



Addis Ababa University  
አዲስ አበባ ዩኒቨርሲቲ



SEEK WISDOM, ELEVATE YOUR INTELLECT AND SERVE HUMANITY !

**Geology, Petrography and Stratigraphy of volcanic products around Worabe, Central Main Ethiopian rift.**

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



**By: Nuredin Shemsedin (Petrology Stream, AAU)**

**GSR/0630/15**

**Advisor: Prof. Dereje Ayalew**

**Co-Advisor: Prof. Gezahegn Yirgu**

**June 2024**

**Declaration for Originality**

This is to certify that the thesis prepared by Nuredin Shemsedin, entitled: “Geology, Petrography and Stratigraphy of volcanic products around Worabe, Central Main Ethiopian rift” is compiled under supervision of Prof. Dereje Ayalew and Prof. Gezahegn Yirgu; submitted in partial fulfillment of the requirements for the Masters of Science in Geological Sciences (Petrology). It is complied with Addis Ababa University's rules and regulations and, it satisfies accepted requirement in terms of originality and quality. I further declare that this work is not presented or submitted to any other university or institution. All secondary information sources are properly referenced and acknowledged.

**Nuredin Shemsedin (MSc candidate)**

**Signature** \_\_\_\_\_ **Date** \_\_\_\_\_

**Signed by the Examining Committee:**

<b>Examiners</b>	<b>Signature</b>	<b>Date</b>
_____	_____	_____
_____	_____	_____

<b>Advisor</b> <b><u>Prof. Dereje Ayalew</u></b>	_____	_____
---	-------	-------

<b>Co-Advisor</b> <b><u>Prof. Gezahegn Yirgu</u></b>	_____	_____
---	-------	-------

---

**Graduate Program Coordinator**

---

**Chair of Department**

## Abstract

In this paper petrographic, Structural, and stratigraphic investigation of volcanic rocks in the central main Ethiopian rift is presented. Normal faults and several rivers (mainly Dijo River) play a significant role in exposing the lithologic units and in controlling the alteration processes observed in the area. This investigation has done with in the central Ethiopian regional state, specifically around Worabe town in Silte zone, about 170 kilometers south of Addis Ababa (capital city of Ethiopia). This investigation aims to detail the area's lithostratigraphy through fieldwork, petrographic analysis, and structural analysis using field observations and satellite imagery. There are five volcanic lithostratigraphic units (Plateau basalt (300m), Welded tuff (250m), Unwelded to poorly welded tuff (270m), Rift floor basalt and associated scoria (80m), Rhyolitic lava dome and Obsidian with felsic pyroclasts (280m)), which are part of quaternary volcanic products and one sedimentary unit (Volcaniclastic sediments(30m)) are presented in the composite stratigraphic section. The pyroclastic fall deposit (Unwelded to poorly welded tuff) is the dominant product with interlayered pyroclastic flow. The rift floor basalt covers smallest area among volcanic unit in this area. The wider area is covered by felsic volcanic products. A total of 19 samples from the four stratigraphic units (plateau basalt, welded tuff, rift floor basalt and rhyolite) are studied by using a petrographic microscope. Petrographic analysis reveals unique mineral compositions and textures, indicative of different volcanic processes and post-depositional alterations. Furthermore, the study highlights structural controls on volcanic activity, alteration processes, and the influence of geological structures on eruption patterns. To have a better understanding of the petrogenetic and magma plumbing systems, further research is required.

## Table of Contents

Abstract .....	i
List of figures .....	iv
List of Tables .....	v
Chapter one .....	1
1. Introduction.....	1
1.1 Overview of the research area.....	2
1.2.1. Physiography.....	4
1.2.2 Climate and Drainage pattern of the research area. ....	4
1.3 Statement of a problem .....	5
1.4. Objective .....	5
1.4.1 General Objective .....	5
1.4.2 Specific Objectives .....	5
1.5 Significance of Research.....	6
1.5.1 Expected Output.....	6
1.6 Methods used in the research .....	6
1.7. Previous works.....	7
Chapter Two.....	10
2. Regional geology and geological setting .....	10
2.1. Introduction.....	10
2.2. Background.....	11
2.2.1 Geologic evolution of Silte Butajira Debrezeyt fault zone .....	15
2.3 Stratigraphy volcanoes related to main Ethiopian rift.....	16
2.4. Lithologies of the western part of the central main Ethiopian rift .....	18
2.4.1. Pre - Rift Volcanics.....	18
2.4.2 Late Tertiary Volcanics.....	19
2.4.3. Quaternary Volcanics /Wonji Group .....	21
2.4.4. Quaternary Sediments .....	24
Chapter Three.....	25
3. Geology of the research area.....	25
3.1 Introduction.....	25

3.2. Lithologic descriptions.....	26
3.2.1. Plateau basalt. ....	26
3.2.2. Highly welded tuff (Worabe ignimbrite) .....	27
3.2.3. Pyroclastic fall and flow (Unwelded to poorly welded tuff).....	30
3.2.4. Rift floor basalt and associated Scoria .....	34
3.2.5. Rhyolitic lava dome and Obsidian .....	37
3.2.6. Volcaniclastic sediments .....	38
3.3. Geological structural features. ....	40
3.3.1. Primary Structures.....	41
3.3.2. Secondary Structures.....	43
Chapter four .....	48
4. Petrographic analysis of selected samples .....	48
4.1. Introduction.....	48
4.2. Analyses result of plateau basalt. ....	48
4.3. Petrographic analysis of samples from highly welded tuff unit.....	50
4.3.1. Highly welded tuff .....	50
4.4. Petrographic analysis of samples from rift floor basalt. ....	52
4.5. Petrographic analysis of samples from Rhyolitic units.....	54
Chapter five.....	55
5. Discussion of results and summary.....	55
Chapter six .....	59
6. Conclusion .....	59
7. Acknowledgment .....	59
References.....	60
Appendix I: .....	63
Appendix II: Petrographic analysis of samples from all units. ....	65

## List of figures

Fig 1.1: Tectonic setting of the Main Ethiopian Rift within the East African Rift system (retrieved from <a href="https://www.researchgate.net/figure/Tectonic-setting-of-the-Main-Ethiopian-Rift-MER-and-Afar-Depression-modifi-ed-from_fig1_275720465">https://www.researchgate.net/figure/Tectonic-setting-of-the-Main-Ethiopian-Rift-MER-and-Afar-Depression-modifi-ed-from_fig1_275720465</a> , on May 21 .....	2
Fig 1.2: Hill shade color map of the Central Main Ethiopian Rift within Ethiopian volcanics with broken rectangle showing the study area figure b (a) and Location and accessibility map of the research area (b).3	3
Fig 1.3: Physiographic map of the research area (DEM).....	4
Table1.1 Shows Methods and activities used in this research. ....	7
Fig 2.1: Map of East Africa shows active volcanoes as red triangles and the Afar Triangle, a triple junction. <a href="https://pubs.ugs.gov/gip/dynamic/East_Africa.html">https://pubs.ugs.gov/gip/dynamic/East_Africa.html</a> retrieved on Jan 5 2024.....	13
Fig 2.2: Topographic Profiles (a) and DEM (b) of the Ethiopian Main Volcanic Sectors. From <a href="http://ethiopianrift.igg.cnr.it/riftvalleygeography.htm">http://ethiopianrift.igg.cnr.it/riftvalleygeography.htm</a> . Accessed on Nov 11, 2023. ....	15
Fig 2.3: Stratigraphic Section of four areas taken from Geological Map of Hosanna Sheet (GSE 2010) unpublished technical report. ....	18
Figure 3.1: Geological map of the research area.....	25
Figure 3.2: Geologic cross-section of the research area .....	26
Fig 3.3: Plateau basalt shows columnar jointing, fractures and alteration. ....	27
Fig 3.4: Different photographs taken with in highly welded tuff. ....	28
Fig 3.5: Panorama showing normal fault at highly welded tuff (ignimbrite). ....	29
Fig 3.6: Panorama of highly welded tuff (ignimbrite) at river cut exposure. ....	29
Fig 3.7: River cut exposure shows the contact of highly welded tuff (ignimbrite), unwelded tuff and basalt. ....	30
Fig3.8: Pyroclastic flow deposit showing poorly sorting, (a, b and c) and exposure image showing contact of pyroclastic flow and highly welded tuff (d). ....	31
Fig 3.9: Panorama of Lithologic contacts of welded tuff. Pyroclastic flow and pyroclastic fall deposit....	32
Fig 3.10: Pyroclastic fall deposit showing well sorted, bedded structures on poorly welded tuff. ....	33
Fig 3.11: approximately 10m thick exposure of pyroclastic deposit (pumice) at quarry site .....	34
Fig 3.12: Quarry of basaltic lava flow (a) and basaltic lava dome. ....	35
Fig 3.13: Petrographic analysis at 10x magnification XPL image taken from basaltic lava flow. ....	36
Fig 3.13: Exposure showing contact of scoria and pyroclastic fall.....	37
Fig.3.14: Image shows the contact of Rhyolitic lava dome and obsidian (left) and obsidian image having flow structure (right). ....	38
Fig.3.15: Field photograph taken at different places. Altered pyroclastic fall deposit (a), reworked volcanoclasts, showing reverse grading (b and c) and mud crack (d).....	39
Fig 3.17: Stratigraphic logs of research area at three sections. The oldest unit here is welded tuff and the youngest unit is Volcaniclastic sediment. ....	40
Fig 3.18: Primary structures at different lithologic units. ....	41
Fig 3.19 lava flow structure (ropy structures) on obsidian (a), horizontal bedding on pyroclastic fall and horizontal bedding on ignimbrite (b and c) respectively. ....	42
Fig 3.20: Scoria cone forms saddle structure and half crater. ....	42

Fig 3.21: Dome structure formed by basaltic scoria at the top and ignimbrite at the bottom. ....	43
Fig 3.22 Secondary geologic structures, Tension joints (open with rough and irregular surface .....	44
Fig 3.23: non-systematic joints on surface of ignimbrite.....	44
Fig 3.24: Normal fault in pyroclastic fall deposit (poorly welded tuff).....	45
Fig 3.25: Normal fault photograph. ....	46
Fig 3.26: Normal fault photograph at western escarpment. ....	47
Fig 3.27: Panorama of normal fault in pyroclastic deposit at western escarpment.....	47
Fig 4.1: Representative thin section image of samples from the plateau basalt; (a) and (b) are at cross polarized light. C and d are the same view but under xpl and ppl view respectively. All photomicrographs are taken in 10X. ....	49
Fig 4.2: Representative thin section images of samples from the welded tuff (ignimbrite). ....	51
Fig 4.3: Representative thin section images of samples from the rift floor basalt. These images show glomerophyric texture (a and b), felsophyric texture (c and d) .The images are taken under xpl and ppl respectively. All images are taken at 4x magnification. ....	53
Fig 4.4: Representative thin section images of samples from rhyolitic lava dome. This unit shows radiating micro crystalline mineral (quartz), felty texture (random orientation of grains). ....	54
Fig 6.1: Stereonet image showing plane (solid lines) and pole (green points) of measured geologic structures. ....	64

## List of Tables

Table 1: Composite stratigraphic log of the research area.....	58
Table 2: List of geologic structures and their measurement value.....	63
Table 3: Petrographic analysis results of each sample.....	65

# Chapter one

## 1. Introduction

The Main Ethiopian Rift (MER) is a significant geological feature in East Africa, characterized by active tectonics and extensive volcanic activity (Bonini et al., 2005). It is part of the larger East African Rift System, which stretches over 3,000 kilometers from the Afar Triangle in northeastern Africa to Mozambique in the south (Corti, 2019). The MER is renowned for its unique volcanic features, diverse landscapes, and ongoing geological processes, making it a crucial area for studying Earth's crustal dynamics and volcanic activity (Bonini et al., 2005). Recent research on the Main Ethiopian Rift volcanism has focused on several key aspects. Geochemical and Petrological studies have aimed to understanding of the origin of magma beneath the Main Ethiopian Rift, investigating the composition, source characteristics, and processes involved in magma generation and evolution (Kidane et al., 2022).

The Central Main Ethiopian Rift (CMER) is a region of significant geological and volcanic activity within the main Ethiopian rift Situated in East Africa. It is characterized by extensive volcanic features and a complex stratigraphic record that provides insights into the region's geological history and volcanic evolution (Hutchison & Ayele, 2021). Volcanism in the CMER is driven by the tectonic forces associated with the ongoing rifting of the Earth's crust This extensional tectonics create pathways for magma from the mantle to ascend towards the surface, resulting in various types of volcanic activity such as explosive eruptions, lava flows, and Volcaniclastic deposits. The composition of the magma, which is bimodal (basaltic and Rhyolitic), influences the style and intensity of volcanic eruptions in the CMER (Abebe et al., 2007).

The volcanic stratigraphy of the CMER comprises a diverse sequence of volcanic rocks, pyroclastic deposits, ash layers, and sedimentary units (Corti, 2021). These layers record the history of volcanic events, eruption styles, environmental conditions, and tectonic processes that have shaped the rift over geological time scales. Understanding the volcanic stratigraphy is crucial for reconstructing past volcanic activity, assessing volcanic hazards, and correlating volcanic deposits across different areas within the CMER (Kidane et al., 2022).

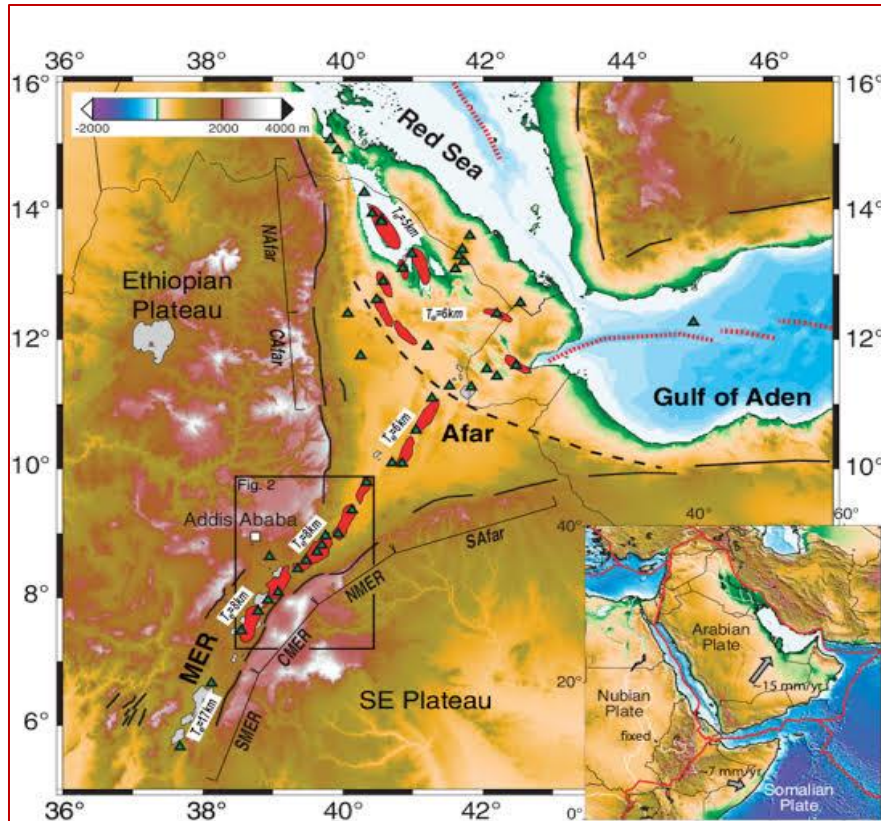


Fig 1.1: Tectonic setting of the Main Ethiopian Rift within the East African Rift system (retrieved from [https://www.researchgate.net/figure/Tectonic-setting-of-the-Main-Ethiopian-Rift-MER-and-Afar-Depression-modifi-ed-from\\_fig1\\_275720465](https://www.researchgate.net/figure/Tectonic-setting-of-the-Main-Ethiopian-Rift-MER-and-Afar-Depression-modifi-ed-from_fig1_275720465), on May 21

### 1.1 Overview of the research area

The investigation has taken place near the Werabe area, situated close to the western rift escarpment of the Central Main Ethiopian Rift (CMER). This region falls within the Silte zone of the central regional state of Ethiopia and spans from 7°43'0"N to 7°55'20"N and 38°6'0"E to 38°20'10"E. Notably, it is located approximately 170 km from Addis Ababa, the capital city of Ethiopia. Access to the study site is facilitated by several routes, including the Addis Ababa to Butajira to Werabe to Hosanna to Arba Minch asphalt road, in addition to other gravel roads that traverse the area. This accessibility enables researchers, stakeholders, and interested parties to reach the location conveniently, making it conducive for scientific investigations, fieldwork, and other geological studies related to the CMER's western rift escarpment.

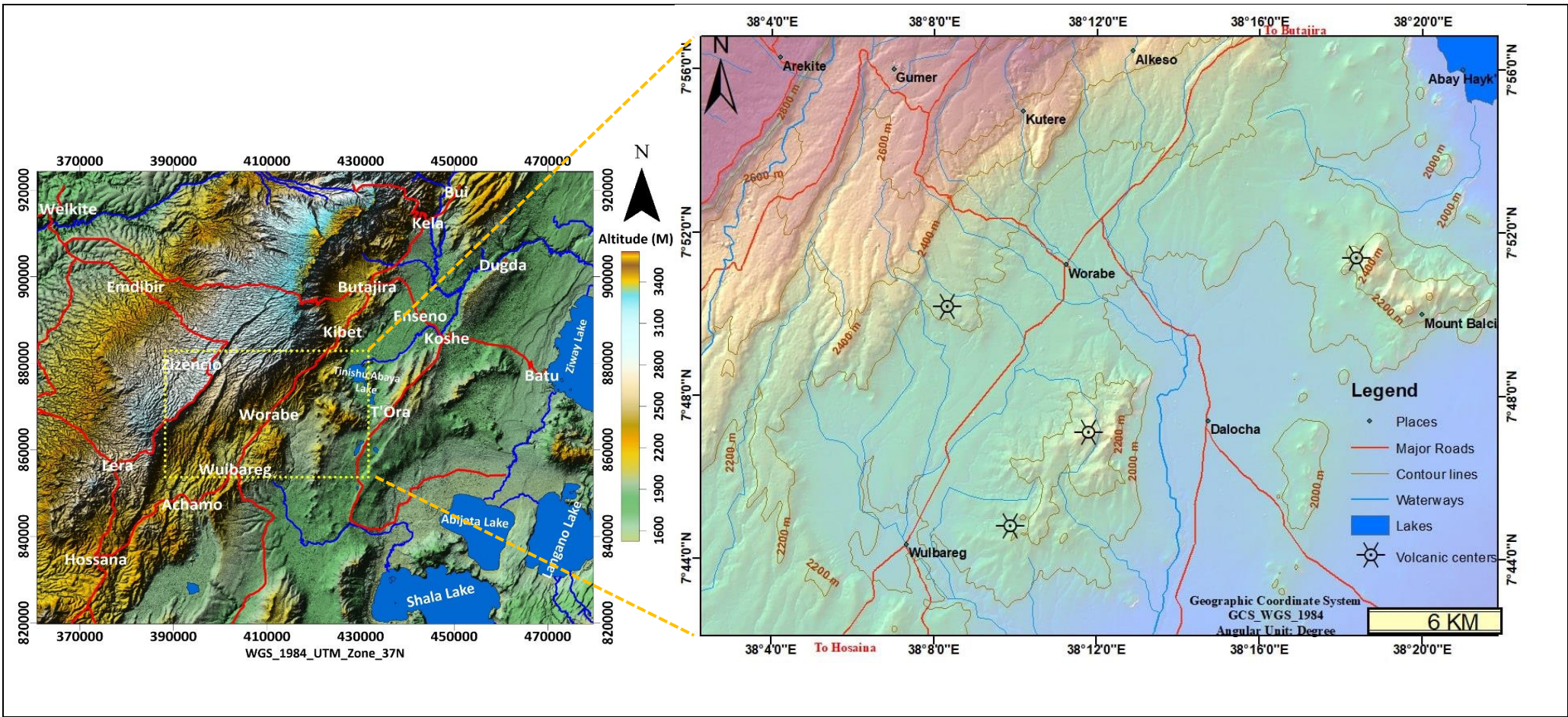


Fig 1.2: Hill shade color map of the Central Main Ethiopian Rift within Ethiopian volcanics with broken rectangle showing the study area figure b (a) and Location and accessibility map of the research area (b).

