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Petrography, and Stratigraphy of Volcanic Rock of Gishe Rabel Area, North Shewa, Central Ethiopia

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SCHOOL OF EARTH SCIENCES

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BY;

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ADVISOR; MINYAHL TEFERI (Ph. D.)

JUNE, 2026

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PETROGRAPHY, AND STRATIGRAPHY OF VOLCANIC ROCK OF GISHE RABEL AREA, NORTH SHEWA, CENTRAL ETHIOPIA

BY

AWEL LEMA ABI

THE THESIS WORK IS SUBMITTED TO THE SCHOOL OF EARTH SCIENCES, BAHIR DAR UNIVERSITY, IN PARTIAL FULFILLMENT OF THE DEGREE OF MASTER OF SCIENCE IN PETROLOGY

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Approval of the thesis work for defense

I hereby certify that I have supervised, read, and commented this thesis work entitled "**Petrography, and Stratigraphy of volcanic rock of Gishe Rabel area, North Shewa, Central Ethiopia**" written by Awel Lema Abi prepared under my guidance and supervision. I recommend the thesis be submitted for defense.

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Research approval form

As a member of the Board of Examiners for the research open defense examination, we have read and evaluated this research prepared and presented by **Mr. Awel Lema Abi,** entitled ***Petrography and stratigraphy of volcanic rocks of Gishe Rabel area, North Shewa, Central Ethiopia.*** We hereby certify that the research is accepted to fulfill the requirements of Master of Science degree in Petrology.

Board of Examiners

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Declaration of Originality

I hereby declare that the thesis work entitled **"Petrography and stratigraphy of volcanic rocks of Gishe Rabel area, North Shewa, Central Ethiopia"** is my original work prepared for the contribution to the scientific journey during the year 2025/26. I further declare that this work is not presented and published anywhere else, and all the used sources and materials are well-referenced and acknowledged.

Awel Lema Abi: ---------------------------------- ---------/--------/------------

Signature Date

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Abstract

The study area is a part of the NW Ethiopian Plateau, is presented in this thesis. The study area is located in the North Shewa district, specifically around Gishe Rabel, in central Ethiopia. The main objective of the study is to provide a complete lithostratigraphy of the research area based on a thorough field investigation (mapping and description), stratigraphic sampling, and petrographic (thin section) description of representative samples. Various techniques were used to achieve the research objectives, including field observation, remote sensing, and petrographic description. Furthermore, the study attempts to integrate these data to relate them to regional studies on geochemical, geochronological, and magma emplacement behavior data about the volcanic provinces of Ethiopia and fill the scarce in a detail volcanic history of the study area. Three volcanic lithostratigraphic units, Lower Basalt, Rhyolitic Lava Flow, and Upper Basalt, are identified in this study as part of the Cenozoic continental flood basalt sequence. The basaltic lava flows (fissural flows) are the dominant products, with interlayered ash and tuff; the felsic products dominate the middle part. These stratigraphic units are separated by a considerable time gap marked by an alteration/erosional surface, paleosol, or sediments, which are related to a decrease in magma flux in the system.

The petrographic characteristics of basaltic units in the study area display a range of textures, including aphyric, mildly phyric, and porphyritic varieties. In the lower basaltic rocks, the principal phenocrysts are pyroxene and olivine, accompanied by opaque. In contrast, the rhyolitic ignimbrite samples are dominated by alkali feldspar (sanidine), quartz, and lithic fragments set within a glassy groundmass. The predominance of alkali feldspar phenocrysts in the felsic units suggests a relatively low magma flux during their formation. The upper basaltic rock is dominated by plagioclase phenocrysts. The occurrence of plagioclase in the upper basaltic rocks indicates that crystal fractionation took place within the shallow upper crust. Meanwhile, the presence of olivine and clinopyroxene (Olv + Cpx) mineral assemblages in some basaltic lavas suggests that fractionation also occurred at deeper crustal levels or near the crust–mantle boundary.

Keywords: Gishe Rabel volcanics, petrography, lithostratigraphy, plumbing system

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List of Acronyms

CFB	Continental Flood Basalt
CMER	Central Main Ethiopian Rift
Cpx	Clinopyroxene
DEM	Digital Elevation Model
GIS	Geographic information system
GPS	Geographic positioning system
HT	High titanium
LIP	Large igneous provinces
Kfs	Alkaline feldspar
Ma	Million years ago,
MER	Main Ethiopian Rift
MORB	Mid Oceanic Ridge Basalt
NMER	Northern Main Ethiopian Rift
NW	Northwestern
OIB	Oceanic Island Basalt
Ol	Olivine
PPL	Plane polarized light
Plag/Pl	Plagioclase
San	Sandine
SEP	Southern Ethiopian Plateau
SMER	Southern Main Ethiopian Rift
WEP	Western Ethiopian Plateau
Qrtz	Quartz
XPL	Crossed polarized light

CHAPTER ONE

INTRODUCTION

1.1. Background of the study

Cenozoic magmatism in East Africa spans a broad region extending from Turkana in the south to Yemen in the north via Ethiopia and Eritrea, this region preserves a comprehensive geologic record of magmatic activity that occurred over the last 45 million years (Krans et al., 2018; Rooney and Yirgu, 2018). The Ethiopian volcanic provinces are largely exposed within the rift and plateaus. Petrographic and Geochemical analysis of volcanic rocks is very important to determine the genesis and the process of fractional crystallization and crustal contamination (Rooney & Yirgu, 2018).

The study area is part of the Oligo-Miocene bimodal volcanic rock suites and is also included in the Woreillu geological map sheet that encompasses the Gishe Rabel area (Fig. 2 .2), located in the northwestern Ethiopian Plateau (Belay et al., 2009). The Ethiopian volcanic sequence was emplaced during the onset of the East African continental rifting in the Oligocene, approximately 30 million years ago (Ayalew & Yirgu, 2003). These volcanic rocks, mainly represented by basalts (traditionally referred to as the trap succession), have an estimated area coverage of not less than 750,000 km^2 before erosion, with a total volume of 350,000 km^3 (Mohr, 1983).

Volcanic stratigraphy is a fundamental aspect of geological mapping in volcanic regions, as it offers critical data for discerning the spatial and chronological links between volcanic rock products and eruptive processes (Martí et al., 2018). In addition, the examination of the stratigraphic sequence of volcanic rocks is very significant to understand the geological evolution, as well as the past and future behavior of volcanoes (Yirgu et al., 2012; Martí et al., 2018). The stratigraphic relationship and correlation between volcanic rocks can be determined by using major and trace element chemistry (Chemo-stratigraphy) from Geochemical analysis, Petrographic analysis (petro-stratigraphy), radiometric dating (Chronostratigraphy), remote sensing, field investigation, and sampling, or Lithostratigraphy (Dimaggio et al., 2008). This study has used petrographic analysis, detailed field investigation, and mapping to determine the stratigraphy of volcanic rocks in the Gishe Rabel volcanic section.

Detailed stratigraphic studies in the area remain limited, and no comprehensive stratigraphic framework has yet been established. However, much of the volcanic succession is well preserved due to its relatively young age compared to other continental flood basalts, providing valuable insights into its eruptive history. This study integrates field observations and petrographic analysis within a stratigraphic framework in an area located near the intersection of the southern Red Sea Rift and the Ethiopian Rift Valley. The objective is to define lithostratigraphic units, interpret their stratigraphic relationships, and reconstruct eruption sequences, including the transition from basaltic to silicic volcanism and the occurrence of pulsed eruptive events.

1.2. Description of the study area

1.2.1. Location and Accessibility

The study area is located in central Ethiopia, specifically in the North Shewa Zone of Gishe Rabel Woreda (Figure 1.1). Geographically, it is bounded between 1150000 and 183000 N and between 548000 and 588000 E. It can be accessed via a 530 km main asphalt road from Addis Ababa to Dessie, Guguftu, and Woreilu, followed by a 40 km stretch of dry, weathered gravel road to reach the target area.

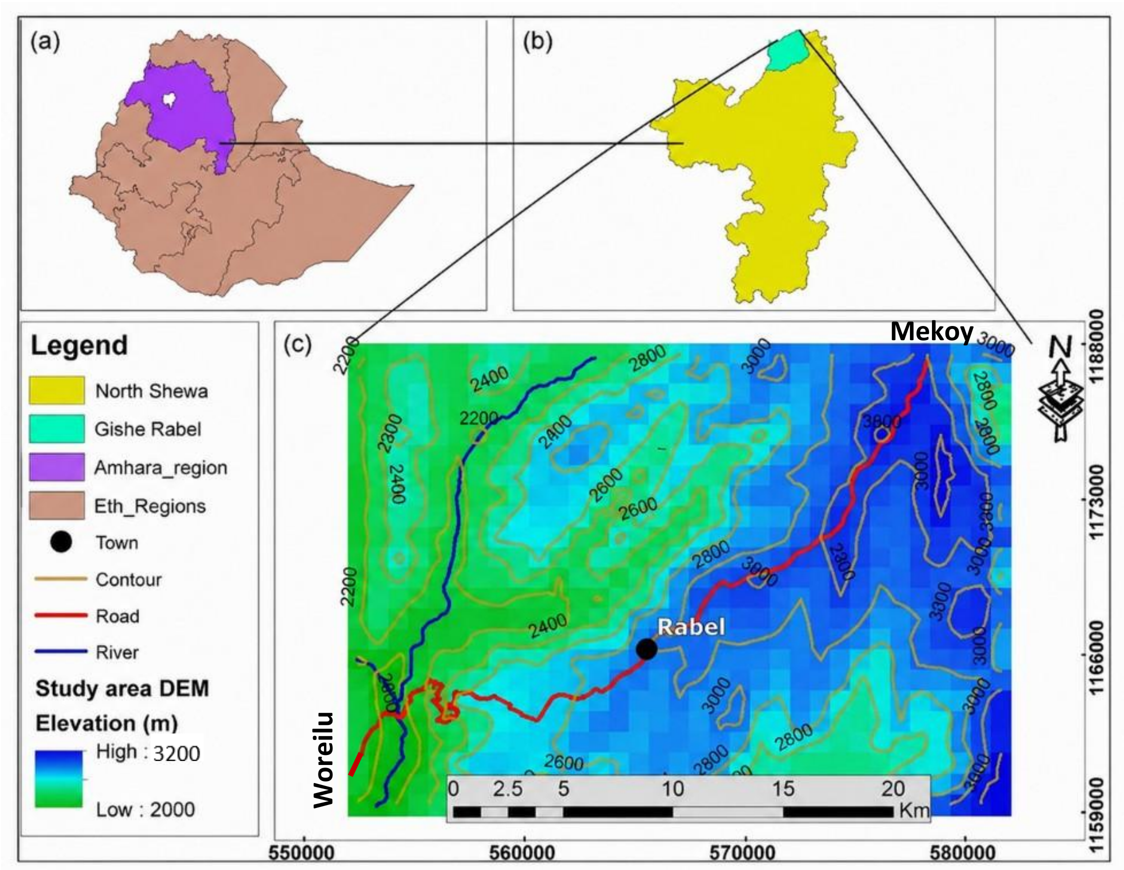

Figure 1. 1 Location and accessibility map of the study area, Ethiopia (a), north Shewa (b), and Gishe Rabel (c)

1.2.2. Climate of the Study Area

The study area is characterized by cold to moderate temperature conditions that vary in different seasons. Since it is bordered by the larger River gorges, most of the time it has warm temperature conditions. The total annual rainfall varies from 889mm to 1500 mm per year. The highest rainfall is recorded during summer, which starts in June and ends in September, and there is little rain in spring, which encompasses March, April, and May. The mean annual temperature of the region varies from 11 °C to 19 °C. The absolute maximum temperature occurs from February to May, and the absolute minimum temperature occurs in December, July, and August.

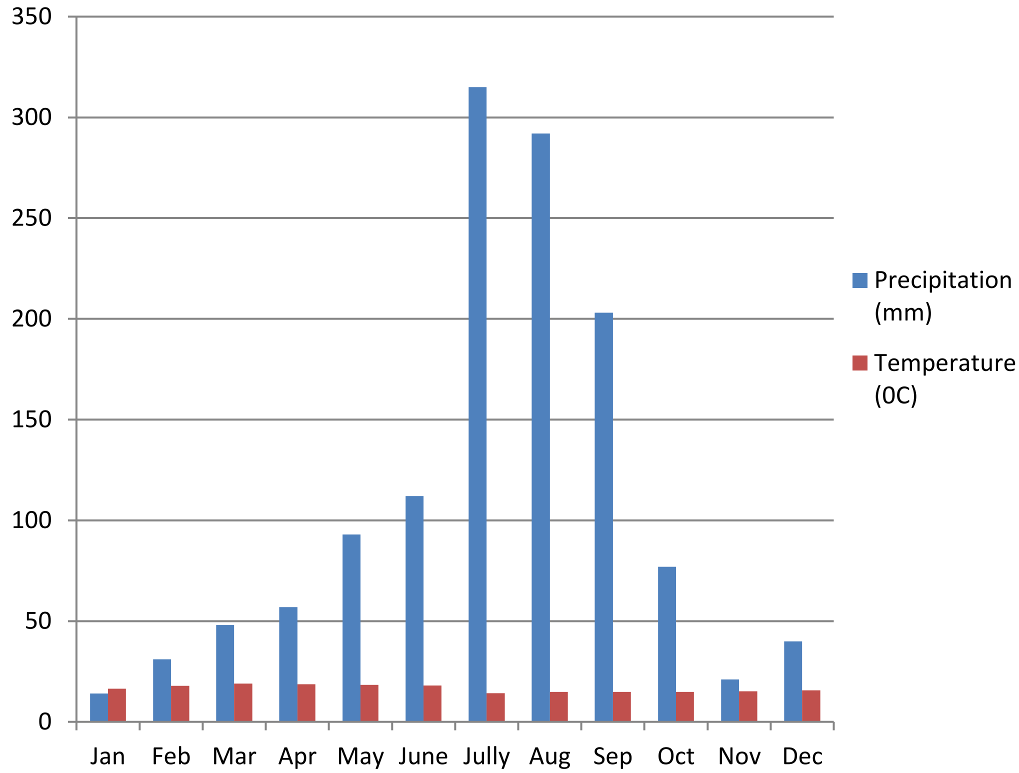

Figure 1. 2 Bar graph shows the Monthly average precipitation and temperature of the study area **(Data Source: Arc GIS world Geocoding service; https://power.larc.nasa.gov/data-access-viewer/ (2025).**

1.3. Review of previous works

Volcanism took place almost continuously, from the Oligocene to the present, and a maximum basalt outpouring has been recorded at about 31 Ma (Hofmann et al., 1997). Volcanism in Ethiopia is dominated by basaltic lavas, rhyolitic, and trachytic pyroclastic products. The Ethiopian Cenozoic volcanic plateaus are parts of the continental flood basalt of relatively young age, and their eruption in a region where plate movements are slow, a complete record of volcanic and tectonic activity is preserved by the nature of volcanism as it changed during the Oligo-Miocene-Quaternary age. (Ebinger et al., 1993; McDougall & Brown, 2009).

Rhyolite emplacement in Ethiopia occurred primarily within a period of ~32-15 Ma in the eastern and northwestern part of Ethiopia, 12-8 Ma in central Ethiopia, and 4.5 Ma-Recent in the central Afar and along the Main Ethiopian Rift (MER) zone (Ayalew & Yirgu, 2003; Peccerillo et al., 2007; Halder et al., 2020). According to studies on Ethiopian volcanism (e.g., Mohr & Zanettin, 1988; Chambers et al., 2019), there are three primary stages of volcanic activity: (1) pre-Oligocene to Miocene, marked by massive flood lava flows (Ashangie and Aiba Basaltic Formations). The onset phase of this stage was characterized by alternating basalt and ignimbrite eruptions, forming the so-called Alajie rhyolitic Formation (e.g., Pik et al., 1998; Keir et al., 2011; Kurkura et al., 2012). (2) Miocene age construction of huge basaltic shield volcanoes (Tarmaber Formation). (3) Pliocene to Quaternary age opening of the main Ethiopian and Afar rift. The area covered by Oligocene flood basalts of the Ethiopian Plateau, excluding the once contiguous Yemen province, is ~600,000 km^2. An area of about 750,000 km^2 was recorded before plateau uplift, and massive erosion occurred during the Pleistocene time (Mohr and Zanettin, 1988). The total volume of the Ethiopian Cenozoic volcanic rocks has been estimated as ~350,000Km^3, of which ~300,000Km^3 are basaltic in composition(Mohr and Zanettin, 1988; George, 1998; Ayalew et al., 2002; Ayalew and Yirgu, 2003; Prave et al., 2016; Rooney, 2017).

In the Ethiopian rift, felsic volcanism is dominated by peralkaline Rhyolitic ignimbrites and pumice and ash-fall deposits, with minor lava flows. Silicic rocks are associated with volumetrically subordinate basaltic products that form cinder cones and lava flows mostly aligned along extensional faults of the Wonji fault belt (Ebinger et al., 1993; Chernet et al., 1998; Natali et al., 2011). The Ethiopian continental flood basalt (~30 Ma) was formed by the impingement of the Afar mantle plume below the lithosphere (Pik et al., 1998; Beccaluva et al., 2009; Desta et al., 2014; Natali et al., 2016). It includes major sequences of rhyolitic and ignimbrites generally found on top of the flood basalt sequence (Ayalew et al., 2002). Flood volcanic rocks in Ethiopia contain a significant component of Rhyolitic, air-fall tuffs, and ignimbrites intercalated with basaltic lava flows (Ukstins et al., 2002).

The NW volcanic province of Ethiopia is formed by different phases and mechanisms due to volcanisms taking place through fissures by the upcoming mantle plume and central volcanism taking place following rift zones (Acocella, 2010). It is categorized under the pre-rift volcanic province of Ethiopia (Meshesha & Shinjo, 2004). Volcanic rocks vary in character based on composition, structure, and degree of weathering (Bellieni et al., 1981; Chorowicz et al.,1998; Mohr & Zanettin, 1988; Kieffer et al., 2004; Beccaluva et al., 2009). According to Tamirat et al., 2021, the magmatic genesis of volcanic rocks in the northwestern Ethiopian plateau is the result of three conditions: 1) Upwelling of a hot mantle plume from the melting of geochemically enriched, fertile, and depleted mantle wedges that are contaminated by subducted fluid/sediments (E-MORB) in the upper asthenosphere, 2) Mixing of melts from E-MORB mantle component and from that of the plume (OIB) possibly is accountable for the formation of the tholeiitic basalts that are part of the Continental Flood Basalts (CFB) in the Ethiopian plateau, and 3) Melting of the base of the sub-continental lithospheric mantle (SCLM), which were triggered by the heat transferred from the hot mantle plume, interacted with melts from the plume (OIB) to produce those alkali and transitional parts of the shield basalts in the plateau. The differentiated intermediate and felsic volcanic rocks are formed either from the basaltic magma by crustal contamination and the fractional crystallization process or from direct partial melting of the lower crustal materials (Ayalew & Yirgu, 2003; Peccerillo et al., 2007; Feyissa et al., 2019).

Geochemically, the NW Ethiopia volcanic plateau is classified into three groups: Low titanium (LT), High titanium one (HT1), and High titanium two (HT2). The LT group commonly exists in the Western and NW sectors, the HT1 group commonly exists along the Southern and SE sectors, and the HT2 group commonly exists along the Northern and NE sectors of the Northwestern Ethiopian volcanic plateau (Pik et al., 1998; Beccaluva et al., 2009; Desta et al., 2014). The LT and HT1 basalts display compositional ranges exactly similar to those of the low-and high-Ti groups from other main CFB provinces like (Parana, Deccan, Karoo, and Siberia). However, the HT2 group exhibits extreme OIB-like compositions, and this unusual geochemical signature observed in the HT2 groups suggests the involvement of the deep mantle in the genesis of the HT2 magmas. The LT compositions rather reflect the direct participation of the continental lithosphere, through mantle-derived melts and/or crustal contamination. (Pik et al., 1998). The LT basalts are transitional to tholeiitic and characterized by low TiO_2, P_2O_5, Fe_2O_3, Nb/La, and high SiO_2. The high titanium 2 (HT2) are sub-alkaline basalts that display high TiO_2, P_2O_5, Fe_2O_3, Nb/La, and low SiO_2. The high Ti-1 (HT1) basalts exhibit intermediate characteristics between the LT and HT2 groups. This proposed research area is located in the Southeastern part of the NW volcanic province, and basically, it is grouped under the HT1 geochemical group. (Pik et al., 1998).

As indicated by a publication from Belay et al., (2009) Geological Survey of Ethiopia, an unpublished technical report that describes the Geology of the Were-Ilu Map sheet covering part of Northern Shewa, Southern Wollo, and Oromia Zones of the Amhara, and Heriresu zone of Afar regional state (Fig 2.2), the mapped area was made of four Cenozoic litho- stratigraphic units that were separated by an unconformity and included: - (i) Pre- Oligocene volanics (Ashange basalt), (ii) Oligocene to Miocene volcanics (Alajae basalt, Molale ignimbrite, TemaberMegezez basalt and Adami basalt), (iii) Early- to Mid-Miocene volcanics (Kemise rhyolite formation) and Upper Miocene volcanics (Dogiya basalt). Cenozoic volcanism in the area ceased during the eruption of the Quaternary Wederage basalt.

