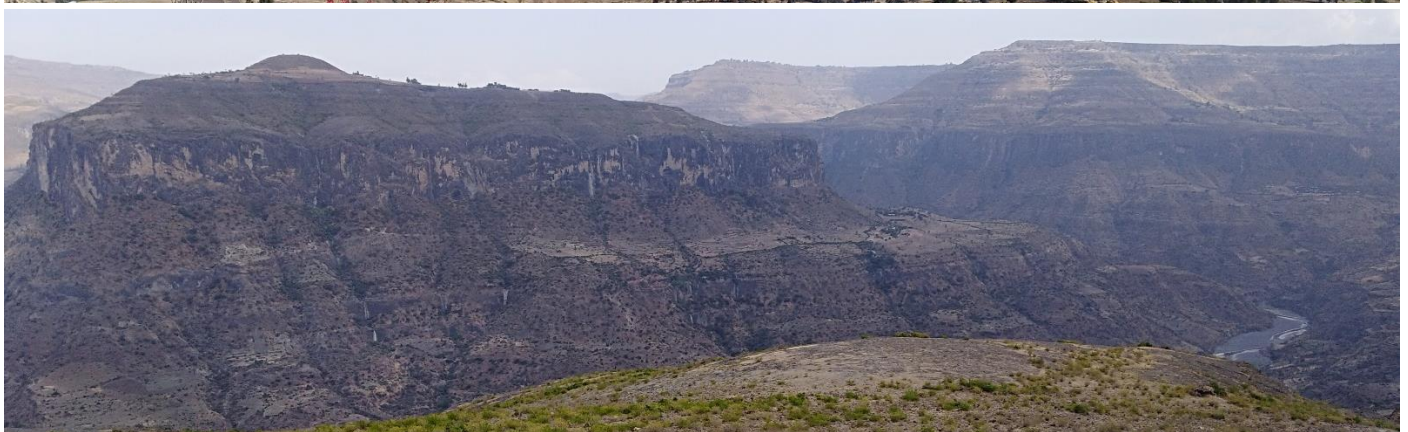


Addis Ababa  
University  
(Since 1950)



**ADDIS ABABA UNIVERSITY**  
**SCHOOL OF GRADUATE STUDIES**  
**SCHOOL OF EARTH SCIENCES**

**PETROSTRATIGRAPHIC STUDY OF VOLCANIC ROCKS IN SELA DINGAY  
AREA, NORTH SHEWA, CENTRAL ETHIOPIA**



**By**

**FAYSEL SEFA**

**ADVISOR: *DEREJE AYALEW (Prof.)***

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

**June 01, 2021  
Addis Ababa, Ethiopia**

**ADDIS ABABA UNIVERSITY  
SCHOOL OF GRADUATE STUDIES  
DEPARTMENT OF EARTH SCIENCES**



**PETROSTRATIGRAPHIC STUDY OF VOLCANIC ROCKS IN SELA DINGAY  
AREA, NORTH SHEWA, CENTRAL ETHIOPIA**

**By**  
**FAYSEL SEFA**  
**ADVISOR: *DEREJE AYALEW (Prof.)***


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

**June 01, 2021  
Addis Ababa, Ethiopia**





### Declaration for Originality

This is to certify that the thesis prepared by Faysel Sefa, entitled: “**Petrostratigraphic Study of volcanic rocks in Sela Dingay area, North Shewa, Central Ethiopia**” is compiled under supervision of Prof. Dereje Ayalew and submitted in partial fulfillment of the requirements for the Masters of Science in Geological Sciences (Petrology). It is complied with Addis Ababa University's rules and regulations and, it satisfies accepted requirement in terms of originality and quality. I further declare that this work is not presented or submitted to any other university or institution. All secondary information sources are properly referenced and acknowledged.

Faysel Sefa Abdu (MSc candidate)

Signature  Date 28/07/2021

#### **Signed by the Examining Committee:**

	<u>Signature</u>	<u>Date</u>
<u>Advisor</u>		
Prof. Dereje Ayalew _____		<u>3/8/2021</u>
<u>Examiners</u>		
Prof. Gezahegn Yirgu _____		<u>30-07-2021</u>
Dr. Takele Chekol _____		<u>05/08/2021</u>
<u>Graduate Program Coordinator</u>		
Dr. Bayisa Regassa _____		<u>30/07/2021</u>

Dr. Balemwal Atnafu

---

**Chair of Department**

## **ABSTRACT**

*A petrostratigraphic study of volcanic rocks in the parts of NW Ethiopian Plateau is presented in this paper. The study area is located in the North Shewa district, specifically around Sela Dingay, in central Ethiopia, about 200 kilometers north of Addis Ababa. The studied stratigraphic successions are cut by Mofar River starting from its tributaries in the highly elevated Termaber section (~3315m) downward into the lowly elevated Gawna section (1540m) in a way from Sela Dingay to Sasit in the central part of the study area. The main objective of the study was to provide a complete lithostratigraphy of the research area based on a thorough field investigation (mapping and description), stratigraphic sampling, and petrographic (thin section) analysis of representative samples. Furthermore, the study attempts to integrate these data to relate them with regional studies on geochemical, geochronological, and magma emplacement behavior data about the whole volcanic provinces of Ethiopia. From the composite stratigraphic section constructed in this study, five volcanic lithostratigraphic units (Lower Basalt, Sela Dingay Rhyolitic Lava flow, Upper Basalt, Sela Dingay Rhyolite-Ignimbrite, and Termaber Shield Basalt) which are a part of Cenozoic continental flood basalt, are identified. The volcanic rocks are underlain by Mesozoic (Cretaceous) Sandstone formation. The basaltic lava flows (fissural flows) are the dominant product with interlayered rhyolitic-pyroclastic deposits with the felsic products dominating the top part and the most top part of the succession is represented by central type shield basalt. These stratigraphic units are separated by a considerable time gap marked by alteration/erosional surface, paleosol, or sediments, which are all related to a decrease in magma flux in the system. Exposed flow fields display three-part features: flow top, flow core, and flow bottom structures. Flow tops are often made up of glassy to very fine-grained vesicular basalt, or scoriaceous to vesicular basalt fragments (brecciated flow top) that lie above a zone of non-fragmented, infrequently vesicular to columnar jointed basaltic core. The flow bottom is characterized by a limited zone of sparsely vesicular, glassy to very fine-grained basalt. A tabular to compound braided flow facies is confirmed by field observations of lava flow fields. A total of 24 petrographic samples from these stratigraphic units are studied by using a petrographic microscope. The majority of the samples are from Basaltic units and have a variety of textures ranging from aphyric to mildly phyrlic to porphyritic. Plagioclase and Olivine are the major phenocryst phase with a proportion of pyroxene and Fe-Ti-oxides. In some samples, the groundmass is made up of microlites of the same phase with a glassy texture. Cumulophyrlic, ophitic, and poikilitic to sieve textured phenocryst phases are embedded in a felty or trachytic groundmass in the porphyritic samples. In most basaltic samples, these features combine to generate porphyritic, holocrystalline to hypocrytalline, and Vitrophyric textures. Alkali feldspar, quartz, plagioclase, and lithic fragments with glassy groundmass predominate in rhyolitic and ignimbrite rock samples. The petrographic data from analyzed samples characterizes a part of HTI flood basalt in geochemically zoned Ethiopian flood basalt. The predominance of plagioclase mineral as a phenocryst and groundmass phase and the occurrence of significant felsic-pyroclastic products coincides with the regional studies relating these character for the late-stage (termination phase) of flood basalt volcanism.*

## **ACKNOWLEDGEMENT**

First and foremost, I want to express my gratitude to Addis Ababa University (AAU) for granting me this great chance to begin my master's degree and for providing me with financial support to complete this thesis. I am thankful to the Department of Earth-sciences of AAU for unlimited access to laboratory facilities.

I am deeply grateful to my advisor Prof. Dereje Ayalew, for his continuous guidance, invaluable advice, comments, and endless suggestions. His comments and recommendations helped me throughout the research and writing of this thesis.

I am grateful to acknowledge all instructors in the school of Earth-sciences of Addis Ababa University, for their teaching, encouragement, and valuable comments in my undergraduate and postgraduate class courses; I have greatly benefited from their teaching and encouragement to finish the fieldwork and thesis writing processes easily. I am extremely grateful to have had them as my teachers.

I also want to express my gratitude to all of the previous and current students at Addis Ababa University for their friendship, motivating discussions, and all of the feedback we've had over the last two years.

Last but not least, I would like to show my thankfulness to the community surrounding the study area (Sela Dingay) as well as any individuals who have directly or indirectly supported my work.

To my lovely family, thanks for everything.

## TABLE OF CONTENTS

ABSTRACT .....	ii
ACKNOWLEDGEMENT .....	iii
TABLE OF CONTENTS .....	iv
LIST OF FIGURES .....	vi
LIST OF TABLES .....	vii
CHAPTER-ONE.....	1
1. INTRODUCTION .....	1
1.1. General introduction.....	1
1.2. Study Area Description .....	3
1.3. Topography and Drainage .....	5
1.4. Population, Climate, and Vegetation.....	6
1.5. Problem statement .....	7
1.6. Objectives.....	8
1.6.1. General Objective .....	8
1.6.2. Specific Objectives .....	8
1.7. Methodology .....	8
1.7.1. Field description of lithostratigraphic units.....	8
1.7.2. Stratigraphic sampling.....	9
1.7.3. Petrographic Analysis.....	9
1.8. Review of previous geological work.....	11
1.9. Significance of the research .....	14
1.10. General chapter schemes of the report .....	14
CHAPTER-TWO.....	15
2. REGIONAL GEOLOGY .....	15
2.1. Continental Flood Volcanisms .....	15
2.2. Flood Basalt magmatism in East Africa.....	16
2.3. Ethiopian Continental Flood Basalts.....	17
2.4. North-Western Ethiopian Plateau.....	19
CHAPTER-THREE .....	24
3. LOCAL GEOLOGY .....	24
3.1. Introduction .....	24
3.2. Descriptions of Local Lithologies .....	26

3.2.1. Mesozoic Sandstone formation .....	26
3.2.2. Lower Basalt (Ashenge Formation) .....	27
3.2.3. Sela Dingay Rhyolitic Lava flow .....	29
3.2.4. Upper Basalt (Aiba formation) .....	31
3.2.5. Sela Dingay Rhyolite-Ignimbrite units (Alajae Formation) .....	33
3.2.6. Shield Basalt (Termaber formation) .....	35
3.3. Morphology of Lava Flow Products .....	38
3.4. Geologic Structures .....	43
3.4.1. Primary Structures .....	43
3.4.2. Secondary structures .....	47
CHAPTER-FOUR .....	49
4. PETROGRAPHY .....	49
4.1. Introduction .....	49
4.2. Samples from Plateau Basalts .....	49
4.2.1. Lower Basalt .....	49
4.2.2. Sela Dingay Rhyolitic Lava flow .....	51
4.2.3. Upper Basalt .....	52
4.2.4. Rhyolite .....	55
4.2.4. Ignimbrite .....	57
4.3. Samples from Shield Basalt .....	58
CHAPTER-FIVE .....	62
5. DISCUSSION AND SUMMARY .....	62
CHAPTER-SIX .....	68
6. CONCLUSIONS AND RECOMMENDATIONS .....	68
6.1. Conclusions .....	68
6.2. Recommendations .....	68
REFERENCES .....	69

## LIST OF FIGURES

Plate 1.1. Topographic Profiles and 3D DEM of the Ethiopian Main Volcanic Sectors.....	2
Plate 1.2. Location and Accessibility Map of the study area; the inset-geologic map of Ethiopian Flood Basalt is from Rooney (2017). .....	3
Plate 1.3. Location and Accessibility Map of the study area from Google map imagery. ....	4
Plate 1.4. 2D and 3D Physiographic map of the study area with Topographic profile. ....	6
Plate 1.5. Average Temperature and Rainfall from 2014-2021 in Sela Dingay (administrative center of Mojana Wereda Woreda).....	7
Plate 1.6. Methodology flow chart illustrating the major components of the study. ....	10
Plate 2.1. Location map of Large igneous provinces (LIPs) of the world, ages are those of the main phase or pulse of volcanism.....	16
Plate 2.2. (a) Cenozoic magmatic activity in Africa and parts of the Arabian Peninsula and (b) map of Oligocene basalts in Ethiopia and Yemen (after Rooney, 2017).....	18
Plate 2.3. Geological map of the northern part of the Ethiopian plateau depicting the distribution of the bimodal basalt–rhyolite flood volcanism and overlying shield volcanoes. ....	21
Plate 2.4. Stratigraphic section from the different parts of NW Ethiopian plateau, with different nomenclatures used by researchers. ....	23
Plate 3.1. a) Geologic map of the study area. b) Inset map showing the location of the study area. The unobserved area is completed by referring geological map of the Were-Ilu Map-sheet by Tigel Belay et al. (2009) (Geological Survey of Ethiopia); c) Geologic cross-section along the line AB in (a). ....	25
Plate 3.2. Different exposures of Mesozoic Sandstone unit at the base of the stratigraphic section of the study area. ....	26
Plate 3.3. Different exposures of Lower Basalt from Gawna section in NW end of the study area.....	28
Plate 3.4. Panoramic view of massive and thicker columnar jointed lower part of Sela Dingay Rhyolitic Lava flow exposure in Gawna section. The most bottom part consists pyroclastic deposit.....	29
Plate 3.5. Outcrops of various products within the Sela Dingay Rhyolitic Lava flow unit from the top part of the unit to the bottom.....	30
Plate 3.6. Panoramic view of the underlaying different units below the Upper Basalt around the Gawna area; the exposure also demonstrates planar composite flows of various thickness lava flows. ....	31
Plate 3.7. Outcrop photographs of various flow units within Upper Basalt from different parts of the study area. ....	32
Plate 3.8. Major lithological units within Sela Dingay Rhyolite-Ignimbrite units. ....	34
Plate 3.9. Outcrop scale exposures of different units in the Shield Basalt from the Termaber area. ....	36
Plate 3.10. Panoramic view showing the contact area of the Shield basalt and the underlying Rhyolitic formation separated by a thick deposit of sediment in the Termaber area. ....	36
Plate 3.11. Stratigraphic section of the various lithologic units in the study area in four different sections (Gawna, Sasit, Sela Dingay, and Termaber) and similar formations are connected by a red line.....	37
Plate 3.12. Photographs of different basaltic exposures (Upper basalt flow units) demonstrating the typical features of lava flow morphologies of flood basalts in the study area.....	39
Plate 3.13. Continued... Photographs of different basaltic exposures (Upper basalt flow units) demonstrating the typical features of lava flow morphologies of flood basalts in the study area.....	40
Plate 3.14. Continued... Photographs of different basaltic exposures (Upper basalt flow units) demonstrating the typical features of lava flow morphologies of flood basalts in the study area.....	41
Plate 3.15. a) Small lobes from compound flows of upper basalt at contact area with the underlying Sela Dingay Rhyolitic Lava flow unit in the Sela Dingay section near to Mofar river. Individual lobes are affected by spheroidal weathering (Exfoliation). b) Compound type flow geometry from the top part of	

the Sela Dingay section along Taj Wuha. c) Thick layer of sheet flow from the Sela Dingay section along Kaskash River. ....	42
Plate 3.16. Panoramic view of morphological topographies formed by the different lava flow products	44
Plate 3.17. Different types of columnar jointing in Sela Dingay Rhyolitic lava flow products from top to bottom part of the unit.....	45
Plate 3.18. Different types of primary structures from different eruptive products. ....	46
Plate 3.19. Exposures of representative secondary structures observed in the study area.....	47
Plate 3.20. Panoramic view of Landscape (ridges and lineaments) formed by the different lava flow products of the Flood Basalt in the Study area. ....	48
Plate 4.1. Representative thin section photomicrographs of samples from the Lower basalt .....	50
Plate 4.2. Representative thin section photomicrographs (a & c) and hand-specimens (b & d) of Glassy Sela Dingay Rhyolitic Lava flow samples.....	51
Plate 4.3. Representative thin section photomicrographs of aphyric basalt samples from the Upper Basalts .....	52
Plate 4.4. Photomicrographs showing certain textural features of Plg-phyric basalt samples from the Upper Basalts .....	53
Plate 4.5. Photomicrographs showing clusters of plagioclase, olivine, and clinopyroxene minerals (Cumulophyric texture) in Plg-Ol-phyric basalt samples from the Upper Basalt. ....	54
Plate 4.6. Photomicrographs showing certain textural features in Plg-Px-phyric basalt sample from the Upper Basalt: .....	55
Plate 4.7. Representative thin section photomicrographs of Rhyolite samples, sanidine, and quartz are the dominant phenocryst phase within a glassy groundmass.....	56
Plate 4.8. Hand-sample photograph (a) and thin section photomicrographs of Ignimbrite sample (b, c, d) (SD-07) .....	57
Plate 4.9. Representative thin section photomicrographs from aphanitic shield basalt.....	58
Plate 4.10. Representative thin section photomicrographs from Porphyritic shield basalt .....	59

## LIST OF TABLES

Table 2.1. The petrographic characteristics of the various lava types from spatially zoned NW Ethiopian plateau basalts .....	22
Table 4.1. Summary of Textural features of the petrographically analyzed rock samples in order of their elevation.....	60
Table 5.1. Composite Litho-stratigraphy of the study area with summary notes. ....	66
Table 5.2. Correlation of the local volcanic Lithostratigraphy to the previous works in proximity to this study area. ....	67

## **CHAPTER-ONE**

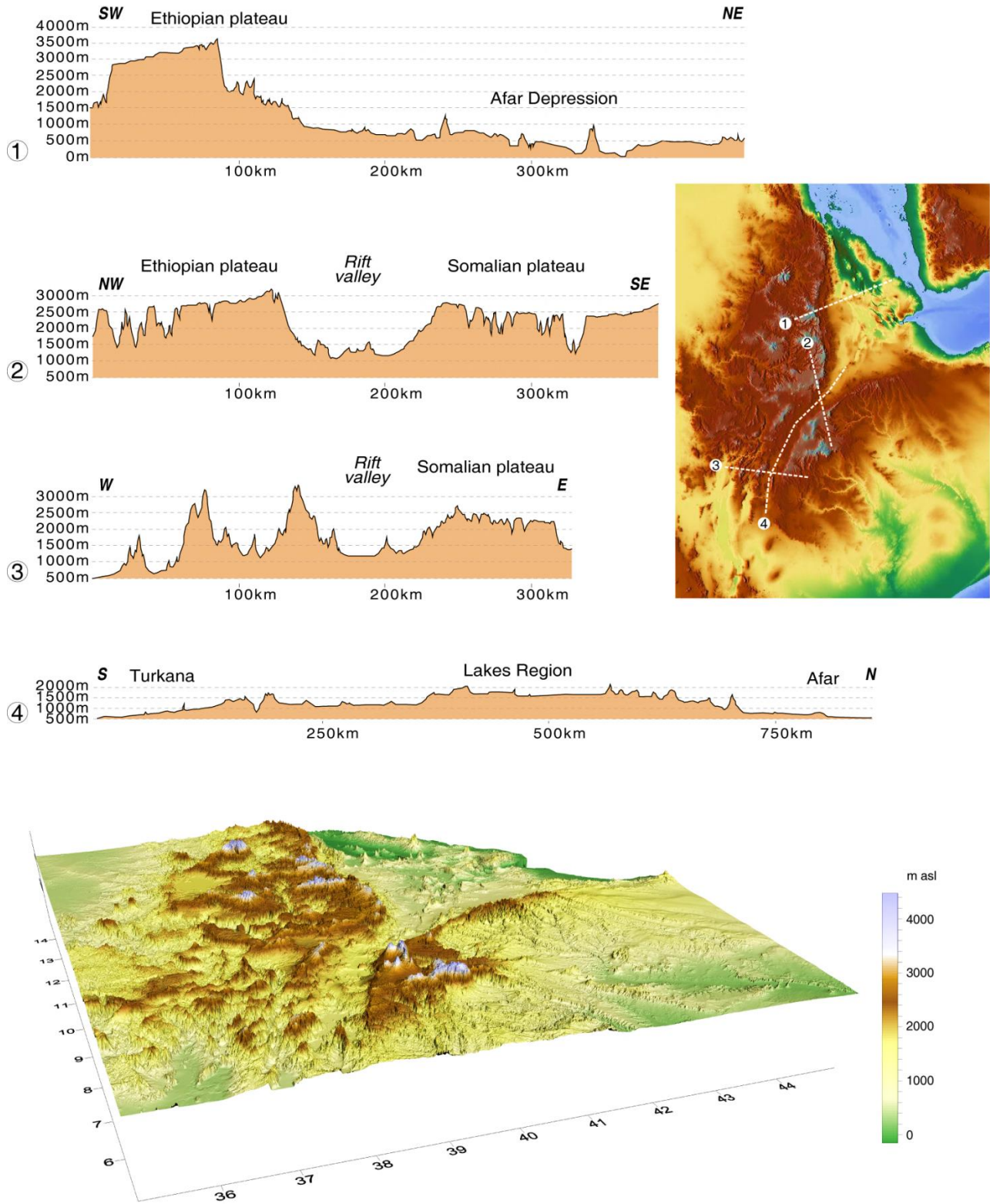
### **1. INTRODUCTION**

#### **1.1. General introduction**

Most of the Earth's crust is of magmatic origin, attesting to the enormous role that volcanic and related magmatic processes have played in forming the outermost solid crust of our planet. In addition, the distribution of volcanoes, past and present, can be closely linked to the dynamics of the crust and mantle within a plate tectonics context. Thus it is hardly surprising that many geoscientists work in terranes or on research topics directly or indirectly associated with volcanic rocks (Tilling, 1989). The generation of a large igneous province is an exceptional volcanic event in Earth history because of the large total volume of predominantly basaltic magma generated, and lava erupted, over brief periods of geological time (usually less than 1–2 m.y., Self et al., 2014). Continental flood basalt provinces are a subset of the broader group of large igneous provinces.

The Ethiopian volcanic province, located at the northern end of the East African Rift System (EARS), is one of the youngest large igneous provinces (LIPs) consisting mainly of flood basalt volcanics with an area of 622,108 km<sup>2</sup> (Rooney et al., 2017) and a younger rift volcanics. These volcanic products are mainly exposed within the rift and plateaus, which can be divided into two main series: Trap Series and Rift Series. Trap series are those groups of formations that are formed before the perfect development of the main Ethiopian rift during the time of rift initiation. They are also known as plateau volcanoes or pre-rift sequences. They are the main igneous units exposed in the northwest and southeastern Ethiopian plateaus covering a total volume of about ~620,147 km<sup>3</sup> (Rooney, 2017), with a layer of mafic and felsic volcanic rocks (Ukstins et al., 2002; Kieffer et al., 2004).

The average Lava thickness estimates are highly variable; NW Ethiopian Plateau (1.6 km), SE Ethiopian Plateau & Chew Bahir Basin (500 m), and Somali/Harrar Plateau (650 m) (Rooney et al., 2017). The plateau volcanics are cut by the rift faulting and are distributed asymmetrically about the margins of Afar and Main Ethiopian Rift; that lying to the west of the rift system are designated the Western Ethiopian plateau (WEP), while others to the east are named the South Eastern Ethiopian plateau (SEP). The WEP comprises the northern, central, and southwestern sectors, whereas SEP includes the eastern, southeastern, and southernmost parts of the Ethiopian flood volcanic province.



**Plate 1.1. Topographic Profiles and 3D DEM of the Ethiopian Main Volcanic Sectors.**  
(<http://ethiopianrift.igg.cnr.it/riftvalleygeography.htm> accessed on Nov 11, 2020).

## 1.2. Study Area Description

The study area Sela Dingay, is a part of the Northwestern Ethiopian plateau in the Central Part of the country, located in Amhara regional state, North Shewa administrative zone, specifically Sela Dingay area, which is the administrative center of Mojana Wadera Woreda. It is ~200Km away from Addis Ababa and ~ 70km from Debre-Brihan town. Geographically it is bounded between the UTM coordinates of ~535000-580000E and 1090000-1105000N.

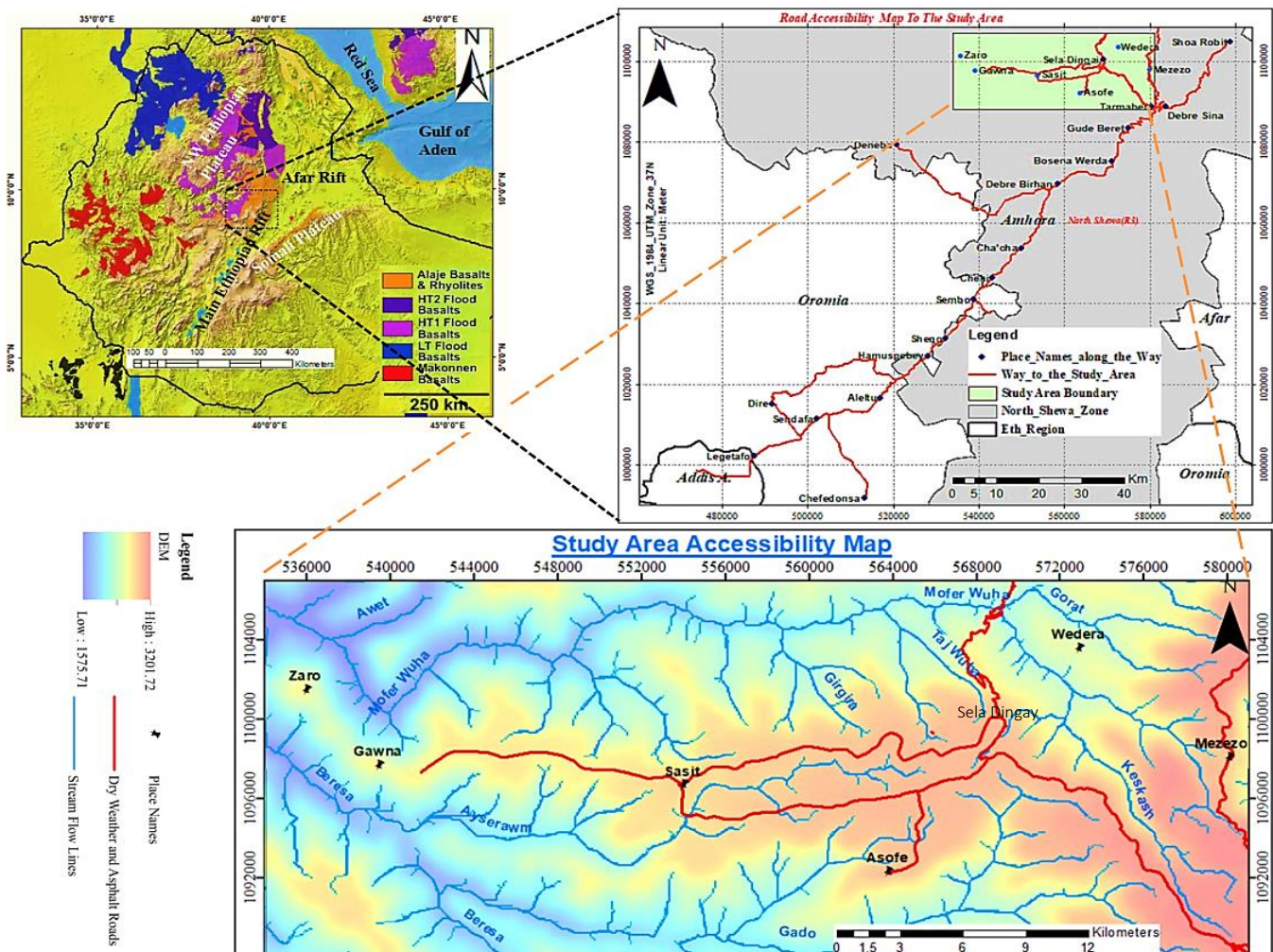
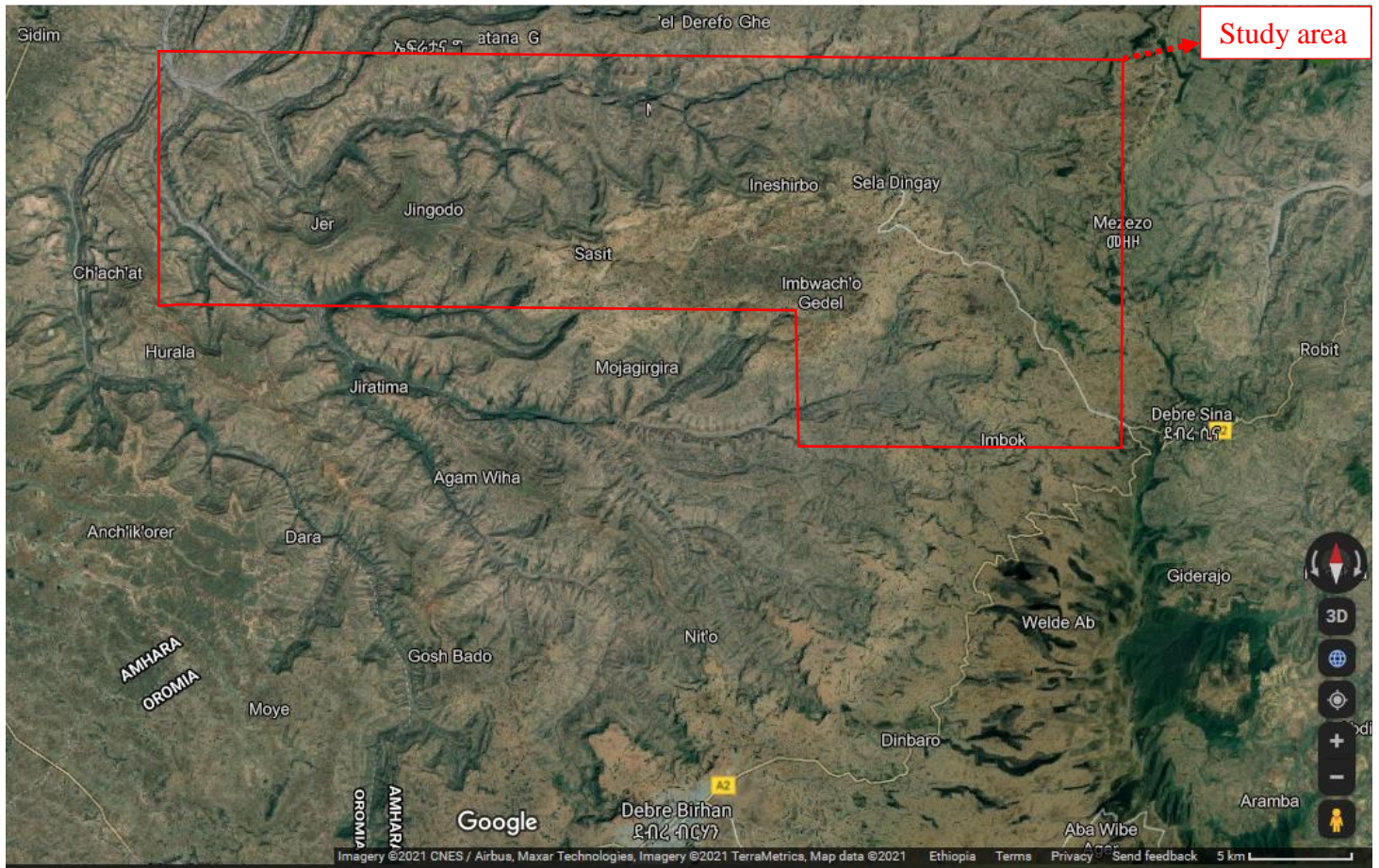


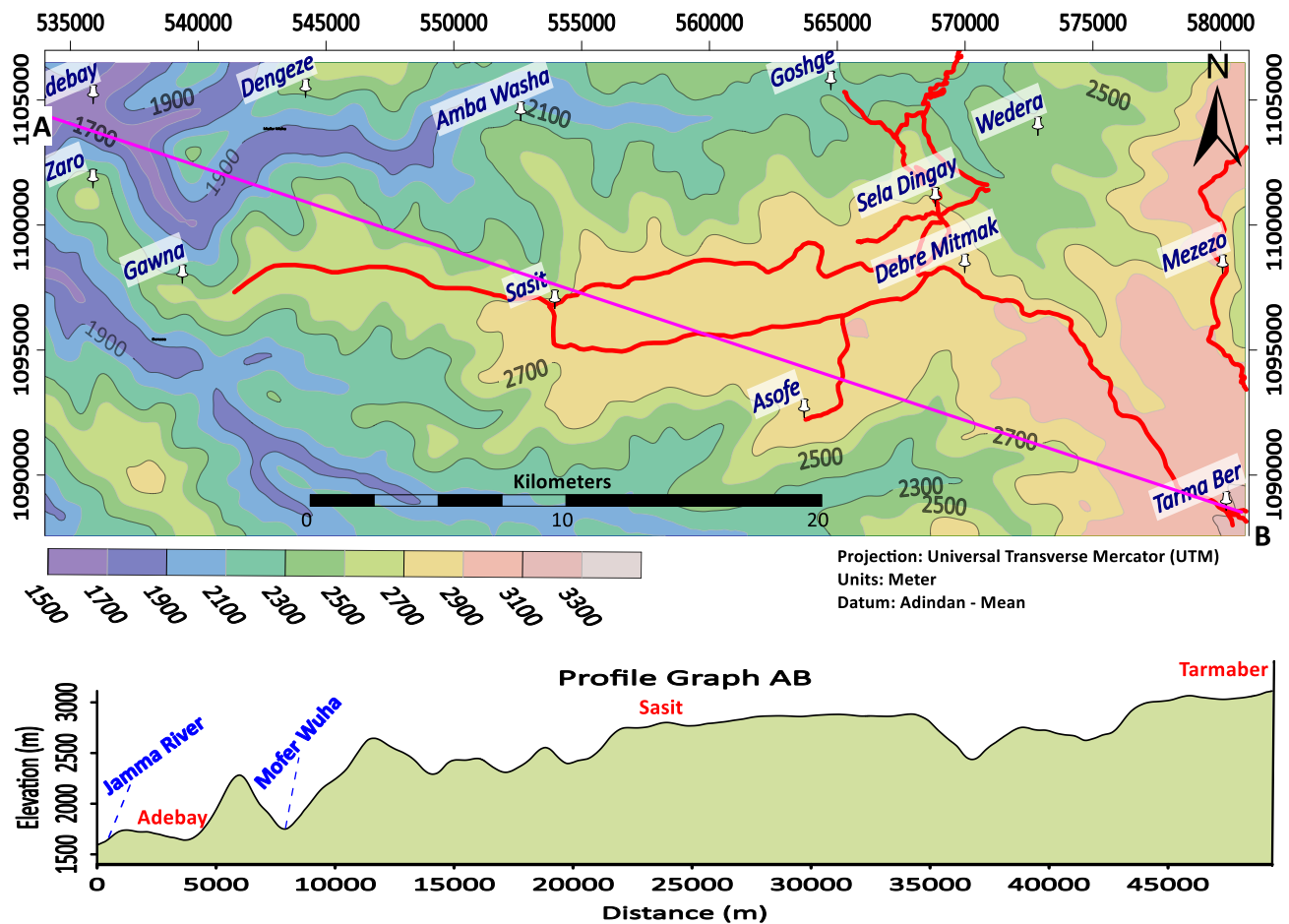
Plate 1.2. Location and Accessibility Map of the study area; the inset-geologic map of Ethiopian Flood Basalt is from Rooney (2017).