### 1.2.1. Physiography

The research area's physiography encompasses both the Central Main Ethiopian Rift and the western rift escarpment, which are defined by associated faults, scoria cones, and lava domes. These features contribute to the area's diverse landscape, boarder faults, minor faults and other geological characteristics.

The Central Main Ethiopian Rift dominates the eastern portion of the research area, showcasing numerous volcanic cones and lava domes. These volcanic formations are indicative of past and ongoing volcanic activity within the rift zone, highlighting the dynamic nature of the region. On the other hand, the Western Rift Escarpment, situated along the western side of the rift, along with the adjacent plateau, presents a different geological profile characterized by distinct central volcanic complexes. This area exhibits unique geological features that contribute to a deeper understanding of the rift's formation and evolution.

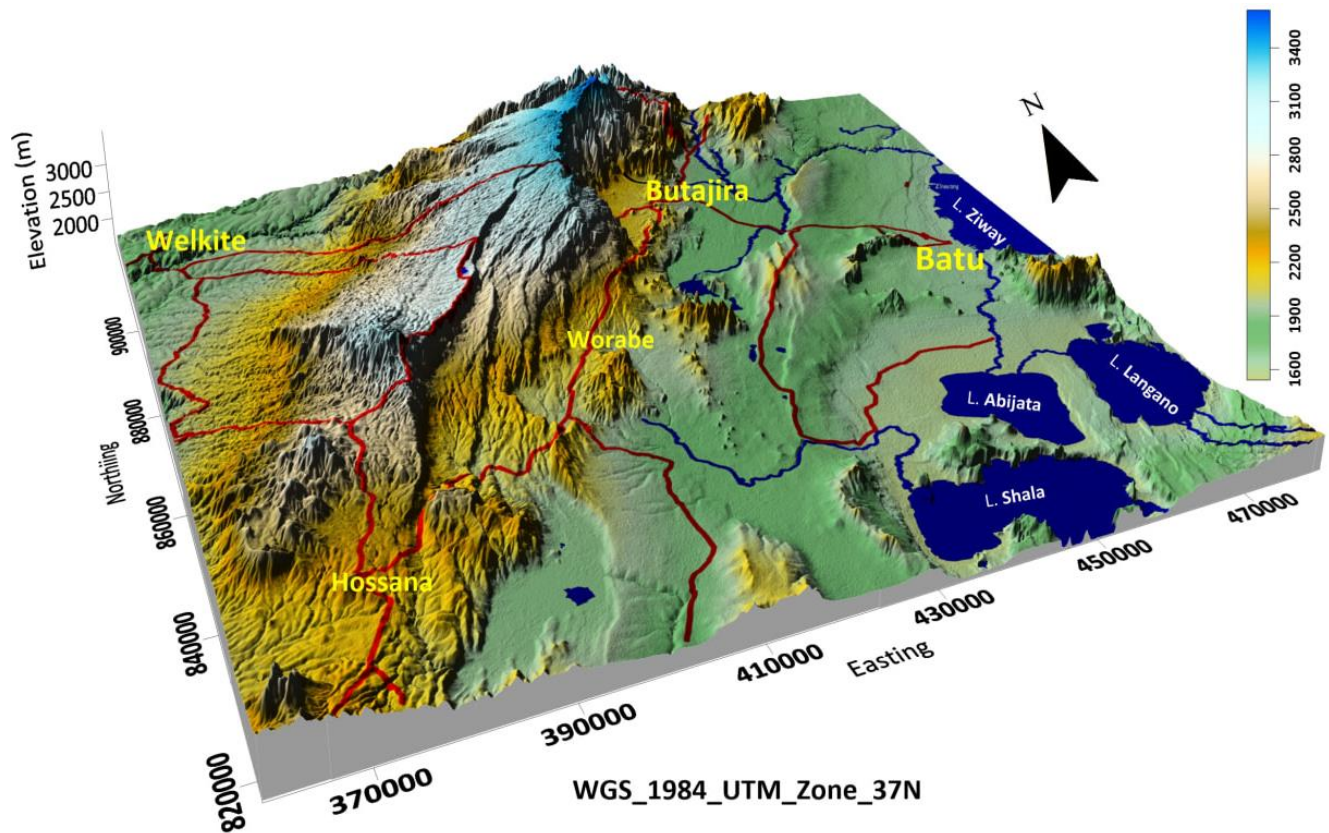


Fig 1.3: Physiographic map of the research area (DEM).

### 1.2.2 Climate and Drainage pattern of the research area.

The research area exhibits a diversity of climatic condition. Across the region, there are distinct climatic zones: the rift floor experiences a subtropical climate known locally as Weina Dega (semi-

arid), while the western escarpment and adjacent highlands enjoy a humid climate referred to as "Dega" (sub-humid). The research area is characterized with a plethora of rivers and streams, with the Dijo River standing out as the largest among them. Beginning its journey from the highlands, situated at an impressive altitude ranging from 3187 meters to 1583 meters, this river ultimately feeds into Lake Shala (Chernet et al., 1982).

### **1.3 Statement of a problem**

Numerous studies have delved into the complexities of the main Ethiopian rift (MER) on both regional and detailed scales. However, a significant gap remains in our understanding of the volcanic rocks within this area, necessitating comprehensive research encompassing lithological unit identification, extent delineation, detailed field relationship descriptions, structural, textural, and mineralogical analyses, and the establishment of a definitive volcanic section. Such an attempt is crucial for gaining a nuanced understanding of the detailed petrologic domains present.

This study is dedicated to investigating the complete structural, stratigraphic, and petrographic aspects of the volcanic products specifically in the Werabe area situated within the central main Ethiopian rift. By doing so, it aims to address the existing data gap comprehensively.

### **1.4. Objective**

#### **1.4.1 General Objective**

The primary aim of this research is to analyze the petrographic characteristics and stratigraphic continuity of volcanic rocks and analyze structural features in the Worabe area, western part of CMER.

#### **1.4.2 Specific Objectives**

In addition to the main objective of this research, there are specific objectives that contribute to achieve the primary goal. These are:- investigating the geology of the area, identifying the type and distribution of rocks, Conducting petrographic analysis, performing structural analysis of the area (identifying type and distribution of geologic structures), and producing a stratigraphic section of the area based on field observation, finally preparing geologic map cross section of the area.

## **1.5 Significance of Research**

### **1.5.1 Expected Output**

As previously mentioned, this area has not been extensively studied in terms of petrography and stratigraphy. This will be the first detailed study on structural features, petrographic characteristics, and stratigraphic continuity. The main expected research outputs will include: An interpretation based on fieldwork and petrographic analyses. Providing structural, petrographic, and stratigraphic aspects of the area for ongoing work. The results of this research will be valuable for both individual researchers and research organizations, as they will gain access to petrographic, structural, and stratigraphic data. This information can be used to deepen their understanding of the studied area and contribute to their ongoing projects. Moreover, this study may provide valuable insights into the research methods employed, particularly in petrographic and stratigraphic studies, making it a useful reference for students and other researchers who are exploring similar topics.

In addition to its academic value, the findings of this study could also benefit investors who are interested in utilizing rock units for economic purposes. These rocks may be important for various applications such as construction materials, decorative elements, and other industrial uses. Having detailed information about the rock units from this research can aid investors in identifying and accessing resources that are valuable for economic development and commercial ventures.

### **1.6 Methods used in the research**

Methodologically, the study used field mapping, systematic sampling, and rigorous laboratory analyses to characterize the volcanic rocks prevalent in the Worabe area. Detailed structural measurements have been conducted to unravel the deformation history and distinguish the structural controls influencing the volcanic units. Petrographic analyses involve thin section petrography, mineralogical identification, and textural characterization, all aimed at elucidating the origins and types of volcanic rocks. To achieve the research goals described above, the main proposed methods are: Review of existing literature, Comprehensive field survey (mapping by traversing, systematic rock sampling of the surrounding volcanic rocks, and taking scaled photographs) and Petrographic analysis to classify the volcanic rocks and establish the area's stratigraphy.

Table 1.1 Shows Methods and activities used in this research.

Pre-field	<p>Previous work review (journals, books, technical reports, satellite images, and other resources)</p> <p>Preparation and collection of field equipment (notebook, pen and pencil, GPS, hand lens, compass, geological hammer, and others)</p>
Field work	<p>Lithology description,</p> <p>Measurement of structural features,</p> <p>Geological and structural mapping,</p> <p>Taking relevant photographs.</p>
Post – field	<p>Selecting samples for thin section</p> <p>Preparing and describing thin sections,</p> <p>Digitizing the field map</p> <p>Writing thesis</p>

## 1.7. Previous works

Several studies have been conducted in the Central Main Ethiopian Rift. Among these, the following are noteworthy.

The researchers Basalfew et al., (2012) in titled "The geology, geochemistry, and gravity survey of the Hosanna area," revealed important findings about the geological composition of the region. The study identified several key geological units in the area, including Pre-rift volcanics, Late Tertiary Volcanics, Quaternary Volcanics/Wonji Group, and Quaternary Sediments. The study area, known as the Hosanna map sheet (NB37-2), is located within the central Ethiopian Regional States and partially overlaps with the Oromia National Regional State. Geographically, it is bounded by 7° 00' to 8° 00' north latitude and 37° 30' to 39° 00' east longitude, representing a central segment of the main Ethiopian rift.

Meshesha et al. (2023) delved into the Petrogenesis of Quaternary Basaltic Rocks in the Butajira-Kibet area within the Central Main Ethiopian Rift. Using major and trace element data, they explored the petrogenetic processes and mantle source compositions of these basalts. The findings

revealed that the basalts exhibit mild alkalinity with moderate to high levels of MgO (6.85-9.00 wt. %) and TiO<sub>2</sub> (2.40-2.92 wt. %).

Abeba et al. (2006) concentrated on quaternary faulting and volcanism within the Main Ethiopian Rift (MER), linking it to bimodal Quaternary magmatism. They identified two primary Quaternary magmatic episodes in the MER, shedding light on the rift's geological evolution.

Megerssa et al. (2019) explored the "Inventory of Key Geosites in the Butajira Volcanic Field" with a vision towards establishing Ethiopia's first Geopark. Their study highlighted various natural attractions, showcasing the potential for developing and conserving these sites as tourist destinations.

Woldegabriel et al. (1992) conducted research on the geochronology and distribution of silicic volcanic rocks from the Pliocene - Pleistocene in the central sector of the Main Ethiopian Rift. Their findings indicated the widespread occurrence of Pliocene -Pleistocene silicic volcanoes, calderas, and associated eruptive products throughout the rift zone

The article titled "Aborted Propagation of the Ethiopian Rift Caused by Linkage with the Kenyan Rift" by Corti et al. (2019) presents a significant study on the geological evolution and tectonic processes of the East African Rift System, focusing specifically on the interaction between the Ethiopian Rift and the Kenyan Rift. In their research, they investigate the structural complexities and tectonic interactions that have influenced the development of the Ethiopian Rift. The study utilizes a combination of geological mapping, geophysical surveys, and numerical modeling to unravel the factors contributing to the aborted propagation of the Ethiopian Rift and its linkage with the Kenyan Rift.

Key points highlighted in this article include: The geological evolution of the East African Rift System, emphasizing the intricate tectonic processes and structural controls that have shaped the rift architecture over millions of years. Tectonic Interactions: The study delves into the interaction between the Ethiopian Rift and the Kenyan Rift, elucidating how these rift segments have influenced each other's development and propagation through time.

Marco Bonini et al., (2005) conducted research on the Evolution of the Main Ethiopian Rift within the broader context of Afar and Kenya rift propagation. Their study offered valuable insights into the intricate structural patterns of the Main Ethiopian Rift and proposed an evolutionary model to explain its development over time. These works offer valuable information for research projects by providing detailed methods for data collection, sample preparation, data analysis techniques,

and interpretation. Additionally, they provide essential background information about the area of interest at a regional scale, enriching the understanding of the research context.

## Chapter Two

### 2. Regional geology and geological setting

#### 2.1. Introduction

Continental flood basalt (CFB) consist of typically basaltic volcanic sequences that are typically up to several kilometers thick and are dominated by fissure –fed compound flow. In Ethiopia there are two main volcanic series: Trap series before the MER development and exposed in the NW and SE Ethiopian plateaus, covering a layer of mafic and felsic volcanic rocks (Ukstins et al., 2002; Kieffer et al., 2004). The second one is Rift Series which is Cutting the plateau units asymmetrically in to NW and SE. the Afar and Main Ethiopian Rift are example of it and younger in age. The first CFC eruption recorded in Ethiopia and Yemen is in Oligocene period and covers 600,000 km<sup>2</sup> and volume greater than 350,000km<sup>3</sup> (Ukistons et al., 2002). This period marked the initial stages of rifting and volcanic activity within the region, as part of the broader tectonic processes associated with the East African Rift system. During this time, the lithospheric extension and thinning of the Earth's crust led to the upwelling of magma from the mantle, resulting in the formation of volcanic features such as shield volcanoes, stratovolcanoes, and fissure vents.

The MER is part of the larger East African Rift system, which extends from the Afar region in northeastern Africa to Mozambique in the south, delineating the separation of the African tectonic plate into the Nubian and Somali plates (Chorowicz, 2005). This rift system is characterized by active extensional tectonics, where the Earth's lithosphere is being pulled apart, leading to the formation of deep rift valleys, volcanic activity, and seismicity. Based on GPS data, it's estimated that the extension rate is about 5 mm per year (Bonini et al., 2005); Saria et al., 2014). Recent studies have provided valuable insights into the tectonic evolution of this rift, shedding light on its initiation, structural complexity, magmatic activity, and current tectonic dynamics. The initiation of rifting in the MER can be traced back approximately 25 million years ago during the Oligocene-Miocene period (Ebinger et al., 2020). This phase marked the onset of extensional tectonics, leading to the gradual stretching and thinning of the Earth's crust in the region. Subsequently, around 10 million years ago, significant faulting and subsidence along the rift axis occurred, initiating the early stages of basin development within the rift (Bastow et al., 2019; Keir et al.,

2021). One of the hallmark features of the MER's tectonic evolution is its intense magmatic activity. The structural complexity of the MER is another key aspect of its tectonic evolution. A complex fault system, including normal faults, strike-slip faults, and associated fractures, has developed over time (Mohr, 2020; Sani et al., 2023). These structures play a crucial role in accommodating the extensional forces and shaping the rift's topography. During the Pleistocene-Holocene era, a significant geological event occurred in the central main Ethiopian rift, associated with the Wonji Fault (Mohr, 1967 cited in Tadesie et al., 2019). This event was a combination of volcanic eruptions and movements in the Earth's crust, leading to the formation of various volcanic materials in an area known as the Wonji Fault Belt. These materials, including pumice, soft tuffs, trachyte, rhyolite lava flows, and obsidians, are collectively referred to as the Wonji Group (Kazmin et al., 1978, and others). Additionally, the Wonji Fault Belt witnessed another type of volcanic activity during the Pleistocene, resulting in recent basalt lava flows originating from fissures in the ground. These basalt formations exhibit rugged surfaces with cracks and are characterized by the presence of chains of cone-shaped structures. The majority of these basaltic features are located on the floor of the rift valley

The Butajira volcanic field, part of the Central Main Ethiopian Rift (CMER), is situated within the Silti-Butajira-Debre Zeyit Fault Zone (SBDFZ) along the western boundary of the Main Ethiopian Rift (MER). This fault zone is characterized by linear chains of scoria cones and associated lava flows (Rooney et al., 2011). According to Rooney et al. (2011), the SBDFZ extends from the foot of the western rift escarpment at approximately 6.5° N to 9° N. Within this belt, the Butajira Volcanic Field (BVF) is one of three active volcanic systems, alongside the Bilate Volcanic Field and the Bishoftu Volcanic Field, which are geographically distinct but connected (Mazzarini et al., 2013).

## **2.2. Background**

The East African Rift System (EARS) is a prominent geological feature that comprises active continental rifts formed approximately 22–25 million years ago (Ebinger et al., 2005). This expansive system consists of several distinct rift basins, extending over thousands of kilometers. The rift system exhibits a complex network of branches and valleys, highlighting the dynamic tectonic processes shaping the African continent. To the north of the Afar Triple Junction, the rift

system bifurcates into two main paths: one extending westward to form the Red Sea Rift and the other diverging eastward towards the Aden Ridge in the Gulf of Aden. Conversely, south of the Afar Triple Junction, the East African Rift (EAR) branches into two primary segments, each characterized by its unique geological features and topography. The Eastern Rift Valley, also referred to as the Gregory Rift, encompasses the Main Ethiopian Rift as it extends southward from the Afar Triple Junction. This branch continues its journey through diverse landscapes, including the Kenyan Rift Valley and traverses several countries such as Congo DR, Uganda, Rwanda, Burundi, Zambia, Tanzania, Malawi, and Mozambique. On the western side of the Afar Triple Junction, the Western Rift Valley emerges, showcasing the stunning beauty of the Albertine Rift and extending southward to encompass the valley of Lake Malawi. These interconnected rift branches and valleys are interconnected by a series of geological connections and tectonic processes, reflecting the ongoing continental rifting and crustal deformation within the East African Rift System.

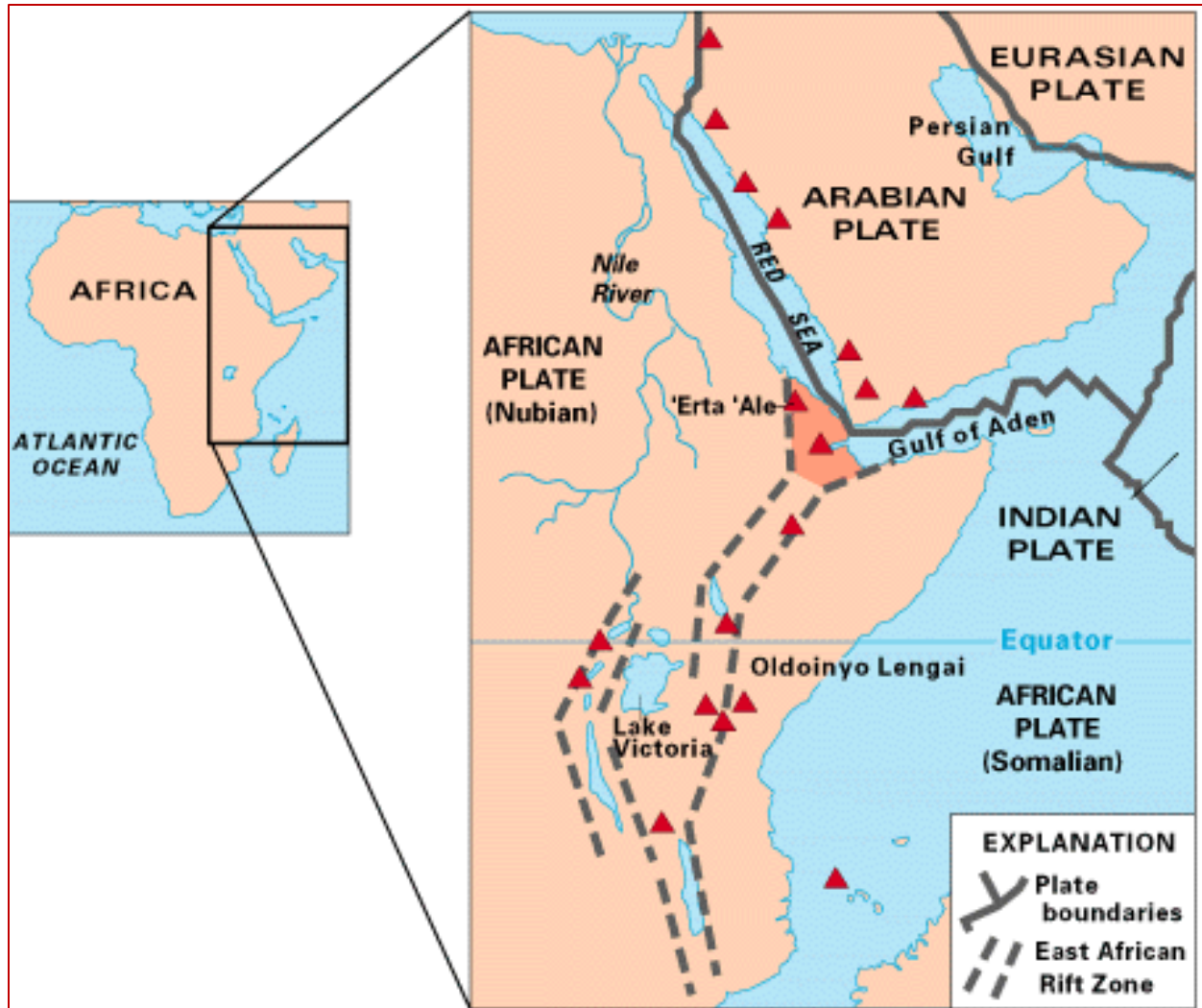


Fig 2.1: Map of East Africa shows active volcanoes as red triangles and the Afar Triangle, a triple junction. [https://pubs.ugs.gov/gip/dynamic/East\\_Africa.html](https://pubs.ugs.gov/gip/dynamic/East_Africa.html) retrieved on Jan 5 2024.