Krans et al., (2018) Provide detailed petrographic investigations within a well-constrained stratigraphy for the western portion of the Ethiopian Yemen flood basalt province (LT flood basalts surrounding Lake Tana area) from commencement to termination. The Ethiopian flood basalt province is divided into three areas: the lower flood basalt, which is predominantly olivine-phyric with Cpx-rich cumulates; the middle flood basalt, which has Plg megacrystic flows and oscillates between Plg-phyric and Ol-phyric flows; and the upper flood basalt, which is predominantly Plg-phyric and devoid of cumulates. Modal investigations show two distinct fractionation regimes: one in the lower crust (dominated by clinopyroxene cumulates without plagioclase) and another in the mid-to-shallow crust (dominated by plagioclase cumulates).

As Alehegn et al., (2024) In their study about the petro-stratigraphy of volcanic rock in Mekene Selam Wollo, they conclude that petrographically, the basaltic rocks are dominated by olivine (mostly Mg-olivine or forsterite), followed by clinopyroxene (augite), plagioclase (labradorite and anorthite), and Fe-Ti oxides (magnetite and spinel-chromium). The groundmass of basaltic rocks is typically composed of olivine, clinopyroxene, and plagioclase, with Fe-Ti oxide coming in first. The differentiated rhyolite rocks and their intrusive counterpart (syenite) are formed of alkali feldspars (mostly sanidine), Fe-Ti oxides (ilmenite), hornblende, amphibole, quartz, and lower amounts of pyroxene (primarily aegirine).

Ayalew & Gibson (2009) reported that a composite stratigraphic profile of the North Shewa volcanic sequence at Yite-Koste shows interlayering of basalt and rhyolite. This volcanic succession extends across a vast area of more than 2,200 km² and, in some locations, reaches thicknesses greater than 1,000 meters.

1.4. Statement of the problem

Most studies on the Ethiopian volcanic plateau have been conducted at a regional scale, with only a limited number of investigations focusing on detailed analyses of specific volcanic sections(e.g., Hofmann et al., 1997; Pik et al., 1998; Kieffer et al., 2004; Meshesha & Shinjo, 2007; Beccaluva et al., 2009; Natali et al., 2011). However, detailed stratigraphic studies of individual sections remain scarce.

In particular, the absence of a comprehensive geological map, cross-sections, and detailed stratigraphic logs for specific localities limits the ability to establish correlations between local volcanic sequences and other parts of the Ethiopian flood basalt province. This gap hinders a thorough understanding of the spatial and temporal evolution of the volcanic system. Therefore, this study addresses this gap by conducting a detailed petrographic and volcano-stratigraphic investigation of the volcanic rocks in the Gishe Rabel area and its surroundings.

1.5. Objectives of the study

1.5.1. General Objective

The main objective of this study is to analyze and interpret the stratigraphy and petrography of volcanic rocks in the Gishe Rabel section.

1.5.2. Specific Objectives

- To prepare a Geological map a scale of 1:50,000
- To construct a detailed stratigraphic section log of the volcanic products of the area
- To establish volcanic history based on petrography and stratigraphy
- To compare the study area volcanic rocks with the subsections of the NW Ethiopian plateau

1.6. Methodologies

This study was conducted in three main stages: pre-fieldwork, fieldwork, and post-fieldwork stages. The pre-field stage involved a comprehensive review of previous studies, geological maps, and relevant literature to identify existing knowledge gaps and refine the research objectives. Fieldwork was carried out through systematically planned traverses across the study area, during which lithological descriptions, stratigraphic relationships, and structural data were recorded, and representative rock samples were collected. In the post-field stage, the collected samples were subjected to detailed analyses, including petrography.

1.6.1. Desk Study

During the initial phase of the research, relevant previous studies on the geology, tectonic setting, and petrology of the study area were thoroughly reviewed from published and unpublished sources, including journal articles, scientific reports, and online databases.

A reconnaissance field survey was subsequently conducted along the pre-determined traverses, allowing for the identification of major lithological units, observation of stratigraphic relationships, and collection of representative rock samples.

1.6.2. Field working and mapping

Systematic traverses were undertaken across the study area to ensure representative geological coverage. The traverses were designed based on pre-field analysis and were adjusted in the field according to exposure conditions and topographic accessibility. At each observation point, detailed descriptions of rock units were conducted at both the outcrop and hand-specimen scales. These descriptions included lithology, texture, mineral composition, weathering characteristics, vascularity, and the nature of contacts between adjacent units. Photographic documentation of representative outcrops and key geological features was systematically conducted to support geological mapping and interpretation. In addition, detailed field notes and sketches, including stratigraphic profiles and outcrop relationships, were recorded throughout the fieldwork. Sampling was conducted using a systematic approach aimed at capturing both vertical and lateral variations in lithology. Particular emphasis was placed on selecting representative sections that exhibit compositional and textural variability. A total of 30 rock samples were collected from carefully selected localities across the study area. Sample locations were recorded using a handheld GPS, and elevation data were used to constrain the relative stratigraphic positions of the samples and to construct outcrop-scale logs within a stratigraphic framework. Stratigraphic relationships and lithological units were distinguished in the field based on a combination of criteria, including variations in weathering profiles, flow morphology, textural characteristics, and mineralogical composition. Additional markers such as paleosol horizons and volcanic unconformities were used to delineate unit boundaries and establish a coherent volcanic stratigraphy for the study area.

1.6.3. Data Organization and Analysis

1.6.3.1 Petrographic analysis

Following field sampling, a total of 25 fresh and representative rock samples were selected for detailed petrography. The selection was based on criteria including freshness (minimal alteration), textural variation, mineralogical diversity, and stratigraphic position to ensure comprehensive representation of the studied units. After the samples were collected and organized, 25 different fresh and representative samples were selected for petrographic analysis. The thin section was prepared at the Geological Institute of Ethiopia, found in Addis Ababa, in their mineralogy and petrographic laboratory. Petrographic analysis of the thin sections was conducted in Mekdela Amba University. Thin sections were prepared at the Geological Institute of Ethiopia in Addis Ababa, using standard procedures involving cutting, mounting, grinding, and polishing to a thickness of approximately 30 μm.

Petrographic analysis was subsequently carried out at the petrographic laboratory of Mekdela Amba University. The thin sections were examined under a polarizing microscope using both plane-polarized light (PPL) and cross-polarized light (XPL). The analysis focused on mineral identification, textural characterization, and the assessment of crystallization sequences and alteration features. Where applicable, modal mineral abundances were estimated to support the interpretation of magmatic processes.

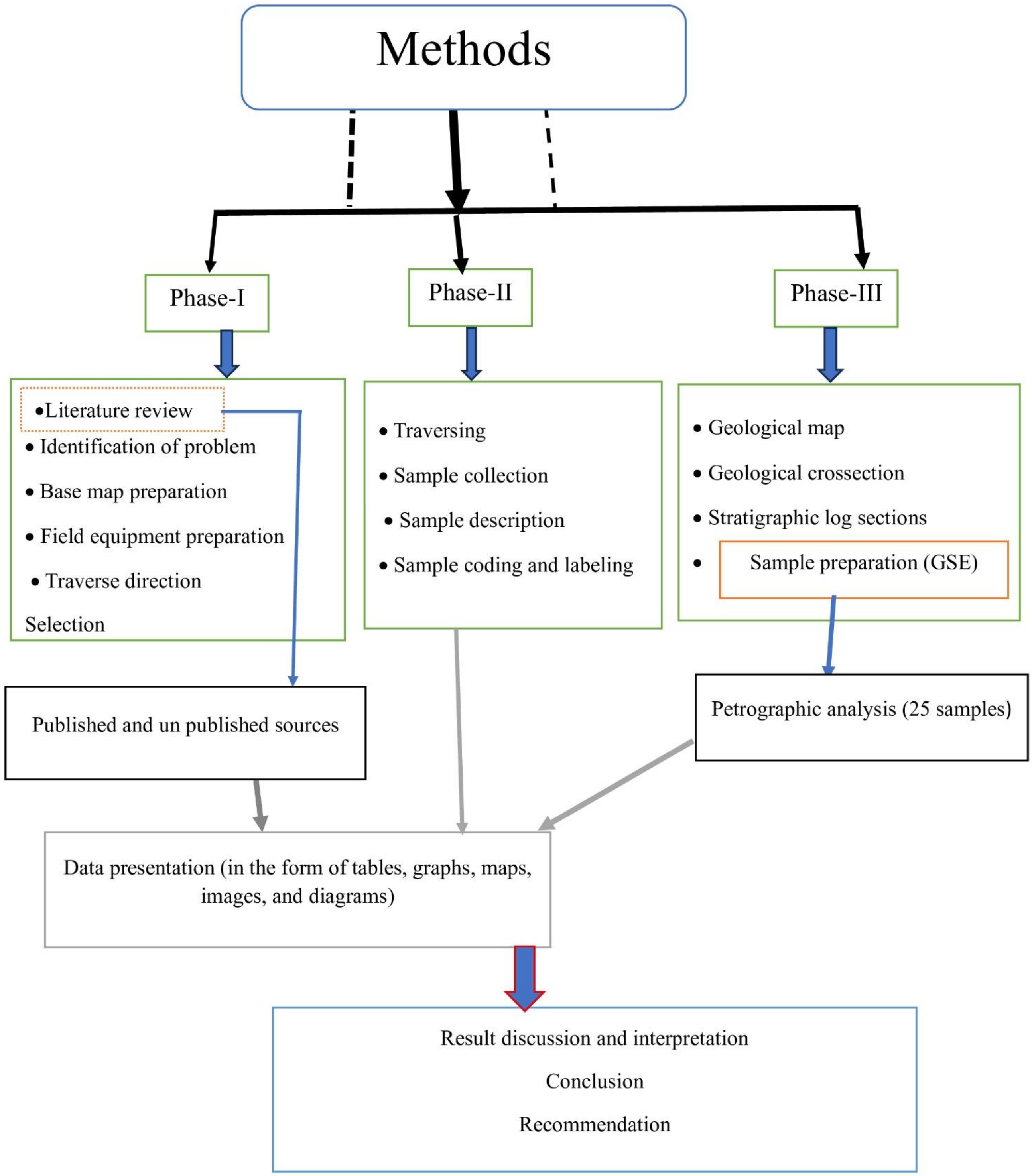

Figure 1. 3 Summary of the workflow chart for the research work.

1.7. Significance of the research

This study aims to address existing knowledge gaps by providing a detailed investigation of the volcanic rocks within the study area from both petrography and stratigraphy perspectives. In particular, it seeks to improve the understanding of lithological variation, mineralogical composition, and stratigraphic relationships within the volcanic sequence.

In addition to its scientific contribution, the study provides essential geological information to support mineral exploration and inform engineering and construction projects. The results are therefore relevant to a range of stakeholders, including the mining industry, engineering practitioners, and other sectors involved in infrastructure development.

1.8. Thesis structure and organization

This research work is structured and organized into seven chapters. The first chapter provides general information about the study area, the purpose of the study, and the methods used in the research. The second chapter provides a regional-scale review of previous works. Chapter three gives a detailed description of the Geology of the study area. In Chapter four, Petrographic analyses of selected fresh and representative rock samples were conducted. In chapter five, the volcanic stratigraphy of the different subsections is constructed and interpreted. In chapter six, Discussion. Finally, in chapter seven, conclusions and recommendations were drawn.

CHAPTER TWO
REGIONAL GEOLOGICAL SETTING

2.1. Introduction

Extensive magmatic activities are often associated with regions of continental break-up (White, 1989). These tectonic processes are commonly associated with huge volumes of flood basalts and variable amounts of silicic volcanics, forming the so-called Large Igneous Provinces (LIPs). Some provinces, such as the Deccan in India, appear to have erupted very rapidly and require adiabatic decompression melting within a mantle plume (Robert White, 1989). Such provinces may also have the potential to cause or at least be influential in mass extinctions (Corti et al., 2004). In contrast, the Paraná basalts of South America erupted slowly, have a distinctive geochemistry, and may have been generated by conductive heating and consequent melting of continental mantle lithosphere above a mantle plume (Turner et al., 1996). The low eruption rates indicate a less marked effect on the biosphere, and this is consistent with the fossil record.

East Africa's Cenozoic plume-dominated magmatism extends from Turkana in the south, the southeastern Ethiopian plateau in the east, Ethiopia and Eritrea in the north, Yemen in the northeast, and Sudan in the west, preserving a stratigraphic record of magmatism over the past 45 Ma (Rooney, 2017). Most of the flood basalts and rhyolites were erupted in a short time period (~1 Myr) at 31–29 Ma, concomitant with the onset of continental rifting in the southern Red Sea (Wolfenden et al., 2004). The lava pile's thickness reaches up to 3 km along the southern Red Sea's western margin and thins to about 500 m both north and south, (Ayalew & Gibson, 2009).

At present, about 30% of Ethiopia has been mapped at the 1:250,000 scale. The distribution of lithologic varieties shows that the country is covered by about 18% Proterozoic crystalline basement, 25% Mesozoic sediment, and 56% Cenozoic volcanic and sedimentary rocks (Solomon Gerra 2000). The Ethiopian Plateau is located in the northwestern sector of Ethiopia. It is confined on the western and eastern sides by the Tana and Afar escarpments, respectively. The Main Ethiopian Rift is a key segment of the EARS that links the Afar depression, at the Red Sea, and the Gulf of Aden (Rosendahl, 1987; Braile et al., 1995). In this area, volcanic activity is still going on in the axial rift zone, where some central-type volcanoes and/or strombolian cones occur, usually erupting transitional to alkaline magmas (Chernet and Hart, 1999). It is an ideal place to examine the breakup of lithospheric plates, the development of continental extension, and the dynamics by which continental deformation is increasingly focused on oceanic spreading centers (Corti, 2009). The Ethiopian rift valley is a major zone of continental break-up and is the site of extensive magmatic activity, which gave rise to a large Oligocene to Miocene plateau and widespread Pleo-Quaternary volcanism in Afar and along the rift (e.g., Merla et al., 1979; Mohr & Zanettin, 1988). Both plateau and rift volcanism include a bimodal distribution of mafic and silicic rocks. Weakly alkaline silicic rocks are present in the plateau series, whereas large ignimbritic sheets and plinian pumice fallout deposits with a peralkaline rhyolite composition cover the rift floor and a large part of the surrounding areas (Yemane et al., 1999). The Ethio-Yemeni volcanic province provides a classic example of continental rifting preceded by the impingement of a mantle plume. Volcanism began in the Oligocene with the emplacement of a massive flood basalt pile and continued to the present day in the Red Sea and Gulf of Aden oceanic spreading centers and the East African continental drift (Hofmann et al., 1997).

Flood basalt in Ethiopia falls into two phases: the Oligocene Trap phase (31-~28 Ma) and the Eocene/LIP flood basalt province (Steiner et al., 2022). The oldest flood basalt lavas have been found in southern Ethiopia (Davidson and Rex 1980; Ebinger et al. 1993; George et al. 1998). The volume of flood lava erupted in southern Ethiopia is very large (Hendrie et al.,1994). There are also several thick siliceous volcanoes in basalt floodplains in Ethiopia and northern Kenya (Steiner et al., 2022).

The Ethiopian plateau is made up of several distinct volcanic centers of different ages and magmatic affinities (Kieffer et al., 2004). The Ethiopian continental flood basalt province is located at the junctions of three rifts: the Red Sea, the Gulf of Aden, and the East African continental Rift (Pik et al., 1998). In nearly all continental flood basalt provinces, the volcanic suites are of bimodal basalt–rhyolite nature with a distinct lack of intermediate compositions (Ayalew and Yirgu, 2003). Cenozoic volcanism in the northwestern Ethiopian plateau started with an eruption of Ashangi basalt during the Eocene-Oligocene and was then followed by extrusion of Aiba basalts and Alajae formation during the Oligocene-Miocene (Alemu, 2019).

The Cenozoic volcanic rocks of Ethiopia are divided into the Trap Series and the Aden Series (Tefera et al., 1996). The term Trap Series is still widely used to refer to the whole pile of the Tertiary flood basalt sequence with intercalation of felsic lava and pyroclastic rocks (commonly in the upper part), which form the northwestern and southeastern plateaus and attain a thickness of up to 3 km and a total volume of 300,000km^3 (Mohr and Zanettin, 1988; Tefera et al., 1996). The name Aden Series has been used for post-rift (Middle Miocene to Quaternary) volcanic rocks of the Main Ethiopian Rift, Afar Depression, and some parts of the Ethiopian plateau.

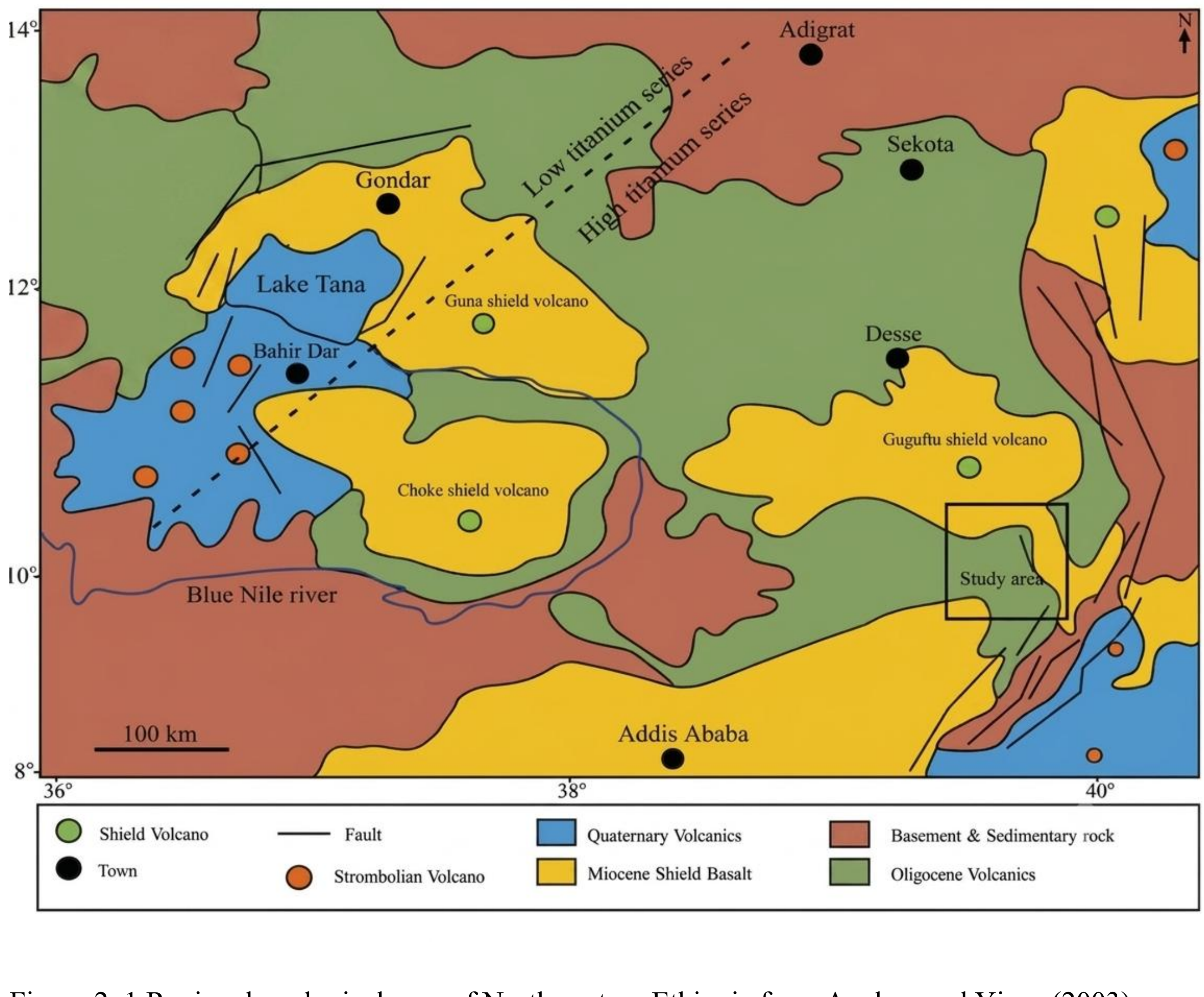

Figure 2. 1 Regional geological map of Northwestern Ethiopia from Ayalew and Yirgu (2003). The small box, which is marked in black, indicates the study area.

According to the traditional classification, the flood basalts of the Ethiopian plateau are divided into four sequences based on their age: Ashangi (pre-Oligocene and Oligocene age), Aiba (Oligocene), Alajie (Oligocene and early phase of Miocene), and Tarmaber (Miocene to Pliocene shield volcanoes) (Mohr & Zanettin, 1988; Pik et al., 1998).

