



Volcanic Stratigraphy and Petrography of the Northwestern Ethiopian Flood Volcanics in Upper Kesem River Section, Central Ethiopia

Misrak Lemma^{1, 2, 3}, Gezahegn Yirgu¹, Belachew Moges^{2, 3, 4}, Takele Chekol^{2, 3, *}

¹School of Earth Sciences, Addis Ababa University, Box 1176, Addis Ababa, Ethiopia

²Department of Geology, College of Applied Sciences, Addis Ababa Science and Technology University, P.O. Box 16417, Addis Ababa, Ethiopia,

³Mineral Exploration, Extraction and Processing Center of Excellence, Addis Ababa Science and Technology University, P.O. Box 16417, Addis Ababa, Ethiopia.

⁴Department of Earth and Environmental Sciences CUHK, Hong Kong

Article Information

Article history:

Received 25 September 2025

Received in revised form 10 October 2025

Accepted 25 Decemebe 2025

Keywords:

Ethiopian volcanic province

Lithostratigraphy

Oligo-Miocene

Petrography

Upper Kesem river

Corresponding author.

E-mail: takele.chekol@aastu.edu.et (T. Chekol)

<https://doi.org/10.69660/jmpt.v2i1.114>

Abstract

A petro-stratigraphic investigation of the volcanic sequence exposed along the Upper Kesem River section is presented. The study area lies in central Ethiopia, within the North Shewa administrative zone, between the Koremash and Shola Gebeya localities, approximately 80 km northeast of Addis Ababa. The section exposes a nearly continuous volcanic succession about 1080 m thick, consisting of stratigraphically preserved basalt flows interbedded with silicic pyroclastic deposits. The basal contact of the volcanic sequence is not exposed in this river section. Based on detailed field investigations, lithostratigraphic logs were constructed for several sections. The volcanic succession is predominantly composed of flood basalts (approximately 78%), while felsic lavas and pyroclastic deposits constitute about 22% of the upper portion of the sequence. The uppermost part of the succession is characterized by shield-forming basaltic lava flows and associated scoriaceous deposits. Thin layers of paleosols and clastic sediments occur intermittently within the volcanic units, indicating pauses in volcanic activity and periods of surface exposure. This stratigraphic sequence records the principal phase of flood basalt volcanism as well as the transition toward the waning stages of flood basalt activity. From the composite volcanic stratigraphy constructed for the area, five lithostratigraphic units have been identified: (1) Lower Basalt, (2) Lower Rhyolitic Ignimbrite, (3) Upper Basalt, (4) Upper Rhyolitic Ignimbrite, and (5) Shield Basalt. These units correlate well with volcanic sequences described from other parts of the northwestern Ethiopian Plateau. Petrographic analysis indicates the presence of only basaltic and felsic volcanic rocks, with no intermediate compositions identified, suggesting a bimodal petrological distribution within the sequence. The basalts display considerable variation in modal mineralogy and phenocryst assemblages. Such variability suggests the existence of a polybaric magmatic plumbing system, with multiple magma chambers formed at different crustal depths, each experiencing independent recharge and fractional crystallization processes. The development of shield volcanism likely reflects a progressive decrease in magmatic flux over time. Furthermore, the presence of large-volume silicic pyroclastic deposits indicates that flood basalt volcanism was associated with the formation of large, shallow magma chambers where basaltic magmas were stored and underwent extensive fractional crystallization and magmatic evolution.

1. Introduction

The Ethiopian Cenozoic volcanic province represents a significant segment of the East African Rift System (EARS) and constitutes a thick sequence of volcanic rocks that span several hundred thousand square kilometers [1]. As one of the latest large igneous provinces (LIPs), the Ethiopian volcanic province is predominantly characterized by flood basalts with minor silicic products, occupying an area of around 622,108 km² [2, 3]. These volcanic formations primarily comprise fissural basalts and lesser amounts of rhyolitic ignimbrites, with basaltic lavas dominating the landscape [4-8].

The Ethiopian flood basalt formations, also referred to as the Ethiopian traps, are part of the Afro-Arabian Igneous Province associated with the Afar plume, the Red Sea, and the Gulf of Aden [9]. The volcanic products are primarily grouped into two categories: the continental flood basalts (CFB) and the rift-related volcanic. The continental flood basalts cover large portions of the Ethiopian highlands and plateaus, while the ongoing rift volcanism is associated with active tectonic rifting in the region. These volcanics are linked to massive basaltic lava eruptions, forming extensive

flood basalt sequences. According to Kieffer et al. (2004), these flood basalts represent the largest, youngest, least deformed, and best-preserved volcanic rocks in the region.