Numerous theories have been proposed to elucidate the evolution of the East African Rift (EARS), with the most recent and widely accepted theory positing a dynamic interaction between magmatic and tectonic processes under oblique rifting conditions (Corti, 2009). This theory suggests that lithospheric thinning triggers volcanic activity, which, in turn, further thins the Earth's outer layer in saturated areas, resembling a Mid-Ocean Ridge (MOR) environment (Beyene and Abdelsalam, 2005). The magmatic model proposes a convecting hot mantle plume beneath an anomalous asthenosphere, leading to the uplift of the Ethiopian dome, widespread volcanism, and rifting (Bonini et al., 2005). The Main Ethiopian Rift (MER), a component of the EARS, has an age ranging from late Oligocene to early Miocene, with a current extension rate of approximately 5

mm per year (Saria et al., 2014). Magmatic activity in the MER exhibits a bimodal distribution (Abebe. B et al., 2006 and Ayalew, D. Et al., 2018) primarily quaternary in age. This magmatism encompasses basaltic flows, ignimbrites, and silicic centers within the rift floor dating back to 2-1 million years ago, and along with axial silicic volcanoes and basalts since 650,000 years ago. The initial phase comprises basaltic flows linked to the Afar Stratoid, mainly visible in the central and northern MER. Quaternary volcanism is concentrated on the rift floor, partly associated with an NNE-SSW trending echelon fault system, known as the Wonji Fault Belt (Rooney et al., 2003, 2007, 2010, 2011, 2014; Hutchison et al., 2016). Scholars agree that the main Ethiopian Rift began to sink approximately fifteen to eighteen million years ago. A significant event in the formation of the rift occurred around 10 Ma, resulting from the faulting of the Oligocene-Miocene age pre-rift volcanic succession (Kazmin et al., 1978; Davidson, 1983, and others). There is extensive Miocene to Quaternary magmatism on the down-failed rift floor as well as on its nearby flanks and shoulders. While modern volcanism has also occurred off-rift, it is primarily concentrated along the rift axis (Ebinger and Casey, 2001; Keranen and Klemperer, 2008; Rooney et al., 2005).

Adjacent plateaus predominantly feature Eocene–Late Oligocene igneous rocks associated with the Ethiopian-Yemen flood-basalt province (Trap series; Corti, 2009; Rooney, 2017). These plateaus are primarily composed of basalt and intercalated silicic volcanics, forming a sub-aerial volcanic pile typically 500–1500 m thick, occasionally reaching 3000 m (Rooney, 2010; Rooney et al., 2014). Following the eruptive events of the flood basalt, numerous large shield volcanoes emerged on the volcanic plateau surface, spanning from 30 million years ago to approximately 10 million years ago (Kieffer et al., 2004; Furman et al., 2006; Rooney et al., 2011

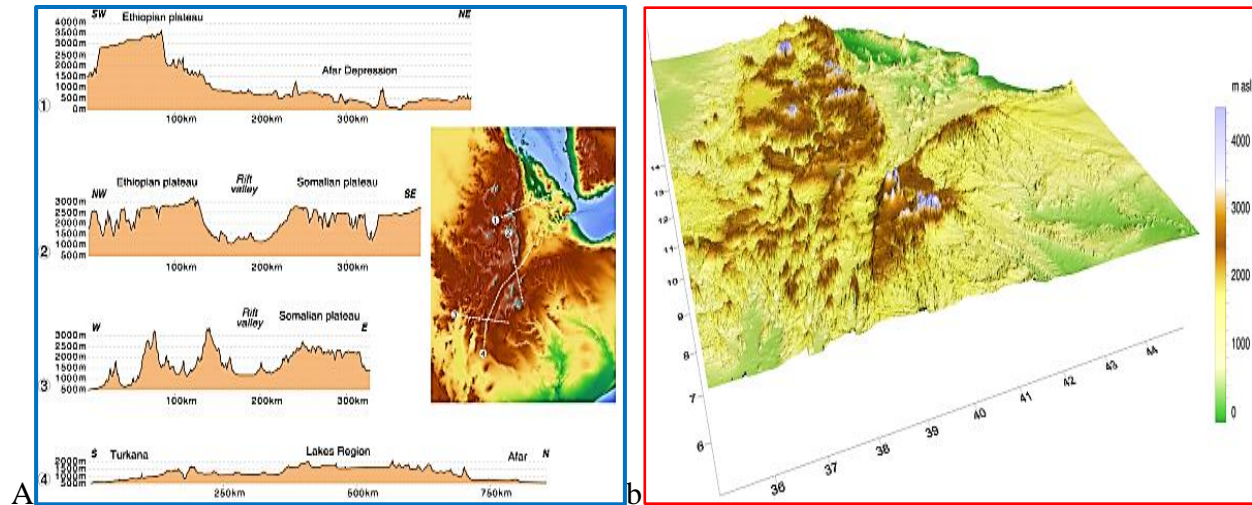


Fig 2.2: Topographic Profiles (a) and DEM (b) of the Ethiopian Main Volcanic Sectors. From <http://ethiopianrift.igg.cnr.it/riftvalleygeography.htm>. Accessed on Nov 11, 2023.

### 2.2.1 Geologic evolution of Silte Butajira Debrezeyt fault zone

The Silte Butajira Debrezeyt Fault Zone (SBDFZ) is a significant geological structure within the Main Ethiopian Rift (MER), associated with the Butajira Volcanic Field. Its geologic evolution, from the Precambrian to the present, reflects the dynamic tectonic processes shaping the Ethiopian Rift system. During the Precambrian, the area that is now the Ethiopian Rift was part of the ancient African craton. The basement rocks in this region primarily consist of high-grade metamorphic rocks and granitoids formed during the Pan-African orogeny (about 600-500 Ma), a significant tectonic event resulting from the collision and amalgamation of proto-continental fragments (Mohr, 1983). The Paleozoic era saw relatively stable conditions with minimal tectonic activity in the region. However, the Mesozoic era (around 250-66 Ma) was characterized by the deposition of extensive sedimentary sequences in a series of basins formed during periods of rifting associated with the breakup of the Gondwana supercontinent (Ebinger et al., 2000).

In the Late Mesozoic to early Cenozoic (approximately 66-30 Ma), the area began experiencing significant tectonic reactivation. This period marked the initial stages of the East African Rift System (EARS) development, driven by the upwelling of the Afar mantle plume. This mantle plume caused widespread volcanic activity and initiated the rifting process (Wolfenden et al., 2005). From the Oligocene to the Miocene (around 30-5 Ma), the MER began to form more prominently. The SBDFZ, as part of the MER, experienced extensive faulting and volcanism. Large-scale basaltic lava flows covered the region, forming the Ethiopian flood basalts. These

volcanic activities were punctuated by periods of faulting that progressively shaped the rift valleys and associated structures, including the Butajira Volcanic Field (Corti, 2009). During the Pliocene to Pleistocene epochs (approximately 5 Ma to 11,700 years ago), the tectonic and volcanic activities intensified. The SBDFZ saw the development of numerous faults and fissures, contributing to the overall extension and subsidence of the rift valley. The Butajira Volcanic Field experienced significant volcanic activity, with the emplacement of various volcanic edifices, including basaltic shield volcanoes, cinder cones, and lava flows. These volcanic structures are aligned along the fault zones, indicating a close relationship between tectonic activities and volcanism (Chorowicz, 2005). In the Holocene epoch (last 11,700 years to present), the region continues to be tectonically and volcanically active. The SBDFZ remains a site of ongoing crustal extension, faulting, and volcanic activity. Recent studies indicate that the Butajira Volcanic Field still hosts geothermal activity, with hot springs and fumaroles present (Keir et al., 2009). The interaction between tectonic processes and volcanic activity continues to shape the landscape, influencing the current geologic and geomorphologic evolution of the region.

### **2.3 Stratigraphy volcanoes related to main Ethiopian rift.**

The MER, located within the broader East African Rift System, exhibits a complex stratigraphic architecture influenced by various geological processes. From the Precambrian basement rocks to the Quaternary volcanic formations, the stratigraphy of the MER reflects a continuum of geological events and tectonic activities. At the base of the MER's stratigraphy lie the ancient Precambrian basement rocks, comprising gneisses, granites, and metamorphic formations that form the foundational layer of the rift. These basement rocks provide a stable substrate upon which subsequent sedimentary and volcanic deposits accumulated.

Overlying the Precambrian basement are sedimentary sequences deposited during different geological time. These sedimentary rocks are sandstones, shales, and conglomerates. The stratigraphy of the MER also encompasses extensive volcanic deposits, reflecting the region's history of magmatic activity. Basaltic lava flow, Rhyolitic ignimbrites, tuffs, and volcanic ash layers form distinctive stratigraphic units, highlighting periods of intense volcanic eruptions and volcanoclastic deposition. In recent times, ongoing volcanic and tectonic activities continue to

modify the stratigraphy of the MER, adding new layers of volcanic ash, lava flows, and fault-related sediments to the geological sequence. Customer officer

The Alaji Group, considered the oldest lithology within the MER, is characterized by transitional mildly alkaline basalt and rhyolite. Following this, the Anchar basalt, displaying mildly alkaline transitional basalt, represents the next oldest unit of pre-rift volcanism, particularly in the western escarpment of the Central Main Ethiopian Rift (CMER). Moving up the stratigraphic sequence, the late Tertiary silicic volcanism is represented by the Nazreth Group, which overlies the Anchar basalt. Subsequently, the Bofa Basalt, a unit of fissural flood basalt, is observed atop the Nazreth Group, marking another phase of volcanic activity within the region.

The late Tertiary volcanism also includes the Chilalo shield volcanoes, characterized by peralkaline basalt and trachyte compositions. A significant geological event in the quaternary age led to the formation of additional volcanic complexes known as the Wonji Group, marking the youngest major event of rift faulting. The Wonji Group comprises three major volcanic complexes: the Dino formation, representing stratoid silicics of the rift floor; central volcanic complexes; and fissural basalts found on the rift floor. Lastly, the Pleistocene-Holocene age lacustrine sediments constitute the youngest stratigraphic succession within the study area, predominantly comprising

the rift floor's geological makeup. The lithostratigraphic succession of the study area, along with approximate thickness, is summarized in (Figure 2.3).

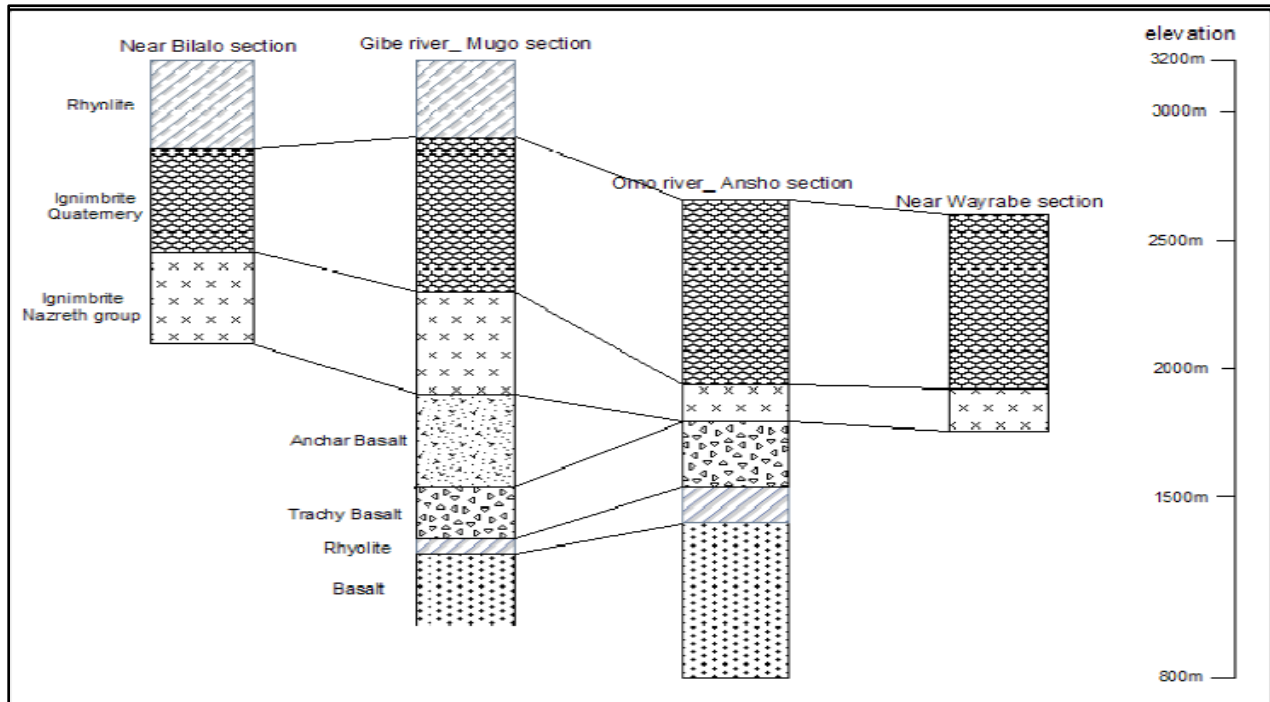


Fig 2.3: Stratigraphic Section of four areas taken from Geological Map of Hosanna Sheet (GSE 2010) unpublished technical report.

## 2.4. Lithologies of the western part of the central main Ethiopian rift

The lithologies within the western CMER can be categorized into pre-rifting and rifting-associated volcanic products. The pre-rifting lithologies, including the Alaji Group, Anchar Basalt and Nazareth Group, signify volcanic activity preceding major rifting events. In contrast, the rifting-associated lithologies such as the Bofa Basalt, Chilalo Shield Volcanoes, and Wonji Group are directly linked to late Tertiary and Quaternary volcanic activities associated with the rifting processes within the CMER

### 2.4.1. Pre - Rift Volcanics

#### 2.4.1.1 Alaji Group.

The Alaji Group represents a significant geological unit within the pre-rift (mid-Tertiary) rocks of the central Main Ethiopian Rift (MER). Comprising basalt, trachy-basalt, trachyte, and rhyolite,

this group showcases a diverse range of rock formations that offer valuable insights into the region's geological history. The basalt within the Alaji Group is characterized by high fracturing and an aphanitic texture, typically found underlying the rhyolite layers. Studies conducted by Kuntz et al. (1975) and Morbidelli et al. (1975) utilized the K-Ar age determination method to date the basalt, revealing ages of approximately 28 and 15 million years old. These age determinations provide crucial information about the timing of volcanic activity and the formation of these rock units within the MER. In addition to basalt, the Alaji Group also includes trachyte formations. These trachytes display significant weathering, fractures, and are often intersected by basaltic dykes. They are predominantly located in the western section of the Gibe River area, contributing to the geological diversity of the MER.

Overall, the Alaji Group's composition and characteristics, including basalt, trachy-basalt, trachyte, and rhyolite formations, highlight the complex geological processes and volcanic activities that have occurred within the central Main Ethiopian Rift during the mid-Tertiary period. Studies and age determinations conducted by researchers like Kuntz et al. (1975) and Morbidelli et al. (1975) have been instrumental in understanding the geological timeline and evolution of this important geological unit within the MER. Adjacent to the Alaji Group is the Anchar Basalt, another important lithological unit within the central main Ethiopian rift.

#### ***2.4.1.2 Anchar Basalts***

The Anchar Basalt is also among pre-rift lithologies and it is made up of a variety of basalts and trachybasalts, along with rhyolitic tuffs. The basalts are olivine tholeiites and quartz tholeiites. They have been dated to be between 11.5 and 8.3 million years old. There are flood basalts, about 300 to 600 meters thick, located west of Butajira town, and they are connected to the Anchar Basalts. These basalts are covered by Pliocene-Pleistocene silicics from the Nazret group

#### **2.4.2 Late Tertiary Volcanics**

##### ***2.4.2.1 Nazreth Group:***

The rift escarpments, particularly in the eastern part near Munesa town, exhibit a diverse array of geological formations, including stratoid silicics, ignimbrites, unwelded tuffs, ash flows, rhyolites, and trachytes. These formations represent a complex history of volcanic activities and sedimentary processes that have shaped the landscape of the region over geological time scales. The older formations, such as the Nazreth group, are estimated to be between 9.5 to 3 million years old,

based on studies by Kazmin and Seife, (1978). These formations consist of pyroclastic rocks and have been extensively explored through deep geothermal wells at Aluto volcano, revealing deposits of over 400 meters in thickness (Abebe, 1984; EIGS-ELC, 1985, and others). Additionally, Weldegabriel et al. (1990) reported the presence of Pliocene pyroclastic units with a thickness exceeding 600 meters in the eastern margin of the rift in the Munesa area. The younger volcanic formations of the Dino group unconformably overlap the older Nazareth group, indicating a subsequent phase of volcanic activity in the region. This geological sequence provides valuable insights into the dynamic nature of volcanic processes and tectonic activities within the Main Ethiopian Rift.

#### ***2.4.2.2 Bofa Basalts***

The Nazret Group, overlain by Bofa fissural flood basalts, forms the upper segment of the Afar Group's basaltic succession and is younger than 4.5 million years. The eruption of the Bofa basalts marked a significant event following major faulting activities in the region. These fissural basalts exhibit distinctive characteristics, being locally vesicular, lacking prominent crystals, and forming well-defined flows with scoraceous surfaces. The rocks are weakly porphyritic, with a ground mass composed of olivine, andesitic labradorite, and augite, while the prevalent intermediate rock type is Andesine. Geological dating using the K-Ar method has reported ages of 2.5 to 2.8 million years for these basalts, indicating a potential age range of 3.5 to 1.5 million years. In the northern basin area, the predominant lava flows consist of plagioclase-phyric basalts with minor occurrences of fine-grained and scoraceous varieties. Some lava flows exhibit olivine and pyroxene-phyric compositions. The basalts are primarily classified as quartz tholeiites with a small proportion being olivine basalts. Along fault escarpments, the exposed thickness of these basalts varies from a few meters to approximately 30 meters. The detailed description of the Nazret Group and the overlying Bofa basalts provides valuable insights into the volcanic processes, rock compositions, and geological events that have shaped the landscape of the region.

#### ***2.4.2.3 Nazret Group and Dino Formation undifferentiated***

The Dino Formation encompasses silicic rocks distributed across various regions, including the rift floor, extensive escarpments, and the nearby plateau, exhibiting similarities to the silicic formations of the Nazret Group. In areas where rift escarpments expose more than 500 meters of

silicic rocks, both the Dino Formation and Nazret Group are likely present, although in many instances, the available data is insufficient to distinguish between these units definitively.