The Ethiopian continental flood basalt ranges from tholeiitic to transitional in composition (Chorowicz et al., 1998; Mohr & Zanettin, 1988; Pik et al., 1998; Kieffer et al., 2004 ; Renne et al., 1996; Beccaluva et al., 2009). Initially, tholeiitic and alkaline types of magma erupted synchronously around 30 Ma, but later magmatism became exclusively alkaline in composition. The shield volcanoes are magmatically similar to the underlying flood basalts, i.e., the tholeiitic Semien shield overlies tholeiitic flood basalts, and the alkaline Choke and Guguftu shields overlie the alkaline flood basalts (Kieffer et al., 2004; Tamirat et al., 2021)(Fig 2.1). The presence of picritic ultramafic rocks in the northern and northeastern Ethiopian flood basalts is also described in the works of (Beccaluva et al., 2009; Natali et al., 2011; Desta et al., 2014) and felsic lavas in upper stratigraphic levels (Ukstins et al., 2002; Beccaluva et al., 2009; Natali et al., 2011; Ayalew et al., 2021).

2.2. East African and Main Ethiopian rift volcanism

The Ethiopian volcanic Plateau is separated into western and eastern shoulders by the Afro-Arabian Rift System. The volcanic rocks are distributed asymmetrically about the Ethiopian rift system (Chernet et al., 1998; Pik et al., 1998; Ukstins et al., 2002; Kieffer et al., 2004). The plateau located west of the rift system is designated as the WEP, while the other to the east is named the SEP (Keranen and Klemperer, 2008; Bianchini et al., 2014; Corti et al., 2018). The WEP comprises the northern, central, and southwestern sectors, whereas SEP includes the eastern, southeastern, and southernmost parts of the Ethiopian flood volcanic province (Ebinger et al., 1993; Furman, 2007; Shinjo et al., 2011; Bianchini et al., 2014).

MER is a NE-trending sector of the East African Rift system that includes a series of rift segments extending from the Afar Depression at the Red Sea-Gulf of Aden intersection to the Kenya Rift (Hofmann et al., 1997; George, 1998; Mohr and Zanettin,1988; Kieffer et al., 2004; Ernst and Bell, 2010; Natali et al., 2011; Feyissa et al., 2019). Magmatism related to rifting in Ethiopia is still active, and there is a chance to observe very young volcanic activity (early Pleistocene, <2 Ma) occurring in the axial sectors of the MER and Afar rift (Chernet et al., 1998; Corti et al., 2018; Feyissa et al., 2019).

Two-phase rift propagation models are recognized in the MER, primarily with initial rift development controlled by lithospheric structure and a later phase in which magmatic processes are dominant. During the initial phase, rift propagation was irregular and at times was diverted away from the modern rift trend along pre-existing structure (Ebinger et al., 1993; Chernet et al., 1998; Keranen & Klemperer, 2008; Corti et al., 2018).

Traditionally, the MER has been divided into three segments based on surface geology and geomorphology, i.e., northern (NMER), central (CMER), and southern (SMER) segments. The NMER extends south from the Afar depression to near Lake Koka. The CMER extends from Lake Koka to Lake Awasa, and the SMER extends south from Lake Awasa into the broadly rifted zone of southern Ethiopia (Ebinger et al., 1993; Keranen & Klemperer, 2008).

2.3. Stratigraphy of the Ethiopian Volcanic Plateau

Flood volcanic rocks of variable composition in Ethiopia were unconformably emplaced on a regional lateralized and hematitized sandstone horizon with an area of about 90,000 km^2(Assefa, 1991; Ukstins et al., 2002). These flood volcanics are also overlain by later-coming Miocene-Pliocene-age shield volcanoes (Ukstins et al., 2002). Initial stratigraphic studies centered on the Northeastern region of the Ethiopian plateau divided the Ethiopian flood basalts into four divisions from oldest to youngest: Ashangie basalt, Aiba fissured basalt, Alajie basalts and rhyolites, and the Tarmaber basalts (Mohr and Zanettin, 1983). The K-Ar dating method, combined with a broad lithological identification technique, provides an essential approach for classifying the volcanic succession or stratigraphic sequence of the northwestern Ethiopian volcanic plateau (Mohr and Zanettin, 1988; Ukstins et al., 2002; Rooney and Yirgu, 2018).

2.4. North-Western Ethiopian Volcanic Plateau

Volcanic rocks in the northwestern Ethiopian plateau either directly overlie the Precambrian basement metamorphic and intrusive igneous rocks or indirectly overlay the Paleozoic and Mesozoic sedimentary succession(Meshesha & Shinjo, 2007; Desta et al., 2014). The geology of the northwestern Ethiopian plateau is characterized by a variety of geological events during the geologic past; each of them is marked by the development of a new stratigraphic sequence (Pik et al., 1998; Beccaluva et al., 2009; Natali et al., 2011).

Cenozoic volcanism in the NW Ethiopian flood basalts started with the eruption of Ashangie basalt during the Eocene/Oligocene, followed by the extrusion of Aiba basalts and Alajie formation during the Oligocene-Miocene age (Keir et al., 2011). These volcanic episodes are characterized by the presence of interbeds of felsic pyroclastic rocks with rhyolitic or less trachytic compositions between the flood basalts) (Pik et al., 1998; Meshesha & Shinjo, 2007; Krivolutskaya et al., 2020). The major volcanic rock units of the WEP are: Oligocene flood volcanics (Trap series), i.e., (Oligocene–Miocene basalts and rhyolites), Miocene-Pliocene shield volcanoes, and Quaternary volcanics (Fig 2.1).

2.4.1. The Oligocene Flood Volcanics

In the WEP, the flood volcanic succession includes basaltic lava flows, basaltic tuffs, as well as a considerable volume of rhyolitic, trachytic, and phonolitic products (Mohr and Zanettin, 1988). In their mineralogical composition, most of the flood basalts are aphyric to sparsely phyric and contain phenocrysts of plagioclase and clinopyroxene with or without olivine, and commonly display tholeiitic to transitional chemical composition (Chorowicz et al., 1998; Mohr and Zanettin, 1988; Pik et al., 1998; Kieffer et al., 2004; Natali et al., 2011). Despite the predominance of basalts, the flood volcanism contains significant volumes of felsic volcanic rocks, usually in the upper parts of the sequence (Pik et al., 1998; Ayalew et al., 2002; Ayalew & Yirgu, 2003). The felsic volcanic rocks are mainly friable tuffs, rhyolites, and ignimbrites, interlayered with flood basalt (Mohr and Zanettin, 1988; Pik et al., 1998).

2.4.2. The Miocene-Pliocene Shield Volcanoes

The Ethiopian flood volcanism was followed by the emplacement of large shield volcanoes and continental rifting (Kieffer et al., 2004). These shield volcanoes are important features of the Ethiopian plateau. About 20 % of the surface of the plateau is covered by shield volcanoes (Fig 2.1). The summits of the shields are about 1.5km above the flood basalt (Hoffmann et al., 1997; Pik et al., 1998; Kieffer et al., 2004). The felsic volcanic rocks (Trachytes, Phonolites, and Rhyolites) occur as a layered massif lava flow overlaying the flood basalt (Ayalew & Yirgu, 2003; Adise, 2006).

The main shield volcanoes in the Northwestern Ethiopian volcanic plateau include Semien Mountain, Choke Mountain, Guguftu Mountain, and Guna Mountains (Fig.2.1). The ages of Semien shield volcano (~30.4 Ma), Choke (~22.4 Ma), Guguftu (~22.3 Ma), and Guna (~10.7 Ma) (Kieffer et al., 2004; Hofmann and Farnetani, 2013). Like the flood volcanics, the shield volcanoes are bimodal in composition and contain sequences of alternating basaltic, rhyolitic, and trachytic lava flows, tuffs, and ignimbrites, particularly near their summits (Kieffer et al., 2004; Natali et al., 2011).

Semien shield volcanoes are characterized by the alternation of aphyric, sparsely phyric, and highly phyric lavas, and they contain very young shield volcanics at the summit area, almost equal in age to the Guna shield volcano (Kieffer et al., 2004). The phenocryst phases are plagioclase, clinopyroxene, and olivine. Choke and Guguftu shields are characterized by plagioclase-phyric basalts with olivine and clinopyroxene phenocrysts. They are distinguished from the basalts of the Semien shield by the presence of a small percentage of olivine in the groundmass, and distinctly pink-brown clinopyroxene grain features indicating that these basalts belong to the alkaline magma series (Kieffer et al., 2004). Furthermore, Different authors have studied and implicated many types of shield volcanoes in the northwestern Ethiopian plateau (e.g., Hofmann et al., 1997; Ukstins et al., 2002; Kieffer et al., 2004).

Table 1 Distribution of shield volcano and recent flood basalts in Northwestern Ethiopia

No.	**Age (Ma)**	**Location**	**Rock formation &type**	**Source of data**
1.	10.6-3.2	North Addis Ababa	Mio-Pliocene Volcano	Ukstine et al., (2002)
2.	10.7	Mt.Guna	Mio-Pliocene Volcano	Kieffer et al., (2004)
3.	11.7-10.9	Between A.A &Dessie	Mio-Pliocene Volcano	Ukstine et al., (2002)
4.	19.8-14.9	Between A.A & Dessie	Mio-Pliocene Volcano	Ukstine et al., (2002)
5.	18.7	Simien Mt.	Mio-Pliocene Volcano	Kieffer et al., (2004)
6.	21.6	Alem Ketema	Mio-Pliocene Volcano	Coulie, (2001)
7.	22.3	Guguftu Mt.	Mio-Pliocene Volcano	Kieffer et al., (2004)
8.	22.4	Mt. Choke	Mio-Pliocene Volcano	Kieffer et al., (2004)
9.	22.3	Anferfira	Mio-Pliocene volcano	Chumburo. (2015)
10.	18.58– 19.1	Lemi and Demasiko	Mio-Pliocene volcano	Chumburo. (2015)

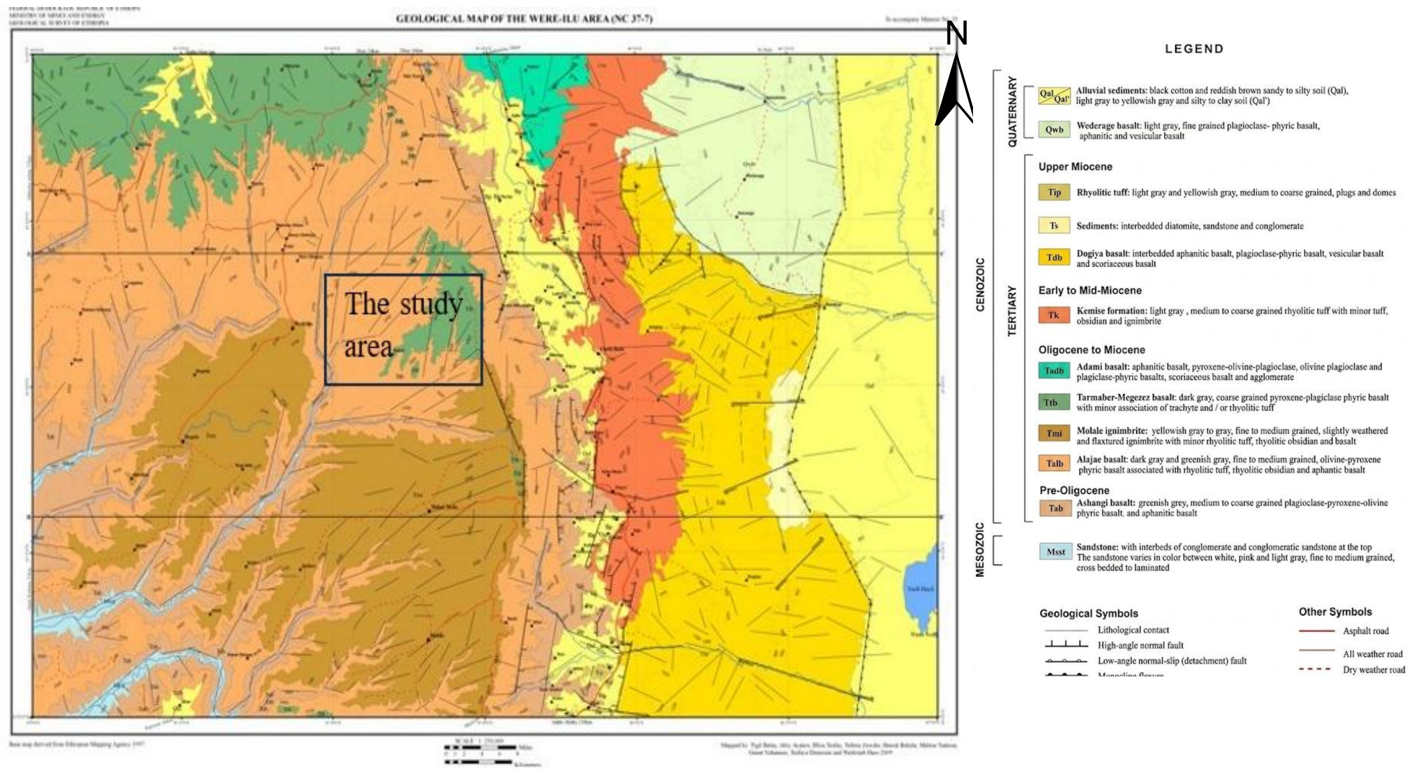

Figure 2. 2 Map of Woreilu map sheet from Belay et al. (2009) The rectangle inset in the map shows the study area.

CHAPTER THREE

GEOLOGY OF THE STUDY AREA

The study area is dominated by a bimodal suite of volcanic rocks, with felsic pyroclastic deposits and massive, often jointed, basaltic flows forming the most prominent outcrops (Fig. 3.1). Felsic pyroclastic layers are frequently interbedded between basaltic flows and occasionally overlie paleosols, suggesting periods of volcanic inactivity during their deposition. Basaltic rocks are widely exposed throughout the area and account for the largest areal coverage, followed by felsic rhyolites.

The basaltic rock units are distinguished by their textural characteristics as aphanitic and porphyritic, with visible minerals of pyroxene, olivine, and plagioclase. The distribution and variation of volcanic rocks in the study area are displayed in the geological map and cross-sectional map below (Fig 3.1a and b). The field descriptions at the outcrop scale, lithologic units with a geological map, geological cross-section, and the geological structure of the study area, including volcanic rocks, are presented in this chapter.

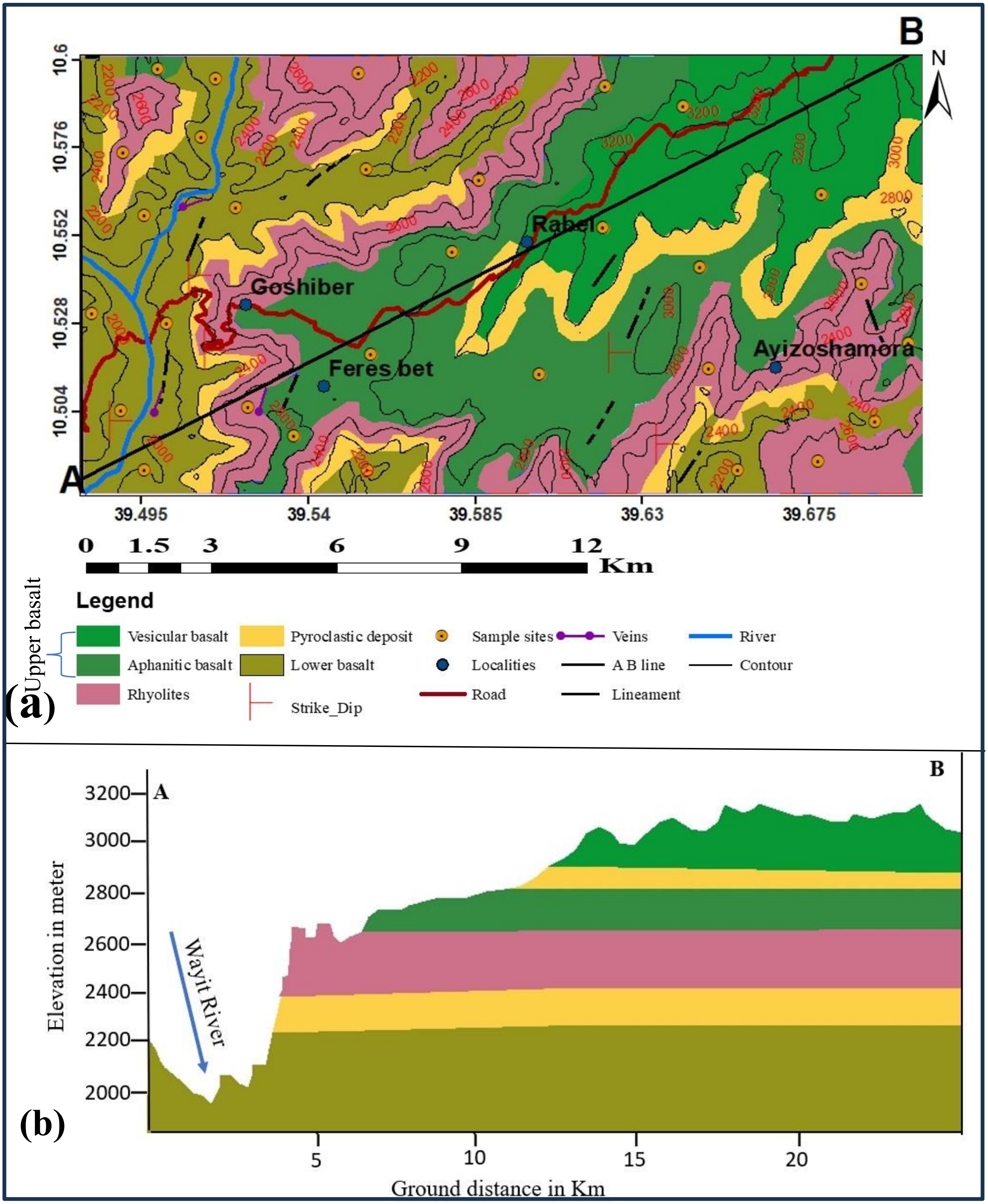

Figure 3. 1 Geological map of the study area(a) and cross-section(b).

3.1. Lithological description of rocks

The geological map of the study area identifies three broad lithological groups: basaltic rocks, pyroclastic rocks, and rhyolitic units. These units were delineated based on detailed field mapping and lithological characteristics observed across the study area. Field observations indicate that the volcanic succession in the Gishe Rabel locality and its surroundings comprises a diverse assemblage of mafic, pyroclastic, and felsic volcanic rocks. The basaltic units are subdivided into two stratigraphic divisions: lower and upper basalt, defined based on variations in lithology, texture, and stratigraphic position within a stratigraphic framework. These basaltic sequences are intercalated with pyroclastic deposits, including tuffs and ash layers, as well as felsic volcanic units such as rhyolitic ignimbrites and rhyolite lava flows. The coexistence of basaltic and rhyolitic units suggests a complex volcanic history involving both effusive and explosive eruptive phases, possibly reflecting bimodal volcanism within the study area.

3.1.1. Lower basalt

The lower basaltic unit is extensively exposed beneath the overlying felsic pyroclastic and rhyolitic rocks, forming the basal portion of the volcanic succession within a stratigraphic framework. The basaltic flows are predominantly massive, with well-developed interior zones characteristic of thick lava emplacement.

The lower basaltic flow unit contains aphanitic, porphyritic, and amygdaloidal basalts intercalated with felsic pyroclastic deposits. Different sets of columnar joints are observed both in the aphanitic and porphyritic basaltic rock units in the study area (Fig 3.2). Olivine and pyroxenes are the dominant visible minerals as phenocrysts in the lower porphyritic basaltic flow. Some of the basaltic rock samples in this lower volcanic section contain vesicles filled with secondary precipitating minerals (amygdaloidal), and these secondary precipitating minerals are calcitic in composition.