**Plate 1.3. Location and Accessibility Map of the study area from Google map imagery.**

### 1.3. Topography and Drainage

The study area is a part of NW Ethiopian Plateau which encompasses varied topography ranging from the deeply dissected wide canyon or gorge along the Mofer river course to very rugged rocky mountainous terrains forming plateau surrounding the gorge. The elevation of the area ranges from ~1540 m (Near the end of Mofer River intersecting Jemma River) to ~3315m a.m.s.l (Around Tarmaber shield basalt). The different products of Continental flood basalt volcanism form numerous discontinuous volcanic ridges with very sharp peaks. Several intermittent streams with dendritic to sub dendritic pattern drains from the mountain and flow as a tributary (e.g. Taj Wuha, Kaskash, and Gorat) into Mofer river systems, and it flows in its downstream side in a way to a large Jemma river system forming a deep gorge.



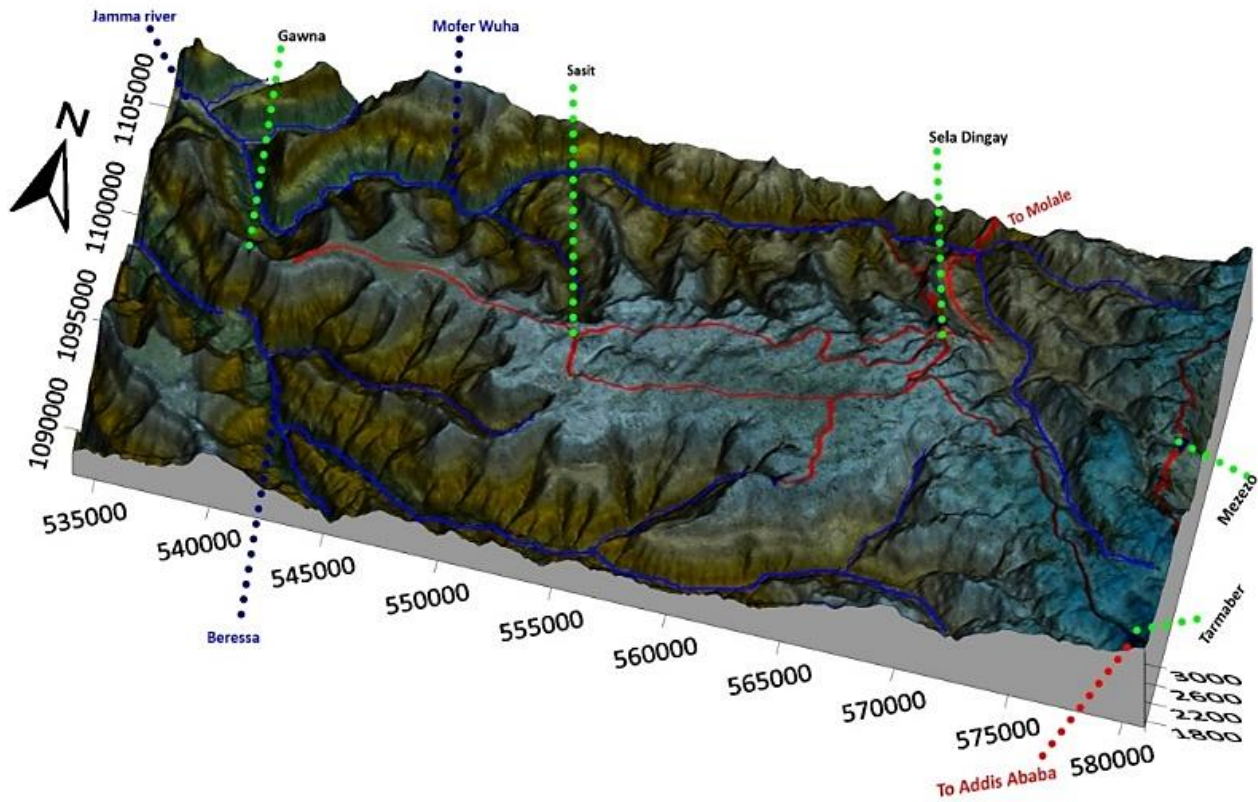


Plate 1.4. 2D and 3D Physiographic map of the study area with Topographic profile.

#### 1.4. Population, Climate, and Vegetation

**Mojana Wedera** is one of the Woreda in the Amhara Region of Ethiopia; part of the North Shewa Zone. The administrative center of this Woreda is Sela Dingay in which this study is centered. Based on the 2007 national census conducted by the Central Statistical Agency of Ethiopia (CSA), this Woreda has a total population of 69,667, of whom 35,186 are men and 34,481 women; 2,477 and 3.56% are urban inhabitants.

The majority of the inhabitants practiced Ethiopian Orthodox Christianity, with 99.87% reporting that as their religion. Based on figures from the Central Statistical Agency in 2005, Sela Dingay town has an estimated total population of 2,707 of whom 1,435 are men and 1,272 are women ([https://en.wikipedia.org/wiki/Mojana\\_Wadera](https://en.wikipedia.org/wiki/Mojana_Wadera) accessed in 13<sup>th</sup> Mar 2021).

The coldest month averaging above 0 °C (32 °F), all months with average temperatures below 22 °C (71.6 °F), and at least four months averaging above 10 °C (50 °F). At least ten times as much rain in the wettest month of summer as in the driest month of winter (an alternative definition is 70% or more of average annual precipitation received in the warmest six months) (<https://www.mindat.org/feature-8621154.html> accessed in 13<sup>th</sup> Mar 2021). According to Köppen and Geiger, this climate is classified as Subtropical highland climate or temperate oceanic climate with dry winters.



**Plate 1.5. Average Temperature and Rainfall from 2014-2021 in Sela Dingay (administrative center of Mojana Wedera Woreda). (<https://www.worldweatheronline.com/sela-dingay-weather-averages/et.aspx> accessed in 13<sup>th</sup> Mar 2021 at 11:05 am)**

**1.5. Problem statement**

Starting from initial stratigraphic studies centered on the Ethiopian plateau Volcanics (Kazmin, 1972; Mohr, 1967; Merla et al., 1979; Zanettin et al., 1980; Berhe et al., 1987 and Mohr, 1983), the volcanic units of the northern and central part of western Ethiopian Plateau have classified as Ashange formation--Aiba basalts--Alajae formation--Tarmaber-Megezez formation (bottom to top chronology). Different stratigraphic classifications (upper and lower unit) are also used by different researchers (Hofmann et al., 1997; Kieffer et al., 2004; Dereje Ayalew & Gibson, 2009; Krans et al., 2018). There are also varies geochemical (Pik et al., 1998; 1999; Dereje Ayalew et al., 2002; Dereje Ayalew and Gezahegn Yirgu, 2003; Kieffer et al., 2004; Beccaluva et al., 2009; Natali et al., 2016) and geochronological (Hoffmann et al., 1997; Ukstins et al., 2002; Coulie et al., 2003) studies. As stated by Kieffer et al., 2004, the Ethiopian volcanic plateau is not a thick, monotonous, rapidly erupted pile of undeformed, flat-lying tholeiitic basalts. Instead, it consists of a number of volcanic centers with different magmatic characters and with a large range of ages. The profound lateral variation in the composition of the Ethiopian Trap lavas, and the apparent synchronicity in eruption, make the prior plateau-wide division into the Ashange, Aiba, and Alajae groups unhelpful in modern magmatic studies (Rooney, 2017 and references therein).

Most previous studies on Ethiopian plateau magmatism have been carried out at a regional scale and detailed investigations on single sections of the plateau are scarce. Many parts of the Ethiopian plateau volcanic rocks require comprehensive study in terms of lithologic unit identification, extent, and field relationship description, detailed textural and mineralogical study, and finalized volcanic section establishment, based on regionally set geochemical frameworks for flood basalt provinces.

As a result of incomplete exploration in terms of petrographic and petrologic characteristics of the volcanic rocks of the Sela Dingay area volcanic units, the aim here is to establish the complete petrostratigraphic section to fill the existing gap in the detailed study of volcanic rocks of Sela Dingay area along the Mofar River, as part of a single section within Northern Shewa of the northwestern Ethiopian plateau. In addition to these reasons, also the area was not exposed well and less accessible during these regional studies, now the area is well exposed due to a new road being in construction of passing the study area and it is a center to access the stratigraphy starting from the base to the top of Plateau volcanics.

## **1.6. Objectives**

### **1.6.1. General Objective**

The main objective of this study is to establish a complete volcanic stratigraphic section based on the petrologic and petrographic investigation of volcanic rocks in the Sela Dingay area a long Mofar River section in North Shewa, Central Ethiopia.

### **1.6.2. Specific Objectives:** the specific objectives of this research work are:-

- To identify the distribution of major lithological units and major lava flow morphologies within the stratigraphic section and collect representative rock samples for petrographic studies.
- To describe variations in the lava flow and emplacement type based on available field data.
- To characterize the petrography and petrology of the volcanic units in the study area and interpret based on regionally set geochemical and geochronological data to flood basalt magmatism in Ethiopia.
- To discuss the possible implication of the field data (lithology and Lava flow morphologies) and petrographic data to the process involved in the geological evolution of the study area.
- To determine the lithostratigraphic succession in the mapped area, correlate them with previous studies, and establish stratigraphic sequence and thickness of the main lithologic units.

## **1.7. Methodology**

The main methodologies used for this study are field description of lithostratigraphic units, stratigraphic sampling, and petrographic analysis. The study consists mainly of three stages of methodologies as field and laboratory studies.

### **1.7.1. Field description of lithostratigraphic units**

This is used to know the distribution of the lithologic units and lava flow morphologies. Activities include during this stage of methodology: detailed rock descriptions, creation of geological maps, taking photographs, and sampling. 1:50,000 scaled base map was used for data collection during the traverse.

### **1.7.2. Stratigraphic sampling**

The samples for this study were collected from the different volcanic units found in the study area during the fieldwork through the description and mapping of the lithologic units. Latitude and longitude position of the sampling locations was undertaken for mapping the different volcanic units, by using a handheld Global Positioning System (GPS) receiver. Elevation was also recorded and used as a representation to log stratigraphic sequences over short distances at the outcrop scale during the field and they are integrated to construct the complete stratigraphic section.

### **1.7.3. Petrographic Analysis**

During the laboratory studies, 24 thin-sections were prepared from the collected representative samples for mineralogical and petrographical examination under a polarizing microscope to designate the relationships in terms of texture, fabric, modal proportion, and mineral composition and also to compare the petrographic features of rock samples from different locations, so to determine the possible connection of those features with their petrology. Among 24 analyzed samples, 17 samples are from basaltic units, 5 samples from rhyolite, 1 ignimbrite sample, and 1 from the Mesozoic sandstone. Samples have been submitted to the Geological Survey of Ethiopia, a laboratory center for thin-section preparation. The thin-section were prepared by cutting from rock samples, cemented to microscope slides, and ground down to 0.03mm thickness so that they readily transmit light. Petrographic examinations were carried out on the Swift and Nikon polarized petrographic microscope and photomicrographs of representative mineral compositions and textures were taken by using the Mobile-Phone camera in Mineralogy and Petrology laboratory, school of earth sciences, Addis Ababa University.

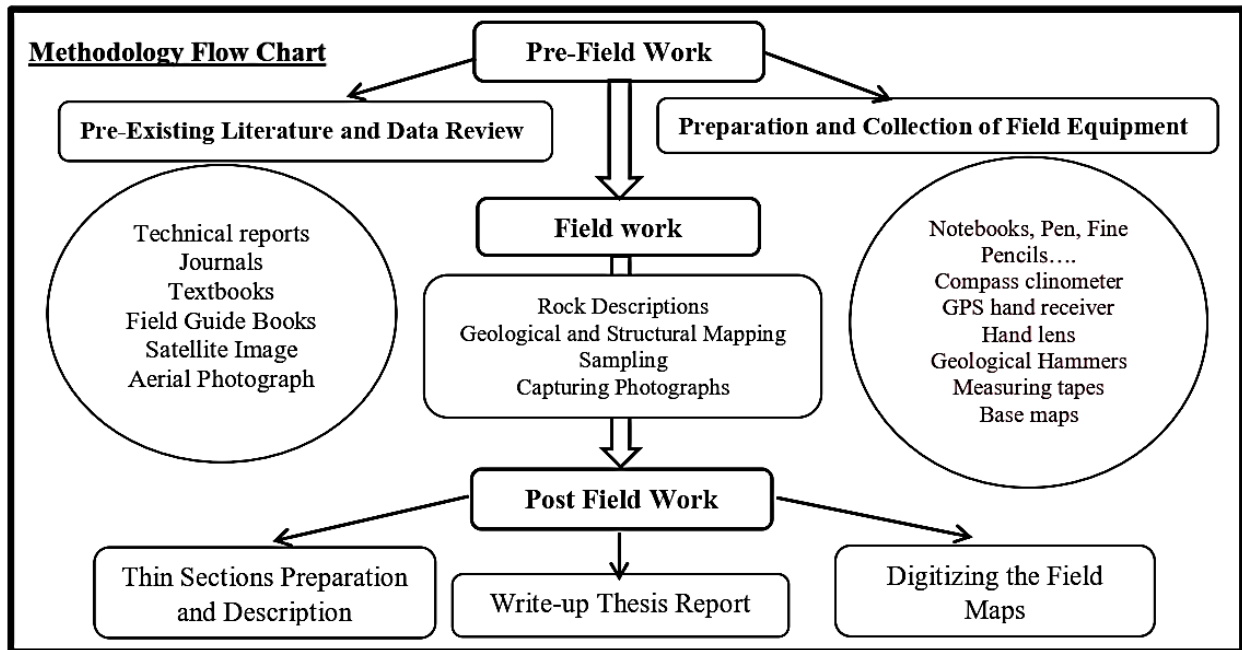
To accomplish the objective of this study, the general framework of the work was presented in three divisions: 1) pre-field work, 2) field work, 3) post-field work.

- a. **Pre-field work:** Before the fieldwork was undertaken a comprehensive review of the relevant preexisting literature was read and written to understand the study area. Some of the major activities conducted during the revision of previous works were collecting previous technical reports, journals, textbooks, extracting relevant information from the satellite image and aerial photograph, reviewing and compiling different kinds of literature (published and unpublished reports) related to the study area. This initial stage was also used for the preparation and gathering of field equipment so that the fieldwork could be undertaken successfully.
- b. **Fieldwork:** The way for collecting the primary data. The main aim of this fieldwork was to know the distribution of the lithologies and lava flow morphologies (both vertically and horizontally), to take photographs, and to take representative samples for further laboratory analysis (especially for petrographic study). This section of the methodology was used to discuss the various methods that were undertaken during the fieldwork such as detailed rock descriptions, creation of

geological and structural maps, and sampling.

The undertaking of the mapping was consist of large walk-over surveys of the study area. Finally, photographs were captured so that a multitude of images to be included within the final thesis submission, to provide a pictorial view of representative lithologies within the study area.

- c. **Post-field work:** This final stage of the methodology will entail the creation of the finalized petrostratigraphic section as well as completing the write-up for the thesis report. This includes transferring field map data (lithological variations, lithological contacts, and the geological structures) to a geological map by using different computer software such as Global Mapper, Arc GIS, Google Earth Pro, and Surfer. Standard thin sections preparation for detailed petrographic study /thin section descriptions/ including mineral identification, modal proportion, textural descriptions (largest grain size diameter along their longest dimension of each mineral, the average grain shape of those existed minerals and grain to grain relationship of the phenocrysts), and rock naming by using a polarized petrographic microscope. This information will help in the rock classification and understanding the magmatic evolution of the area.



**Plate 1.6. Methodology flow chart illustrating the major components of the study.**

## **1.8. Review of previous geological work**

Many geological studies have been conducted both on the Main Ethiopian Rift (MER) and the adjacent volcanic Plateaus in the western and eastern margin. In this section, based on a review of previous studies the most important works in the understanding of the geology of the study area are listed briefly in historical order. The details of the geologic setting of the study area with an emphasis on local characteristics will be given in [chapter 2](#).

The earlier published work by **Mohr and Zanettin (1988)**, identified the total area covered by flood basalts in the Ethiopian province has been estimated as 600,000 km<sup>2</sup>, and not less than 750,000 km<sup>2</sup> before erosion (erosion has followed plateau uplift). Eruption of basalt and subordinate other lavas has built up a subaerial volcanic pile, typically 500-1500 m thick and locally attaining 3000 m. The bulk of the eruptions was from fissures. The volcanic units of the northern and central part of western Ethiopian Plateau have classified as Ashangi formation--Aiba basalts--Alaji formation--Tarmaber-Megezez formation (bottom to top chronology) (**Mohr, 1967; Kazmin, 1972; Merla et al., 1979; Mohr, 1983; Berhe et al., 1987; Mohr and Zanettin, 1988**). Flood volcanism was succeeded by emplacement of large shield volcanoes and by continental rifting (**Mohr, 1983** and **Hofmann et al., 1997**). According to **Hofmann et al. (1997)**, the earlier study to use a modern method of geochronological (<sup>40</sup>Ar/<sup>39</sup>Ar) and magnetostratigraphic results for the Ethiopian traps, most of the Ethiopian flood basalts erupted 30 Myr ago, during a short 1 Myr period, to form a vast volcanic plateau.

**Pik et al. (1998)** under take detailed geochemical studies on the Oligocene flood basalts of the northwestern Ethiopian trap series. The trap basalts are grouped into three distinct geochemical groups based on Ti- concentration (low Ti, High Ti-1, and high Ti -2). The mantle and crustal source involvements on the genesis of pre-rift continental flood basalts of northwestern Ethiopian Plateau have been identified by **Pik, et al. (1999)**.

The study by **Dereje Ayalew et al. (2002)** about the source, genesis, and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts, identified that the initial volume of the Oligocene ignimbrites of the western plateau was probably at least  $6.3 * 10^4$  km<sup>3</sup>; on average 20% of the volcanic pile, the volume of ignimbrites removed by erosion is estimated to be at least  $2 * 10^4$  km<sup>3</sup>. Three regionally distinct Oligocene rhyolite units are recognized: (1) the Lima Limo rhyolites in the northwest plateau forming several beds capping low-Ti basalt floods, (2) the Wegel Tena rhyolites in the east corresponding to very thick ignimbrites overlaying high-Ti flood basalts, and (3) the Jima rhyolites located in the southwestern plateau overlaying high-Ti flood basalts. The Miocene rhyolites are situated in the Molale-Debre Birhan area close to the rift margin and overlay Miocene low-Ti flood basalts. There is no contact between the three Oligocene rhyolite outcrops in the field. These volcanic rocks are consistent with their derivation by fractional crystallization of basaltic magmas similar in composition to the exposed flood basalts.

**Dereje Ayalew and Gezahegn Yirgu (2003)**, in their study about crustal contribution to the genesis of Ethiopian plateau rhyolitic ignimbrites, conclude that the origin of the rhyolite suites is attributed to low-pressure fractional crystallization of basaltic magmas, similar in composition to the exposed flood basalts, combined with assimilation of mafic crustal rocks. Assimilation–fractional crystallization modeling suggests that the genesis of Lima Limo rhyolites involved higher amounts of contamination by crustal material relative to those of Wegel Tena.

**Kieffer et al. (2004)** investigated the petrology, geochemistry, and isotopic compositions of the large shield volcanoes compared them to those of the flood volcanics and traced the variations in eruption style and magma flux of lavas from the peak of flood volcanism to the onset of major rifting in the northern part of the volcanic plateau (ranging from 30 to ~10 Ma). They suggested that the shield volcanoes from northwestern Ethiopia are magmatically similar to the underlying flood basalts. The thickness of the flood basalt pile varies from about 1500 m in the thickest sections in the Lima Limo region to less than 200 m to the north of the town of Sekota and in the Nile Valley, about 400 m to the south and towards the supposed center of the province.

Most of the 30 Ma old flood basalt province outcrops in the Ethiopian region, west of the rift valley, and forms a lava plateau locally exceeding 2000 m of thickness. On the plateau, Quaternary volcanic activity developed in the Tana graben (S-SW of Tana Lake), connected with extensional tectonics, producing fissure-type lava fields and small- to medium-sized tuff cones, tuff rings, and maars. Most of these volcanic structures formed along extensional faults, which are NNE–SSW oriented and sub-parallel to MER faults, and which gave origin to alkali basaltic magmatism (**Ferrando et al., 2008**).

Composite stratigraphic section of the north Shewa volcanic succession at Yite-Koste illustrating the intercalation of basalt and rhyolite formations presented in a paper by **Dereje Ayalew & Gibson (2009)**, determined that the north Shewa succession of basalts and rhyolites is distributed over a large area (>2200 km<sup>2</sup>) and locally exceeds 1000 m in thickness. The volcanics lie unconformably on Cretaceous sandstone. The topmost part of the sequence consists of a thick ignimbrite unit that often forms topography typical of plateau morphology. They subdivided the succession into Upper and Lower Basalts, and Upper and Lower Ignimbrites.

According to a study by **Tigel Belay et al. (2009) (Geological Survey of Ethiopia)**, an unpublished technical report on the Geology of the Were-Ilu Map-sheet encompassing parts of Northern Shewa, Southern Wello, and Oromia Zones of the Amhara and Heri-Resu Zone of the Afar Regional States; the mapped area consisted of four Cenozoic volcanic lithostratigraphic units, separated from each other by an unconformity. These are: - (i) Pre- Oligocene volcanics (Ashange basalt), (ii) Oligocene to Miocene volcanics (Alajae basalt, Molale ignimbrite, Termaber-Megezez basalt, and Adami basalt), (iii) Early- to Mid-Miocene volcanics (Kemise rhyolite formation), and Upper Miocene volcanics (Dogiya basalt). Cenozoic volcanism in the area ceased by the eruption of the Quaternary Wederage basalt.

The northwest Ethiopian volcanic plateau which represents the so-called ‘Ethiopian flood basalt province’ evolved during at least two major pulses: at 30 Ma in the northern plateau and 20 Ma in the central plateau. The study by **Dereje Ayalew (2011)**, suggests that volcanism commenced in north-central Ethiopia c. 20 Ma, 10 Ma after initial magmatism in the northern Ethiopian plateau. The isotopic compositions of north Shewa basalts and rhyolites indicate the increasing involvement of crustal materials in the evolution of north Shewa magmas with time, probably as a consequence of thermal weakening of the crust triggered by repeated injections of hot basaltic magmas in the lithosphere during rifting.

Three-time periods that are equivalent to the most significant magmatic events each followed by a bimodal or silicic magmatic activity, in East Africa during the Cenozoic are given by the work of **Rooney (2017)**. These periods are (i) Eocene Initial Phase (45 to 34 Ma) focused in Southern Ethiopia and Northern Kenya (Turkana), (ii) Oligocene Traps phase (~33.9 to 27 Ma) observed from Turkana in the south to Yemen in the north, to Sudan in the west, and the margin of the Somali Plateau to the east and (iii) Early Miocene resurgence phase (plume-dominated magmatic activity) (~26.9 to 22 Ma) seen throughout the regions. In this work, a new estimation on the volume, area, and thickness of the 720,000 km<sup>3</sup> volume of magmatism in East Africa from ca. 45 to 20 Ma is given. From this, the northwest and southeastern Ethiopian plateaus cover a total volume of about ~620,147 km<sup>3</sup>.

Detailed, flow-by-flow petrographic analyses, framed within a well-constrained stratigraphy are given by **Krans et al. (2018)** from initiation to termination of the western portion of the Ethiopian–Yemen flood basalt province (LT flood basalts around Lake Tana area). The study demonstrates three divisions within the Ethiopian flood basalt province, defined broadly as the lower flood basalt, which is dominantly Ol-phyric with Cpx-rich cumulates; the middle flood basalt, which exhibits Plg-megacrystic flows and oscillation between Plg-phyric and Ol-phyric flows; and the upper flood basalt, which is dominantly Plg-phyric and devoid of cumulates. Modal analyses indicate evidence of two fractionation regimes, one in the lower crust (dominated by the crystallization of clinopyroxene cumulates in the absence of plagioclase) and a second in the mid-to-shallow crust (dominated by plagioclase cumulates).

A study on dikes associated with the LT flood basalts erupted in western Ethiopia to examine the magmatic plumbing system of the province, is done by **Rooney et al., 2018**. In this work, they showed that the western Ethiopian dike swarm was largely contemporaneous with the eruption of the Oligocene flood basalts and is similar in composition. They identified also the western Ethiopian dike swarm as a locus of magmatism for the LT flood basalt lavas.

### **1.9. Significance of the research**

- ❖ This study was used to fill the existing gap in the detailed study of volcanic rocks of the Ethiopian plateau concerning the petrologic and petrographic investigation.
- ❖ The results and the findings of this research work will provide detailed information on these volcanic units such as their petrological, petrographic, and field relationships.
- ❖ The detailed geological map and the stratigraphic section of the study area will serve as a basic source of data for understanding the geological history of the study area, as a part of the northwestern Ethiopian plateau.
- ❖ The methodology and findings of this study will serve as a basis for all future similar investigations in Ethiopian volcanic provinces with a similar setting.
- ❖ It will serve as a scientific basis for understanding the tectonic and petrologic evolution of the area.
- ❖ It may inspire other scholars to investigate the area using a different methodology to discover more information.

### **1.10. General chapter schemes of the report**

The introductory chapter ([Chapter 1](#)) includes a general background introduction with a description of the study area, the problem of the statement, the objectives of the study, the methodology used, a review of previous works related to this study area, and finally, the main significance of the study is incorporated. Detailed regional geology in the frame of this study is presented in [Chapter 2](#) of the thesis report. This chapter includes general information about continental flood basalt provinces, followed by a review of regional studies about Ethiopian large igneous provinces including the flood basalt provinces. The final portion of this chapter combines details (Stratigraphy, Petrography, and Classification) of different studies about the North-Western Ethiopian plateau.

Details of field observation about the local geology of the study area are presented in [Chapter 3](#). This chapter includes a geologic map of the study area, field extent, and their field relationship of the different lithologic units in the study area with representative photographs of exposures and the stratigraphic section of the lithologic units at different localities. The last part of the chapter encompasses data about flow characteristics of these basaltic flow products and geologic structures (primary and secondary) observed in the study area.

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

## **CHAPTER-TWO**

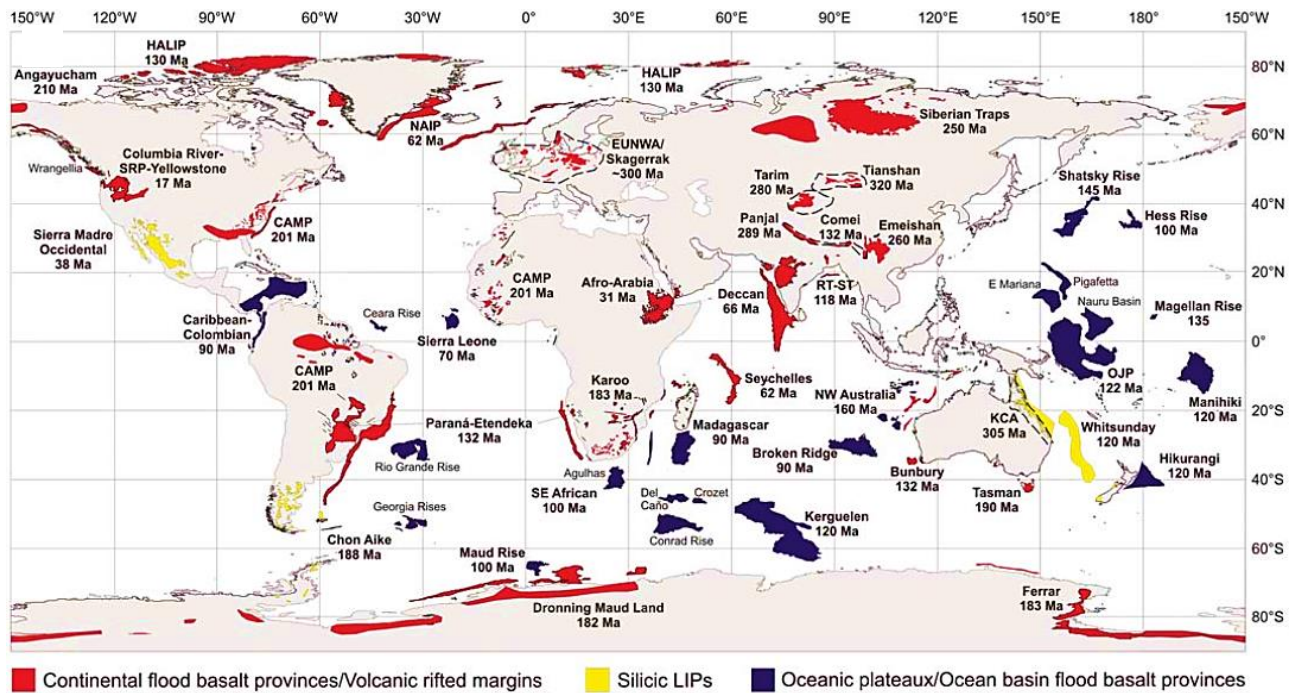
### **2. REGIONAL GEOLOGY**

#### **2.1. Continental Flood Volcanisms**

A Continental Flood Basalt Provinces (CFBP) can be defined as a series of volcanic outpourings erupted onto areas of continental crust and which are comprised predominantly of great thicknesses of basaltic lava flows, which may affect either continental (e.g., Parana–Etendeka, Deccan, etc.) or oceanic crust (e.g., Ontong Java) (Jerram and Widdowson, 2005). Continental flood volcanism (CFV) represents massive outpourings of basaltic lava flows and, in some cases, rhyolitic lavas and pyroclastic rocks (Baker et al., 1996; Dereje Ayalew et al., 2002; Kieffer et al., 2004; Ukstins et al., 2002), often with volumes in excess of  $1 \times 10^6 \text{ km}^3$  (Rochette et al., 1998). The volcanic suites in nearly all continental flood basalt provinces have a bimodal basalt–rhyolite nature with a distinct lack of intermediate compositions (Dereje Ayalew and Gezahegn Yirgu, 2003; Dereje Ayalew, 2011) and they contain significant volumes (up to 20% of the total volcanics) of acidic eruptive, usually in the upper part of the sequence capping the basalts (Dereje Ayalew, 2011). The continental flood basalt (CFB) province and associated continental break-up are thought to be related to the upwelling of mantle plume impinged on the base of the lithosphere (Rooney et al., 2007).