An observation noted across both sides of the rift is that the upper part of the section often displays indications of lacustrine sedimentation, manifested in bedded waterlain tuffs, sediments, and similar deposits. This bedded sequence shows strong lithological correlation with young (Pleistocene) rift floor silicic formations and is believed to be of the same geological age.

The presence of silicic rocks in the Dino Formation across different geographical settings within the Main Ethiopian Rift underscores the widespread occurrence of volcanic and sedimentary processes that have shaped the region. Understanding the stratigraphic relationships and age correlations between the Dino Formation, Nazret Group, and associated sedimentary deposits is crucial for reconstructing the geological history and environmental changes that have influenced the rift's development over time.

#### **2.4.3. Quaternary Volcanics /Wonji Group**

The most recent volcanic activity in the Ethiopian Rift is closely linked to the Wonji Fault Belt, as documented by Mohr (1967) and other researchers. In 1975, Meyer et al. introduced the term "Wonji series" to describe volcanic rocks in the rift younger than 1.6 million years, specifically associated with the Wonji fault belt. However, further research by Kazmin and Seife (1978) revealed that Pleistocene volcanic eruptions were not confined solely to the Wonji Fault Belt but also occurred in various parts of the rift. Consequently, Kazmin and Seife (1978) reclassified the "Wonji series" as the "Wonji group," encompassing all rift volcanism that formed after the last major event of rift faulting, subsequent to the deposition of the Bofa basalts.

The Wonji group, as delineated by Kazmin and Seife (1978) and Kazmin et al. (1980), comprises three primary complexes:(a) Stratoid silicic volcanics found on the rift floor and shoulders, identified as the Dino Formation, (b) Pantelleritic products originating from central volcanoes and (c) Fissural basaltic eruptions, represented by basalts located on the rift floor. This classification highlights the diversity of volcanic activities within the Wonji group, ranging from silicic formations to pantelleritic products and basaltic eruptions.

#### ***2.4.3.1. Dino Formation***

The Dino Formation stands out as a prominent geological formation spanning the rift floor in the Ethiopian Rift. Comprising compacted fiamme ignimbrites, aphyric basalt, and unwelded pyroclastics, this formation exhibits varying thicknesses, ranging from a few meters to up to 30 meters in different areas. Notably, in the North-West region of Lake Hawassa, rocks from the same period showcase coarse, light-colored unwelded pumiceous pyroclastics reaching thicknesses of up to 250 meters. The eruption of these pyroclastics is thought to be associated with the formation of large calderas like Hawassa and Shala. These calderas, characterized by their expansive depressions formed after volcanic eruptions, are likely the result of intense volcanic activities and the deposition of volcanic materials, including the pyroclastics from the Dino Formation. The distinct lithological composition and thickness variations within the Dino Formation provide valuable insights into past volcanic events, magma compositions, and eruption dynamics within the Ethiopian Rift.

#### ***2.4.3.2. Basalts of the Rift floor***

Another significant aspect of volcanic activity within the Wonji Group involves eruptions from fissures of Pleistocene and recent basalts. While the majority of these late basalts are concentrated in the Wonji fault belt, eruptions also occur in the western marginal part of the rift. These basalts are notably influenced by extensional fractures, presenting fresh, rough surfaces, and forming chains of scoraceous cones along fracture lines. They can be observed east of Lake Ziway, south of Lake Shalla, and far northeast of Lake Abiyata near Mito town. The flows from these eruptions often follow depressions in the relief or cascade over fault escarpments. Typically, basaltic eruptions occurred subsequent to the formation of silicic pantelleritic volcanoes, although some basaltic activity may have been contemporaneous with the early stages of their development. Other expressions of recent and sub-recent basaltic volcanism include explosion craters and basaltic hyaloclastites found in various locations south of Lake Shalla and in the southern part of the study area around the Bilate River. The chemical compositions of these basalts are predominantly alkaline or transitional, primarily exhibiting mildly alkaline properties. Common variants such as low-aluminum Hawaiites, mugearites, and benmoreites indicate significant differentiation

processes within the basaltic lava. Porphyritic types with megaphenocrysts up to 3 cm in size are quite prevalent.

Alkali basalts typically comprise magnesian olivine, augitic clinopyroxene, labradorite, and opaque phenocrysts, with alkali feldspar occasionally present in the groundmass. Transitional alkali basalts closely resemble alkali basalts but lack alkali feldspar entirely, with clinopyroxene primarily occurring in the groundmass. Absolute age determinations place most of these basalts in the Pleistocene epoch, providing valuable insights into the timing and duration of volcanic activity within the Wonji Group (Morton et al., 1979).

#### ***2.4.3.3. Central Volcanic Complexes***

The central volcanoes of the Wonji group are primarily located along the axial zone of the rift, known as the Wonji fault belt. These volcanic centers manifest as large conical mountains or calderas formed in the locations of older volcanoes. Among the prominent volcanic centers within the rift, progressing from north to south, are Aluto, Shala, and Corbetti. However, the precise positioning of some volcanoes and calderas may not be clearly defined. Some are situated on the rift floor outside the tensional belts, like the Gademotta caldera, while others appear on the rift shoulders, such as the volcanoes and calderas northwest and southwest of Hosaina. Additionally, certain centers like Tembero, Wagebeta, and Ambericho exhibit a discrete east-west alignment and may follow transverse faults.

The predominant rock types found in these central volcanoes are rhyolitic and trachytic lava flows. Some centers also exhibit alkaline and per-alkaline products, primarily represented by pumice and unwelded tuffs, often associated with obsidians and pitchstones that typically mark the final stages of volcanic activity. Early products in certain centers, particularly northwest of Hosaina, include fiamme or other ignimbrites. It's worth noting that the sequence of eruption of different rock types varies among different volcanoes.

The majority of products from central volcanoes consist of peralkaline rhyolites and trachytes, exhibiting pantelleritic or occasionally comenditic affinity, as noted by various researchers (Gibson, 1970; Di Paola, 1976; Brotzu et al., 1980; Tsegaye et al., 2005). These volcanic rocks were simply referred to as "pantellerites or comendites". The composition of these volcanic

materials varies from center to center. In pantellerites, for instance, the phenocrysts typically include aenigmatite, clinopyroxene needles, and opaque minerals. Radiometric dating techniques, mainly using K-Ar dating and fission track analysis on obsidian and alkali feldspar-separated minerals, have provided age estimates mainly within the Quaternary period, ranging from 1.6 to 0.1 million years ago (Morbidelli et al., 1975; Kazmin et al., 1980; W/Gabriel et al., 1990, and others).

#### **2.4.4. Quaternary Sediments**

##### ***2.4.4.1 Volcano-Sedimentary Rocks***

Lacustrine sediments, composed mainly of ashes and tuffs, are intercalated with volcanics, forming a volcano-sedimentary sequence as observed in the vicinity of Shone town (Kazmin et al., 1980). These sediments extend over a large area and are prevalent in the eastern regions. In the rift, Quaternary sediments of mostly lacustrine origin are intermingled with Pliocene to Pleistocene ignimbrites across the rift floor and rift shoulders. The older sediment layers consist of lacustrine diatomites, tuffaceous clays, and silts interbedded with basal ignimbrites from the Nazret Group. During the early Quaternary period, a vast ancestral lake spanned from the Chamo-Abaya lakes in the south to the Awash basin in the north, later separating into the present lakes due to late Pleistocene tectonic shifts. Pleistocene-Holocene lacustrine sediments, which encompass a significant land area, were deposited in this expansive lake, with its water level estimated to have been 100 meters higher than its current level between 3500 to 2100 years ago (Kazmin et al., 1980). These lacustrine sediments are characterized by intercalated redeposited volcanic ash and tuffs, primarily consisting of sand and silt. The sediments predominantly comprise volcanic components such as pumice, volcanic ash, obsidian, rhyolite, and basaltic rock fragments (Tsegaye et al., 2005; Bevenuti et al., 2002). Along the rift floor, interlayering of primary air fall pyroclastic deposits and lacustrine deposits is commonplace. Subaqueous pyroclastic deposits can be distinguished by their reverse graded bedding of pumice layers, indicating their underwater deposition. Rounded rock fragments within these sediments indicate abrasion during transportation by rivers and lake waves. The sediments also exhibit poor consolidation and contain evaporites like soda or trona ( $\text{NaHCO}_3$ ) and micro-organic deposits like diatomite.

## Chapter Three

### 3. Geology of the research area

#### 3.1 Introduction

The Main Ethiopian Rift is a part of the EARS having an age of late Oligocene-early Miocene period. This study is conducted near the Worabe area, which is close to the western rift escarpment of the Central Main Ethiopian Rift (CMER). In this area different types of volcanic products are exposed. Lava flows and pyroclastic falls and flows happen in varying amount. The mappable lithologic units, in this area are:- from older to younger are ignimbrite, moderately to poorly welded tuff and pyroclastic deposits, basaltic lava flow with scoria cones, rhyolitic lava dome and obsidian flow with associated felsic pyroclastic fall (pumice, and volcanic ash). In the next section each of these lithological units are discussed in detail.

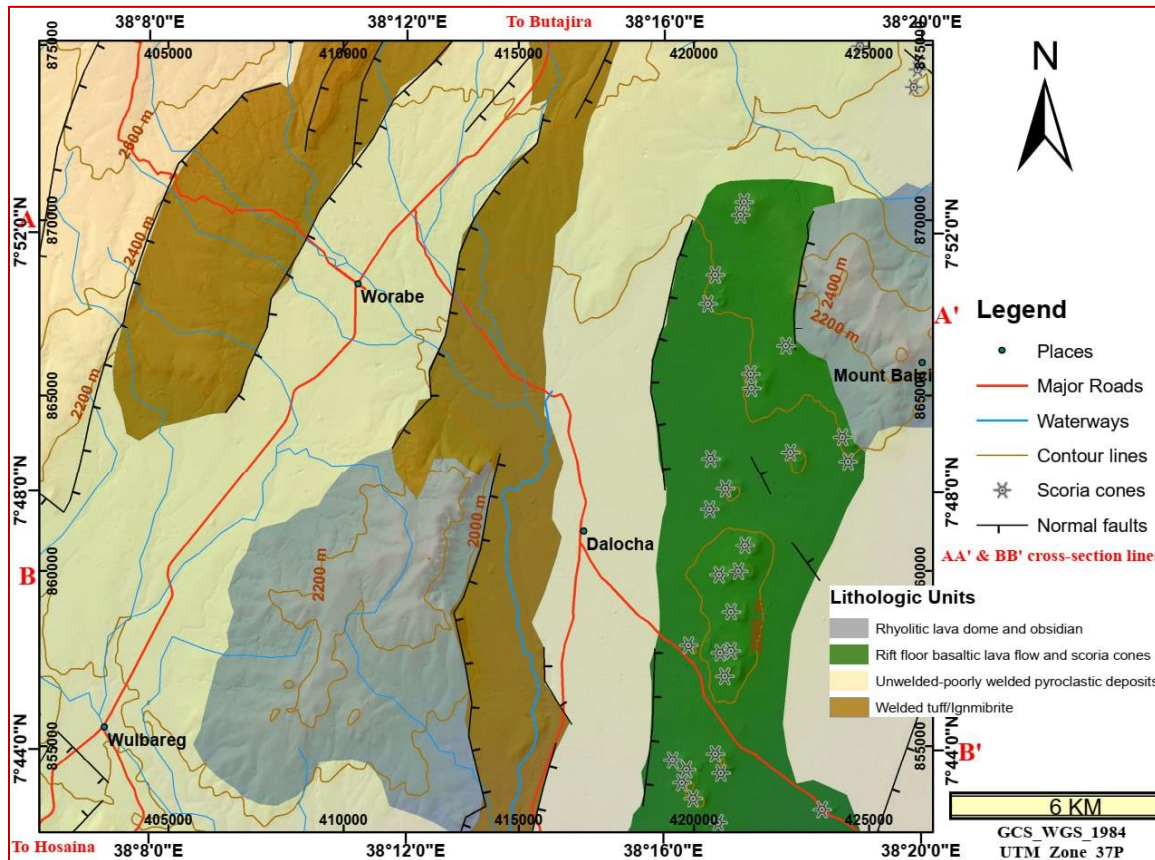


Figure 3.1: Geological map of the research area.

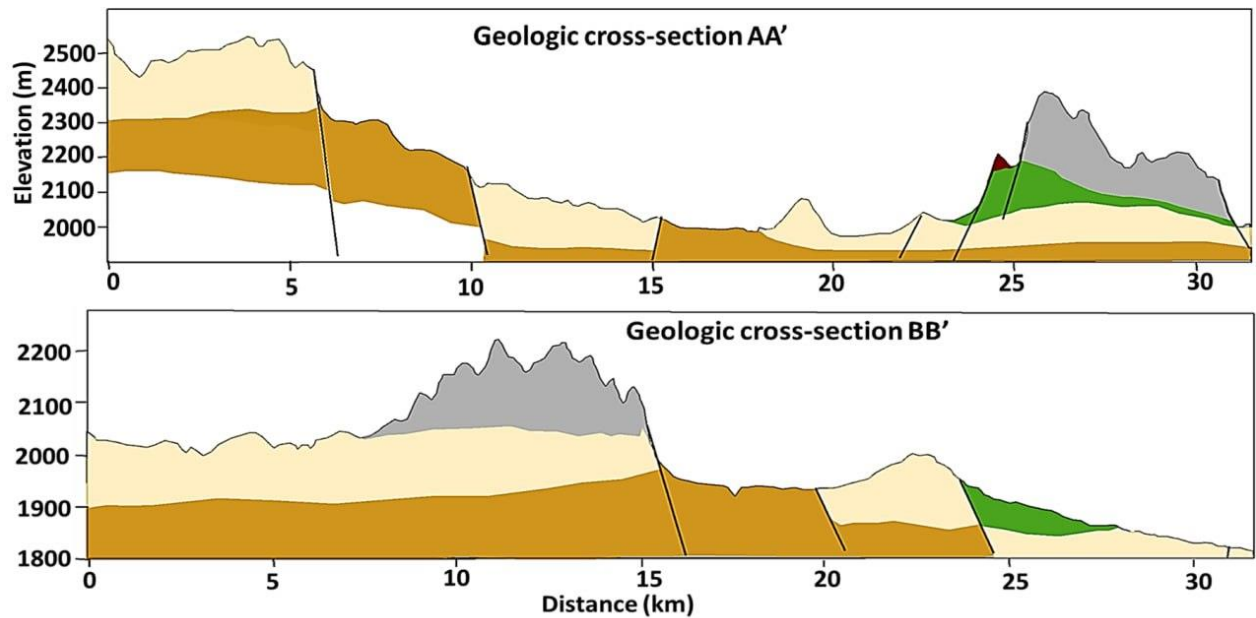


Figure 3.2: Geologic cross-section of the research area

### 3.2. Lithologic descriptions

In this work six lithologic units are investigated. Out of them the two lithologic units (Plateau basalt and volcano sediments) are not mappable in this research area. These are from oldest to youngest. Plateau basalt Highly welded tuff (Worabe ignimbrite), unwelded to poorly welded Pyroclastic fall and flow, rift floor basalt and associated scoracious basalt, rhyolitic lava dome and Obsidian flow with associated felsic pyroclastic fall (pumice, and volcanic ash) and volcano sediments

#### 3.2.1. Plateau basalt.

However, this lithological unit is found out of research area, basaltic lava flows create a steep to gently sloped terrain in the northwest of the research area, which is south ward continuity of Guraghe basalt. This rock is mostly aphanitic with some areas showing a vesicular texture. The color of this unit is dark grey. The basaltic lava flows also exhibit columnar jointing, creating a distinct pattern on the rock surface. Petrographic analysis of this unit gives the following results. This basalt is aphanitic in texture. Plagioclase feldspar contains in average up to 78%. Olivine contains in average up to 8.3%. Pyroxene contains in average up to 13.3%. In addition to these minerals opaque (Fe - Ti oxides) and alkali feldspar are present in this rock unit.



Fig 3.3: Plateau basalt shows columnar jointing, fractures and alteration.

### 3.2.2. Highly welded tuff (Worabe ignimbrite)

A welded tuff (ignimbrite) unit directly underlies the widespread pyroclastic fall and/or flow deposit and at some localities basaltic lava flow. This lithologic unit has yellow and grey color and contains lithic fragments. The lithic fragments are dark and light colors in addition to lithic fragments glasses (made up of obsidian) are found. The grey to white matrix of the ignimbrite is mostly fine-grained and porphyritic with white visible crystals. There are Phenocrysts that make up around 40% of the rock, and mostly contains alkali feldspar (50.42%), quartz (24.85%), opaque minerals (5%) and plagioclase (7.14%). The groundmass is dominantly composed of opaque minerals, quartz and alkali feldspar. From this modal proportion distribution of the phenocrysts it is inferred as rhyolitic in composition. Contact between highly welded tuff and ash fall (a) hand specimen of ignimbrite showing fimens and large crystals(b) , River cut exposure showing

horizontal bedding at the top and inclined (N40E, 45°SE) at the bottom, (c), thin section image taken at 4x magnification(d) shows phenocrysts of alkali feldspar and quartz with opaques. The ground mass is composed of quartz, alkali feldspar and glasses and acidic lava flow shows lava flow direction with non-systematic joints and different fractures and (e).

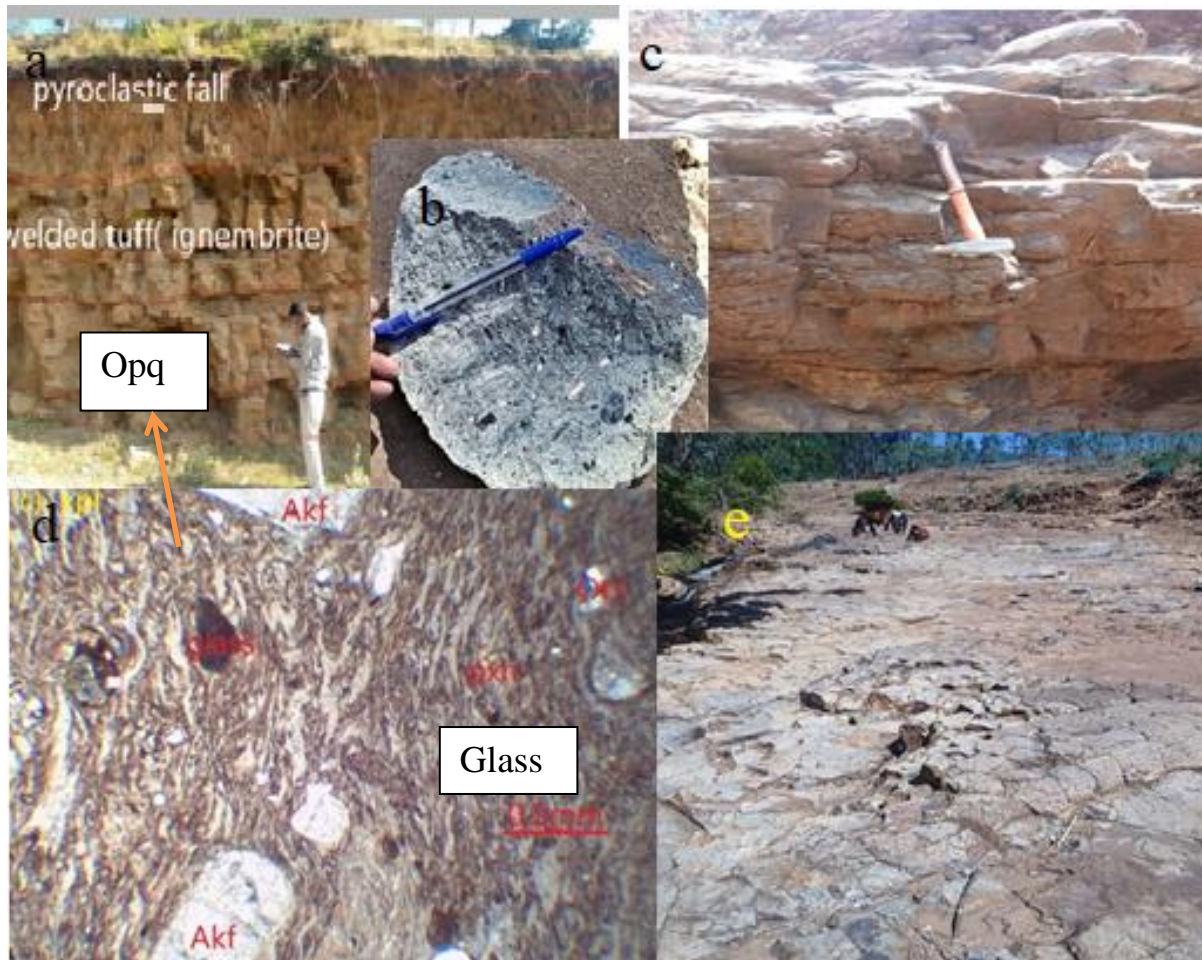


Fig 3.4: Different photographs taken with in highly welded tuff.



