. The average annual temperature of the area is about 16.6 °C. In a similar way, the rainfall distribution of the area is characterized by a more increment in summer seasons than winter months. The average annual rainfall is estimated around 758 mm and the precipitation difference is also about 221 mm in between the driest and wettest months. Overall, the climatic condition of the study area is revealed by the bar graph (see Fig.1.3). Highlands of Gashena-Kon and Hamusit areas are extremely vegetated with Eucalyptus which is very common throughout the plateau. However, the lowland along Jita stream and its tributaries has sparsely growing shrubs and short trees like Embachio, Girar, and Tinjut (which is adapted from Ethiopian name).

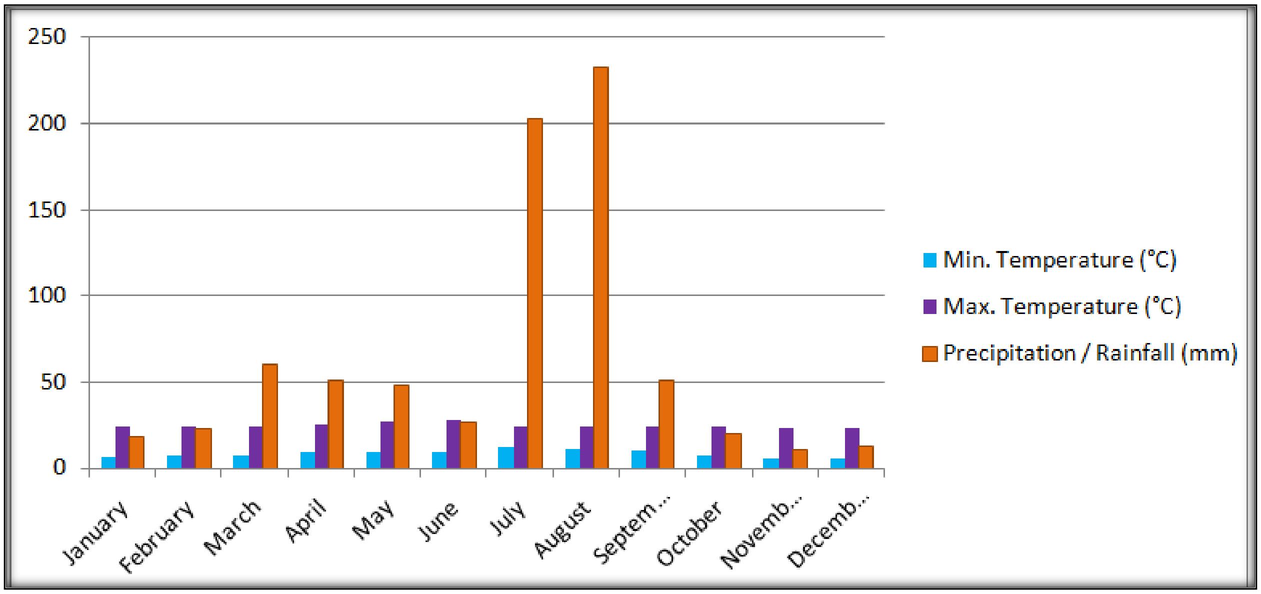

Figure.1.3: A bar graph represents the average monthly temperature and precipitation condition of the study area. https://en.climatedata.org/africa/ethiopia/amhara/debot-564611/28/3/2019.

1.2.4. Population and settlement

The study area is covered around 90% by Kon district which is one of the Weredas in the North Wollo Zone. It is bordered to the southeast by Delanta (Wegel Tena), in the southwest by Dawunt, in the north by Meket, and in the northeast by Guba Lafto Wereda. Due to the large areal coverage of the study locality, the population data of Wadela Wereda has been taken for this study. Based on the 1994 national census (reported by the Central Statistical Agency of Ethiopia (CSA)), a total population of the area was about 106,681 in which around 24,473 are households, and 54,760 are men and 51,921 are women; 1,506 or 1.41% of its population are urban dwellers. The largest ethnic group reported in the Wereda is Amhara nationality, which accounted for 99.94%. Amharic is a first language for all dwellers. The majority of dwellers in the area follow the Ethiopian Orthodox Christianity and they are around 96.21% and 3.78% of the population are Muslim dwellers. However, since the 2007 national census has counted by the former already mentioned statistical agency, the area has a total population of 128,170, an increase of over the 1994 census, of whom 64,574 are men and 63,596 women in which 4,291 or 3.35% are urban inhabitants and the remaining are rural dwellers.

The rural dwellers commonly practice a sedentary type of farming. They cultivate cereal crops such as Barley, Maiz, Teff, Sorghum and Wheat. From these listed crops, Sorghum and Wheat are mainly cultivated in the highland of cold plateau topographic areas. However, Maize and Teff are commonly cultivated in the rugged terrain (along Jita River). In addition to crop production, they also engage in animal raring in the highland area.

1.3. Statement of the problem

A number of studies (e.g., Mohr, 1983; Mohr and Zanettin, 1988; Pik et al., 1998, 1999; Kieffer et al., 2004; Becclauva et al., 2009 and references therein) have been carried out in the northwestern Ethiopian plateau continental flood basalts including some shield volcanic centers with a regional scale, but detailed investigations on a single sections of lava flows within the plateau are very scarce. Similarly, the Jita River flood volcanic series has been studied at a regional scale showing the underlying trap basalt, overlain by the rhyolitic-ignimberite sequences of Wegel Tena locality and have produced a regional geological map, stratigraphic sections with the help of petrographic and geochemical analysis sampled from the whole area (e.g., Hofmann et al., 1997; Ayalew et al., 2002; Ayalew and Yirgu, 2003, respectively).

As a result, incomplete and very limited petrographic and volcanic-stratigraphy data's were available along Jita River flood volcanic province. Therefore, there was a scientific gap and the current research work aims at detailed, flow- by- flow petrographic investigations of flood volcanic rocks in terms of their volcano stratigraphic framework to fill the existeing scientific gap and also constraint the magmatic plumbing systems or eruption history of the volcanic flows for having the full scientific information of the area.

1.4. Objectives of the research

1.4.1. General Objective

- The main objective of this thesis work is to establish the volcanic-stratigraphy of flood volcanics and describe the petrography of these rocks.

1.4.2. Specific Objectives

- To produce a geological map presents the distribution of different lithological units.
- To reconstruct the eruptive style (magmatic plumbing systems) and history of the volcanic rocks on the basis of mineral phenocryst and microphenocryst phases.

1.5. Significance of the research

As illustrated in the statement of the problem, this thesis work is the first to provide a detailed petrography and volcano-stratigraphic study along Jita river flood volcanics. Finally, the following outcomes are provided:-

- This study is important to fill the existing scientific gap of the area from the previous researchers by conducting a detailed petrographic description in each volcanic flow and also preparing a geological map of the area to provide a qualitative scientific data.
- A new petrovolcanic stratigraphy results in this study makes a contribution to understand the magmatic plumbing system or petrogenetic evolution (history) of rocks in the area.
- Moreover, this study will be used as an input of data and reference framework for students, scientific community and other researchers in order to use for further study.

1.6. Previous works

The Ethiopian large volcanic province (LVP) is composed of a Tertiary basaltic pile, with an estimated thickness varying from 700 to 2000 m. It covers an area of several hundred kilometers across on the Ethiopian plateau on either side of the Main Ethiopian Rift (MER) and Afar Depression (Berhe et al., 1987). Kieffer et al. (2004) have noted that the petrological, geochemical, and isotopic data of flood basalts associated with shield volcanoes, by comparison of their compositions and also traced their variations in terms of eruption style and magmatic flux of lavas having a range of ages from the peak of flood basalt volcanism to the onset of major shield volcanism in the northwestern part of the Ethiopian volcanic plateau. These Volcanic successions also exposed on a sub-horizontal Mesozoic sedimentary stratum in the southwestern part of the northwestern Ethiopia volcanic regions. Ayalew et al. (1999) have documented that interlayered felsic lavas and pyroclastic rocks of (rhyolitic-ignimbrite) and subordinate trachytic volcanic rocks found at the upper volcanic stratigraphy, associated with the flood basalt. Some regional works have revealed that the Ethiopian continental flood basalts are aphyric to sparsely porphyritic with phenocrysts of plagioclase and clinopyroxene with or without olivine minerals (e.g., Mohr, 1983; Mohr & Zanettin, 1988; Pik et al., 1998). Additional study has been conducted by Dereje Ayalew and Gezahegn Yirgu (2003) that these Ethiopian continental flood basalt (CFB) province (~30 Ma, with volume of >3 x 10^5 km^3) has formed as the result of the impingement of the Afar mantle plume head beneath the Ethiopian lithosphere.

According to Mohr, P. (1983); Hofmann et al. (1997) and Kieffer et al. (2004) the outpouring fissural flood basalt volcanism was succeeded by the overlying emplacement of large shield volcanoes. Such a large shield volcanoes are Simen, Guguftu, Choke and Guna which situated in the northwestern Ethiopian plateau developed on the peak surface of the volcanic region. Additionally, Ukstins et al. (2002), and Kieffer et al. (2004) have provided an absolute 40Ar/39Ar age determination on Oligocene-Miocene flood volcanics and Miocene-Pliocene volcanoes from this volcanic region. On the other hand, Pik et al. (1998, 1999) documented that the detailed geochemical studies on the Oligocene flood basalt (Trap formation) of the Northwestern Ethiopian plateau regions and subdivided it into three distinct geochemical groups which already mentioned earlier.

According to Gezahegn Yirgu (1997), the Ethiopian Cenozoic volcanic province constitutes one of the largest intracontinental magmatic provinces which erupted during the Cenozoic age with the emission of huge amounts of flood basalts and interbedded ignimbrites, in which the flood lava sequence is partly overlain by shield volcanos of Tarmaber formation. The recent study revealed that the southwestern part of the northwestern Ethiopian plateau is covered by alkaline lavas of Quaternary volcanic centers (Beccaluva et al., 2009). The study area is located in the part of the northwestern Ethiopian plateau, which has conducted regionally by using geochemical study to compaire with other Ethiopian volcanic sections for understanding of magma-crust interaction during the emplacement of bi-modal Cenozoic volcanism in Ethiopia (Ayalew et al., 2002 and Kieffer et al., 2004). Temporally, Northern and NW Ethiopian flood basalts are classified into four main stages based on time of eruption by Zanttien et al. (1978). After a decade, Berhe et al. (1987) classified the

NW Ethiopian flood basalts into three stages as the Ashangi, Aiba and Alaji formation based on their lithology, ages and chemical characteristics. Although it seems to be no apparent break in volcanism between the Aiba and Alaji Basalts, it is clear that the Alaji is represented by bimodal volcanism (abundant rhyolitic-ignimbrites and basaltic volcanism, with a subordinate of phonolites). However, shield volcanoes were considered as a fourth stage because many of them are separated by thick palaeosols which indicate a time gap between fissural volcanism and central volcanoes, and they form the most alkaline rocks of the whole volcanic succession (Kieffer et al., 2004).

1.7. Research Materials and Methods

1.7.1. Materials

To conduct the present research work, the following materials have been used:

- ❖ Topographic map with a scale of 1:50,000.
- ❖ Hand lens, Brunton compass, Geological hammer, Digital camera and GPS with high accuracy.
- ❖ Field notebook, Pen, Pencil, Marker, Plaster and Sample bag.
- ❖ Petrographic microscope (Leica).
- ❖ Software's (Surfer, Starter 4, Arc GIS 10.4, Global Mapper 20, DEM 30 m, Google earth (2019) and ERDAS (2015).

1.7.2. Methods

To achieve the general and specific objectives of the study; the following major methods have been conducted.

1.7.2.1. Revision of previous works

Collecting of any related secondary data from different sources presented in journals, technical reports, unpublished papers, textbooks, and websites, which focus on the study of northern and northwestern Ethiopian plateau intracontinental Cenozoic flood and shield volcanoes with respect to petrology and geochemistry investigations. Reviewing these collected data's helped to get a broader understanding on petrography and insight into the general geologic framework. Based on these previous studies, procedures and ways of data analysis, synthesizing, presentation, and interpretation techniques, this study has been accomplished. Moreover, reviewing any related secondary data which have been conducted in northeastern, central and southern Ethiopian flood basalt and shield volcanic plateau have been used as a reference input for the present study.

1.7.2.2. Field observation, description and stratigraphic sampling

The following major activities have been carried out during field work

- Tracing traverse lines (3 in number) on the topographic map.
- Proper stratigraphic sampling, labeling and sectioning of fresh and unaltered rock samples from representative bedrock for petrographic analysis.
- Making detailed geological mapping and delineating structural continuity or contacts
- Estimate thickness of each lava flow.
- Flow- by -flow rock descriptions with respect to stratigraphic framework from the base of the section towards the top of the stratigraphic sequence.
- Recording on GPS data from each sample location.
- Photographs have been taken at representative structures and outcrop features.

1.7.2.3. Petrographic analysis

Thin-section samples were analyzed for determination of different minerals, textures and modal proportion for detailed understanding of rock formation. A total of 13 fresh and representative stratigraphic rock samples have been collected from each flow and these thin section samples have been prepared at Addis Ababa university thin-section laboratory. After the preparations of these thin-section, detailed descriptions have been done under the petrographic microscope (used both PPL and XPL view).

1.7.2.4. Data synthesis, interpretation and presentation

Data analysis, synthesizing and interpretations are the basic tasks for this research work. The data has been synthesized using petrological models in order to get coherent and meaningful information for final interpretation. Data collected from field work and laboratory analysis have been analyzed, interpreted and presented with tables, graphs/figures and maps as well as text in order to reach this final report.

The manuscript provides description of the lava flows and petrographic observations. However, the data of thin-section descriptions and climatic conditions have been presented with tables and bar graphs, respectively. The previous documented data were used as an input of reference to strengthen the actual work.

1.8. Thesis framework

This thesis work is structured in five chapters. The first chapter reveals general information of the study area, and also methods, objectives and purpose of the research. Second chapter provides a regional overview of the geological setting of the area. Chapter three gives a detailed description of petrography and volcanic stratigraphy of lava flow, in terms of mineralogy (representative phenocryst and some microphenocryst phases), textures and geological structures of the study area. Chapter four consists of that the discussion and interpretation on the magmatic evolution (eruptive history) of Jita volcanic suites. Finally, chapter five comprises the conclusion of the current study and some recommendations for further study in the future.

CHAPTER TWO

2. Regional Geological Setting

2.1. Ethiopian continental flood volcanism

By following the Mesozoic regression of the sea from the east and southeast, an epirogenic uplift of Afro-Arabia (East Africa, Arabia peninsula and the intervening regions of Red Sea and Gulf of Aden) occurred on an immense scale of Ethiopian LIP magmatism (e.g., Cherenet et al., 1998). The cause and initiation of the major uplift and the first eruption of flood basalts in Ethiopia is closely related to a mantle plume head. Henceforth, this continental flood basalt volcanism was widespread in the early Eocene to Oligocene (Trap flood basalt) and extended in the northwestern and southern Ethiopian plateaus (Mohr and Zanettin, 1988; Ebinger et al., 1993; references therein). This Ethiopian Cenozoic continental flood basalt is considered as the youngest flood basalt on the earth's surface with respect to other continental flood provinces worldwide (e.g., Baker et al., 1996a; George et al., 1998; Ayalew et al., 1999; Dereje Ayalew and Gezahegn Yirgu, 2003; Kieffer et al., 2004). The basaltic plateau is almost entirely composed of lava flows, occasionally including dyke swarms (Mège and Korme as cited in Abbate et al., 2014), and underlain by Mesozoic sedimentary units or the Pan-African crystalline basement (Beccaluva et al., 2009 and references therein).

Geomorphologically, this intra-continental flood basalt province is located at the junction of three rifts: two of oceanic rifts that are Red Sea and Gulf of Aden, and the third one is a continental rift which is the East African rift (Pik et al., 1998; Dereje Ayalew and Gezahgn Yirgu, 2003). These two oceanic rifts are connected to the less developed east African rift at the Afar triple junction. This triple junction is the center of active large volcanic province, which is exposed in Ethiopia (Pik et al., 1998). In addition, this young continental flood volcanism is situated in Yemen that presumed to be associated with the Afar plume head (Ayalew et al., 2002; Ukstins et al., 2002) and the initial role of the mantle plume changes spatially within the Ethiopian province (Ayalew et al., 1999). Supporting idea has been raised by Abbate et al. (2015) that the present-day morphology of Ethiopian plateau is linked to the formation of the Afar depression and MER, and these events are networked with the impinging triggering factor of either one or more mantle plumes under the Afro-Arabian plate and the elevated topography of these Ethiopian plateaus (George et al., 1998). The earlier ideas have been strengthened by the recent works (e.g., Abbate et al., 2015) by describing the impinging plume gave the extrusion of huge amounts of magma, uplift, and fragmentation of the continental crust and contributed to the birth of the Red Sea, Gulf of Aden, East Africa Rift valley, and the adjoining Afar depression. Overall, this continental flooding magma situated in Ethiopia and Yemen has been registered as a pre-continental extension (Hawkesworth et al., 1999).

However, the earliest Eocene volcanism in Ethiopia is mainly restricted in southern and southwestern part of Ethiopia and northern tip of Kenya, which having an age of about ~45 Ma and called Mekonnen basalts (e.g., Ebinger et al., 1993; George et al., 1998; references therein). The estimated magmatic flux of Eocene initial phase is significantly lower than that of Oligocene trap phases. Furthermore, within NW Ethiopian plateau, the old flood basaltic flow rested under the Aiba basalts named as Ashangi basalt of around 33 to 30 Ma (Berhe et al., 1987). Afterwards this event, this continental flood volcanism has been widespread throughout Ethiopian and Yemenite regions associated with subordinate felsite pyroclastic rocks (Baker et al., 1996a; Hofmann et al., 1997; Pik et al., 1998, 1999; Ayalew et al., 2002; Dereje Ayalew and Gezahegn Yirgu, 2003; Kieffer et al., 2004). After the main volcanic emplacement of trap flood basalt, a number of large shield volcanoes were commenced around 30 to 10 Ma on the surface of the northwestern Ethiopian volcanic plateau (Kieffer et al., 2004; Beccaluva et al., 2009).

Volcanism in Ethiopia has been explained to be bimodal with respect to silica content that developed in a thick succession of lavas flow and pyroclastic rocks, with a range of value from 500-1500 m thick, and covering an estimated area about 6×10^5 km^2. It is exposed on the western and eastern uplifted plateau and the Main Ethiopian rift (MER) and also Afar depression (Mohr, 1983; Peccerillo et al., 2003). These spectacular landscapes of Ethiopia were formed by geodynamic and geomorphic processes which shaped this territory; mainly since the Oligocene time (Abbate et al., 2015). Plateau volcanic rocks are mainly represented by basalts, which were traditionally referred to as the trap succession. It is estimated to be cover an area greater than 750,000 km^2 before erosion (Abbate et al., 2015) and has a total volume of about 350,000 km^3 (Mohr, 1983).

Earlier, the stratigraphy of volcanic rocks in Ethiopia have been grouped into three major classes (e.g., Pre-oligocene, Oligo-Miocene and Mio-pliocene) with four subdivisions on the basis of time of eruption, such as pre-Oligocene (Ashangi), Oligocene (Aiba formation and Alaji Termaber Guassa), Miocene (Alaji molale and Termaber Megezez) and Miocene-pliocene (Bishoftu Formation) stages by Zanettin et al. (1978, 1980). Moreover, these volcanic rocks have been subdivided into five major provinces based on their lithological development, volcanic activity, and frequency of volcanic centers and age of effusion (Abbate and Sagri, 1980). These are volcanics of the northern plateau; southern plateau; Somalian plateau; Afar volcanites; and Main Ethiopian Rift (MER) volcanics. The first three groups comprise the major part of the Ethiopian volcanites (Merla et al., 1979) see Fig.2.1. Recently, the earlier volcanic classification systems were modified by Peccerillo et al. (2003) who revealed that magmatic evolution in Ethiopia has commenced as three main stages. The first stages recorded about 50-10 Ma, in which the Ethiopian plateau was developed by the eruptions of flood tholeiitic to transitional basalt lava flows, and interbedded with mildly alkaline trachytic and rhyolitic-ignimbrites (Mohr & Zanettin, 1988). A second stages of volcanic activity commenced around 10-5 Ma and were constructed several shield volcanic centers made from transitional to sodium rich alkaline basalts and minor trachytes (Peccerillo et al., 1979). The last stages are ranging from Pliocene to present, which are more directly related to the formation of Main Ethiopian Rift (MER) and Afar depression.

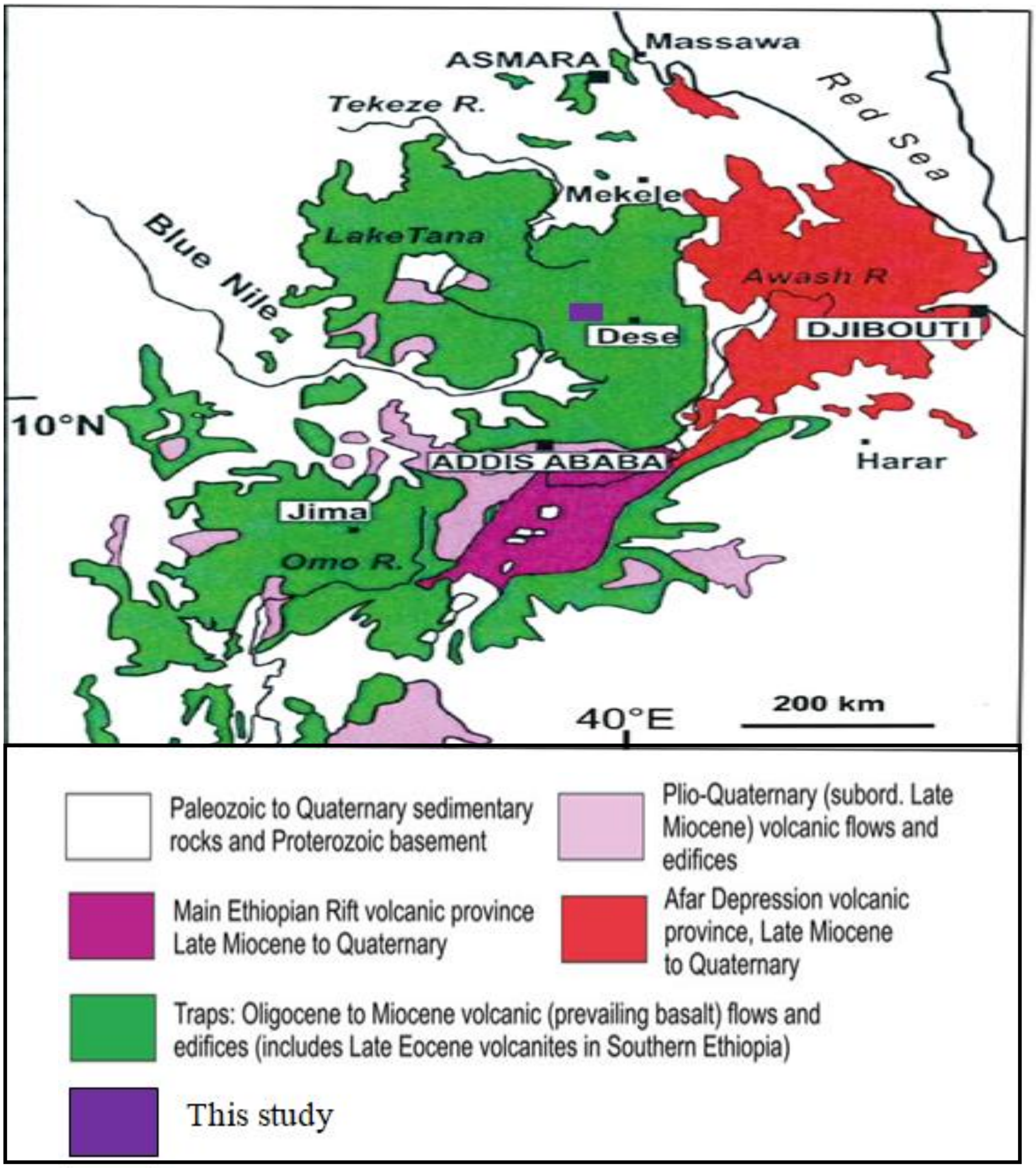

Figure 2.1: The main volcanic provinces in Ethiopia (adapted from Abbate et al., 2014).

2.1.1. Volcanics of northwestern Ethiopian plateau

The Ethiopian CFB province comprises the NW plateau which is clearly associated with rifting (extensional tectonics), which appears to be the consequence of lithospheric stretching, associated with the upwelling of Afar mantle plume head (Marty et al., 1996). Volcanism initiated around 30-31

Ma (belongs to Oligocene time) in the northern portion of the northwest Ethiopian plateau and continues episodically up to the present time (Hofmann et al., 1997). Following the end of Oligocene, the volcanic activities were shifted toward the Afar depression, which was experiencing a progressive stretching, and successive movement in between southern Ethiopian and Somali plateau, in correspondence with the formation of Main Ethiopian Rift (Abbate et al., 2015). Onset of rifting, the earliest magmatism predates around 28 Ma (Ukstins et al., 2002). This Continental flood volcanism (CFV) is the massive outpourings of basaltic lava flows with associated rhyolitic lavas and pyroclastic rocks (Baker et al., 1996a; Ayalew et al., 2002; Ukstins et al., 2002 and Kieffer et al., 2004) in the upper stratigraphic level. The ideas of Marty et al. (1996) have been supported by some scholars (e.g., Dereje Ayalew and Gezahegn Yirgu, 2003; Rooney, 2017) that these NW Ethiopian continental flood basalt (CFB) provinces and associated continental break-up volcanic rocks are formed from the upwelling of mantle plume impingement under the base of the lithosphere. Most part of NW CFB provinces that contains a significant volume (about 20%) of the total of acidic volcanic rocks (rhyolite) usually capping in the upper part of the basaltic sequence (Ayalew et al., 2002). These volcanic plateaus are overlain by conspicuous low-angle shield volcanoes whose composition matches that of the underlying flood basalts and rhyolites (Ayalew et al., 2002; Kieffer et al., 2004; references therein). Furthermore, this Ethiopian continental flood basalt province has bimodal basaltic-rhyolite rocks in all volcanic suites with lack of intermediate compositions (Ayalew et al., 2002; Dereje Ayalew and Gezahegn Yirgu, 2003). This Ethiopian volcanic province is typically distinict from other worldwide volcanic regions by the presence of conspicuous shield volcanic centers (e.g., Choke, Guguftu, Simen, Guna and Megezez) that overlie a series of flood basalts Mohr & Zanettin (1988); Kieffer et al. (2004). This northwestern Ethiopian volcanic plateau is a thick, monotonous, and rapidly erupted pile of flat-lying tholeiitic basalts on the contrary to worldwide continental flood basalts (e.g., Deccan and Karoo provinces (Kieffer et al., 2004)).