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

According to Pik et al. (1999), most of the lavas from main CFB provinces (Parana', Deccan, Siberia, Karoo, etc.) have isotopic and trace element signatures that are not typical of OIB, suggesting that they are probably not derived directly from the deep mantle. Instead, in most continental-flood-basalt (CFB) provinces, the magmatism includes variable contributions of melts derived from both lithospheric and convecting mantle sources, and also readily-fusible crust (Baker et al., 1996; Hawkesworth et al., 1999). Most continental flood basalt provinces (CFBs) are associated with low volume alkaline rocks (e.g., Ethiopia, Kieffer et al., 2004; Paraná- Etendeka, Ewart et al., 1998 as cited in Dereje Ayalew et al., 2006).



**Plate 2.1. Location map of Large igneous provinces (LIPs) of the world, ages are those of the main phase or pulse of volcanism; (NAIP stands for North Atlantic Igneous Province and CAMP for Central Atlantic Magmatic Province (Adopted from Self et al., 2014).**

## 2.2. Flood Basalt magmatism in East Africa

East Africa's Cenozoic plume-dominated magmatism extends from Turkana in the south, the southeastern Ethiopian plateau in the east, Ethiopia and Eritrea in the north, Yemen in the northeast, and Sudan in the west, preserving a rich stratigraphic record of magmatism over the past 45 Ma (Rooney, 2017). Most of the flood basalts and rhyolites were erupted in a short time period (~1 Myr) at 31–29 Ma, concomitant with the onset of continental rifting in the southern Red Sea (Wolfenden et al., 2005). The lava pile's thickness varies greatly, reaching up to 3 km along the southern Red Sea's western margin and thinning to about 500 m both north and south, overlying a Mesozoic sedimentary basin (Dereje Ayalew and Gibson, 2009).

The earliest volcanism in the East African rift system (EARS) occurred in southwestern Ethiopia, southeastern Sudan, and northern Kenya at 40–45 Ma (Ebinger et al., 1993; George et al., 1998). Soon after, between 31 and 22 Ma, volcanism was widespread throughout Ethiopia, Eritrea, and Yemen where flood basalts and associated felsic pyroclastic rocks erupted (Baker et al., 1996; Hofmann et al., 1997; Pik et al., 1998, 1999; Kieffer et al., 2004; Dereje Ayalew, 2011). Immediately after the peak of volcanic activity related to the flood basalt emplacement, a number of large shield volcanoes developed from 23 Ma to about 10 Ma on the surface of the volcanic plateau (Kieffer et al., 2004).

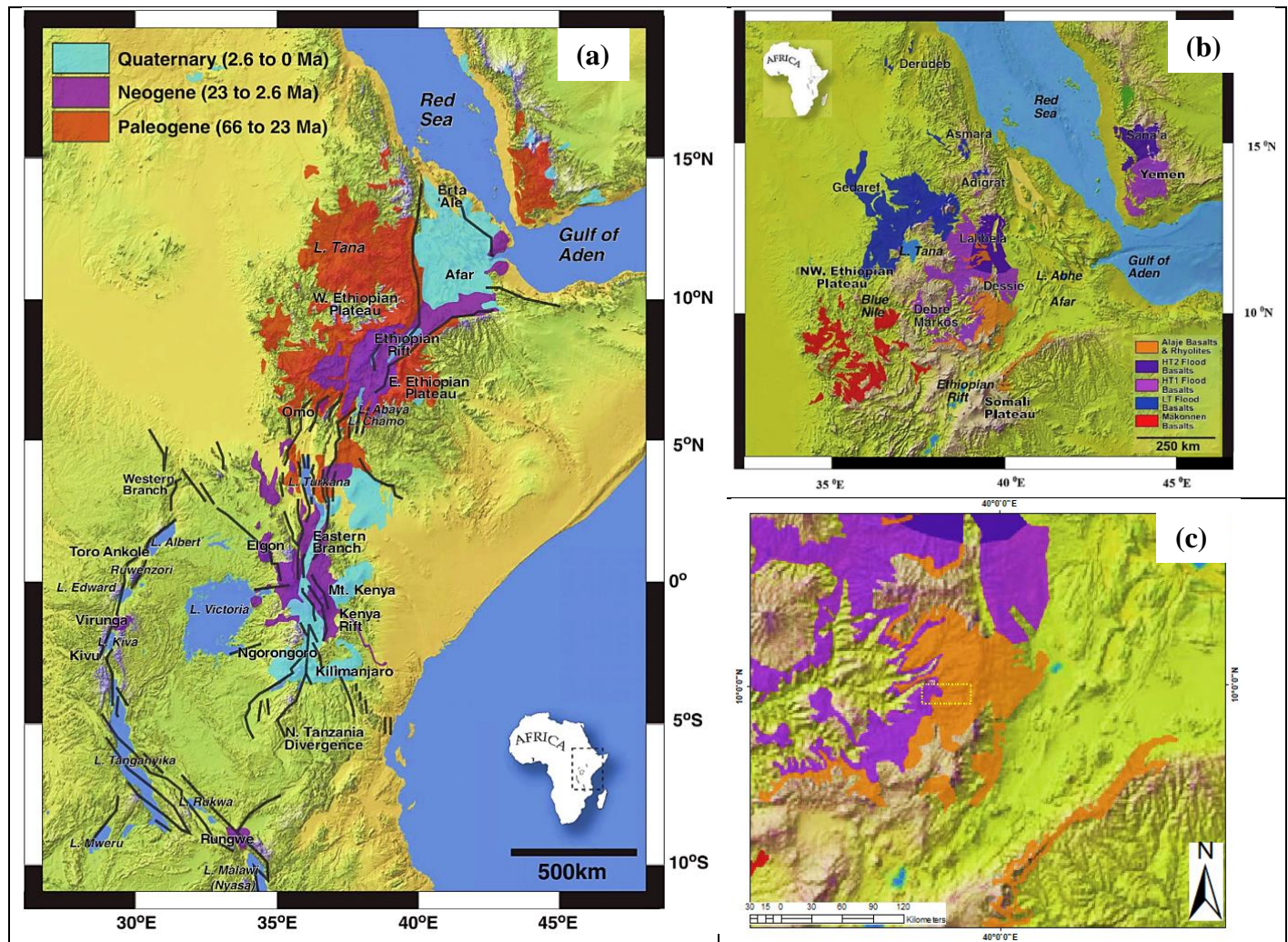
According to Rooney (2017), the 720,000 km<sup>3</sup> of Basaltic magmatism in East Africa is divided into three time periods (Plate 2.2. (a)):

1. Eocene initial phase (45–34 Ma): volcanism was restricted to southern Ethiopia and northern Kenya and dominantly basaltic,
2. Oligocene trap phase (~33.9–27 Ma): the eruption of the Ethiopian–Arabian plateau flood basalts significantly increased, the aerial extent of volcanism includes northern Ethiopia and Yemen, and
3. The early Miocene resurgence phase (~ 26.9–22 Ma): a resurgence in basaltic activity occurred in the form of shield building activity in the NW Ethiopian plateau, fissure eruptions on the SE Ethiopian plateau, and increased eruptions in the Turkana region, which is later followed by bimodal lavas and silicic volcanism.

### **2.3. Ethiopian Continental Flood Basalts**

The Ethiopian Large Igneous Province (LIP), which is located near the triple junction of the Red Sea, Gulf of Aden, and East African Rifts, is considered as a young example of continental flood basalt volcanism linked to continental breakup (Kieffer et al., 2004), which provoked widespread basaltic magmatism around 30 Ma (Hofmann et al., 1997; Coulie et al., 2003) is presumed to be associated with the Afar plume (Ukstins et al., 2002; Dereje Ayalew et al., 2002). Most of the ~30 Ma old flood basalt provinces were extruded over a short time period, possibly 1 - 2 Ma (Hofmann et al., 1997). Nevertheless, small volumes of basalts as old as 45 Ma or as young as 27 Ma are found in southwest Ethiopia (Ebinger et al., 1993; George et al., 1998) and Yemen (Baker et al., 1996), respectively. Because of their relatively young age and their eruption in a region where plate movements are slow, a complete record from the initial, high-flux, flood volcanic phase through to its shutdown and the onset of continental rifting, and finally the initiation of sea-floor spreading is found in these LIP (Kieffer et al., 2004).

As a whole, these basalts are transitional to tholeiitic in character, with 90% of the province preserved in Ethiopia (Dereje Ayalew and Gibson, 2009), west of the rift valley, and forming a lava plateau with a thickness exceeding 2000 m locally, with the rest of the plateau in Yemen (Ferrando et al., 2007). The present remnants of Ethiopian flood volcanism which are exposed in the NE Ethiopian Plateau, SE Ethiopian Plateau, and Somali/Harrar Plateau, covers an area of 622,108 km<sup>2</sup> and have a total volume of about ~620,147 km<sup>3</sup> (Rooney, 2017) with a layer of basaltic and felsic volcanic rocks (Kieffer et al., 2004). Estimates of the original volume reach up to 10<sup>6</sup> km<sup>3</sup> (Rochette et al., 1998). The evolution of volcanic activity in Ethiopia consists of three main stages (Peccerillo et al., 2003). During **the first stage** (about 50-10 Ma), the Ethiopian plateau was constructed by eruptions of flood tholeiitic to transitional basaltic lava flows and interbedded mildly alkaline trachytic and rhyolitic ignimbrites (Mohr & Zanettin, 1988). The **second stage** of activity occurred around 10-5 Ma and constructed several shield volcanoes made of transitional to Na-alkaline basalts and minor trachytes (Peccerillo et al., 1979; Kieffer et al., 2004). The **final stage** is Pliocene to Present and is more directly related to the formation of the main Ethiopian and Afar rift.



**Plate 2.2. (a) Cenozoic magmatic activity in Africa and parts of the Arabian Peninsula and (b) map of Oligocene basalts in Ethiopia and Yemen (after Rooney, 2017).**

The HT flood basalt provinces (purple) are restricted to the eastern half of the NW plateau and Yemen. The LT flood basalt province (blue) is restricted to the western half of the Ethiopian plateau. The boundary of this study area within the map (b) is shown in (c) with a yellow box.

Fissure-fed basaltic lavas dominate the Ethiopian volcanic plateau, with subordinate rhyolite forming the volcanic plateaus bounding the current Afar and MER. The rhyolites are found throughout the volcanic stratigraphy as ash layers between basaltic lava flows or as individual eruptive units comparable in volume to individual mafic lava units. They become thicker towards the uppermost part of the lava sequences (Dereje Ayalew, 2011). Rocks of intermediate composition (53–66 wt. % SiO<sub>2</sub>) are absent, and the volcanic successions define a strong silica gap (Mohr and Zanettin, 1988; Pik et al., 1998), as is observed also in other CFB provinces. The volcanic plateau is overlain by low-angle shield volcanoes whose composition and age match that of the underlying flood basalts and rhyolites (Kieffer et al., 2004).

## **2.4. North-Western Ethiopian Plateau**

### **Stratigraphy, Petrography, and Classification**

The plateau volcanics are cut by the rift faulting and are distributed asymmetrically about the flanks of Afar and Main Ethiopian Rift that lying to the west of the rift system is designated the Western Ethiopian plateau (WEP), while the other to the east is named the South Eastern Ethiopian plateau (SEP). The northern Ethiopian volcanic plateau is not a thick, monotonous, rapidly erupted pile of undeformed, flat-lying tholeiitic basalts. Instead, it consists of a number of volcanic centers of variable magmatic character and age (Kieffer et al., 2004). It is evolved during at least two major pulses: at 30 Ma in the northern plateau and 20 Ma in the central plateau, and volcanism commenced in north-central Ethiopia c. 20 Ma, 10 Ma after initial magmatism in the northern Ethiopian plateau (Dereje Ayalew, 2011).

The Ethiopian flood basalts were initially divided into four divisions, from oldest to youngest, by stratigraphic studies (Zanettin et al., 1980 as cited in Krans et al., 2018) centered on the northeastern region of the Ethiopian plateau: Ashange basalt, Aiba fissure basalt, Alajae basalts and rhyolites, and Termaber basalts. The Ashange is characterized by thin (~ 5 m) dipping flows restricted to only a few kilometers in extent. These flows are locally zeolitized and are unconformably overlain by flat-lying flows (Aiba Formation). The Aiba Formation is characterized by massive flows (up to 100 m when ponded) that are generally olivine basalt with columnar jointing common. Locally, sparse interbedded pyroclastic deposits of varying thickness are observed in this formation at Amba Aiba. This formation is overlain by the Alajae Formation, characterized by ignimbrites with sparsely interbedded basalt flows and Termaber Formations which are shield volcanism (Mohr and Zanettin, 1988). Hofmann et al. (1997) used the Lima-Limo section north of Lake Tana, which is 1950 m thick, to divide the province into upper and lower units based on morphological boundaries. The lower and upper stratigraphic divisions on the Simien shield volcano and underlying flood basalts are also used by Kieffer et al. (2004).

The characteristics used by Mohr and Zanettin (1988) to define the upper and lower units of the initial stratigraphic classification were based on local observations that were not consistent throughout the flood basalt province (Krans et al., 2018). Krans et al. (2018) applied stratigraphic divisions as lower, middle, and upper flood basalts based on petrographic differences observed in North-western LT flood basalts. In this study, three divisions within the Ethiopian flood basalt province defined broadly as the lower flood basalt (consists of 400 m of flows), which is dominantly Ol-phyric with Cpx-rich cumulates, the middle flood basalt (nearly 1000 m of flows), which exhibits Plg-megacrystic flows and oscillation between Plg-phyric and Ol-phyric flows, and the upper flood basalt (~ 330 m of flows), which is dominantly Plg-phyric and devoid of cumulates.

The major volcanic units of the Western Ethiopian Plateau (WEP) include:

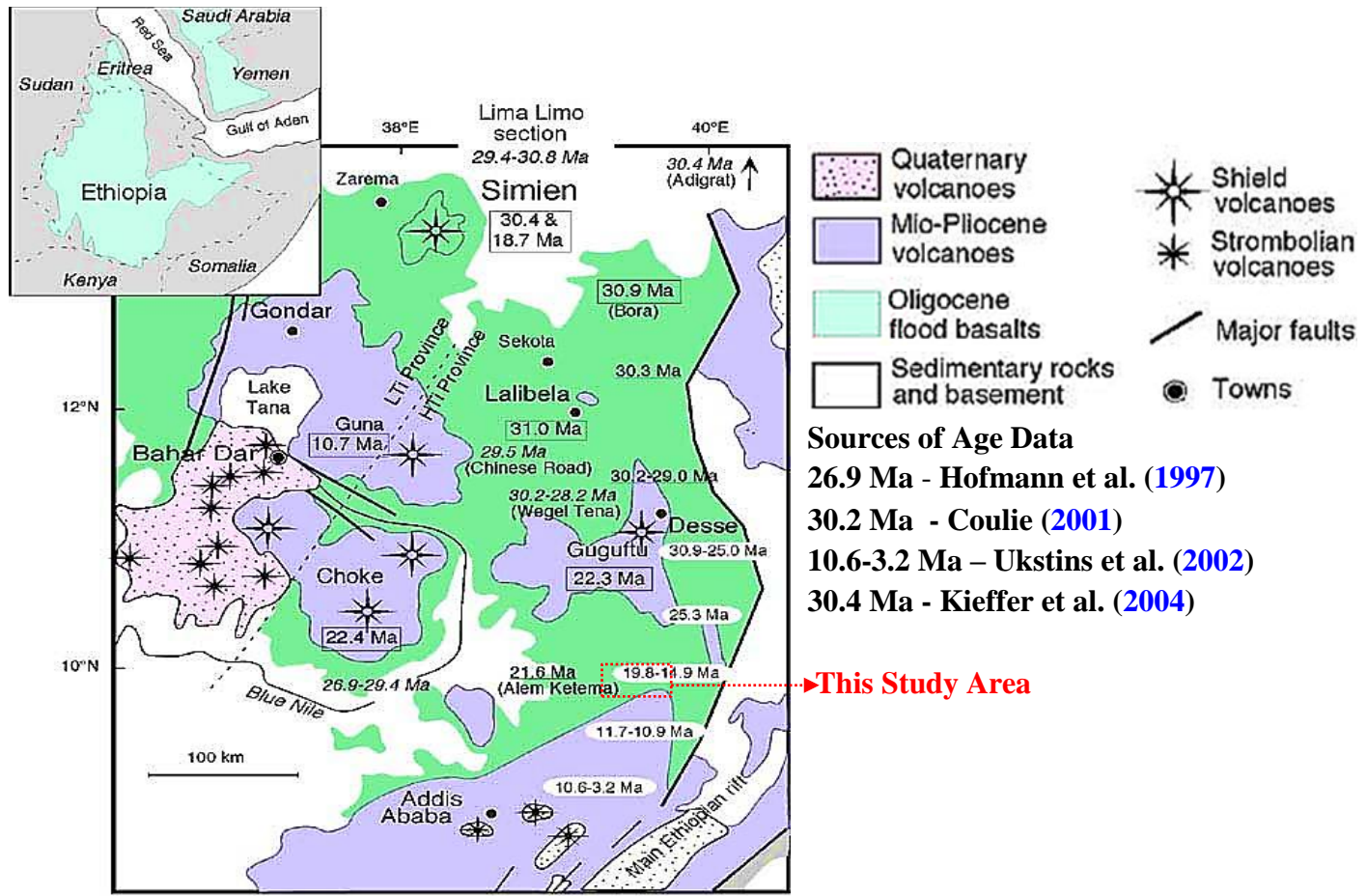
- The Oligocene flood volcanics (Trap series) i.e. (Oligocene –Miocene basalts and rhyolites)
- Miocene- Pliocene shield volcanoes
- Quaternary volcanics

The occurrence of Cenozoic volcanism in the northwest Ethiopian flood basalts started the eruption of Ashange basalt during Eocene/Oligocene followed by extrusion of Aiba basalts and Alajae formation during the Oligocene-Miocene (Mohr and Zanettin, 1988). Flood basalts with interbeds of pyroclastic rocks of rhyolitic or less trachytic compositions are the characteristics of these volcanic episodes (Berhe et al., 1987; Pik et al., 1998, 1999). In the WEP the flood volcanic succession includes basaltic lava flows, basaltic tuffs, as well as a considerable volume of rhyolitic, trachytic, and phonolitic products (Mohr and Zanettin, 1988). Despite the predominance of basalts, the flood volcanics (Trap series) contains significant volumes of felsic volcanic rocks usually in the upper parts of the sequence (Dereje Ayalew et al., 2002; Dereje Ayalew and Gezahegn Yirgu, 2003). The felsic volcanic rocks are mainly friable tuffs, rhyolites, and ignimbrites, interlayered with the flood basalt particularly in the upper parts of the sequence (Dereje Ayalew et al., 1999; Mohr & Zanettin, 1988; Pik, et al., 1998).

Low-angle shield volcanoes (e.g. Simen, Mt Choke, Gugufu, and Mt Guna) erupted from large central vent volcanoes that are magmatically similar to the underlying flood basalts, i.e. tholeiitic shields overlie tholeiitic flood basalts and alkaline shields overlie alkaline flood basalts (Kieffer et al., 2004). The volume of the shields is about 20% of that of the flood basalt (that is about  $4 \times 10^4 \text{ km}^3$ ) (Kieffer et al., 2004).

Quaternary plateau basalts and volcanics comprise all Quaternary alkaline basalts and trachyte emplaced in the region south of Lake Tana on the northwestern plateaus (Kieffer et al., 2004), which occur due to local rift structures north-south trending extensional faults (Chorowicz et al., 1998). Volcanic cones and flows of scoriaceous basalts are well preserved in the Lake Tana graben. The volcanic rocks of the Lake Tana area are usually described as olivine alkaline basalts (Merla et al., 1979).

The Ethiopian Plateau Basalts have a difference in geochemical and petrographic characteristics and vary in spatial distribution. Three main magma types are spatially zoned according to their  $\text{TiO}_2$  content (Pik et al., 1998). They are characterized by a clear zonal arrangement with Low-Ti tholeiites (LT) to the west; High-Ti tholeiites (HT1) to the east and very High-Ti (ultra-titaniferous) transitional basalts and picrites (HT2) close to the Afar triple junction (Pik et al., 1998; Kieffer et al., 2004; Beccaluva et al., 2009). The petrographic characteristics of the various lava types from spatially zoned NW Ethiopian plateau basalts are presented in [Table 2.1](#).



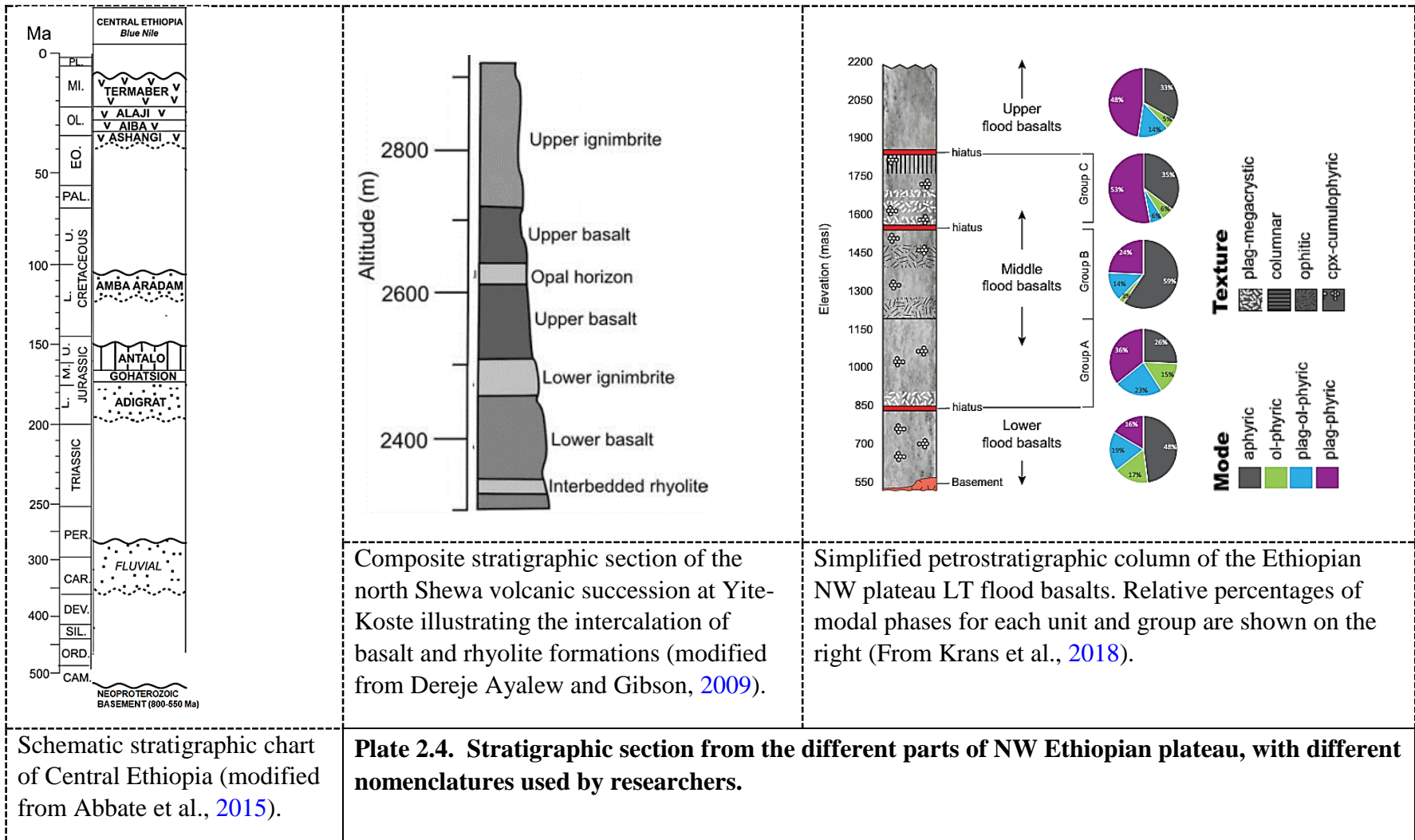
**Plate 2.3. Geological map of the northern part of the Ethiopian plateau depicting the distribution of the bimodal basalt–rhyolite flood volcanism and overlying shield volcanoes. Note that the age of volcanism decreases towards the south in conjunction with the onset of rifting in the Main Ethiopian Rift (MER) (Modified by Nicholas, 2005. (<http://www.largeigneousprovinces.org/> accessed on Jan 26, 2021) and reference therein).**

The plateau rhyolites are geographically correlated with the basalts, with low- and high-TiO<sub>2</sub> rhyolites occurring in association with low- and high-TiO<sub>2</sub> flood basalts (Dereje Ayalew et al., 2002). Three regionally distinct Oligocene rhyolite units are recognized by Dereje Ayalew et al. (2002): (1) The Lima Limo rhyolites in the northwest plateau forming several beds capping low-Ti basalt floods, (2) The Wegel Tena rhyolites in the east corresponding to very thick ignimbrites overlaying high-Ti flood basalts, and (3) The Jima rhyolites located in the southwestern plateau overlaying high-Ti flood basalts.

The Miocene rhyolites are situated in the Molale-Debre Birhan area close to the rift margin and overlay Miocene low-Ti flood basalts. There is no contact between the three Oligocene rhyolite outcrops in the field (Dereje Ayalew et al., 2002).

	<b>Low-Ti basalts</b>	<b>HT1 basalts</b>	<b>HT2 basalts and picrites</b>
Phenocrysts textures	Hypocrystalline to microcrystalline to doleritic, with a porphyritic index varying in the range 0-10%, coarser-grained (intergranular and aphyric–ophitic) textures; phenocrysts are predominately plagioclase ± olivine, and often glomerophyric	Mainly aphyric with variable grain size. Sub-ophitic to doleritic textures appear holocrystalline, coarse-grained, with plagioclase laths, poikilitic (pinkish) clinopyroxene, and small magnetite crystals sometimes associated with rare phlogopite	More porphyritic in texture with phenocrysts of olivine, sometimes including Cr-spinel, pinkish Ti-rich clinopyroxene (up to 5 mm across), and rare plagioclase.
Groundmass	Locally sub-ophitic with plagioclase laths, interstitial clinopyroxene, and abundant Fe–Ti oxides magnetite and ilmenite microcrystals; brownish interstitial glass is occasionally present	Olivine is common in the groundmass, along with pinkish clinopyroxene (in PPL) and abundant Fe–Ti oxides.	Microcrystalline to hypocrystalline, and is made up of the same phenocryst phases plus Ti-magnetite, scarce phlogopite, and alkali feldspar.
Magma character	Tholeiitic basalts	Slightly more alkaline and hydrated character with respect to the LT magmas	Ultra-titaniferous transitional-alkaline basalts and picrites
Mantle sources	Outer comparatively less metasomatized mantle sources	More metasomatized mantle domains closer to the plume axis	Innermost (hottest) part of the Afar plume from highly metasomatized mantle domains
Zonal arrangement in Northern Ethiopian plateau basalts	NW	Southeastwards	Concentrated in the Lalibela area, closer to the center of the Afar triangle

**Table 2.1. The petrographic characteristics of the various lava types from spatially zoned NW Ethiopian plateau basalts** (Data sources from Pik et al., 1998; Beccaluva et al., 2009; Natali et al., 2016; Krans et al., 2018).



Schematic stratigraphic chart of Central Ethiopia (modified from Abbate et al., 2015).

Composite stratigraphic section of the north Shewa volcanic succession at Yite-Koste illustrating the intercalation of basalt and rhyolite formations (modified from Dereje Ayalew and Gibson, 2009).

Simplified petrostratigraphic column of the Ethiopian NW plateau LT flood basalts. Relative percentages of modal phases for each unit and group are shown on the right (From Krans et al., 2018).