Fig 3.5: Panorama showing normal fault at highly welded tuff (ignimbrite).



Fig 3.6: Panorama of highly welded tuff (ignimbrite) at river cut exposure.



Fig 3.7: River cut exposure shows the contact of highly welded tuff (ignimbrite), unwelded tuff and basalt.

### 3. 2.3. Pyroclastic fall and flow (Unwelded to poorly welded tuff)

This group encompasses a significant portion of the research area and comprises terrain ranging from steep slopes to gently sloping and flat surfaces. These deposits are thick and intercalated with other rock types (pumice, poorly welded tuff). Both pyroclastic fall and flow deposits are prevalent in this region, categorized as ash fall and ash flow respectively.

Ash flow deposits exhibit a whitish-gray color, moderate welding, poor sorting, and contain coarse minerals (felsic minerals such as quartz, feldspars) and lithic fragments (obsidian, pumice, and rhyolite). They display variations in vertical thickness, with some areas reaching up to 8m.

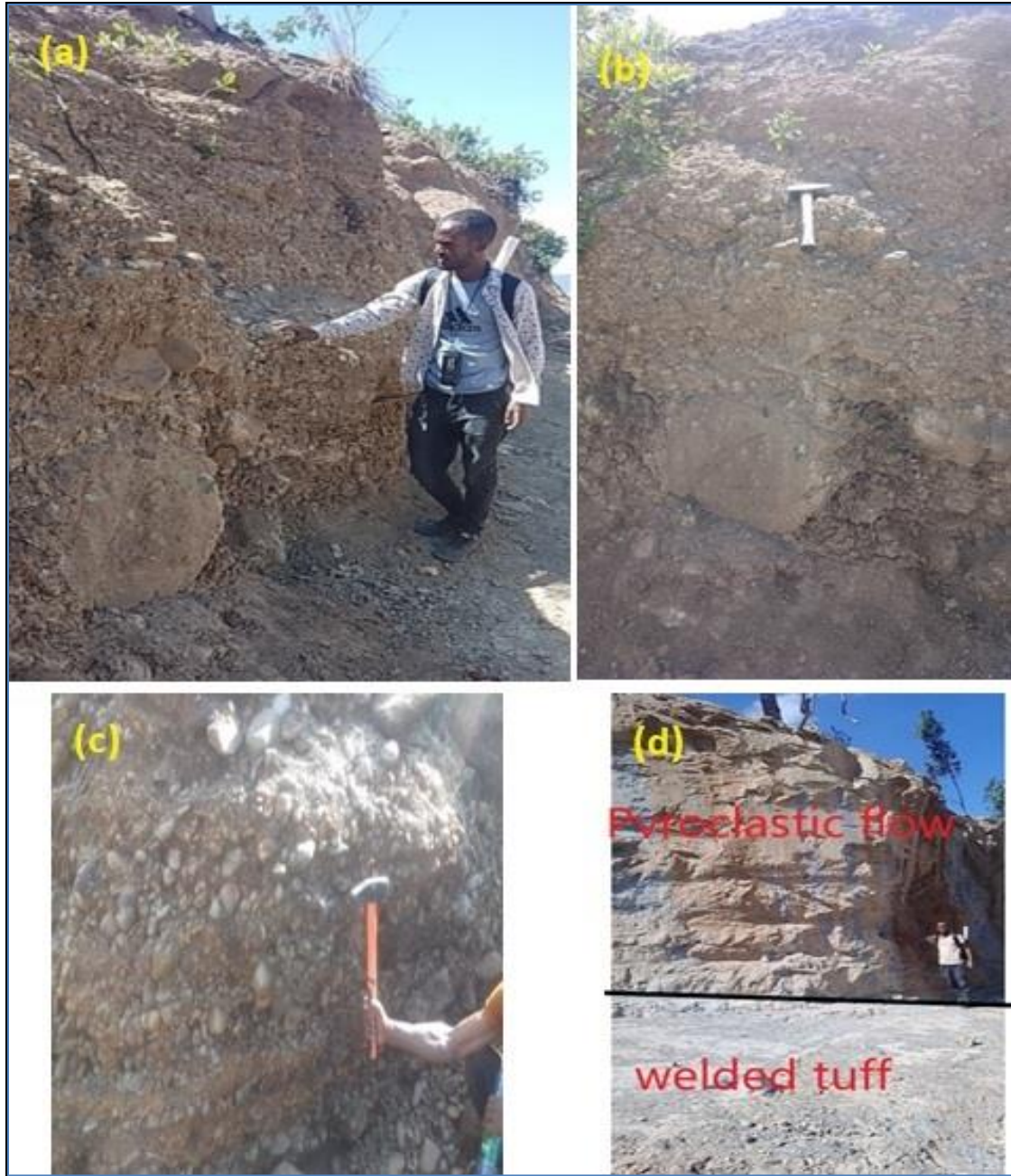


Fig3.8: Pyroclastic flow deposit showing poorly sorting, (a, b and c) and exposure image showing contact of pyroclastic flow and highly welded tuff (d).

Ash fall deposits exposed in this area are whitish to grey, well sorted, partially indurated and have a local thickness, up to a maximum of 10 m. These deposits are fine-grained pyroclastic deposits and occur intercalated with pumice fall and ash flow deposits. In most locations, the base of this unit is characterized by welded tuff (ignimbrite), while in others, it is overlain by scoria and basalt.



Fig 3.9: Panorama of Lithologic contacts of welded tuff. Pyroclastic flow and pyroclastic fall deposit.



Fig 3.10: Pyroclastic fall deposit showing well sorted, bedded structures on poorly welded tuff.



Fig 3.11: approximately 10m thick exposure of pyroclastic deposit (pumice) at quarry site

### **3.2. 4.Rift floor basalt and associated Scoria**

The other volcanic products found in the research area are the basaltic lava flows and basaltic scoria. Basaltic lava flow has grey color and vesicles. In some areas vesicles are filled with secondary minerals. While the Scoria is red, highly vesicular, also vesicles are partially filled with secondary minerals. In some area alteration also affect the scoria fall deposits and they form cone like structures that are typically characterized by a steep slope on one side of the cone and gentle on other side of the cone. Hence they are easily identifiable on a topographic map. Almost all cones show different structures like saddle structure, half crater and an elliptical geometry with their longest axis parallel to the regional tectonic NE to SW direction. As cited in (Taddese et al, 2019) this geometry indicates that their eruption is controlled by preexisting structures (e.g. Mazzarini et al., 2016).

The basaltic lava flows have maximum thickness of 6 m and are closely associated with the scoria deposits. The basalts are dark-grey, porphyritic and vesicular, with some vesicles filled with secondary minerals (calcite and quartz). Basalts form gentle slope, flat plains and lava dome. Blocks of basalt (fig 3.12 b, c), vesicles, fractures at basaltic lava flow (fig 3.12 d) and exposure showing contact of basalt (bottom) and pyroclastic fall (top) deposit (e).



Fig 3.12: Quarry of basaltic lava flow (a) and basaltic lava dome.

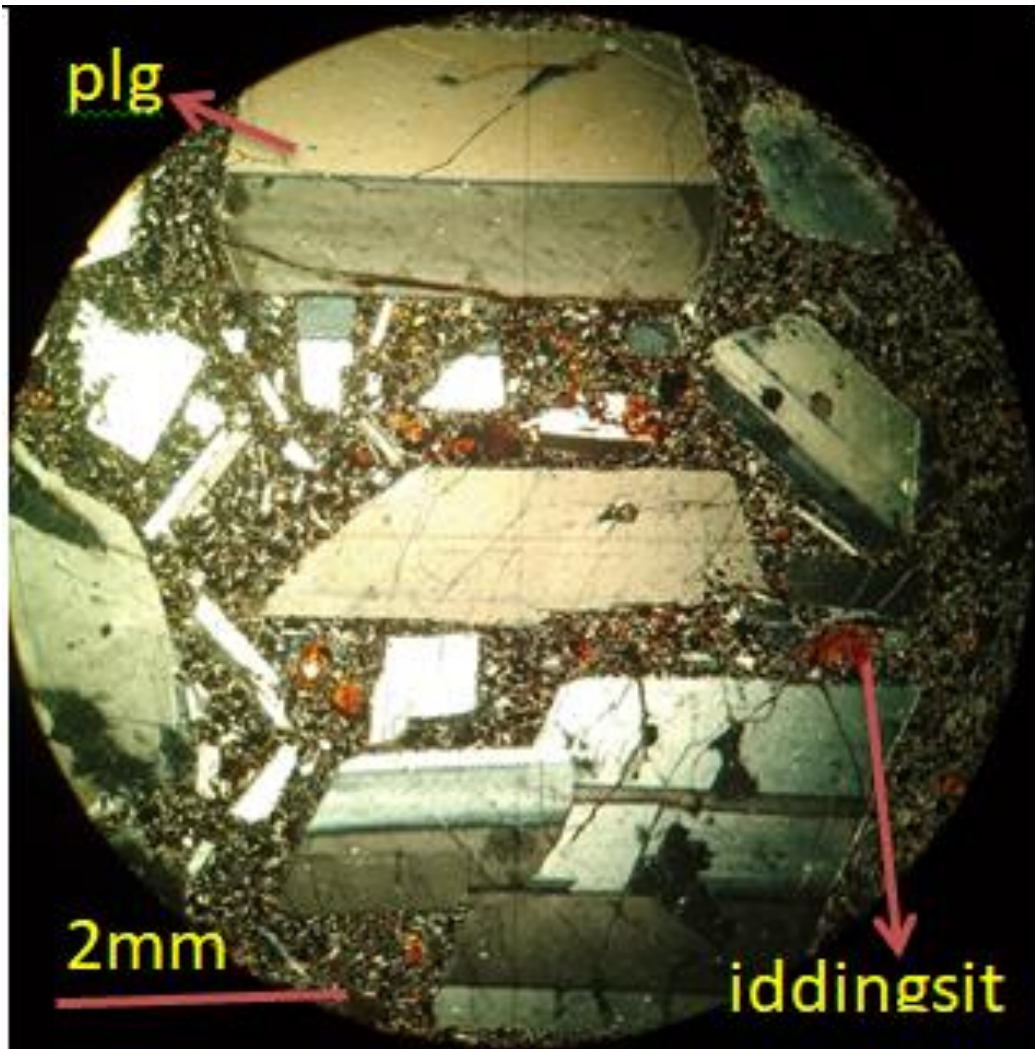


Fig 3.13: Petrographic analysis at 10x magnification XPL image taken from basaltic lava flow.

Petrographic analysis of this rock shows that it has a porphyry texture and contains a range of phenocryst grain sizes. The phenocrysts are mainly composed of plagioclase feldspar (80%), with Fe-Ti oxides (up to 10%), olivine (3%), clinopyroxene (3%), orthopyroxene (2%), and alkali feldspar (2%). The groundmass is composed of microphenocrysts of orthopyroxene, Fe-Ti oxides, olivine, clinopyroxene, and plagioclase. Scoria fall deposits are primarily found in cliffs and quarries where they are extracted as raw material for road and earth dam construction, often used as filling material combined with ash. The deposits, red and black in color, can reach a maximum thickness of 150 m and exhibit rhythmic bedding with blocks and bombs ranging from 5 to 50 cm in diameter.



Fig 3.13: Exposure showing contact of scoria and pyroclastic fall

### 3.2.5. Rhyolitic lava dome and Obsidian

The rhyolitic lava dome holds the highest elevation in the composite stratigraphy. It is exposed at two different areas forming large mountain. It has whit to pink colour and generally has a flat top surface with steep slope. In the lower part of rhyolitic lava there is intercalation with poorly welded ash flow deposits and ash fall deposits (which is found at the top of rift floor basalt in Dalocha area fig 3.9) and at the top of rhyolitic dome there is fragmented obsidian. The largest lava dome material at this area is around 200m. This is interpreted as “the rhyolite to have been dome-forming because of its large height relative to its width, and the appearance of sub vertical flow banding” (Taddese. A 2019). The texture of this rock shows trachytic and larger minerals crystals with in it. The dominant minerals are quartz and alkali feldspar.



Fig.3.14: Image shows the contact of Rhyolitic lava dome and obsidian (left) and obsidian image having flow structure (right).

There are two types of obsidian in this area. These are massive obsidian and fragmented (fragile) obsidian. Massive obsidian exposed in the upper part of the stratigraphy, is intercalated with light grey, rhyolitic lava. The fragmented one is intercalated with the rhyolite lava dome and ash flow. Also obsidian shows bedding structure and interpreted as the evidence of lava flow.

### 3.2.6 Volcaniclastic sediments

Sedimentary rocks are abundantly found in the river side, having undergone reworking (Fig.3.15, b &c) as sediment. Their defining features include a lack of sorting, with fragments ranging from rounded to angular shapes, spanning from clay to pebble sizes, deposited along river streams. Additionally, in certain zones, volcanic rocks have transformed into clay materials (Fig.3.15, a), appearing white, very fine, and soft. Moreover, lacustrine sediments are present, distinguished by layers of redeposited volcanic ash and tuffs. These layers primarily consist of sand and silt and are

rich in volcanic components such as pumice, volcanic ash, obsidian, rhyolite, and basaltic rock fragments. This lithologic unit is youngest in the stratigraphy of this area, and not mappable.

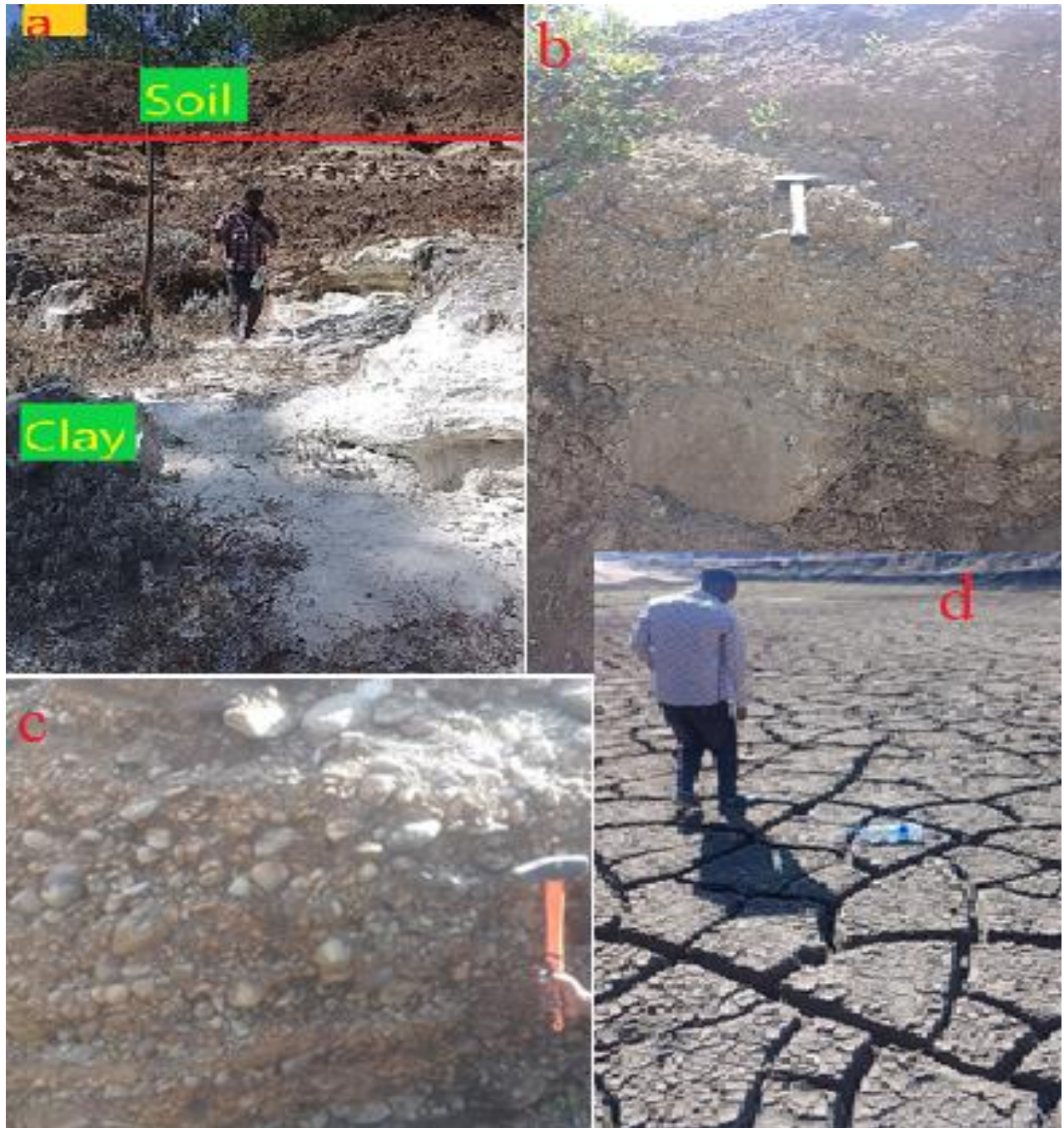


Fig.3.15: Field photograph taken at different places. Altered pyroclastic fall deposit (a), reworked volcanoclasts, showing reverse grading (b and c) and mud crack (d).