The magmatic character varies from north to south of the NW Ethiopian plateau and within each region, but the character of the overlying shield volcanoes matches that of the underlying flood basalts. The compositions of these flood and shield basalts reflect that the two types of eruption were fed by the same conduit system (Kieffer et al., 2004). On the contrary, in between Lalibela and Dessie towns, these basaltic flows are strongly deformed and commonly encountered a dip value range from 20 to 60° (Merla et al.,1979). This observation has emphasized that these deformations occurred synchronously during the magmatic eruption of flows (Pik et al., 1998; Kieffer et al., 2004).

The study area lies in the central part of northwestern Ethiopian plateau and the area is underlain by Pre-rift volcanic successions outpoured during Oligocene time (Kieffer et al., 2004).

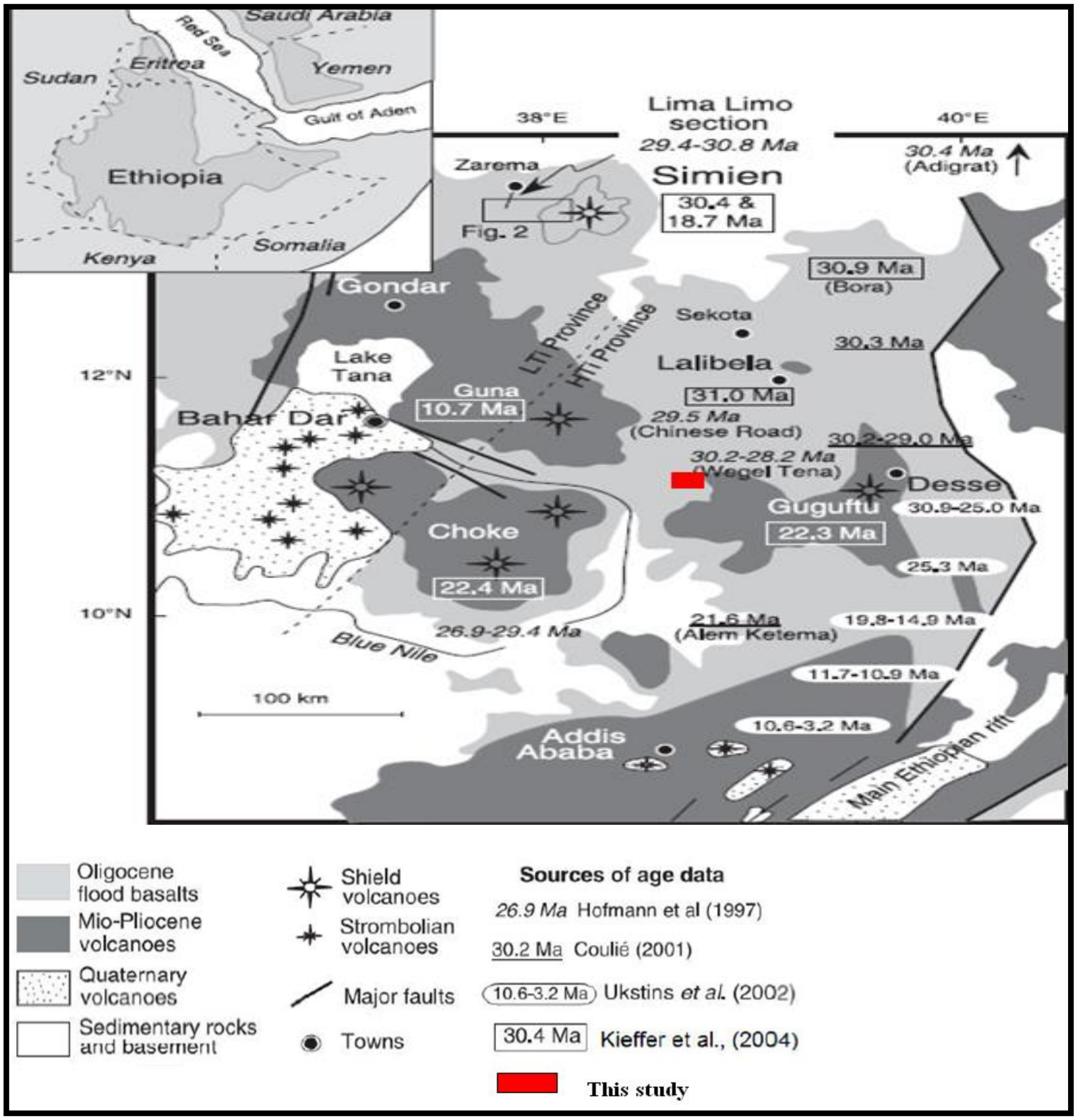

Figure 2.2: Geological map of the Central and Northwestern Ethiopian plateau flood volcanism (after Kieffer et al., 2004) and the red rectangular box locate the area of the present work.

2.1.2. Volcanic stages in Northwestern Ethiopian plateau

Earlier, the NW Ethiopian Tertiary volcanism were also categorized into three main stages with their subdivisions which separated by periods of quiescence (Zanettin et al., 1978, 1980). Each stage has been subdivided into one or more volcanic formations. However, some volcanic stages were added by some authors such as Wegel Tena Oligocene rhyolitic-ignimbrite (e.g., Ayalew et al., 2002) and near Lake Tana graben Quaternary volcanics mainly erupted in the Pliocene time (e.g.,Tefera et al., 1996).

2.1.2.1. Pre-Oligocene stage

2.1.2.1.1. Ashangi Formation

The Ashangi Formation represents the earliest fissure-fed flood basalt volcanism on the northwestern Ethiopian plateau (Tefera et al., 1996). This trap lava flow is mainly characterized by faulted, tilted, crushed and weathered nature found unconformly under the major Oligocene (Aiba) basalt, having of several hundreds of meters to kilometers thickness (Zanettin et al., 1980). This temporal volcanic classification scheme has been supported by radiometric age determination (K/Ar). However, without other field and geochemical evidence this K/Ar dates alone may not provide a conclusive criterion of volcanic succession of the regions (Tefera et al., 1996). From the work of Zanettin et al. (1980), this tilted and crushed basaltic flows of the Ashangi Formation gave K/Ar ages younger than that of the overlying Aiba basalts. In such scenario, the field evidence such as intensity of alteration (often highly zeolitized) and weathering enabled to distinguish between the two volcanic pulses.

In addition, Ashangi Formation consists of predominantly mildly alkaline basalts with interbedded pyroclastic and rarely rhyolitic lava flow, which is commonly injected by doleritic sills and dykes (Tefera et al., 1996). In the upper part of the unit, there are more tuffacious and interbeded lacustrine deposits with lignite coal seams. It was believed that these early flood basalt flows are restricted in the northwestern Ethiopian volcanic regions (Zanettin and Jusetin Visentin, 1975; Merla et al., 1973 as cited in Tefera et al. (1996). The age of the Ashangi Formation in the northwestern plateau remains uncertain (Zanettin et al., 1980). The oldest reported age data for volcanic rock preserved on the northwestern Ethiopian plateau is about 54 Ma (Kazmin, 1979 as cited in Tefera et al. 1996). Furthermore, basaltic lava flows and tuffs are interbedded with Jurassic and Cretaceous sediments that have been mapped in Sekota area which is a part of NW Ethiopian plateau which is an evidence for the earlier basaltic volcanism is not only restricted in southern Ethiopian plateau and also not only restricted by Oligocene time in NW Ethiopian plateau (Merela et al., 1973 as cited in Tefera et al. (1996). Due to this reason, the general eruption age remains unresolved for this Ashangi lava flow with a range of age from Eocene to Oligocene time (Tefera et al., 1996).

2.1.2.2. Oligocene stage

2.1.2.2.1. Aiba transitional basalt

The Aiba basaltic lava flow is the second major volcanic pulse of fissural succession on the northwestern Ethiopian plateau (Tefera et al., 1996). The vast part of peneplain of Ashangi flows were uniformly fractured and flooded by huge quantities of Aiba basalts. Its composition is transitional between tholeiitic and mildly alkaline (Zanttin et al., 1974a; 1975 as cited in Zanttin et al., 1978; Zanettin et al., 1980). These lava flows are generally characterized by aphyric and compacted nature and also in their exposure site, they show stratification with a rare patchy interbedded basaltic tuffs (Tefera et al., 1996). This continental basalt flow is unconformably overlain on the Ashangi Formation and accounts for a range of thickness around 200-600 meters. Locally, scattered and interbedded pyroclastic deposits with variable thickness are observed in this flood volcanic unit.

This volcanic formation is overlain by the Alaji and Termaber volcanic units which are characterized by rhyolitic- ignimbrite with sparsely interbedded basalt flows and shield volcanism, respectively (Mohr and Zanettin, 1988). The Aiba basalts consist of well-developed vertical to sub-vertical columnar joints and massive transitional flood-basalt flows, but locally intercalating with agglomerate beds (Hofmann et al., 1997; Ukstins et al., 2002). The absolute age of the Aiba basalts ranges from 34 to 28 Ma which places them within Oligocene stage subdivisions (Zanettin et al., 1978). On the contrary, Hofmann et al. (1997); Pik et al. (1998); Ukstin et al. (2002); Kieffer et al. (2004) suggested that this lava flow erupted around 31-29 Ma. To sum up, the exact age of this flow has been not resolved so far as to compare with the previous age data.

2.1.2.2.2. Wegel Tena rhyolitic-ignimbrite

The name of Wegel Tena rhyolite-ignimbrite is adopted from Hofmann et al. (1997) and Ayalew et al. (2002) with a range of about 30.2±0.1 and 30.1 ±0.4 Ma, respectively. This felsic unit situated in northwestern Ethiopian plateau continental flood basalt (CFB) province was formed as the result of the impingement of the Afar mantle plume beneath the Ethiopian lithosphere which is generally found on top part of the flood basalt sequence (Ayalew et al., 2002). Additionally, Ayalew et al. (2002) noted that the volume of Wegel Tena rhyolite with other rhyolitic eruptions (Lima limo area) capping the upper level of the NW Ethiopian flood basalts and Jimma rhyolite layer which are estimated to be about 4.3×10^4 km^3, totally represents 20% of that of the trap basalts. The ignimberite forms highly elevated plateau topography, which is clearly observed in Delanta (Wegel Tena), Dawunt and Wadla districts. The thick unit is mainly exposed in the northern part of Wegel Tena town and it is extensively eroded and dissected by the deep gorges of Jita and Bashilo rivers which formed steep cliffs on both sides in these listed out districts (Ayalew et al., 2002).

This unit has maximum thickness of about 500 m (Ayalew et al., 2002), it is bedded and individual flows vary in thickness from 3 up to 15 m. The individual layers show variation in texture; they are dominantly porphyritic with microlitic in glassy matrix. Densely welded ignmbrites have a glassy appearance and exhibit a well-developed columnar jointing and are characterized by pink, white, light gray weathered to fresh color with fine to coarse grained pyroclastic materials. On the other hand, its composition varies from purely rhyolite to rhyolitic ignimbrite and coarse ignimbrite (GSE, 2010). Furthermore, Ayalew et al. (2002) explained from petrographic approach with phenocryst mineral assemblage phases (alkali feldspar, quartz, aegyrine-augite, ilmenite ± Ti- magnetite, richterite, and eckermanite) and determined a range of temperature values (740-900℃) and low water content (<2wt.%). Based on major and trace element patterns, they are likely to be derived from fractional crystallization of basaltic magmas with only limited crustal contribution and having similar composition to the underlying exposed flood basalts (Hofmann et al., 1997; Ayalew et al., 2002; Ayalew and Yirgu, 2003).

2.1.2.3. Oligocene-Miocene stage

2.1.2.3.1. Alaji Formation

The Alaji Formation mainly consists of aphyric flood basalt lava flows which are with rhyolitic - ignimbrite and subordinate trachytes. This formation has a range of ages between 31-13 Ma (Zanettin et al., 1980). This flood volcanism progressively decreased from the north to south region which indicated the occurrence of the older volcanic lava flow on the northern part of northwestern Ethiopian plateau. This fissural lava flow preserved in the bulk of the volcanic succession rest conformably on Aiba basaltic flow which have been noted by Tefera et al. (1996); whereas this formation is overlain by Wegel Tena rhyolitic-ignimbrite layer (Ayalew et al., 2002; Dereje Ayalew and Gezahegn Yirgu, 2003). Alaji Formation contains basalts from transitional to tholeiitic in composition and an increase in alkalinity mostly observed in the younger members of the formation.

Thus, the Miocene members of the Alaji flows are more alkaline and are associated with sub-alkaline acidic members (Tefera et al., 1996).

2.1.2.3.2. Termaber Guassa alkali basalts

The earlier fissural lava flows are followed by the emplacement of large shield volcanoes and later the development of continental rift (Mohr., 1983, 1988; Hoffmann et al., 1997). The work of Kieffer et al. (2004) supported the idea of Mohr and Hofmann by explaining the thick succession of the flood basalt is overlain by a number of large shield volcanic centers which are developed on the surface of the NW Ethiopian volcanic plateau.

These volcanic centers were erupted from the end of Oligocene to middle of Miocene period (26-16 Ma) exposed particularly along the escarpments of northwestern Ethiopian plateau and the western margin of Afar (Zanettin et al., 1978; Tefera et al., 1996). In this region, there is an exposure of Oligocene alkaline rich basalts, instead of rhyolite which are known as Termaber Gussa Formation as transition from fissural to cental or occurred both along the escarpment and within the plateau of southeastern and northwestern regions. This shield volcano becomes younger in age from north towards south, but relatively older than shield volcanic formation of Termaber Megezez Formation (Tefera et al., 1996). Therefore, the older volcanics were locally buried by volcanic edifies (Shield) which formed by alkaline basalts with hawaiites, phonolites and basanite compositional variations**.** According to this volcanic evolutionary stages, the shield volcanic centers of Semien (18.7 Ma), Choke (22.4 Ma), Guguftu (22.3 Ma) and Alem Ketma (21.6 Ma) are grouped under this volcanic stage and their ages have been registered by Kieffer et al. (2004).

2.1.2.3. Miocene stage

2.1.2.3.1. Termaber Megezez Formation

The earlier fissural volcano ended up by central volcanism with alkaline affinities having a range of ages from 15 to 7 Ma, which is closely similar in composition to that of Termaber Guassa Formation (Zanettin et al., 1978). In addition, Kieffer et al. (2004) documented the age of Guna shield volcanic center (ca.10.7 Ma) which falls in this Miocene time period. They are fissure-fed low angle shield volcanoes.

2.1.2.4. Quaternary volcanos (after 2 Ma)

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

2.1.3. Geochemical divisions of NW Ethiopian plateau lavas

The Northwestern Ethiopian volcanic plateau comprises the entire range of CFB magmas, ranging from Low-Ti to High-Ti basalts and picrites (Pik et al., 1998; Beccaluva et al., 2009; references therein). These magma types only indicate a spatial variation in the plateau, but do not reflect a temporal sequence in the regions. The work of Beccaluva et al. (2009) has further documented that the fissure-fed CFB erupted in a well-defined space and time interval, and followed by the younger shield alkaline basalts and peridotitic xenoliths that indicated a direct evidence of the nature of the mantle beneath the Ethiopian plateau.

In spatial variation, the northwestern Ethiopian continental flood volcanic regions have been categorized three geochemical divisions based on their titanium and trace element differences such as low-Ti (LT) western province around Simen Gonder, High-Ti (HT1), south-eastern included in this study, and an eastern High-Ti (HT2) province which is close to Lalibela (Pik et al., 1998). The LT basalts are tholeiitic characterized by low TiO_2 (1–2.6 wt.%), Nb/La (0.55–0.85) and higher SiO2 (47–51 wt.%). The LT suites display the lowest incompatible trace element contents or (relative deplations in Nb, Ta, Th, Rb, and peaks at Ba and Pb compared to oceanic basalts) higher compatible to crustal contamination (Pik et al., 1999). In contrast, the HT2 basalts are the most enrichment in incompatible elements (lower compatible to crustal contamination). However, the HT1 basalts generally display trace element compositions intermidate between those of HT2 and LT basalts (Pik et al., 1999). In Petrographic observation, this low TiO_2 suite has dominant plagioclase phenocrysts with aphyric-intergranular and aphyric-ophitic textures, and also presence or absence of olivine phenocrysts (Beccaluva et al., 2009; Natali et al., 2016) see Fig.2.3. The matrix comprises plagioclase with interstitial clinopyroxene and Fe-Ti oxides (Pik et al., 1998); their characteristics are consistent with tholeiitic magmas.

The HT basalts represent a continuous range in between LT and HT2 magma compositions which are highly characterized by aphyric to Ol-phyric that range from microcrystalline to coarser-grained textures. Plagioclase is rarely found as a phenocryst phase and it exhibits a sieve texture (Pik et al., 1998). Pik et al. (1998) have noted that olivine is common in the groundmass associated with clinopyroxene phenocrysts and abundant Fe-Ti oxides, which is consistent with more alkaline magmatic compositions. HT2 flood lavas are characterized by transitional to alkaline basalts and picritic compositions with a higher value of TiO_2 (2.6-5 wt.%), higher Nb/La (1.1-1.4), and lower SiO2 with 44-48.3 wt.% (Pik et al., 1998). These HT2 basalts are typically porphyritic with olivine minerals found as phenocryst phase with or without clinopyroxene, Cr-spinel, and occasionally plagioclase. Overall, LT and HT1 volcanic provinces are characterized by dominant plagioclase phenocryst phases with various amounts of olivine and clinopyroxene minerals which revealed that crystal fractionation occurred at shallow level in the upper crust. However, olivine and pyroxene mineral phases are dominated within HT2 lava suits which suggest a deeper fractionation level, either in the crust or even at the crust-mantle boundary (Pik et al., 1998). Beccaluva et al. (2009) explained these HT2 lavas of groundmass level comprise similar phases with Ti magnetite and rare alkali feldspar and phlogopite minerals.

Based on their spatial variations, the clear regional distinction between LT and HT lava suits has been made for investigations of their magmatic sources with respect to geochemical and isotopic data analysis (Pik et al., 1998, 1999; Kieffer et al., 2004; Beccaluva et al., 2009; Minyahl Teferi et al., 2014; Natali et al., 2016). The HT lavas has been generated by the melting of the Afar plume head (Pik et al., 1999; Natali et al., 2016) while the source of LT lavas was not resolved clearly which remains as a controversial issue (Pik et al., 1999; Kieffer et al., 2004; Beccaluva et al., 2009). However, the works of Pik et al. (1998) have suggested that the LT magmas were derived by shallow fractional crystallization processes which is understood from normative mineralogical models. Afterwards, at a two-stage of AFC process for LT magmas, which indicated a lower crustal and upper crustal component influencing geochemical trends (Pik et al., 1999).

The different trends and crystallization sequences suggest that the HT2 parent magmas were enriched in MgO and FeO and depleted in SiO_2 compared to the LT parent magmas. The lack of primitive basalts within the HT1 suite does not allow precise investigations of its differentiation sequence. However, according to their trends, the HT1 group apparently exhibits more similarities with the LT group than with the HT2 lava piles, but the origin of LT magmas remains unresolved due to the difficulty of constraining AFC processes using whole rock geochemistry (Pik et al., 1998). This study area is located in the HT1 province that presents the petrography and volcanic-stratigraphy of individual flows and uses these data sets to know magma-lithosphere interactions and their magmatic plumbing system. In conclusion, the Ethiopian plateau continental flood basalts have been generated by several factors in which: 1) lowered solidus temperatures of plume metasomatized mantle sources; 2) heat transferring by the plume buoyancy flux which raised the regional geotherm; and 3) decompression of the upwelling mantle (Beccaluva et al., 2009; Natali et al., 2016). Therefore, Ethiopian fissural and uplifting continental flood basalts of the plateaus and the developments of both Afar and Main Ethiopian rift (MER) systems have been attributed to upwelling of a mantle plume that is potenitaly linked with the African super plume (Pik et al., 1998; Kieffer et al., 2004; Becclauva et al., 2009; Natali et al., 2016 and references therein).

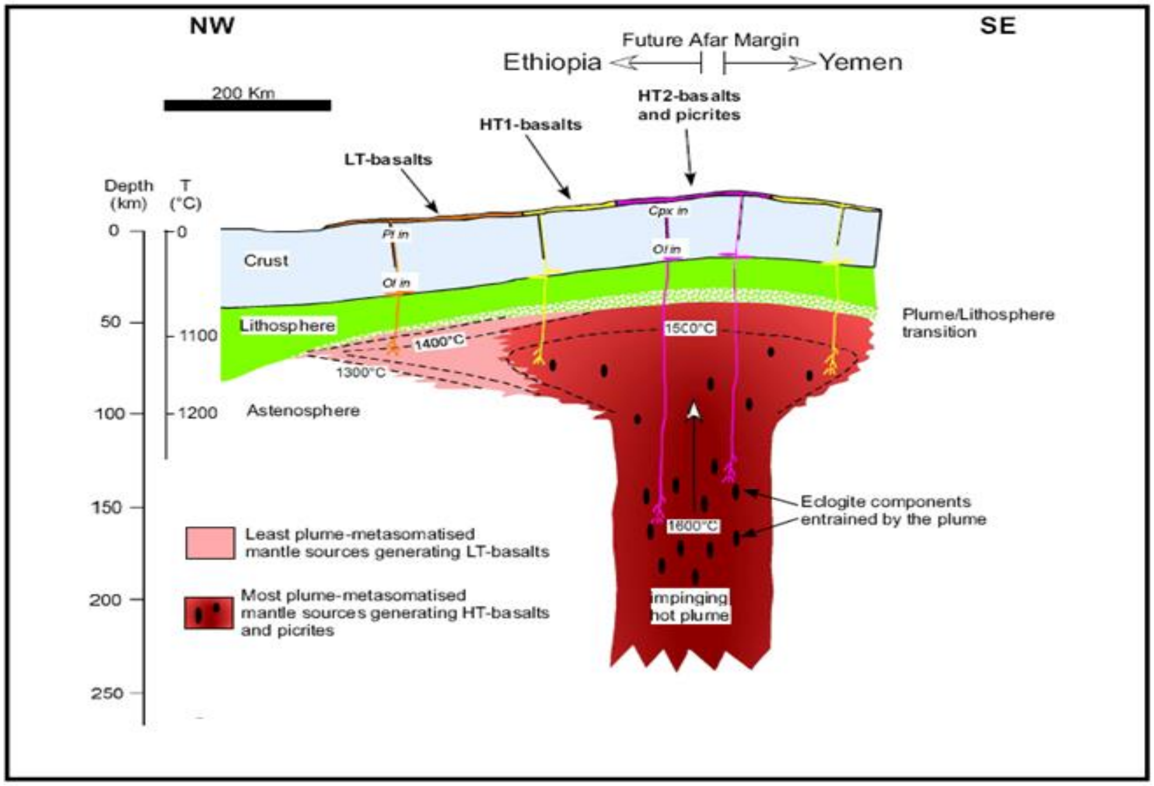

Figure 2.3: Impingement of Afar plume head on the Afro-Arabian lithosphere that led to generated the Oligocene Northern Ethiopia plateau and Yemenite CFBs from a thermally and compositionally zoned hot plume (adapted from Beccaluva et al., 2009; Natali et al., 2016).

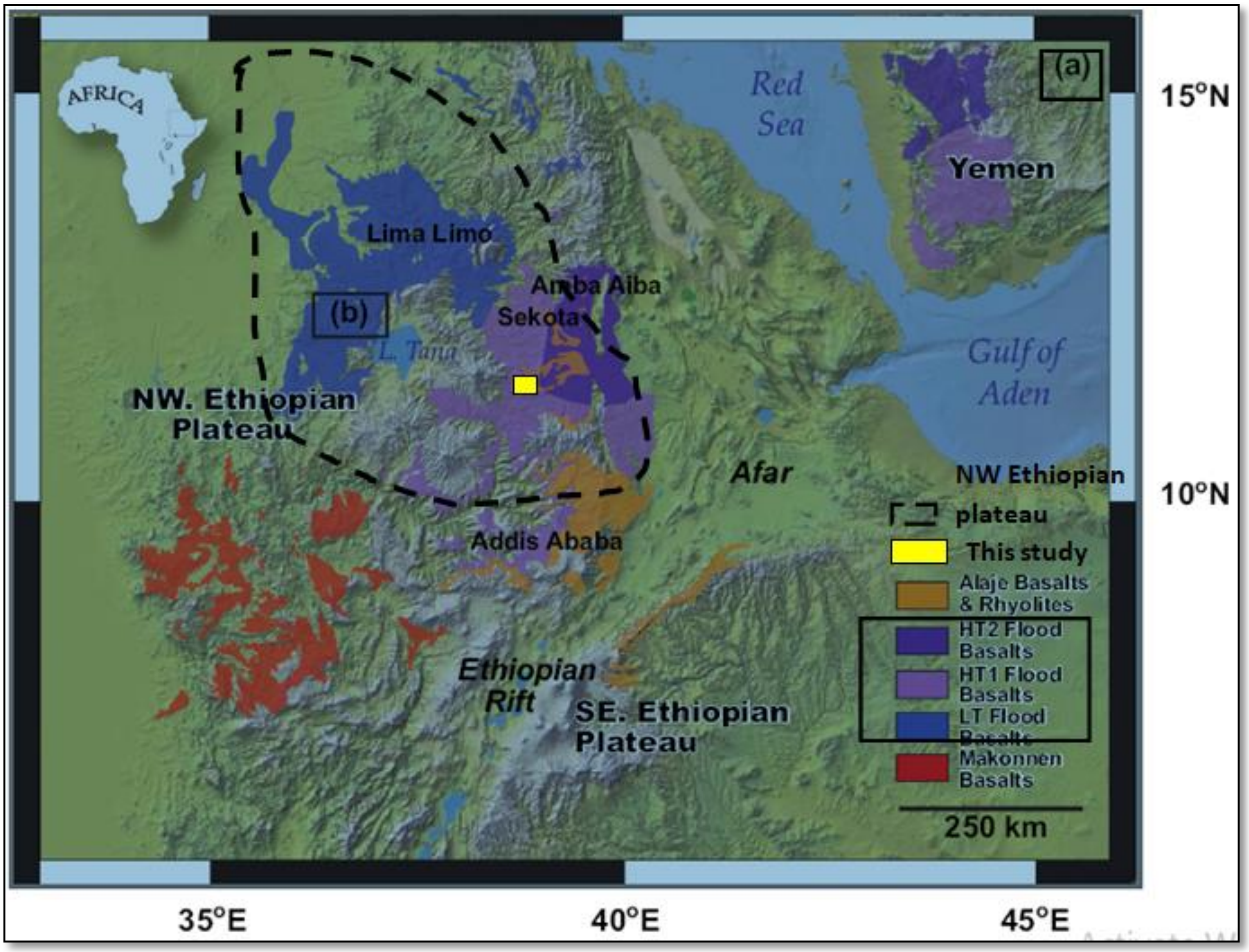

Figure 2.4: Geological map of the Ethiopian large igneous provinces (LIP) including Yemenite conjugate margins, with respect to titanium distributions: LT= low-Ti tholeitic basalts, HT1= high-Ti tholeitic basalts, HT2= very high-Ti transitional basalts and picrites (after Rooney, 2017).