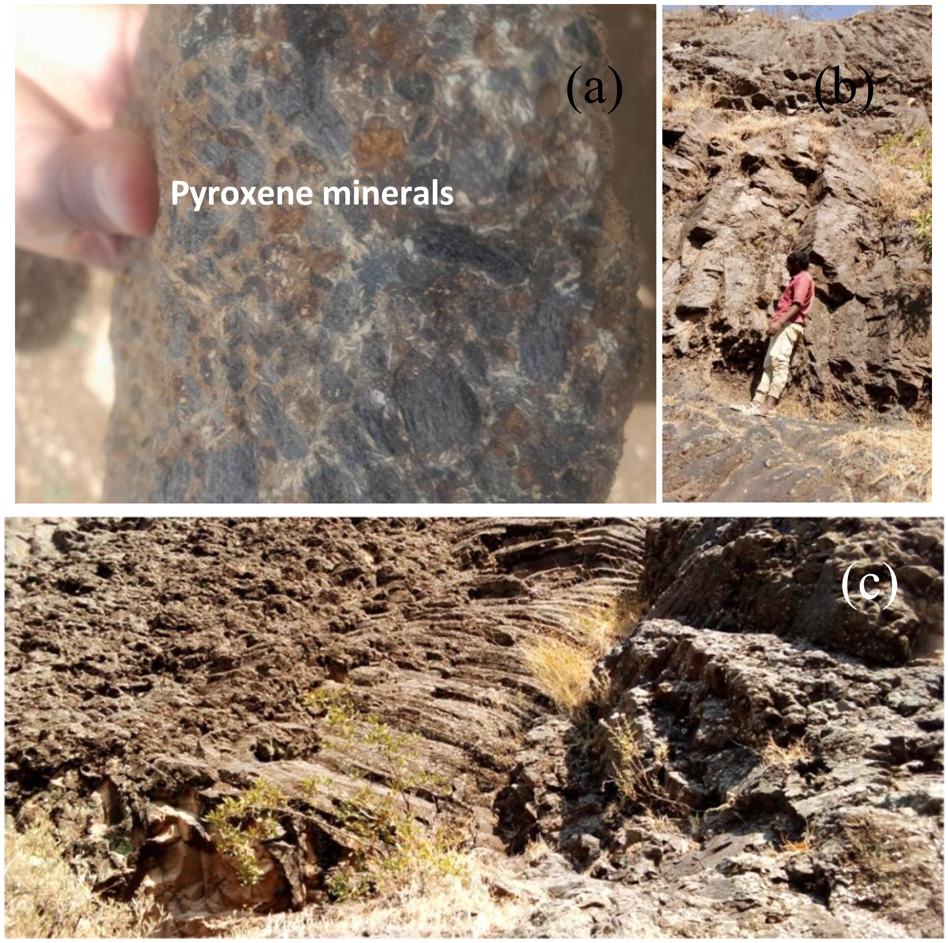

Figure 3. 2 Field outlook images of the lower basaltic rock units. Large pyroxene minerals observed even to our naked eye (a), highly jointed columnar joint (colonnade joint) basalts (b), and irregular, curved, and less orderly columns (entablature joint) of basalt (c).

3.1.2. Pyroclastic deposits

The pyroclastic rocks, including tuffs and ash deposits, are predominantly exposed in the study area. These units commonly occur intercalated with both the aphanitic and vesicular basaltic flows (Fig 3.3), indicating alternating episodes of effusive and explosive volcanic activity within a stratigraphic framework. The pyroclastic deposits are typically fine-grained and dominated by ash-sized material, with subordinate lithic fragments. They are generally poorly consolidated, friable, and exhibit low mechanical strength, allowing them to be easily disaggregated in the field. In some localities, the tuffs show evidence of oxidation, resulting in reddish coloration due to the formation of iron oxides such as hematite. This alteration likely reflects post-depositional weathering or low-temperature oxidation processes. Based on grain-size characteristics, the deposits are primarily composed of ash-sized particles, with lesser proportions of coarser fragments. These features suggest deposition from explosive volcanic eruptions, likely involving ash fall and/or fine-grained pyroclastic flows.

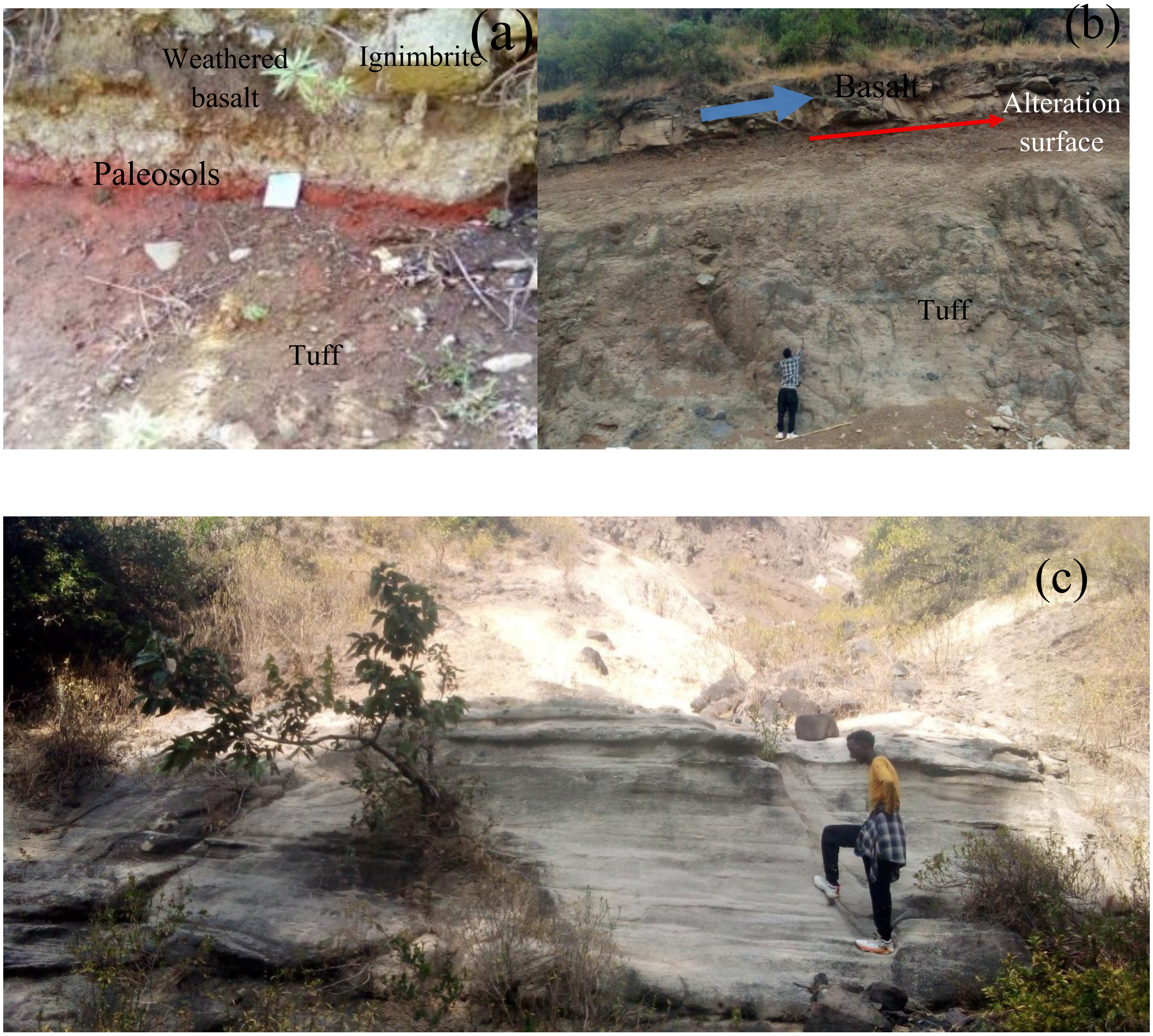

Figure 3. 3 Field outlook image of pyroclastic deposits from different sites of the study area; Tuff deposit with lithic fragments or crystals associated with it and separated by thin layer of paleosols (a), tuff and basalt separated by a thin layer of alteration (b), ash deposits showing some directional alignments are called a surge deposit (c)

3.1.3. Rhyolite

The rhyolite unit constitutes the dominant lithology in the Gishe Rabel area and is characterized by prominent cliff-forming exposures, reflecting its relative resistance to erosion. The rocks are typically light grey to grey in color and exhibit predominantly aphanitic textures, although subtle variations may occur locally. Stratigraphically, the rhyolite unconformably overlies the felsic pyroclastic deposit and lower basalt unit, indicating a significant break in deposition consistent with an unconformity. The rhyolitic succession attains a thickness of up to 140-250 m and forms laterally extensive units that can be traced for tens of kilometers across the study area.

In some areas, the lower part of the rhyolite unit is vesicular, and the upper layer is columnar jointed in its structure (Fig 3.4). Rhyolite extends laterally for at least tens of kilometers, indicating that it was fluid and mobile due to perhaps reduced viscosity as a result of compositional factors.

Figure 3. 4 Field outlook of rhyolite; columnar joint rhyolite forms when the lava cools and contracts, creating evenly spaced fractures. These fractures propagate downward as the rock cools, producing the characteristic column-like structures.

3.1.4. Upper basalt unit

The upper basaltic unit is widely preserved across much of the plateau and attains a maximum thickness of approximately 500 m. It is predominantly composed of massive, dark-colored, dense basaltic flows, locally intercalated with 5–50-m-thick layers of ash. The flow top of the upper basalt is sparsely vesicular, and those vesicles are not filled with secondary mineralization.

The basaltic flows exhibit both aphanitic and vesicular textures with some porphyritic, reflecting variations in cooling history and crystallization conditions. The basal portions of some flows are porphyritic, whereas finer-grained aphanitic textures dominate elsewhere. Columnar joints occur in aphanitic basaltic rock units in the study area (Fig. 3.5). Mineralogically, the basalt is dominated by plagioclase and pyroxene phenocrysts, with plagioclase in relatively higher proportions. Vesicles are generally sparse in the top flow and commonly unfilled. However, in some localities, vesicles are filled with secondary calcite, forming an amygdaloidal texture.

Figure 3.5 Field outlook of basaltic rocks from the upper lava flow sequences. Basaltic rock units with vesicles filled by secondary calcite (a), and vesicles on the basaltic rock surface (b).

3.2. Geological structures

Geological structures are primarily the result of tectonic processes. Except for the friable pyroclastic rock units, all other lithological units exhibit distinct sets and orientations of geological structures. In competent (hard) rocks, fractures and joints are particularly well developed due to their brittle behavior under stress. In contrast, dykes and dyke swarms are more prominently exposed within the friable pyroclastic deposits, where erosion and lower mechanical strength enhance their surface expression.

3.2.1. Joints

The orientation of the joint is variable from place to place and also from lithology to lithology. In addition to columnar joints, several other smaller fracture-type joints are also available in hard rocks like basalt and rhyolite (Fig. 3 .6). But in highly altered and weathered types of rocks and also in felsic pyroclastic deposits like ash, tuff, and other friable products, the existence of fractures and joints is not likely. Columnar joints are mainly oriented from north to northwest in a rhyolite with a strike direction of N330°W, and east to northeast in an aphanitic basalt with a strike direction of N48° E. Generally, different sets and orientations of joints are extensively found in the study area of volcanic rocks.

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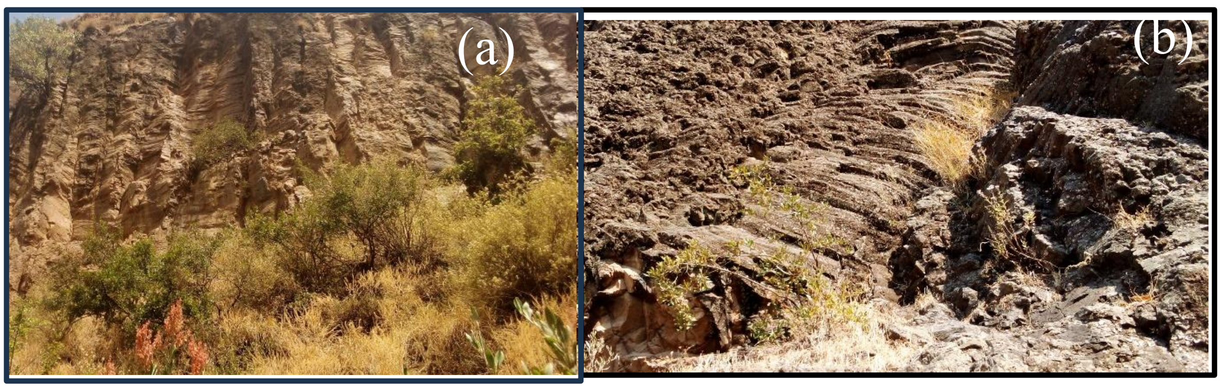

Figure 3. 6 Columnar joint structures; columnar joints-oriented NE to SE direction on rhyolite (a), and fracture joint on basalt-oriented NW to SE direction on basalt (b).

3.2.2. Fractures and veins

Secondary minerals, particularly calcite and quartz, commonly precipitate within pre-existing fractures on rock surfaces, forming mineralized veins (Fig 3.7). These veins may locally intersect in radial or irregular patterns, and their thickness generally reflects the aperture of the host fractures or joints. In the study area, most veins show a preferred orientation toward the north to northeast (N–NE). However, some occur in the opposite direction, indicating multiple phases of fracturing and mineralization. Basaltic rocks in the area exhibit numerous surface fractures, some of which are infilled with secondary minerals like calcite and quartz, forming distinct veins.

Figure 3. 7 Secondary infilling materials in the study area are basaltic rock units; SW to NE-oriented calcitic veins on the basaltic flow unit.

3.2.3. Volcanic domes

Volcanic domes are particularly common around Rabel town, occurring mainly to the northeast and northwest of the area. Their formation is generally linked to central volcanic activity for dome-shaped volcanism (Fig 3.8).

Although dome-shaped landforms can form from basaltic, intermediate, or felsic lavas, the majority of volcanic domes in the study area are composed predominantly of basaltic material and characterized by small size. This suggests that dome formation in the area is largely controlled by localized eruptive centers and the emplacement of relatively viscous basaltic lava.

Figure 3. 8 Volcanic dome shapes (central volcanoes) are available in the study area, particularly at the lower basaltic sequences of the study area which indicates the morphology of igneous area related to relative viscos magma.

3.3. Orientations of the Geological structures

The orientations, or attitudes, of geological structures in the study area were measured in the field using a compass-clinometer. Columnar joints are mainly oriented from north to northwest in a rhyolite with a strike direction of N330°W, and east to northeast in an aphanitic basalt with a strike direction of N48° E. Linear veins and fractures within the volcanic rocks predominantly follow a northeast direction, with a strike direction of N315°W, N40°E, and N10° E.

The orientations of these structures are illustrated in the rose diagrams shown in (Fig 3.9). These diagrams were created using field-measured GPS data processed with GeoRose software, providing a clear visualization of the structural trends across the study area.

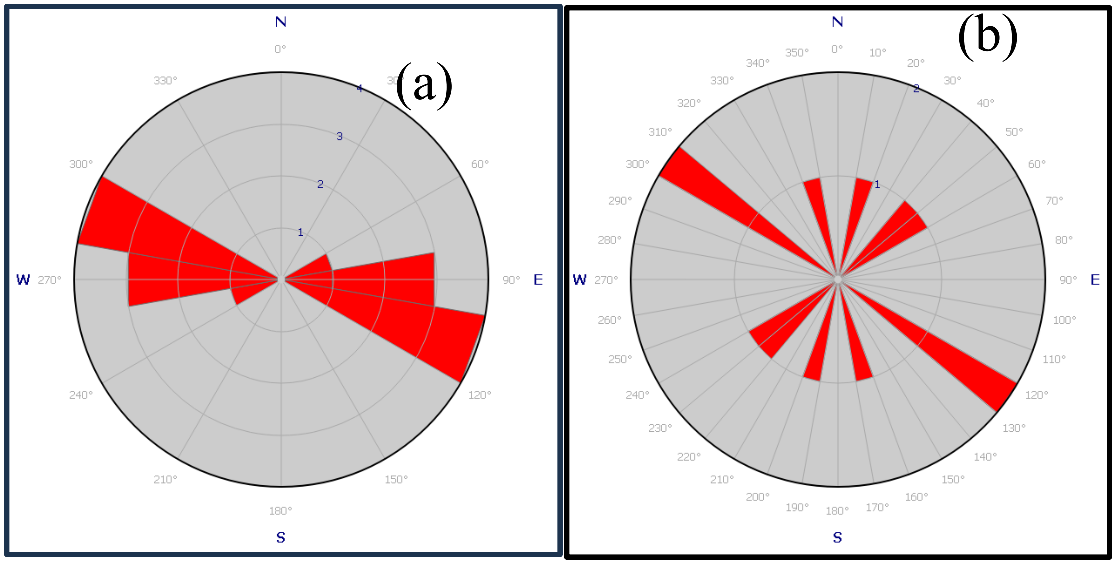

Figure 3. 9 Rose diagram or polar plot of: a) Shows the orientation or trend of paleosols and major contacts traced in between lithologic units, b) Columnar joints and Fracture joints.

CHAPTER FOUR

PETROGRAPHY OF VOLCANIC ROCKS OF THE AREA

4.1. Introduction

Petrographic analysis of rocks is crucial for determining the modal abundance of the rock and identifying the different minerals. It is used to provide petrological conclusions about the texture, mineral assemblages, cooling history, and magmatic processes of the rock (Alehegn et al., 2024). Rock-forming minerals are useful for recognizing genetic relationships among rocks with different degrees of magmatic evolution (e.g., basalt, basaltic andesite) or for discriminating magmatic series affinity (e.g., alkali or tholeiitic basalts). The following scenarios were taken into consideration to give the textural name of the rock: crystallinity (degree of crystallization, the relative proportion of crystals and glass in the rock), Granularity (grain size, the absolute and relative size of crystals), Grain shape, and the mutual relationship between crystals and other amorphous materials in the rock (MacKensie & Guilford, 1980).

A total of 25 thin sections were prepared and investigated under the PPL and XPL views via a transmitted light microscope. Even though the stratigraphic section and lithological descriptions, including the geological map construction, are expressed in terms of the spatial distribution of lava flows, the petrographic description of rocks of the study area is expressed in terms of texture and fabric variability, because rocks with similar textural and fabric relationships have existed in different layers of lava flows in the study area.

Based on modal composition, phenocryst mineral assemblage, and textures, the study area volcanic rocks are grouped as Plagioclase phyric basalt, undifferentiated basalt, Pyroxene phyric basalt, Olivine phyric basalt, Pyroxene-plagioclase phyric basalt, Olivine plagioclase phyric basalt, and Rhyolite.

4.2. Petrographic description of rocks

4.2.1. Plagioclase phyric basalt

The plagioclase-phyric basaltic rocks are predominantly exposed in different parts of the study area. Particularly in the eastern and western sections of the area. The plagioclase phenocrysts are characterized by polysynthetic twining and an elongated habit (Fig 4.1). This rock unit is composed of phenocrysts of plagioclase mineral (~100%) from the phenocryst, and the groundmass is composed of laths of plagioclase (~45%), opaque minerals (20-35%), and pyroxene (~30%). The plagioclase phenocrysts are range in size from 1mm to 5mm. Generally, the phenocryst counts ~30% in proportion relative to ground mass proportion.

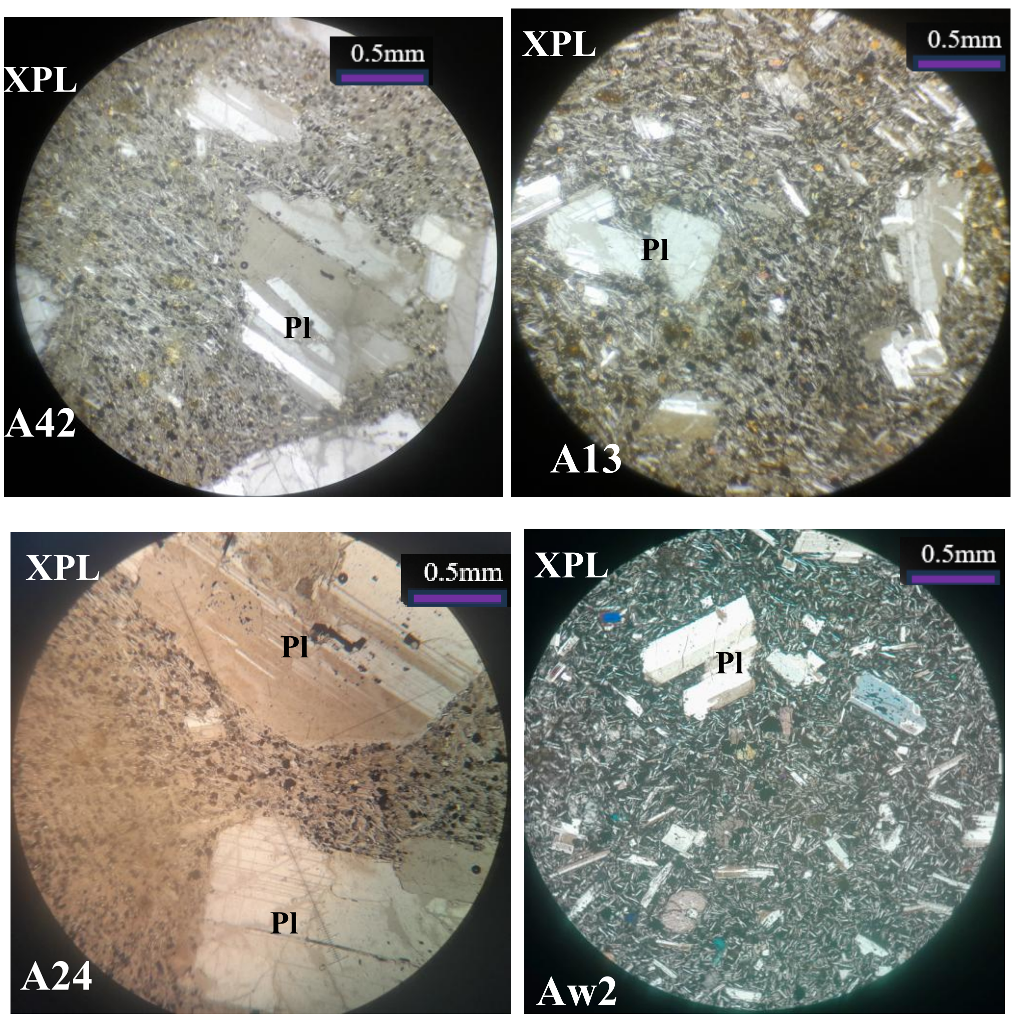

Figure 4. 1 Photomicrograph of plagioclase phyric basalt. The abbreviation Plag refers to Plagioclase. All are XPL views under 4X magnification of the microscope.