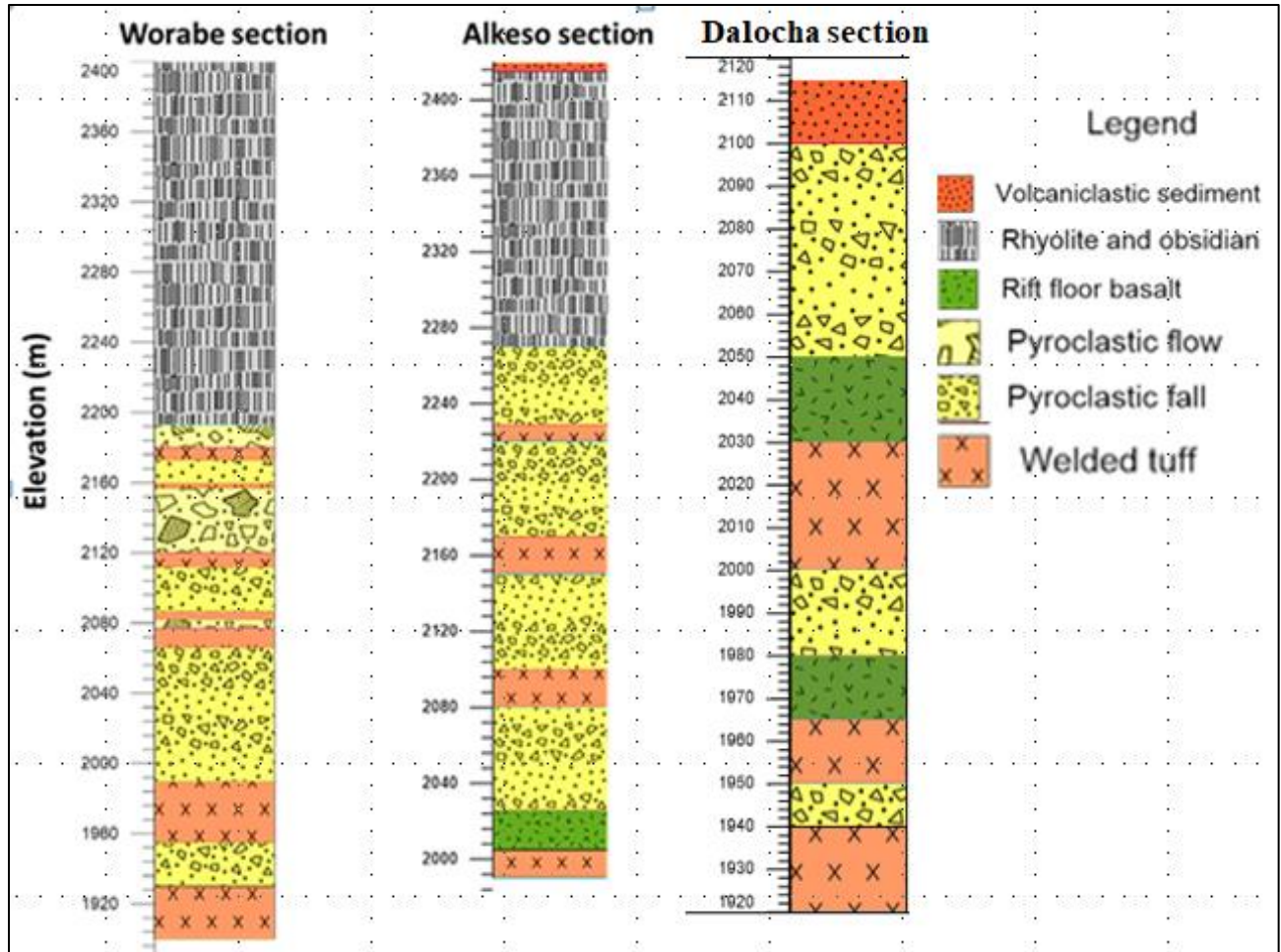


Fig 3.17: Stratigraphic logs of research area at three sections. The oldest unit here is welded tuff and the youngest unit is Volcaniclastic sediment.

### 3.3. Geological structural features.

The region under study exhibits diverse geological features, linked to processes involving magma cooling and deformation. These features are categorized into primary and secondary structures. Primary structures form during the rock's initial creation, while secondary structures develop after the rock's deposition due to tectonic activities impacting the rock. Primary structures encompass features like bedding, foliation, and mineral alignment, providing insights into the rock's original formation. Conversely, secondary structures such as faults, and joints offer valuable information about the tectonic history and deformation events that have impacted the area. Additionally, there are lava domes (form as a result of slow extrusion of highly-viscous silicic lava) and ridges in the area. Analyzing these geological structures enables a better understanding of the geological history

and tectonic processes that have shaped the landscape over time. In the next section each structures will discussed.

### 3.3.1. Primary Structures

These are formations created by volcanic activity. The main structures in the area are lava flows (fig 3.19 a), different types of columnar joints in basalt and ignimbrite (Fig 3.18 a & b), almost vertical and horizontal flow banding in obsidian (fig 3.19 a), scoria cone (Fig 3.20), and rhyolite lava flow banding (fig 3.19 a) and dome (Fig 3.18d & e) units, as well as horizontally graded layering of pyroclastic fall deposits.



Fig 3.18: Primary structures at different lithologic units.

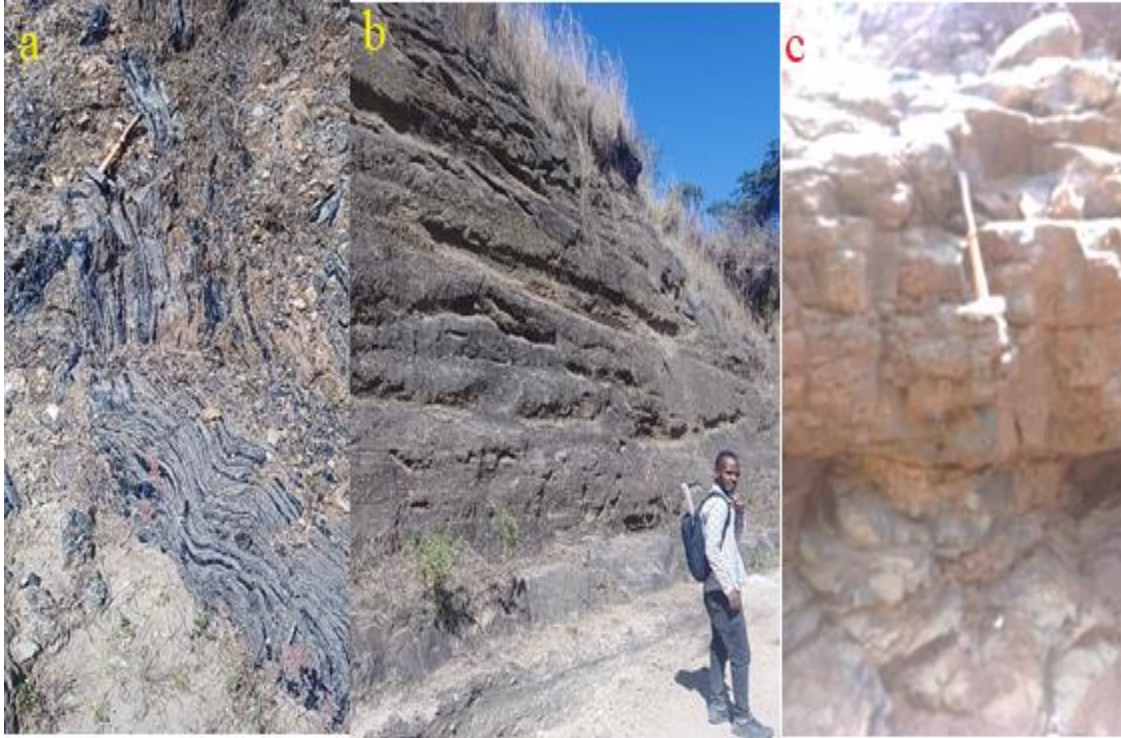


Fig 3.19 lava flow structure (ropy structures) on obsidian (a), horizontal bedding on pyroclastic fall and horizontal bedding on ignimbrite (b and c) respectively.



Fig 3.20: Scoria cone forms saddle structure and half crater.



Fig 3.21: Dome structure formed by basaltic scoria at the top and ignimbrite at the bottom.

### 3.3.2. Secondary Structures

The secondary structures like faults and joints that have been observed in the research area are a result of the tectonic and erosional forces that have been at work in the region.



Fig 3.22 Secondary geologic structures, Tension joints (open with rough and irregular surface



Fig 3.23: non-systematic joints on surface of ignimbrite.



Fig 3.2.4: Normal fault in pyroclastic fall deposit (poorly welded tuff).

In this image the two blocks (hanging walls) have opposite dipping directions. Erosion acts up on foot wall.

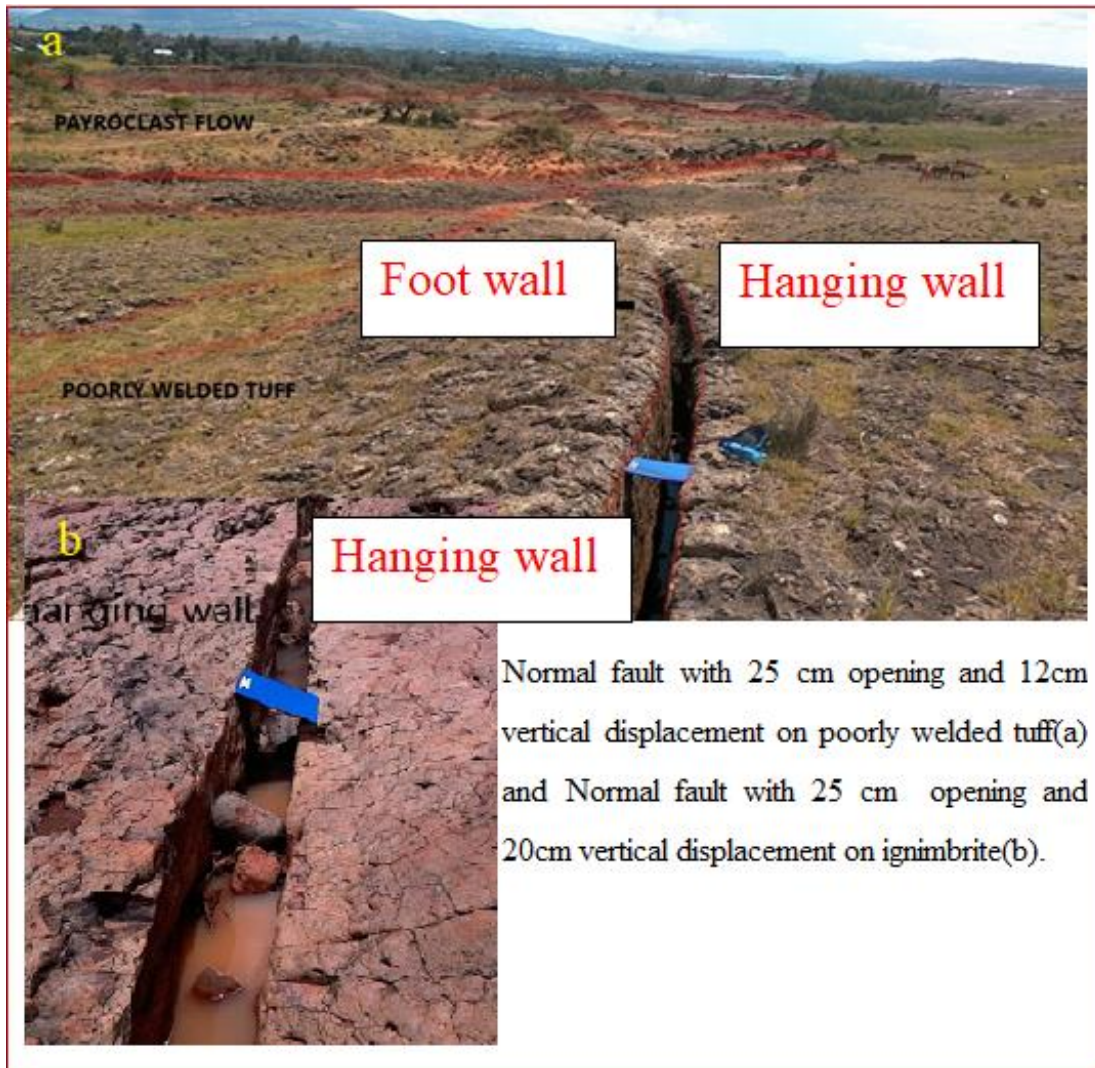


Fig 3.25: Normal fault photograph.



Fig 3.26: Normal fault photograph at western escarpment.



Fig 3.27: Panorama of normal fault in pyroclastic deposit at western escarpment

## Chapter four

### 4. Petrographic analysis of selected samples.

#### 4.1. Introduction

Petrographic analyses were conducted for 19 samples of volcanic rocks collected from the research area. Among these samples, three samples of basalts from the plateau (Figures 4.1) and seven samples (Figures 4.3) from the rift floor were found to be dominant. The remaining nine samples consist of six samples (Figures 4.2) from welded tuff (Ignimbrite) and three rhyolite samples (Figures 4.4) from two sections around Balchi and Worabe. All of these lithologic units were discussed in detail in the previous chapter (Chapter 3). This chapter presents the microscopic properties of selected samples along with representative thin section images for better understanding and analysis. Symbols for minerals are, Quartz (qtz), Alkali feldspar (akf), plagioclase (plg), hornblende (hbd), clinopyroxene (cpx), orthopyroxene (opx) pyroxene (pxn), olivine (olv) and opaque (opq).

#### 4.2. Analyses result of plateau basalt.

The analysis results for plateau basalt predominantly comprises plagioclase, along with olivine, pyroxene, and opaque minerals like iron and titanium oxides. This basaltic unit is characterized by holocrystalline and little bite phyric texture. Regional studies show this basalt has alkaline affinity (D. Meshesha et al., 2021) and Miocene in age. In this unit olivine shows alteration mineral, reddish brown color, (iddingsite). Over all mineral proportion is 0.5 – 2.5mm subhedral to euhedral Plagioclase = 50%, 0.5–1 mm subhedral pyroxene 15%, 0.5–1.5 mm olivine olv 15% and Fe – Ti oxides 20%.

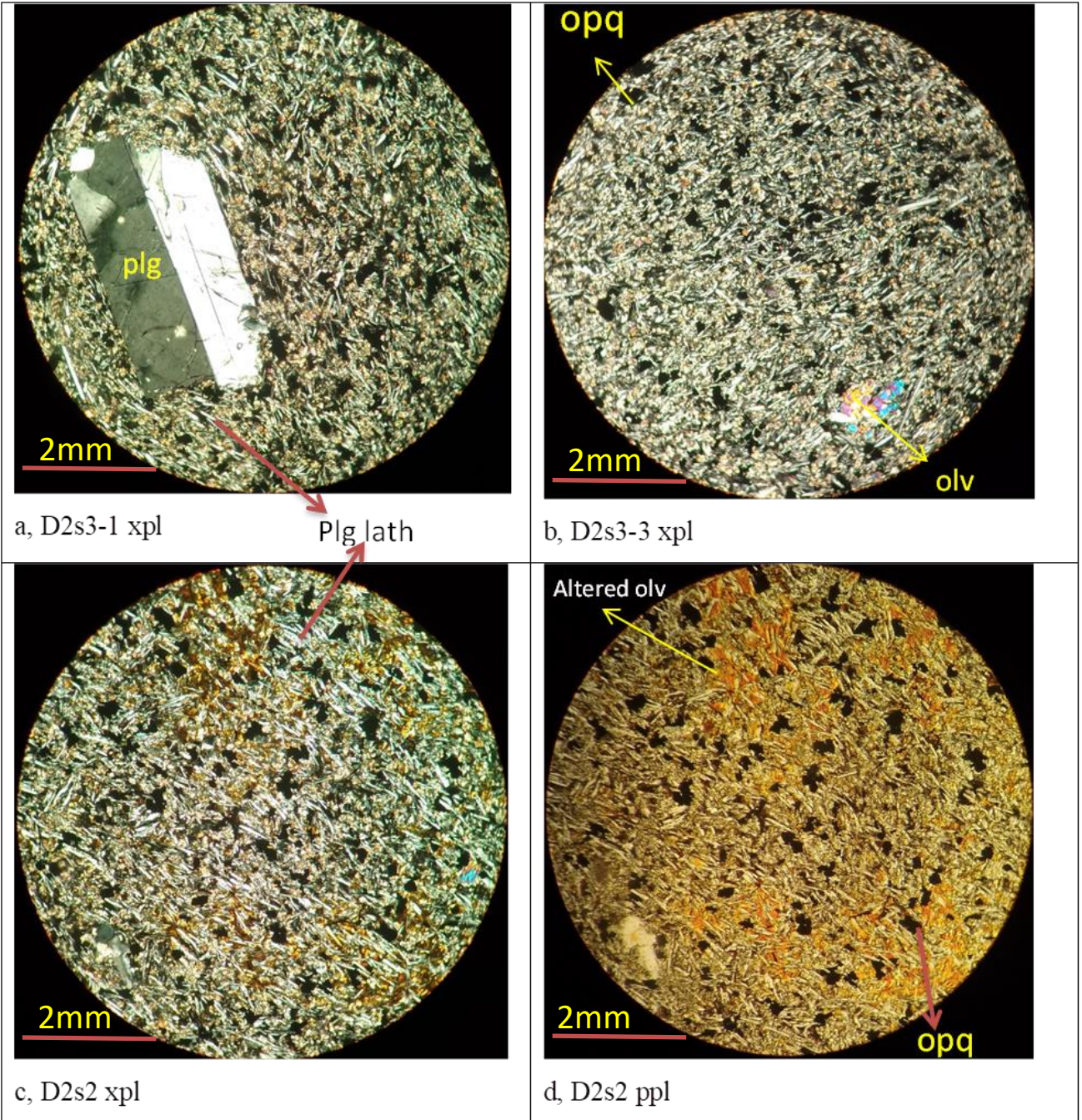


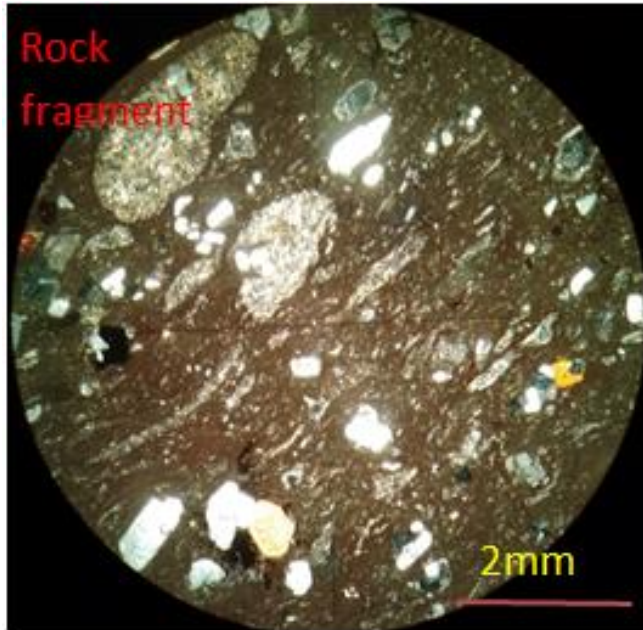
Fig 4.1: Representative thin section image of samples from the plateau basalt; (a) and (b) are at cross polarized light. C and d are the same view but under xpl and ppl view respectively. All photomicrographs are taken in 10X.

### **4.3. Petrographic analysis of samples from highly welded tuff unit**

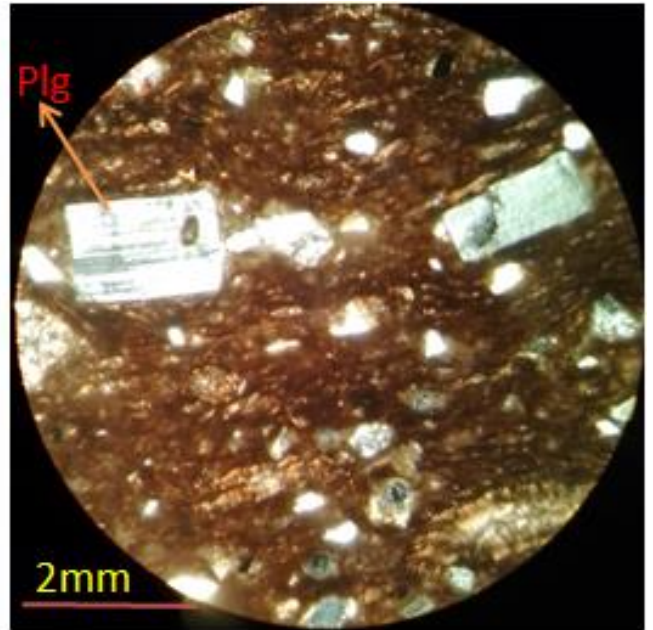
The highly welded tuff (ignimbrite) unit in this area consists of lapilli-sized (>2mm) elongated glasses called fiamme embedded within a vitric groundmass. Alongside these lithic fragments, such as pumice and glasses are also present.