CHAPTER THREE

3. Geology of the study area

3.1. Introduction

The present study area lies within the northwestern Ethiopian plateau, which comprises three large volcanic rock sequences. These exposed volcanic rocks have ages of about $30.2\pm\mathbf{0.1}$ Ma for lower basalts (Hofmann et al., 1997), rhyolitic-ignimbrite ($30.1\pm\mathbf{0.4}$ Ma, Ayalew et al., 2002), and 26.4 to 27.8 Ma for upper basalts (Hofmann, 1997) as cited in Pik et al. (1998). This study investigated each volcanic rock unit in detail, flow- by- flow with respect to stratigraphy. From field observation, lava flows are generally exposed as layers in which rhyolitic units rest on the lower basalt and in turn overlain by upper basaltic flows. The units are exposed extensively along erosional escarpments, flat laying plateau and undulating places. They are generally variable in mineral assemblages, color, textures and thickness. In addition, two textually different basaltic flows and Kfs phyric rhyolite units are encountered with columnar joints. Mostly, the basaltic rocks are found as thick lava sequence and also intercalated with basaltic tuff, thin layered basaltic agglomerate and Kfs vitrophyric rhyolite (within lower basaltic unit).

3.2. Volcanic successions and petrographic descriptions

By integral study of field observation and petrographic analysis, the Jita volcanic products have been investigated. Geomorphologically, the area is extensively eroded and dissected by deep gorges of Jita River. In this case, the area was investigated along three selected traverses to encounter different exposures in the area. These traverses are the new road; river cutting and also cross-cutting of the erosional escarpment with footpath all used during field work. During field observation, identification of rocks and stratigraphic sampling were conducted in detail. In the area, various volcanic flows have been sampled and they have been differentiated based on their field relations, mineralogical and textural characteristics.

From field and petrographic perspective, the area comprises 15 different flows. The composite volcanic-stratigraphy is established based on these different flows with marker contacts. The major volcanic flows identified in this study are; aphyric-intergranular basalt, aphyric-trachy basalt, augite cumulophyric basalt, olivine-augite phyric basalt, Kfs (Sa) vitrophyric rhyolite, augite phyric basalt, basaltic tuff, columnar-aphyric-intergranular basalt, non-columnar-aphyric-intergranular basalt, moderately welded rhyolitic tuff, Kfs (Sa) phyric rhyolitic-ignimbrite, and columnar Kfs (Sa) phyric rhyolite, columnar-aphyric- basalt, thin layer of basaltic agglomerate and slightly vesicular columnar aphyric basalt.

Aphyric intergranular basalt is exposed at the base of the Jita section which is tilted with fractures filled with calcite veins. This flow terminates with paleosoil having a range of thickness from 0.8 to 0.5 m. Below this flow, there are no other visible exposures either sedimentary or basement rock stratigraphy. All stratigraphic samples have been collected when changes occur in flow morphology, texture and mineralogy. All stratigraphic flows exhibit variable textures, mineral assemblages, thickness and also structures from the base of the volcanic sequence to the uppermost lava flow. The Jita section volcanic suits are terminated by slightly vesicular basaltic flow , in which vesicles are not filled by secondary minerals such as zeolite and calcite while the lower basaltic regions of olivine-clinopyroxine phyric flow is highly characterized by iddingsitic alteration along the fracture and the rim of olivine crystals. All these lithological units have their own descriptions presented separately in this chapter.

The overall volcanic-stratigraphy of the area has been classified as lower basaltic unit, middle rhyolitic-ignimbrite unit and upper basaltic rocks identified in this study. This classification scheme has served to present the rock units on geological map of the area. Because most lava flows have a small thickness which allowed merging together with its compositionaly related thick flows in the geological map. In this study, a sharp volcanic contact considered to be delineating the felsic rock from basalt flows, whereas the paleosol, thin layer basaltic agglomerate and basaltic tuff contacts separate basaltic lava flows (these contacts served as a gradational volcanic flow marker). These volcanic unconformities are typical criteria to separate each lava flows and finally they were used to establish the volcanic stratigraphy of the area. To provide the detailed scientific information, Jita volcanic products have been described on the basis of textural and modal mineralogy perspective in hand specimen and thin section observation. All these lava flows are described on the basis of their volcano-stratigraphic setting (they are all presented in the composite volcanic-stratigraphy log section (see Fig.3.3) from the base to the top terminal flow).

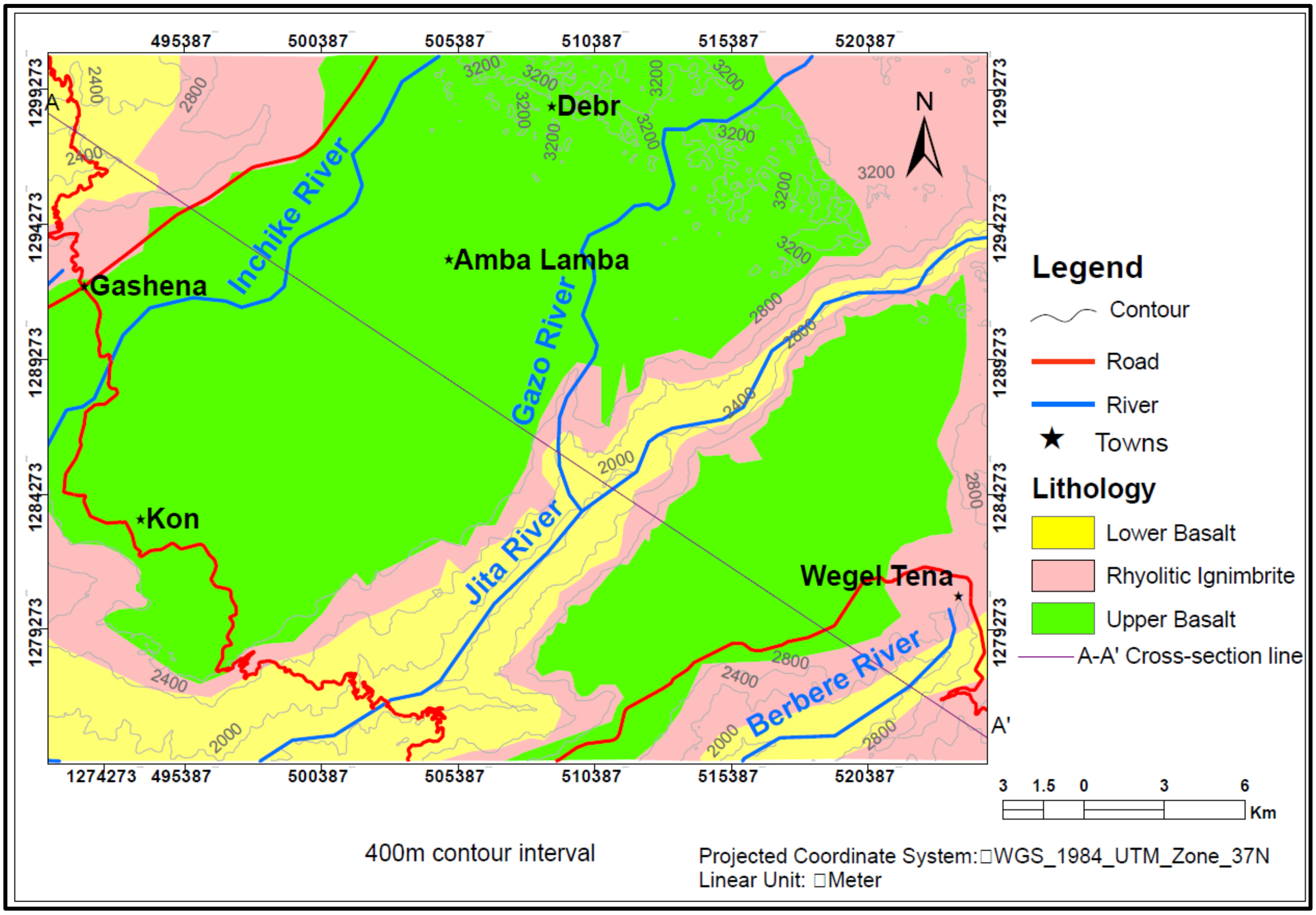

Figure 3.1: Geological map (1:35,000) of the study area.

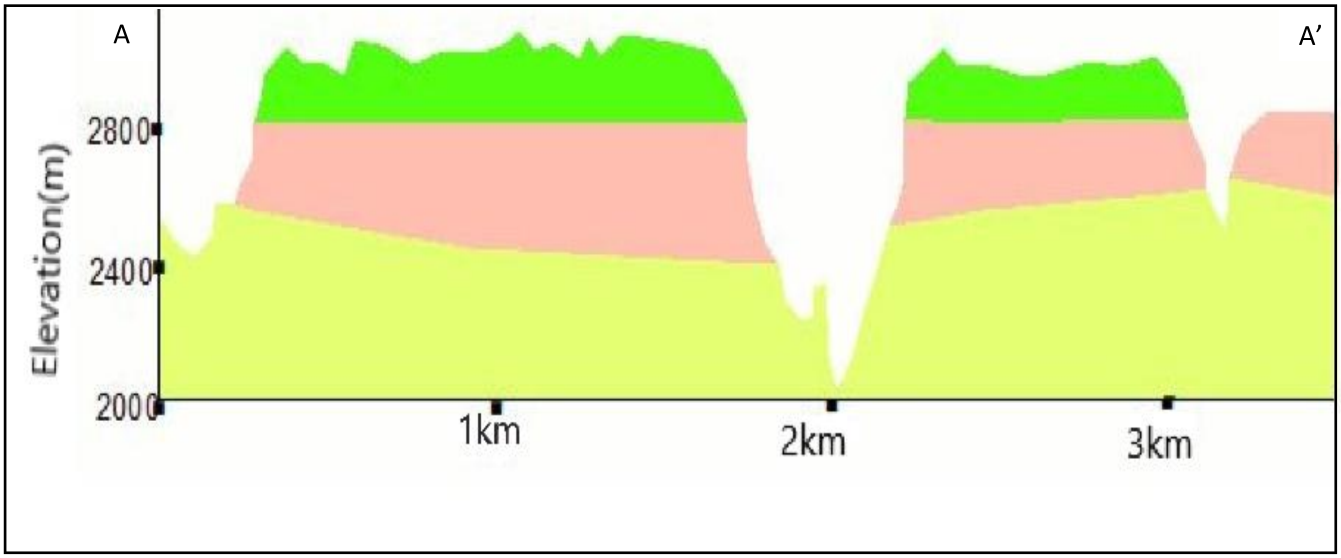

Figure 3.2: Cross-sectional profile (A-A’) of the study area.

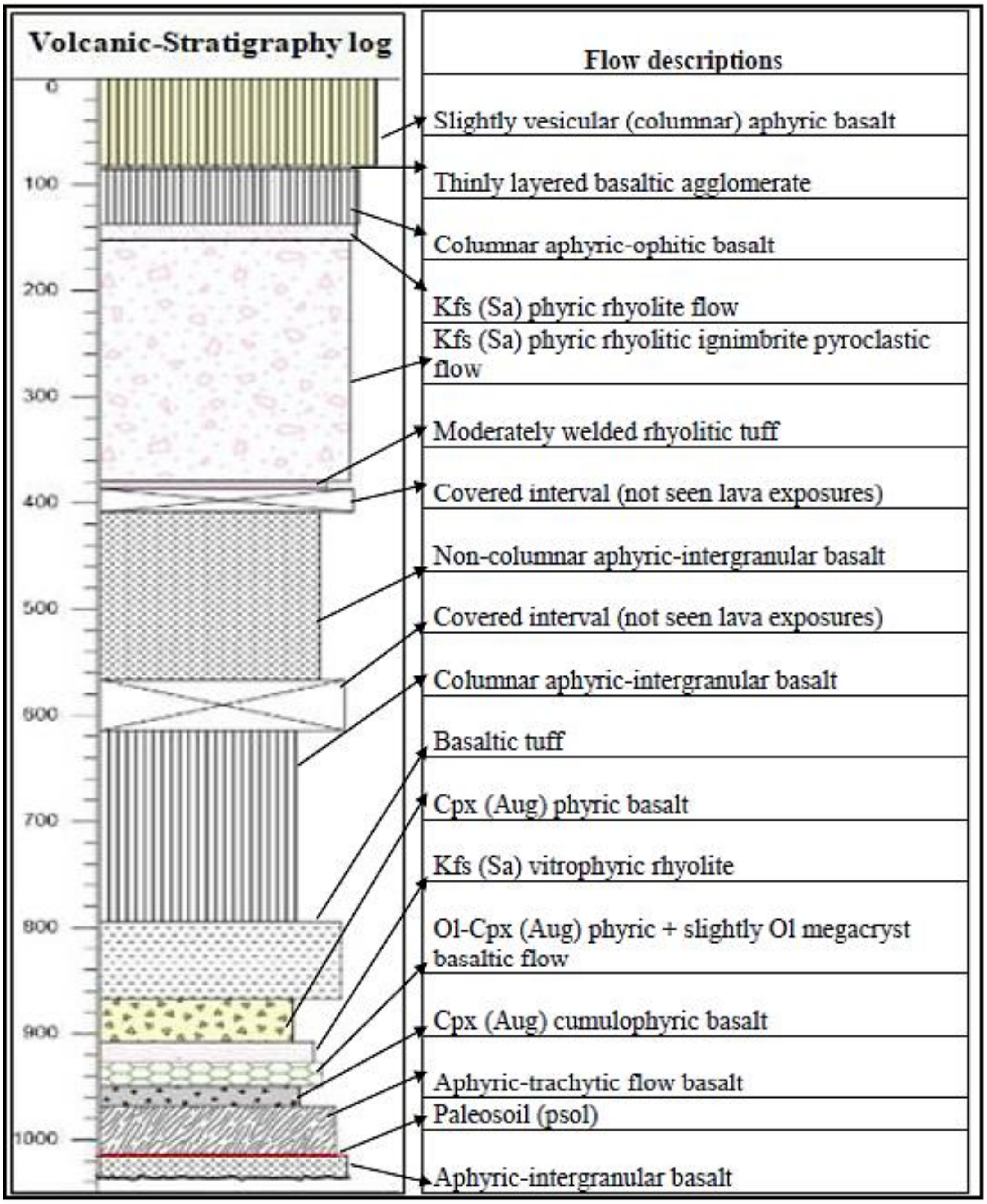

Figure 3.3: Composite volcanic stratigraphy of Jita area intermittent volcanic flows with respect to their vertical thickness. The vertical scale leveled by 20 m intervals. The zigzag line at the bottom of the lower flow revealed there is no other visible exposure below except deeply dissected by Jita River.

3.2.1. Aphyric-intergranular basalt

This basaltic rock is exposed at the base of Jita volcanic sequence along the lower elevation. Laterally, this lava flow is sometimes buried making it difficult to follow. It is not exposed throughout the stratigraphy and has variable thickness. However, it has been delineated easily by the overlying marker of red massive and friable paleosols. It is a highly weathered and fractured flow. Scattered fractures filled with calcite minerals, which measured about 135°/60° SW strike and dip, respectively. The overall dip of the flow is measured 10° SE. In this lava flow, the degree of weathering and fracturing dramatically increases laterally in both directions. The fresh color of the sample is dark gray with shining nature, but pale brownish in weathered surface.

The average thickness of the flow has been estimated about 21 m and the sample coded as JI1 (JI stands for Jita throughout the chapter) based on locality name. This lava flow is aphyric in hand sample, but coarser with intergranular texture in thin section observation (see Fig.3.4). Under thin section observation, it contains a few lath-shaped plagioclase phenocrysts (<2%) having distinguishable mineral assemblages found in groundmass level, mainly plagioclase with 1-2 mm in length. Fe-Ti oxides have 0.2-0.4 mm length, and also other altered clinopyroxene and olivine mineral phases are measured 0.4 and < 0.6 mm length, respectively. The arrangements of these crystals are shows no preferred directions in the groundmass level. The name of this lava flow is aphyric-intergranular basalt. Because the space between the lath shaped crystals of plagioclases in this flow are occupied by augite, olivine and Fe-Ti oxide minerals, which have an intergranular appearance.

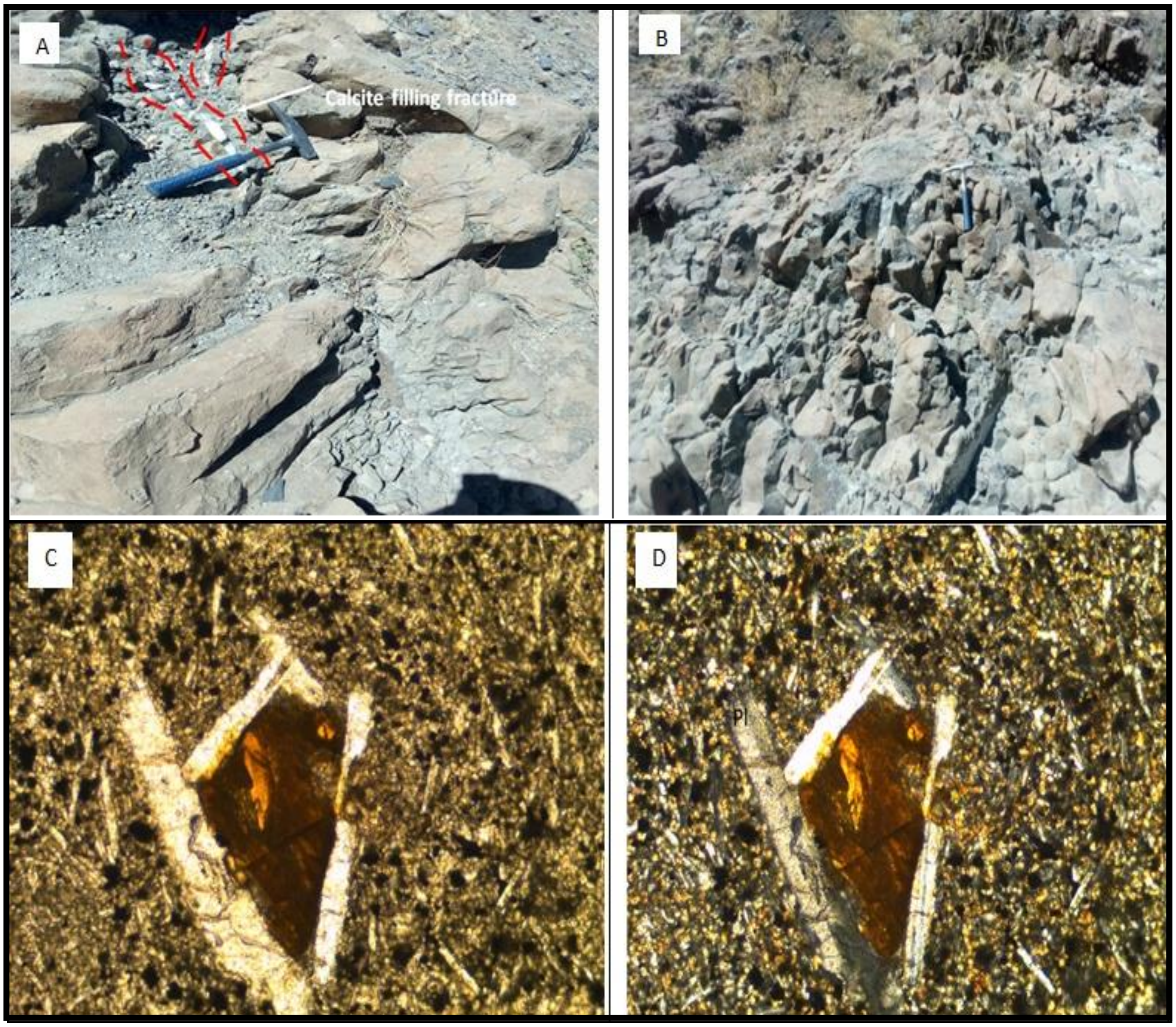

Figure 3.4: Outcrop photograph of aphyric-intergranular basaltic lava flow taken at locality Eribekentu (E-0502087, N-1276684, Z -1791(A)); (B) hackly fractured and pale green basaltic outcrop (E-05020805, N-1276674, Z-1810); plates C&D show microphotographs of aphyric-intrgranular basalt under the PPL and XPL view, respectively. Thin section photos are presented with 10x magnification. Where E- is Easting and N- is Northing and Z- is elevation, they are all measured in meters throughout the chapter.

3.2.2. Aphyric-trachy flow basalt

This basaltic flow rests on the lower basaltic unit separated with stacked paleosoil horizon, but laterally the paleosoil is changed into friable nature and much thinner in NE part. This lava flow is characterized by highly fractured, moderately steep to cliff forming topographic features. Laterally, it continues throughout the study area, but the thicknesses vary thinning from SW to NE direction. The degree of fracturing also increases along stream cutting and erosional escarpment faces. The rock is aphyric in hand sample, but having discrete lath shaped plagioclase grains in thin-section investigation. The fresh color of the sample is gray, which shows shining rock surface, but pale greenish in weathered color. The thickness of the flow unit has been estimated about 45.2 m and the sample labeled as JI2. The strike of the flow is N45° E , but the dip is towards southeast (ca.15°).

In petrographic investigation, this flow unit contains coarser plagioclase lath shaped microphenocrysts (15%) having 1 to 3 mm in length and it associated with distinguishable minerals in groundmass level in which plagioclase crystals dominate. The groundmass has plagioclase (0.1-0.3 mm in length). Fe-Ti oxides (0.8 mm in length), minute Cpx (0.2-0.6 mm) and Ol (0.2-0.4 mm) minerals are observed. The arrangement of plagioclase microphenocrysts is rarely radiating, but generally they have sub-parallel to parallel orientations. Sometimes, it slightly shows intergranular groundmass textures. However, the overall texture observed in this volcanic rock is trachytic and the rock name established on the basis of the dominant plagioclase micro-phenocryst alignments.

Figure 3.5:Outcrop photo of moderately fractured and slightly flow banded light greenish aphyric basalt (A) (E-0502232, N-1276939, Z-1812); B) close up view of highly fracture greenish aphyric trachytic flow (E-05022011, N-1276914, Z-1823) in specific locality name of Mekundi, the sample recorded as JI2).

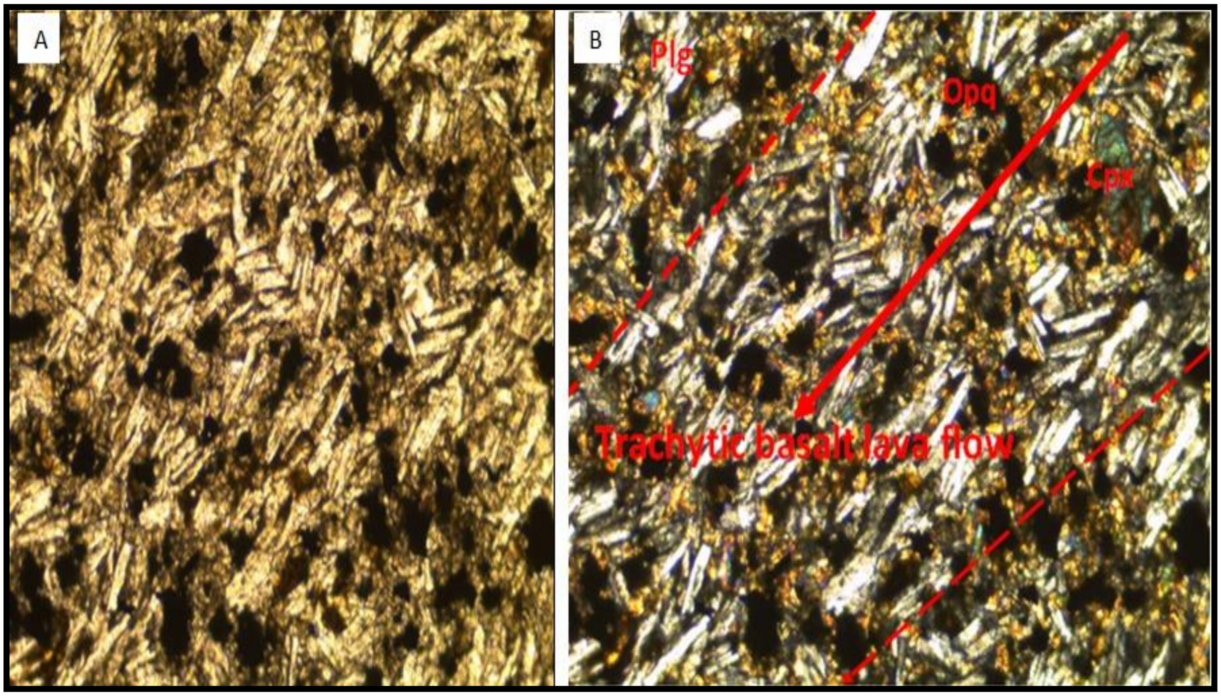

Figure 3.6: Microphotographs of aphyric basalt under PPL (A) and XPL (B); photos taken with 10x magnification power.

3.2.3. Cpx (Aug) cumulophyric basalt flow

This rock unit is characterized by slightly porphyritic texture which has been named based on its modal mineralogical basis with greater than five volume percent of phenocrysts in the groundmass. This lava flow is gradationally exposed on aphyric basalt, with an estimated thickness about 19 m. The unit is pale greenish to gray in color with black shining pyroxene minerals having a range of slightly phenocrysts during field observation. Laterally, this basaltic lava flow shows continuous exposure, but becoming thinner towards NE part of the study area. In a similar way, the flow has a variable degree of weathering both vertically and laterally. Generally, this rock unit is highly altered and fraible of nature. Mostly, in the upper level of the flow, the degree of weathering is dramatically increased.

Petrographically, this lava flow comprises the glomeroporphyritic aggregates of Cpx (Aug) minerals with opaque (Fe-Ti oxide) phenocrysts in which augite phenocrysts constitute 20 vol.% and having about 2-4 mm length and euhedral to subhedral shape and also showing simple twinning (see Fig 3.7 C). The phenocrysts of clustered Fe-Ti oxide are estimated around 11% and have a range of shapes from subhedral to anhedral. These coarser opaque mineral phases measured 1-3 mm length. They contain very small volume proportions of (~2 vol. %) olivine microphenocrysts. At the groundmass level, minute and elongated pale brownish altered olivine and clinopyroxene crystals are observable, but plagioclase crystals are absent in this flow. The overall groundmass texture of the sample shows highly altered sericitic nature which accounts for 77%.