4.2.2. Pyroxene phyric basalt

Clinopyroxene is the dominant phenocryst phase, comprising approximately 90% from the phenocryst assemblage, and 20% to 45% relative to the groundmass (Fig 4.2), with minor occurrences of olivine from the phenocryst proportion. The clinopyroxene crystals are typically anhedral and exhibit high relief under plane-polarized light. Locally, they display intergranular to sub-ophitic textural relationships with surrounding plagioclase. Olivine occurs in subordinate amounts as subhedral to anhedral grains, commonly showing high relief and minor alteration along fractures The groundmass is fine-grained and composed of plagioclase laths, clinopyroxene, minor olivine, and opaque. These minerals form an intergranular to intersertal texture

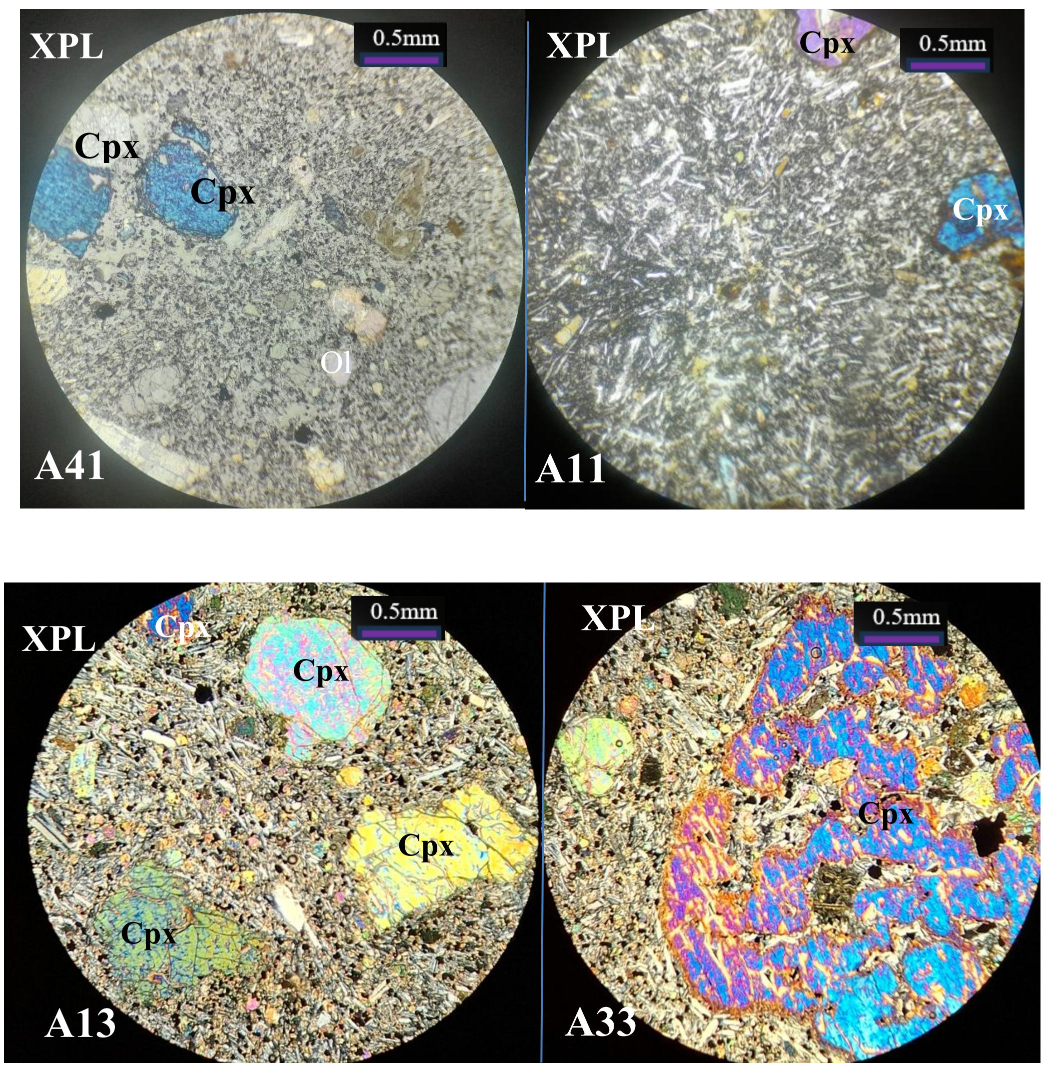

Figure 4. 2 Photomicrograph of pyroxene phyric basalt. The abbreviations of the minerals are: Ol is Olivine, and Cpx is clinopyroxene. All are in XPL view.

4.2.3. Aphyric basalt

Aphyric, aphanitic basalt is widely distributed across the study area and has been sampled from the lower, middle, and upper stratigraphic sections of the basaltic lava flow sequence. Due to its very fine-grained nature, individual minerals are not distinguishable in hand specimen. This rock unit is entirely composed of smaller-sized plagioclase 50%, opaque ~ 45%, and pyroxene, and olivine minerals are less than 5% (Fig 4.3).

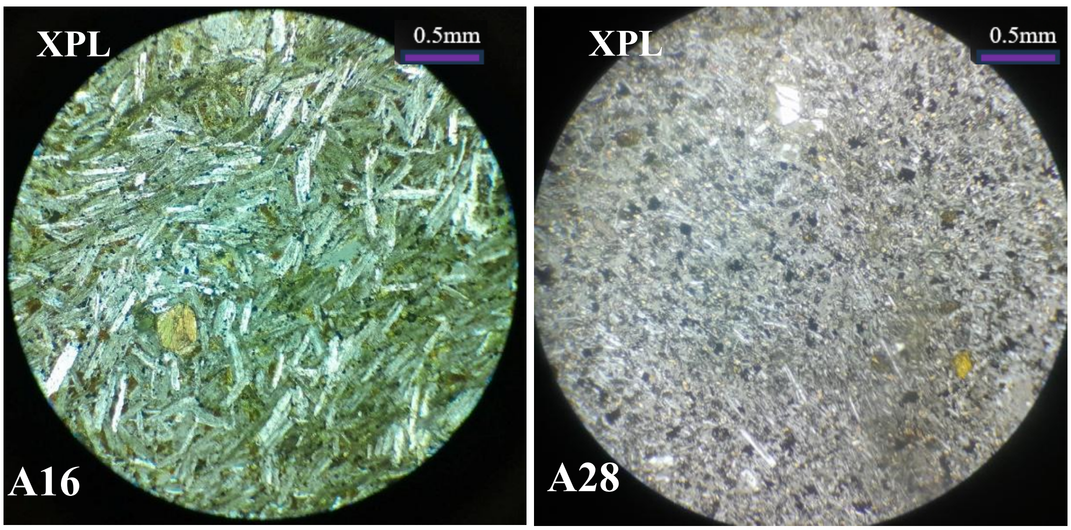

Figure 4. 3 Photomicrograph of aphyric basalt.

4.2.4. Rhyolite lava flow unit

The rhyolite lava flow unit is overlain the lower basaltic lava flow unit and overlain by aphanitic, and vesicular basalt. Rhyolite is associated with obsidian along the Wayit River. It is composed of a high-temperature alkali feldspar mineral (Sanidine)~90% phenocryst with smaller amounts of Iron oxide from the phenocryst assemblage (Fig 4.4). The groundmass component of this rock type is basically volcanic glass. Over all groundmass ~ 80% from the entire petrographic view.

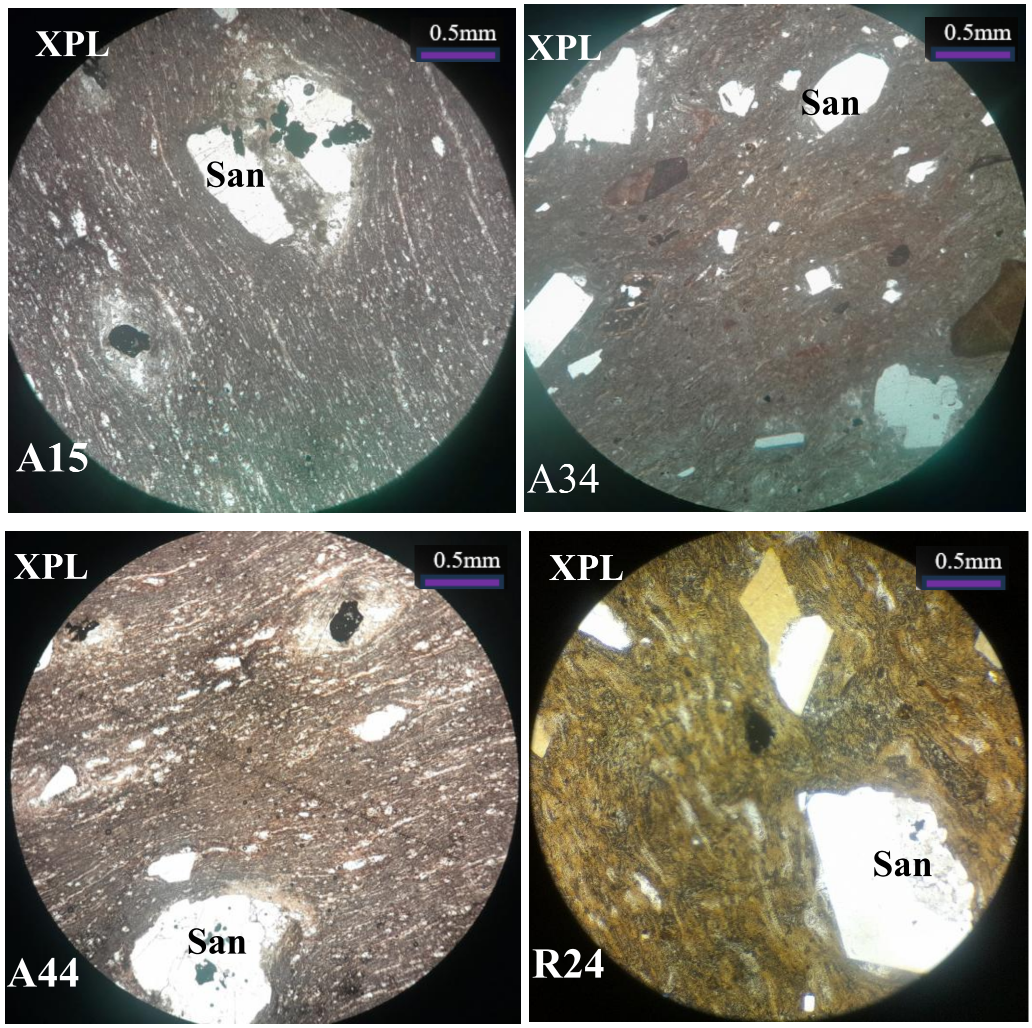

Figure 4. 4 Photomicrograph of felsic volcanic rocks in the study area. The abbreviations used, San for Sanidine. The proportion of phenocryst relative is to the phenocryst abundance.

4.2.5. Pyroxene-Plagioclase phyric basalt

The rock sample is dominated by pyroxene phenocrysts mostly clinopyroxene (Cpx) in a proportion of 80-85% in a sample A21 relative to the phenocryst, and 60% in a sample A12 with smaller amounts of orthopyroxene (Opx), and laths of plagioclase with a proportion of ~ 35%. Opx is distinguished from Cpx by its parallel extinction under the microscope, whereas Cpx shows inclined extinction. Overall, the phenocrysts include pyroxene and plagioclase ~35% proportion relative to groundmass. Clusters of ferromagnesian minerals give the rock a glomerophyric texture (Fig. 4.5).

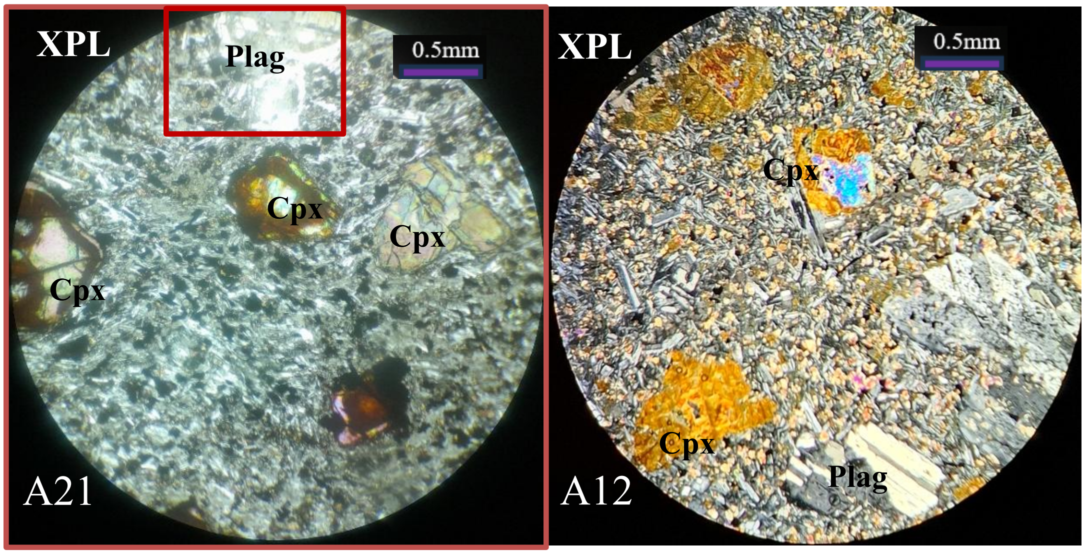

Figure 4. 5 Photomicrograph of plagioclase and pyroxene phyric basalt

4.2.6. Olivine phyric basalt

In lower basalt units of the study area there is highly alkaline and made up almost entirely of olivine phenocrysts (about 80–95%) with a small amount of clinopyroxene relative to the abundance of phenocryst and about 37% relative to ground mass. These crystals are 0.5–1 mm in size, rounded to anhedral, and often show irregular fractures and surface alteration (Fig. 4.6). Secondary minerals fill the fractures and appear deep yellow to brown which is iddingsite with strong birefringence. The olivine crystals appear as subhedral to anhedral phenocrysts embedded within a fine-grained groundmass. They show high relief and irregular fractures, which are typical optical features of olivine.

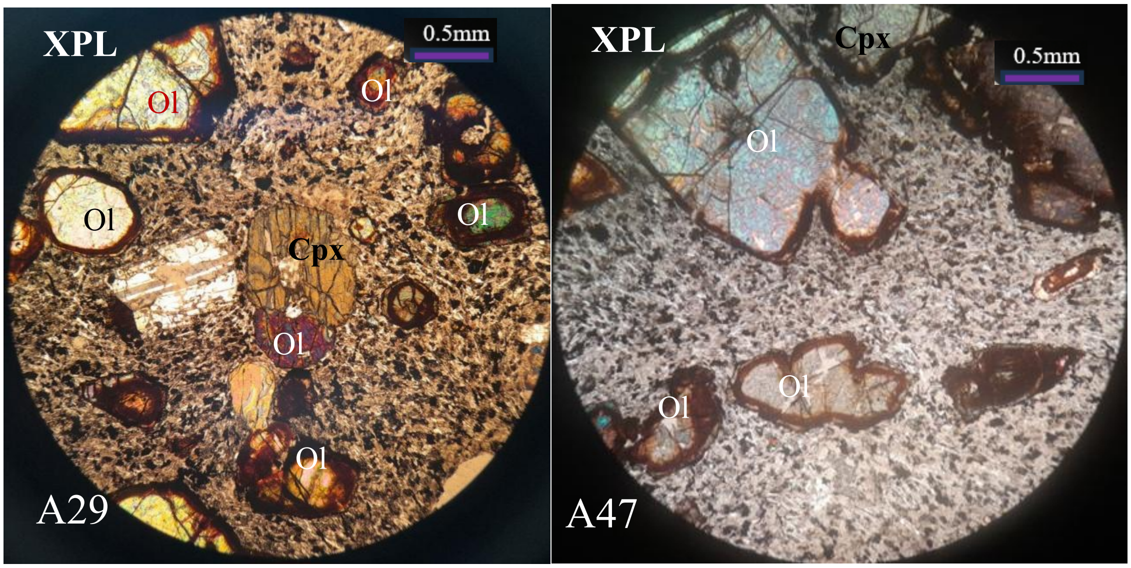

Figure 4. 6 Photomicrograph of olivine-rich lower basalt, represents primitive mantle-driven magma eruption.

4.2.7. Olivine- Plagioclase phyric basalt

The olivine plagioclase phyric basalt is characterized by various phenocryst types as shown in (Fig 4.7), which are predominantly comprised of olivine (~60%) and plagioclase (~30%) mineral phases as well as lesser amounts of opaque mineraloids (~5%) and clinopyroxene (Cpx) crystals (~5%). The rock possesses a groundmass primarily made of opaque, plagioclase, clinopyroxene, and ferromagnesian mineral components. Generally, groundmass count ~ 60% from the entire unit.

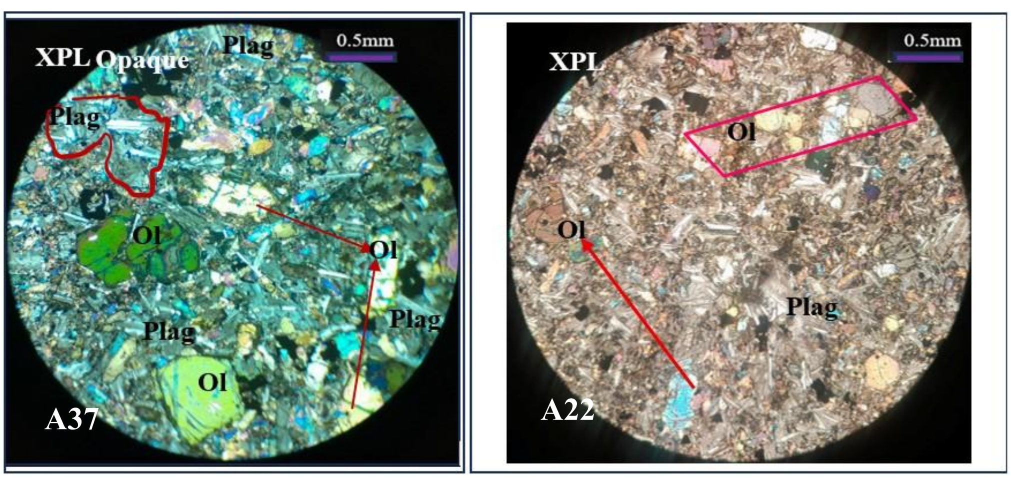

Figure 4. 7 Photomicrograph of olivine-plagioclase-rich porphyritic basalt at 4x magnification under a light-transmitted microscope in XPL view.

CHAPTER FIVE

VOLCANIC STRATIGRAPHY

5.1. Introduction

The volcanic stratigraphy of the study area was developed through comprehensive fieldwork supported by detailed petrographic analysis. The stratigraphic log was prepared to clearly illustrate the vertical and lateral variations in the rock units. Field investigations revealed three major stratigraphic sections: the Lihot River, Goshiber-Wayte River, and Ayizoshiamora areas.

The construction of the stratigraphic log is based on observable differences in texture, mineral composition, and grain-to-grain fabric relationships within the volcanic units. In line with the standard geological framework of Ethiopia, the stratigraphy is organized chronologically from the oldest Precambrian basement rocks to the youngest Quaternary volcanic and sedimentary deposits.

The study also aligns with and references existing regional stratigraphic frameworks to ensure consistency and geological accuracy.

5.2. Stratigraphic log based on detailed field investigation

5.2.1. Ayizoshamora section

The Ayizoshamora volcanic sequence extends widely to the southeast of Rabel town. In this area, the volcanic rocks are well exposed and display a clearly defined stratigraphic arrangement (Fig 5.1). The sequence begins with the lower basaltic flows representing the lower flood basalts and progresses upward to the upper basalt units, showing a well-organized vertical succession of volcanic products.

The stratigraphy consists of lower flood basalts overlain by pyroclastic unit. The lower basalt unit estimated cumulative thickness of ~300 meters. These flows are generally massive, fine-grained, and with sparse olivine phenocrysts.

The rhyolitic unit overlies the pyroclastic deposit and is overlaid by the upper basalt, with an approximate thickness of ~140 meters exposed as hill side. The rhyolite is moderately porphyritic, with sanidine phenocrysts in a fine-grained to glassy matrix.

The upper basalt unit is thicker (~400 meters total thickness) and sandwiched the pyroclastic tuff~50m thick. It consists of 2–5 flows characterized by aphanatic, vesicularity and increased plagioclase phenocryst abundance. The distinction between lower and upper basalts is based on field relationships, vesicularity, and petrographic differences.