**Plate 2.4. Stratigraphic section from the different parts of NW Ethiopian plateau, with different nomenclatures used by researchers.**

## **CHAPTER-THREE**

### **3. LOCAL GEOLOGY**

#### **3.1. Introduction**

This study, which covers the litho-stratigraphic study of the Sela Dingay area volcanic complex in North-Western Ethiopian plateau, has a 1775 m-thick sequence (from 1540 to 3315masl elevation). The study tries to construct a complete litho-stratigraphic section of Mofar River from four different localities: Termaber, Sela Dingay, Sasit, and Zaro/Gawna Area. In the Termaber area, where the tributaries of the Mofar River starts, the youngest units outcrop forming the top part of the successions. The main lithostratigraphic units are studied along the central part of Mofar River in the Sela Dingay area; in addition to this other sub-traverses along the tributary rivers with similar succession are made from the central part of the river, including Kaskash, Taj Wuha, and Sasit area. The base of the composite litho-stratigraphy is made around the Zaro area locally called Adabay, where the Mofar River intersects the large Jemma basin exposing lower elevated units of the study area. From this comprehensive work, the area consists of six main formations listed below from older to younger with their respective regional stratigraphic name;

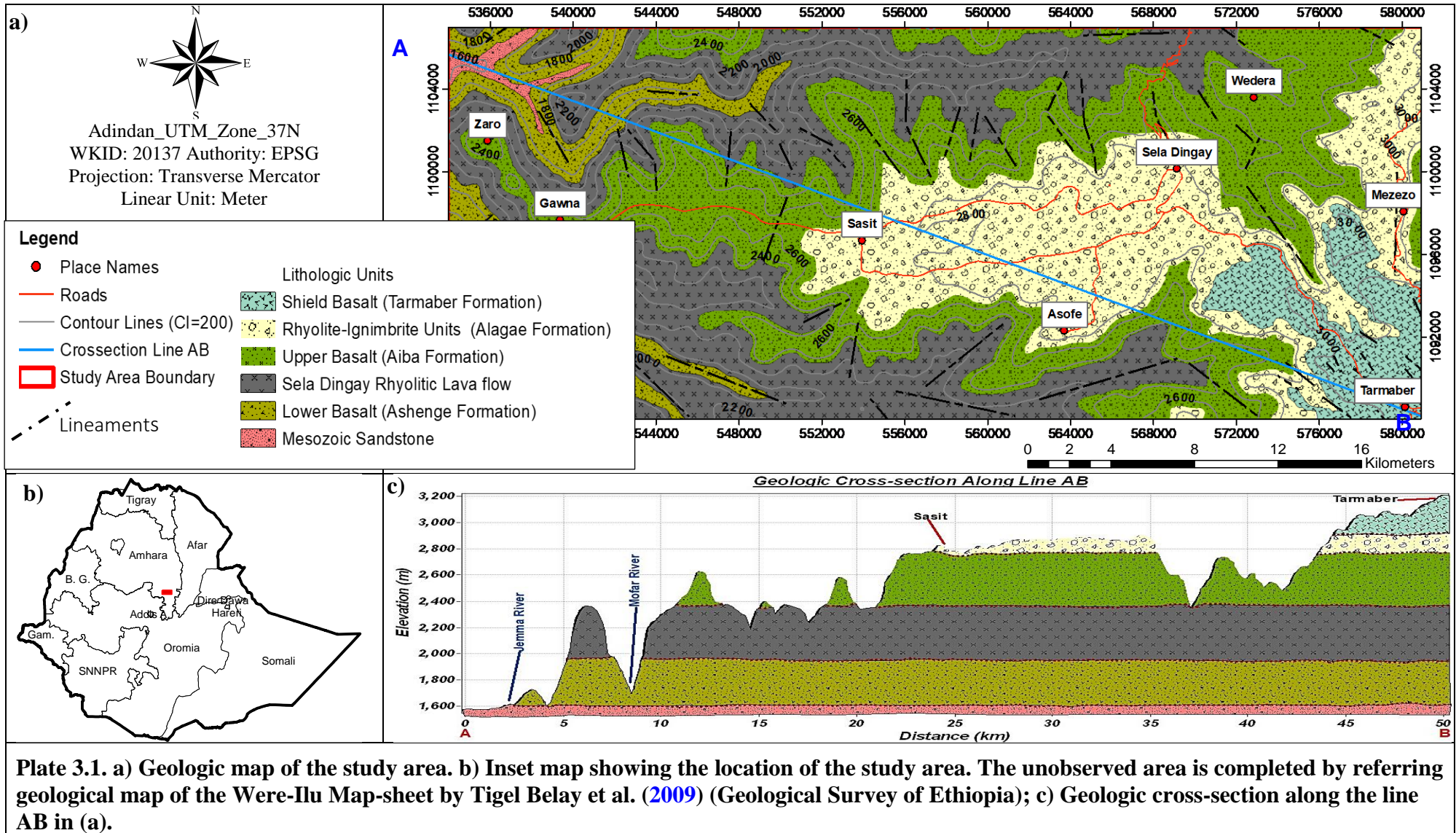
#### **Mesozoic Sedimentary rock**

1. Sandstone formation (Amabradam Formation or Debre-Libanos sandstone formation)

#### **Oligocene-Miocene volcanics**

2. Lower Basalt (Ashenge Formation)
3. Sela Dingay Rhyolitic Lava flow
4. Upper Basalt (Aiba formation)
5. Sela Dingay Rhyolite-Ignimbrite units (Alajae Formation); and
6. Shield Basalt (Termaber formation)

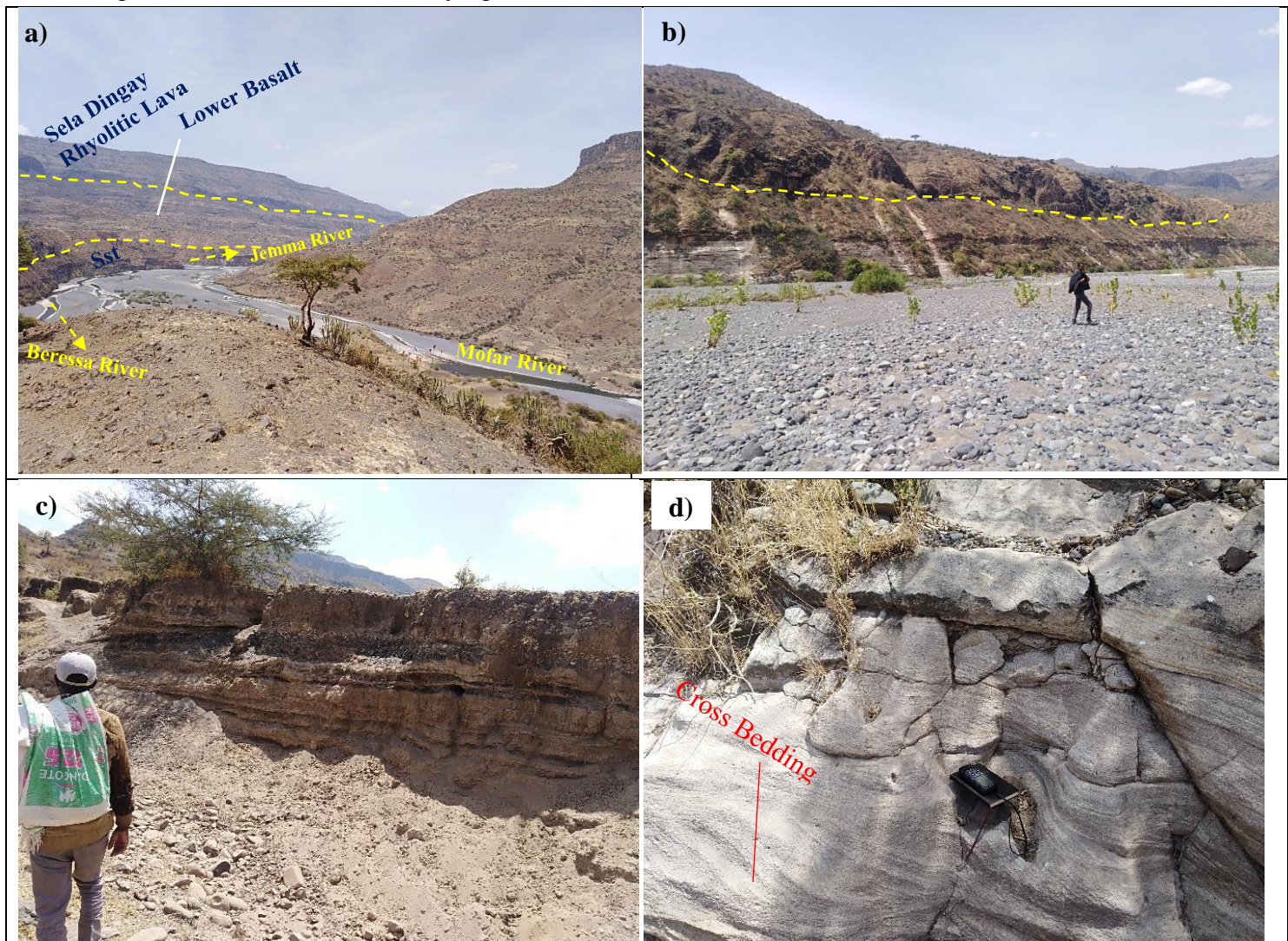
Formational names for Oligocene to Miocene volcanics are taken from Mohr and Zanettin 1988; the sandstone is referred to as Debre-Libanos sandstone (Assefa, 1991) or and Upper sandstone or Amabradam Formation (Abbate et al., 2015). In the following sections, field observations in these different areas, from where the petrographic samples were derived will be summarized in detail from oldest to youngest for each Litho-stratigraphic unit. The rock units are described according to stratigraphic succession from their vertical contact relationship in the field and information from previous absolute dating data. The Litho-stratigraphic section of the study area from different localities is presented in the last section of this chapter.



### 3.2. Descriptions of Local Lithologies

#### 3.2.1. Mesozoic Sandstone formation

This unit, which is the oldest rock unit exposed in the study area at the deep gorges made by an intersection of Mofar and Jemma River locally the area called Adabay, in the Northwestern end of the study area at the base of Zaro section. The exposed unit has a thickness of 80 m (approximately from 1540 to 1620 amsl elevation). The unit is overlain unconformably by lower basalt (**Ashenge Formation**); the unconformity surface is characterized by the unevenly eroded irregular surface over which unconsolidated sediments are deposited. The sandstone is white, light grey, and pale pink colored, fine to medium-grained, and cross-bedded to cross-laminated at the exposed base and the top part of the unit composed of intercalation of conglomerate and silty sediment with the sandstone along the contact area to the overlying unit.



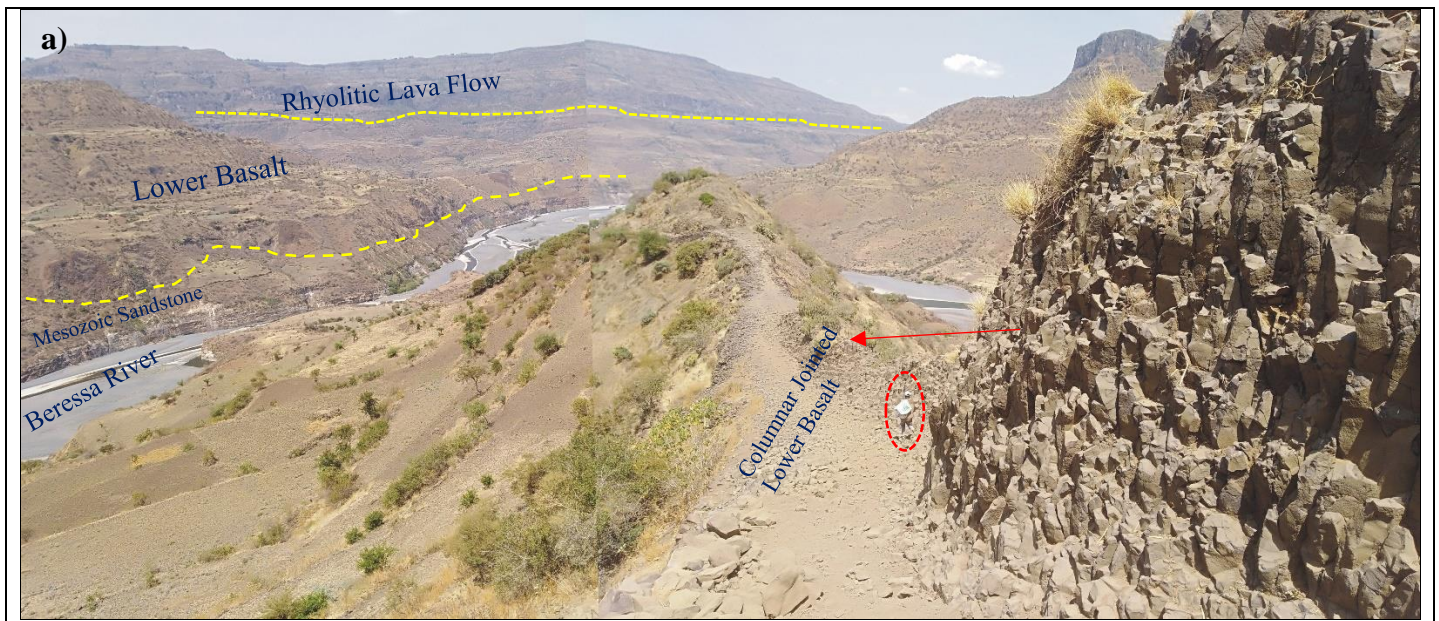
**Plate 3.2. Different exposures of Mesozoic Sandstone unit at the base of the stratigraphic section of the study area. a) panoramic view of the contact relationship between the overlying unit and the Sandstone formation (Sst) near the intersection of the Beressa, Mofar, and Jemma rivers. b) unconformable (erosional) contact between the Sandstone and Lower basalt. c) intercalating conglomerate-sand-silt units on the top part of the Sandstone formation. d) close-up view of the Sandstone with cross-stratification.**

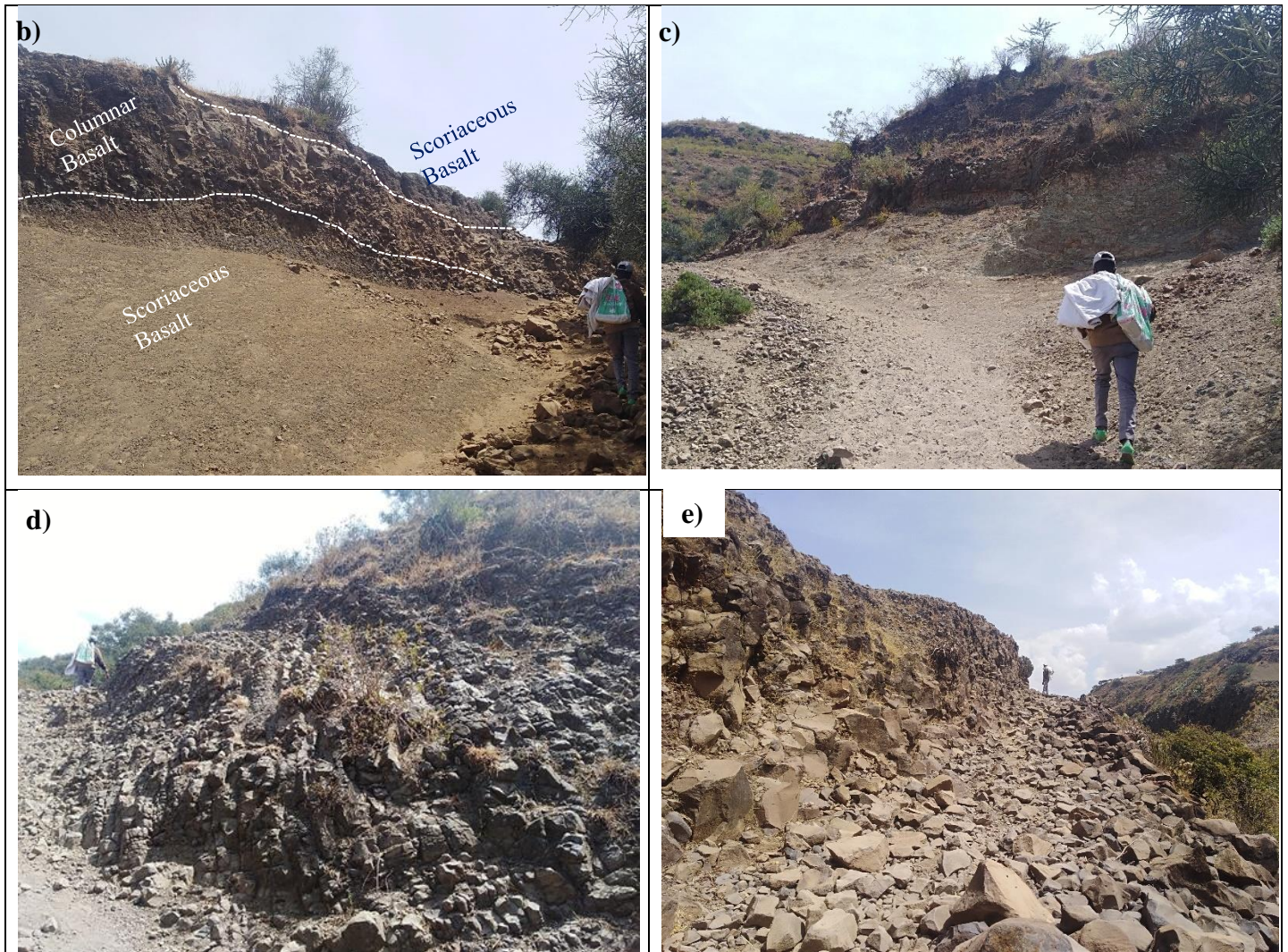
### **3.2.2. Lower Basalt (Ashenge Formation)**

Lower basalt regionally called **Ashenge Formation** is exposed along the deep gorge formed by the Mofar river section in the Northwestern end of the study area around the Zaro area. It lies unconformably on the sandstone, in which the unconformity is marked by a 3-7 m thick soil horizon on an erosional surface. This unit is dominantly composed of basalt with varying proportions of aphyric basalt, vesicular basalt, scoriaceous basalt, and porphyritic basalt with minor interlayered silicic-pyroclastic deposits towards the top part of the succession. The thickness of this formation within the study area is about ~ 330m (from ~1620 to 1950m amsl).

The exposures of the Formation have majorly light-black to dark-gray fresh color and light-gray weathered color, aphanitic to poorly porphyritic texture. The formation is strongly weathered, intensely fractured, jointed and in some portion dipping (10-30°) columnar joints observed. The top part contains deeply weathered, altered, and modified materials, which are typically colored into red, yellow, and green by ferruginous clay iron oxide pigments; this alteration surface is an indication for change that causes deposition to cease for a considerable period forming unconformity to the overlying unit.

This basaltic formation consists of different lava flow sub-units, including massive basalt, columnar basalt, fractured basalt, and scoriaceous basalt. The precise number of flows is difficult to determine, because this formation contains strongly weathered, intensely fractured, and jointed lava flow units. The thickness of these lava flows varies approximately from 6 to 50m. The different flow units are separated by each other by paleosol or inter-trappean sediments, alteration surfaces, and minor felsic units including pyroclastic deposits and rhyolitic units.





**Plate 3.3. Different exposures of Lower Basalt from Gawna section in NW end of the study area. a) Panoramic view of Lower Basalt in between the underlying and Overlaying units and a columnar joint around the contact area. b) composite flow field with columnar jointed flow core Basalt and scoriaceous top and base. c) pyroclastic deposit (tuffaceous layer) interlayered within lower Basalt. d) dipping columnar joints (~ 30<sup>0</sup> dip angle). e) exposure of fractured Basalt.**

### **3.2.3. Sela Dingay Rhyolitic Lava flow**

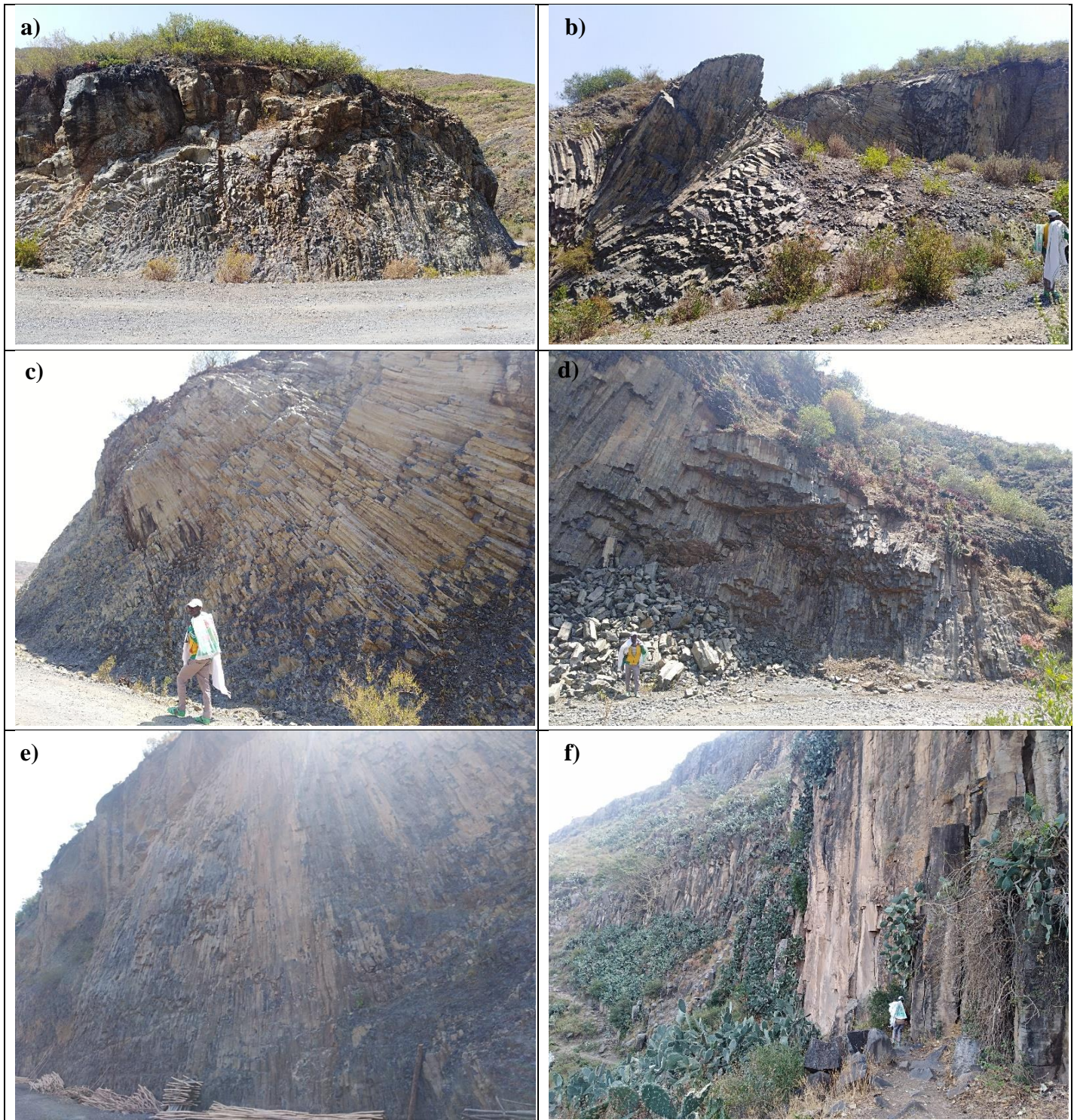
This rock unit is exposed in Sela Dingay, Sasit, and Gawna sections. It is overlain unconformably by Upper basalt (Aiba Formation) and underlain unconformably by Lower basalt (Ashange Formation); represented by paleosol deposit and an alteration surface that is observed around the contact area due to alteration of the basaltic lava flow, respectively. From the previous stratigraphic studies, this unit was grouped under Aiba Formation. The approximate thickness of this unit is estimated as 400m thick (1950 – 2350m amsl).

The unit composes glassy textured lava products of rhyolitic lava flow including rhyolite, rhyolitic obsidian, ignimbrite, and pyroclastic deposits (ash flow and fall deposits). In the top part, the unit is characterized by thinly irregular columnar jointed (Entablature type) rhyolitic obsidian, which is dominantly exposed in the Sela Dingay section. Porphyritic glassy rhyolite from this top part is observed consisting of Plagioclase phenocrysts in a glassy groundmass. The middle and bottom part of this unit is composed of thick massive glassy rhyolite with regularly oriented thicker columnar joints (Colonnade type). The lower part of this unit (near the contact area with the underlying basaltic unit) contains thick and intercalating pyroclastic deposits (volcanic glass) and variable thickness rhyolitic layers. Generally, these flows are horizontally continuous especially the bottom massive part; forming cliff topography in the study area.

The color of the exposure varies based on the different categories comprised with the unit, which shows dark, greyish dark, greyish light, and brown weathered color. It has a glassy texture, with a conchoidal fracture, and has a shiny appearance in hand specimen predominantly the top part of the unit.



**Plate 3.4. Panoramic view of massive and thicker columnar jointed lower part of Sela Dingay Rhyolitic Lava flow exposure in Gawna section. The most bottom part consists pyroclastic deposit.**



**Plate 3.5. Outcrops of various products within the Sela Dingay Rhyolitic Lava flow unit from the top part of the unit to the bottom. a) road cut exposure of Glassy Rhyolite with massive top and irregular jointed columns at the base in the Sela Dingay section. b) and c) road cut exposure of columnar jointed Rhyolitic Obsidian (Entablature type) in the Sela Dingay section. d) And e) thinly regular jointed columns in the middle part of the Rhyolitic Obsidian unit in the Sela Dingay section. f) massive regular jointed thicker Glassy Rhyolite unit (Colonnade type) at the bottom part in the Gawna section.**

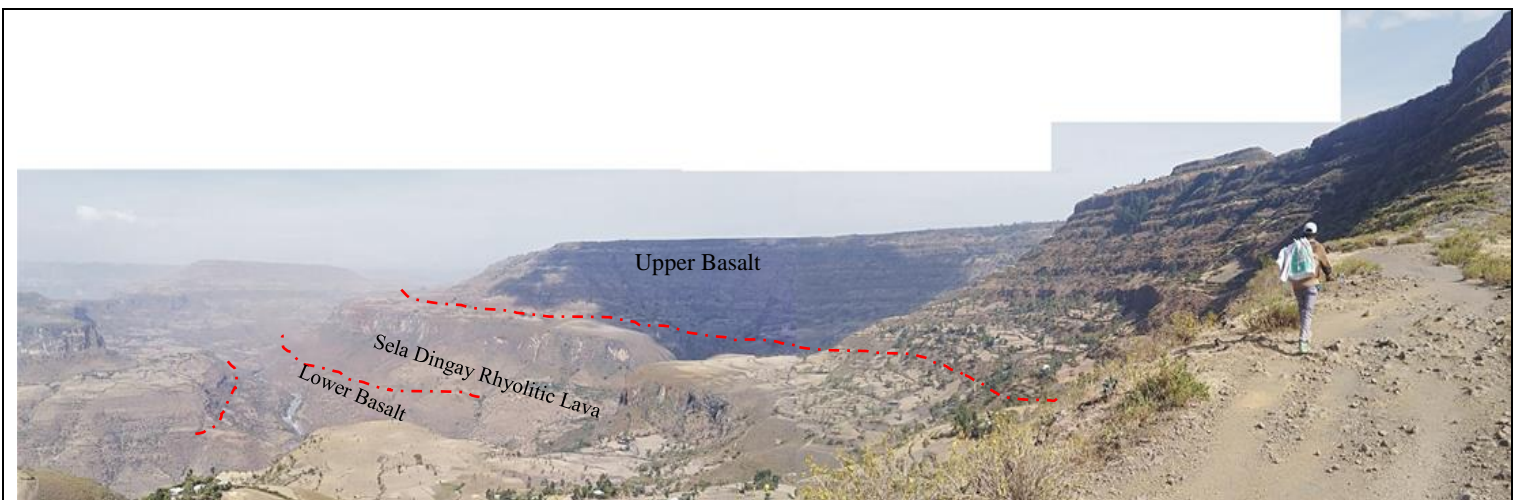
### **3.2.4. Upper Basalt (Aiba formation)**

The name Aiba formation is given to this basaltic formation regionally. Stratigraphically this basaltic formation possesses the central part of the study area, exposing along Sela Dingay, Sasit, and Gawna sections. It overlies unconformably on the Sela Dingay Rhyolitic Lava and overlain unconformably by Sela Dingay rhyolite-Ignimbrite units (Alajae Formation) the unconformity surfaces are expressed by intertrappean sediments (paleosol). It forms a relatively flat-topped cliff, forming plateau topography. An estimated thickness of this unit at the different sections reaches up to ~ 440m (From 2350 to 2790m amsl).

Lithologically, this basaltic formation is dominantly represented by the association of different basaltic lavas and subordinate pyroclastic rocks. The basalts consist of phryic-aphanitic varieties, scoriaceous basalt, vesicular basalt, and massive fractured basalts. The exposure of this unit shows black to dark grey color and changes to yellowish gray to greenish upon weathering. The basaltic lithology of this formation is composed of successive lava flows with a dominant flow thickness of 10-50m. The different basaltic units and the subordinate felsic products at a different portion of the stratigraphic section are separated by paleosol or alteration surfaces.

The pyroclastic deposits are composed of rhyolitic tuff, rhyolitic obsidian, and ignimbrites with rhyolitic lava flows. The lower part of this formation consists of various thicknesses ranging from 3m to 20m ignimbrites, rhyolitic tuff, and volcanic ash (loosely welded tuff) intercalation. Fresh ignimbrites show greenish light color with variable degrees of weathering. Intercalated welded glassy tuff (rhyolitic tuff) (5-20 meters thick) characterizes by yellowish-gray dominated by glassy texture.

Within this basaltic formation, there is a colorful (reddish, greenish dark to green) glassy thin layer (0.5 – 1m) bounded by the different basaltic flows is observed in the study area; which represents the regionally studied opal layer with lower quality varieties (Plate 3.8 (c) and (e)).



**Plate 3.6. Panoramic view of the underlying different units below the Upper Basalt around the Gawna area; the exposure also demonstrates planar composite flows of various thickness lava flows.**



**Plate 3.7. Outcrop photographs of various flow units within Upper Basalt from different parts of the study area. a) Panoramic view of contact area with the underlying Sela Dingay Rhyolitic Lava flow unit along Sela Dingay road. b) inter layered flow fields of Columnar Basalt and Scoriaceous Basalt from river cut exposure (Kaskash section) in the Wedera area. c) Scoriaceous Basalt incorporating Greenish Glass (Opal) which is Overlain by fractured Basalt in Sasit section. d) irregularly jointed columnar basalt from the Wedera area. e) Hand specimens that are taken from thin layers of colorful glass (c) at different positions.**

### **3.2.5. Sela Dingay Rhyolite-Ignimbrite units (Alajae Formation)**

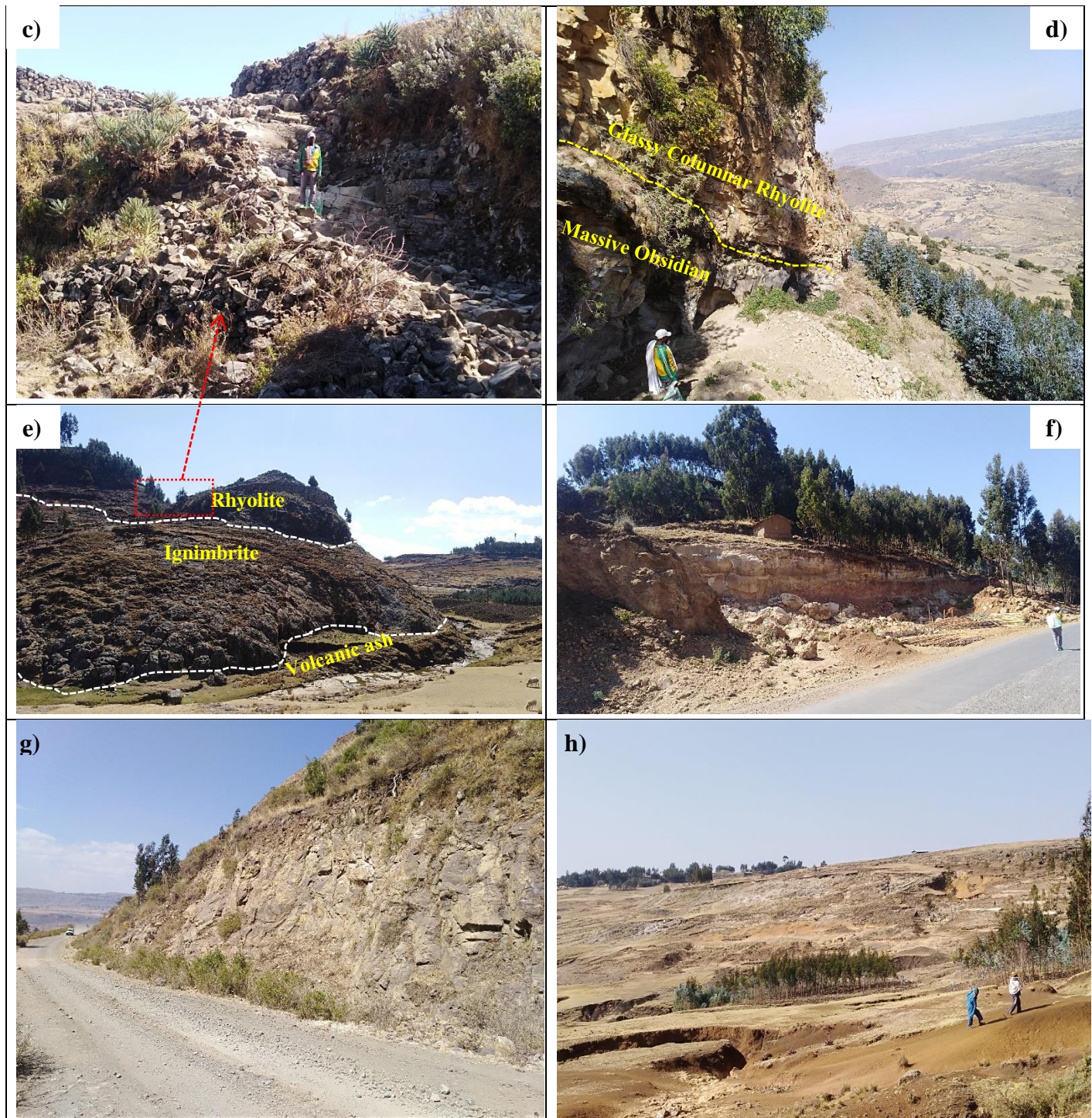
This felsic deposit dominating the topmost flood basalt successions of the study area is regionally called **Alajae Formation**. This rock unit is exposed in the top part of Sela Dingay to the Sasit section in the study area overlaying the upper basalt (Aiba Formation); in the Termaber section, this formation is overlain by Termaber shield basalt. It has an approximate thickness of up to 118m (from 2790 to 2908 m amsl). The formation consists of varieties of felsic deposits including rhyolite, ignimbrite, rhyolitic tuff, rhyolitic obsidian, and pyroclastic deposits (pyroclastic fall and flow with tuffaceous layers) lacking basaltic units in the study area.

From the major lithological units observed in this formation rhyolitic lava flow is the main unit that has a major thickness relative to the rest in the rock succession. The unit shows flow banding. The thickness of the unit ranges from 30m to 50m. The exposure of this unit can be described as light gray fresh color with brownish weathering color, sparsely porphyritic, and shows columnar jointed structures.