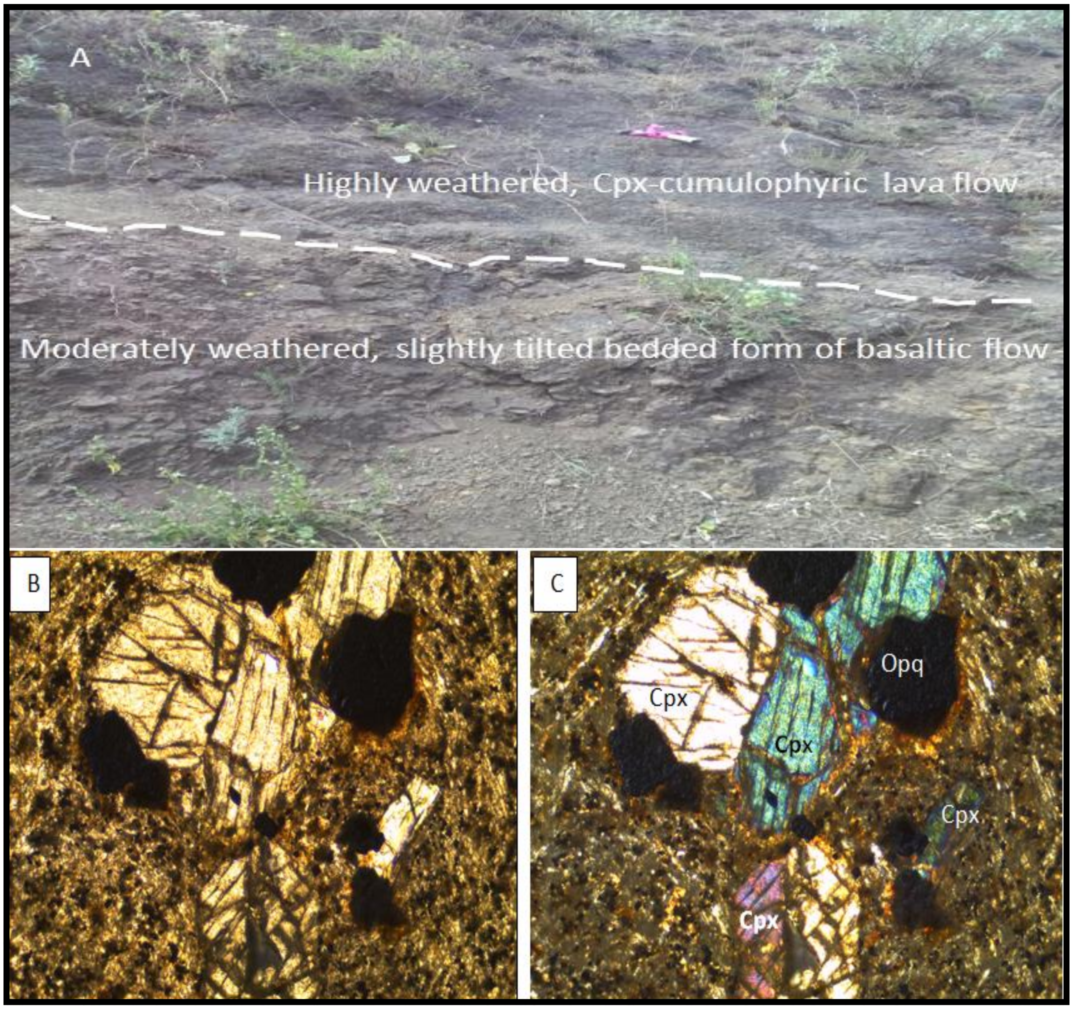

Figure 3.7: (A) Outcrop photo of highly altered porphyritic basaltat locality name of Kefodingay, sample leveled as JI3 (E-0502166, N-1276991, Z-1858); (B) and (C) show microphotographs of Cpx (Aug) cumulophyric basalt under PPL and XPL views, respectively. Thin section photos taken with a 4x magnification power.

3.2.4. Olivine-Augite phyric basalt

This basaltic lava flow is characterized by highly exfoliated weathering (see Fig.3.8 A) with non-penetrating rounded to sub-rounded vesicles on its rock surface which are not filled by secondary minerals. Laterally, the thickness of the flow is thinner in both NE and SW directions of the area compared to its central exposure, but generally has an estimated thickness of about 22 m. In hand specimen and outcrop, it has coarse and highly porphyritic texture having rounded to elongated phenocryst minerals. The rock unit has been seen as light gray to light greenish weathered color, but its fresh surface encountered with light black. The flow is coded as JI4 during sampling when it has been delineated from the underlying basaltic unit by showing of sharp textural variation in both vertical and lateral extent.

From petrographic investigation, this porphyritic rock with 35% olivine and 24% augite minerals in the phenocryst phase (Fig.3.9). However, its average phenocryst abundances isestimated about 25-30 vol. % with higher proportions of an aggregated (10%) minute grains of Fe-Ti oxide crystals surrounding the rims of olivine crystals and also in rare cases at the augite outline in the groundmass level. These minute Fe-oxide crystals are found as inclusions within augite and olivine phenocrysts and also Cpx included within big crystals of olivine (megacryst ~1cm in length in hand sample and <3 vol.% in thin section observation). Simple twining is developed on the gray-blue augite phenocrysts that have subhedral shape and lengths ranging from 0.5 to 3 mm. Olivine phenocrysts are 1-4 mm in length and they commonly have euhedral crystal faces. These olivine phenocrysts are dominant in this flow with distinctive fractures developed on its crystal surface. Along the fracture faces and the rim of the crystals, partially iddingsite alterations are developed.

In this lava flow, orthopyroxen and plagioclase are absent. The overall groundmass of the sample is estimated about 60-61%. Based on their higher olivine phenocryst volume proportion, the name of the flow established as Ol-Cpx (Aug) phyric basalt.

Figure 3.8: (A) Close-up view of pale-greenish altered porphyritic basalt in specific locality name of Girar wuha (E-0502190, N-1271998, Z-1877); (B) Eastern side panorama view of ol-cpx phyric lava flow at locality of Ziban (E-0508235, N-1278665, Z-2884).

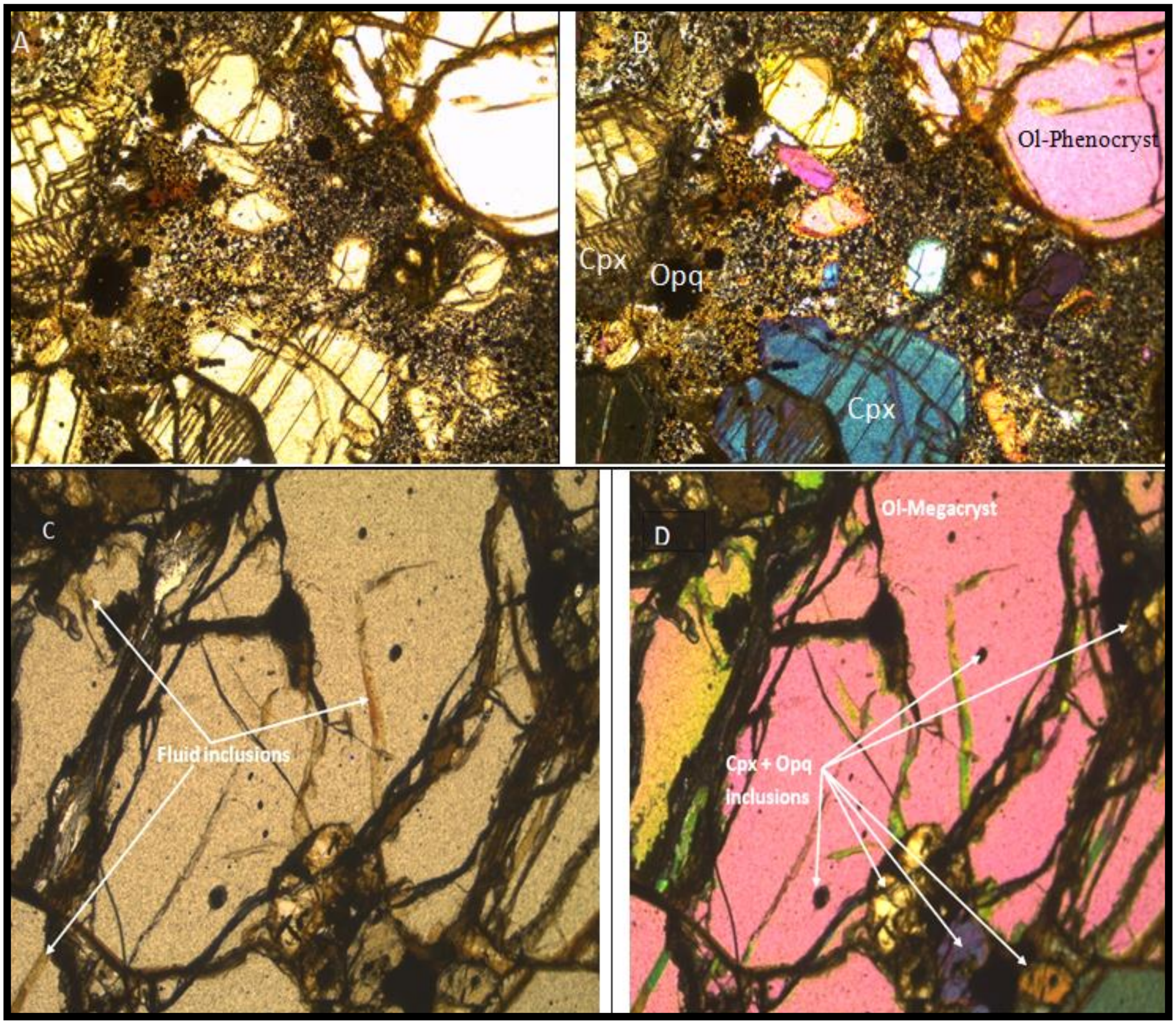

Figure 3.9: Microphotographs of olivine-augite phyric basalt under PPL (A) and XPL (B) view; in this sample iddingsite alteration is highly developed along the olivine fractures and its rim. Plates C and D show microphotographs of the olivine megacrysts with some inclusions under PPL and XPL, respectively. These thin- section photos taken with a 4x magnification power.

3.2.5. Kfs-vitrophyric rhyolite

This unit is found overlying the Ol-Cpx lava flow as patchy and interlayered form within the lower basaltic flow. Macroscopically, it is characterized by porphyritic texture with shining crystals (see Fig.3.10) and exhibiting flow banding nature. It shows a range of colors from gray pink to pale brown. It can be scratched with fingernail at the face of its fractures and sometimes it shows friability. Generally, it shows moderately crystalline nature with highly fractured, moderately weathered and shining surface from field observation. However, the degree of weathering is increased at the cliff morphology and sometimes it resembles kaolinitic. This flow unit has an estimated thickness of about 20 m, but its thickness is not uniform in the section. Under petrographic microscope, this rhyolitic flow has about 30% K-feldspar phenocryst phase and 12% quartz microphenocrysts and around 55% glassy groundmass which show flow banding features. The shapes of the Kfs crystals are subhedral to tabular form and rarely embayed Qtz microphenocrysts are observed in this sample. These Kfs phenocrysts are sanidine minerals in this flow with lengths ranging from 2 to 5 mm and microphenocrysts of Qtz are 0.4-0.6 mm, respectively. Based on higher proportions of glassy groundmass and Kfs phenocrysts, the flow is named as Kfs vitrophyric rhyolite flow and its sample labeled as JI5.

Figure 3.10: Close-up field photo of the highly fractured, flow-banded, porphyritic rhyolite flow which is exposed as patchy and interlayer form at locality of Merken (E-0502197, N-1277001, Z-1899).

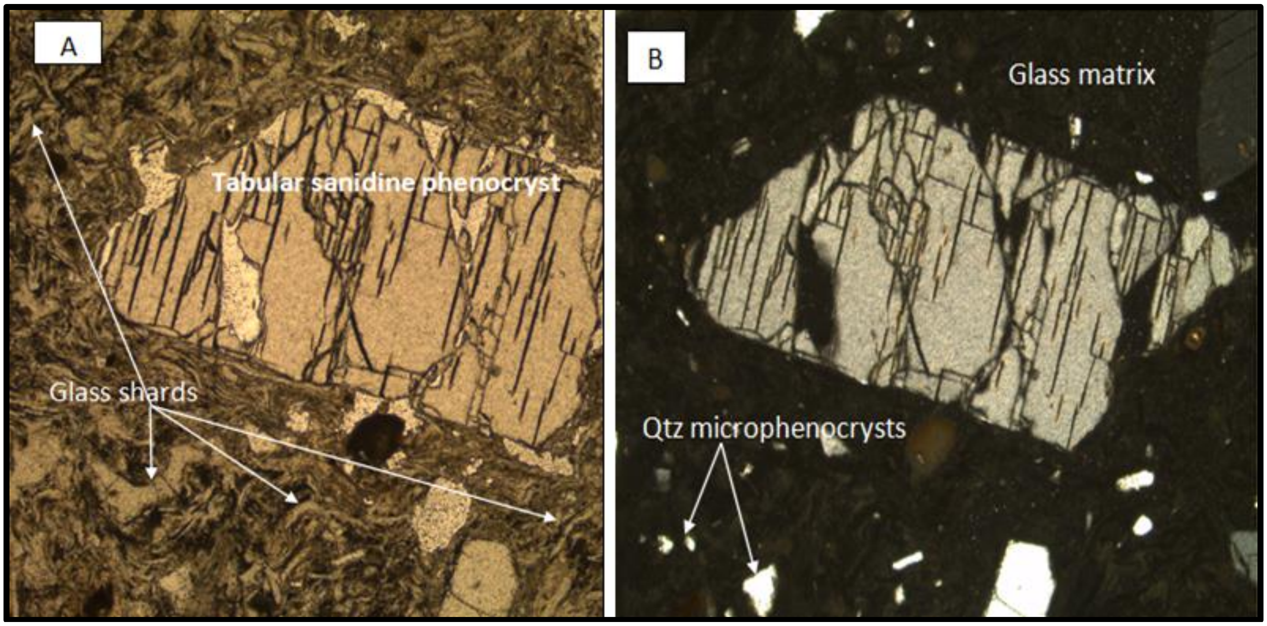

Figure 3.11: Microphotographs of sanidine phyric rhyolitic flow under PPL (A) and XPL (B) view, respectively. Thin section photos taken with a 4x magnification power.

3.2.6. Cpx (Aug) phyric basalt

This basaltic lava flow is exposed in the lower basaltic unit which separated from the underlying patchy like rhyolitic flow. It is characterized by bedded and massive forms (see Fig.3.12) and rarely shows inflated flow structure forming moderately steep topographic features. During field observation, the rock shows pale-greenish color with black shining pyroxene minerals and also non-penetrative vesicles are easily observable on rock surfaces. Laterally, this basaltic flow is extensive and continuous but it shows a range of thickness on average 40 m and the sample was labeled as JI6.

Under petrographic investigation, this highly porphyritic rock comprises about 38% augite phenocryst and 15% Fe-Ti oxides in the microphenocryst level (Fig.3.13). Aggregated minute grains of Fe-Ti oxides are found in the groundmass and they are also included within large ring bone augite crystals and its rim, which is estimated around 5%. Simple twinning and herringbone patterns are well developed on the large augite phenocrysts having euhedral to subhadral shape and lengths ranging from 3 to 4 mm.

Figure 3.12: Close-up view photo taken from layered porphyritic (augite phyric) basalt with pale-gray in color, the local name is Yekont at E-0502098, N-1277028, Z-1912

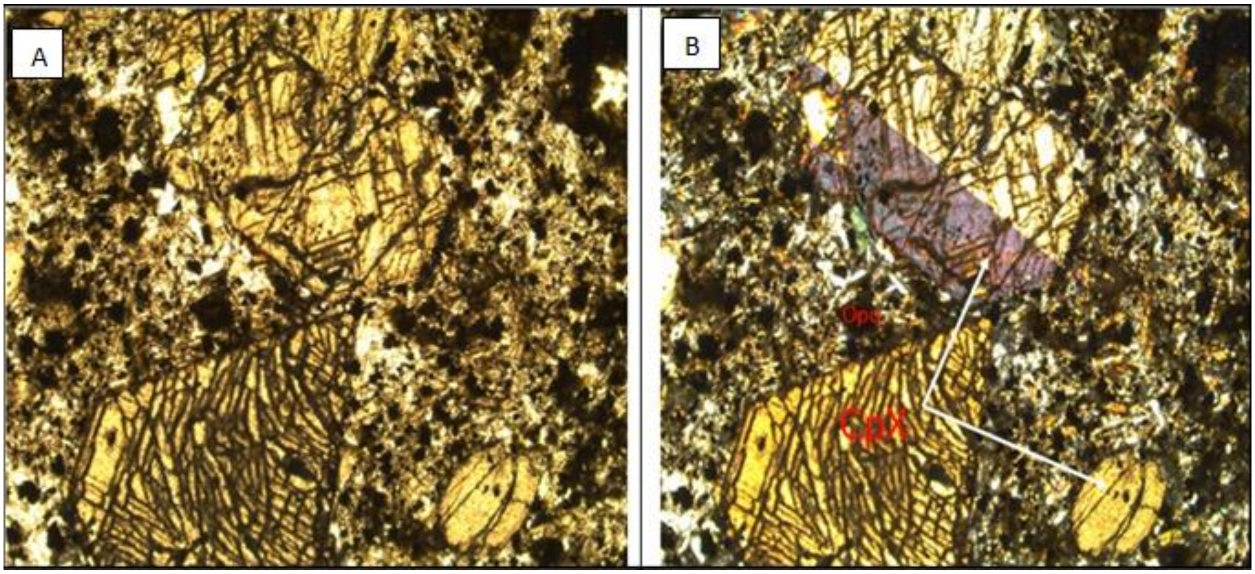

Figure 3.13: Microphotographs of augite phyric basalt under PPL (A) and XPL (B) view, respectively; thin section photos were taken with a 4x magnification power.

3.2.7. Basaltic tuff

This unit is highly friable at the upper level (see Fig.3.14), and it comprises some brecciated basaltic materials. Fragments have a range in size from 2 to 8 cm and their shape also varies from subrounded to angular. It is characterized by pale-greenish color and poorly sorted nature. The basaltic unit is cemented by ash and show compacted nature at its base. It is not sampled for petrography analysis due to poorly sorted nature. It is estimated to be about 73 m thick, but laterally it thins out in both SW to NE directions. Texturally, it is finer at upper stratigraphic level.

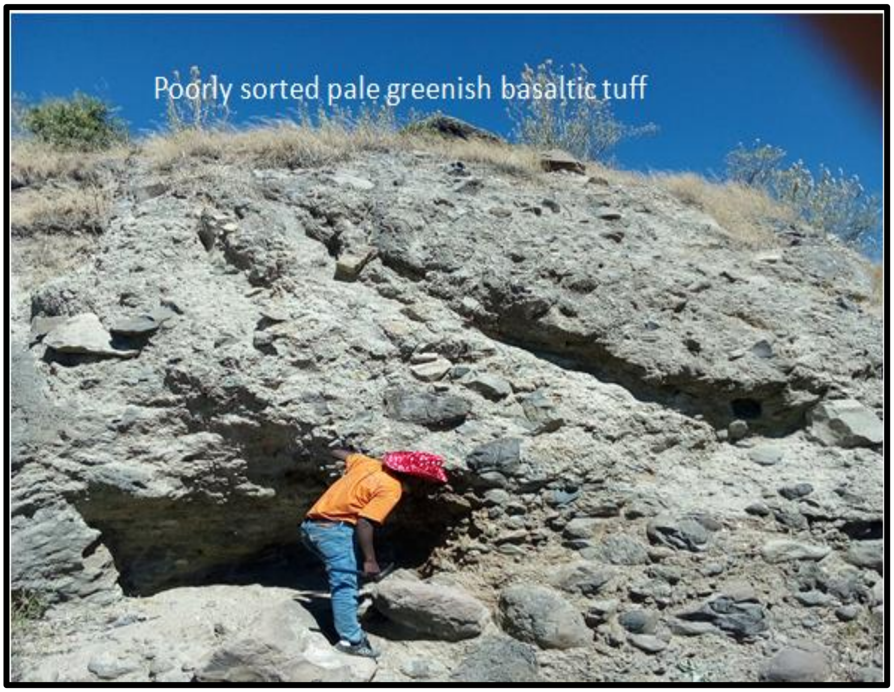

Figure 3.14: Close up view of basaltic ash with brecciated basaltic fragments exposed at specific locality of Yekont (E-0501685, N-1276816, Z-1899).

3.2.8. Columnar aphyric basalt

This basaltic lava flow exposed at nearly top part of the lower basalt flow region which is characterized by systematic sub-vertical columnar joints with non-irregular colonnade -like pattern. Laterally, this basalt flow is poorly exposed in the western part of the Delenga village whereas it is continuously extended with relatively the same thickness in the eastern part of Delenga Kola. From the megascopic view, it has a range of colors from pale black shining surface to pale gray. The columnar features are developed along its margin. Faces of columns are not homogenous, it shows some range on average, they encountered 15 to 40 cm. The columns have 5 to 6 sides; they are easily observable at sliding and quarrying rock faces. It has an estimated thickness of about 180 m and the sample labeled as JI7. In the field, this type of lava flow has been delineated from the underlying basaltic tuff by having of textural variation in both vertical and lateral extent in the locality. On top of this lava flow, the area is flat lying or farmland (at specific locality of Merken) which is estimated about 48 m thickness. This is referred as “covered interval” see the stratigraphy log in Fig.3.3. This interval is extended laterally in both East-West directions for some distance, but not throughout the volcanic-stratigraphy. The lava flow is again overlain on the covered interval area by a highly weathered aphyric intergranular basalt (labeled as JI8) having an estimated thickness of 150 m. By the absence of the joint structure, it typically differs from the lower columnar aphyric intergranular basalt (JI7). This non-columnar aphyric-intergranular flow is terminated by covered interval with 22 m thickness. Due to the presence of columnar structure and thickness variation in the field observation, samples were taken from each flow for petrographic investigation, but they are not showing much petrographic difference, both of them being characterized by aphyric-intergranular texture with the same mineralogy.

However, the modal proportions of mineral assemblages are slightly different in both samples. The columnar aphyric intergranular flow estimated around 15% lath shaped microphenocryst of plagioclases having non-preferred arrangements, but it sometimes shows radiating crystal patterns. Rarely, the plagioclase microphenocrysts (<1%) show sieve texture in which the chadacryst grains are clinopyroxne and opaques (see Figs.3.15 C & D). Groundmass contains Cpx and opaque minute crystals and their mineral proportion is estimated (see Appendix 1). Plagioclase microphenocrysts have lath shape and sometimes show bladed sieved plag phenocrysts and their length ranges from 0.5 to 1.4 mm. The overall texture of this flow is intergranular. Based on the integration of field and microscopic observations, these flow units are differentiated as columnar and non-columnar aphyric intergranular basalt.

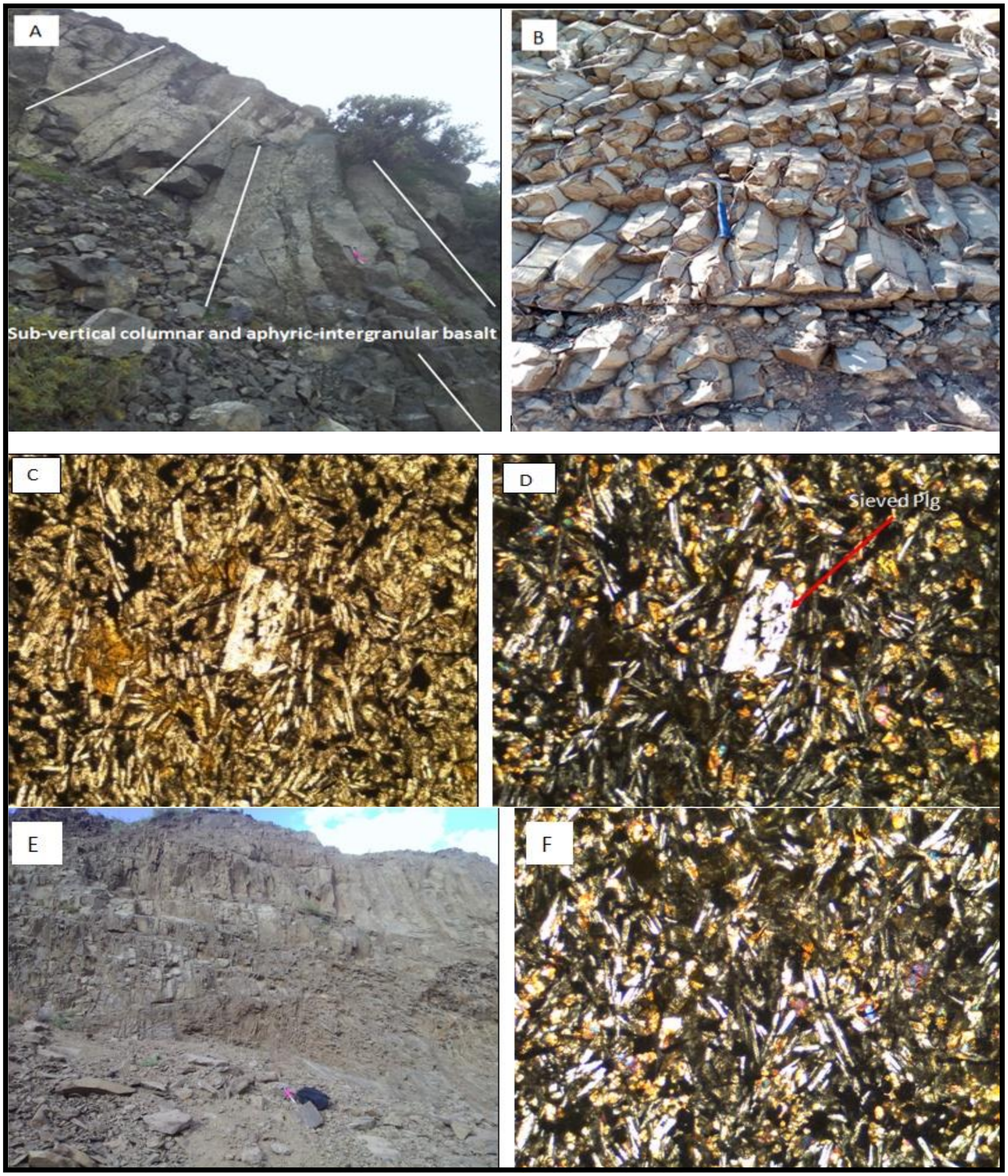

Figure 3.15: (A) Close - up views of aphyric basalt which are strongly jointed with vertical to sub-vertical columns (E-0501653, N-127714, Z-2032)) and (B) (E-0497967, N-127799, Z-2134); Plates of C &D are showing the PPL and XPL views of columnar aphyric intergranular basalt, respectively. (E) Non-columnar exposure of aphyric- intergranular basalt exposed by quarry site (E-0498101, N-1278229, Z-2268) while plate F shows the XPL view of non-columanted aphyric intergranular basalt. Thin section photos are taken with 10x magnification.