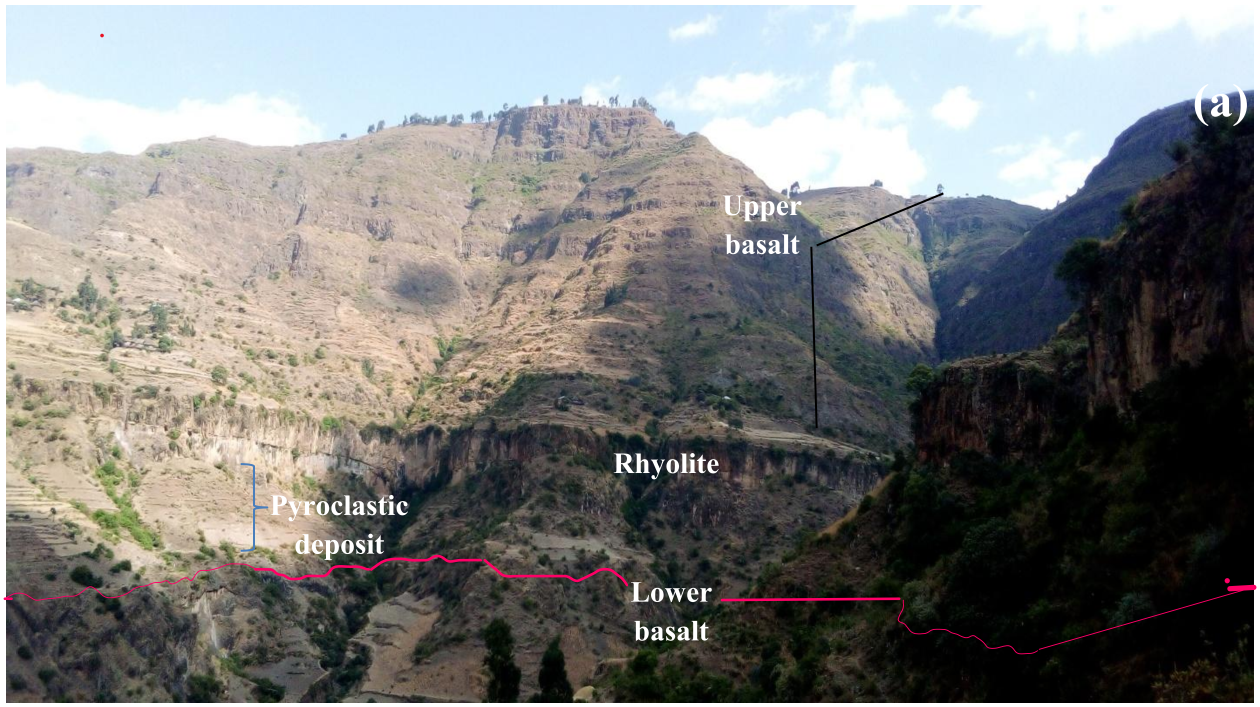

Figure 5. 1 Field outlook of Ayizoshamora section (a), and its stratigraphic log(b).

5.2.2. Lihot river section

The Lihot River section is located in the western and northwestern part of the study area. This major stratigraphic section includes aphanitic basalt, lower basalt units interbedded with felsic pyroclastic deposits, porphyritic basalts containing olivine and pyroxene phenocrysts, and sanidine-rich rhyolite that forms prominent cliffs. The basaltic units in this area are particularly notable for their steep topography and their high content of olivine and pyroxene minerals.

The stratigraphic sequence starts with lower basalt flows that are exposed by a river cut and overlaid by rhyolitic units (Fig 5.2). The lower basalt layer has a cumulative thickness of about 200 meters and is made up of three to five separate flow units. These flows are often massive, porphyritic, fine-grained basalt flows with pyroxene and olivine phenocrysts intercalated with felsic pyroclastic deposits that are thought to be ash tuffs form an alternate eruptive phase. These pyroclastic strata show intense volcanic activity and range in thickness from 50 to 100 meters.

The rhyolitic unit consists of sanidine-rich rhyolite forming resistant cliffs, with an approximate thickness of about 250 meters. The rhyolite is moderately porphyritic, with sanidine phenocrysts in a fine-grained to glassy matrix.

Lihot river log section

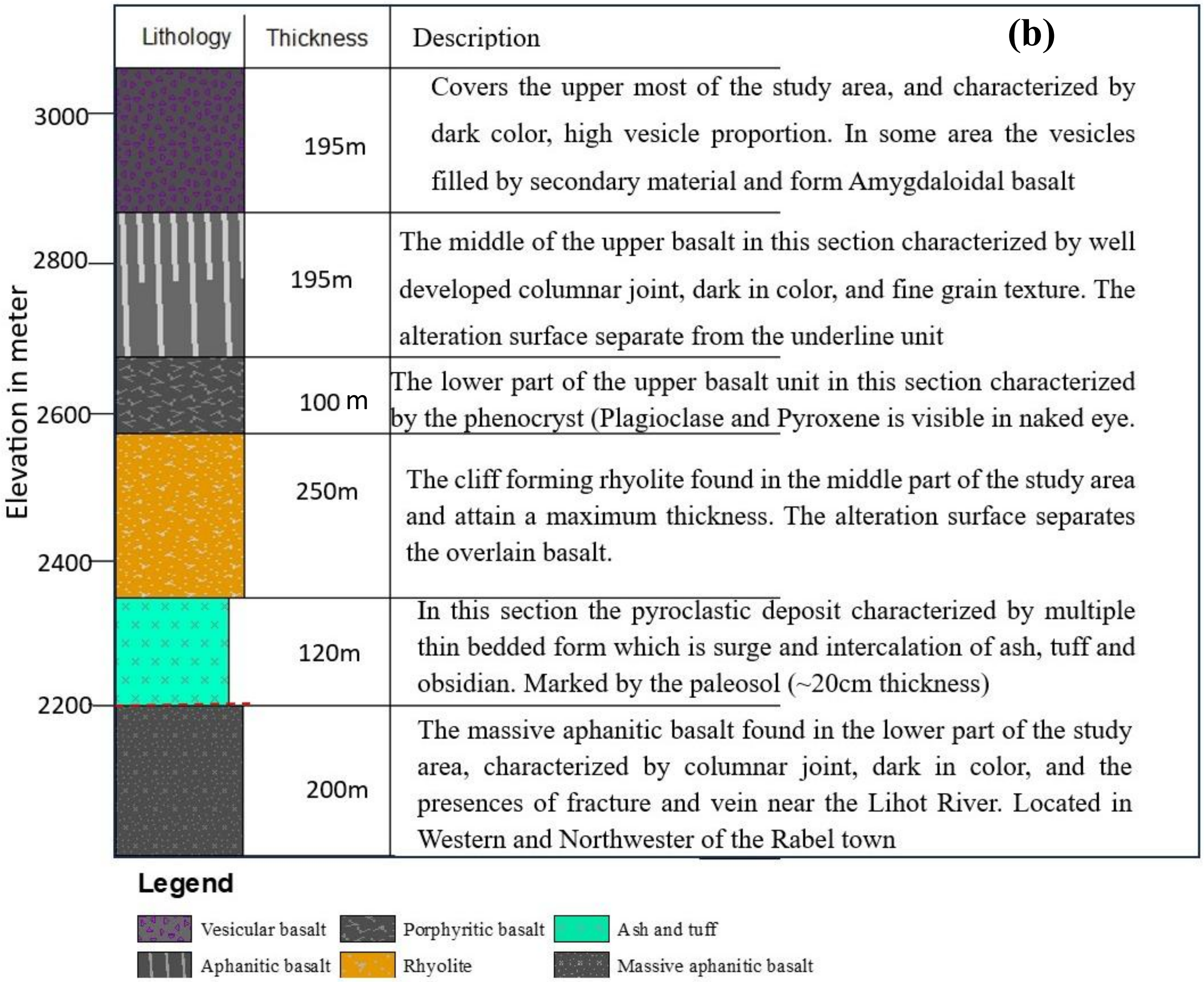

Figure 5. 2 Field outlook of the Lihot River stratigraphic section which taken northeast photo view direction, in which the lower basalt is intercalated with the pyroclastic tuff on the upper part of lower basalt, and weathered on the lower part of the lower basalt(a), and stratigraphic log of the Lihot River section(b).

5.2.3. Rabel Goshiber -Wayite river section

The Wayite River section lies to the west and southwest of Rabel. This area is characterized by prominent cliffs and ridges formed by volcanic rocks, mainly rhyolite and upper basalt, which display a more complex and well-developed stratigraphy than the other sections. In contrast, the lower basalt units in this area form relatively gentle, flat, and dome-shaped landforms. The exposures are mainly along road cuts, cliffs, and ridges formed by resistant volcanic units.

There are several lithologic units in this section, including lower basalt, rhyolite, ash, tuff, ignimbrite, and, upper basalt. The lower basalt, which is thought to be ~250 meters thick, creates dome-like shapes and mild slopes.

Road cuts reveal felsic pyroclastic deposits (ignimbrites and tuffs) that are intercalated between basaltic flows and have individual layers that range in thickness from ten to fifteen meters (Fig 5.3a). Because of its strong resistance to erosion, the ~200 m thick rhyolite unit generates cliffs. The upper basalt unit (400–450 m thick) overlies the rhyolite and consists of vesicular flows with moderate phenocryst (microphenocryst of plagioclase) content. The complexity of this section is demonstrated by multiple flow units, intercalated pyroclastic deposits, and minor lateral variations (Fig 5.3a and b).

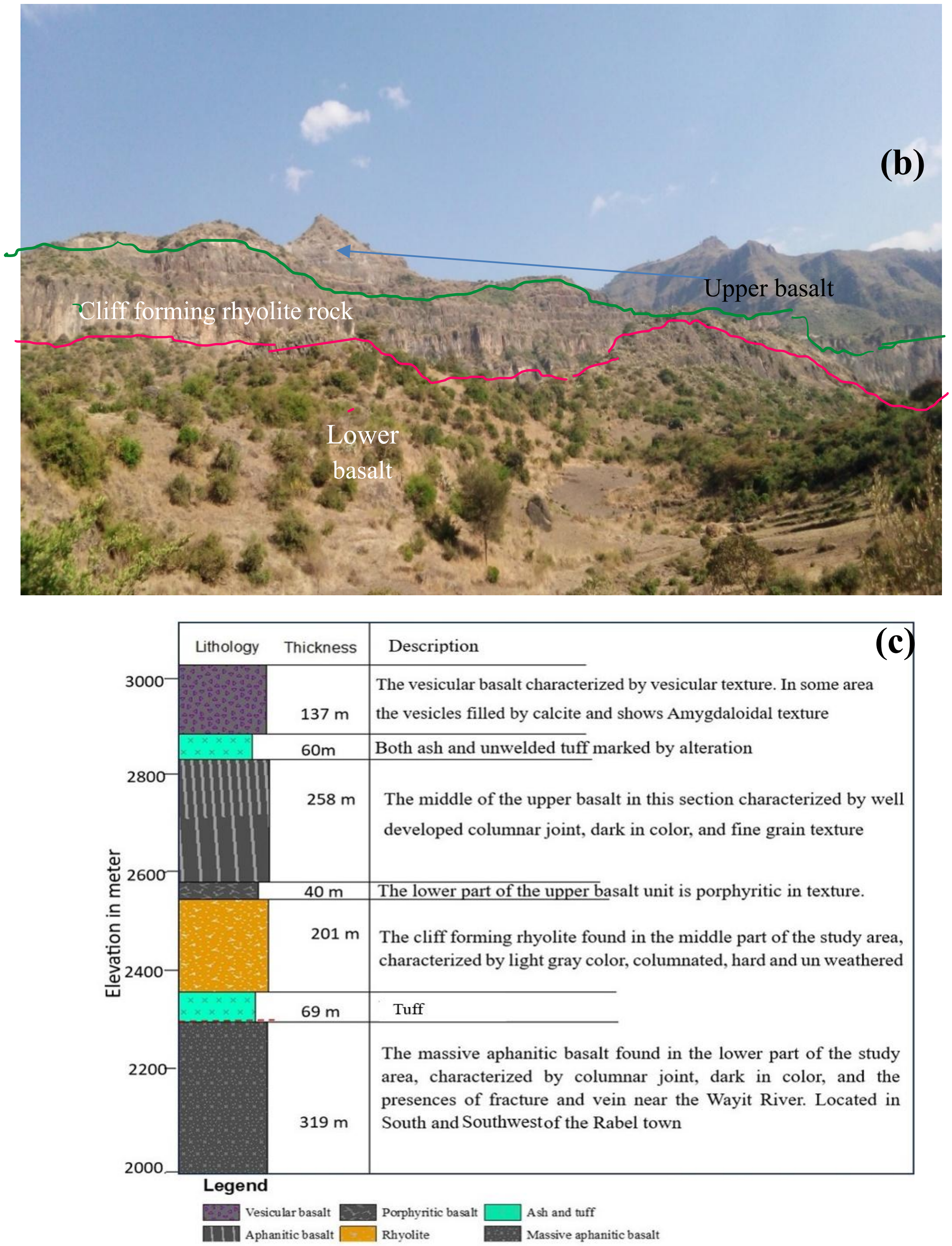

Figure 5. 3 Field outlook of the Goshiber-Wayit river stratigraphic formation (a, and b), and stratigraphic log(c) red dash line indicates paleosol unconformity.

5.3. Stratigraphy based on petrography

The petro-stratigraphic sequence (Fig 5.4) is presented to provide a clearer understanding of the vertical and lateral arrangement of the felsic and basaltic units in the study area. The petrographic names assigned to the rock samples reflect not only the dominant phenocryst minerals but also the textures and fabric relationships observed among the mineral grains. This approach helps convey both the mineralogical composition and the internal characteristics of each rock type.

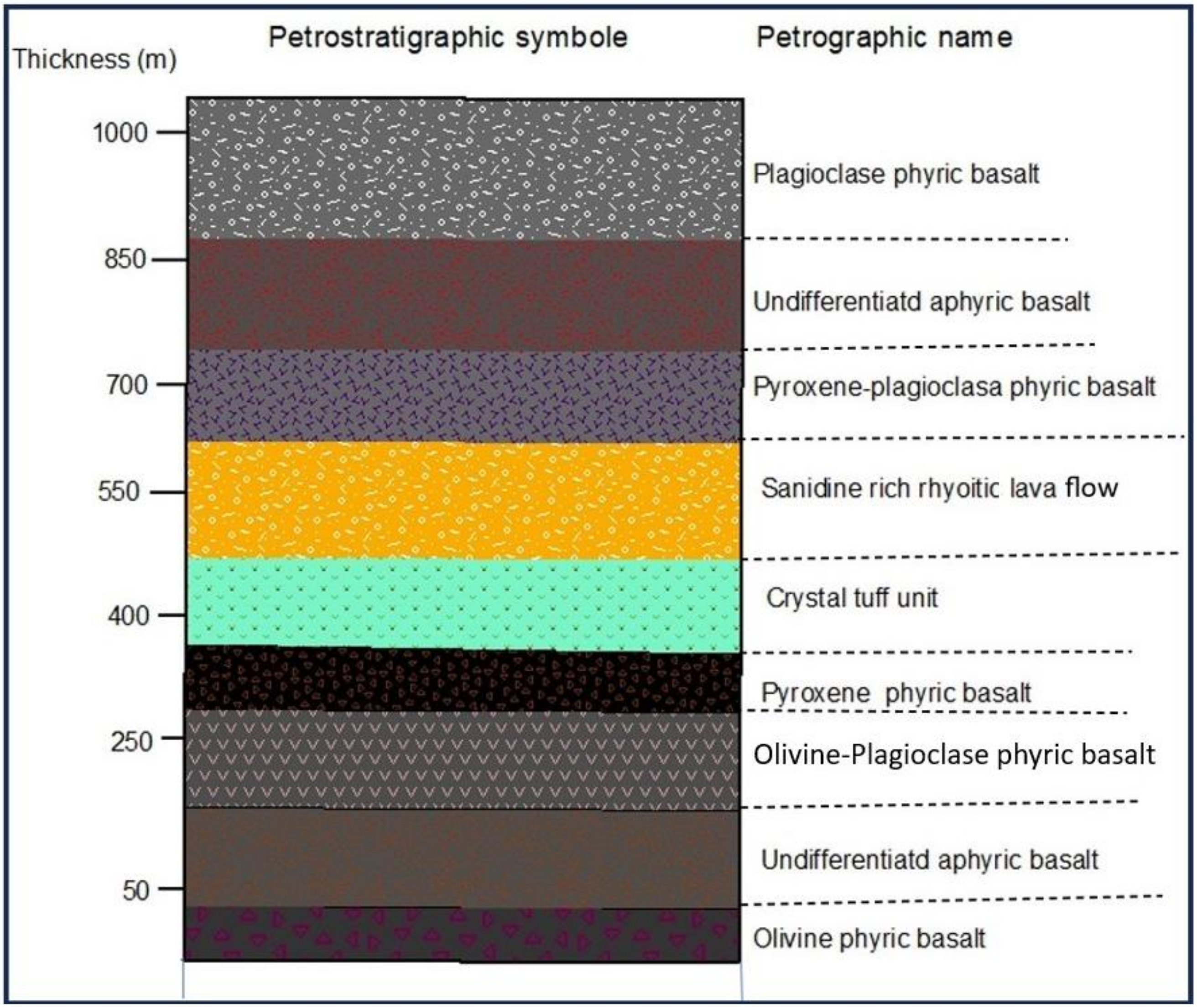

Figure 5. 4 Petrological stratigraphic succession of the Gishe Rabel area.

5.4. Inter litho- stratigraphic log section.

The Ayzoshamora, Lihot River, and Rabel-Goshiber sections are correlated stratigraphically shown in (Fig 5.5). The correlation lines aid in reconstructing the region's volcanic history by identifying units that were formed during the same depositional or volcanic events.

The three sections exhibit strong stratigraphic continuity, demonstrating that they belong to the same volcanic succession. Correlation of the lower basalt, pyroclastic deposits, rhyolite, and upper basalt indicates regionally extensive volcanic events. However, significant lateral thickness variations, particularly the northward thickening of rhyolite and pyroclastic deposits toward the Lihot River section, suggest proximity to silicic eruptive centers and the influence of paleotopography during deposition. The overall succession records a transition from early flood-basalt volcanism to explosive and silicic volcanism, followed by renewed mafic eruptions, a pattern characteristic of the volcanic evolution of the Gishe Rabel area.

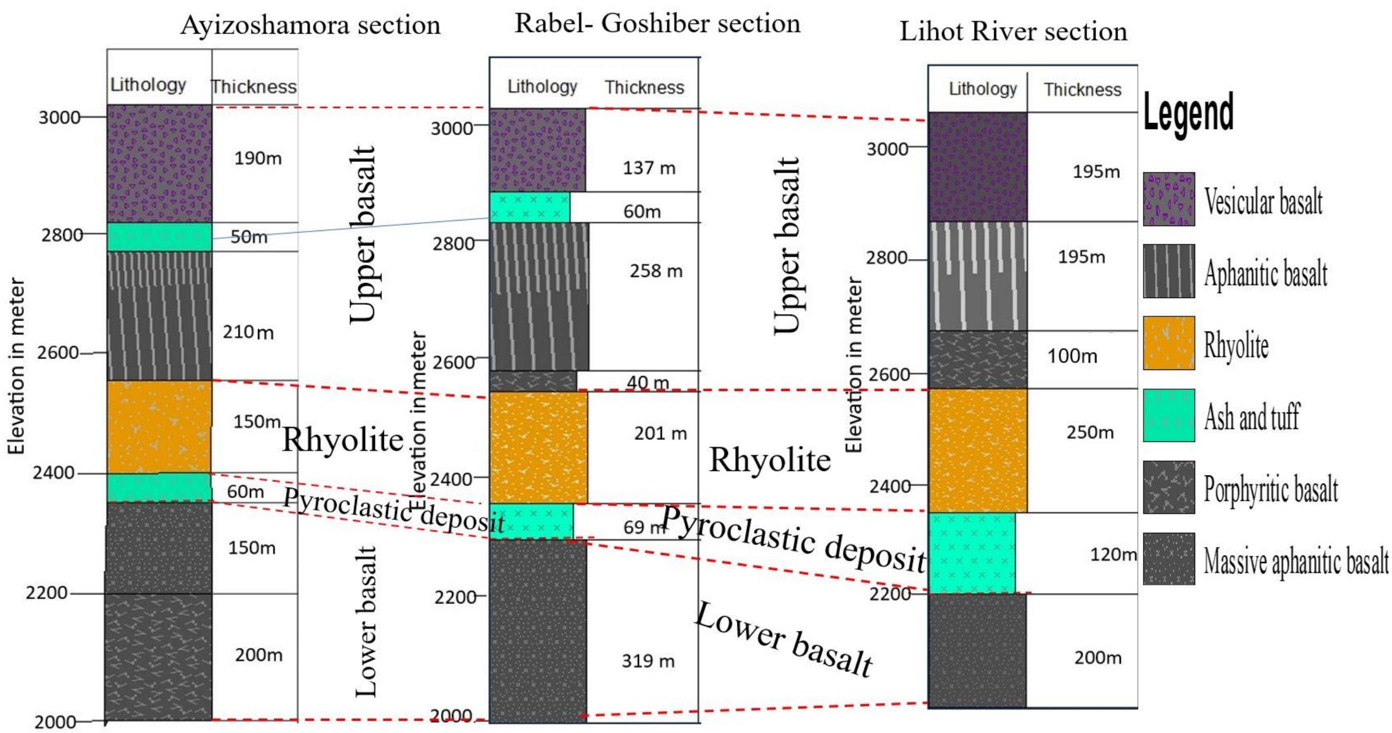

Figure 5. 5. Correlation of local stratigraphic log section

CHAPTER SIX

DISCUSSION

6.1. The thickness of the volcanic product

Flood-basalt eruptions have played a key role in the formation of the Ethiopian high plateau. Today, the plateau features alternating basaltic and rhyolitic units, creating rugged landscapes often cut by road networks. In many areas, the lowest basalt flows are poorly exposed, making it difficult to determine the total preserved thickness of the volcanic succession. To estimate this thickness, reliable data on the elevations of both the upper and lower boundaries of the basalt sequence are necessary.