The study of these volcanic rocks has revealed varying geochemical characteristics across the region. [10] classified the NW Ethiopian flood basalts into three distinct geochemical types: low-Ti basalts (LT-type), high-Ti1 basalts (HT1-type), and high-Ti2 basalts (HT2-type). These units represent the complex magmatic processes that have shaped the volcanic landscape of northern Ethiopia. In addition to these, large shield volcanoes such as Guna, Gugufu, Megezez, Simien, and Choke are prominent features that overlay the flood basalt formations in the region [6, 11].

This research focuses on the Upper Kesem River section, located in the North Shewa Zone, Amhara Region, Central Ethiopia (Fig. 1). It aims to provide detailed insights into the volcanic stratigraphy and petrography of the flood basalt units exposed in this region. The study will involve constructing a detailed stratigraphic section and petrographic descriptions based on fieldwork and laboratory analyses, contributing to a better understanding of the magmatic processes and tectonic evolution of the Ethiopian flood basalt province.

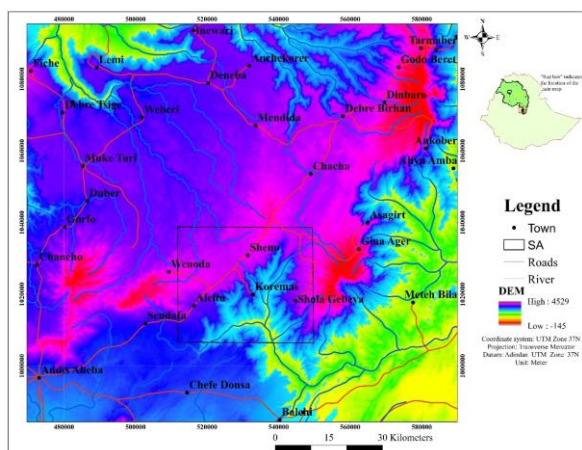


Figure 1. Location map of Upper Kesem river section (study area).

2. Regional Geological Setting

2.1 East African Continental Flood Volcanism

The East African Rift (EAR) system is home to some of the largest continental flood basalt provinces in the world (Fig. 2). Volcanism in the EAR is associated with regional uplift, particularly in areas like the Ethiopian and Kenyan domes [12]. The magmatic evolution in Ethiopia has occurred in three main stages, with the first stage spanning approximately 50 to 10 Ma. This phase was characterized by the eruption of tholeiitic to transitional flood basalt lava flows, intercalated with alkaline trachytic and rhyolitic ignimbrites. The second stage, occurring around 10–5 Ma, saw the formation of shield volcanoes with transitional to sodium-rich alkaline basaltic rocks and minor trachytes. The third stage, from the Pliocene to present, has been marked by the rifting and expansion of the Main Ethiopian Rift (MER) and the Afar Depression [13-15].

2.2 Ethiopian Continental Flood Volcanism

The Ethiopian flood basalts, erupted during the Cenozoic era, represent one of the largest intercontinental magmatic provinces in the world (Fig.2). Located at the junction of the Gulf of Aden, Red Sea, and the East African Rift, this province spans about 720,000 km², with an estimated volume of 720,000 km³ [3]. The volcanic rocks within the Ethiopian flood basalt province include both mafic (basaltic) and felsic (rhyolitic) volcanic rocks, which form a layer up to 2 km thick in some regions [6]. The province has been divided into several volcanic stages, with the major classifications being Pre-Oligocene, Oligo-Miocene, and Miocene-Pliocene. These stages encompass different volcanic units such as the Ashengi, Aiba, Alaji, and Termaber formations [16].

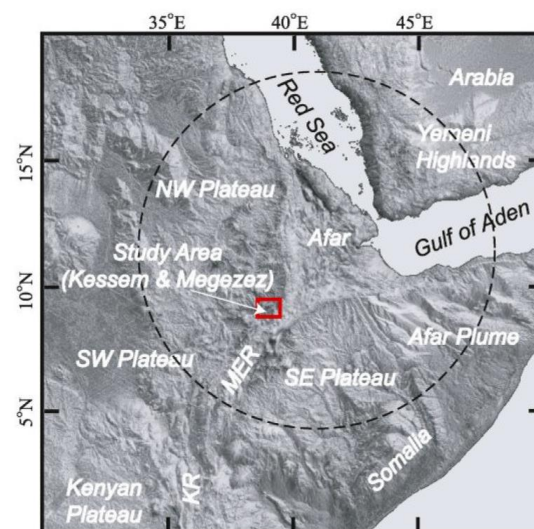


Figure 2. Shaded relief map of East Africa and Arabia (NASA SRTM30) illustrating the position (Main Ethiopian Rift=MER, Kenyan Rift=KR), as well as the Ethiopian and Yemeni plateaus which surround the Afar depression. The circle dash line indicates the extent of Afar plume. The location of study area site is also indicated by red box.