The Ignimbrite unit is one of the lithological units found in this formation. In the study area, the ignimbrite has 10 - 35 m thick and consists of yellowish-gray to gray slightly weathered and fractured ignimbrite. The rock unit contains fiamme and rock fragments. The rock fragment has a light grey color and shows layering. The fiamme has black color with a glassy texture. The remaining part of the rock is composed of fine-grained and visible crystals. The fine material shows grey to white and makes up the groundmass. Visible crystals are light-colored. This rock unit is associated with minor interlayers of rhyolitic tuff and rhyolitic obsidian units.

Pyroclastic flow and fall deposits are the other main lithological units that cover the study area forming a flat topography. This unit is very thin and intercalates with other units. Lithologically this unit is composed of pyroclastic ash and poorly welded to welded tuffaceous layers. All the pyroclastic fall deposits show similar characteristics of pale yellow to grey color, well-sorted, loosely welded, and have a consistent local thickness (0.5m – 3m). The flow deposits have characteristics of pale yellow to greyish color, show moderate welding, are poorly sorted, have a lithic fragment, and show variation in vertical thickness.





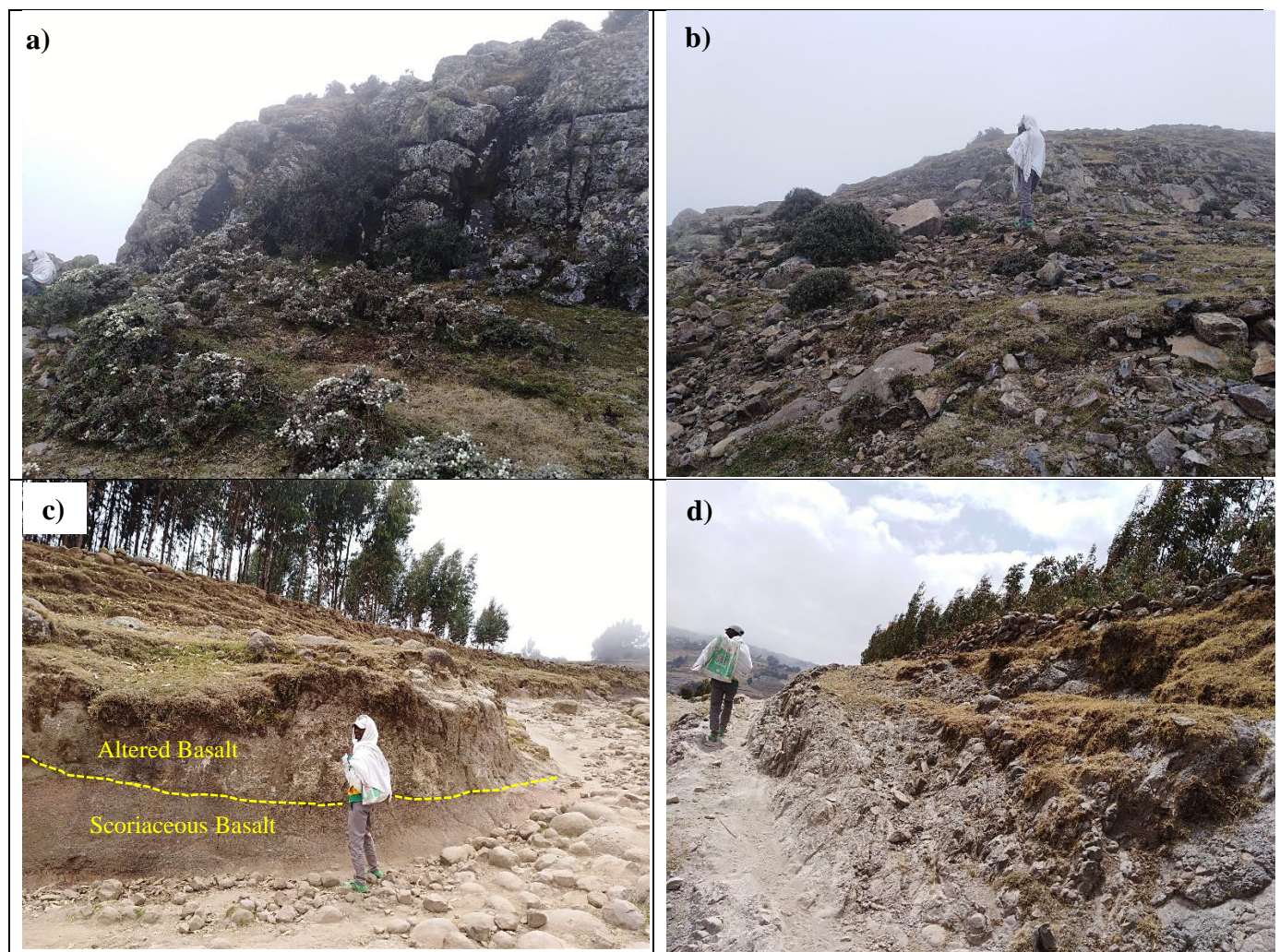
**Plate 3.8. Major lithological units within Sela Dingay Rhyolite-Ignimbrite units. a) A thick Rhyolitic lava flow from Sela Dingay Road exposure. b) Columnar jointing showing banding in Rhyolite from the top of the Sasit section. c) Close-up view of fractured rhyolite from a photograph (e). d) Glassy columnar jointed Rhyolite overlaying an Obsidian layer at the top of Sasit Section. e) silicic-pyroclastic deposits from the top part of Sela Dingay near Debre Mitmak village. f) Welded Pyroclastic Tuff near Sela Dingay town. g) Road cut exposure of typical ignimbrite unit from Sela Dingay road. h) Top part along Sela Dingay-Sasit Road covered with pyroclastic deposits.**

### **3.2.6. Shield Basalt (Termaber formation)**

This shield basalt is exposed in the southeastern corner of the study area only around the Termaber locality, which forms ridges and mountain chains creating shield topography. It overlays the rhyolitic formation (Alajae Formation) unconformably; the contact area is dominated by deposition unconsolidated sediments over an erosional surface. The elevation of this formation starts from 2908m to a maximum elevation at the shield center reaches up to 3315m amsl; from this, the maximum thickness attained by this unit is about 407m in this study area.

This formation is represented by various basaltic flow units (massive blocky basalt, fractured basalt, columnar jointed basalt, and scoriaceous basalt) and interlayer of subordinate felsic units (rhyolite and tuffaceous layer), separated by reddish-brown paleosol and an alteration surface. The basalt has dark-grey to greyish fresh color and reddish-brown, light-gray, light-yellow, and greenish-gray weathered colors and aphanitic to porphyritic grain size texture. Altered varieties of this basaltic formation show light-grey colored infillings replacing coarse-grained minerals.

A thick (~ 35m) deposit of unconsolidated sediments is observed long the contact area of this formation, which shows variegated (red, grey, light-green) color.



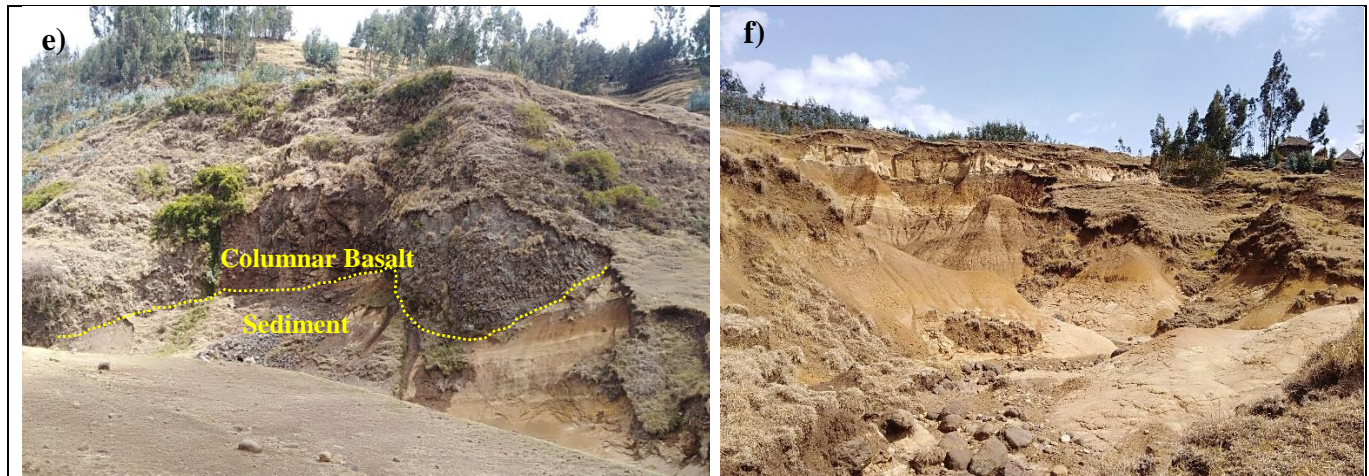
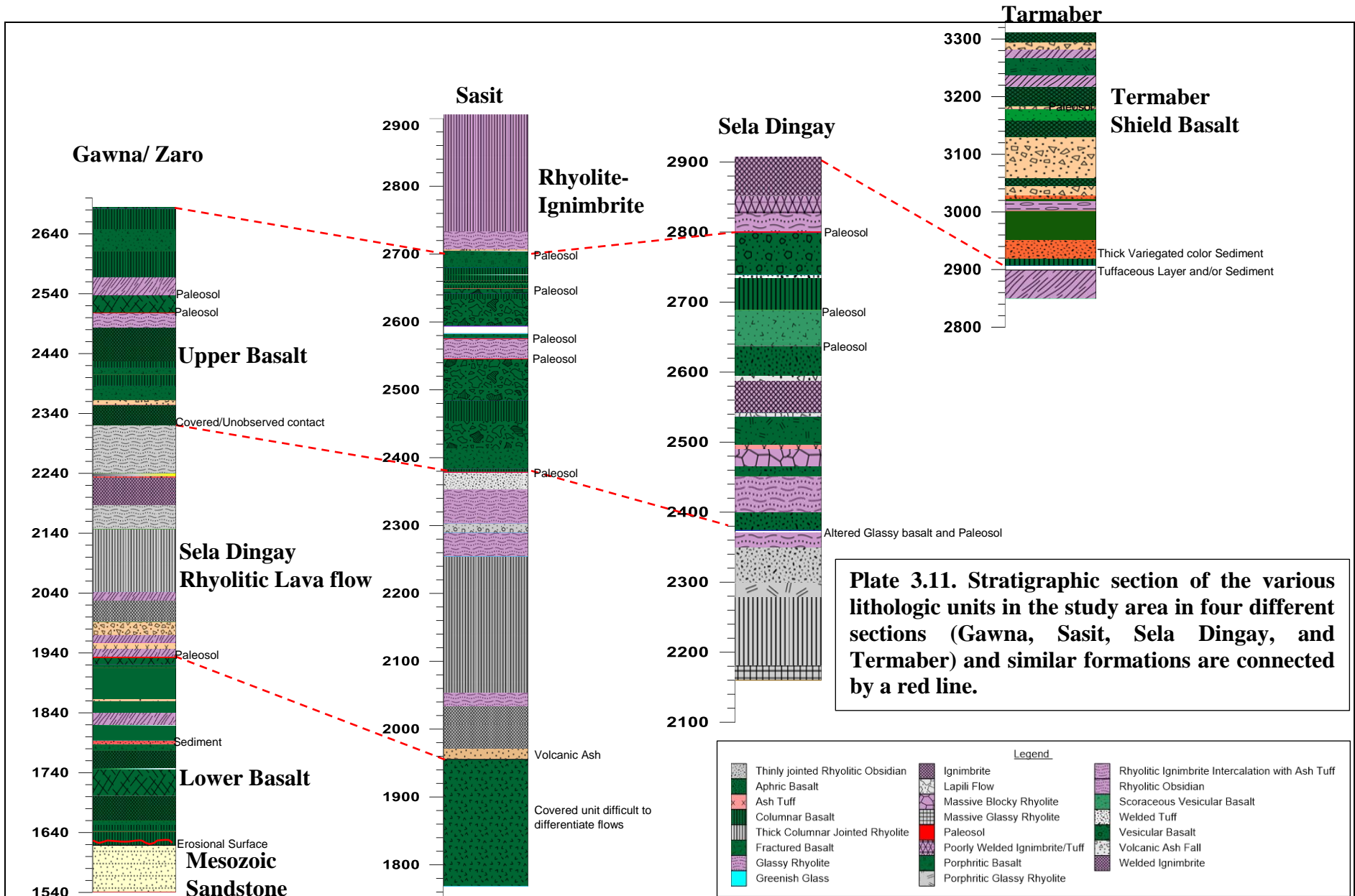


Plate 3.9. Outcrop scale exposures of different units in the Shield Basalt from the Termaber area. a) and b) massive blocky basalt and fractured basalt on the top part of the shield respectively. c) and d) Scoriaceous Basalt and a thin layer of rhyolitic unit with banding interlayered in the middle part of the formation respectively. e) thinly columnar jointed basalt overlaying thick sediment at the contact area to the underlying rhyolitic formation. f) intercalation of variegated color sediment shown in the photograph (e).



Plate 3.10. Panoramic view showing the contact area of the Shield basalt and the underlying Rhyolitic formation separated by a thick deposit of sediment in the Termaber area.



### 3.3. Morphology of Lava Flow Products

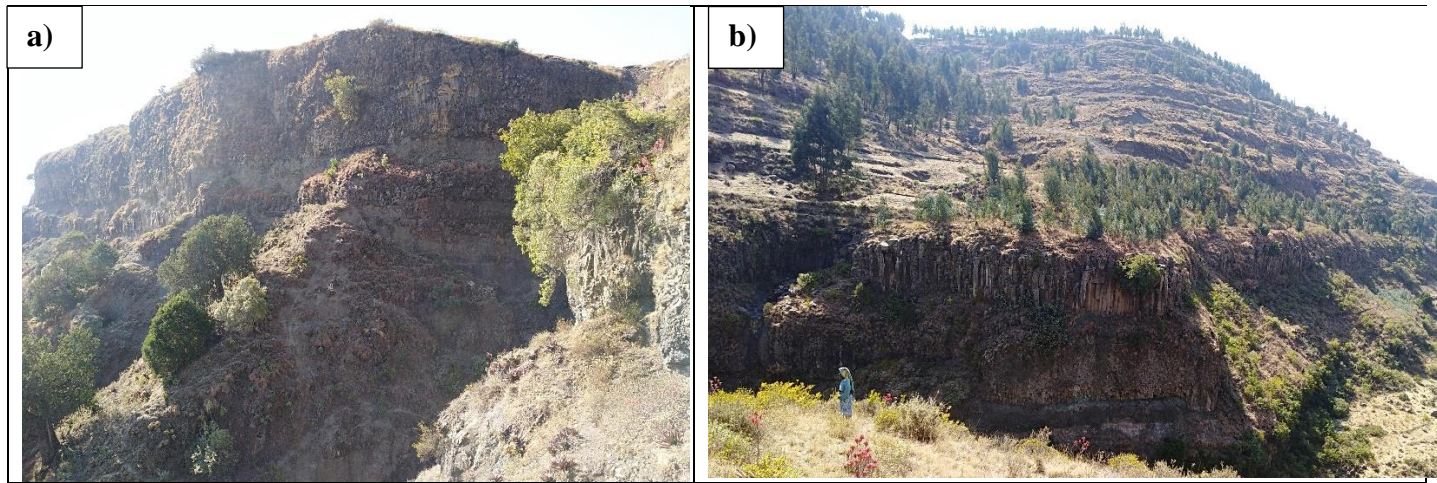
Terminologies used to distinguish the characteristics of the different flow fields for continental flood basalts lava flow products which are used by regional studies (e.g. Self et al., 1997; Walker, 1971 cited in Hachimi et al., 2011) includes flow lobe, lava flow, and lava flow field.

A **flow lobe** is used to describe an individual set of lavas surrounded by a chilled lava crust. **Individual lava flows** are the product of a single outpouring of lava that can be composed of one or more flow lobes which are typically separated by weathering surface and/or clastic lithologies. If a lava flow consists of a single flow lobe it is referred to as a **simple lava flow**, which are single eruptive units with a larger thickness; if the lobe has a sheet-like or tabular geometry it is classified as a sheet lobe. Conversely, **compound flows** are made up of several individual flow units (flow lobes) of any geometry or size erupting one after the other. A **flow field** is the aggregate product of a single eruption, which comprises one or more lava flows. The morphological types of flood basalt lava flows also include pāhoehoe, ‘a’ā, and pillow-type lava flow units.

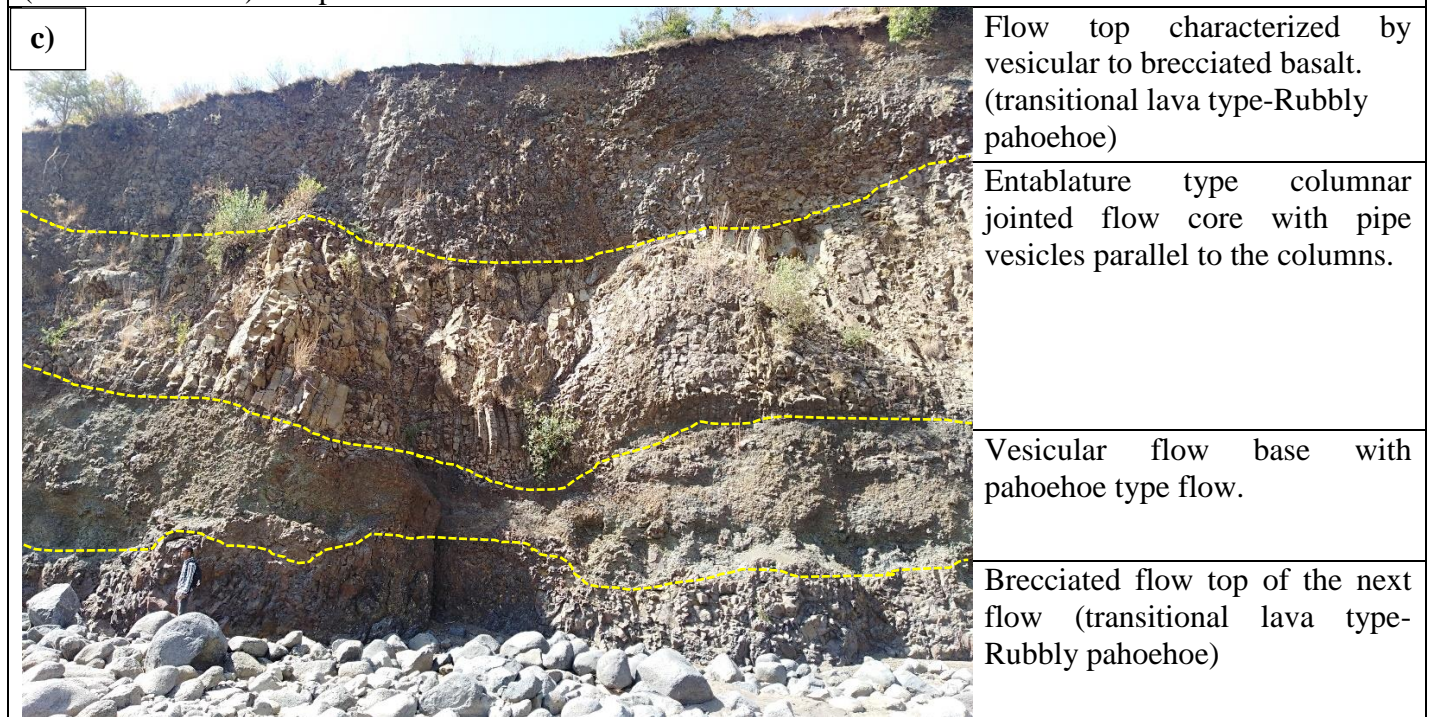
The basaltic lava flow types in this study area consist of sheet-like or tabular flow structures of individual units. The different flow units are separated by a thin layer of sediment (paleosol), weathering surface, and pyroclastic deposits (ash tuff). Flow tops in exposed flow fields are characterized by pāhoehoe flow surface and in some flows, also smooth as well as brecciated/‘a’ā type vesicular surfaces are observed. Flow cores are characterized by massive, vesicle poor columnar jointed flow lobes. The columnar joints are mostly vertically oriented blocky columnar joints (well-developed columnar jointing- Colonnade jointing from Reidel et al., 2013), which are 30 – 80 cm wide with 5-10cm joint spacing. In some flow lobe, the core portion displays patterns varying from numerous, irregular jointed small columns to randomly oriented cooling joints (Entablature type from Reidel et al., 2013). The flow bases are observed to be a thin planar surface. The morphology of the flow base observed in different flow fields is highly dependent on the underlying unit.

“There are two basic types of flow geometries (<https://slidetodoc.com/geometry-of-crbg-lava-flows-sheet-vs-compound/>) – **compound flows and sheet flows**. When lava flows advance away from their vent in a series of distinct and separate lobes (flows), they form a **compound flow**. As the lava emplacement continues, each lobe is gradually covered by subsequent lava lobes. This results in the accumulation of elongated bodies of basalt with numerous, local, discontinuous, and relatively thin layers of basalt lava. A **sheet flow**, on the other hand, results when lava is erupted at a rapid rate and can advance away from the vent as a single, uniform sheet of lava. This type of flow is made up of a single layer or "sheet" of lava that is relatively extensive. Each successive sheet flow will create a similar layer, with the flow boundaries being delineated by distinct vesicular flow tops and flow bottoms.”

Individual, large-volume basaltic lava flows in this study area display characteristics consistent with sheet flows. Local exposures of small flows are observed displaying compound-braided flows.



Columnar-jointed pāhoehoe sheet lobes juxtaposed against and stacked above each other, which are thicker (each flows > 2m) compound flows.



Flow top characterized by vesicular to brecciated basalt. (transitional lava type-Rubbly pahoehoe)

Entablature type columnar jointed flow core with pipe vesicles parallel to the columns.

Vesicular flow base with pahoehoe type flow.

Brecciated flow top of the next flow (transitional lava type-Rubbly pahoehoe)

**Plate 3.12. Photographs of different basaltic exposures (Upper basalt flow units) demonstrating the typical features of lava flow morphologies of flood basalts in the study area; Location of the section where photographs taken is from Sela Dingay area: a) & c) a long Kaskash river and b) from Taj Wuha section.**

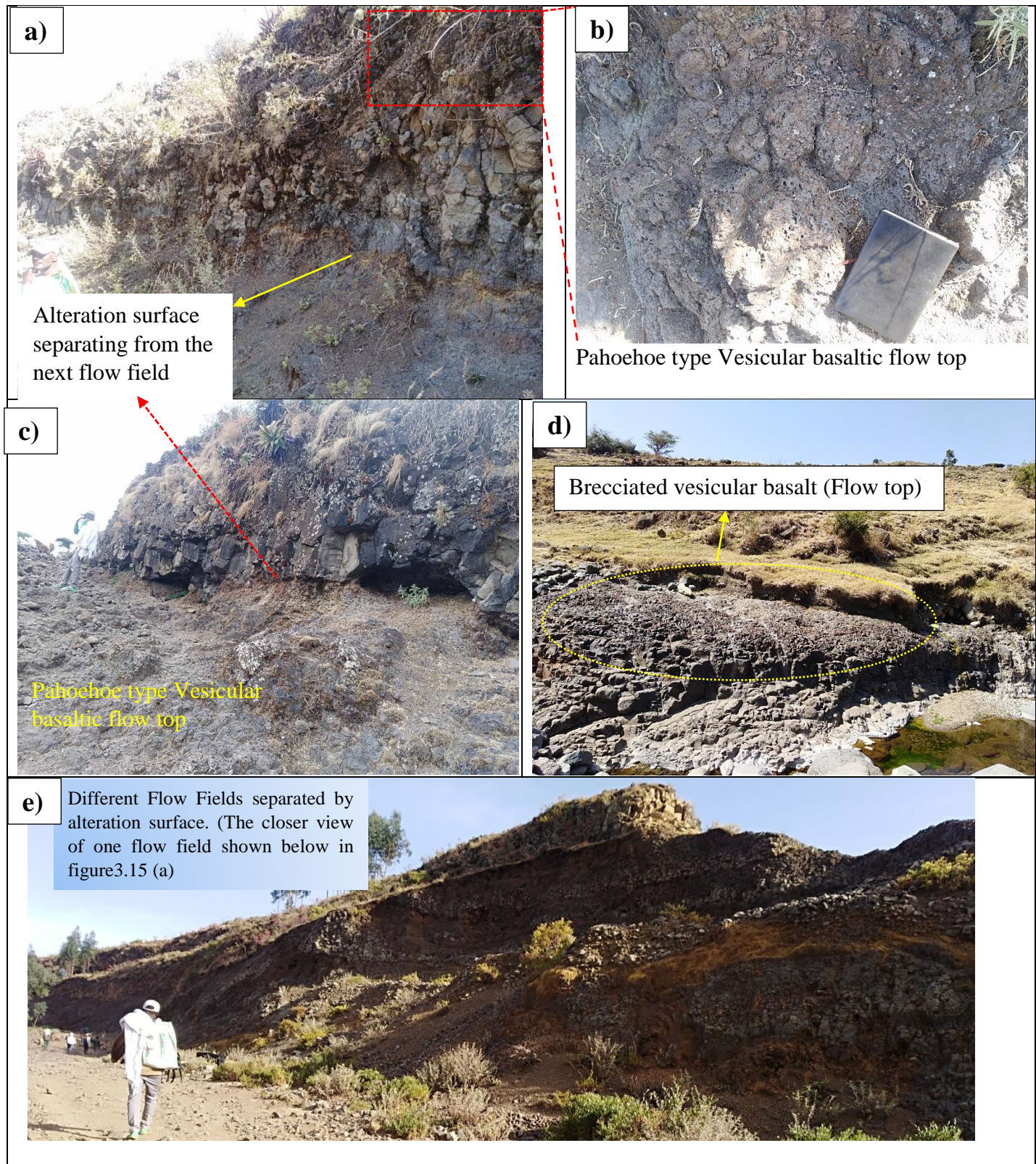
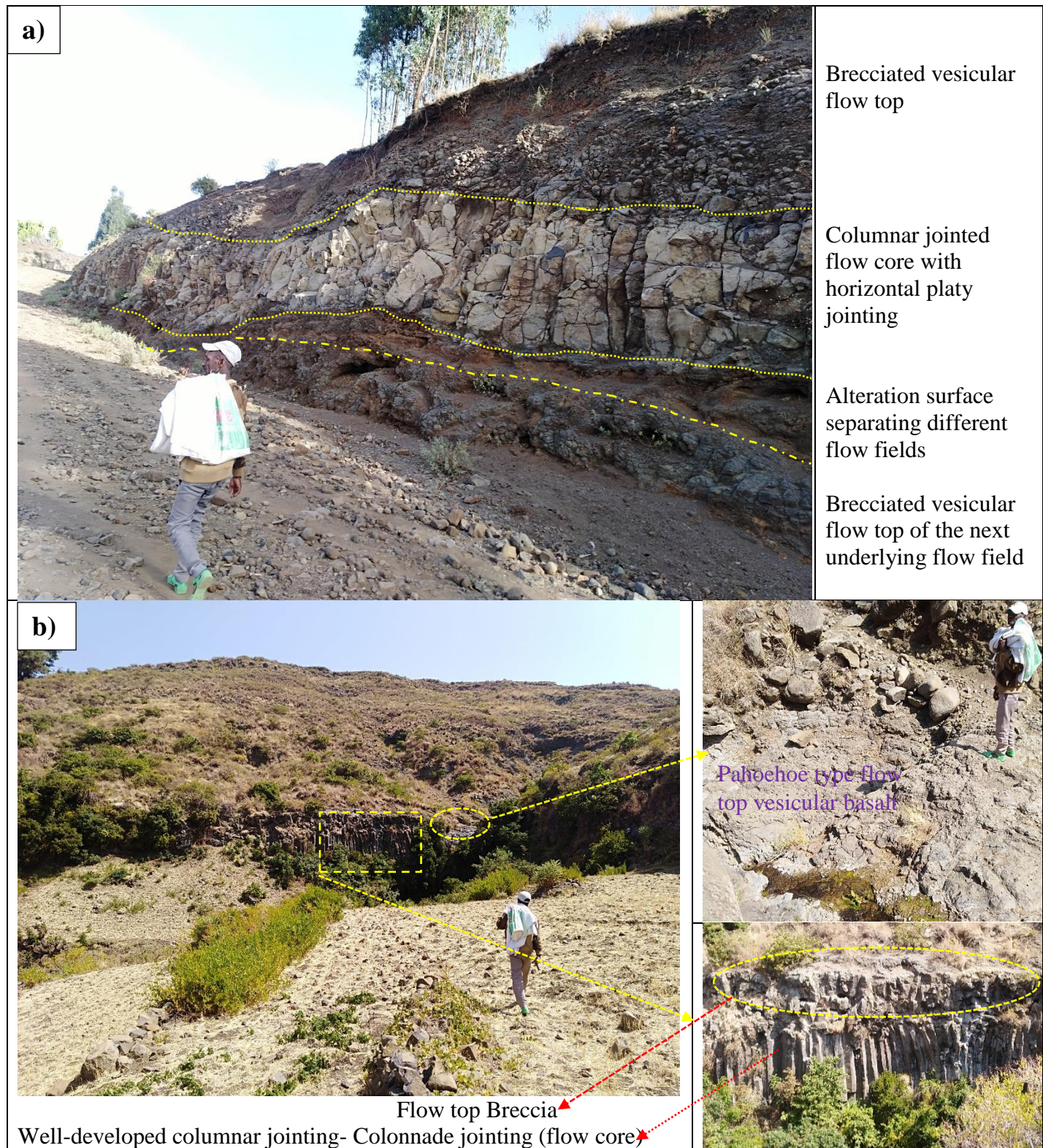
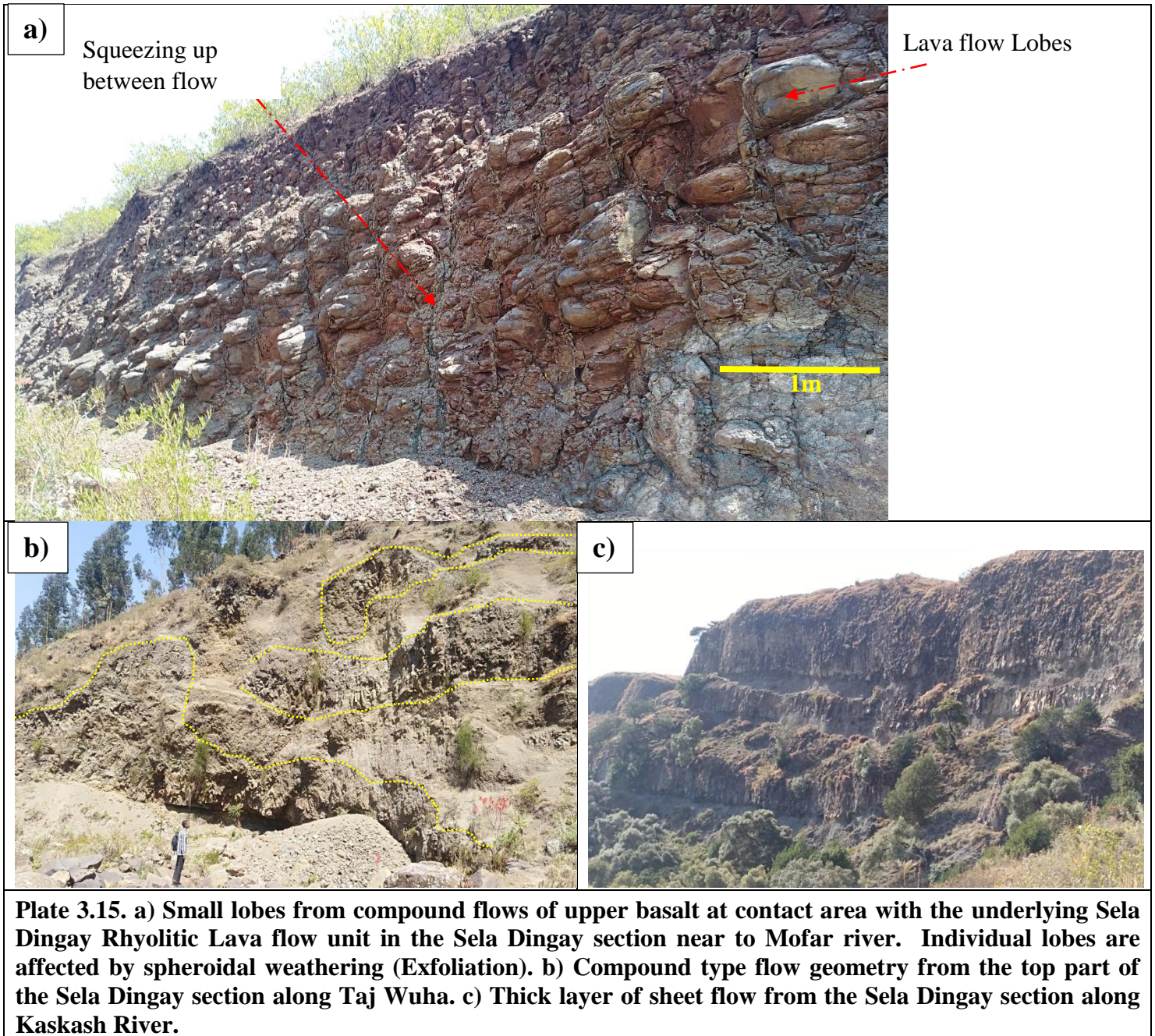


Plate 3.13. Continued... Photographs of different basaltic exposures (Upper basalt flow units) demonstrating the typical features of lava flow morphologies of flood basalts in the study area; Location of the section where the photographs taken is a, b & c are from Sasit area, d) from Sela Dingay section and e) from top part of Gawna section.