#### **4.3.1 Highly welded tuff**

Thin section photomicrographs of Ignimbrite samples are composed of abundant crystals (Quartz (Qtz), plagioclase, Alkali feldspar (A<sub>1</sub>), and pyroxene (pxn) minerals) and glasses and rock fragment; and they show a typical dark lens of glassy material (fiamme). These samples show porphyritic texture with large proportion of ground mass (70%) and phenocrysts (felsic minerals) comprise 30% of samples. The ground mass is composed of felsic minerals. So this rock is rhyolitic in composition. The overall mineralogical proportion of this unit is 0.3 – 1.2mm euhedral plagioclase (10%), 0.1 – 1mm subhedral to anhedral alkali feldspar (45%) and <1.5mm anhedral quartz (40%) and opaque (5%). Trachytic texture is notably seen and shows degree of welding (highly welded).



a, D5s5 xpl



b, D1s5 xpl

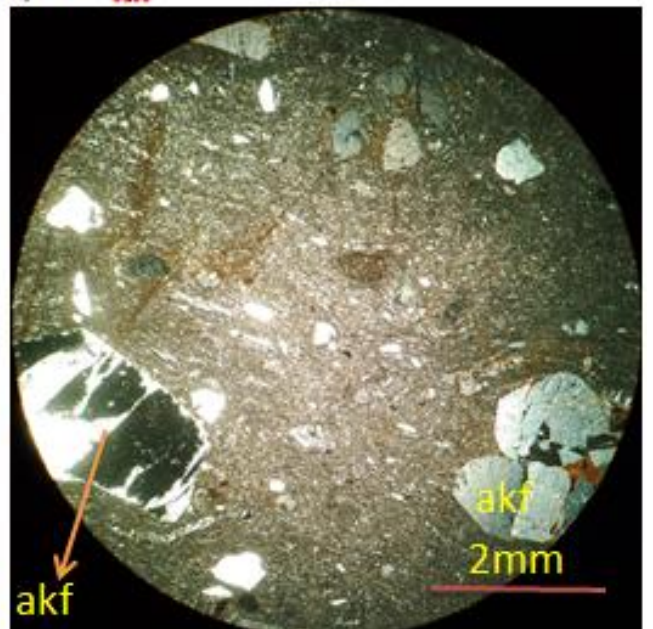
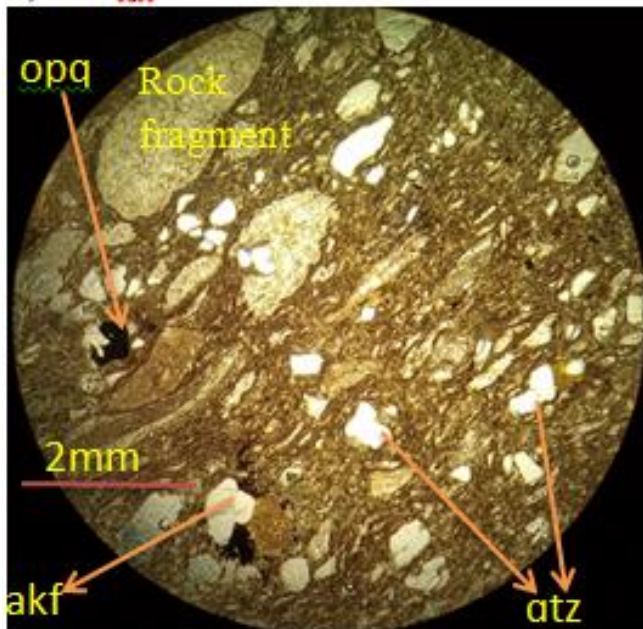
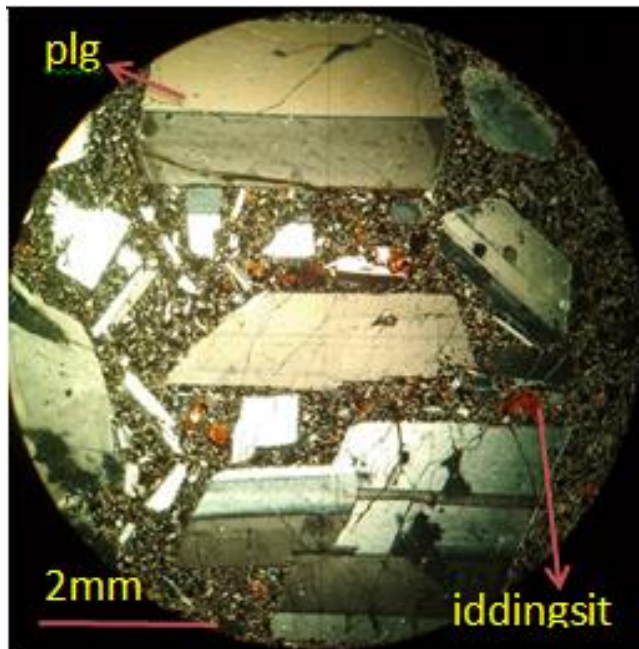


Fig 4.2: Representative thin section images of samples from the welded tuff (ignimbrite).

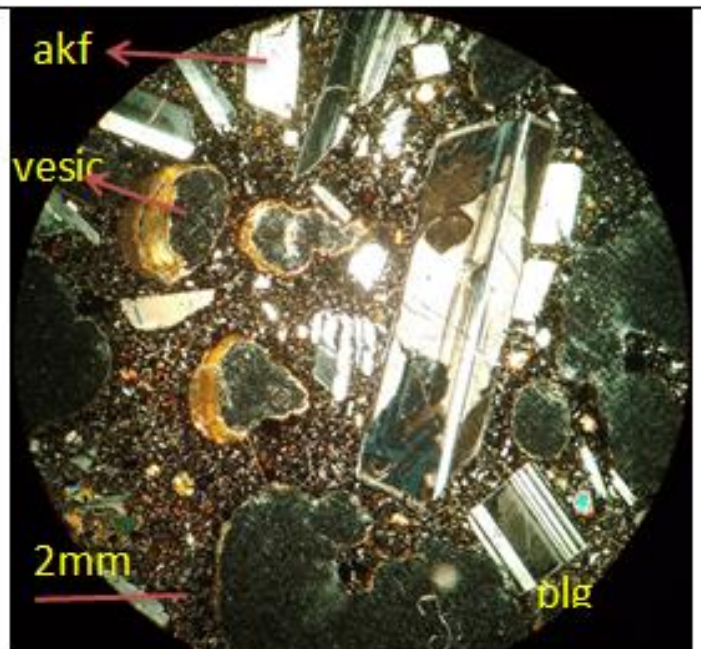
Here phenocrysts are clustered and forms glomerophytic texture. All photomicrographs are taken at 4X magnification.

#### **4.4. Petrographic analysis of samples from rift floor basalt.**

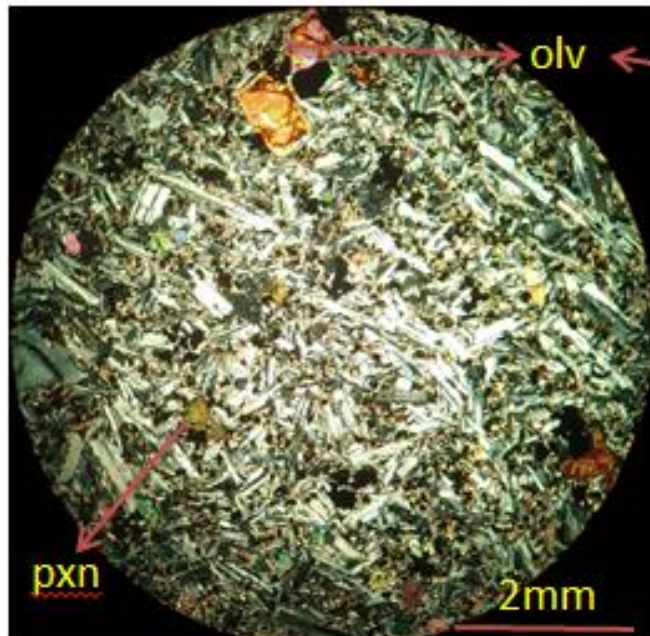
This unit is porphyritic basalt with groundmass dominated by plagioclase lath (microcrystalline-intergranular), pyroxene, altered olivine and opaque minerals. This unit is holocrystalline, the proportion of phenocrysts reach 30% and ground mass about 70%. Over all mineral proportion is 0.5 to 3mm plagioclase (70%), 0.3 to 1mm pyroxene (8%), 0.5 1.2mm olivine(10%) and 0.5 to 1.3mm opaque(Fe – Ti oxides)( 12%). fig(4.3b) vesicles are clearly observed. These thin section images are from rift basalt near Yelos town. Representative Thin section image of samples from rift basalt near Dalocha town (fig4.3 c and d); are at the same view under cross polarized light and plane polarized light respectively. It shows altered olivine (reddish- brawn color), which is called iddingsite. This unit is porphyritic, holocrystalline (felsophyric texture). In addition to these properties, samples (D4s2-2 and D4s2-3), (fig4.3 a ,b) shows euhedral, (1mm to 4mm long) crystals of plagioclase clustered(glomerophyric texture) and in Regional studies show this basalt has alkaline affinity (D. Meshesha et al., 2021) and quaternary in age.



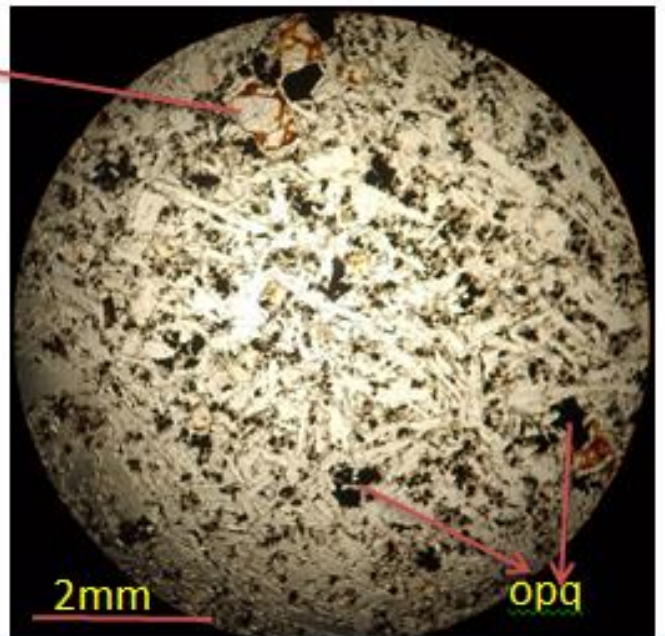
a, D4s2-2 xpl



b, D4s2-3 xpl



c. D6s2 xpl



d D6s2 ppl

Fig 4.3: Representative thin section images of samples from the rift floor basalt. These images show glomerophytic texture (a and b), felsophytic texture (c and d). The images are taken under xpl and ppl respectively. All images are taken at 4x magnification.

#### 4.5. Petrographic analysis of samples from Rhyolitic units.

Three representative thin section are prepared from Rhyolitic lava. These samples show several minerals and igneous textures. Samples from the rhyolite, at Worabe and Balchi area (fig 4.4a and b) are at the same view under cross polarized light and plane polarized light respectively. And (fig 4.4 c and d) are different samples of rhyolite under cross polarized light. These images show radiating texture of microcrystalline quartz. (All photomicrographs are taken in 10X). Over all proportion is 0.2 to 0.5mm anhedral alkali feldspar (akf), (25%) of 0.2 to 0.5mm anhedral quartz (Qtz) 35%, 0.5 to 1mm subhedral hornblende (hbd) 8(%) and glass 32%.

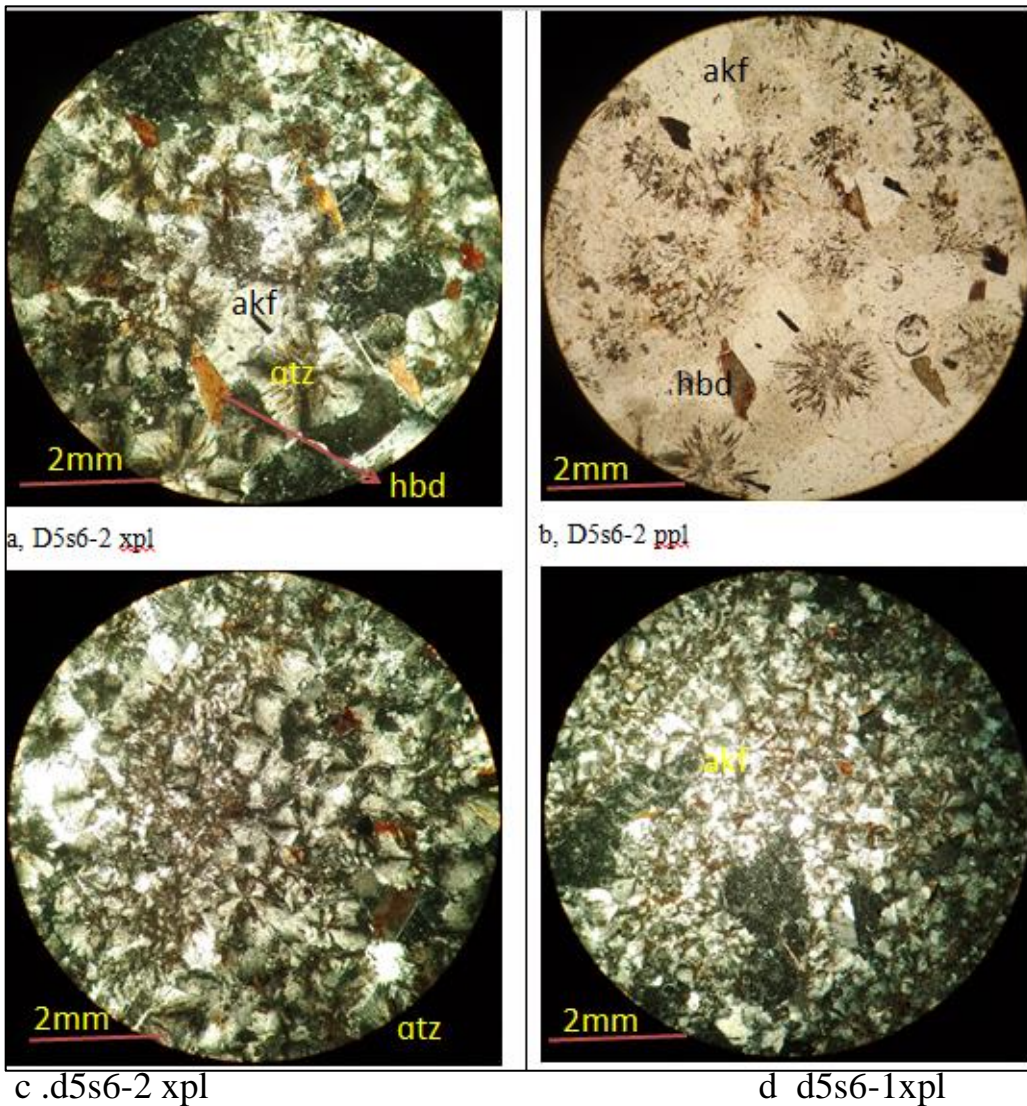


Fig 4.4: Representative thin section images of samples from rhyolitic lava dome. This unit shows radiating micro crystalline mineral (quartz), felty texture (random orientation of grains).

## Chapter five

### 5. Discussion of results and summary

The research area is situated in the Silte Zone of the Central Main Ethiopian Rift, within the central Ethiopian regional state. This region is characterized by Miocene to Pleistocene volcanic activity, with typical bimodal mafic-felsic associations. Most of the area is covered by felsic volcanic products. This chapter explores the complete stratigraphy of volcanic products in the Worabe area, along with Quaternary sedimentation within the same region, encompassing both the western rift escarpment and the rift floor. Additionally, it addresses the correlation of each stratigraphic unit with the nomenclature proposed by various researchers, ultimately presenting a composite stratigraphy of the Lithologic units within the research area along with a summarized overview of each unit. The stratigraphy includes diverse Lithologic units (from oldest to youngest) the plateau basalt (300 m thick), welded tuff (Ignimbrite, 250 m thick), Unwelded to poorly welded pyroclastic fall and/or flow deposits (270 m thick), rift floor Basaltic lava flow and scoria cones (80 m thick), Rhyolitic lava dome with obsidian and associated pyroclastic fall (280 m thick), and rift floor Volcaniclastic sediments (30 m thick).

The plateau basalt, located near the northwestern part of the study area, approximately 20 km from the main research area, is considered the oldest lithologic unit. The following key points highlight the geological conditions under which plateau basalt likely formed: The basaltic flows within the plateau basalt are primarily horizontally bedded. This indicates a depositional environment where lava flows settled and solidified in a horizontal manner over time. The basaltic flows originated from volcanic eruptions that produced lava with low viscosity, allowing for horizontal spreading and deposition. The presence of columnar joints in the basalt suggests a specific cooling history. Columnar joints form as lava cools and contracts, resulting in the development of vertical and tilted layers of rock. This cooling process likely occurred after the initial deposition of the basaltic flows. Petrographic analysis of samples from the plateau basalt reveals an aphyric texture, indicating a lack of visible crystals or phenocrysts within the rock. Additionally, the presence of altered minerals indicates subsequent alteration processes, possibly due to hydrothermal or weathering activities. In regional geological studies, the plateau basalt is referred to as the Guraghe

Anchar Basalt (Miocene in age and has Alkaline affinity) providing a regional context for its identification and classification.

Overlying plateau basaltic unit is welded tuff (ignimbrite), petrographic and field analysis of welded tuff (ignimbrite) gives composition of abundant crystals Quartz (Qtz), Alkali feldspar (Akf), Hornblende (hbd) minerals, glasses, and rock fragment (pumice). And it shows dark elongated glassy materials (fiamme). And also shows porphyritic texture with large proportion of ground mass (70%) and phenocrysts (dominantly quartz and alkali feldspar). The ground mass is composed of felsic minerals and glass. Hence this rock is Rhyolitic in composition. The presence of fiamme, porphyritic texture, lava flow banding, and a rhyolitic composition indicates that it formed under conditions of intense volcanic activity with explosive eruptions, rapid cooling of pyroclastic materials, and deposition in successive flow events. Regional works gave a name as Dino formation which is late Miocene to Pliocene (Tsegaye et al., 2005).

On the top of Welded tuff (ignimbrite) this area is covered by wide volcanic product, which is pyroclastic fall and pyroclastic flow. These deposits are thick and intercalated with other rock types (pumice, poorly welded tuff). Both pyroclastic fall and flow deposits are prevalent in this region, categorized as ash flow and ash fall. Pyroclastic Flow Deposits characterized by their whitish-gray color, moderate welding, and coarse mineral content (felsic minerals and lithic fragments), suggest explosive eruptions with significant pyroclastic flows. The variations in thickness and stratigraphic position (overlying ignimbrite or ash fall units) indicate changing eruption dynamics and source materials. Pyroclastic Fall Deposits: The whitish to yellow color, good sorting, and partial induration of these deposits imply less energetic eruptions compared to ash flows, resulting in the settling of finer ash particles. The intercalation with pumice fall and ash flow deposits suggests multiple eruptive phases or varying eruption intensities. The consistent presence of welded tuff (ignimbrite) at the base of both pyroclastic flow and pyroclastic fall units indicates a common volcanic origin and possibly sequential volcanic events.

In addition to the volcanic products mentioned earlier, the area also features basaltic lava flows that extend thinly but extensively. These flows cover a significant area and are associated with scoria cones, overlaying the pyroclastic fall/flow unit. The basaltic lava flows exhibit a grey color and contain vesicles, some of which are filled with secondary minerals. Similarly, the scoraceous basalt is characterized by red color, high vesicularity, and partial filling of vesicles with secondary

minerals. In certain regions, scoria fall deposits, leading to the formation of cone-like structures. These structures are easily recognizable on topographic maps due to their distinct steep slope on one side and gentle slope on the other. The cones exhibit various shapes such as saddle structures, half craters, and elliptical geometries, with their longest axes aligned parallel to the regional tectonic direction (NE to SW). This alignment suggests that the eruptions of these cones were influenced by preexisting geological structures (Mazzarini et al., 2016) as cited in (Tadesse et al., 2019). The basaltic lava flows have a maximum thickness of 6 meters and are closely associated with the deposition of scoria. These basalts display characteristics such as dark-grey color, porphyritic texture, and vesicularity, with some vesicles containing secondary minerals like calcite and quartz. The basalts form gentle slopes, flat plains, and occasionally lava domes.