2.3 Northwestern Ethiopian Plateau Volcanism

The Upper Kesem River section lies within the northwestern Ethiopian plateau, a region known for its complex volcanic stratigraphy and mineralogical diversity. This plateau is characterized by several eruption centers with varying magmatic compositions and a wide range of ages [6]. The flood basalt volcanism in this region has been followed by the formation of large shield volcanoes and further volcanic activity associated with continental rifting [6,17]. The volcanic units in this region are divided into several stages, ranging from the pre-Oligocene Ashangi Formation to the Miocene-Pleistocene volcanic units such as the Termaber-Megezez basalts [16,18]. The volcanic products in this region predominantly include basaltic flows, but also include minor rhyolitic and trachytic components.

The volcanic succession in the northwestern Ethiopian plateau has been extensively studied and divided into several stages based on stratigraphy

and geochemical characteristics. The early stage, known as the Ashangi Formation, represents the earliest fissure-fed flood basalt volcanism in the region [18]. This unit consists of basalts of transitional tholeiitic and alkaline compositions, often intercalated with pyroclastics and rhyolitic lava flows [19]. Following the Ashangi Formation, the Aiba, Alaji, and Termaber formations represent later stages of volcanic activity, with a predominance of basaltic flows and minor rhyolites [16,18]. These volcanic stages provide a detailed record of the tectonic and magmatic evolution of the northwestern Ethiopian plateau, helping to understand the broader geodynamic processes shaping the region's volcanic landscape.

3. Materials and methods

3.1 Remote Sensing and GIS Studies

Geospatial analysis using remote sensing data and Geographic Information System (GIS) tools was employed to map the study area and identify the geological units. Digital Elevation Models (DEM) and hill-shading techniques were used to create detailed topographic maps, providing essential information for fieldwork planning. GIS-based software, including ArcGIS and Global Mapper, were used for spatial analysis and to produce geological maps, cross-sections, and other related outputs.

3.2 Field Investigation and Sampling

Field investigations were carried out to collect data on lithostratigraphic units, geological structures, and geomorphology in the Upper Kesem River section. Detailed descriptions of lithologies, including lava flow morphologies, were documented through field traverses. Representative rock samples were collected from various stratigraphic intervals for subsequent petrographic analysis. The stratigraphic sampling strategy focused on capturing the variability in lithology and the spatial extent of different volcanic units.

During the fieldwork, a 1:50,000-scale base map was used for accurate data collection, and all sampling locations were recorded using a hand-held GPS device. The field observations were complemented by photographing key outcrops and measuring geological structures such as bedding, jointing, and faults.

3.3 Petrographic Studies

After the field data collection, 25 representative rock samples were selected based on their lithological diversity and the variation in physical properties observed in the field. Thin sections of these samples were prepared at the Central Geoscience Laboratory of the Geological Survey of Ethiopia. The thin sections were examined under a polarizing microscope to analyze their mineralogical composition, texture, and modal proportions. Mineralogical and textural observations were used to determine the petrology of the volcanic rocks and to interpret the magmatic processes that contributed to their formation.

3.4 Geological Mapping and Stratigraphic Section Construction

The geological map and stratigraphic section of the Upper Kesem River section were constructed based on field observations and laboratory data. The stratigraphic section was compiled by correlating the lithological units

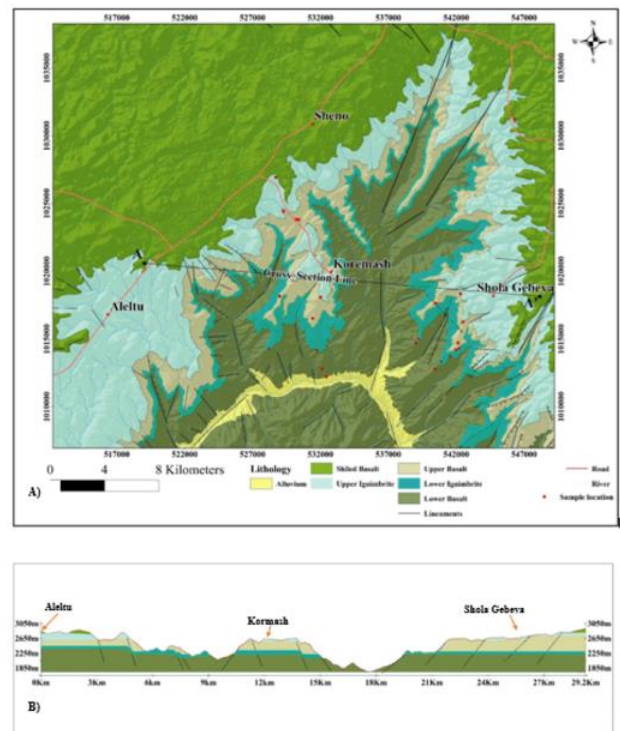
observed in the field, establishing the sequence of volcanic eruptions, and interpreting their relative ages. A geological cross-section was also produced to visualize the subsurface structure of the study area, helping to identify the lateral continuity of volcanic units and their tectonic relationships.