**Plate 3.14. Continued... Photographs of different basaltic exposures (Upper basalt flow units) demonstrating the typical features of lava flow morphologies of flood basalts in the study area; Location of the section where the photographs taken is a) sheet flow from Gawna section and b) sheet flow product from Sela Dingay area along Tej Wuha section.**



### **3.4. Geologic Structures**

Different geological structures are observed in the studied area. These structures are associated with the behavior of magma cooling and deformational structures. The geological structures observed are divided into primary and secondary structures. Primary structures are structures formed at the time of formation of the rocks (during magma cooling). In contrast, geological structures which are formed after the deposition of the rocks as a result of the tectonic activities to which the rock is subjected are called secondary structures.

#### **3.4.1. Primary Structures**

These structures are volcanic structures that are formed at the time of magma cooling. The most observed structures in the study area are primary structures which include lava flows, different types of columnar joints (Colonnade which is more regular and a coarser pattern often found at the base of the flow and Entablature is more irregular, and often found near the top of flows Reidel et al., 2013), nearly vertical and horizontal flow banding in rhyolitic units and horizontal graded layering of pyroclastic fall deposits. The topographic structures in the study area are dominantly plateau and ridges (which are secondary structures formed by dissecting of plateaus by stream drainage valleys leaving intervening ridges) formed by different types of lava products. The most top part of the geologic succession in the Termaber area forms three-dimensional shield topography.

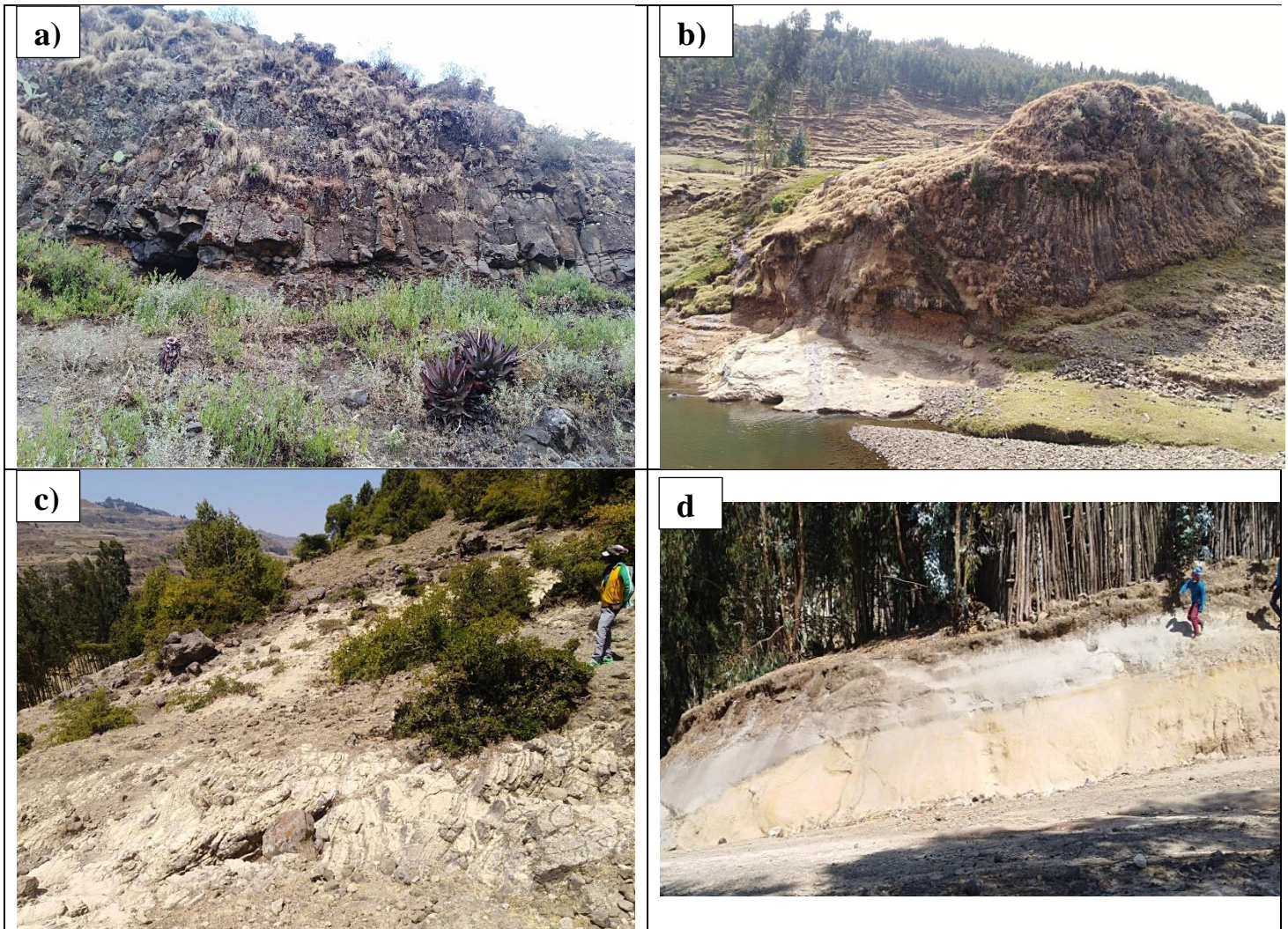




**Plate 3.16. Panoramic view of morphological topographies formed by the different lava flow products; a) panorama of a basaltic plateau formed by upper basalt in Wedera area along Kaskash river section, b) view of upper basaltic lava flow sequences in Sela Dingay section and c) typical pyramidal topography formed by rhyolite in Sela Dingay section (Alajae Formation).**



Plate 3.17. Different types of columnar jointing in Sela Dingay Rhyolitic lava flow products from top to bottom part of the unit; (a, b, & c) are Entablature type irregular jointing on the top part of the succession, (d) and (e) are regular patterned thinner columns, and (f) represents a thicker more regularly jointed columns (Colonnade type) at the lower part of the unit.



**Plate 3.18. Different types of primary structures from different eruptive products. a) vertically oriented regular Columnar jointing in Upper basaltic flow. b) thinly jointed Columns from the Shield basalt displaying shield topography. c) Flow banding formed by Rhyolitic flow. d) pyroclastic fall deposits forming graded layering.**

### 3.4.2. Secondary structures

The large-scale prominent secondary structure observed in the study area is a lineament formed by an alignment of hills. Other small-scale structures observed in the study area are fractures, joints, and faults.





**Plate 3.20. Panoramic view of Landscape (ridges and lineaments) formed by the different lava flow products of the Flood Basalt in the Study area.**

## **CHAPTER-FOUR**

### **4. PETROGRAPHY**

#### **4.1. Introduction**

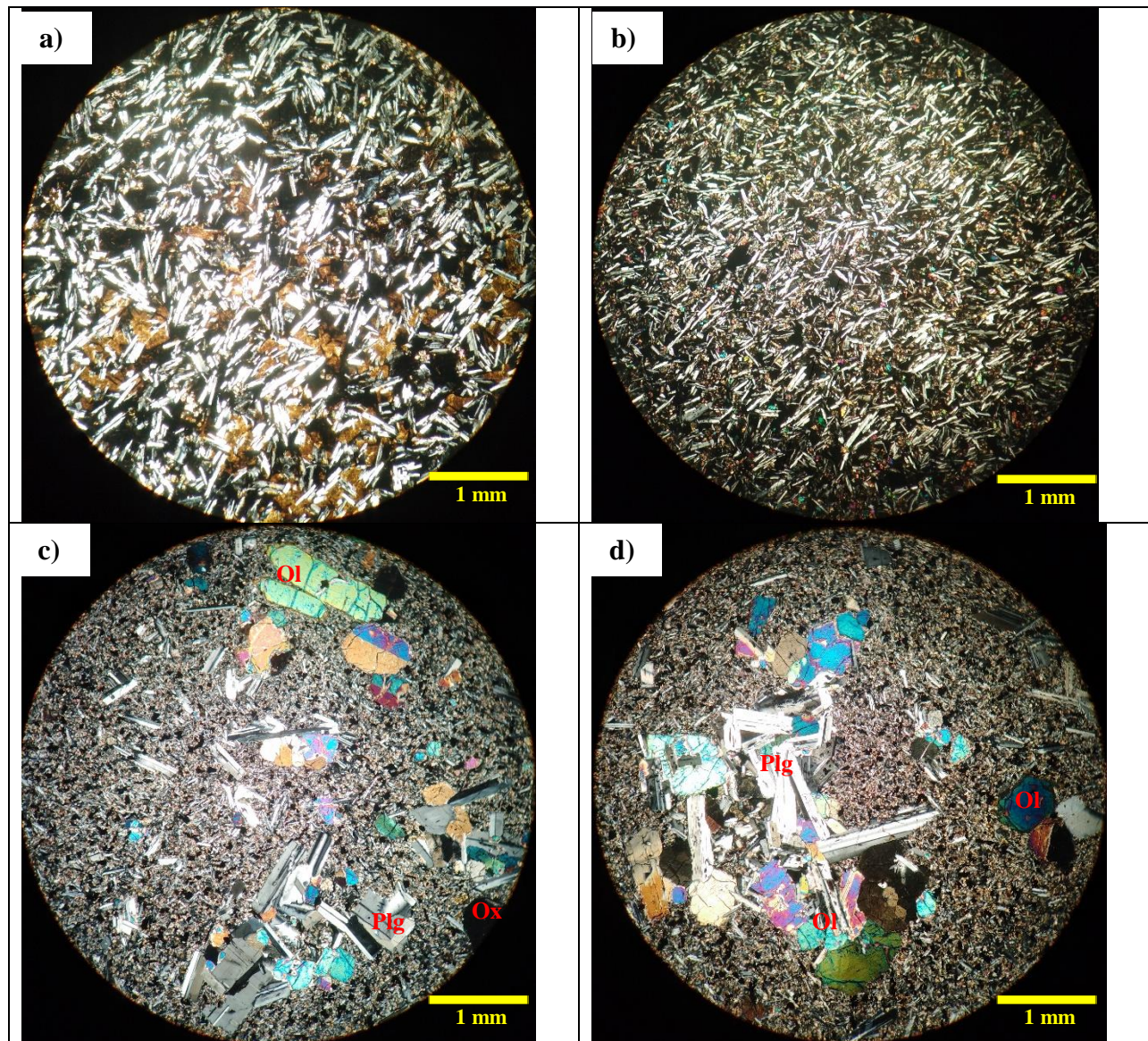
In this chapter details of representative samples taken from different lithological units identified in Chapter 3 are examined under a polarizing microscope and presented with an illustrative micro-photograph. A total of 24 samples are analyzed for petrographic purposes. Among them, 16 samples are from basaltic units, 6 samples from rhyolite, 1 ignimbrite sample, and 1 from the Mesozoic sandstone. The 23 volcanic rock samples are described in detail based on mineralogical and textural features, such as crystallinity, granularity, and degree of alteration. The different nomenclatures (e.g. Plg-phyric, Plg-Ol-phyric, Plg-Px-phyric, Plg-Ol-Px-phyric, intergranular, aphyric–ophitic, etc.; descriptions of these textural and modal terms are given in Krans et al., 2018) which are used in the regional studies for other CFB are applied for basaltic samples. Samples from flood basalt are described in the first portion followed by interlayered felsic products and finally samples from the shield basalt. The summary of each petrographically analyzed sample is attached in the last part of this chapter in table format.

#### **4.2. Samples from Plateau Basalts**

The basaltic samples which are taken from the different stratigraphic flood lava flow layers (lower and upper basalt) in this study display alternation of aphyric, sparsely phyric, and highly phyric lavas.

##### **4.2.1. Lower Basalt**

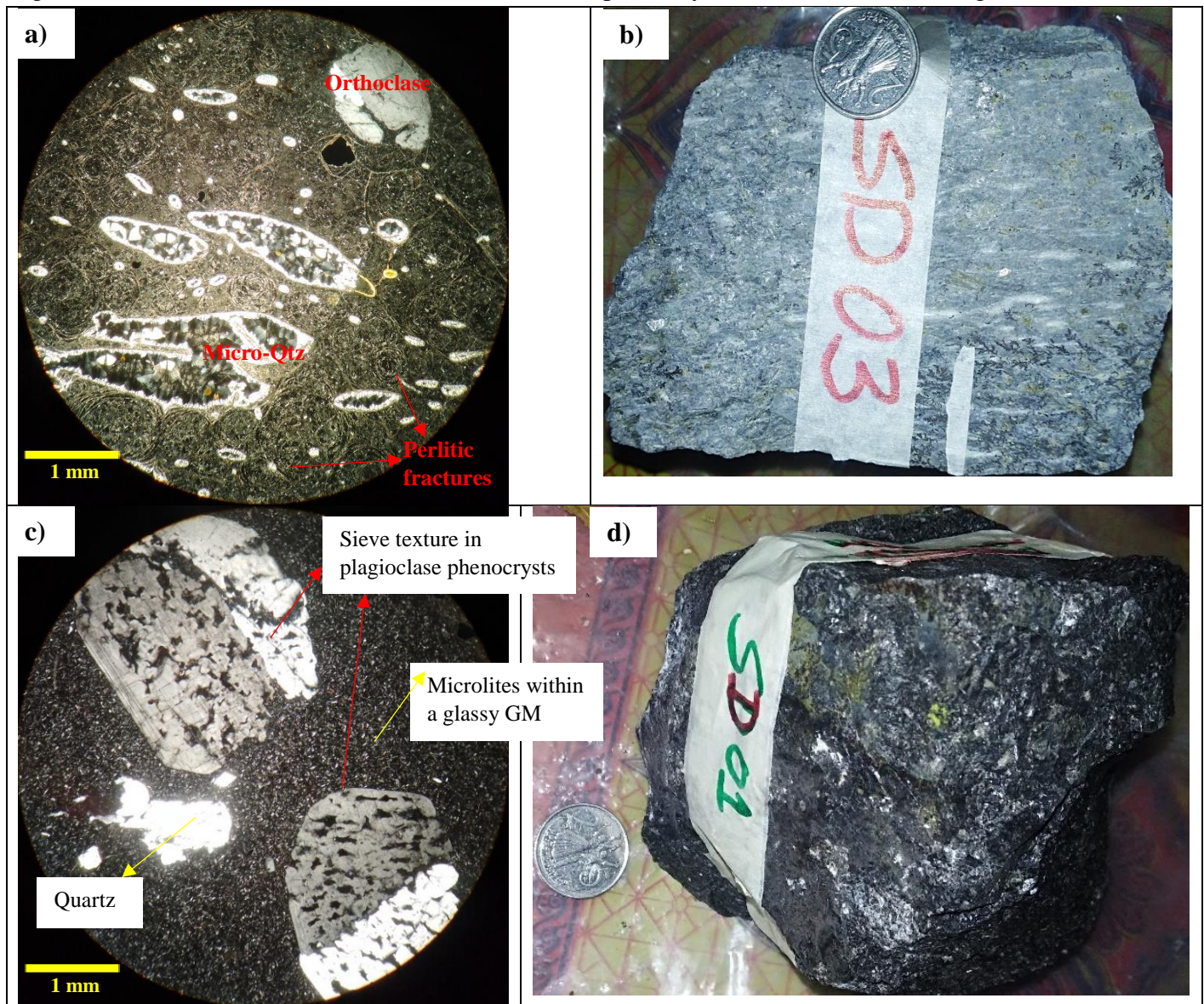
Samples from this unit show two ranges of grain size texture; aphyric (SD-28 & SD-31) and phyric (SD-30) varieties. The aphyric samples consist of finer microlites of plagioclase, olivine, and Fe-Ti oxides in a Felty and vitrophyric groundmass with <1% phenocrysts of plagioclase mineral. Equigranular aphyric grains show an intergranular texture in the groundmass (SD-28). The porphyritic sample is dominated by phenocrysts of plagioclase and olivine minerals (Plg-Ol phyric basalt) embedded in a glassy and finer groundmass consists of plagioclase, olivine, and Opaque Minerals (Fe-Ti oxides). Iddingsitised olivine is common in the groundmass of this unit. The abundance of phenocrysts in sample SD-30 is 20% with olivine 40% and plagioclase 55%. The groundmass in these samples shows pilotaxitic texture formed by intergranular randomly oriented plagioclase microlites and glassy groundmass observed in sample SD-30. The maximum size of the phenocryst mineral grains is olivine typically < 1.5 mm, but occasional crystals up to 2.5 mm in sample SD-30 and plagioclase 2-2.75mm in the longest dimension.



**Plate 4.1. Representative thin section photomicrographs of samples from the Lower basalt;** (a) SD-31 and (b) (SD-28) Aphric Lower basalt; groundmass dominated by finer plagioclase (microcrystalline-intergranular), altered olivine and opaque minerals; (c & d) Cumulo-phyllic texture formed by plagioclase and olivine phenocrysts (SD-30). (All photomicrographs are taken in 4X magnification in cross-polarized light)

#### 4.2.2. Sela Dingay Rhyolitic Lava flow

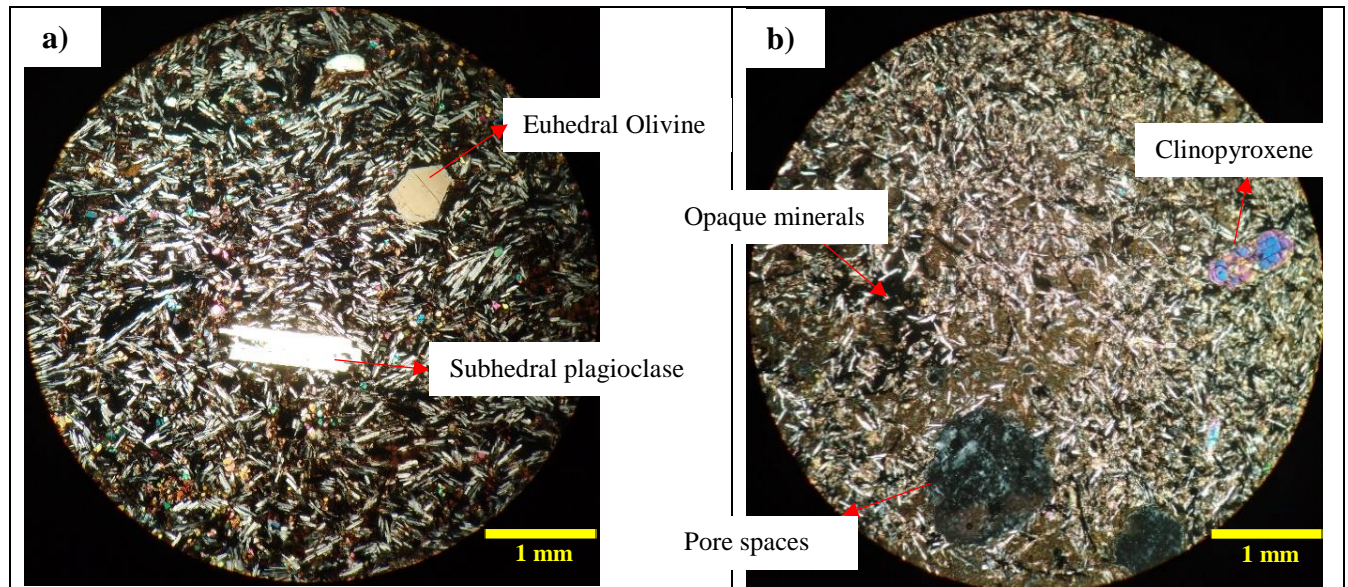
The porphyritic glassy rhyolite samples from the top part of this glassy textured unit SD-01 and (SD-03) show phenocrysts within vitric groundmass. Sample SD-01 is dominated by sieve textured plagioclase phenocrysts and (SD-03) is observed that containing microcrystalline quartz mineral (chalcedony- radiating crystals) embedded within a glassy groundmass. The alkali-feldspars (Sanidine and Orthoclase) are subhedral to anhedral, some grains with a simple twinning and it shows a sieve texture with perlite fracturing (concentric cracks). The quartz grains are anhedral with a clear surface. Most of the phenocrysts contain inclusions of glass.



**Plate 4.2. Representative thin section photomicrographs (a & c) and hand-specimens (b & d) of Glassy Sela Dingay Rhyolitic Lava flow samples.** a) (SD-03) the sample is composed of alkali-feldspar (Orthoclase), microcrystalline quartz, and opaque minerals; and it shows a clear perlitic fracture in the glassy groundmass; (c) sieve texture in an isolated plagioclase phenocryst (SD-10). (Both photomicrographs are taken in 4X magnification in cross-polarized light).

### 4.2.3. Upper Basalt

Aphyric basaltic samples from this unit (SD-12 and SD-17) consist of <3% phenocrysts (commonly plagioclase and rare olivine) minerals and microlites of various minerals occupy the fine groundmass. The groundmass is microcrystalline in most samples with felty or trachytic texture. The microlites show an intergranular texture consisting of plagioclase (dominant distinguishable phase), olivine, pyroxene, and large proportions of Fe-Ti oxides (dark in both PPL and XPL view). The olivine is partially or completely altered to iddingsite (reddish-brown colored secondary mineral). The plagioclase when it occurs as an observable scale it is euhedral to subhedral with a

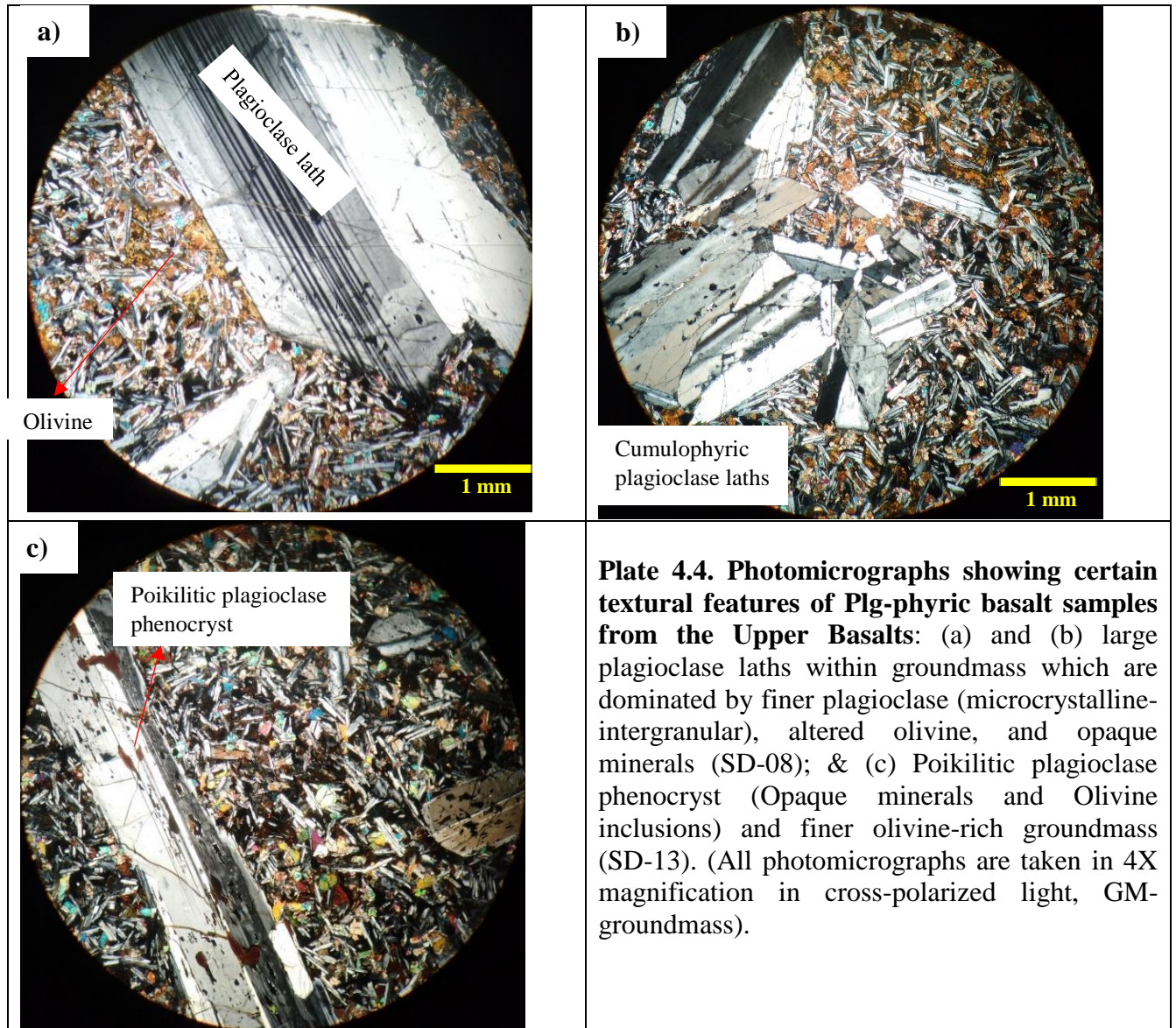


**Plate 4.3. Representative thin section photomicrographs of aphyric basalt samples from the Upper Basalts:** (a) intergranular plagioclase microlites forming the groundmass (SD-12); (b) vesicular aphyric basalt with a small proportion of phenocrysts (e.g. pinkish Clinopyroxene (XPL)) (SD-17); (Both photomicrographs are taken in 4X magnification in cross-polarized light).

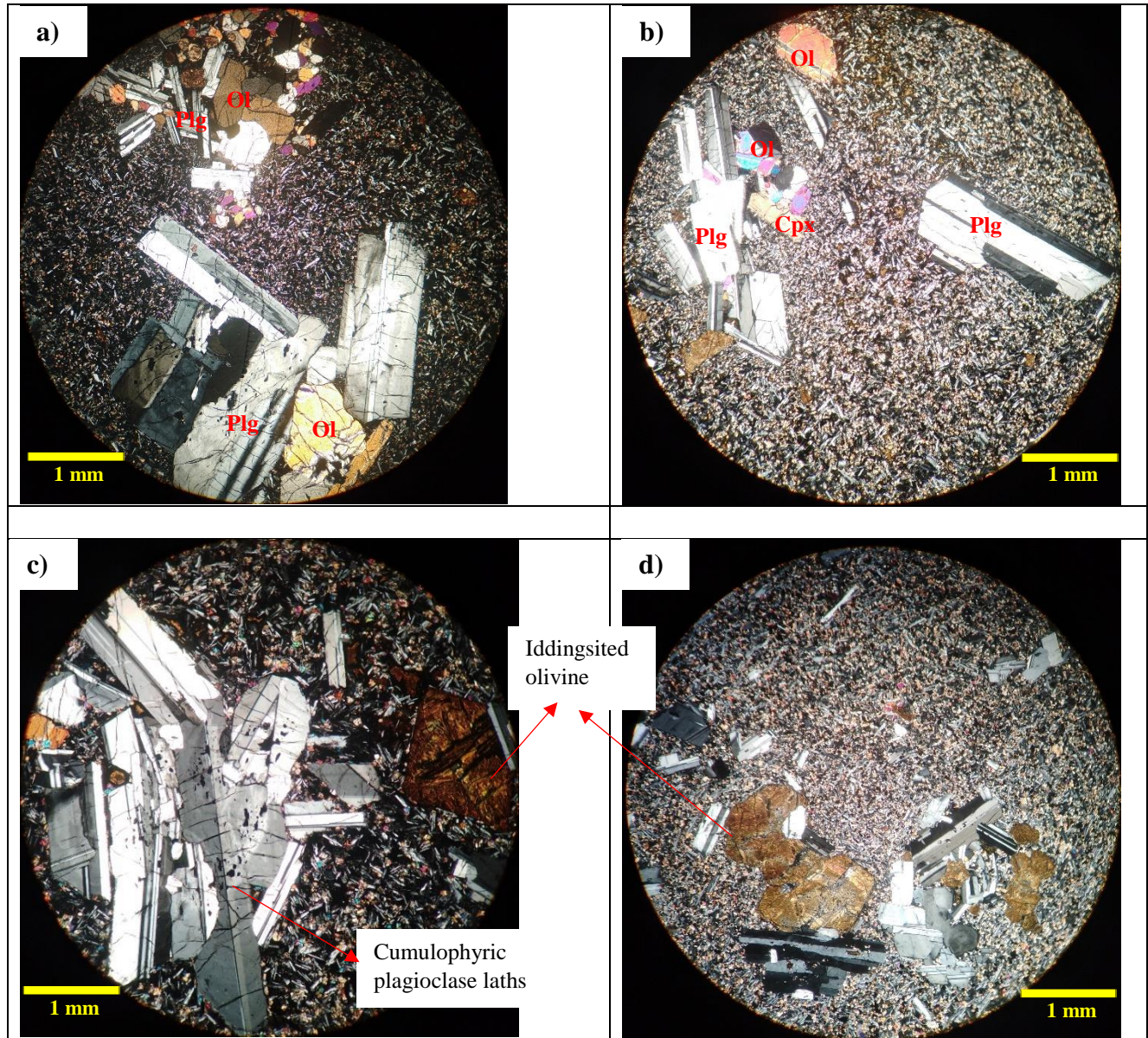
grain size <1mm.

**Porphyritic samples from the upper basalt** show different types of mafic phenocrysts mineral phases (plagioclase, olivine, and pyroxene) with a variable proportion of Fe-Ti oxides (opaque minerals) and secondary alteration minerals. The total proportion of phenocrysts abundances is 6-30% within a groundmass of holocrystalline to hypocrySTALLINE forming felty or trachytic texture. In addition to the presence of plagioclase as a phenocryst phase, it is the dominant mineral phase within the groundmass forming subhedral to anhedral twinned crystals. Based on the dominant phase in the phenocryst, these basalts are classified as Plg-phyric, Plg-Ol-phyric, Plg-Px-phyric, etc., when they occur in a similar proportion.

**Plg-phyric Basalt:** a porphyritic rock with the dominant phenocryst phase is plagioclase (SD-08 and SD-13). The proportion of plagioclase from the total phenocrysts present is > 65%. Plagioclase occurs as single isolate phenocrysts as well as glomerophyric clusters of several crystals. The maximum phenocrysts grain size elongated plagioclase laths within the different samples varies from 2.75-7.5mm. Euhedral-subhedral grains of plagioclase display cumulophyric texture (clusters of plagioclase mineral only) in some of the samples. Some grains also form oscillatory zoning and on the surface of elongated plagioclase laths enclose inclusions of olivine and opaque minerals (poikilitic texture).