Another prominent Quaternary volcanic product in the area is Rhyolitic lava flow, accompanied by fragments of obsidian, forming a stratovolcano. The Rhyolitic lava dome is visible in two distinct areas, forming large mountains. It exhibits whitish to pink colour and typically has a flat top surface with steep slopes. The lower part of the Rhyolitic lava flow shows intercalation with poorly welded ash flow deposits, while fragmented obsidian is found at the top of the Rhyolitic dome. The largest lava dome in this area reaches around 250 meters in height. The rhyolite's dome-forming nature is evident from its significant height relative to its width and the presence of sub-vertical flow banding. The texture of the Rhyolitic rock indicates trachytic features and contains many mineral crystals such as quartz, feldspar and hornblende. Thin sections of the rhyolite reveal a porphyritic texture with approximately 18% to 23% volumetric proportions of phenocrysts. These phenocrysts consist of up to 13% alkali feldspar, 4-7% opaque minerals (Fe-Ti oxides), and 4-5% quartz. The groundmass comprises microcrystalline quartz, alkali feldspar, and reddish stains, possibly indicating hydrothermal alteration and the presence of clay minerals.

The alteration of volcanic rocks into clay materials hints at past volcanic activity in the region, with subsequent weathering and breakdown of volcanic minerals into finer sediments. The white, fine, and soft nature of these clay materials indicates their potential for easy erosion and transport by water or wind. The intercalated layers of volcanic ash and tuffs in lacustrine sediments point to periods of volcanic eruptions and subsequent deposition in nearby lakes or water bodies. The composition of these sediments with volcanic components like pumice, obsidian, and different types of volcanic rocks suggests a volcanic influence on the geological history of the area.

Overall, the data indicates a complex volcanic history with multiple eruptive phases, varying eruption styles, and changes in magma composition.

Table 1: Composite stratigraphic log of the research area

Composite Stratigraphy	Petrographic Sample	Lithologic Units and Average thickness (m)	Regional Names	Age (Abebe et al., (2010), Tsegaye et al., (2005) and WoldeGabriel et al., (1990))
1200		Volcaniclastic sediment and Reworked Pyroclastic deposits (30 m)	Quaternary Sediments	Quaternary (~< 1.6 Ma)
1100	D5S6-1, D5S6-2 and D5S6-3	Rhyolitic lava dome and silicic pyroclastic deposit (280 m)	Central Volcanic Complexes	Pleistocene to Holocene (1.6 to 0.1Ma)
1000				
900	D4s2-1, D4S2-1, D4S2-2, D4S2-3, D6S1, D6S2, D6S3 and D6S4	Rift Basaltic lava flow (80 m)	Rift floor basalts	Pleistocene (1.6 to 0.1Ma)
800				
700		Unwelded to poorly welded pyroclastic deposits (270 m)	Upper Dino formation	Pleistocene (1.6 to 0.1Ma)
600				
500				
400	D1S6, D2S1, D2S2, D2S4, D3S3 and D5S5	Welded tuff (Ignimbrite) (250 m)	Lower Dino formation	Late Miocene–Pliocene (5.2-2.6 Ma)
300				
200	D2S3-1, D2S3-2, D2S3-3	Plateau basalt (300 m)	Guraghe-Anchar Basalts	Lower Miocene (12-5 Ma)
100				
0				

## **Chapter six**

### **6. Conclusion**

This area is characterized by an initial eruption of effusive, fissural volcanic products followed by an explosive eruption of a central volcano. The effusive volcanic activity occurred during the Miocene, while the central volcanic activity took place in the Pliocene. The center of these eruptions is not well known, likely obscured by more recent volcanic activity and tectonic processes. Subsequently, young rift floor basalts erupted, closely related to the Wonji fault belt. The final volcanic episode involved the eruption of central, dome-forming effusive volcanism accompanied by ash falls. Finally, rift sediments were deposited along riverbanks and within the graben, representing the youngest deposits in the area. Volcanic cones align in a northeast direction, and large normal faults trending northeast separate the rift margin from the rift floor.

In conclusion, the Worabe area exhibits a complex geological history characterized by bimodal (mafic and felsic) volcanic products, eruption styles, depositional environments, and alteration processes. The felsic rocks hold largest areal coverage of the research area and 77.8% of composite stratigraphy. The geologic evolution of the Silte Butajira Debrezeyt Fault Zone within the context of the Butajira Volcanic Field highlights the dynamic and complex tectonic history of the Ethiopian Rift system. From the stable Precambrian basement to the active rift and volcanic activities of the present, this region exemplifies the interplay between tectonics and volcanism in an evolving rift setting.

### **7. Acknowledgment**

I would like to extend my sincere gratitude to Addis Ababa University (AAU) for providing the financial support necessary to complete this research work. I am also grateful to Werabe University (WRU) for sponsoring my MSc program. My thanks go to the Department of Earth Sciences at AAU for granting unlimited access to their laboratory facilities and to the Geological Survey of Ethiopia for their assistance with thin-section preparation. Additionally, I am deeply appreciative of all the staff members in the Department of Earth Sciences at both AAU and WRU for their invaluable comments and suggestions during the preparation of this paper.

## References

- Abebe, B., Acocella, V., Korme, T., & Ayalew, D. (2007). Quaternary faulting and volcanism in the Main Ethiopian Rift. *Journal of African Earth Sciences*, 48, 115–124.
- Abebe, T., Balestrieri, M. L., & Bigazzi, G. (2010). The Central Main Ethiopian Rift is younger than 8 Ma: Confirmation through apatite fission-track thermochronology. *Terra Nova*, 22(6), 470–476.
- Abebe, T., Manetti, P., Bonini, M., Corti, G., Innocenti, F., Mazzarini, F., & Pecskey, Z. (2005). Geological map (scale 1:200,000) of the northern Main Ethiopian Rift and its implication for the volcano-tectonic evolution of the rift. *Geological Society of America Map and Chart Series*, MCH094.
- Acocella, V., & Korme, T. (2002). Holocene extension direction along the Main Ethiopian Rift, East Africa. *Terra Nova*, 14, 191–197.
- Acocella, V., Korme, T., & Salvini, F. (2003). Formation of normal faults along the axial zone of the Ethiopian rift. *Journal of Structural Geology*, 25, 503–513.
- Ayalew, D. (2000). Origin by fractional crystallization of transitional basalt for the Asela to Ziway pantellerites. *Chemical Geology*, 168, 1–3.
- Ayalew, D., Barbey, P., Marty, B., Reisberg, L., Yirgu, G., & Pik, R. (2002). Source, genesis and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts. *Geochimica et Cosmochimica Acta*, 66, 1429–1448.
- Ayele, A. (2000). Normal left-oblique fault mechanisms as an indication of sinistral deformation between the Nubian and Somalian plates in the Main Ethiopian Rift. *Journal of African Earth Sciences*, 31, 359–367.
- Basalfew, Z., Mathios, A., Meskerem, T., Mekdes, T., Mekonen, B., Mohamed, E., Getachew, B., & Ezra, Y. (2012). The geology, geochemistry and gravity survey of the Hosaena area [Unpublished technical report].
- Bonini, M., Corti, G., Innocenti, F., Manetti, P., Mazzarini, F., Abebe, T., & Pecskey, Z. Evolution of the Main Ethiopian Rift in the frame of Afar and Kenya rifts propagation. *Tectonics*, 24(1-24), TC1007.
- Chorowicz, J. (2005). The East African Rift System. *Journal of African Earth Sciences*, 43(1-3), 379-410.

- Corti, G. (2009). Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa. *Earth-Science Reviews*, 96(1-2), 1-53.
- Corti, G. (2019). Rifts and passive margins: Geological, geophysical, and geodynamic processes (Vol. 475). Geological Society of London.
- Corti, G., Cioni, R., Franceschini, Z., Sani, F., Scaillet, S., & Molin, P. (2019). Aborted propagation of the Ethiopian Rift caused by linkage with the Kenyan Rift. *Nature Communications*, 10, 1309.
- Corti, G. (2022). Magmatic architecture of the Main Ethiopian Rift: Insights from new geochemical and petrological data. *Tectonophysics*, 833, 230869.
- Ebinger, C.J., Yemane, T., Harding, D.J., Tesfaye, S., Kelley, S., & Rex, D.C. (2000). Rift deflection, migration, and propagation: Linkage of the Ethiopian and Eastern rifts, Africa. *Geological Society of America Bulletin*, 112(2), 163-176.
- Gani, N.D., Abdelsalam, M.G., Gani, M.R., & Gera, S. (2007). Strain accommodation within an oblique rift system: Fault patterns, ductile deformation, and syn-rift stratigraphy of the Mesozoic-Paleogene Anza Rift, Kenya. *Journal of African Earth Sciences*, 48(4), 275-294.
- Hutchison, W., & Ayele, A. (2021). The dynamics of volcanic activity in the East African Rift: Insights from volcano-tectonic interactions in the Main Ethiopian Rift. *Journal of Volcanology and Geothermal Research*, 412, 107232.
- Keir, D., Bastow, I.D., Whaler, K.A., Daly, E., Cornwell, D.G., & Hautot, S. (2009). Lower crustal earthquakes near the Ethiopian rift induced by magmatic processes. *Geology*, 37(2), 83-86.
- Megerssa, L., Rapprich, V., Novotný, R., Verner, K., Erban, V., Legesse, F., & Manaye, M. (2019). Inventory of key geosites in the Butajira Volcanic Field. The European Association for Conservation of the Geological Heritage.
- Meshesha, D., Chekol, T., Negussia, S. (2021). Major and trace element compositions of basaltic lavas from the western margin of the central main Ethiopian rift: Enriched asthenosphere vs. Mantle plume contribution. *Heliyon*, 7, e08634.
- Mohr, P.A. (1983). Volcanotectonic aspects of the Ethiopian Rift evolution. *Bulletin of Volcanology*, 46(2), 147-160.
- Rooney, T. O. (2017). The Cenozoic magmatism of East-Africa: Part I Flood basalts and pulsed magmatism. *Lithos*, 286(Supplement C), 264–301.

- Tadesse, A. Z., Ayalew, D., Pik, R., Yirgu, G., & Fontijn, K. (2019). Magmatic evolution of the Boku Volcanic Complex, Main Ethiopian Rift. *Journal of African Earth Sciences*. <https://doi.org/10.1016/j.jafrearsci.2018.08.003>
- Ukstins, I. A., Renne, P. R., Wolfenden, E., Baker, J., Ayalew, D., & Menzies, M. (2002). Matching conjugate volcanic rifted margins:  $^{40}\text{Ar}/^{39}\text{Ar}$  chrono-stratigraphy of pre- and syn-rift bimodal flood volcanism in Ethiopia and Yemen. *Earth and Planetary Science Letters*, 198(3-4), 289-386. doi: 10.1016/s0012-821x(02)00525-3.
- Wolfenden, E., Ebinger, C., Yirgu, G., Renne, P.R., & Kelley, S.P. (2005). Evolution of a volcanic rifted margin: Southern Red Sea, Ethiopia. *Geological Society of America Bulletin*, 117(7-8), 846-864

## Appendix I: Measurements of structures

Table 2: List of geologic structures and their measurement value

Type of structure	Measurement (strike/ dip and dip direction)		Lithological unit from which structure is measured
	Strike	Dip with dip direction	
Fault	15	45 SE	Welded tuff
Fault	17	60 SE	Welded tuff
Fault	25	55 SE	Pyroclastic fall
Fault	40	50 SE	Unwelded tuff
Fault	30	85 SE	Unwelded tuff
Columnar joint	75	85NW	Welded tuff
Columnar joint	55	48SE	Welded tuff
Columnar joint	40	60 SE	Welded tuff
Columnar joint	30	57NW	Basalt
Columnar joint	80	80 SE	Welded tuff
Columnar joint	30	75 NW	Welded tuff
Normal fault	30	33NW	Unwelded tuff
Normal fault	25	48SE	Unwelded tuff

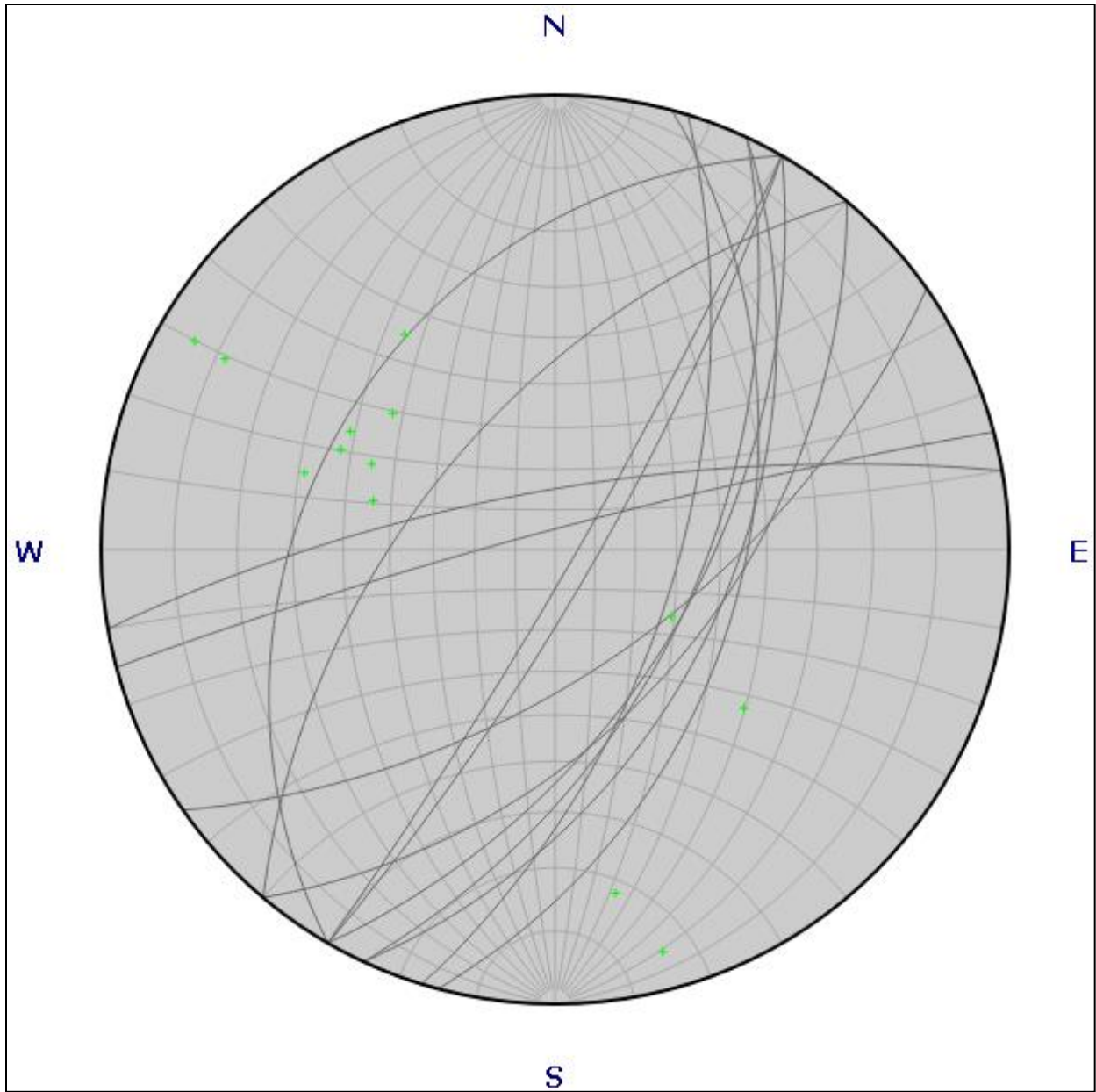


Fig 6.1: Stereonet image showing plane (solid lines) and pole (green points) of measured geologic structures.

## Appendix II: Petrographic analysis of samples from all units.

In this part analysis results, Sample code, Location UTM, Lithostratigraphic unit from which sample was taken, Igneous texture, Distinguishable Mineral Constituent, Dominant phase in phenocrysts and % of Phenocrysts with modal Name of rock presented.

Table 3: Petrographic analysis results of each sample.

Sample code	Location UTM (Zone 37P)	Litho stratigraphic unit	Texture	Distinguishable Mineral Constituent	Dominant phase in phenocryst	% Of Phenocrysts	Modal Name
D1s6	406391 864952	ignimbrite	Porphyritic	Quartz, alkali feldspar, plagioclase	Qtz =15 Akf =70 Plg=15	40	Ignimbrite
D2 s1	415167 887543	Ignimbrite	Porphyritic	Quartz, alkali feldspar, Glass inclusion	Qtz =30 Akf =70	45	Rhyolitic ignimbrite
D2s2	415507 888994	Ignimbrite	Porphyritic	Quartz, alkali feldspar,	Qtz =40 Akf =60	30	Rhyolitic ignimbrite
D2s3-1	417221 888800	Basalt	Aphanitic	Olivine, plagioclase, pyroxene Fe- Ti oxides(opaque).	Olivine 12 plagioclase 76 Pyroxene 12	45	Aphyric basalt
D2s3-2	417221 887550	Basalt	Aphanitic	Olivine, plagioclase, pyroxene Fe- Ti oxides(opaque).	Olivine 9 plagioclase 76 Pyroxene 15	40	Aphyric basalt

D2s3-3	416721 887800	Basalt	Aphanitic	Olivine, plagioclase, pyroxene Fe- Ti oxides(opaque).	Olivine 15 plagioclase 70 Pyroxene 15	35	Aphyric basalt
D2s4	416621 889571	Ignimbrite	Porphyritic	Quartz, alkali feldspar and plagioclase	Qtz =40 Akf =55 Plg 5	30	Rhyolitic ignimbrite
D3s3	409637 875392	Ignimbrite	Porphyritic	Quartz, alkali feldspar and plagioclase	Qtz =40 Akf =50 Plg 10	35	Rhyolitic ignimbrite
D4s2-1							
D4s2-2	424198 874030	Amygdaloidal basalt	Porphyritic basalt	Plagioclase Olivine Pyroxene Calcite Orthoclase Opaque minerals	Plagioclase= 80 Olivine =10 Pyroxene =10	70	Porphyritic basalt
D4 s2-3	421445 874030	Amygdaloidal basalt	Porphyritic basalt	Plagioclase Olivine Pyroxene Calcite Orthoclase Opaque minerals	Plagioclase= 85 Olivine =8 Pyroxene =7	55	Porphyritic basalt
D5 s6-2	414300 863600	Rhyolite	Aphanitic	Quartz Orthoclase hornblende Glasses Biotite	Quartz= 45 Orthoclase = 55	40	Rhyolite
D5 s5	411933 864556	Ignimbrite	Porphyritic	Quartz Orthoclase Glasses	Quartz= 30 Orthoclase = 70	30	Ignimbrite

D5 s6	412593 863500	Rhyolite	Aphanitic	Quartz Orthoclase Glasses	Quartz= 50 Orthoclase = 50	30	Rhyolite
D5s6.1	412580 863550	Rhyolite	Aphanitic	Quartz Orthoclase Glasses	Quartz= 45 Orthoclase = 55	35	Rhyolite
D6s1	420219 857100	Basalt	Porphyritic	Plagioclase Olivine Pyroxene Orthoclase Opaque	Plagioclase =70 Olivine =20 Pyroxene=10	60	Basalt
D6s2	422123 860500	Basalt	Porphyritic	Plagioclase Oliven Pyroxene Orthoclase Opaque	Plagioclase =75 Oliven=15 Pyroxene=10	65	Basalt
D6s3	420537 857393	Basalt	Aphanitic	Plagioclase Olivine Pyroxene Orthoclase Opaque	Plagioclase =70 Olivine =15 Pyroxene=15	40	Aphyric basalt
D6s4	420819 868340	Basalt	Porphyritic	Plagioclase Pyroxene Orthoclase Quartz, Olivine, opaque	Plagioclase =55 Olivine =25 Pyroxene=20	50	Porphyritic Basalt