4. Results

4.1 Geology of the Upper Kesem River Area

The Upper Kesem River area, located in the northwestern Ethiopian Plateau, features a complex geological setting characterized by a series of volcanic lithostratigraphic units (Fig. 3). The region's geology is shaped by various volcanic events and tectonic processes, which have resulted in diverse lithologies and structural features. The study area spans an elevation range of 1700 to 2780 meters above sea level (masl), with a total stratigraphic thickness of approximately 1080 meters.

Figure 3. A) Geological sketch map of upper Kesem River area at the scale



of 1:50,000; (B) Geological cross section of the study area A to A' with vertical exaggeration (2X)

4.2 Lithology and petrography of the study area

The geology of the Upper Kesem River area is dominated by volcanic units, primarily basalts and ignimbrites, interspersed with pyroclastic (Fig. 3). Based on field observations, mapping, and sample descriptions, five major lithostratigraphic units have been identified in the region. These units are described from bottom to top, reflecting their stratigraphic succession (Lower Basalt, Lower Rhyolitic Ignimbrite, Upper Basalt, Upper Rhyolitic Ignimbrite and Shield Basalt; Fig. 4).

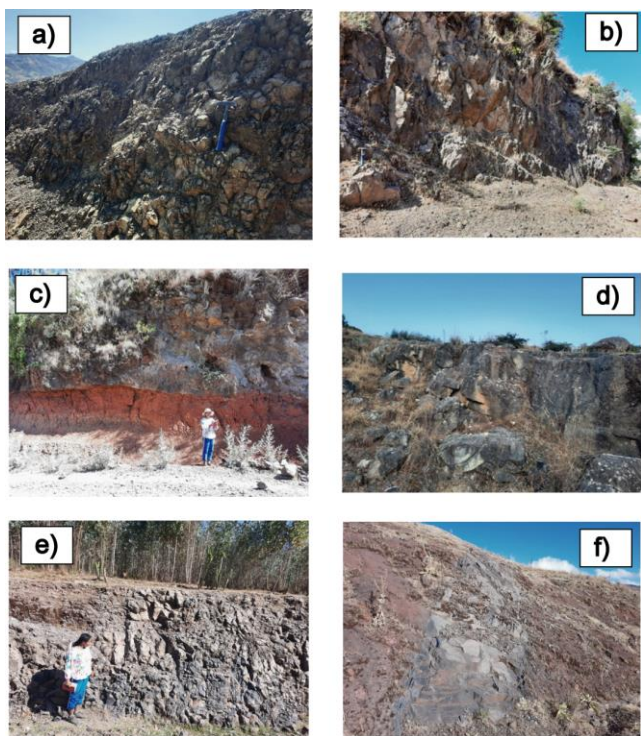


Figure 4. The photographs show a) the rugged topography of lower basalt unit b) the topographic expression of the lower ignimbrite unit from Sosit Amba area c) upper basalt d) upper ignimbrite around Koremash area, e) and f) Shield-forming basalts.

4.2.1 Lower Basalt Unit

The Lower Basalt Unit is characterized by aphanitic basalts intercalated with plagioclase-phyric basalts. These flows are typically poorly to moderately porphyritic, with some vesicular basalt present. The unit exhibits intense fracturing, irregular jointing, and spheroidal weathering, which complicates the determination of the number of individual flows. The observed thickness of this unit ranges from 300 to 450 meters. Its surface exhibits relatively gentle topography, and while its lower contact is not exposed, the basalt flows are highly weathered, making their stratigraphic boundaries difficult to ascertain.

For Petrography investigations, four samples were selected from the Lower Basalt unit (KES 202, KES 204, KES 101, and KES 302; Fig. 5). This unit exhibits a range of textures from poorly phyric to phyric basalt. Samples KES 202 and KES 204 are poorly phyric, consisting of plagioclase, clinopyroxene (augite), and opaque oxides. The groundmass is microcrystalline with plagioclase laths and opaque oxides. KES 202 also contains an abundance of glass, which is absent in KES 204.

KES 101 and KES 302 are classified as phyric intergranular basalts. In these samples, phenocrysts make up approximately 15% of the total rock

composition. KES 101 contains 31.2% clinopyroxene and 37% plagioclase, while KES 302 contains 6.6% clinopyroxene and 42.5% plagioclase. The groundmass is pilotaxitic, with randomly oriented large laths of plagioclase and clinopyroxene crystals surrounded by microcrystalline plagioclase and ferromagnesian minerals.