3.2.9. Moderately welded rhyolitic tuff

This volcanic unit is exposed as layered form and rests below the rhyolitic-ignimbrite pyroclastic flow, which contains lithic pumice and glassy fragments. It has pale gray weathered and brown fresh colors observed under field observation. Welded glassy shards with eutaxtic texture are easily observable under thin-section investigation. Generally, it shows a discontinuous lamination feature (Fig.3.16 C). Vertically, the unit accounted for ca.7 m in thickness, but laterally, it gets thinner and thinner in both weast to northeast directions of the stratigraphic position. In the upper part of the exposure, the degree of welding is dramatically decreasing, which typically changed to light gray friable ash material. Similarly, the degree of welding decreases in lateral extent also.The sizes of lithic fragments are ranging from 1 to 2 cm. Under petrographic observation, this flow encountered with 13% glassy shards and 80% glassy groundmass with 4% quartz microphenocrysts and also estimated about 2% Kfs and Fe-Ti (~1%) oxide minerals.

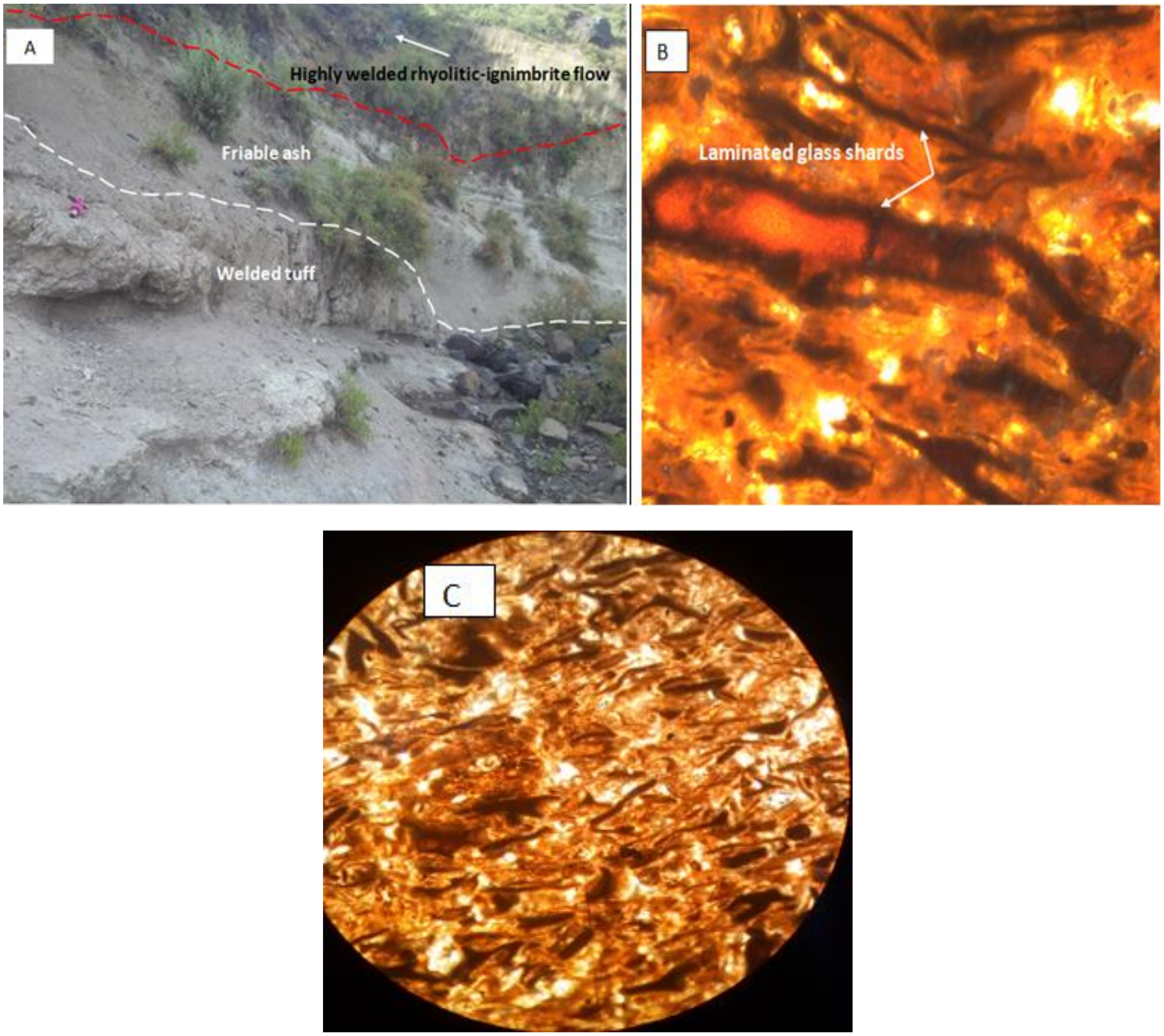

Figure 3.16: A) Outcrop photo of moderately welded ash flow exposed at locality of Delenga Kola(E-0498216, N-1278012, Z-2440); Thin section pictures of welded rhyolitic tuff with dominant glass shards under XPL (B) and PPL (C) views with 4x and 10x magnification, respectively.

3.2.10. Kfs phyric rhyolitic-ignimbrite flow

This pyroclastic flow is exposed in the middle part of the Jita volcanic sequence, its exposure starts at the elevation of 2447 m above mean sea level. Laterally, the flow unit is well preserved as layered form which is convenient property to discern its exposure throughout the study area with different thickness along erosional escarpment, especially NE direction (near Gazo River). On the contrary, the unit gets thinner and thinner towards south of Kon erosional escarpment (west of Delenga village) see Fig.3.1. The thickness of the pyroclastic flow in this area varies, but on average it has been estimated about 227 m and the sample coded as JI10. This flow is crystal-rich and secondary jointing is developed on its surface (non systematic fractures have different openings which range from 5 to 20 cm, see Fig.3.17). At the base of this deposit, it is characterized by highly weathered and green alteration (chalcedony) features with small greenish pumice fragments. In a similar way, the degree of weathering is varying in lateral extent. Generally, the degree of weathering increases towards the base of the flow and sometimes very thin ash layers are intercalated with it. Systematically, it was delineated from moderately welded rhyolitic tuff, which is resting under different colored friable material.

This rhyolitic-ignimbrite flow is characterized by poorly sorted and prophyritic texture that comprises pumice and glass fragments (10%) and minute shining crystals with different size. On average, the sizes of fragments are about 0.5 to 4 cm in the field observation, but they do not show fiamme nature in thin-section analysis. This volcanic unit generally strikes N 5° E and dips 10° SE. At exposure level, the fresh part of the sample is dark pink, but gray weathered surface. Under thin section observation, this flow unit contains Kfs phenocrysts (25%) with subhedral to anhedral shape and microphenocrysts of Qtz (12%) having rounded to anhedral shape. Opaque phenocrysts are easily observable with anhedral shape which estimated about 1%. Higher proportion is encountered with glassy groundmass in this flow. However, all crystals are diverse not have signs of oriented direction either from the groundmass or phenocryst level. The big subrounded pumice fragment is easily observable under thin-section investigation; it measures about 4 mm size. Overall, the texture is named as pyroclastic flow, but due to higher proportions of Kfs phenocryst phases, the rock name established as Kfs phyric rhyolitic ignimbrite flow.

Figure 3.17: Outcrop photo of layered rhyolitic-ignimbrite flow with highly observable pumice and glassy rock fragments, but dominantly pumacieous one and exposed at the local name of Delenga Kola at E-0498115, N-1278054, Z-2447.

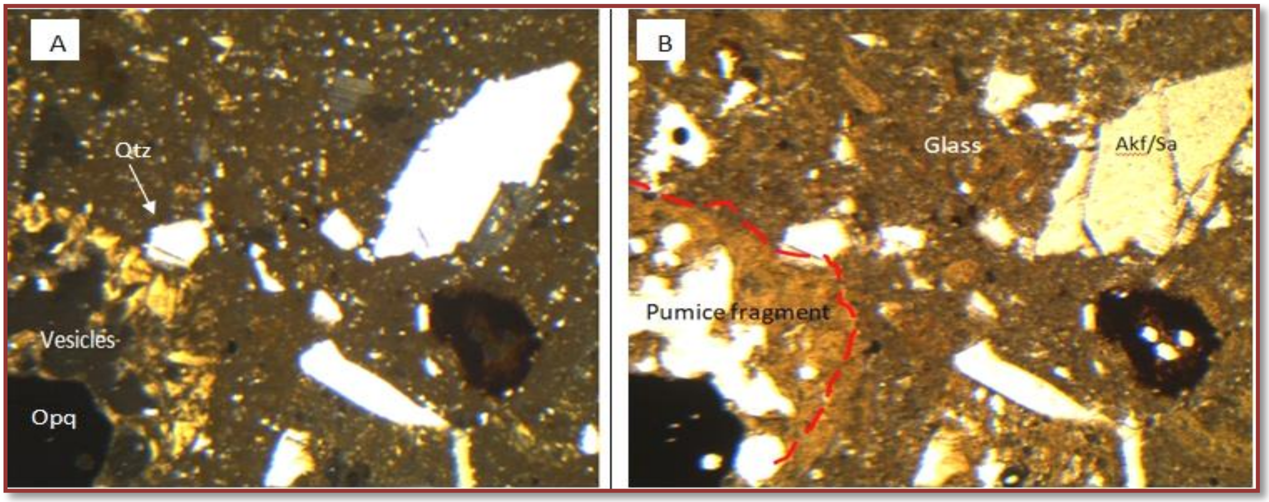

Figure 3.18: Microphotographs of rhyolitic-ignimbrite pyroclastic flow under XPL (A) and PPl (B) view, respectively. Thin section photos were taken with a 4x magnification power.

3.2.11. Kfs phyric rhyolite

This volcanic flow is purely rhyolitic composition which exposed on the rhyolitic ignimbrite unit. Both laterally and vertically, this flow is well preserved as banded form throughout the study area with a range of thickness.In the southwestern portion of Kon and near Gazo area, it is much thicker and much thinner at the sampled stratigraphic level which is southeast of Kon erosional escarpment (north of Delenga village). On average, the thickness of the flow is estimated about 15 m and the sample labeled as JI11. In the upper part, it is highly crystalline and fractured with slightly curved columnar lava flow (see Fig.3.19), but at the base of the flow which is moderately weathered and friabe. In a similar way, the degree of weathering is varying laterally. In the field, this unit has been delineated from the pyroclastic flow by the absence of fragmental materials and baked nature of fine grain rhyolitic material which has an estimated thickness of 0.8 m. This purely rhyolitic flow is characterized by a prophyritic texture that comprises shining large sized crystals on rock surface and sometimes the crystals are friabile. When scratched with fingernail, it shows sandy like nature. In outcrop, the fresh color of the sample is pale gray to dark pink, but light gray weathered surface.

From petrographic investigation, this flow unit comprises dominant Kfs (Sa) phenocrysts (30%) with carlsbad twining and sometimes it is found as non-twinned having a range of crystal shapes from subhedral to elongated. The Qtz phenocrysts (4%) are found as suhedral to embayed nature, but it accounts for 10% of microphenocryst phase with anhedral shape. The minor proportions of opaque minerals (0.5%) are easily observable in the glassy groundmass with rounded shape. The crystals do not exhibit sign of preferred orientation in both groundmass and phenocryst level. The phenocryst sizes of sanidine crystals are measure about 1-4 mm in length. Overall, the texture of the flow is porphyritic and due to the higher proportions of Kfs phenocryst, the rock is nameed as Kfs (Sa) phyric rhyolite flow (Fig.3.20).

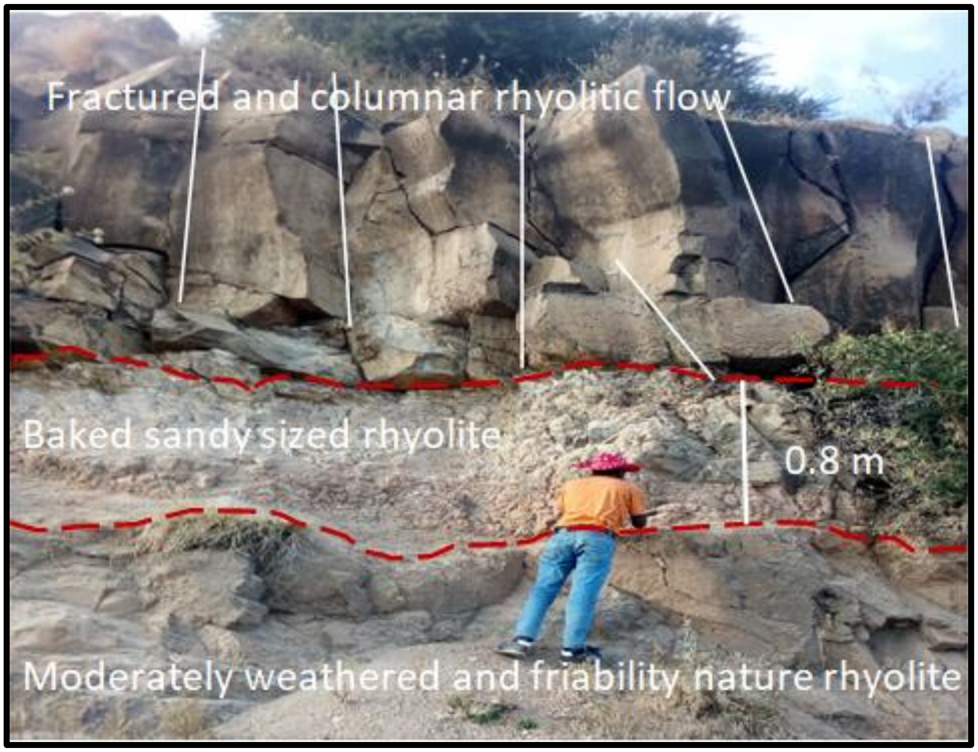

Figure 3.19: Close up view of layered rhyolite with a range of color ranging from light gray to pale pink.The local name that this lava flow exposed in the middle part of Delenga kola at E-0497824, N-1278453, and Z-2674.

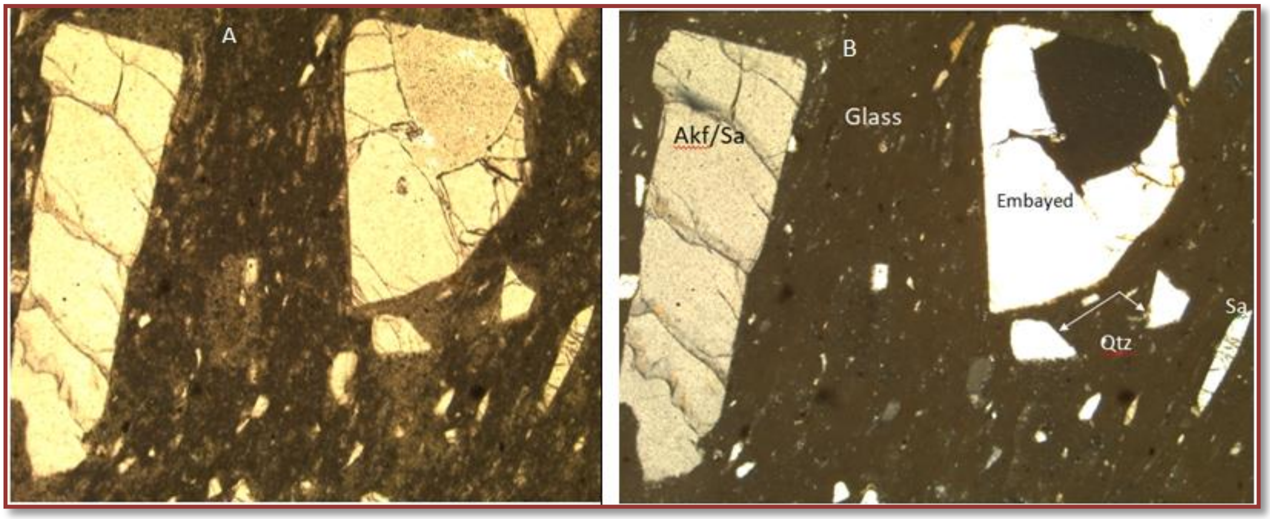

Figure 3.20: Microphotographs of sanidine-phyric rhyolite under PPL (A) and XPL (B), respectively with high proportion of glassy groundmass and less embayed Qtz phenocrysts. Thin section photos are taken with 4x magnification.

3.2.12. Columnar-aphyric basalt

This basaltic rock unit is exposed nearly at the top of Jita volcanic sequence along the erosional escarpments and is highly characterized by columnar lava flows (see Fig.3.21). From field observation, the joint sets range from vertical to sub-vertical columns with nearly parallel and systematic alignments. Mostly, these joints have curved and irregular nature, but some of them are straight. In hand specimen, the rock shows aphyric texture with pale gray color. Laterally, this lava flow is well preserved along erosional escarpment throughout the study area, but it terminates around the western part of Robit locality due to replacement of the thick rhyolitic ignimbrite flow (see geological map of this study). In addition, this columnar lava flow is exposed with cliff morphology which rests on thin layered columnar rhyolitic unit and it terminates by the overying agglomerate deposit.

However, under petrographic investigation, the rock has coarser texture (aphyric-ophitic) in which plagioclase lath shaped microphenocrysts are involved in augite microphenocrysts. In this flow, some microphenocrysts of plagioclases show radiating nature and the total estimate is 20% having 1-2mm length and rarely show anhedral shape. The Cpx microphenocrysts (10%) are associated with some Fe-Ti oxide (8 %) microphenocryst crystals. The overall groundmass texture of the sample is estimated about 62% modal proportions.

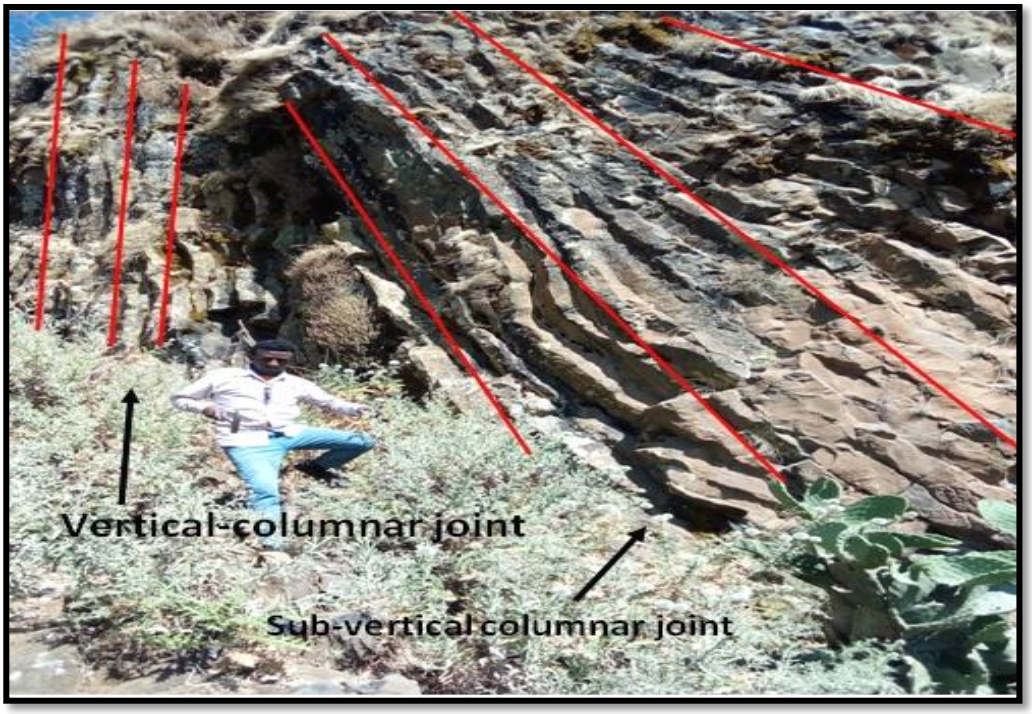

Figure 3.21:Close-up view of pale-brownish and highly algal weathering columnar aphyric-ophitic basalt.This lava flow is mainly exposed around Zinjero Gedel locality (E-0497921, N-1278549, and Z-2689).

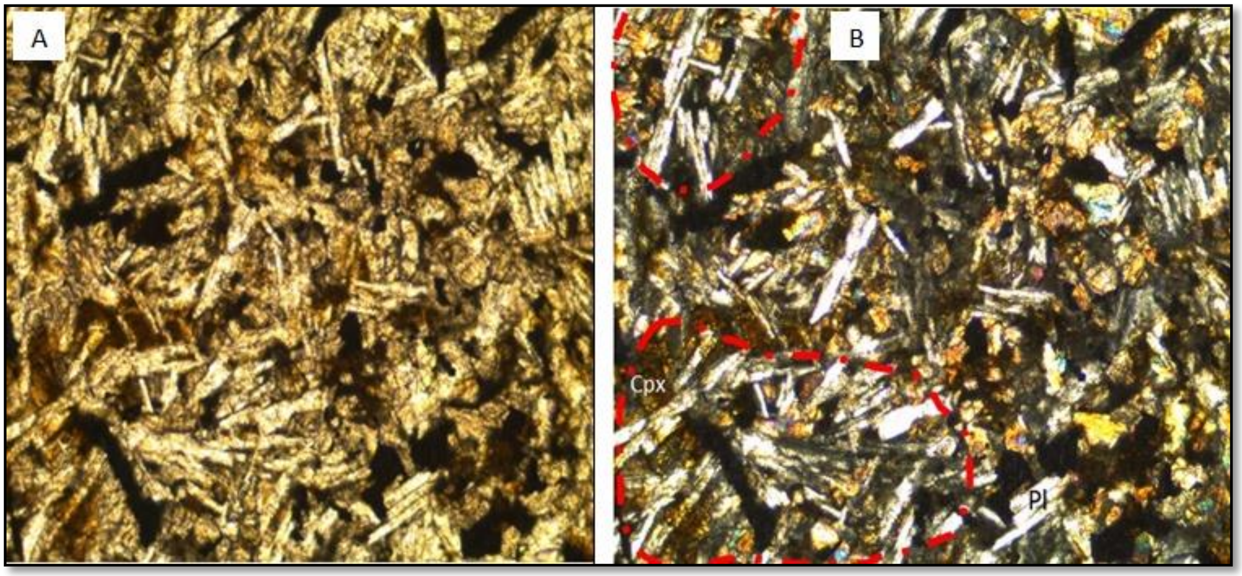

Figure 3.22: Microphotographs of columnar aphyric-ophitic basalt flow under PPL (A) and XPL (B), respectively with 10x magnification. The red circular dashed lines pointed out the coarser groundmass ophitic textures.

3.2.13. Basaltic agglomerate

This basaltic agglomerate (Fig.3.23) occurred as a thin layer which shows poorly sorted nature and with a groundmass of fine ash and sometimes well oriented. On average, it is ca.1.5 m in thickness. Laterally, it is continuous throughout the stratigraphic position and having rounded to ellipsoidal pebble size grains. This volcanic unit is exposed along the cliff morphology, which is difficult to discern easily. It separates the two texturally different basaltic flows, such as columnatr aphyric-ophitic basalt and sparsely vesicular plus columnar aphyric lava flow and they are found in lower and upper stratigraphic sequence, respectively. This agglomeratic deposit is overlain by vesicular aphyric basalt.

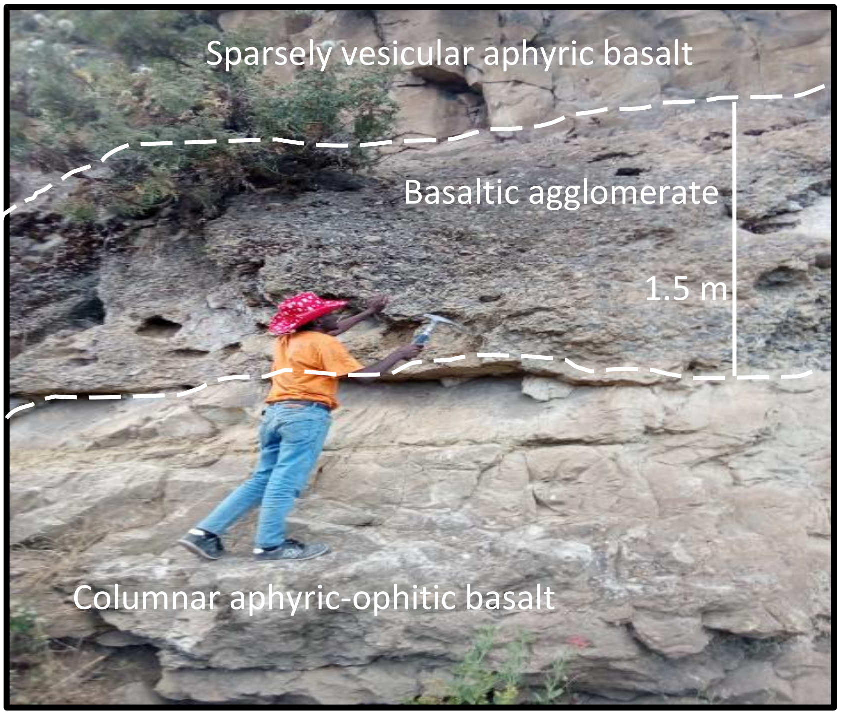

Figure 3.23: Outcrop photo of basaltic agglomerate, which is a contact between columnar aphyric basalt flow and sparsely vesicular aphyric basalt at locality of Zenjero Gedel (E-0497248, N-1278132, Z-2739).

3.2.14. Sparsely vesicular aphyric basalt

This rock unit is exposed at the top (termination) of Jita volcanic sequence along the erosional escarpments and flat lying plateau with higher elevation.The flow has an estimated average thickness of about 84 m, which is mainly characterized by columnar structure with vesicular texture, especially the southern, western, and the southeastern part of Kon. In most parts of the study area, this lava flow is subjected to weathering and light brown color, but it has a light gray fresh surface. From field observation, the flow doesn’t show its mineral composition easily, due to aphyric nature. Furthermore, the vesicles are not filled with secondary minerals of either calcite or zeolites. The shapes of vesicles are variable ranging from spherical to elongated. The joint sets are systematic ranging from vertical to sub-vertical columns. Due to their non-curved or regular nature, they are characterized by colonnade like joint structure with five sided columns. However, some joints are encountered with the irregular patterned columns with parallel alignments. Laterally, this highly columnar lava flow is exposed as layered along cliff morphology which rests on the thin layered (ca.1.5 m) poorly sorted basaltic agglomerate and in vertical position found nearly at the top of the flow. The proportions of vesicles are dramatically increased towards top (5%).