In this study, we used the maximum observed thicknesses of each major unit at their best-exposed locations. In the Ayizoshamora area, the lower basalt section reaches about a thickness of 200 to 350 m, while the rhyolite unit in the type locality forms a roughly 250 m-thick sequence. In contrast, the Upper Basalt attains a preserved thickness of up to 500 m along the Lihot river section (Fig 5.1). Combining these measurements, we estimate the presently exposed volcanic pile to be approximately 1100 m thick.

6.2. Origin of flood basalt and Magma generation of the Ethiopian plateau

Detailed stratigraphic measurements from sites within the study area highlight three main observations. First, the areas of greatest present-day topographic elevation on the volcanic plateau rising roughly 3200 meters above base level (Fig 1.1) align with the rift shoulder along the plateau Afar rift escarpment, centered near 11°41′25″ N; 39°26′13″ E. This alignment suggests substantial uplift of the Ethiopian Plateau, which most likely occurred before the onset of volcanism (before ~30 Ma; Sembroni et al., 2016). Second, the volcanic succession reaches its maximum thickness near the Afar Plateau rift boundary. This pattern indicates that magma production was most intense beneath the central zone of Ethiopian uplift and that most fissure-fed eruption sites were located close to, or directly along, the Afar rift margin (Rooney et al., 2018). Third, the volcanic sequence becomes progressively thinner both (a) with increasing distance from the rift escarpment and (b) away from the elevated plateau around 11°47′25″ N; 39°26′13″ E. Along the plateau Afar margin, thickness decreases northward to approximately 500 meters in the Adigrat area (Beccaluva et al., 2009) and southward to about 1600 meters in the Bati area (Ukstins et al., 2002).

These observations support the idea that Ethiopian magmatism originated from a concentrated mantle upwelling, commonly interpreted as a mantle plume. Our findings build on earlier studies that have sought to connect the development of the Ethiopian flood basalt province to the emergence of the Afar mantle plume (Marty & Yirgu, 1996; Sembroni et al., 2016). Evidence suggests that this plume-related volcanic province has experienced variations in magmatic activity over time, spanning from approximately 45 million years ago to the present, likely influenced by changes in underlying magmatic plumbing systems (Rooney, 2017).

The northwestern Ethiopian flood basalts are divided into three geochemical groups based on variations in titanium and trace elements: the low-Ti (LT) western province near Simien Gondar, the southeastern High-Ti (HT1) province (included in this study), and the eastern High-Ti (HT2) province near Lalibela (Pik et al., 1998).

The LT basalts are tholeiitic in composition and contain relatively low TiO_2 (1–2.6 wt.%), lower Nb/La ratios (0.55–0.85), and comparatively higher SiO_2 (47–51 wt.%). They are depleted in incompatible trace elements such as Nb, Ta, Th, and Rb, with relative enrichment in Ba and Pb, and show stronger evidence of crustal contamination (Pik et al., 1999). In contrast, the HT2 basalts are more enriched in incompatible elements and display less crustal influence, while HT1 basalts generally have compositions that fall between the LT and HT2 types (Pik et al., 1999).

Petrographically, the low-Ti basalts are dominated by plagioclase phenocrysts and typically show intergranular to ophitic textures, with variable amounts of olivine (Beccaluva et al., 2009). Their groundmass consists mainly of plagioclase, interstitial clinopyroxene, and Fe–Ti oxides, consistent with a tholeiitic magma affinity (Pik et al., 1998).

Regional differences between the low-Ti (LT) and high-Ti (HT) lava suites have been widely used to investigate their magmatic sources through geochemical and isotopic studies (Pik et al., 1998, 1999; Beccaluva et al., 2009; Desta et al., 2014; Kieffer et al., 2004; Natali et al., 2016). The HT lavas are generally interpreted as products of the melting of the Afar mantle plume head, whereas the origin of the LT lavas remains debated(Pik et al., 1999; Kieffer et al., 2004; Beccaluva et al., 2009). Some studies suggest that LT magmas formed through shallow fractional crystallization, later evolving through a two-stage assimilation and fractional crystallization (AFC) process involving both lower and upper crustal components (Pik et al., 1998, 1999).

Geochemical trends further indicate that HT2 parent magmas were richer in MgO and FeO and poorer in SiO_2 compared to LT parent magmas. The absence of primitive basalts in the HT1 suite limits detailed evaluation of its differentiation history, although HT1 compositions appear more similar to LT than to HT2 lavas. Despite these similarities, the precise origin of LT magmas remains uncertain, largely because whole-rock geochemistry alone cannot tightly constrain AFC processes (Pik et al., 1998).

The present study focuses on the HT1 province, examining the petrography and volcanic stratigraphy of individual lava flows to better understand magma lithosphere interactions and the structure of the magmatic plumbing system. Overall, the Ethiopian continental flood basalts are thought to have formed through a combination of processes: reduced solidus temperatures in plume-metasomatized mantle, heat input from plume-related buoyancy that elevated the regional geotherm, and decompression melting of upwelling mantle material (Beccaluva et al., 2009). The widespread fissural volcanism, plateau uplift, and development of the Afar and Main Ethiopian Rift systems are therefore linked to mantle plume upwelling, potentially connected to the larger African superplume(Pik et al., 1998; Kieffer et al., 2004; Beccaluva et al., 2009)

6.3. The eruption of Ethiopian volcanism

The current understanding of magmatism in East Africa shows that magmatism pulses occur after the main flood basalt events (~45-28 Ma) end, leading to shield building and rift-related volcanism (Tamirat et al., 2021a). The age of the lava flows (20-10 Ma) suggests they are linked to periods of extension (Wolfenden, 2003). Although these younger lavas may appear as stratiform sheet flows, their magmatic origin, both petrologically and geochemically, differs from the initial flood basalt pulses. (Rooney, 2017). Therefore, they are classified as a separate sequence from the Oligocene flood basalts (Oligocene traps phase). A whole-rock Rb-Sr isochron on intercalated rhyolites within the lower basalt dates to about 20.7 Ma (Ayalew, 2011), indicating an earlier onset of volcanism. Geochronologic data indicate that volcanic activity in the region commenced during the early Miocene, characterized by a large release of flood basalts and rhyolites (the Oligocene traps phase, 31-~28 Ma). The volcanic record in the area features intermittent pulses of basalt flows, capped by silicic volcanic layers.

Extensive intervals between succeeding flows, both within and between specific formations, are evidenced by the common development of paleosols and alteration surfaces, implying extensive eruption time spans. This Miocene activity is often defined as a large basaltic event followed by a period of quiescence or silicic activity, corresponding with the breakup and merging of regional units (Steiner et al., 2022). Yet, this long period, suggesting pulsed magma eruption, has resulted in the Ethiopian pile building up to the same order of thickness as other major flood basalt provinces (Marzoli et al., 1999).

6.4. Eruption of silicic volcanism

Silicic volcanics are a significant component of many flood basalt provinces (Halder et al., 2021). Thick silicic volcanics exist both in the flood basalts of Ethiopia and northern Kenya, and in subsequent younger lavas (Rooney, 2017; Steiner et al., 2022). Within the volcanic sequence, silicic materials appear either as thin ash layers sandwiched between basaltic flows or as larger, stand-alone eruptive units whose volumes can rival those of the mafic lavas. The rhyolitic ignimbrites and lavas, in particular, form cooling units that can be traced for many kilometers, pointing to eruption from extensive fissure systems. Silicic rocks are widespread throughout the study area and often occur directly above or interlayered with basaltic flows, suggesting that silicic eruptions took place intermittently during the volcanic history. Excluding the smaller interlayered rhyolites, the major felsic units make up roughly 20% of the entire volcanic pile by volume (Fig. 3.1). The presence of these substantial silicic caps a top the lower basalt succession provides important clues about the processes that generated silicic magmas in the region.

The dataset presented (20-10 Ma) suggests that these younger lavas are related to extension (Rooney, 2017). This allows for the shallow ponding of mafic magma, followed by the production of silicic magma, presumably via fractional crystallization, and, eventually, periodic eruptions. This is demonstrated by the presence of vast rhyolites in the lava sequence, which indicates the progressive evolution of magma over time. This implies that the frequency and volumetric importance of silicic volcanism rose gradually in younger lavas.

6.5. Litho-stratigraphic evolution and regional correlation

The Cenozoic volcanics in the area consist of three lithology units, separated from each other by erosional and/or paleosol and hiatuses. From oldest to youngest, these are: (i) lower basalt, (ii) rhyolite formation, (iii) upper basalt.

The Oligocene to Miocene volcanics are represented by Alajae basalt, Tarmaber-Megezez basalt, and Adami basalt (Belay et al., 2009). The Alajae basalt and the Molale trachyte and ignimbrite appear to be associated with the same stage of volcanism, in which volcanism commenced with the eruption of Alajae basalt and was subsequently followed by Molale trachyte and ignimbrite (Belay et al., 2009). Zanettin (1978) Grouped both the Alajae and Molale into the same litho-stratigraphic divisions and referred to it as the Alajae-Molale sequence, which was later named the Alajae formation (Tefera et al., 1996). The Tarmaber-Megezez basalt is characterized by hills and ridges forming a domical shape, which is typical of a central volcano (Belay et al., 2009). By the above discussion, the lower basalt in the study area is a shield volcano, and central type eruption volcanism is connected with the Tarmaber-Megezez basalt. This is because the lower basalt in my study area is characterized by hills and ridges, creating a domical shape.

The Miocene activity is typically dated as a significant basaltic event followed by a period of quiescence or silicic activity, consistent with the breakdown and merging of regional units (Rooney, 2017). The Alajae-Molale sequence comprised basaltic flows and silicic volcanics made up of alkaline rhyolites and comenditic ignimbrites (Justin-Visentin et al., 1974). Wolfenden, (2003) related to those silicic volcanics exposed west of the marginal graben along the escarpment to be part of Kemise formation. The presence of a dike in rhyolite formation is permissive of a period of crustal extension and rifting. A rhyolite from west of the Afar escarpment has been dated by Wolfenden, (2003), Who reported an age of 25.9 ± 0.16 Ma. This age is interpreted as the initiation of extension and rifting on the Western Afar Margin related to Kemise rhyolite (Belay et al., 2009). Therefore, the eruption of the rhyolite in the study area is related in time and space to the evolution of the Western Afar Margin. So, the rhyolite formation in the study area correlates with the Kemise rhyolite formation.

Dogiya basalt consists of 50 to 150 m interbedded aphanitic basalt, plagioclase-phyric basalt, vesicular basalt, and scoriaceous basalt, which is unconformably underlain by the Kemise rhyolitic formation (Belay et al., 2009). The Dogiya basalt may be correlatable either with the Bercha formation or the Aneno formations of Wolfenden (2003), who reported an age of 7.12 ± 0.04 Ma and 15.9 ± 0.5 Ma for the Bercha and Aneno formations, respectively. The eruption of the rhyolitic(silicic) volcanics is followed by the extrusion of the Upper Miocene upper basalt. The upper basalt in my study area is unconformably overlying the rhyolitic formation and interbedded with aphanatic basalt, plagioclase phyric basalt, and vesicular basalt. The Upper basalt of the study area correlated with the upper Miocene Dogiya basalt (Belay et al., 2009).

6.6. Petrographic discussion

Petrographic examination of the samples shows a wide range of mineral compositions and textures throughout the volcanic sequence. The lava flows contain minerals that occur at different scales: phenocrysts, microphenocrysts, and groundmass phases, each present in varying proportions. In the basaltic units, the dominant phenocrysts include clinopyroxene (augite), plagioclase, olivine, and Fe-Ti oxides. A noticeable upward increase in plagioclase content is also evident within the stratigraphy. In contrast, the felsic units, such as rhyolites and accompanying pyroclastic deposits, are characterized by sanidine (K-feldspar) and quartz microphenocrysts embedded within a largely glassy groundmass (Fig. 4.4). To evaluate the magmatic processes connected with the volcanic sequence based on their stratigraphic position, some criteria that regulate the crystallization of mineral phases in basaltic and felsic rocks during eruption must be assessed. These criteria are: (1) the composition of the parent magma, (2) pressure or depth of crystallization, and (3) the amount of volatiles in the magma (Müntener et al., 2001; Feig et al., 2006; Krans et al., 2018). The mineral assemblages of Ol + Cpx in the basaltic lavas suggests that fractional crystallization 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 crystal fractionation occurred at a relatively shallow levels in the upper crust (Krans et al., 2018). These crystallization phases of different minerals within lava flows play a crucial role in understanding the behavior of the magmatic plumbing system in the study area. It is also known that an increase in water concentration in liquid magma changes the mineral crystallization sequence or delays the order of crystallization (Müntener 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 (Feig et al., 2006). Conversely, in a relatively dry magma, plagioclase minerals preferentially crystallize over clinopyroxene crystals at lower pressures (<5 kbar), while clinopyroxene and olivine minerals crystallize at high pressure (10–20 kbar) at the expense of plagioclase(Krans et al., 2018). Furthermore, according to Krans et al. (2018), the mechanism and order of crystallization along the liquid line of descent are determined by the parental magma's composition. This observation is supported by Natali et al. (2011), who have described Ol + Plag in Low Ti lavas, and Ol + Cpx phenocrysts in High Ti 1 and High Ti 2 lavas.

The Afar mantle plume induces deep decompression melting of magma (Pik et al., 1998; Beccaluva et al., 2009; Desta et al., 2014; Natali et al., 2016), which then undergoes fractionation through many crustal strata, resulting in silica-rich compositions. This process produces both explosive and continuous eruptions of basaltic and rhyolitic lavas (Fig 6.1).

Large olivine phenocrysts can be found because the magma in the magma chamber beneath the Earth's surface cooled and fractionated at a slower, deeper level before an eruption. Olivine phenocrysts are hence indicative of the existence of sufficient time to equilibrate with the refractory melt material at a specific mantle level, primarily for the mafic and ultramafic alkali basaltic rocks (Ayalew et al., 2021). Another clue to the medium and shallow crustal level cooling and fractionation is the growth of plagioclase and pyroxene phenocrysts. Petrographic analysis shows that opaque or Fe-Ti oxide phenocrysts are little to absent from basaltic rocks; instead, they have existed as a groundmass in the rock sample's bodies. This occurrence indicates that titanomagnetite mineral fractionation has not occurred in the basaltic rocks.

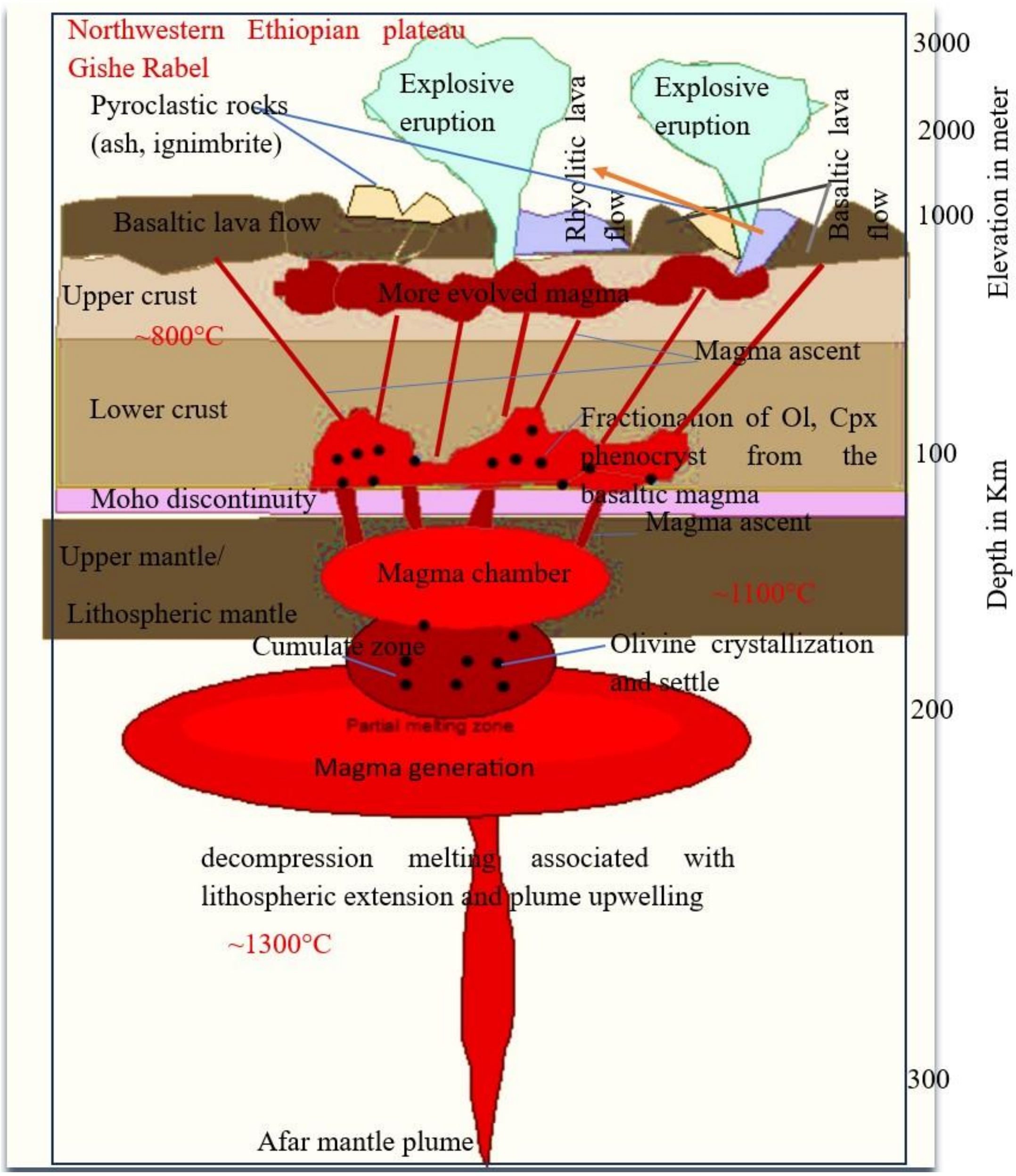

Figure 6.1. Magmatic eruption model of the Gishe Rabel area in relation to the northwestern Ethiopian plateau (this magma evolution model is developed by the author/myself based on the petrographic characteristics of the volcanic rock in the study area and comprehensive reviewing and synthesis of previous studies such as,(Mohr, 1983; Robert White, 1989; Marty & Gezahegn, 1996; Pik et al., 1998; ; Sembroni et al., 2016; Rooney & Yirgu, 2018; Ayalew et al., 2021; Belachew et al., 2021).

6.7. Petrographic evolution of volcanic sequence

Three distinct groupings or divisions are suggested by the petrographic research reported in this study: 1) the lower flood basalt group, which primarily contains Cpx, Ol and Ol-Plag phenocryst phases; 2) the middle felsic group, which has glassy groundmass and Kfs (san) phenocrysts; and 3) the upper flood basalt group, which has a greater proportion of Plag micro-phenocrysts but no Ol phenocrysts or small Cpx cumulates. The thick volcanic pile's magma features are addressed in the following ways using these unique petrographic findings.

6.7.1. Lower basalt series

In the lower basalt sequence, the most common phenocryst phases include clinopyroxene (augite), which often occurs as glomerocrysts, along with Ol, Cpx and Cpx-rich phenocrysts distributed throughout the stratigraphy. Notably, plagioclase is absent in both the Cpx-phyric and the Ol phyric basalt flows. The dominance of clinopyroxene together with opaque mineral assemblages provides insight into the early evolution of these lavas, suggesting that they crystallized under relatively high-pressure conditions consistent with mid- to lower-crustal depths (Belachew et al., 2021).