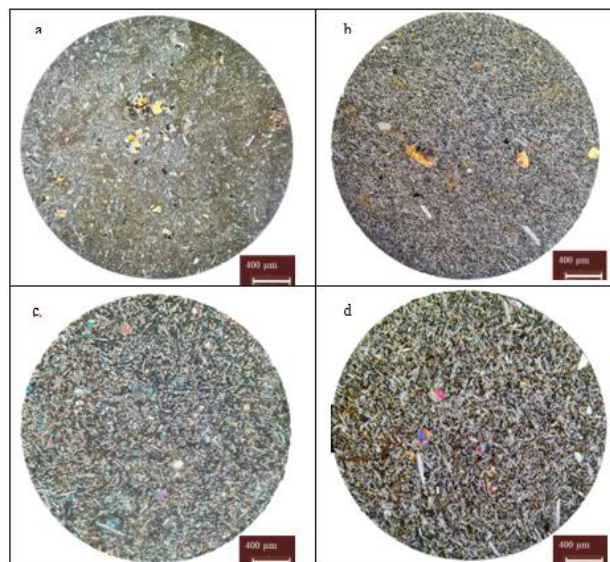


Figure 5. Thin section photomicrographs of basaltic samples from the Lower Basalt unit. (a) KES 202 and (b) KES 204 show an aphyric to microporphyritic texture with a groundmass dominated by plagioclase laths. (c) KES 101 and (d) KES 302 show an intergranular microcrystalline texture formed by plagioclase and clinopyroxene microphenocrysts. All photomicrographs are taken in cross-polarized light at 4X magnification.

4.2.2 Lower Rhyolitic Ignimbrite Unit

The Lower Rhyolitic Ignimbrite Unit is a pyroclastic deposit exposed in both the Koremash and Shola Gebeya sections. This unit is limited in thickness compared to the Lower Basalt Unit, varying between 50 meters to 150 meters, depending on the locality. The ignimbrite exhibits a greenish-gray to light gray color and is massive, slightly fractured, and lithic-poor. It contains moderate amounts of crystals and is well-developed with columnar jointing. The degree of welding within this unit varies, with less welded and highly weathered sections observed around the Weyn Amba area, while other parts are highly welded, exhibiting a glassy texture with visible minerals.

For Petrography investigations, four samples were selected from the Lower Rhyolitic Ignimbrite unit: KES 010, KES 207, KES 303, and KES 304. KES 010 is a fine-grained, lithic-poor pyroclastic rock with alkali feldspar and quartz crystals embedded in a microcrystalline quartz and volcanic glass matrix (Fig. 6). KES 207 is similar to KES 010 but contains larger alkali feldspar crystals. KES 303 shows alkali feldspar and quartz crystals alongside lithic fragments in a vitric groundmass. KES 304 contains quartz, sanidine, and lithic fragments. Alkali feldspar (mostly sanidine) is subhedral to anhedral, while the quartz grains are anhedral, with most crystals containing glass inclusions.

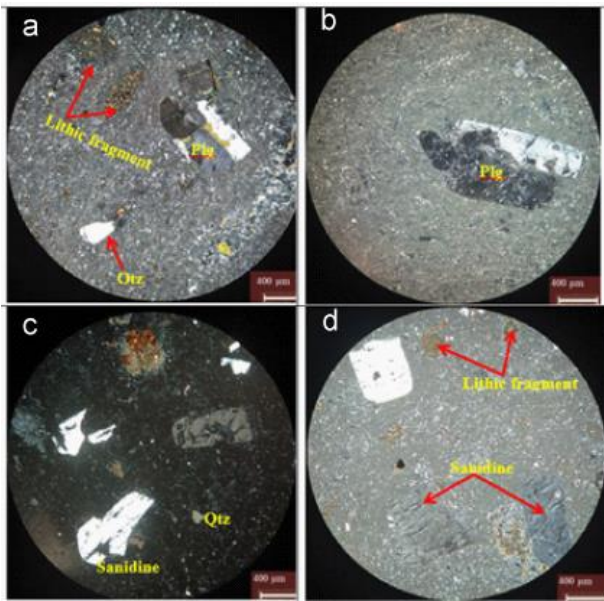


Figure 6. Representative thin section photomicrographs of rhyolitic ignimbrite samples. (a) KES 010, (b) KES 207, (c) KES 303, and (d) KES 304. The samples show sanidine and quartz as dominant crystal phases within a glassy groundmass. Photomicrographs are taken at 4X magnification in cross-polarized light.

4.2.3 Upper Basalt Unit

The Upper Basalt Unit unconformably overlies the Lower Ignimbrite Unit and is a thick sequence of basaltic lava flows interspersed with pyroclastic layers. The estimated thickness of this unit ranges from 300 to 400 meters, with individual basalt flows ranging from 20 to 55 meters thick. The basalts exhibit porphyritic textures, containing plagioclase, olivine, and pyroxene phenocrysts. Some flows are columnar-jointed, while others are massive and fractured. The weathered surfaces of these flows range from dull gray to reddish-brown and light gray. The Upper Basalt Unit is characterized by steep cliff faces, particularly in the Shola Gebeya section, contributing to the rugged topography of the area.