From petrographic investigation, the rock has aphyric-vesicular texture, in which microphenocrysts of plagioclases dominate with lath shaped and they exhibit randoml orientation (see Figs.3.24 C & D). These microphenocrysts of plagioclases are estimated about 20% with 1-2mm in length and they sometimes show anhedral shape. Large amount of Fe-Ti oxides is found in the groundmass level. In conclusion, this lava flow does not have phenocryst and megacryst mineral phases. The overall groundmass texture of this rock unit is amounts to about 75% modal proportion.

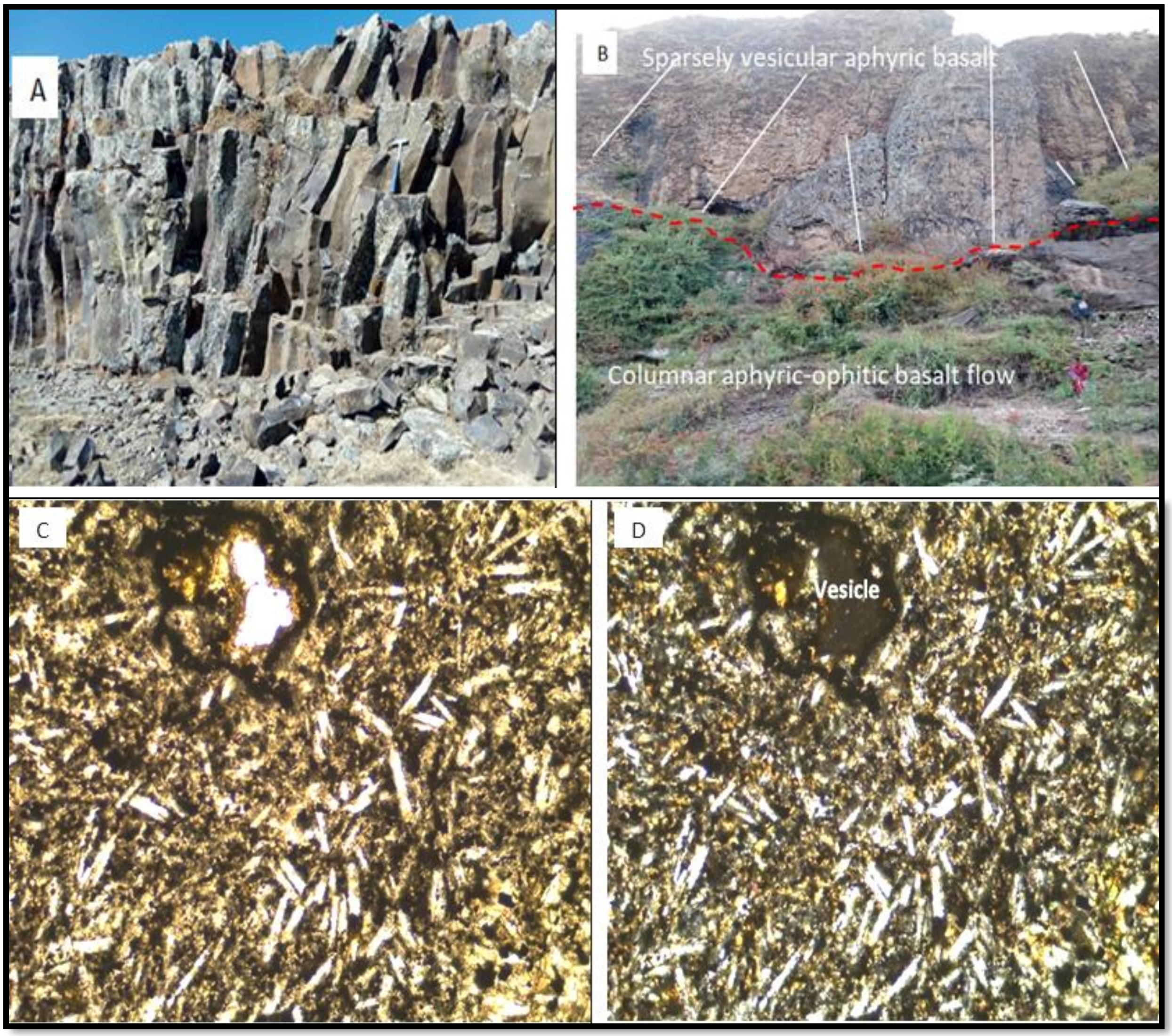

Figure 3.24: A &B are close up view of pale gray to brown slightly vesicular aphyric basalt with moderately algal weathering at E-0497162, N-1278549, and Z-2741. Plates of C&D are show the PPL and XPL views, respectively.

3.3. Contact relationship

The felsite and basaltic volcanic layers have different types of contacts in between them; they reflect different depositional histories of the area.

3.3.1. Sharp contact

In the study area, the contacts found in between the lower basaltic flow and rhyolitic-ignimbrite and upper basaltic units are sharp (see Figs.3.26 & 3.27), because they are mineralogically and texturally different. Similarly, the patchy and thin layered Kfs vitrophyric rhyolite (Fig.3.10) found as interlayered form within lower basaltic lava flow region which is considered as sharp relation.

3.3.2. Gradational contact

This type of contact is found in between basaltic to basaltic flows which characterized by paleosoils (Fig.3.5), agglomerate unit (Fig.3.23), basaltic tuffs (Fig.3.14) and baked sandy sized rhyolite fragments (Fig.3.19). In addition, the basaltic flows show a variety of mineralogical assemblage and textures which help to delineate their gradational contacts within the basaltic regions. This gradational contact is also used to separate moderately welded rhyolitic tuff from overlaying rhyolitic-ignimbrite pyroclastic flows and purely rhyolitic unit which is resting on the rhyolitic-ignimbrite flows.

3.4. Geological structures

The major structures were observed in the study area are classified as primary (Columnar joints (Fig.3.25) and stratified volcanic flows (Fig.3.26) and secondary (erosional escarpments and fractures (Figs.3.17 & 3.19) structural features. The primary geological structures are formed during the outpouring of lava flows to reach out the earth surface, but the secondary structures are formed by the action of stress on the existing rock after the rock formation (Spry, 1962 as cited in phillips et al., 2013). These primary and secondary structures of columnar joints and fractures are mainly observable in the present study and they discussed in detail within the lithological unit description part while in this section presented additional information of the two primary structures.

3.4.1. Columnar joint

Spry (1962) as cited in Phillips et al. (2013) also explained these primary structure do not exhibit a relative displacement between the columns found on the two margins of joint sets which is the result of magmatic activity formed due to magma cooling. These structures are dominated in both basaltic and rhyolitic flow in the study area. In the lower basaltic flow they only exhibit sub-vertical joint sets as shown in Fig.3.15 A, but they have vertical to sub vertical orientation in the upper two basaltic lava flows (see Figs.3.21 & 3.24 A &B). Similarly, in the rhyolitic flow, the general orientations of joint sets are vertical to sub vertical (see Fig.3.19). Overall, all joints show systematic orientations in the rock units of the area.

Figure 3.25: Close up view of systematic sub-vertical joints from aphyric -ophitic basalt flow (E-0497944, N-1278551, and Z-2695) having with two column faces and the rock is highly subjected by algal weathering.

3.4.2. Stratified volcanic structures

This primary structure is predominantly found in the study area. It is the main indication that the order of lava outpouring setting from initiation to termination. It is encountered in both flows except upper flat laying plateaus around Kon, Gashena, south of Istayish and west of Wegel Tena area. Generally, these structures are oriented with NE-SW direction.

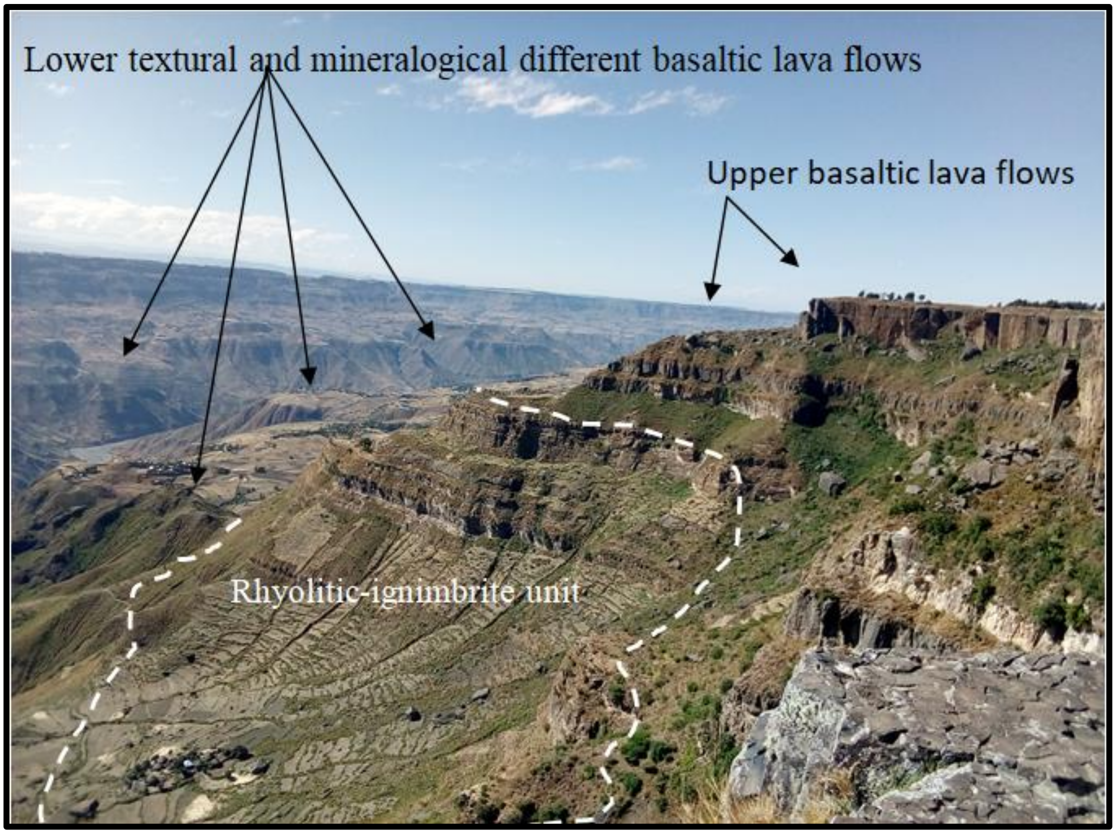

Figure 3.26: Panoramic view of the volcanic pile at Jita River section. The white dashed lines show the unconformity found in between lower basaltic flow and rhyolitic-ignimbrite units and also upper layered basaltic lava flows. The photo taken at the top NE side of the escarpment at the locality of Yedogit Mariam (E-0506411,N-1283634,Z-2992).

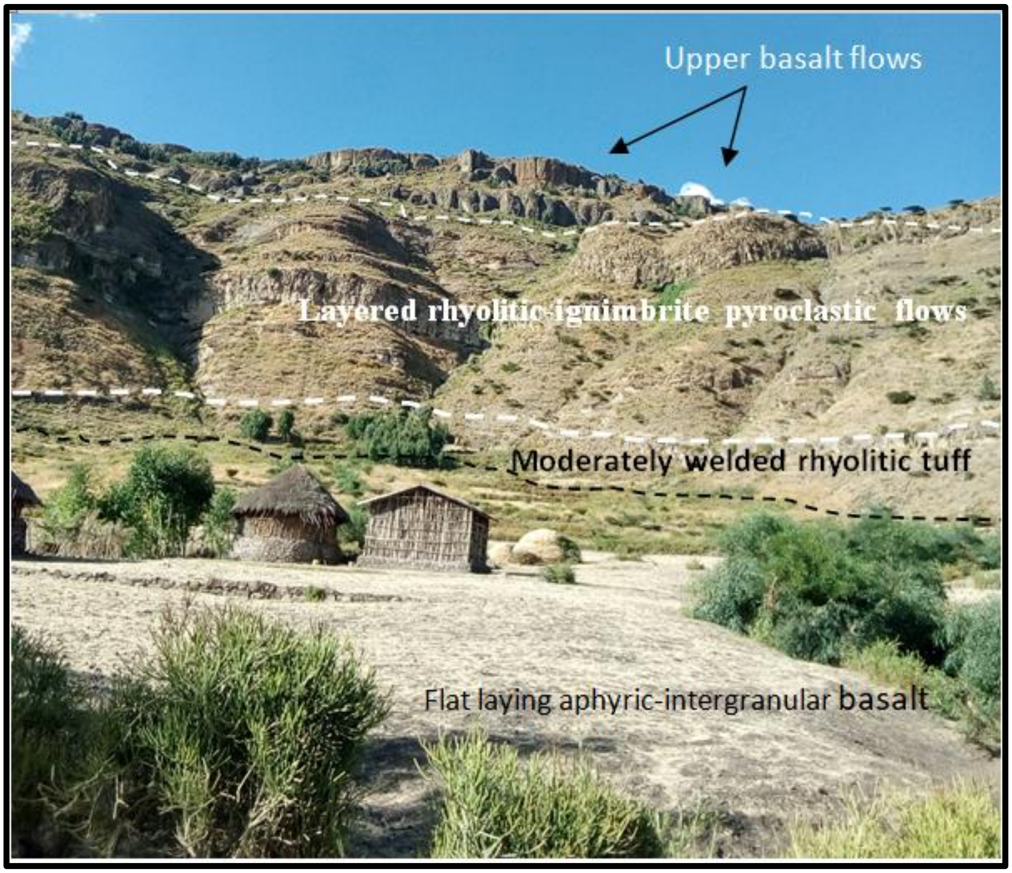

Figure 3.27: Middle to top panoramic view of the volcanic-stratigraphy of the study area. The photo is taken at the locality of Merken (E-0501653, N-127714, Z-2030).

CHAPTER FOUR

4. Discussion

4.1. Introduction

The study area is part of northwestern Ethiopian volcanic plateau, which is categorized as the Oligocene flood basalt (Hofmann et al., 1997; Ayalew et al., 2002; Kieffer et al., 2004 and references therein) and geochemically, this volcanic provience falls in the High-Ti (HT1) suites, which is restricted to the southeastern portion of NW Ethiopian plateau region (Pik et al., 1998). This study mainly establishes the volcano-stratigraphic setting (see Fig.3.3) of lava flows by the combination of field relation and petrographic analysis. Both these field observations and petrographic investigations have illustrated that the area is covered by extensive basaltic lavas with interlayered rhyolitic ignimbrite flows.

4.1.1. Petrographic characteristics of Jita volcanic section

This study analyzed about 13 fresh samples on the basis of mineralogical assemblage (both phenocryst, microphenocryst and groundmass phases), and micro-textures with the integration of field observation. Based on these petrographic analysis and field observation methods, the study area is comprises fifteen volcanic flows such as aphyric-intergranular basalt, aphyric-trachy flow basalt, Cpx cumulophyric basalt, Ol-Cpx phyric basalt, basaltic tuff, Cpx phyric basalt, columnar aphyric-intergranular basalt, non-columnar aphyric-intergranular basalt, thin layered Kfs vitrophyric rhyolitic flow, moderately welded tuff, Kfs phyric crystalline rhyolitic ignimbrite, Kfs phyric columnar rhyolite, columnar aphyric-ophitic basalt and slightly vesiculated columnar aphyric basalt, and thin layered basaltic agglomerate.

4.1.2. Volcano-stratigraphy of Jita flood volcanics

The petrovolcanic stratigraphy column is established using the petrographic characterstics on the basis of mineral phenocryst phases and textures described in the previous chapter. The intermittent flows are all encountered with about 1035.5 m vertical thickness.The earlier stratigraphic study of northwestern Ethiopian plateau did not clearly put the volcanic suites and distinctions between the Ashangi, Aiba, Alaji, and Termaber Guasa and Megezez shield flood volcanism (e.g., Mohr and Zanettin, 1988), because they were simply characterized as upper and lower units, which relied only on the basis of local morphology (not consistent with the entire volcanic province in terms of petrography).

Further, Hofmann et al. (1997) have improved these morphological distinctions found in between upper and lower flood basalts, but lack detailed petrological constraints. Therefore, based on the petrographic differences, this study established three major volcano stratigraphic classification schemes which have been investigated by the characterization of individual lava flow mineral assemblages and textures such as lower and upper flood basalts and rhyolitic-ignimbrite lava flow. However, these large flows comprise different texturally and mineralogically different lava flows within them (fifteen in number) see Fig.3.3. Generally, these composite classification schemes are used here for the discussion and interpretation purpose following the following section.

4.1.2.1. Lower basaltic lava flows (1791-2440 masl)

The lower lava flow sequences are totally about 649 m thick, and comprise the aphyric-intergranular basalt, aphyric-trachytic flow basalt, Cpx cumulophyric basalt, Ol-Cpx phyric basalt with slightly Ol megacrysts, one thin interlayered Kfs vitrophyric rhyolitic flow, Cpx phyric basalt, basaltic tuff, columnar and non-columnar aphyric-intergranular basalt flows, respectively. The precise numbers of flows in this region is nine, and these separated flows have variable mineral assemblages and textures. At the bottom of this lava sequence, there is no visible exposure, of either metamorphic or sedimentary units despite the deep dissection by Jita River (Fig.3.3 in the stratigraphic log).

In this region, iddingsite alterations are developed along the large olivine phenocryst fractures and sometimes around their rims. The other aphyric flows comprise intergranular to trachytic groundmass. One columnar lava flow in this region is found in between 2032 to 2212 masl. A thick of 73 m basaltic tuff and 20 m Kfs vitrophyric rhyolite are also observed in between 1959 to 2032 and 1899 to 1919 masl, respectively.The basaltic flow below the paleosoil is highly weathered with sparse calcite veins; it is tilted with aphyric-intrgranular flow. In theupper portion of the lower flow region are separated by a covered interval (48 m) in between flows of columnar aphyric-intergranular (180 m) basalt and non-columnar aphyric-intergranular basalt units (150 m) and similarly, this covered interval is found also in between moderately welded rhyolitic tuff and non-columnated aphyric-intergranular basalt, with estimated thickness around 22 m. In this part of lower basalt, the clinopyroxene phyric flow shows simple twining and herring bone structure having euhedral-subhedral and anhedral shapes. The shapes of the crystals reflects the order of magma crystallization in which euhedral and subhedral shapes imply that the minerals crystallized first, but the anhedral minerals is crystallized later. In similar explanation, Cpx and Fe-Ti oxide minerals are involved within large olivine megacrysts as inclusion phase, which also demonstrate that the chadacrysts (the enclosed crystal) are formed earlier than the host olivine phenocrysts. Generally, this lower lava flow is the thickest portion within Jita volcanic stratigraphy sequences and has dominant phenocryst phases of Cpx and Fe-Ti oxide cumulophyric, Ol-Cpx (rarely with Ol megacrysts), Cpx phyric and Kfs vitrophyric magma types.

4.1.2.2. Rhyolitic ignimbrite flows (2440-2689 masl)

This felsite volcanic flow is found in the middle portion of the volcanic sequence in the area which unconformly rests on the texturally different lower basaltic units. This region comprises three texturally different flows having a total thickness reached around 249 m; these flows are moderately welded rhyolitic ash, Kfs phyric rhyolitic ignimbrite flow and Kfs phyric columnar rhyolite unit, in which the two later flows are exposed as layered covering parts of the flat plateau, specifically Gazo hill tops and plains which are found in the northeastern part of the study area. They are dominantly composed of sanidine minerals in all phases, but small amount of Qtz mineral phenocrysts with greater glassy groundmass.

4.1.2.3. Upper flood basalt flows (2689-2825 masl)

The upper basaltic region has two basaltic lava sequences, over all, it is estimated about 136 m and is exposed at the top of the plateau at the termination of volcanic stratigraphy.These flows are highly characterized by columnar structure with different coarser aphyric textures (ophitic and vesicular, respectively), and they are separated by thin layered aphyric basaltic agglomerate. The modal proportion of the lath shaped plagioclase microphenocrysts are increasing towards the termination of these upper flows.

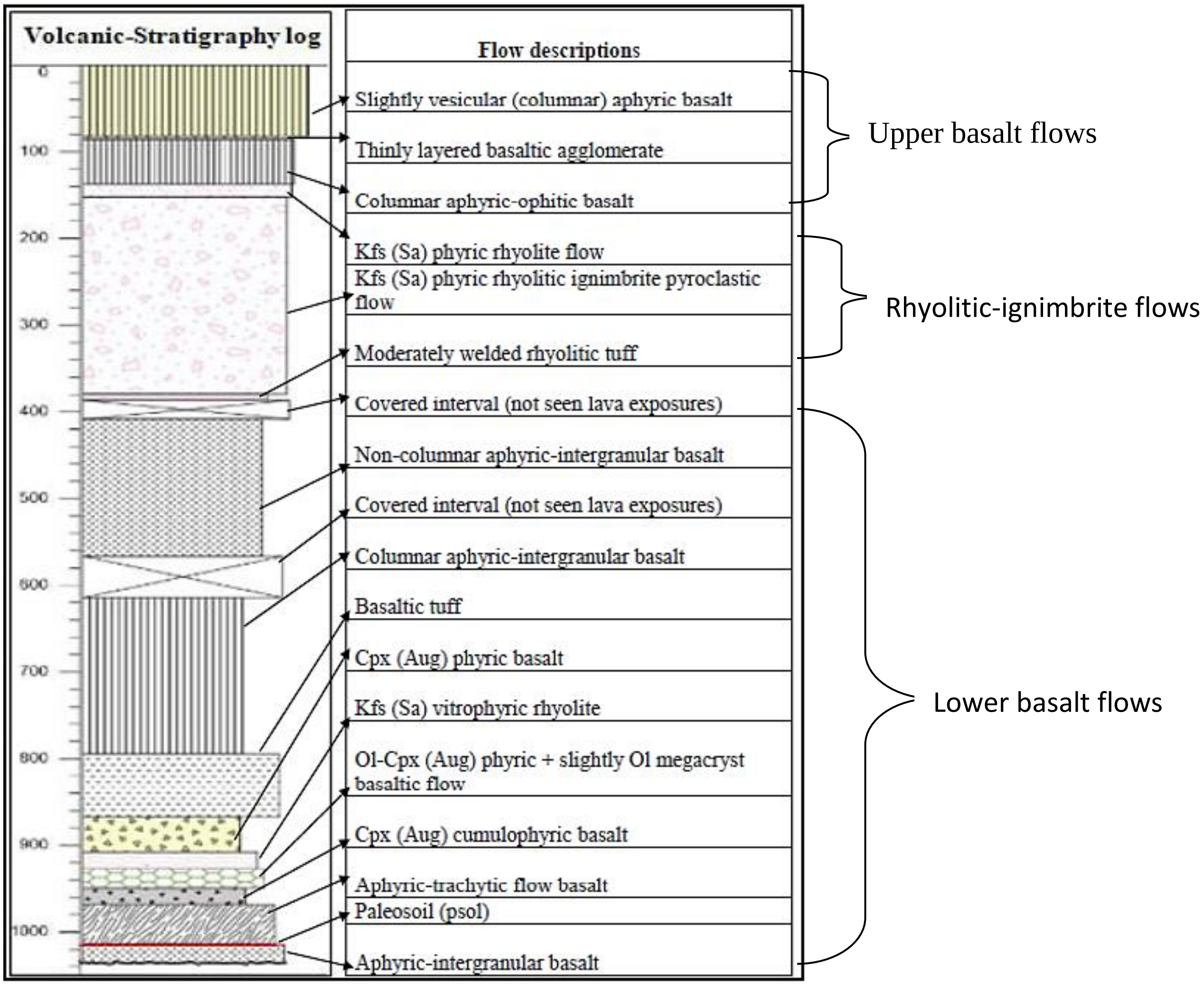

Figure 4.1: Volcanic stratigraphy sub-divisions of Jita River section.

4.2. Magmatic evolution inferred from petrography and volcanic stratigraphy

The discussion here develops a generalized description of the magmas that were erupted to form the thick sequence of lava flows and pyroclastic deposits exposed at Jita River section. The discussion is constrained by the results which address magma storage conditions inferred from the dominant mineral assemblages represented by phenocryst, megacryst, and microphenocryst variations in a given flow with an assumed depth of fractionation and magnitude of magma flux into the lithosphere. Similarly, coarser aphyric texural differences also provide clues for understanding the behavior of the magmatic plumbing system.

The petrography of the analyzed samples from this study shows a range of mineral compositions and textural features in the stratigraphic framework. The flows constitute different mineral phases in phenocryst, microphenocryst and groundmass level, having different modal percentages. For example, in the basalt flows, Cpx (Aug), Ol and Fe-Ti oxides are the major phenocrysts whereas plagioclase is found only as microphenocrysts and groundmass. It is also observed that the percent proportion of plagioclase increases from bottom towards the top of the stratigraphy. On the contrary, the felsic units comprising the pyroclastic deposits have major phenocrysts of Kfs (Sa) and Qtz as microphenocryst phase with largely glassy groundmass. For evaluating the magmatic processes associated with the volcanic sequence on the basis of their stratigraphic position, an assessment is required of certain parameters that control the crystallization of mineral phases in both basaltic and felsic rocks during eruption. These parameters are: (1) composition of the parental magma, (2) pressure or depth of crystallization, and (3) the amount of volatiles in the magma (Mountener et al., 2001; Feig et al., 2006; Krans et al., 2018 and references therein).

The mineral assemblages of Ol + Cpx in the basaltic lavas imply that crystal fractionation has taken place at a deeper level in the crust or at the crust-mantle boundary, while assemblages of Plag + Cpx + Ol minerals suggest that fractionation occurred at a relatively shallow levels in the upper crust (Pik et al.,1998; Krans et al., 2018 and references therein). These crystallization phases of different minerals within lava flows play a crucial role to understand the behavior of the magmatic plumbing system in the study area. It is also known that increasing of water concentration in liquid magma changes the mineral crystallization sequence or delays the order of crystallization (Mountener et al., 2001; Feig et al., 2006). Under such circumstances, a relatively hydrated magma that contains water (>3wt %) clinopyroxene is crystallized over plagioclase at shallow crustal depths/pressure (Feig et al., 2006). On the other hand, in a relatively dry magma, crystallization of clinopyroxene and olivine minerals are favored at high pressure (10-20 kbar) at the expense of plagioclase, whereas the plagioclase minerals preferably crystalize over clinopyroxene crystals at lower pressures (<5 kbar) in the same magma (Morse 1980; cited in Krans et al., 2018).

In addition, Bartels et al. (1991) as cited in Krans et al. (2018) have noted the composition of the parental magma controls the mode and order of crystallization along the liquid line of descent.This observation is supported by Natali et al. (2016) who have described Ol + Plag in Low Ti lavas, and Ol + Cpx phenocrysts in High Ti 1 and High Ti 2 lavas (see Fig.2.3).