Ethiopian high Ti oxide basalts are interpreted to have been generated from the melting of a mantle plume head (Pik et al., 1999). High concentrations of these opaque oxides are found in the ground mass, phenocrysts, and microphenocrysts in the lower basalt flow of the study area stratigraphic section. These abundances indicate that the magmas originated from the partial melting of deep mantle material, and that the initial melts from the impinging plume head may have migrated upward through the sub-continental lithospheric mantle due to their buoyancy until they reached the crust-mantle boundary, where they could accumulate and fractionate.

Rooney et al. (2017), reported that the calculated equilibrium pressures correspond to conditions near the crust–mantle boundary, indicating that orthopyroxene- and clinopyroxene-rich cumulates are genetically linked to low-Ti (LT) flood basalt magmatism. The Cpx (Aug) phyric fluxes seen in this study region are based on this scenario. As a result, augite cumulates in this research region are thought to have formed from stalled magmas in the lower to intermediate crust. A magmatic plumbing system of Cpx (Aug) phyric basalt from stalled magmas in the mid to lower crust (Fig 6.2). The flow layers are presented from bottom to top as olivine phyric basalt, paleosol, undifferentiated aphyric basalt, plagioclase-olivine phyric basalt, and pyroxene (Cpx) phyric basalt. According to Belachew et al. (2021)The occurrence of weathering horizons (paleosols) within the lower basalt sequence indicates intervals of inactivity or breaks in volcanic eruptions during the formation of the lower basalts. These layers serve as clear markers separating successive lava flows in the lower flood basalt succession.

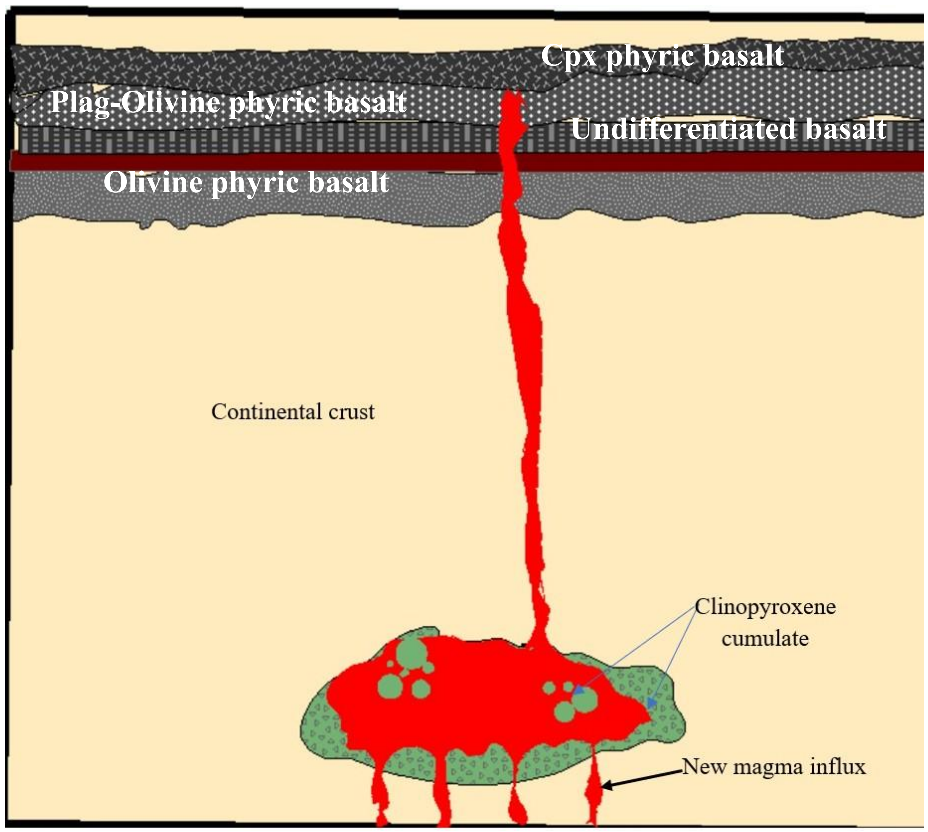

Figure 6. 2 Magmatic conduit system of pyroxene phyric basalt, modified from (Belachew et al., 2021)

According to Beccaluva et al. (2009), The earliest lava flows tend to be more primitive and are supplied by relatively small magma feeders, especially when they appear alongside weathered horizons (paleosols) formed during pauses in activity. In the study area, the lower basaltic phase, particularly along the deeply incised Lihot River, begins with olivine-aphyric basalt flows. These flows are interlayered with thin red paleosols, typically only 25–40 cm thick. Such features suggest that the early magmatic system was receiving a reduced magma supply, producing rapid but low-volume eruptions followed by slower cooling periods. This pattern points to a significant decrease in magma flux during the earliest stages of volcanism (Belachew et al., 2021).

The variation in modal mineralogy observed in the lower basalt flows in this study supports the interpretation that separate feeder systems were active during the early stages of the magmatic plumbing system's development. The upper sections of the lower basalt group are marked by columnar lava flows as well as non-columnar, aphyric flows. This pattern further indicates that the supply or volume of magma did not steadily increase and may have gradually declined toward the upper, shallower levels. Despite this, the eruptions occurred at relatively high extrusion rates (Belachew et al., 2021).

6.7.2. The rhyolitic unit

This study was identified felsic units with an increase in Kfs (san)-rich rhyolitic flows underlying pyroclastic, and the lower flood basalt series in the middle section of the volcanic stratigraphy. The highly welded rhyolitic tuff that terminates the underlying lower basaltic flows and marks the onset of rhyolitic volcanism with larger amounts of glassy groundmass. The lower flow of the rhyolite unit is also suggested by the predominance of sanidine, and fractionation of the magmas in the shallow crustal reservoir would be facilitated by a decrease in magma recharge events (Fig 6.3). Columnar jointing at the top of this unit indicates that the flow unit's volumes are likewise decreasing(Hetényi et al., 2012).

The geochemical findings of Ayalew et al. (2002), also suggested that these felsic units formed from fractional crystallization of the parental basaltic magma. Furthermore, shallow fractionation phases show that shallow reservoirs or shallow magmatic plumbing systems are involved (Krans et al., 2018).

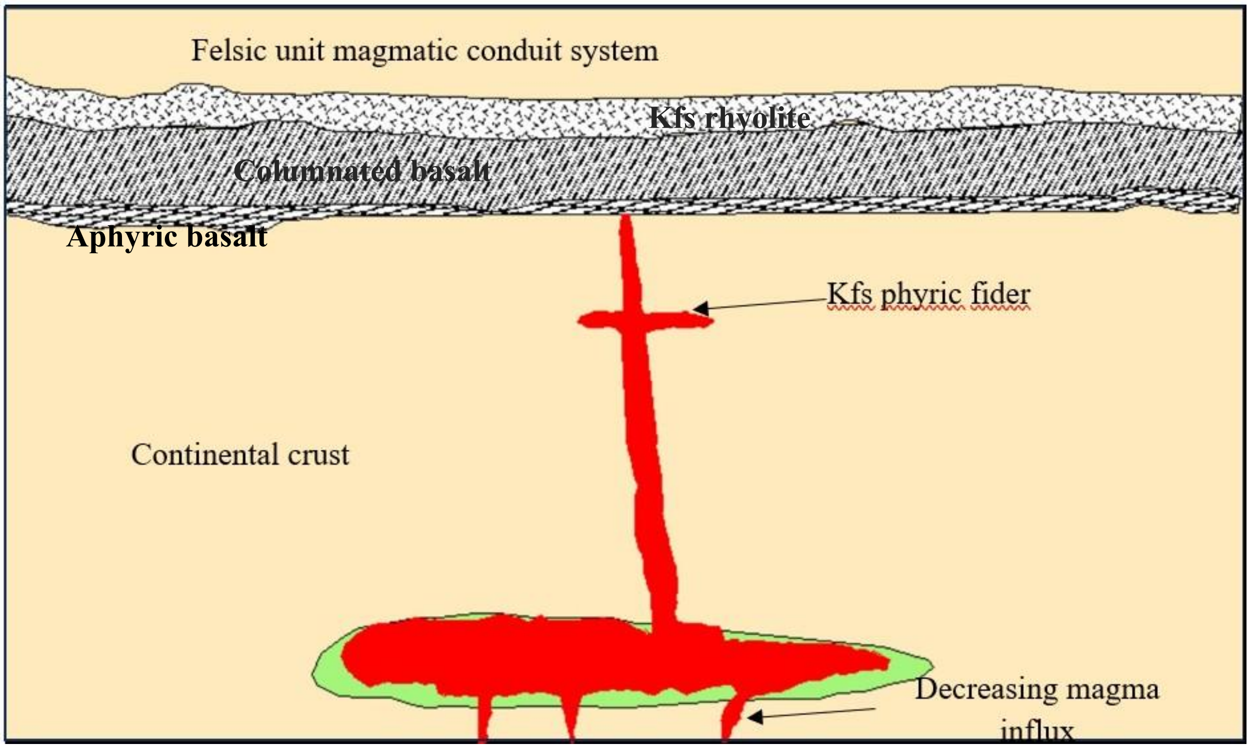

Figure 6. 3 Fractionation of the rhyolitic volcanic unit eruptive model, modified from (Belachew et al., 2021)

6.7.3. Upper basalt series

The upper basaltic flows in the Wayit River region are predominantly aphyric to weakly vesicular and display well-developed columnar jointing, indicative of contraction during cooling. Upper basaltic flow represents the flood basalt termination in the volcanic series of the Rabel area, which lies on the felsic volcanic deposits. The mineralogical assemblage of Plag+Cpx in these flows supports the idea that fractionation occurred at a shallow to mid-level in the upper crust (Pik et al., 1999). Plagioclase microphenocrysts predominate in this basaltic sequence. Since shallow crystal fractionation of the magmas residing in the lithosphere occurs at low pressure, and is characterized by an increase in the modal proportion of plagioclase microphenocrysts (Krans et al., 2018). These flows indicate the recharging of new primitive magma into the shallow plumbing system with significantly reduced magma volumes (Fig 6.4). Contractional cooling, or columnar jointing, occurs when mechanical tension accumulates as the lava cools and compresses, creating the network of cracks that define the column borders (Hetényi et al., 2012). According to Hetényi et al. (2012), Columnar jointing is invariably linked to a drop in magma volume, which causes tensional forces inside the body. From this point of view, the lower magmatic fluxing at the shallow plumbing system seems to be the source of the upper basaltic flows. Vesicles toward the top of the volcanic stratigraphic column have further implications for a shallower magma production inflow (Pik et al., 1998). This suggests that there is a decrease in magma recharge into the plumbing system that produces the plagioclase microphenocryst flood basalt unit (Belachew et al., 2021). Less dense vesiculated flow typically caps the top of the upper basaltic section. They show how the Rabel area's flood basalts ended in vesicular lava flows. They lack Cpx-cumulates and Ol-megacrysts and are dominated by plagioclase microphenocrysts. Magma stagnated and fractionated at the shallow crustal level, as evidenced by these plagioclase-rich flows.

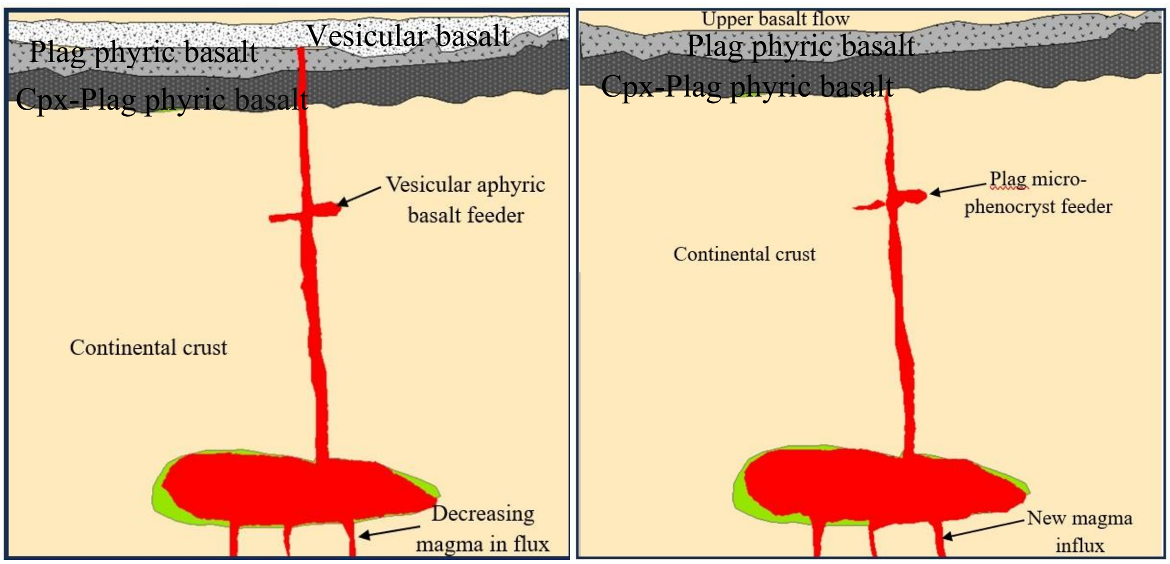

Figure 6. 4 Upper basalt flow eruptive flow model, modified from (Belachew et al., 2021).

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1. Conclusion

The key findings of this study are summarized in this section. These conclusions are based on insights gathered from detailed field investigations, systematic stratigraphic sampling, petrographic examinations, and lithostratigraphic interpretations.

1. Stratigraphically, the volcanic rocks in the study area are organized from bottom to top into three main units: the lower basaltic unit, the rhyolitic flow, and the upper basalt. Between these dominant, competent, and hard rock layers, there are also significant amounts of felsic pyroclastic deposits, mainly tuff and ash, that were taken into account in the analysis.
2. Petrographic studies show that the basaltic rocks in the area are primarily composed of olivine (mainly Mg-rich forsterite), clinopyroxene (augite), plagioclase, and Fe-Ti oxides. The groundmass of the basalt displays an inverse relationship, being dominated by Fe-Ti oxides, with smaller amounts of olivine, clinopyroxene, and plagioclase. The lower basaltic series is characterized by abundant clinopyroxene and olivine phenocrysts. This mineral assemblage indicates that the basaltic flows were supplied by magmas that underwent significant fractionation at mid- to deep-crustal levels. It also suggests a continuous influx of fresh, primitive magma during the eruption of the lower flow units. The felsic rhyolitic units in the Rabel area are rich in sanidine, suggesting a reduced magmatic influx and indicating that these rocks were supplied by a shallow-level magma chamber. Their mineralogy reflects advanced fractionation processes occurring within the upper crust. The upper basaltic flows are characterized by aphyric basaltic agglomerates, suggesting that eruptions shifted from high-volume to lower-magnitude lava flows. Over time, the magma plumbing system became shallower, leading to an increase in plagioclase microphenocrysts as the magma settled in the upper crust. The absence of clinopyroxene cumulates and olivine phenocrysts further supports a shallow magma reservoir.

7.2. Recommendation

1. This study is based on field observations, stratigraphic logging, geological mapping, and petrographic analysis. Still, it lacks detailed major and trace element geochemical data that are essential for fully understanding the petrogenesis of the rocks. Therefore, additional comprehensive geochemical analyses and mineral chemistry studies are highly recommended to better constrain the magmatic processes involved.
2. The stratigraphic log in this study is based on detailed field observations and petrographic analysis. However, to better define and understand the stratigraphic sequence, accurate age determinations are necessary. Chronostratigraphic analyses such as Rb–Sr, K–Ar, and Sm–Nd isotopic dating are recommended to more precisely establish the timing and development of the rock units.
3. Finally, this study recommends that future researchers focus more on assessing and exploring the areas. During field traverses, coal occurrences were observed, especially at the contact between the lower basalt and the overlying rhyolite unit. These observations emphasize the need for more detailed investigation.

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APPENDIXES

1. Structural data measured in the field and above in chapter three, used to construct rose diagrams, are all included here in tabular form

Type of Structure	GPS coordination		Host rock	Altitude/orientation	
	Easting	Northing		Strike	Dip-plug
Fracture and Vein	39.4898	10.5014	Pyroclastic	N315W	N419E
	39.6372	10.4953	Aphanitic basalt	N40E	N320W
	39.62468	10.52015	Rhyolite	N10E	N280W
Columnar Joint	39.51556	10.52083	Rhyolite	N330W	N84E
	39.51139	10.54124	Aphanitic basalt	N48E	N326W

2. The GPS reading of all samples collected during fieldwork

Sample Code	Easting	Northing	Elevation
A11	39.51139	10.54123	2032
A12	39.51389	10.58761	2140
A13	39.55622	10.555	2227
A45	39.56735	10.58441	2576
A15	39.51556	10.52083	2493
A16	39.49423	10.59157	2805
A47	39.51761	10.49815	2202
A41	39.50817	10.51482	2196
A42	39.69139	10.52124	2932
A43	39.675	10.55562	3000
A21	39.45594	10.55309	2000
A22	39.495	10.55279	2185
A23	39.58924	10.51543	2950
A24	39.68468	10.53015	2737
R24	39.68713	10.485	2623
A28	39.56224	10.472	2214
A29	39.65725	10.46853	2286
A31	39.58799	10.55411	2900
A32	39.60167	10.56661	2760
A33	39.58516	10.56065	2096
Aw2	39.58985	10.55232	2917
A34	39.57722	10.55327	2493
A44	39.58572	10.55834	2487
A37	39.577	10.56147	2106
Mw2	39.717	10.504	2058

3. Petrographic feature of rock samples

Sample code,	**Lithostratigraphic unit**	**Texture**	**Distinguishable Mineral Constituent**	**Dominant phases in phenocrysts**	**Ground Mass Texture**
A11,	Lower Basalt	Intergranular	Cpx,	Cpx~100%	Opaque, plag, Cpx
A12	Lower Basalt	Porphyritic, cumulophyric	Cpx, Plg	Cpx (~80%), Plag (20%)	Cpx, plag, opaque
A13	Lower basalt	Aphanitic, Intergranular	Plg, Opaque Minerals	Plg (~95%)	Plag, opaque, pyroxene
A45	Rhyolitic Lava Flow	Hypocrystalline and Sieve textured Plag	Alkaline feldspar(san) and Opaque Minerals	Sandine~85%	Felty, vitric
A15	Rhyolitic Lava flow	Hypocrystalline, Vitrophyre	Sandine, opaque	Sandine~70%	Vitric, perlitic fracture
A16	Upper Basalt	Lath texture	Plg,	Microphenocryst of plagioclase	Plag, opaque
A47	Lower basalt	Reaction rim texture	Olivine	Olivine~100%	Plage, Opaque
A41	Lower basalt	Hypocrystalline, Vitrophyre	Alkali-Feldspar, Qtz	Afelds (60%), Qtz (50%)	Vitric
A42	Upper Basalt	Intergrowth micro texture	Plg,	Plg (100%), olv, px,	Plg, opaque, Cpx
A43	Upper Basalt	Hypocrystalline, Vesicular	Plagioclase, opaque	Plagioclase ~90%	Vitric
A21	Lower basalt	Rim texture of cpx	Cpx, plag	Cpx~85%, ~15% of plag	Plage, opaque, pyroxene
A22	Lower basalt	Aphanitic	Olivine, Plg, Opaque Minerals	Ol~45%, plag~35% Opaque Minerals	Plage, Ol, opaque
A23	Upper Basalt	Porphyritic, Cumulophyric	Plg, Olv, Cpx, Opaque Minerals	Plg (~60%)	Felty
A24	Upper Basalt	Hypocrystalline, Vitrophyre	Plag	Plag (100%)	Plag, opaque, pyroxene
R24	Rhyolitic lava flow	hypocrystalline,	Sandine	San~100%	Glassy
A28	Lower basalt	Sieve texture of plagioclase	Plg, Opaque Minerals	Aphyric	Plage, opaque

A29	Lower basalt	Porphyritic, rim texture, intergrowth	Olivine, Opaque Minerals, cpx	Olivine (~85%), cpx~5%	Opaque, cpx, olivine
A31	Upper Basalt	Aphanitic, Intergranular	Plg, Opaque Minerals	Plag, Opaque	Felty, vitric
A32	Upper Basalt	Porphyritic	Plg, Opaque Minerals	Plag (~85%)	Felty, vitric, Intergranular
A33	Lower basalt	Intergrowth micro texture	Cpx	Cpx~95%	Plag, opaque, cpx
Aw2	Upper basalt	Porphyritic, Cumulophyric	Plg, pyroxene, Opaque	Plag (~90%)	Plag, pyroxene
A34	Rhyolite lava flow	Hypocrystaline	Sandine, lithic	San (90%)	Glassy
A44	Rhyolitic lava flow	Hypocrystalline, sieve texture of san	Sandine, opaque	San~95%	Sandine
A37	Lower basalt	Aphanitic	Olivine, plag, opaque	Olivine~55%, Plag~35%	Plage, opaque, olivine, cpx
A25	Upper basalt	Aphanatic, Intergranular	Plag, Opaque minerals	Plag~95%	Plag, opaque

NB. The proportion of the phenocryst that reflect in this table is from the abundance of phenocryst not the entire petrographic view.