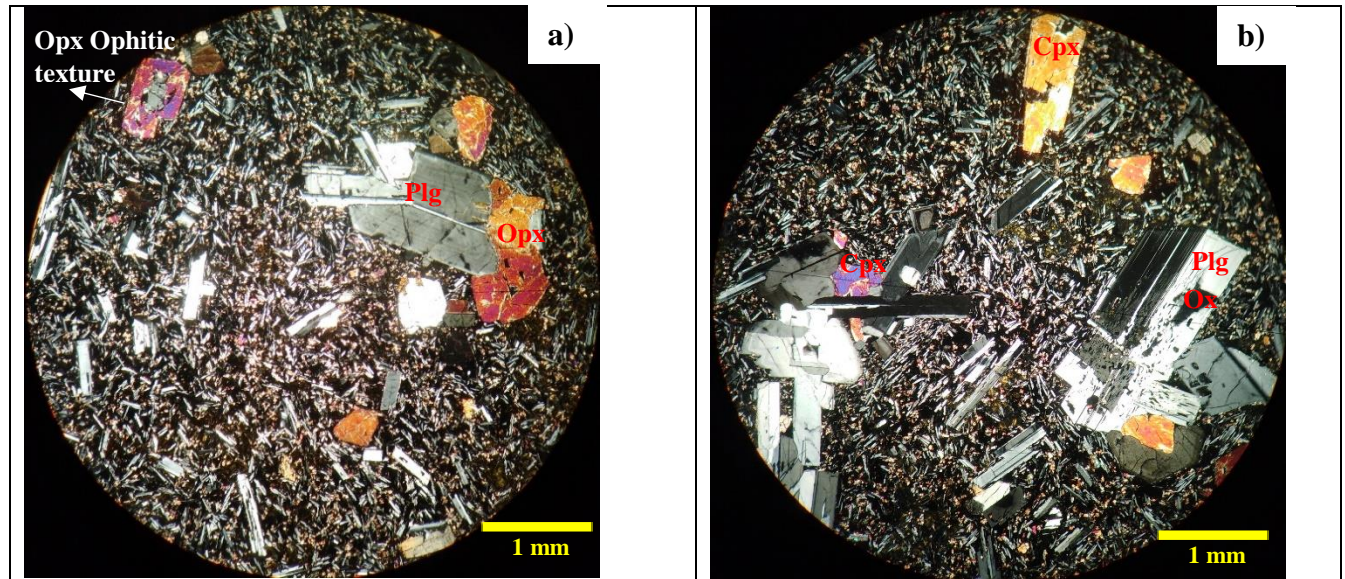


**Plg-Ol-phyric Basalt:** (SD-10, SD-24 & SD-26) which contain 30% phenocrysts phase including dominantly plagioclase phenocrysts (~75% and 3mm max. size) with a considerable proportion of Olivine (1.5mm) and infrequent clinopyroxene (<1mm) minerals. The groundmass varies from microcrystalline to intergranular forming poorly intergranular to pilotaxitic texture (Plate 4.5).



**Plate 4.5. Photomicrographs showing clusters of plagioclase, olivine, and clinopyroxene minerals (Cumulophyric texture) in Plg-Ol-phyric basalt samples from the Upper Basalt.** (a & b) Cumulophyric texture formed by Plg, Ol and Cpx (SD-26); (c) Cumulophyric plagioclase phenocryst and completely altered olivine reserving its euhedral shape in Glassy GM (SD-10); & (d) Cumulophyric texture formed plagioclase and iddingsitised olivine phenocrysts (SD-24). (All photomicrographs are taken from the same sample in 4X magnification in cross-polarized light)

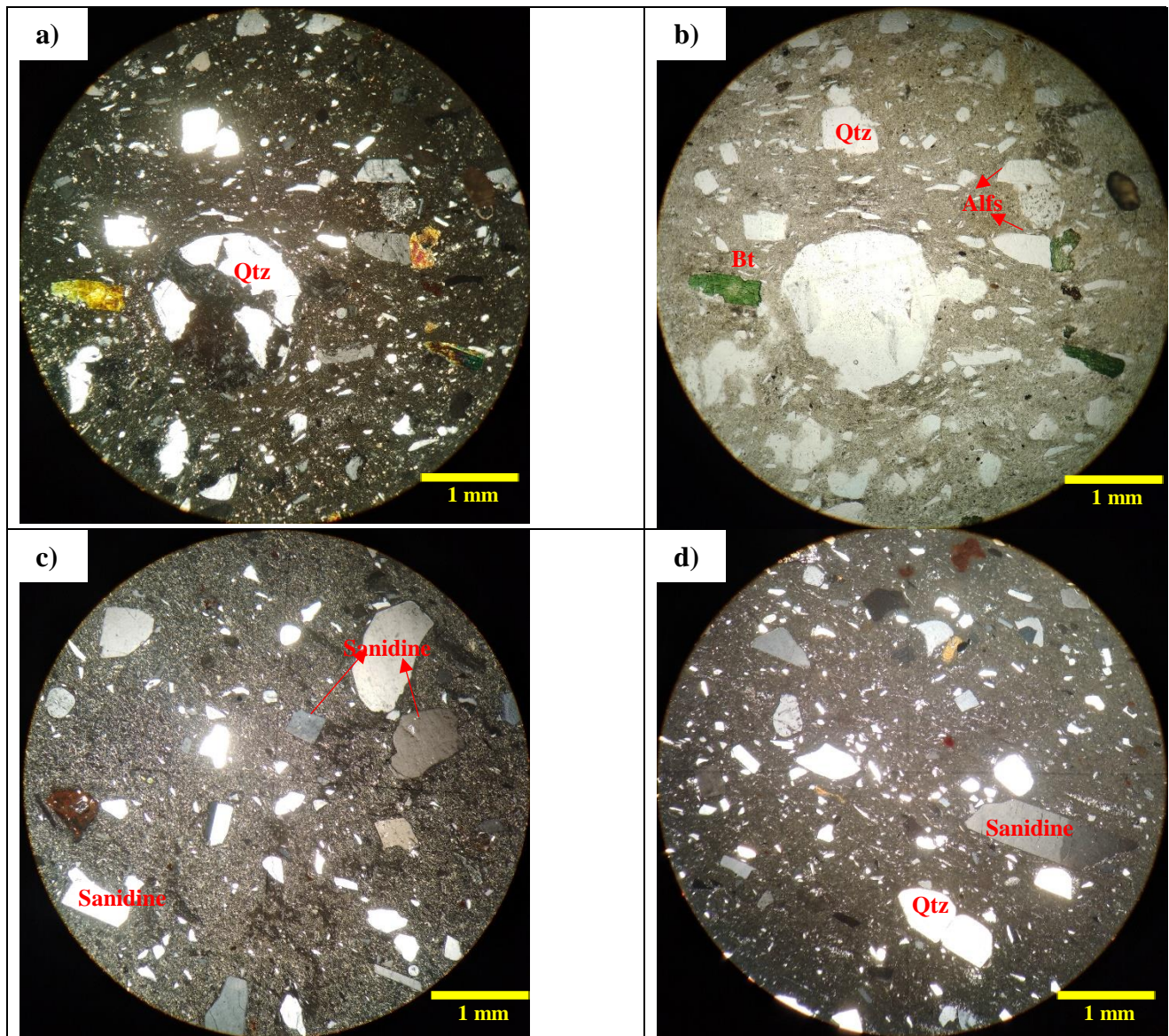
**Plg-Px-phyric Basalt:** sample SD-21 the dominant phenocrysts (25%) are plagioclase (60%) and pyroxene (~30% both clinopyroxene and Orthopyroxene) mineral phases. Other distinguishable minerals in this sample include iddingsitised olivine and opaque minerals. These all minerals occur as both in phenocryst phase and finer ones form groundmass which is dominated by plagioclase microlites identified by their noticeable twinning. In the phenocryst phase, the maximum size of the grains is plagioclase (2.5mm), pyroxene and olivine both <1mm. Elongated plagioclase laths enclose inclusions of pyroxene and opaque minerals forming poikilitic texture.



**Plate 4.6. Photomicrographs showing certain textural features in Plg-Px-phyric basalt sample from the Upper Basalt:** (Both photomicrographs are taken from the same sample in 4X magnification in cross-polarized light; Plg: plagioclase; Opx: orthopyroxene; Ox-oxides (opaque minerals)).

#### 4.2.4. Rhyolite

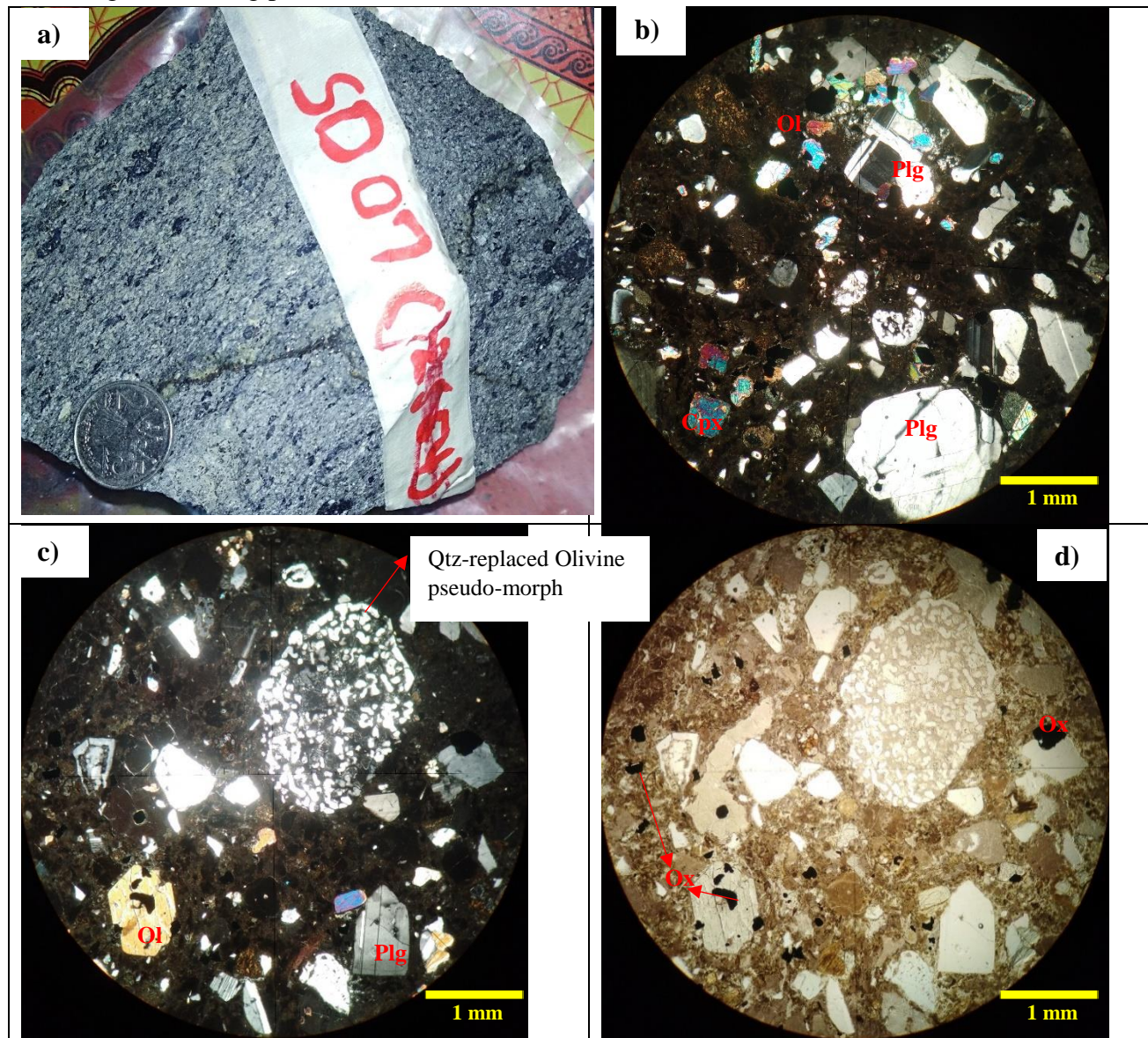
A total of five rhyolitic samples (SD-05, SD-11, SD-18, and SD-20) from the different stratigraphic positions which are interlayered the flood basalt and also on the top of the basaltic succession are prepared for petrographic description. These samples form a hypocrystalline texture with a dominant composition of alkali-feldspars (Sanidine and Orthoclase) (50-65%) and quartz (20-30%) minerals with some proportion of plagioclase feldspar and mica minerals. The phenocrysts phase in these samples varies from 10-30%. Phenocrysts phase with a glassy (vitric) groundmass is a common feature observed in all of the samples (Vitrophyre texture).



**Plate 4.7. Representative thin section photomicrographs of Rhyolite samples, sanidine, and quartz are the dominant phenocryst phase within a glassy groundmass; (a) & (b) SD-05; (c) SD-11; & (d) SD-18; (All photomicrographs are taken in 4X magnification in cross-polarized light, except b which is in Plane polarized).**

#### 4.2.4. Ignimbrite

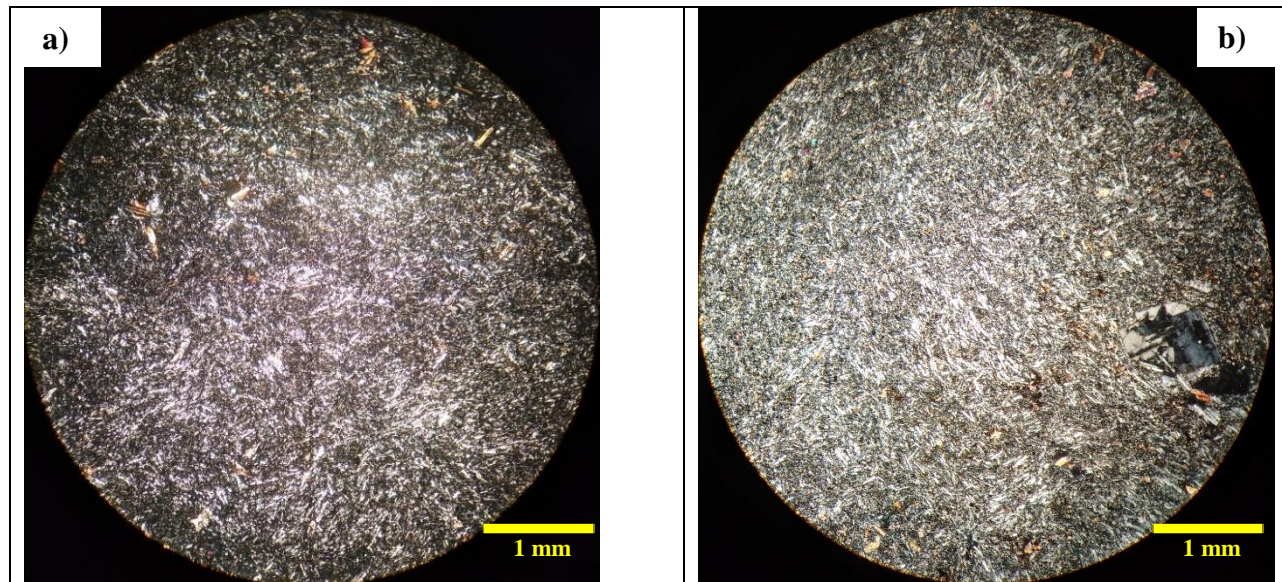
Sample SD-07 is an ignimbrite unit in a hand specimen it is composed of lapilli-sized (>2mm) flattened glass (fiamme) within a vitric groundmass. In the thin section, it is observed that it is composed of basaltic rock and crystal fragments which are dominantly composed of mafic minerals (olivine, plagioclase, pyroxene, and opaque minerals). The groundmass of the sample is dominated by the flattened vitric textured glass with finer lithic and crystal fragments. The is also composed of olivine grains composed of inclusion of later coming quartz grains replacing the olivine grain forming poikilitic texture.



**Plate 4.8. Hand-sample photograph (a) and thin section photomicrographs of Ignimbrite sample (b, c, d) (SD-07); the sample is composed of abundant crystal (plagioclase (Plg), olivine (Ol), pyroxene (Cpx), and opaque (Ox) minerals) and rock fragment; and it shows atypical dark lenses of glassy material (fiamme), (a); (All photomicrographs are taken in 4X magnification in cross-polarized light, except d which is in Plane polarized).**

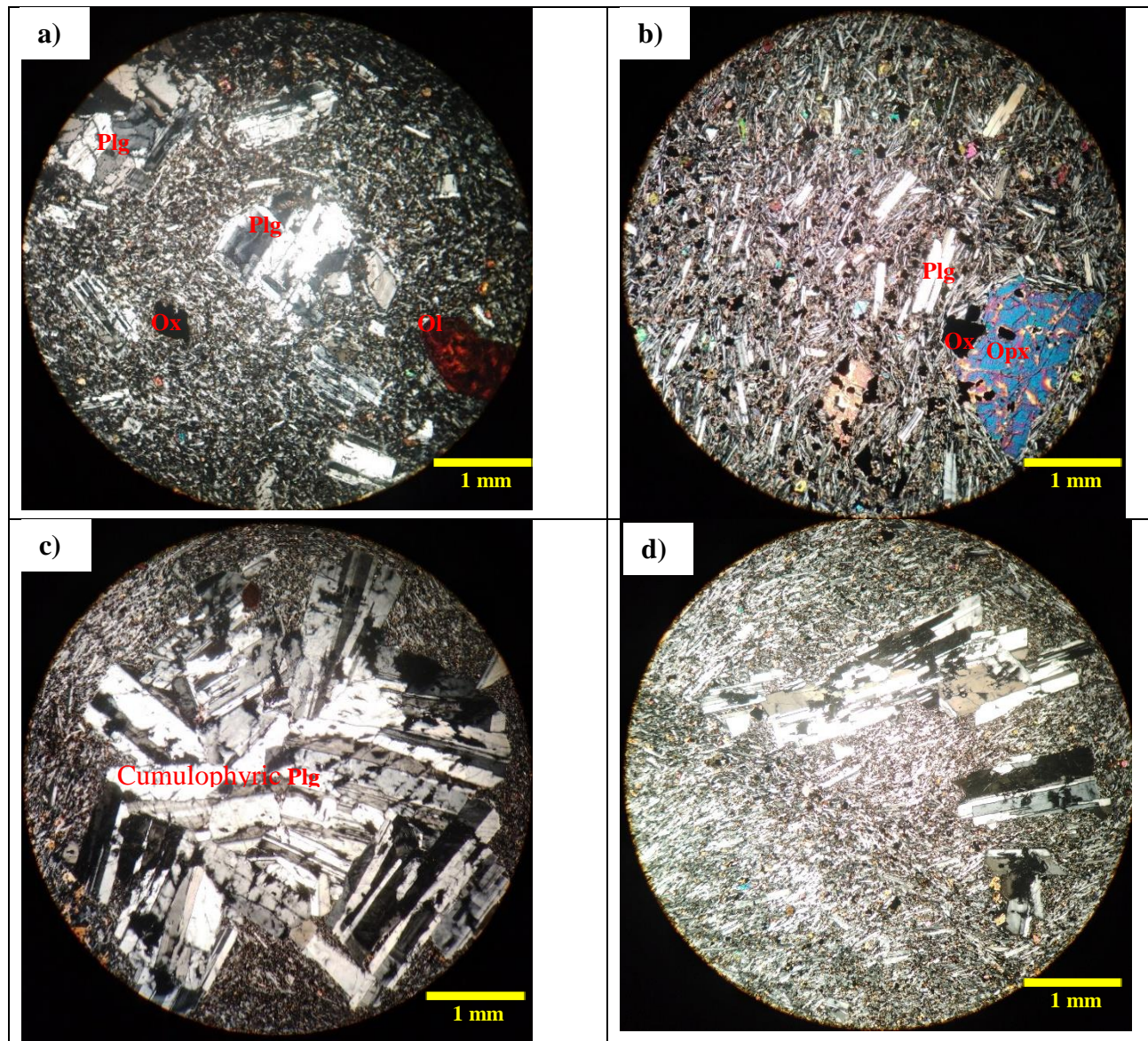
### 4.3. Samples from Shield Basalt

Four samples from the shield basalt are prepared for petrographic analysis. These samples contain both porphyritic and aphanitic basalts (SD-34). The porphyritic samples include Plg-phyric (SD-33 and SD-36) and Plg-Px-phyric (SD-37) samples and the dominant phase in all of the samples is plagioclase feldspar in various grain sizes. Other components of the samples include olivine, opaque minerals, and a groundmass which is composed of similar finer minerals with plagioclase microlites as a dominant phase forming intergranular to trachytic texture.



**Plate 4.9. Representative thin section photomicrographs from aphanitic shield basalt: (a) (SD-34) and (b) (SD-35) plagioclase microlites forming the groundmass (Both photomicrographs are taken in 4X magnification in cross-polarized light).**

The porphyritic samples are textural glomerophyric and the abundance of phenocrysts is <15%. Plagioclase phenocrysts occur as single isolated crystals as well as glomerophyric clusters of several crystals and are ranging up to 2.5 to 6.25 mm in length. The olivine (max. size reaches 1.25mm) is partially or completely altered to iddingsite in most cases and recognized by its euhedral shape. The pyroxene observed in sample SD-37 is orthopyroxene with parallel extinction to its longest dimension (~2mm) and it is subhedral in shape. The aphanitic basalts are dominated by microlites of plagioclase with <3% phenocrysts.



**Plate 4.10. Representative thin section photomicrographs from Porphyritic shield basalt:** (a) completely iddingsitised olivine phenocryst in Plg-phyric sample (SD-36); (b) thin section demonstrating Plg-Px-phyric basalt (SD-37); (c) and (d) Plg-phyric sample (SD-33), several plagioclase phenocrysts are aggregated together with cumulo-phyric texture and poikilitic texture. (All photomicrographs are taken in 4X magnification in cross-polarized light; Ol: olivine; Plg: plagioclase; Opx: orthopyroxene; Ox-oxides (opaque minerals)).

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

<b>Sample code, Elev<sup>n</sup> (m)</b>	<b>Location UTM (Zone 37P)</b>	<b>Lithostratigraphic unit</b>	<b>Texture</b>	<b>Distinguishable Mineral Constituent</b>	<b>% of phenocrysts</b>	<b>Dominant phases in phenocrysts</b>	<b>Ground mass texture</b>	<b>Modal Name</b>
SD-00, <b>1561 m</b>	E-0534056 N-1105317	Mesozoic Sandstone	Equigranular, grain supported, sandy grains (medium-grained <2mm)	Alkali-Feldspar, Quartz and finer cementing minerals	-	Feldspar (>70%), Quartz (<25%)	-	Arkosic-Arenite
SD-28, <b>1621 m</b>	E-0534553 N-1105002	Lower Basalt	Aphanitic, Intergranular	Plg, Oliv, Opaque Minerals, Alkali-Feldspar	<1	Plg	Felty, vitric	Aphyric basalt
SD-30, <b>1746 m</b>	E-0534783 N-1104679	Lower Basalt	Porphyritic, cumuloxyphyric	Plg, Oliv, Opaque Minerals	20	Plg (~50%), Ol (40%)	Felty, vitric	Plg-Ol-phyric basalt
SD-31, <b>1869 m</b>	E-0535102 N-1104222	Lower Basalt	Aphanitic, Intergranular	Plg, Oliv, Opaque Minerals	<1	Plg	Felty	Aphyric basalt
SD-01, <b>2163 m</b>	E-0564952 N-1101682	Sela Dingay Rhyolitic Lava flow	Hypocrystalline and Sieve textured Plag	Plg, Afelds and Opaque Minerals	15	Plg (~65%)	Felty, vitric	Glassy Rhyolite
SD-03, <b>2280 m</b>	E-0568796 N-1105207	Sela Dingay Rhyolitic Lava flow	Hypocrystalline, Vitrophyre	Afelds, microcrystalline Qtz, Bt, Ms, Plg, Opaque Minerals	30	Afelds, Qtz	Vitric, perlitic fracture	Glassy Rhyolite
SD-24, <b>2258 m</b>	E-0550747 N-1100939	Upper Basalt	Porphyritic, cumuloxyphyric	Plg, Oliv, Opaque Minerals	12	Plg (>80%)	Felty, vitric	Plg-Ol-phyric basalt
SD-20, <b>2407 m</b>	E-0572733 N-1099208	Upper Basalt	Hypocrystalline, Vitrophyre	Alkali-Feldspar, Qtz, Plg	<10	Afelds, Qtz	Vitric	Glassy Rhyolite
SD-11, <b>2420 m</b>	E-0565019 N-1101815	Upper Basalt	Hypocrystalline, Vitrophyre	Alkali-Feldspar, Qtz	20	Afelds (60%), Qtz (50%)	Vitric	Rhyolite
SD-26, <b>2442 m</b>	E-0551672 N-1099222	Upper Basalt	Porphyritic, cumuloxyphyric	Plg, Oliv, Cpx, Opaque Minerals	30	Plg (75%), olv, px,	Felty	Plg-Ol-phyric basalt
SD-05, <b>2472 m</b>	E-0567604 N-1104219	Upper Basalt	Hypocrystalline, Vitrophyre	Alkali-Feldspar, Qtz, Bt	25	Afelds (60%), Qtz (30%), Bt	Vitric	Rhyolite

						(5%)		
SD-17, <b>2477 m</b>	E-0570587 N-1101307	Upper Basalt	Aphanitic, vesicular	Plg, Olv, Cpx, Opaque Minerals	<2	Ol, Opaque minerals	Felty	Aphyric-vesicular basalt
SD-10, <b>2488 m</b>	E-0568948 N-1105468	Upper Basalt	Porphyritic, cumulophyric	Plg, Olv, Cpx, Opaque Minerals	25	Plg (~60%)	Felty	Plg-Ol-phyric basalt
SD-18, <b>2489 m</b>	E-0570800 N-1101493	Upper Basalt	Hypocrystalline, Vitrophyre	Alkali-Feldspar, Qtz	30	Afelds (45%), Qtz (50%)	Vitric	Rhyolite
SD-07, <b>2554 m</b>	E-0567445 N-1102283	Upper Basalt	Porphyritic, cumulophyric, hypocrystalline, Vitrophyric	Plg, Alkali-Feldspar, Basaltic Rock Fragment (Olv, Px, Plg, Oxides)	>20	olv, px, plag	Vitric	Ignimbrite
SD-21, <b>2610 m</b>	E-0571193 N-1099184	Upper Basalt	Porphyritic, ophitic	Plg, Olv, Cpx, Opx, Opaque Minerals	25	Plg (~60%), Px (~30%)	Microcrystalline Plg-Microlites	Plg-Px-phyric basalt
SD-08, <b>2756 m</b>	E-0566120 N-1100570	Upper Basalt	Porphyritic	Plg, Olv, Opaque Minerals	10	Plag (~85%)	Felty, Intergranular	Plg-phyric basalt
SD-12, <b>2780 m</b>	E-0568447 N-1100732	Upper Basalt	Aphanitic, Intergranular	Plg, Olv, Px, Opaque Minerals	<1	Plag, Ol	Felty, vitric	Aphyric basalt
SD-13, <b>2800 m</b>	E-0568502 N-1100614	Upper Basalt	Porphyritic	Plg, Olv, Opaque Minerals	6	Plag (~85%)	Felty, vitric, Intergranular	Plg-phyric basalt
SD-37, <b>2908 m</b>	E-0577213 N-1088239	Shield Basalt	Porphyritic	Plg, Olv, Opx, Opaque Minerals	8	Plag (~40%), Px (~30%)	Trachytic, Intergranular	Plg-Px-phyric basalt
SD-36, <b>3055 m</b>	E-0578657 N-1089344	Shield Basalt	Porphyritic, cumulophyric	Plg, Olv, Opaque Minerals	15	Plag (~80%)	Trachytic	Plg-phyric basalt
SD-33, <b>3284 m</b>	E-0581280 N-1088047	Shield Basalt	Porphyritic, cumulophyric	Plg, Olv, Opaque Minerals	<10	Plag (95%)	Trachytic	Plg-phyric basalt
SD-34, <b>3305 m</b>	E-0581306 N-1087962	Shield Basalt	Aphanitic	Plg, Olv, Px, Bt	<3	px, plag	Trachytic	Aphyric basalt
SD-35, <b>3314 m</b>	E-0581287 N-1087964	Shield Basalt	Aphanitic	Plg, Opaque Minerals	<1	Plag	Trachytic	Aphyric basalt

## CHAPTER-FIVE

### 5. DISCUSSION AND SUMMARY

This chapter discusses the petrostratigraphic construction of flood basalt products in the Mofer river section of the North-Western Ethiopian plateau, starting from the underlying sedimentary unit up to the topmost part of the succession (shield basalt) overlaying these units. The data from chapters 3 (local geology) and 4 (petrographic data) are integrated for discussion with regional studies in terms of field geological relationships, petrography, petrology, and magmatic system. The discussion also includes the correlation of each stratigraphic unit with their respective previous stratigraphic names given by the different researchers. Finally, the composite stratigraphy of lithologic units in the study area is presented with a summary of each unit.

The study area is a part of central Ethiopian within the North Shewa province in the North-Western Ethiopian Plateau. The Oligocene-Miocene volcanics of the study area lie unconformably on a Cretaceous (the Barremian-Cenomanian Debre-Libanos Sandstone, Wolela, 2009) sandstone formation. The unconformity surface is described by the rugged erosional surface and also the nature of lava flow (e.g. dipping columnar jointing and layers of lava flow following the underlying uneven surface around the contact area) of the overlaying lower basalt. The lower basalt which is regionally called Ashange basalt, a 330m thick oldest basaltic formation exposed in the lower section of the study area near Jemma River in the Gawna. The flows in this basalt are generally horizontally bedded, with rare tilted layers towards the contact area to the underlying sedimentary unit which is interpreted as lava flow on an erosional uneven surface.

Sela Dingay Rhyolitic Lava flow which is ~400m thick, is composed of layers of rhyolitic lava flow deposits in the topmost part with visible porphyritic minerals within a glassy groundmass, and a massive, fine, and glassy textured thick layer in the lower part, in between the lower and upper basalt, was previously mapped as a part of upper basalt in different studies. It is separated from the lower basalt by an alteration surface overlain by a deposit of pyroclastic deposit layers and a thin layer of paleosol separates it from the upper basalt. The composition of this glassy textured unit is dominantly rhyolitic as inferred from a thin section of a porphyritic sample. Near instantaneous melt solidification (glass-forming) process results from two major mechanisms (Hefferan and O'Brien, 2010): **quenching and rapid gas loss**. Quenching occurs when melts of any composition come into contact with liquid water or air; mostly basic (low SiO<sub>2</sub>) glasses quench when volcanoes erupt on the ocean floor or as massive flood basalts. The second mechanism limited to silicic melts occurs by rapid loss of dissolved gas. The porphyritic varieties (Vitrophyric textures) in this lava product represent the partial crystallization of the magma before its rapid solidification. Since the glassy unit in this study area is rhyolitic, the possible formation relates to a rapid loss in gas by viscous lava fluxing at a higher rate to a cooler surface air condition. The continuous layer formed by this unit needs less viscous rhyolitic lava flow to cover a larger area.

The top part of the Sela Dingay Rhyolitic Lava flow unit comprises a porphyritic layer of glassy rhyolite and it is separated from the upper basalt (Aiba formation ~440m thick in this study area) by a thin (<1m) layer of paleosol. The upper basalt consists of layers of basaltic flow units with intercalating silicic-explosive products of variable thickness. The silicic products dominate the top part of the flow; finally, the top part of the succession is covered by rhyolite and welded tuff units (Alajae Formation). The thickness of this felsic deposit in this study area reaches up to ~118m. The contact area taken for this unit and the underlying upper basalt is a layer of paleosol, where basaltic flow units end. The fissural type flood basalt succession is overlain by a central type shield basalt (Termaber shield basalt). A pause in eruption is represented by the presence of thick unconsolidated sediment (~ 35m).

The products of different eruptions are separated by the presence of weathered/altered flow surfaces and deposition of fine clastic sediments (or paleosol), indicating significant time intervals separating the emplacement of each layer of lava flow units. The thickness of these separating materials is directly related to the rate of magma flux in the source during the different eruptions. These pauses reflect a reduction in magma flux; magma may still be flowing into the lithosphere, but not at a high enough rate to cause eruptions at the surface (Krans et al., 2018). In addition to these layers, even though the felsic products are pronounced toward the final stages of the flood basalt sequence, the presence of considerable layers of felsic lava products (or non-effusive lava products e.g. tuffaceous layers, volcanic ash, ignimbrites) and a layer of rhyolitic units intercalating between the basaltic lava flows, represents the presence of a contemporaneous felsic eruption (Krans et al., 2018).