For Petrography investigations, a total of 11 samples were analyzed from the Upper Basalt unit, including KES 108, KES 310, KES 110, and KES 114, which are classified as poorly phyric basalts (Fig. 7). These samples contain less than 3% phenocrysts of plagioclase and exhibit a groundmass of fine microlites and plagioclase, with a sub-intergranular texture.

Porphyritic samples from the Upper Basalt unit show a variety of phenocryst assemblages, including plagioclase, olivine, pyroxene, and secondary alteration minerals. The Plg-phyric basalts (KES 007 and KES 117; Fig. 8) contain plagioclase as the dominant phenocryst phase, with secondary calcite in KES 117. The groundmass is characterized by microcrystalline to intergranular plagioclase, altered pyroxene, and opaque oxides.

The Plg-Px-Ol-phyric basalts (KES 004, KES 005, KES 013, KES 211, and KES 308) show a greater diversity of phenocryst phases, including plagioclase, olivine, and clinopyroxene (Fig. 9). These basalts have a holocrystalline or intergranular groundmass with microlites of plagioclase, and some samples show evidence of alteration along mineral boundaries.

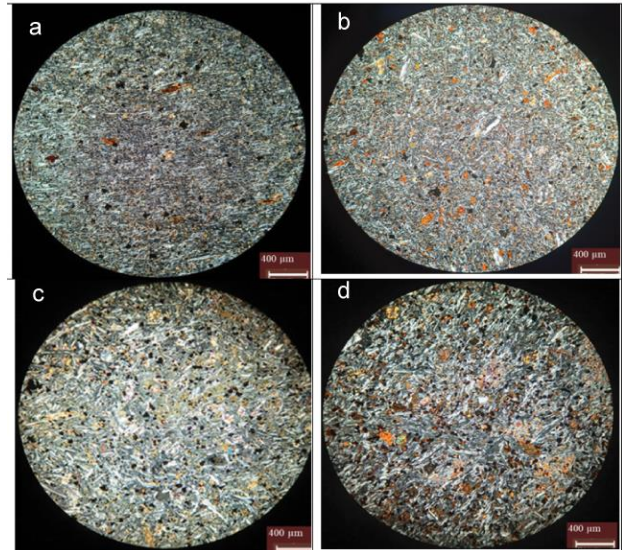


Figure 7. Thin section photomicrographs of aphyric basalt samples from the Upper Basalt unit. (a) KES 108, (b) KES 310, (c) KES 110, and (d) KES 114. All photomicrographs are taken in cross-polarized light at 4X magnification.

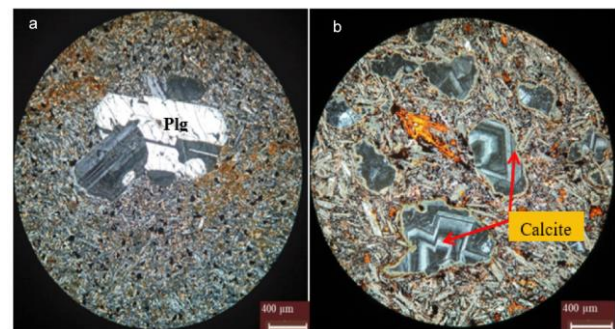


Figure 8. Photomicrographs of Plg-phyric basalt samples. (a) KES 007 and (b) KES 117 show plagioclase phenocrysts with altered pyroxene and opaque minerals. All photomicrographs are taken in cross-polarized light at 4X magnification.

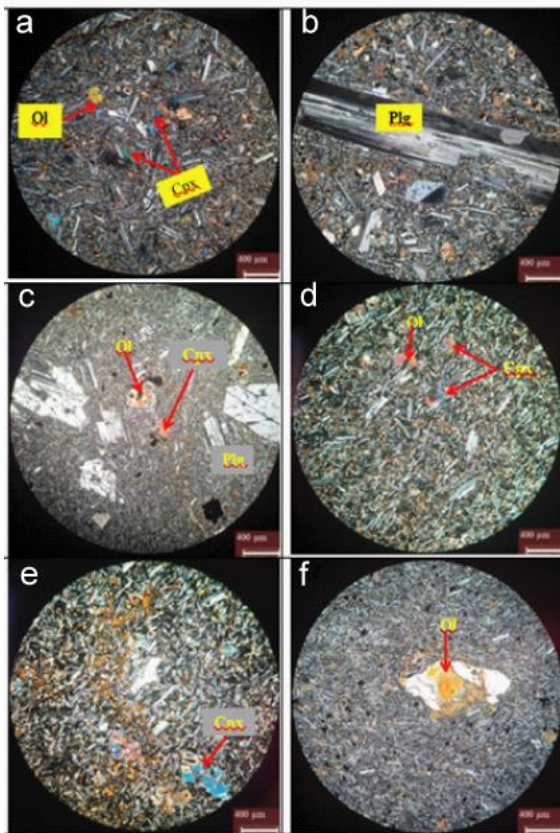


Figure 9. Photomicrographs of Plg-Px-Ol-phyric basalt samples. (a) KES 004, (b) KES 005, (c) KES 013, (d) KES 211, and (e) KES 308. Photomicrographs are taken in cross-polarized light at 4X magnification.