4.2.1. Conceptual models for the evolution of the volcanic sequence

The petrographic investigations presented in this study suggest three different groups or divisions: 1) the lower flood basalt group, which dominantly contain phenocryst phases of Cpx, Ol-Cpx with rare

Ol megacrysts; the basalt lava flows are sometimes interlayered with Kfs vitrophyric rhyolite, 2) the middle felsic group which exhibits Kfs phenocrysts with glassy groundmass, and 3) the upper flood basalt group, which comprise higher percentage of Plag microphocrysts with absence of Plag phenocrysts and Cpx cumulates. These distinctive petrographic results are used to address magma characteristics of the thick volcanic pile as follows.

4.2.1.1. Lower basalt series

The major phenocryst phases observed in the lower basalt section are clinopyroxene (augite) in the form of glomerocrysts followed by Ol-Cpx and then Cpx in the form of phenocrysts within the stratigraphic framework. Both Cpx and Cpx-Ol phyric basalt flows do not contain plagioclase. The clinopyroxene and opaque-rich assemblages clearly suggest that they crystallized at higher pressures, consistent with mid to deep crustal levels and this provides an insight to the early evolution of the lava flows.

Ethiopian high Fe-Ti oxide basalts are interpreted to be generated from melting of a mantle plume head (Pik et al., 1998). The lower basalt flows at Jita river section are characterized by high amounts of these opaque oxides present as phenocrysts, microphenocrysts and in the groundmass. These abundances suggest magmas originated from the partial melting of deep mantle material and initial melts derived from the impinging plume head could have migrated upwards through the sub-continental lithospheric mantle due to their buoyancy till the melts reached the crust-mantle boundary where they could accumulate and fractionate.

Furthermore, Rooney et al. (2017) conducted petrological study of pyroxenite xenoliths from Cenozoic volcanism in the northwestern Ethiopian plateau and explain an equilibrium pressures consistent with the crust/mantle boundary which suggest a linkage between Opx + Cpx rich cumulates and LT flood basalt magmatism. Based on this scenario, the Cpx (Aug) phyric flows observed in this study are devoid of orthopyroxene minerals at all. Therefore, augite cumulates in this study are interpreted as they were crystallized from the stalled magmas in the lower to middle crust (see Fig.4.2). These lower to middle crust magma chambers are fed by more primitive magmas derived from lower crust.

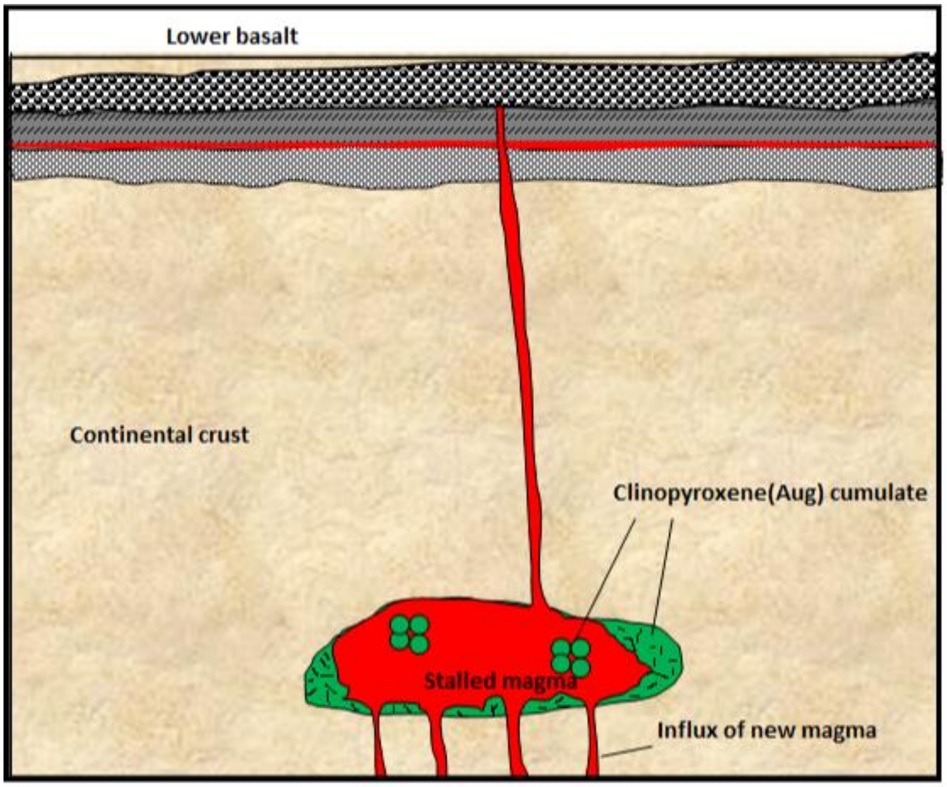

Figure 4.2: A magmatic plumbing system of Cpx (Aug) phyric basalt from stalled magmas in the mid to lower crust.The flow layer symbols are presented sequentially from bottom to top throughout the models based on stratigraphic log (see Fig. 3.3).

The presence of weathering horizons (paleosoils) within the lower basalt sequence represents pauses or periods of non-eruption during lower basalt development. This is the distinctive feature which punctuates eruption of lava flows in the lower flood basalt. Similarly, the occurrence of basaltic tuff reflects that the volume of magmatic influx was weak during extraction of basaltic magma (Levitskii et al., 2013). These pauses in lava flows suggest a decrease in magma flux into the lithosphere and the rate of the magma was not high enough to erupt at the surface (Krans et al., 2018).

Aphyric basalt flow occurs at the beginning of the lower basaltic sequence which is deeply dissected by Jita River. Consequently, these flows marked by relatively thin layers 50-80 cm red paleosols provide evidence for sharp decrease in earlier magmatic flux and the earlier plumbing system fed by a lower flux of magma with high extrusion and relatively slow-cooling rates (see Fig. 4.3). This idea is supported by the work of Beccaluva et al. (2009) who have shown that at the initial magmatic phase, early lavas tend to be more primitive, and of lower volume feeder when they are intercalated with weathering horizons (paleosols). Accordingly, in this study these characterstics are interpreted to reflect the magma involved in early eruptions with experienced limited fractionation in short pulse separated by pauses from later predominantly cpx-cumulophyric, Ol-Cpx and Cpx phyric lava eruptions in the area.

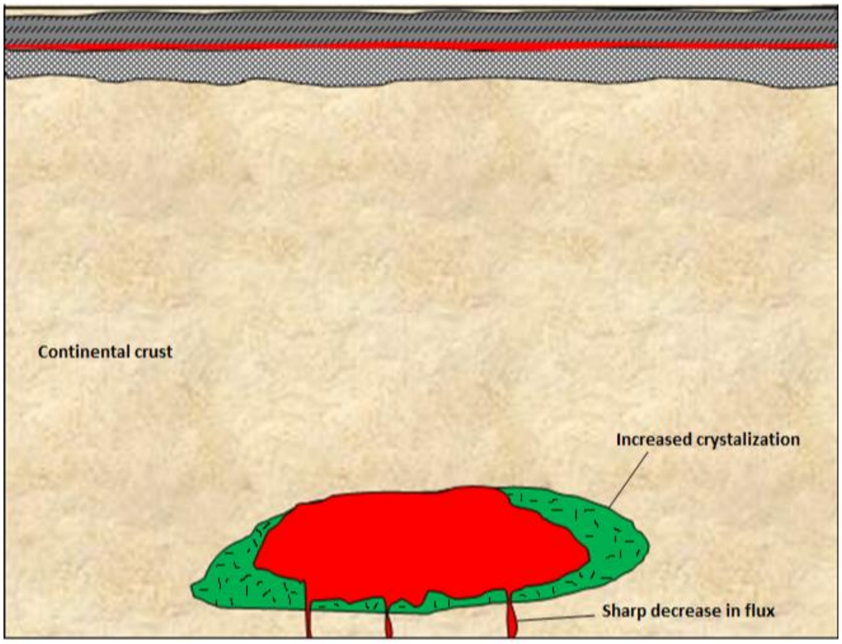

Figure 4.3: Hiatus in between the early lower flows of aphyric-intergranular basalt and aphyric trachytic lava. A pause presented here in between these coarser aphyric basalt eruptions allow for the formation of paleosoil. Magma flux into the magmatic plumbing system has decreased and the magmas stalled at lower crustal level started to rapid crystallize. The plumbing system is shut down and is no longer capable to recharge the shallow reservoirs.

On the other hand, the aphyric-trachytic basalt lavas suggest they were erupted by high extrusion rates with aphyric phases which appeared by a higher flux of magma into the plumbing system after the pause.

The Cpx cumulophyric flow followed by Ol-Cpx phyric plus rarely Ol megacrystic phases in this lower region appears to be a case of the disordering of fractional crystallization during a pulse of magma which revealed they were erupted with wet condition (>3 wt%). The effect of this high water content is taken into account the delaying of mineral crystallization order and also the inclusion of cpx within big ol crystals also support the idea of disordering mineral fractional crystallization sequences in the area (see Figs. 3.9 C & D). In addition, the olivine megacrysts also reflect there was multiple magma recharging events from deeper magmatic chamber in the lower crust. This idea strengthen by the work of Krans et al. (2018) who have explained that high flux magma and recharge volumes into the lithosphere could produce and sustain large megacrystic flows and they require some duration of residence time in between eruptions. Furthermore, Kuritani (1999) noted that the higher water content of magma in a relatively deep reservoir produces a larger driving force for crystallization of these big crystals during ascent of magma to the surface. Further, duration of residence (Ol megacrysts in this study) within the lithosphere provide additional insights into the flux of plume-related magmas (Krans et al., 2018). Iddingsite olivine alterations also reflect there is influx of new magma which causes reaction of the pre-existing Ol crystals when the pressure in the chamber increases (https:en.m.wikipedia.org.iddingsite). Overall, these Cpx and Ol-Cpx phyric flow pathway observed in the lower basaltic section of the volcanic sequence depicts that the early formation of the deeper magmatic plumbing system of lavas traversed through the crust.

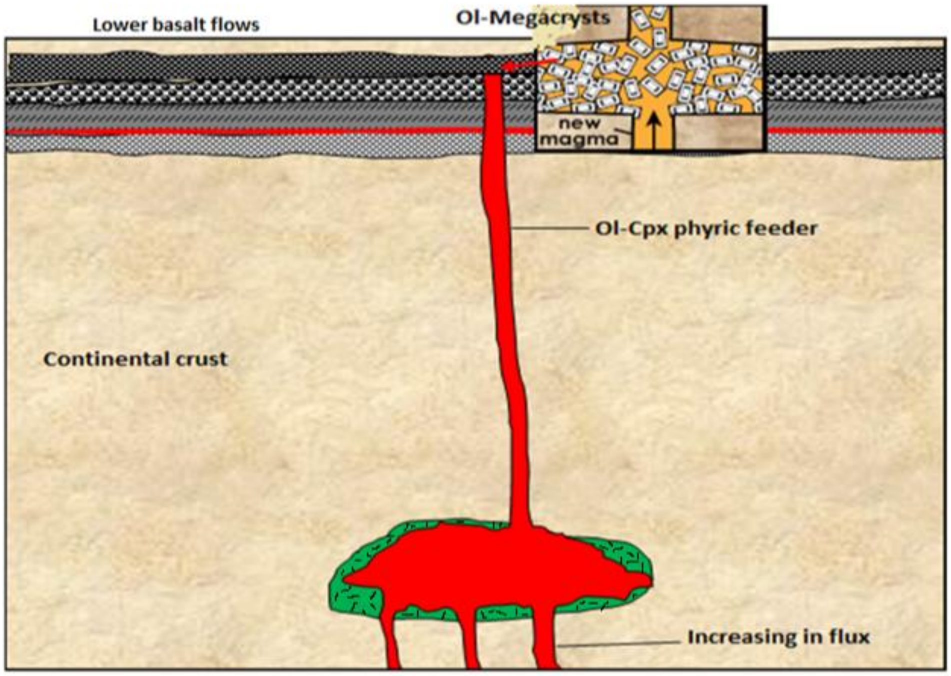

Figure 4.4 : Ol-Cpx phyric basalt plumbing system fed by deeper crustal level magma reservoir with high influx and volume rate. The top inset diagram shows the injection/recharging of new magma to the deeper crust plumbing system to produce ol-megacrysts with residence time.

Overlying the Ol megacryst and Ol-Cpx phyric lava flows, there is a thin layer of Kfs (sanidine) vitrophyric rhyolite flow. This indicates that at the end of the extrusion of the Ol-Cpx basalt flow, the influx of magma decreased from the deeper chamber and implies fractionation within the shallow plumbing system or significantly reduced magma recharging or volume. The Ol-Cpx flow is terminated by this unit. This Kfs vitrophyric rhyolite is a transitition flow from Ol-Cpx phyric to Cpx phyric flows in the lower flood basalt sequence and it appears to cause modal variation between the stratigraphy and it suggests an isolated fractionation path for magma traversing to the lithosphere. Under this petrographic view, the Kfs phyric rhyolite eruption was fed by long-lived magma reservoirs that slowly differentiated between mafic recharges.

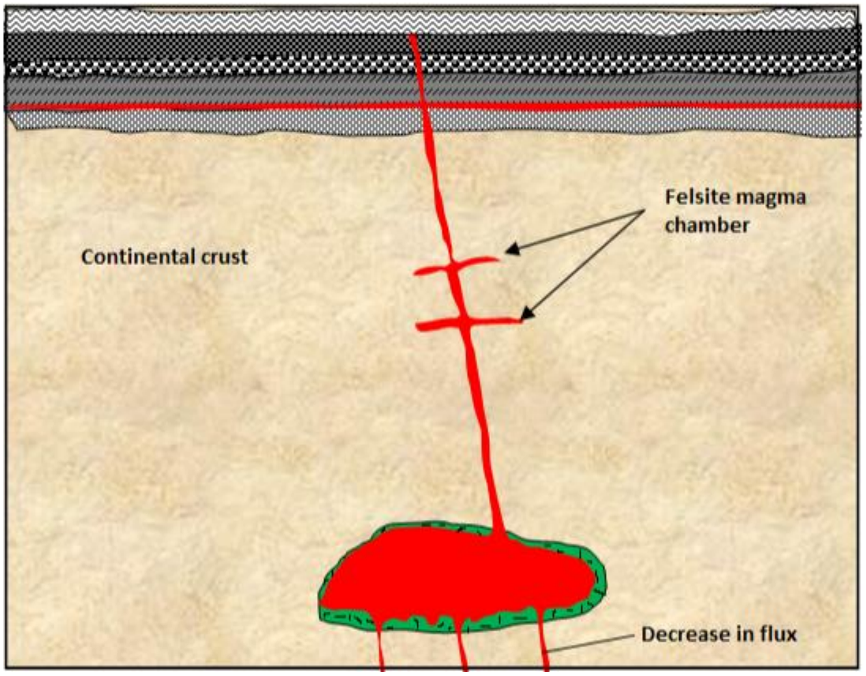

Figure 4.5: A model showing the interlayred Kfs phyric rhyolite volcanism derived by low pressure fractionation in the shallow reservoir or it formed when decreasing deeper magma flux at the nearly shallow crust.

Afterwards, the Cpx phyric basalt eruption began, it shows the fractionation order is normal, which means Cpx fractionated after Ol crysatals, it reflects dry condition (<3 %) or start a simple fractional crystallization process. In addition, this flow indicates that the magma flux or volume increasing again from the deep magmatic plumbing system (lower crust).

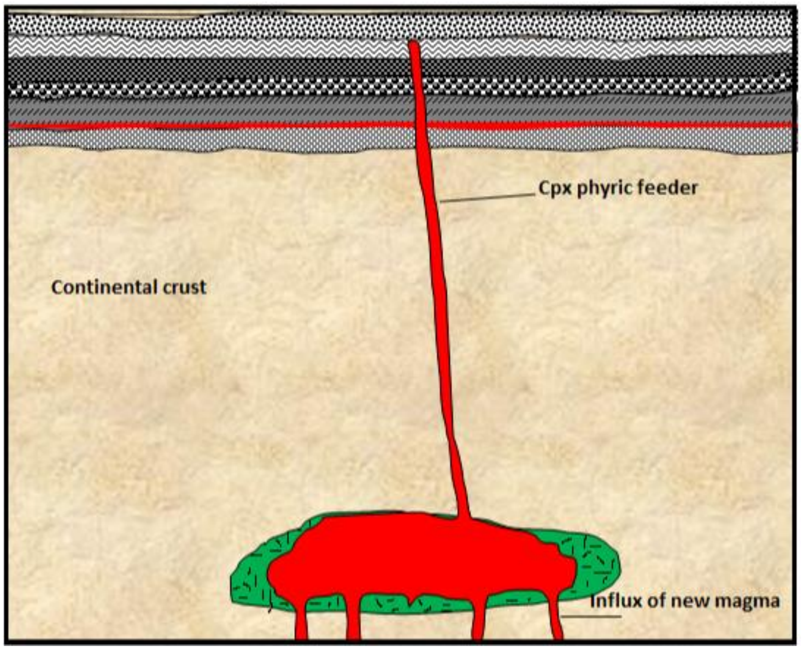

Figure 4.6: A Cpx phyric basalt model shows the increasing of magma at deeper crustal level.

The observed variability in modal mineralogy found in the lower basalt flows in this study supports the idea of isolated feeder systems during early development of magmatic plumbing system. The uppermost portions of the lower basaltic group are characterized by columnar lavas and non-columnar aphyric flows devoid of Cpx-phenocrysts also suggesting the magma influx or volume is not continuously increased or it is decreased over time towards top (shallower stage). However, they were erupted by high extrusion rates.

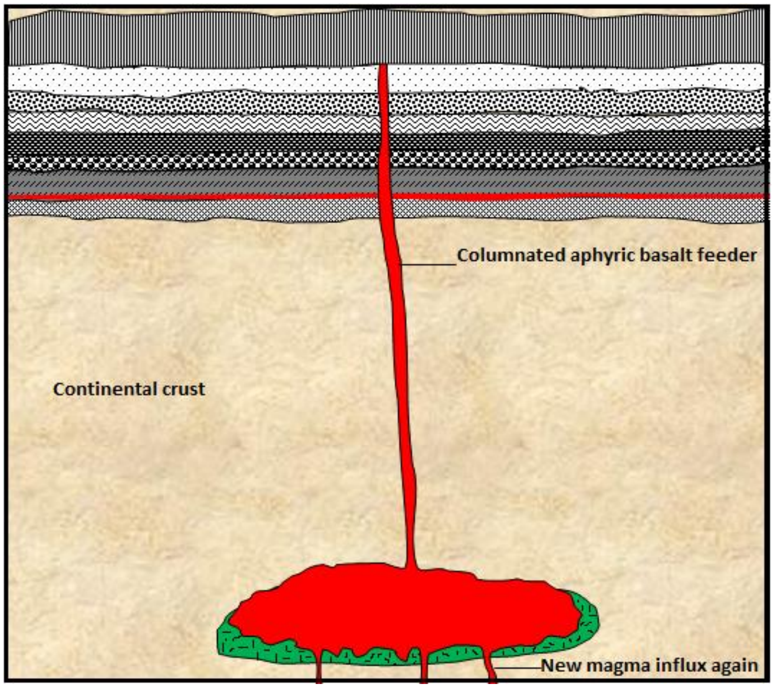

Figure 4.7: The plumbing system for columnar aphyric intergranular basalt.

At the end of these aphyric basalt magma extrusions, there may be crystal fractionation or melting of the crust within the shallow magma chambers, which resulted in the formation of moderately welded rhyolitic tuff. These reflect that near the end of extrusion aphyric basalts, there is a decrease in the influx of magma from the deeper chamber (Krans et al., 2018). Generally, in the lower basaltic sequence, modal and textural variations in between nine intermittent individual lava flows reflect there were isolated fractionation paths during early development of magmatic plumbing system for magma traversing to the lithosphere. On the flow- by -flow observation, there is no apparent systematic variation in modal mineralogy or flow thickness and overtime it indicates the magma plumbing system was too complex.

4.2.1.2. Middle felsic volcanic series

In the middle portion of the volcanic stratigraphy, this study has identified felsic units with an increase of Kfs- rich pyroclastic flows overling the lower flood basalt sequence. The underlying lower basaltic flows are terminated by moderately welded rhyolitic tuff (ca.7 m) and began this rhyolitic ignimbrite pyroclastic flow with higher proportions of glassy groundmass. The dominance of Kfs in these deposits also suggests lower flux, while a decrease in magma recharging event would facilitate fractionation of the magmas residing in the shallow crustal reservoir. The top of this flow is characterized by columnar jointing which suggests also decreasing volumes of the flow unit (Hetenyi et al., 2012).

The above conclusions are supported by the geochemical data of Ayalew et al. (2002) who proposed that these felsic units evolved from parental basaltic magma by fractional crystallization process. Moreover, shallow fractionation stages are evidence for the involvements of shallow magmatic plumbing system or shallow reservoirs (Krans et al., 2018).

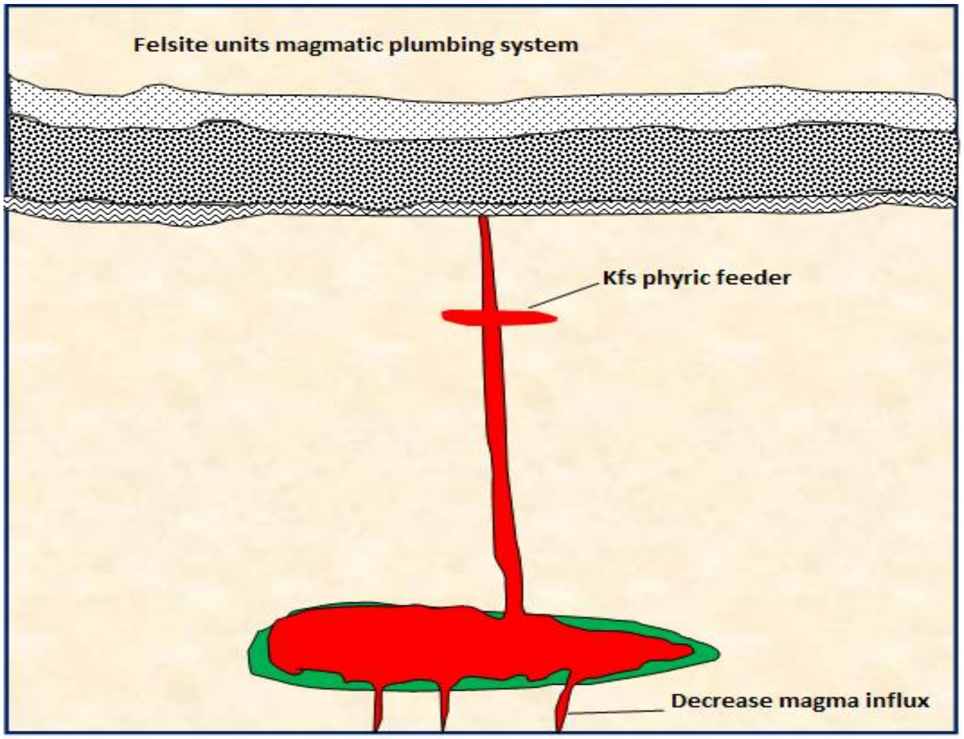

Figure 4.8: The rhyolitic ignimbrite volcanics eruptive phase from the shallow reservoir.

4.2.1.3. Upper basalt series

The upper basalt lava sequences at Jita river section are characterized by highly columnar eruptions of aphyric and slightly vesicular aphyric basalts, respectively. They are marked by the presence of thinly layered aphyric basaltic agglomerate in between them, which suggests a decreasing of magmatic influx from aphyric ophitic flow towards vesicular top unit. The upper basalt flows rest on the felsic volcanic deposits and they represent flood basalt termination in the volcanic sequence of Jita area. The mineralogical assemblage of Plag+Cpx+Ol in these flows supports the idea that fractionation occurred at shallow level in the upper crust (Pik et al., 1998). In this basaltic sequence, there are no Ol phyric, Cpx-glomerocrysts and plagioclase phenocryst phases, but are dominated by microphenocrysts of plagioclase. The absence of plagioclase phenocryst assemblages reflect that the lower (decrease) influx into the shallow chambers could no longer produce the recharge volumes necessary to sustain the growth of crystals. However, the increase in the modal proportion of plagioclase microphenocrysts in these flows reveals that the recharging of new primitive magma into the shallow plumbing system with significantly reduced magma volumes, since shallow crystal fractionation of the magmas residing in the lithosphere takes place at low pressure in the shallow crust.

Columnar jointing is contractional cooling, which means that the network of fractures forming the column boundaries develops due to mechanical stress build up while the lava cools and contracts (e.g., Raspe, 1776 as cited in Hetenyi et al., 2012). This flow structure provides further explanation for magma magnitude as explained by Hetenyi et al. (2012); the columnar jointing is always associated with a decrease in magma volume, creating tensional stresses within the body. Starting from this scenario, the upper basaltic flows appear to be generated by lower magmatic fluxing at the shallow plumbing system. The presence of vesicles towards the top of the volcanic stratigraphic section has other additional implication for shallower influx of magma generation. However, the extrusion rate of the flow is high with slow-cooling coarser texture (aphyric ophitic).This suggests that there is a decrease in magma recharge into the plumbing system that produces the plagioclase microphenocryst flood basalt unit. Generally, upper basaltic section capped by less dense vesiculated flow.

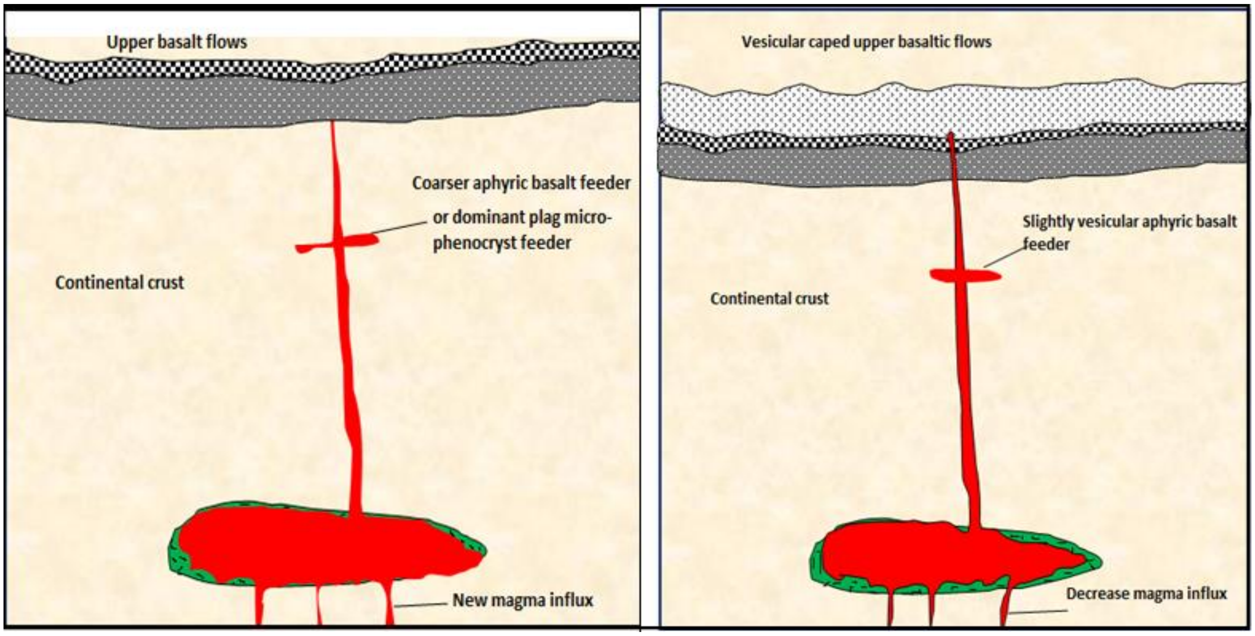

Figure 4.9: Upper columnar basalt flows eruptive phases.