From the field observations, the lithostratigraphic units suggest the existence of a continuous lava sequence from the base to the top of the plateau. As depicted from the age data given in the map of the north-western Ethiopian plateau the age of these flood basalt products in this study area represents Late-Oligocene-Miocene volcanics. The deposition of thick sediments marks a period of quiescence of flood basalt volcanism in the study area before the eruption of the shield basalt. In the central part of the plateau, shield basalts are better interpreted as peripheral parts of a 23 Ma shield. The general picture seems to involve prolonged but periodic eruption of alkali basalt, from 30 Ma to < 10 Ma (Kieffer et al., 2004).

The morphological types of flood basalt lava flows (pahoehoe, 'a'ā' etc.) serve as indicators of their emplacement dynamics, with the relationships between flow conditions (Hachimi et al., 2011; Sheth, 2018). Basaltic flow fields and flow lobes of the studied flood basalts display the three-part structure common to other CFBs, in which massive vesicle poor columnar jointed flow core bounded by fractured and vesicular flow top. The morphology of the flows in different lithologic units forms a thick continuous horizontal layer in this study area, depicting the fissural type lava flow in the flood basalt units in contrast to the overlaying central type products of shield basalt, which forms dipping typical shield topography. Morphological descriptions of individual flow fields depend on different factors during magma emplacement; from these topography is frequently thought to be the dominant control on lava emplacement and also other factors include channelized flow along depressions,

nonlinear flow field characterization, and divergence of flow pathways during emplacement (Vye et al., 2013).

The lava flow products in this study area are categorized under both tabular-classic facies, laterally extensive, thick lava flow layers separated by paleosol and/or various terrestrial clastic lithologies often characterized by well-developed columnar jointing and compound-braided flow facies architecture, which comprises thin anastomosing pahoehoe flow sheets and lobes up to several meters thick, representing lavas emplaced at low effusion rates (Walker 1971 as cited from Hachimi et al., 2011).

When inferring processes and rates for flood basalt eruptions, the sizes and shapes of lobes that make up a flow field, as well as intra-lava characteristics, may be crucial (Vye et al., 2013). Emplacement history and spatial changes within whole flow fields can be deduced by a comparison of the internal structure between lobes and the correlation of lobes within flow fields. These characteristics observed from exposed flow fields in this study area are typical of 'a'ā type-pahoehoe lobes; this supports the emplacement of these flow fields by inflation (Walker 1991 as cited from Vye et al., 2013). A morphological form that differs from typical pahoehoe and a'a is lava flows with preserved bases and brecciated upper crusts (transitional lava type-Rubbly pahoehoe). Rubbly pahoehoe lava flows which have extensively fractured and brecciated upper crusts are emplaced at a slightly higher lava effusion rate than pahoehoe (lava flows that have preserved, unbroken upper crusts) (Duraiswami et al., 2014). As lava continued to flow, a lava lobe (a single cooling unit varying in size from centimeters to meters) inflated, due to lava supply lifted upper crust; subsequent fast inflation causes pahoehoe slabs to brecciate, resulting in flow-top breccia and a continuously thickening lobe of rubbly pahoehoe (Sheth et al., 2017).

It is observed that alternation of aphyric, sparsely phyric, and highly phyric lavas from hand-specimen observation and petrographically analyzed basaltic samples. The phenocryst phases in porphyritic samples are plagioclase, olivine, and clinopyroxene in order of abundance in the most of analyzed samples. In addition to these mineral phases, the studied samples comprise a higher proportion of opaque minerals (Fe-Ti oxides). The groundmass in these basaltic samples is dominantly small grains of plagioclase and olivine minerals. These basaltic samples from the flood basalt and the shield basalt are similar in mineral composition. Most of the samples are Plg-phyric with a variable proportion of olivine (Plg-Ol-phyric) and pink-purple clinopyroxene (Plg-Px-phyric) phenocrysts. The phenocrysts are embedded in a microcrystalline matrix consisting of the same phase as the phenocryst assemblage. Pyroxene and subhedral-anhedral grains of opaque minerals infrequently occur as a phenocryst phase and they occur in the groundmass as a microcrystalline phase. These features indicate that these basalts belong to the alkaline magma series (Kieffer et al., 2004) and they resemble HT1 type flood basalts of Pik et al. (1998).

The rhyolites and ignimbrite samples are sparsely to highly porphyritic (with up to 10-30% phenocrysts) and are comprised of alkali feldspar (dominant sanidine with minor orthoclase), quartz and minor mica, plagioclase, and opaque minerals. The groundmass of the rhyolites is microlites of similar minerals embedded in a glassy matrix (Vitrophyric texture) and one glassy rhyolite sample

with perlitic fracturing. Dark ignimbrite samples consist of crystals of feldspar and quartz together with flattened and compacted glass shards displaying a eutaxitic texture, and rock fragments basaltic composition. These characteristics indicate that they were formed by remelting a partially solidified magma body before the eruption at high temperatures (Dereje Ayalew and Gibson, 2009).

The dominance of plagioclase in these petrographically analyzed basaltic samples and the presence of considerable intercalating silicic-explosive eruptions are an indication of a decrease in magma flux and waning or termination phase of magmatism. As mentioned by Krans et al. (2018), magma involved in early eruptions experiences less fractionation than magma involved in later, which is mainly plagioclase-phyric flood basalt eruptions. Termination phases of continental flood basalt provinces are characterized by a significant decrease in erupted volume and frequency of eruption, longer hiatuses between successive eruptive episodes, more widely distributed volcanic centers, and, in many cases, an increase in the silicic components of the eruptive units or products (Jerram and Widdowson, 2005).

This interpretation is also supported by age data which is mentioned by Dereje Ayalew (2011) (volcanism in north-central Ethiopia is commenced at 20 Ma, 10 Ma after initial magmatism in the northern Ethiopian plateau) and temporal migrations in the magmatic plumbing system of flood basalt in eastward direction (Rooney et al., 2018). The study area also comprises a younger Middle-Miocene Tarmaber shield basalt supporting a decrease in magma flux, which is consistent with the transition from flood basalt eruption to shield activity, and more broadly the termination of CFBs (Kieffer et al., 2004; Krans et al., 2018).

	Lithologic Unit with approx. thickness	Summary Description
	<p>Termaber Shield Basalt (407 m)</p>	<p>Dominantly basaltic flow with thin layers of rhyolite and welded tuff. The product of this basalt forms a typical shield topography overlaying a fissural type laterally thick flood basalt successions. Aphyric-porphyrific basalt with phenocrysts of plagioclase, olivine, pyroxene, and a significant proportion of opaque minerals similar to the underlying flood basalt units. The groundmass generally shows trachytic texture.</p>
	<p>Rhyolite-Ignimbrite (118 m) Alajae Formation</p>	<p>Felsic deposits dominating the topmost part of the flood basalt successions; include rhyolite, ignimbrite, rhyolitic tuff, rhyolitic obsidian, and pyroclastic deposits.</p>
	<p>Upper Flood Basalt (440 m) (Aiba Formation)</p>	<p>Basaltic lava flows with intercalated felsic-explosive layers. The flows show a regionally identified flow top, flow core and flow bottom features, in which the flow tops are characterized by fractured vesicular layers overlaying on columnar jointed flow cores. The bottom of the flow fields shows massive nature. Alterations of aphyric, slightly phyric, and phyric lava products with plagioclase as a dominant phase both as a phenocryst and microlites in the groundmass. The other components include olivine, pyroxene, and Fe-Ti oxides.</p>
	<p>Sela Dingay Rhyolitic Lava flow (400 m)</p>	<p>Columnar jointed thick glassy textured lava flow product with thin layers of porphyritic glassy rhyolite on the top part of the succession. The columnar joint varies from irregularly oriented thin columns on the top and thick regularly jointed columns of the massive thicker layer in the bottom part. Petrographic samples from the top part of this unit are hypocrySTALLINE and vitrophyric rock in which phenocryst minerals (Plagioclase, Alkali feldspars, and quartz) are embedded in a glassy perlitic groundmass.</p>
	<p>Lower Flood Basalt (330m) Ashange Formation</p>	<p>Dominantly composed of basalt with varying proportions of aphyric-porphyrific basalt with minor interlayered pyroclastic towards the top. Highly weathered and fractured. Plagioclase phyric with olivine and opaque minerals within a felty groundmass. The olivine phenocrysts are highly altered to iddingsite (oxidative weathering of olivine).</p>
	<p>Mesozoic-Sandstone (80m)</p>	<p>Sandstone with interlayers of conglomerate and siltstone. Equigranular, grain-supported, sandy grains with a laminated surface compositionally dominated by alkali-feldspars with a higher proportion of quartz.</p>

**Table 5.1. Composite Litho-stratigraphy of the study area with summary notes.**

**Table 5.2. Correlation of the local volcanic Lithostratigraphy to the previous works in proximity to this study area.**

Thickness	<p><b>Lima-Limo (LL)</b> volcanic pile (Hofmann et al., 1997 &amp; Rochette et al., 1998); <b>2,000 m (~1200-3200 masl)</b></p>	<p><b>North Shewa</b> volcanic succession at <b>Yite-Koste</b> (Dereje Ayalew and Gibson, 2009); Locally exceeds <b>1000 m (~2300-&gt;3000)</b></p>	<p>Stratigraphy of the <b>NW LT flood basalts</b> (Krans et al., 2018); ~ <b>1600 m (~540-2175 masl)</b></p>	<p>Stratigraphy of <b>Sela Dingay area</b> (this study); ~ <b>1700 m (~1620-3315 masl)</b></p>
Volcanic lithostratigraphy	<p>Predominantly basaltic flows, with scarce acidic rocks (rhyolites) in the middle of the section, where they determine a flat geomorphological discontinuity, and on the top of the plateau.</p> <ul style="list-style-type: none"> <li>• Ashangi Formation (lower basalt lower 900-m-thick): is composed of thin lava flows (&lt;10 m) and is characterized by a smooth morphology.</li> <li>• Aiba Formation (Upper Basalt 1,000-m-thick): is a succession of massive cliffs corresponding to thick (10–50 m) basaltic flows).</li> <li>• More recent shield-building volcanism with much smaller volumes ends the LL section.</li> </ul>	<p>Basaltic lava flows in the lower part with a conspicuous layer of rhyolitic ignimbrites midway through the sequence. The topmost part of the sequence consists of a thick ignimbrite unit forming plateau morphology.</p> <ul style="list-style-type: none"> <li>✓ Lower Basalt Formation (320 m thick) with thin rhyolite layers</li> <li>✓ Lower Ignimbrite (80 - 120 m thick) with no interbedding of basalts</li> <li>✓ Upper Basalt Formation (&gt;280 m thick) with thin rhyolite layers</li> <li>✓ Upper Ignimbrite Formation (&gt;230 m thick) with no interbedding of basalts</li> </ul>	<p>Based on petrographic differences they define three stratigraphic divisions: lower, middle, and upper flood basalts.</p> <ul style="list-style-type: none"> <li>▪ Lower flood basalts (540–940 masl) (400 m)</li> <li>▪ Middle flood basalts (850–1844 masl) (~1000 m)</li> <li>▪ Upper flood basalts (1844–2175 masl) (~ 330 m)</li> </ul>	<p>The stratigraphic sequence is composed of bimodal basalt-rhyolite which is predominantly basaltic with layers of subordinate rhyolitic-pyroclastic deposits. Silicic-explosive lava products increase significantly from the bottom to the top part of the succession with no interlayering of basaltic flows within the rhyolitic lava products in the middle and the top of the succession. The central type shield basalt ends the stratigraphy.</p> <ul style="list-style-type: none"> <li>✚ Lower Flood Basalt (330m)</li> <li>✚ Sela Dingay Rhyolitic Lava (400 m)</li> <li>✚ Upper Flood Basalt (440 m)</li> <li>✚ Sela Dingay Rhyolite-Ignimbrite (118 m)</li> <li>✚ Termaber Shield Basalt (407 m)</li> </ul>
Petrography	<ul style="list-style-type: none"> <li>• Basalts from Ashange have intergranular textures often exhibiting a sub-ophitic tendency</li> <li>• Aiba Formation is composed of more differentiated basalts with glomerophyric, rarely aphyric, textures.</li> </ul>	<ul style="list-style-type: none"> <li>✓ The mafic lavas vary from aphyric to porphyritic with phenocrysts (up to 7 vol. %) of plagioclase (bytownite and labradorite), olivine, and clinopyroxene.</li> <li>✓ The rhyolites are sparsely porphyritic (with up to 10 vol. % phenocrysts) and are comprised of alkali feldspar (sanidine and anorthoclase), quartz, and minor ilmenite.</li> </ul>	<ul style="list-style-type: none"> <li>▪ The lower flood basalt is dominantly Ol-phyric with Cpx-rich cumulates,</li> <li>▪ The middle flood basalt exhibits Plg-megacrystic flows and oscillation between Plg-phyric and Ol-phyric flows, and</li> <li>▪ The upper flood basalt, which is dominantly Plg-phyric and devoid of cumulates.</li> </ul>	<ul style="list-style-type: none"> <li>✚ The basaltic lavas are dominantly composed of plagioclase (bytownite and labradorite) phenocrysts and microlites with olivine, pyroxene, and abundant Fe-Ti oxides.</li> <li>✚ The rhyolitic rocks (with up to 10-30% phenocrysts) are compositionally dominated by alkali feldspar (sanidine and orthoclase), quartz, and minor plagioclase and micas.</li> <li>✚ Ignimbrite interlayering within the upper basalt is composed of mafic lithic and crystal fragments</li> </ul>
Magma character	<p>Transitional to tholeiitic and belong to the low-Ti magma type (LT)</p>	<p>The bimodal basalt and rhyolites show a tholeiitic and peralkaline composition respectively.</p>	<p>The majority of flows consistent with LT lavas. Only a few flows, restricted to the lower 200 m of the stratigraphy, are observed as transitional basalts similar to HT lavas.</p>	<p>These flows have intergranular textures with plagioclase as a dominant constituent, pinkish-brown clinopyroxene, and abundant Fe–Ti oxides. They are also composed of phenocryst and finer grains of olivine (common in Groundmass) which are altered to iddingsite in some of the samples. These observations are consistent with the slightly alkaline compositions of HT1 magmas</p>

## **CHAPTER-SIX**

### **6. CONCLUSIONS AND RECOMMENDATIONS**

#### **6.1. Conclusions**

Based on Petrographic and Petrologic studies of Lithostratigraphic units along the Mofar River section in parts of North Shewa-Central Ethiopia, the following conclusions are made.

- ❖ The rock-units in the studied areas are composed of several Lithostratigraphic units (the Lower basalt (Ashenge Formation), the Sela Dingay Rhyolitic Lava, the Upper Basalt (Aiba Formation), the Sela Dingay Rhyolite-Ignimbrite Units (Alajae Formation), and the most top Termaber Shield basalt) which represent the Oligocene-Miocene Volcanic Complex as a part of North-western Ethiopian plateau. These volcanic rocks are underlain by a cretaceous Sandstone Formation (Debre Libanos Sandstone).
- ❖ The flood basalt sequence in the study area is composed of bimodal volcanism with the number of rhyolitic lava flow layers increasing significantly from bottom to top part of the succession. These lithostratigraphic successions are deposited as fissural type lava flows in the flood basalts and central type shield volcanos with layers of silicic-explosive products. The morphology of lava flows is characterized by the presence of both tabular-classic and compound-braided flow facies.
- ❖ Hiatus layers (erosional surfaces, deposition of sediments or paleosol, and altered/weathered layers) are an implication for change in the magma flux system.
- ❖ The petrographic data reveals that the studied volcanic rocks show aphyric to Plagioclase and Olivine Phyric with few phenocrysts of Clinopyroxene and the rocks lack mega-phenocrysts of any of the mineral phases, representing HT1 characteristics.
- ❖ Increased thickness of silicic volcanism, the dominance of the amount of plagioclase as both a phenocryst and groundmass component, and a transition from fissure-fed flood basalt eruptions to magmatism centered on large volcanic shields are implications for that the study area characterizes the end of the eruptive phase.
- ❖ Finally, it is concluded that the Ethiopian volcanic plateau is not a thick, monotonous, rapidly erupted tholeiitic basalts as stated by Kieffer et al. (2004). Instead, it consists of a number of volcanic centers with different magmatic characters, and variable thickness lava products with a large range of ages.

#### **6.2. Recommendations**

For a better understanding of the petrogenetic and magma plumbing systems, further works are recommended on

- Magma flux and depth of fractionation to assess the origin and relationship between the spatial distribution of felsic lavas and mafic lavas.
- Paleo-environment control during the emplacement of these different lava flow layers.
- Detailed geochemical study of the area to give a clear relationship between the different bimodal lava products.
- Feeder system (mantle source) for geochemically zoned Ethiopian flood basalt provinces.

## **REFERENCES**

- Abbate, E., Bruni, P. and Sagri, M. (2015). Geology of Ethiopia: A review and geomorphological perspective. Springer 33-59.
- Assefa, G. (1991). Lithostratigraphy and environment of deposition of the Late Jurassic- Early Cretaceous sequence of the central part of Northwestern Plateau. N. Jb. Geol. Paläont. Abh. 182, Stuttgart.
- Baker J, Snee L. and Menzies M. (1996). A brief Oligocene period of flood volcanism in Yemen: implications for the duration and rate of continental flood volcanism at the Afro–Arabian triple junction. *Earth Planet Sci Lett* 138:39–55.
- Beccaluva, L., Bianchini, G., Natali, C. and Siena, F. (2009). Continental flood basalts and mantle plumes: a case study of the northern Ethiopian plateau. *Journal of Petrology*, 50: 1377– 1403.
- Berhe, S.M., Desta, B., Nicoletti, M. and Tefera, M. (1987) Geology, geochronology and geodynamic implications of the Cenozoic magmatic province in W and SE Ethiopia. *Journal of the Geological Society of London* 144, 213-226.
- Chorowicz, J., Collet, B., Bonavia, F., Mohr, P., Parrot, J.F. and Tesfaye Korme (1998). The Tana basin, Ethiopia: intra-plateau uplift, rifting and subsidence. *Tectonophysics* 295:351–367.
- Coulie, E., Quidelleur, X., Gillot, P.Y., Courtillot, V., Lefivre, J.C. and Chiesa, S. (2003). Comparative K-Ar and Ar-Ar dating of Ethiopian and Yemenite Oligocene volcanism: implications for timing and duration of the Ethiopian traps. *Earth and Planetary Science Letters*, 206: 477-492.
- Coulie, E. (2001). Chronology  $^{40}\text{Ar}/^{39}\text{Ar}$  et K/Ar de la dislocation du plateau Ethiopia et de la déchirure continentale dans la Corne de l’Afrique depuis 30 Ma. Ph.D. thesis, Université de Paris Sud, Orsay.
- Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P. and Besse, J. (1999). On causal links between flood basalts and continental breakup. *Earth and Planetary Science Letters*, 166: 177-195.
- Dereje Ayalew & Gibson, I.S. (2009). Head-to-tail transition of the Afar mantle plume: geochemical evidence from a Miocene bimodal basalt–rhyolite succession in the Ethiopian large igneous province. *Lithos*, 112: 461–476.
- Dereje Ayalew (2011). The relations between felsic and mafic volcanic rocks in continental flood basalts of Ethiopia: implication for the thermal weakening of the crust. *Geological Society, London, Special Publications*, 357: 253-264. doi:10.1144/SP357.13.8.
- Dereje Ayalew and Gezahegn Yirgu (2003). Crustal contribution to the genesis of Ethiopian plateau rhyolitic ignimbrites: Basalt and rhyolite geochemical provinciality. *Journal of the Geological Society*, 160: 47-56. Doi: 10.1144/0016-764901-169.

- Dereje Ayalew, Barbey, P., Marty, B., Reisberg, L., Gezahegn Yirgu and Pik, R. (2002). Source, genesis, and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts. *Geochimica et Cosmochimica Acta*, 66(8): 1429–1444.
- Dereje Ayalew, Gezahegne Yirgu and Pik, R. (1999). Geochemical and isotopic (Sr, Nd and Pb) characteristics of volcanic rocks from southwestern Ethiopia. *Journal of African Earth Sciences*, 29: 381-391.
- Dereje Ayalew, Marty, B., Barbey, P., Gezahegn Yirgu and Endale Ketefo (2006). Sub-lithospheric source for quaternary alkaline Tepi shield, southwest Ethiopia. *Geochemical Journal*40: 47–56.
- Ebinger, C.J., Tesfaye Yemane, Gidey WoldeGabriel, Aronson, J.L. and Walter, R.C. (1993). Late Eocene Recent volcanism and faulting in the southern Main Ethiopian Rift. *Journal of the Geological Society of London*, 150: 99–108.
- Ewart, A., Milner, S. C., Armstrong, R. A. and Ducan, A. R. (1998). Etendeka volcanism of the Goboboseb Mountains and Messum igneous complex, Namibia. Part 1: geochemical evidence of early Cretaceous Tristan plume melts and the role of crustal contamination in the Paraná- Etendeka CFB. *J. Petrol.* 39:191–225.
- Ferrando, S., Frezzotti, M.L., Neumann, E.R., De Astis, G., Peccerillo, A., Dereje Ayalew, Gezahegn Yirgu and Teklewold, A. (2008). Composition and thermal structure of the lithosphere beneath the Ethiopian plateau: evidence from mantle xenoliths in basanites, Injibara, Lake Tana Province. *Mineralogy and Petrology*, 93(1–2), pp.47–78.
- George, R., Rogers, N. and Kelly, S. (1998). Earliest magmatism in Ethiopia: evidence for two mantle plumes in one flood basalt province. *Geology*, 26: 923-926.
- Hachimi, H., Youbi, N., Madeira, J., Bensalah, M., Martins, L., Mata, J., Medina, F., Bertrand, H., Marzoli, A., Munh, J., Bellieni, G., Mahmoudi, A., Abbou, M. and Assafar, H. (2011). Morphology, internal architecture and emplacement mechanisms of lava flows from the Central Atlantic Magmatic Province (CAMP) of Argana Basin (Morocco). 10.1144/SP357.9.
- Hawkesworth, C., Kelley, S., Turner, S., Le Roex, A. and Storey, B. (1999). Mantle processes during Gondwana break-up and dispersal. *Journal of African Earth Sciences*, 28: 239-261.
- Hefferan, K. & O'Brien, J. (2010). *Earth Materials*. Wiley-Blackwell, 624 Pages. ISBN: 978-1-444-33460-9. [www.wiley.com/go/hefferan/earthmaterials](http://www.wiley.com/go/hefferan/earthmaterials).
- Sheth, H., Pal, I., Patel, V., Samant, H. and D'Souza, J. (2017). Breccia-cored columnar rosettes in a rubbly pahoehoe lava flow, Elephanta Island, Deccan Traps, and a model for their origin. *Geoscience Frontiers*, 8 (6): 1299-1309. <https://doi.org/10.1016/j.gsf.2016.12.004>.
- Hofmann, C., Courtillot, V., Féraud, G., Rochette, P., Gezahegn Yirgu, Endale Ketefo and Pik, R. (1997). Timing of the Ethiopian flood basalt event and implications for plume birth and global change: *Nature*, 389: 838–841.
- [Http://ethiopianrift.igg.cnr.it/riftvalleygeography.htm](http://ethiopianrift.igg.cnr.it/riftvalleygeography.htm) accessed on Nov 11, 2020

[Http://www.largeigneousprovinces.org/05jan](http://www.largeigneousprovinces.org/05jan) accessed on Jan 26, 2021

[Https://en.wikipedia.org/wiki/Mojana\\_Wadera](https://en.wikipedia.org/wiki/Mojana_Wadera) accessed in 13<sup>th</sup> Mar 2021

[Https://slidetodoc.com/geometry-of-crbg-lava-flows-sheet-vs-compound/](https://slidetodoc.com/geometry-of-crbg-lava-flows-sheet-vs-compound/) accessed in 23<sup>th</sup> Mar 2021

[Https://www.britannica.com/science/Koppen-climate-classification](https://www.britannica.com/science/Koppen-climate-classification). Accessed 17 May 2021.

[Https://www.mindat.org/feature-8621154.html](https://www.mindat.org/feature-8621154.html), accessed in 13<sup>th</sup> Mar 2021

[Https://www.worldweatheronline.com/sela-dingay-weather-averages/et.aspx](https://www.worldweatheronline.com/sela-dingay-weather-averages/et.aspx) accessed in 13<sup>th</sup> Mar 2021.

Jerram, D.A. and Widdowson, M. (2005). The anatomy of continental flood basalt provinces: geological constraints on the processes and products of flood volcanism. *Lithos* 79:385–405.

Kazmin, V. (1972). Geological map of Ethiopia, scale 1:2,000,000. Ethiopian Institute of Geological Survey, Addis Ababa, Ethiopia.

Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Gezahegne Yirgu, Dereje Ayalew, Weis, D. and Jerram, D.A. (2004). Flood and shield basalts from Ethiopia: magmas from the African superswell. *J Petrol* 45:793–834.

Krans, S. R., Rooney, T. O., Kappelman, J., Gezahegne Yirgu and Dereje Ayalew (2018). From initiation to termination: A petrostratigraphic tour of the Ethiopian low-Ti flood Basalt Province. *Contributions to Mineralogy and Petrology*, 173(5), 37. <https://doi.org/10.1007/s00410-0181460-7>.

Merla, G., Abbate, E., Azzaroli, A., Bruni, P., Caunti, P., Fazzuoli, M., Sagri, M. and Tacconi, P. (1979). Geological map of Ethiopia and Somalia (1973):1:2,000,000 and comment with major land forms, 2-98.

Mohr, P. (1967). Review of the geology of the semien mountains. *Bulletin of the Geophysical observatory of Addis Ababa* 10, 7993.

Mohr, P. (1983). Ethiopian flood basalt province. *Nature* 303, 177-584.

Mohr, P. and Zanettin, B. (1988). The Ethiopian food basalt province. In: Macdougall, J.D. (Ed.), *Continental flood basalts*. Kluwer Academic Publishers, 63–110.

Natali C, Beccaluva L, Bianchini G, Ellam RM, Savo A, Siena F, Stuart FM (2016) High-MgO lavas associated to CFB as indicators of plume-related thermochemical effects: the case of ultra-titaniferous picrite–basalt from the Northern Ethiopian–Yemeni Plateau. *Gondwana Res* 34:29–48.

Peccerillo, A., Barberio, M.R., Gezahegn Yirgu, Dereje Ayalew, Barberi, M. and Wu, T.W. (2003). Relationships between mafic and acid peralkaline magmatism in continental rift settings: a petrological, geochemical and isotopic study of the Gedemsa volcano, central Ethiopian Rift. *Journal of Petrology*, 44(11): 2003-2032. Doi: 10.1093/petrology/egg068.

- Peccirillo, E.M., Justin-Visentin, E., Zanettin, B., Joron J.L. and Treuil M. (1979). Geodynamic evolution from plateau to rift: major and trace element geochemistry of the central eastern Ethiopian Plateau volcanics. *Neues Jb. Geol. Palaont. Abh.*158:139-179.
- Pik, R., Deniel, C., Coulon, C., Gezahegn Yirgu and Marty B. (1999). Isotopic and trace element signatures of Ethiopian flood basalts: Evidence for plume–lithosphere interactions. *Geochimica et Cosmochimica Acta*, 63(15): 2263–2279.
- Pik, R., Deniel, C., Coulon, C., Gezahegn Yirgu, Hofmann, C. and Dereje Ayalew (1998). The Northwest Ethiopian plateau flood basalts: classification and spatial distribution of magma types. *Journal of Volcanology and Geothermal Research*, 81: 91–111.
- Duraiswami R. A., Gadpallu P., Shaikh T. N. and Cardin N. (2014). Pahoehoe–a’a transitions in the lava flow fields of the western Deccan Traps, India-implications for emplacement dynamics, flood basalt architecture and volcanic stratigraphy, *Journal of Asian Earth Sciences*, 84: 146-166. <https://doi.org/10.1016/j.jseae.2013.08.025>.
- Reidel, S.P., Camp, V.E., Tolan, T.L. and Martin, B.S. (2013). The Columbia River flood basalt province: Stratigraphy, areal extent, volume, and physical volcanology. *Geological Society of America Special Paper* 497, p. 1–43, doi: 10.1130/2013.2497 (01).
- Rochette, P., Tamrat, E., Féraud, G., Pik, R., Courtillot, V., Endale Ketefo, Coulon, C., Hofmann, C., Vandamme, D. and Gezahegne Yirgu (1998). Magnetostratigraphy and timing of the Oligocene Ethiopian raps. *Earth planet.Sci.Lett*, 164:497-510.
- Rooney, T. O. (2017). The Cenozoic magmatism of East-Africa: Part I—Flood basalts and pulsed magmatism. *Lithos*, 286(Supplement C), 264–301.
- Rooney, T. O., Krans, S. R., Mège, D., Arnaud, N., Tesfaye Korme, Kappelman, J. & Gezahegne Yirgu (2018). Constraining the magmatic plumbing system in a zoned continental flood basalt province. *Geochemistry, Geophysics, Geosystems*, 19, 3917–3944. <https://doi.org/10.1029/2018GC007724>.
- Rooney, T., Furman, T., Bastow, I. D., Dereje Ayalew & Gezahegne Yirgu (2007). Lithospheric modification during crustal extension in the Main Ethiopian Rift. *Journal of Geophysical Research*, 112, B10201. <https://doi.org/10.1029/2006JB004916>.
- Self, S., Schmidt, A. and Mather, T.A. (2014). Emplacement characteristics, time scales, and volcanic gas release rates of continental flood basalt eruptions on Earth. *Geological Society of America Special Papers*. 505. SPE505-16. 10.1130/2014.2505 (16).
- Self, S., Thordarson, T. H. & Keszthelyi, L. (1997). Emplacement of continental flood basalt lava flows. In: Mahoney, J. J. & Coffin, M. F. (eds) *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. AGU Geophysical Monograph Series, Washington, 100, 381–410.
- Sheth, H.C. (2018). *A Photographic Atlas of Flood Basalt Volcanism*. Springer, 363p. <https://doi.org/10.1007/978-3-319-67705-7>.
- Tigel Belay, Ilfios Tesfay, Abiy Ayalew, Genet Yohannes, Teferi Zewdie, Henok Bekele, Melese Tadesse, Tesfaye Demisse and Tadesse Alemu (2009). *Geology of the Were-Illu area*. Geological Survey of Ethiopia, unpublished report, 63pp.

- Tilling, R.I. (1989). Volcanic hazards and their mitigation: progress and problems. *Reviews of Geophysics*, 27(2), pp.237-269.0.
- Ukstins, I.A., Renne, P.R., Wolfenden, E., Baker, J., Dereje Ayalew and Menzies, M. (2002). Matching conjugate 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, 289–306.
- Vye-Brown, C., Self, S. & Barry, T.L. (2013). Architecture and emplacement of flood basalt flow fields: case studies from the Columbia River Basalt Group, NW USA. *Bull Volcanol* 75, 697. <https://doi.org/10.1007/s00445-013-0697-2>.
- Walker, G. P. L. (1971). Compound and simple lava flows and flood basalts. *Bulletin Volcanologique*, 35, 579–590.
- Wolela, A. (2009). Sedimentation and depositional environments of the Barremian-Cenomanian Debre Libanose Sandstone, Blue Nile (Aby) Basin, Ethiopia. *Cretaceous Research - CRETACEOUS RES.* 30. 1133-1145. 10.1016/j.cretres.2009.04.002.
- Wolfenden, E., Ebinger, C., Gezahegn Yirgu, Deino, A. and Dereje Ayalew (2004). Evolution of the northern Main Ethiopian rift: birth of a triple junction. *Earth and Planetary Science Letters* 224(1): 213-228.
- Zanettin, B., Justin-Visentin, E., Nicoletti, M. and Peccerillo, E.M. (1980). Correlation among Ethiopian volcanic formations with special references to the chronological and stratigraphic Problems of the “Trap Series “.In: *Geodynamic Evolution of the Afro-Arabian rift system*. Accademia Nazionale dei Lincei, Roma, 47: 231-52.