4.2.4 Upper Rhyolitic Ignimbrite Unit

The Upper Rhyolitic Ignimbrite Unit forms the uppermost pyroclastic deposit in the stratigraphy of the area. This unit is predominantly composed of fine-grained, lithic-poor pyroclastic material, with moderate amounts of alkali feldspar crystals. It is exposed in the upper sections of the Koremash and Shola Gebeya sections and has a thickness of up to 80 meters. The ignimbrite is light to medium gray, moderately weathered, and fractured, and it is horizontally layered with slight columnar jointing, forming the uppermost part of the volcanic succession.

Petrographically, the Upper Rhyolitic Ignimbrite samples consist of fine-grained, lithic-poor deposits with scarce crystals of sanidine and quartz set in a cryptocrystalline groundmass (Fig. 10). The sanidine crystals are typically euhedral, while the quartz crystals exhibit resorption with rounded and embayed edges. The groundmass displays devitrified and eutaxitic textures.

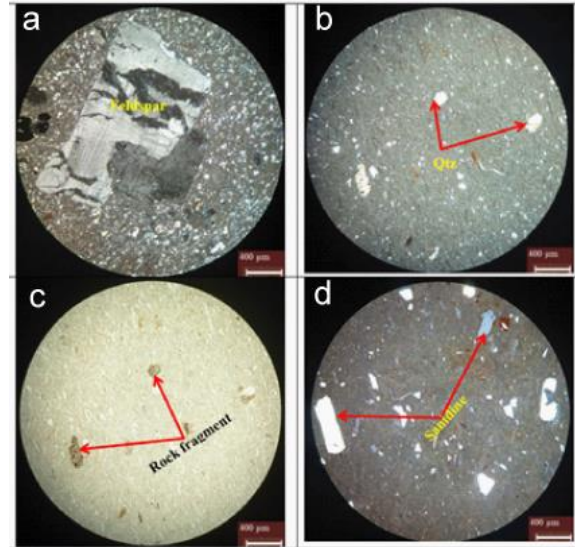


Figure 10. Thin section photomicrographs of upper rhyolitic ignimbrite samples. (a) KES 001, (b) KES 214, (c) KES 214 (PPL), and (d) KES 312. Photomicrographs are taken at 4X magnification in cross-polarized light (except for c, which is in plane-polarized light).

4.2.5 Shield-forming Basalt Unit

The Shield-forming Basalt Unit is found in the Megezez Mountain area, part of the Tarmaber formation, and represents one of the Mid-Miocene shield volcanoes in the region. This basaltic unit consists of thinner flows, less continuous than those of the Lower and Upper Basalt Units, and has an estimated thickness of 521 meters. These flows are more porphyritic, containing abundant plagioclase and olivine phenocrysts. The basalts are dark gray in color when fresh and light gray when weathered. The unit also exhibits vesicular and aphanitic textures, with some dike intrusions cutting through the flows.

One sample, KES 315A, was taken from the Shield Basalt unit for petrographic description (Fig. 11). This sample is dominated by microphenocrysts of plagioclase and opaque oxides set in a microcrystalline groundmass. The rock texture is aphanitic, with little visible crystallization in the groundmass.

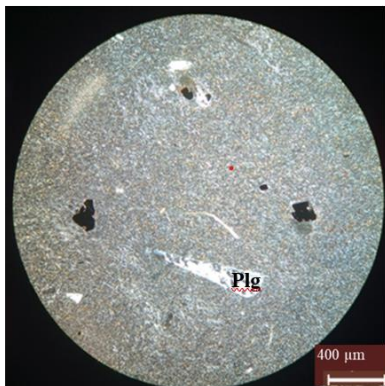


Figure 11. Thin section photomicrograph of shield basalt sample KES 315A. The sample shows microphenocrysts of plagioclase and opaque oxides set in a microcrystalline groundmass. Photomicrograph taken in cross-polarized light at 4X magnification.

5. Discussion

5.1 Introduction

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

This section also contains the correlation of each stratigraphic unit from different sections of the study area (four stratigraphic sections in total—two from the Hamus Gebeya-Koremash-Kesem section and two from the Koto-Shola Gebeya-Kesem section). The final composite stratigraphy of the study area is presented, with the correlation of the regional geology of the North-Western Plateau based on different published works from various areas.