They demonstrate the termination of flood basalts in Jita area capped with vesicular lava flows. They are dominated by plagioclase microphenocrysts with devoid of Cpx-cumulates and Ol-megacrysts. These plag rich flows reflected that magma stalled and fractionated in the shallow crustal level, but no longer enough to produce large plag phenocryst phases.

4.3. Correlation of Jita volcanic units

The composite stratigraphy of Jita volcanic products is correlated with the regional stratigraphy of Wegel Tena section which conducted by Dereje Ayalew and Gezahgn Yirgu (2003). The correlation result indicates aphyric-intergranular basalt, aphyric-trachytic flow basalt, augite cumulophyric basalt, olivine-augite phyric basalt, Kfs (Sa) vitrophyric rhyolite flow, augite phyric basalt, basaltic tuff, columnar-aphyric-intergranular basalt and non-columnar-aphyric-intergranular basalt correlate to lower HT flood basalt. Middle portion of rhyolitic ignimbrite flows (moderately welded rhyolitic tuff, Kfs (Sa) phyric rhyolitic-ignimbrite flow, Kfs (Sa) phyric rhyolite) are correlate with poorly welded and less welded lithic rich regional units of Wegel Tena rhyolite. Finally, the last volcanic products; aphyric-ophitic basalt, thin layer basaltic agglomerate and sparsely vesicular aphyric basalt (upper basalt flows) correlated to upper HT flood basalt unit. The radioactive dating after Hofmann et al. (1997); Hofmann (1997) as cited in Krans et al. (2018) and Ayalew et al. (2002) suggest the age of each major units; 30.2 ±0.1 ,30.1 ±0.4 and 26.4 to 27.8 Ma, respectively. The stratigraphic arrangement of the volcanic products in the Jita section tells the nature of the eruption is non-explosive at first then explosive and finally become non-explosive.

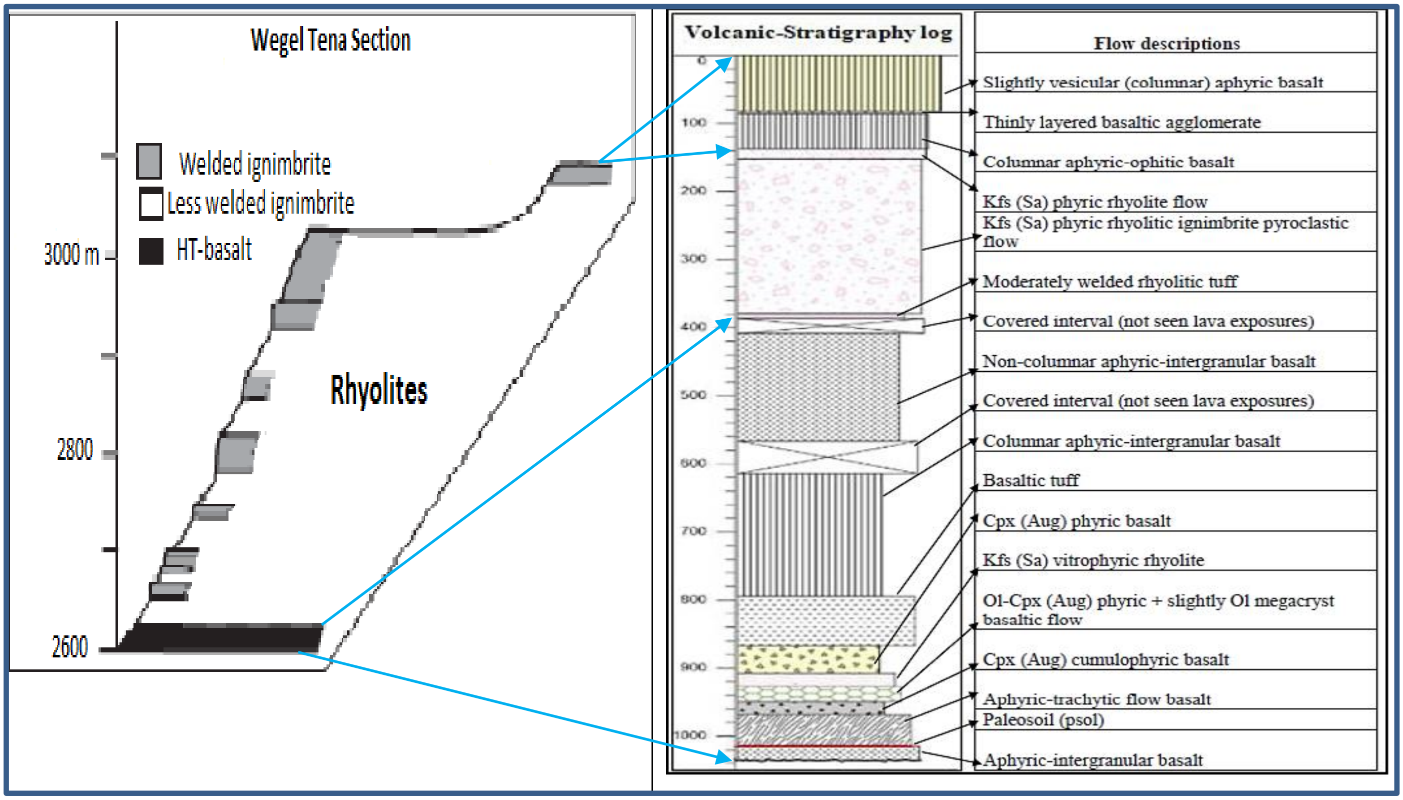

Figure 4.10: Volcano-stratigraphic correlation between Jita river section and Wegel Tena area. The Wegel Tena section has developed by Ayalew et al. (2002).

CHAPTER FIVE

5. Conclusions and Recommendations

5.1. Conclusions

According to the work of Pik et al. (1998), the volcanic sequence at Jita river section was considered as HT1 suite with respect to other NW Ethiopian volcanic plateau regions. The volcanic pile in the area consists of both basaltic and rhyolitic units, but the former one is highly extensive (having of different textures and mineral assemblages). They are situated as a well-preserved volcano-stratigraphic sequence from the base to the top section. By integration of field relations and petrographic investigation, this study provided a new insight into the evolution of magmatic plumbing system in basaltic and felsic volcanics of the area. The major findings from this study are listed out as follows:

- From the detailed flow-by-flow petrovolcanic-stratigraphic investigation having around 1035.5 m total thickness, the area comprises fifteen (15) intermittent volcanic flows such as aphyric-intergranular basalt, aphyric-trachytic flow basalt, augite cumulophyric basalt, olivine-augite phyric basalt, Kfs (Sa) vitrophyric rhyolite flow, augite phyric basalt, basaltic tuff, columnar-aphyric-intergranular basalt, non-columnar-aphyric-intergranular basalt, moderately welded rhyolitic tuff, Kfs (Sa) phyric rhyolitic-ignimbrite flow, Kfs (Sa) phyric rhyolite, aphyric-ophitic basalt, thin layer basaltic agglomerate and sparsely vesicular aphyric basalt. The former nine flows exposed in the lower basaltic series with dominant Cpx-cumulates, Ol-Cpx (Ol megacryst) and Cpx phenocrysts. This observation suggests that the lower basaltic flows are fed by magmas that have experienced deeper fractionation from mid- to deep crustal level. The flux of new primitive magma erupted continuously throughout in this lower flow region, but its magnitude changed over time and they punctuated by magmatic pauses (psol and tuffs) in between flows. For example, changes in a flux magnitude control number of lava erupt at the surface as well as hiatuses in eruption. The olivine megacryst composition and iddingsite alterations in this flow piles indicating there is a constant feeding or recharging of new magma to deeper plumbing system while Kfs vitrophiric rhyolite reflect that the rate of magma flux was decreased along with shallow plumbing system and crystallized it at shallow crustal level with shallow pressure. Additionally, the lower region show disordering mineral fractionation sequences (e.g., Cpx over Ol phenocrysts) which suggest they are extruded with hydrated magma conditions, but not throughout the stratigraphy. Because afterwards, it changes to normal cystalization order (Cpx after Ol) with dry magma plumbing system. Initial lava flow (aphyric basalt situated at the base of Jita River) of the area is tending to be more primitive and lower volume which intercalated with weathering horizons. This suggests magma influx into the magmatic plumbing system has sharply decreased, and the lower crustal stalled magmas begin to crystallize. As recharge to the deep reservoirs shuts down, and the plumbing system is no longer capable of sustaining large grains. Overtime, the plumbing system becomes polybaric thus reflecting the settling of magma in both shallow and deep crust in this lower basalt flow region.

- The upper two basaltic flows are marked by the aphyric basaltic agglomerate that indicates lava flows were punctuated during eruption from high volume magma influx to lower magnitude. Consequently, through time the plumbing system is shallower and the fractionation becomes enriched with microphenocrysts of plagioclase and thus reflecting the settling of magma in shallow crust. The absence of Cpx cumulates and Ol megacrysts here are an evidence of shallow magma plumbing system fed by shallow reservoir. The dominance of capped vesicular flow is further information to perceive the shallower magmatic recharging system of the area.
- In a similar way, the felsic units (rhyolitic-ignimbrites) indicate that the magmatic influx decreased and fed by the shallow magmatic chamber at shallow crustal level (upper crust). These flows shut down the lower basaltic eruption phases. In this flow region, there is also a red marker with rhyolitic composition; it is also a magmatic plumbing modifier from thicker rhyolitic ignimbrite to pure rhyolitic flow. This reflects that the higher magnitude magma flux decreased overtime and they evolved from shallow magmatic reservoirs at upper crust.

5.2. Recommendations

The study area needed further investigation to understand the magmatic evolution in detail

- Mineral chemistry analysis for phenocryst, microphenocryst phases and groundmass level is required to know the mineral composition of volcanic suits qualitatively.
- Isotopic geochemistry analysisis recommended to know the rock geochronologic history
- Detail Geothermobarometry study of minerals is required to determine the pressure and temperature condition of rocks for more constraints of their magmatic plumbing system.

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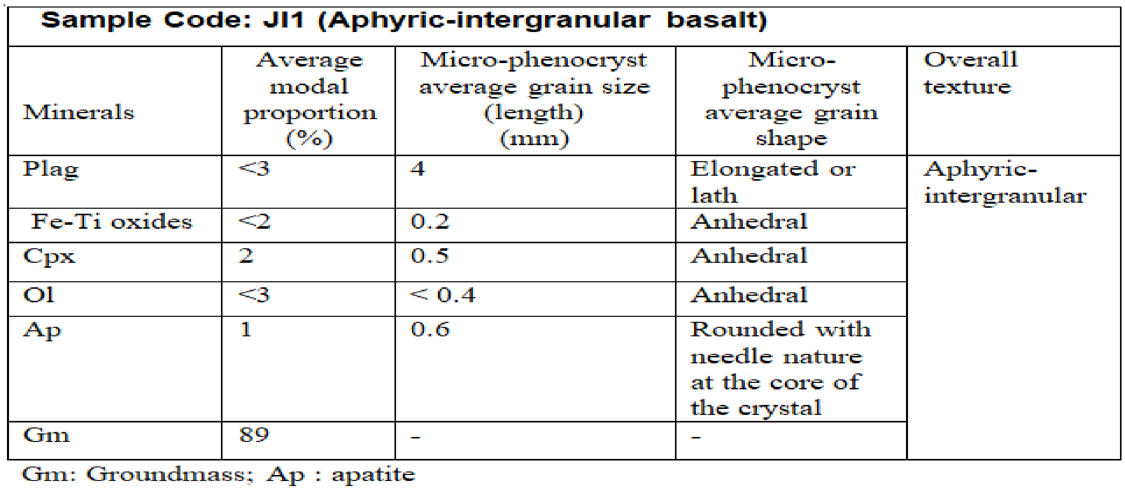
Appendix

Appendix 1

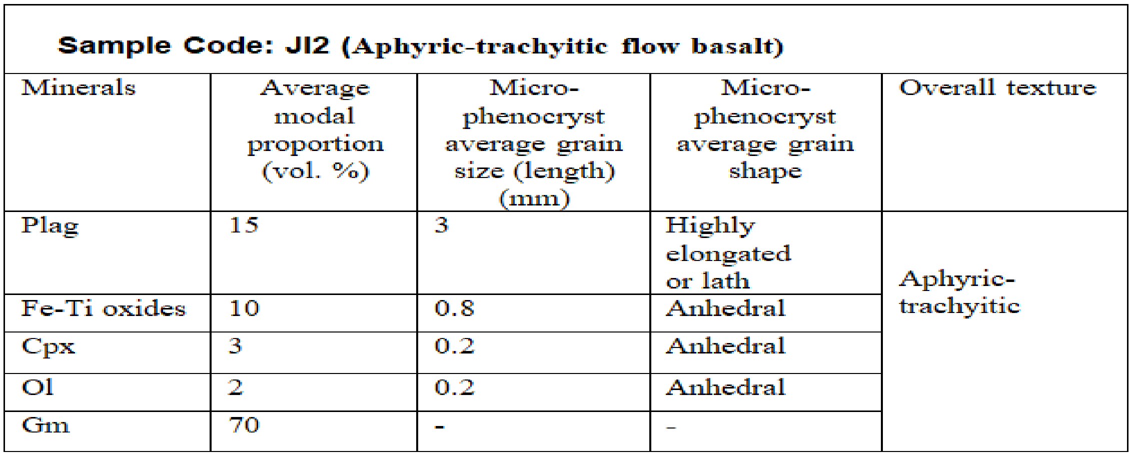
Petrographic Analysis



Sample Code: JI1 (Aphyric-intergranular basalt)

Minerals	Average modal proportion (%)	Micro-phenocryst average grain size (length) (mm)	Micro-phenocryst average grain shape	Overall texture
Plag	<3	4	Elongated or lath	Aphyric-intergranular
Fe-Ti oxides	<2	0.2	Anhedral	
Cpx	2	0.5	Anhedral	
Ol	<3	< 0.4	Anhedral	
Ap	1	0.6	Rounded with needle nature at the core of the crystal	
Gm	89	-	-	

Gm: Groundmass; Ap : apatite



Sample Code: JI2 (Aphyric-trachyitic flow basalt)

Minerals	Average modal proportion (vol. %)	Micro-phenocryst average grain size (length) (mm)	Micro-phenocryst average grain shape	Overall texture
Plag	15	3	Highly elongated or lath	Aphyric-trachyitic
Fe-Ti oxides	10	0.8	Anhedral	
Cpx	3	0.2	Anhedral	
Ol	2	0.2	Anhedral	
Gm	70	-	-	

Sample Code:JI3 (Aug cumolophyric basalt)

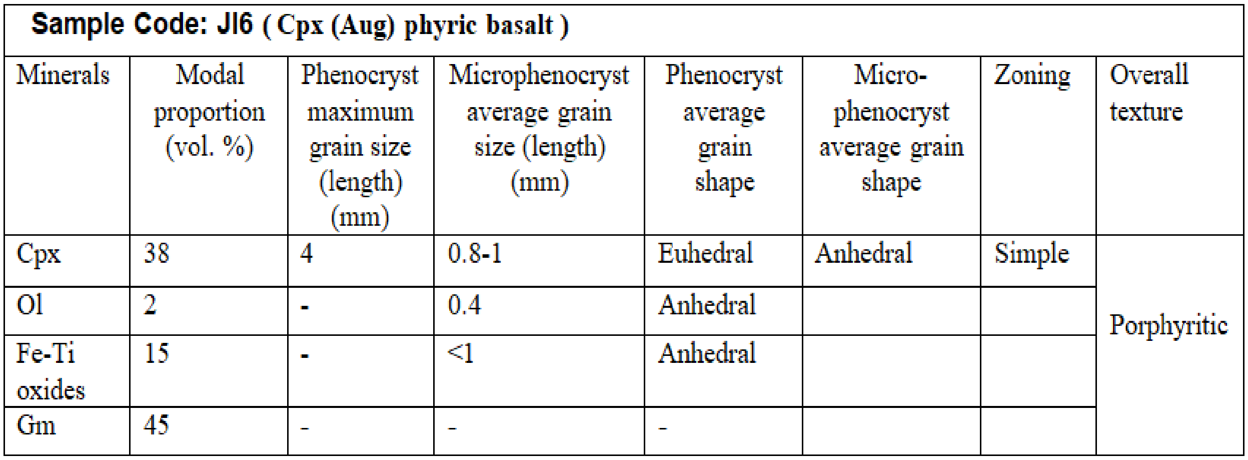
Minerals	Average modal proportion (vol. %)	Phenocryst average maximum grain size (length) (mm)	Microphenocryst average grain size (length) (mm)	Phenocryst average grain shape	Micro-phenocryst average grain shape	Overall texture
Cpx (Aug)	20	4	1.4	Euhedral	Subhedral	Glomero-porphyritic
Fe-Ti oxides	11	2.5	1	Subhedral	Anhedral	
Ol	2	-	0.8	-	Anhedral	
Gm	77	-	-	-	-	

Sample Code: JI4 (Ol-Aug phyric basalt)

Minerals	Modal proportion (%)	Phenocryst average maximum grain size (length) (mm)	Microphenocryst average grain size (length) (mm)	Phenocryst average grain shape	Micro-phenocryst average grain shape	Alterations	Overall texture
Ol	35	3	1.4	Subhedral	Rounded	Iddingsite	Porphyritic
Cpx (Aug)	24	2.6	1	Euhedral	Subhedral		
Fe-Ti oxides	10	1.2	0.8	Anhedral	Rounded		
Gm	41	-	-	-	-		

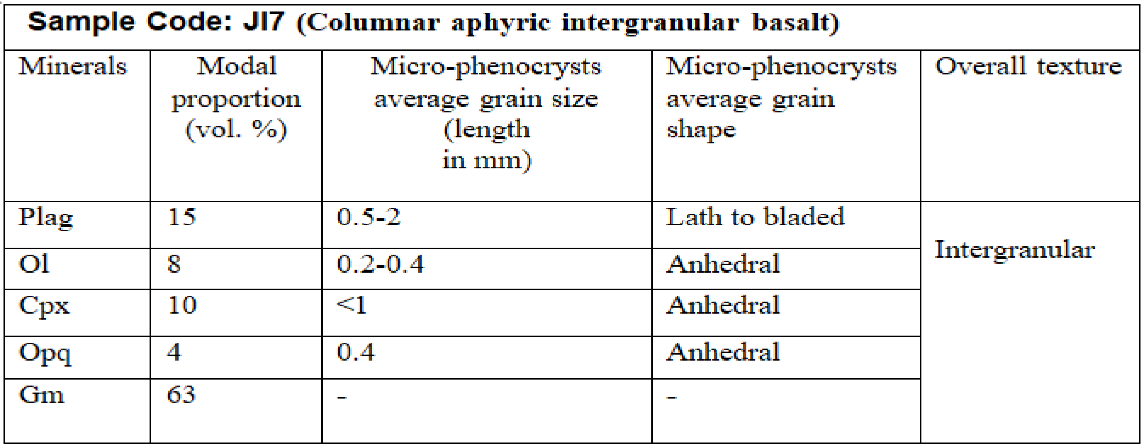
Sample Code: JI5 (Kfs vitrophyric rhyolite lava flow)

Minerals	Average modal proportion (vol. %)	Phenocryst maximum grain size (length) (mm)	Microphenocryst Average grain size (length) (mm)	Phenocryst average grain shape	Micro-phenocryst average grain shape	Zoning	Overall texture
Kfs	30	3.4	0.6-1	Suhedral	Anhedral	Carlsbad	Vitrophyric
Qtz	12	-	0..5	-	Anhedral		
Fe-Ti oxides	2	-	0.2-0.4	Anhedral			
Gm (dominantly glass)	56	-	-	-			



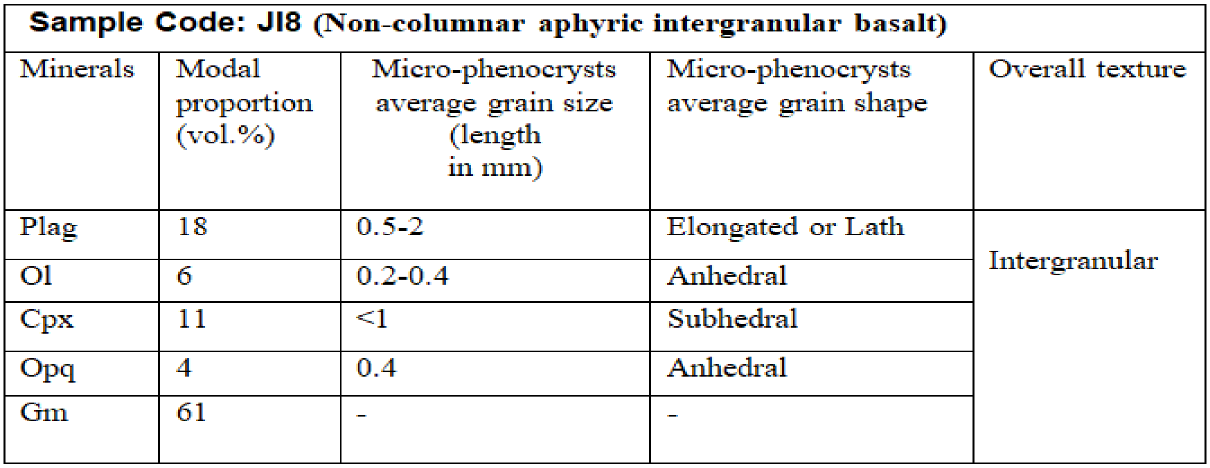
Sample Code: JI6 **(Cpx (Aug) phyric basalt)**

Minerals	Modal proportion (vol. %)	Phenocryst maximum grain size (length) (mm)	Microphenocryst average grain size (length) (mm)	Phenocryst average grain shape	Micro-phenocryst average grain shape	Zoning	Overall texture
Cpx	38	4	0.8-1	Euhedral	Anhedral	Simple	Porphyritic
Ol	2	-	0.4	Anhedral			
Fe-Ti oxides	15	-	<1	Anhedral			
Gm	45	-	-	-			



Sample Code: JI7 **(Columnar aphyric intergranular basalt)**

Minerals	Modal proportion (vol. %)	Micro-phenocrysts average grain size (length in mm)	Micro-phenocrysts average grain shape	Overall texture
Plag	15	0.5-2	Lath to bladed	Intergranular
Ol	8	0.2-0.4	Anhedral	
Cpx	10	<1	Anhedral	
Opq	4	0.4	Anhedral	
Gm	63	-	-	



Sample Code: JI8 **(Non-columnar aphyric intergranular basalt)**

Minerals	Modal proportion (vol.%)	Micro-phenocrysts average grain size (length in mm)	Micro-phenocrysts average grain shape	Overall texture
Plag	18	0.5-2	Elongated or Lath	Intergranular
Ol	6	0.2-0.4	Anhedral	
Cpx	11	<1	Subhedral	
Opq	4	0.4	Anhedral	
Gm	61	-	-	

Sample Code: JI9 (Moderatly welded rhyolitic tuff)

Minerals /glass shards	Modal proportion (vol. %)	Microphenocryst average grain size (length) (mm)	Glass shards average size (mm)	Micro-phenocryst average grain shape	Glass shards average shape	Overall texture
Glassy shards	13	-	5	-	Elongated	Eutaxtic
Qtz	4	0.4	-	Anhedral	-	
Fe-Ti oxides	~1	0.2	-	Rounded	-	
Kfs	2	0.8	-	Elongated	-	
Gm (mainly glass)	80	-	-	-	-	

Sample Code: JI10 (Kfs rhyolitic-ignimbrie)

Minerals/rock fragments	Modal proportion (vol. %)	Phenocryst maximum grain size (length in mm)	Micro-phenocrys taverage grain size (length in mm)	Lithic fragment average grain size (mm)	Phenocryst average grain shape	Micro-phenocryst average grain shape	Lithic fragment average shape	Overall texture
Kfs	25	4	1.6	-	Subhedral	Elongated	-	Porphyritic
Qtz	12	-		-	-	Subhedral	-	
Fe-Ti oxides	1	2	-	-	Anhedral	-	-	
Cpx	0.5	-	0.8	-	-	Subhedral	-	
Lithic fragments	10	-	-	5 (pumice)	-	-	Anhedral	
Gm (mainly glass)	51.5	-						

Sample Code: JI11 (Kfs phyric rhyolitic flow)

Minerals	Modal proportion (%)	Phenocryst average grain size (length in mm)	Microphenocryst average grain size (length in mm)	Phenocryst average grain shape	Micro-phenocryst average grain shape	Zoning	Overall texture
Kfs (Sa)	30	3	0.8	Subhedral	Elongated	Carlsbad	Porphyritic
Qtz	14	1.4	0.6	Subhedral	Subhedral	-	
Fe-Ti oxides	0.5	-	0.4	-	Rounded	-	
Gm (mainly glass)	55.5	-					

Sample code: JI12 (Columnar aphyric-ophitic basalt)

Minerals	Modal proportion (%)	Micro-phenocryst average grain size (length) (mm)	Micro-phenocryst average grain shape	Overall texture
Plag	20	1.4	Lath /elongated	Aphyric-ophitic
Cpx	10	0.8	Anhedral	
Fe-Ti oxides	8	0.4	Anhedral	
Gm	62	-	-	

Sample Code: JI13 (Slightly vesicular aphyric basalt)

Minerals	Modal proportion (%)	Micro-phenocryst average grain size (length) (mm)	Micro-phenocryst average grain shape	Average size of pore spaces (cm)	Overall texture
Plag	20	1.4	Lath /elongated	-	Vesicular+aphyric
Pore spaces	5	-	-	1	
Gm of Cpx+Opq+Ol	75	-	-	-	