5.2 Lithological Comparisons and Correlation of the Northern Kesem (Upper) River Section with Other Studied Sections

Lower Basalt (Ashange Basalt, 1700 to 2150 m)

The Upper Kesem River Section, which is the focus of this study, is part of the North-Western Ethiopian Plateau, located on the escarpment of the western part of the main Ethiopian Rift. The bottom lithological units exposed are lower basalts, regionally referred to as the Ashange basalt, which range in thickness from 300 to 450 meters. These units are the oldest basaltic formations exposed in the lower section of the study area, near the Keseme/Germame River in the Koremash and Shola Gebeya sections.

The flows in this basalt are generally horizontally bedded, and in some

localities, they form sheeting. The lower basalt is characterized by rugged morphology and is relatively gentler than the upper basalt. The rock units are extensively affected by fractures and weathering, ranging from slight to complete weathering. Another geological feature observed in this unit is the presence of dikes.

Previously, these lithological units, including the lower basalt, lower ignimbrite, tuffaceous sediments, and upper basalts, were considered a single unit and were named the Kesme Basalt [20,21]. In this study, these three different lithological units are clearly separated, described, and mapped.

Earlier studies by [22] around the North-Western Ethiopian Plateau in the North Shewa Yita Koste section describe this lithological unit with a thickness of 320 meters. Two recent studies [23,24], conducted by master's students from Addis Ababa University in the North-Western Plateau, indicate a thickness of 330 meters at Sela-Dngay and 258 meters at Debrelibnos.

For the petrographic study, samples from the lower basalt were taken from different elevations. The samples include:

- KES202 (1710 m): Dominated by Plagioclase (Plg), Clinopyroxene (Cpx), and opaque oxides, with an aphanitic texture.
- KES204 (1820 m): Dominated by Plg and a small amount of Cpx, with a microcrystalline aphyric texture.
- KES101 (2150 m): Dominated by Plg, Cpx, and oxides, with an intergranular texture.

The petrographic studies conducted by others, such as Ayalew and Gibson (2009) and the unpublished research by Sefa (2021) and Yemenu (2022), show similar compositions to the current study.

Lower Rhyolitic Ignimbrite (~100 to 150 m thick)

The lower rhyolitic ignimbrite consists of ignimbrite with varying degrees of welding and crystals. In the Shola Gebeya section, the contact between the lower basalt and the ignimbrite is characterized by glassy ignimbrite, indicating rapid cooling of pyroclastic flows. Petrographic studies reveal quartz and sanidine minerals in this unit, with a rhyolitic composition inferred from thin section study. The glassy texture results from two major processes: quenching and rapid gas loss [25].

The porphyritic varieties (vitrophyric textures) represent partial crystallization of magma before its rapid solidification. The rapid gas loss and high viscosity of the rhyolitic lava likely resulted in the formation of these textures. The ignimbrite in this area shows tightly columnar-jointed structures, indicating high-temperature formation.

In the Koremash section, this unit also shows columnar jointing. Generally, the lower rhyolitic ignimbrite is a key felsic rock unit that separates the Lower and Upper Basaltic flows of the region. The thickness of this unit varies across the study area due to paleogeographical factors, with variations likely resulting from faulting in areas such as Koremash and Shola Gebeya.

Upper Basalt (Aiba Basalt, 2300 to 2700 masl)

Above the lower ignimbrite and sediments, the upper basalt unit is exposed in all sections, from Koremash to Kesem and Shola Gebeya to Kesem. This unit consists of several lava flows, up to ten different basaltic flows, separated by paleosols. The flow thickness ranges from 20 to 55 meters, with a total thickness of ~300 to 400 meters. According to Ayalew and Gibson (2009), this unit is estimated to have a thickness of >280 meters.

Field observations show that the bottom part of the flow exhibits scoriaceous basalt, the middle section shows columnar jointed structures, and the top exhibits vesicular basalts. Eleven samples were selected for petrographic study. The lower part of this unit shows poorly phyrific microcrystalline texture, while others show intergranular textures. The mineralogical composition includes Plg, Px, Ol, and oxides, with most samples exhibiting a holocrystalline groundmass.

Petrographic studies from different areas (Ayalew and Gibson, 2009; Sefa, 2021), indicate that this unit is dominated by plagioclase phenocrysts ranging from 3 to 8 mm in diameter. The modal percentage of minerals in this unit shows plagioclase (50 to 75%), Clinopyroxene (4 to 22%), and Olivine (10 to 25%).

Upper Rhyolitic Ignimbrite (Alaje Formation, 2700 to 2800 masl)

At the top of the basaltic flows, this silicic unit is exposed around Koremash, Hamus Gebeya, and Shola Gebeya areas, with an approximate thickness of 80 meters. Field observations show that this unit forms gentle topography atop the flood volcanic flows. In some areas, it exhibits columnar joint structures with lithic-poor to moderately crystal-rich textures. Petrographic studies show a glassy/hyaline texture with feldspar, quartz crystals, and lithic fragments. Given the dominance of quartz and feldspar crystals, the pyroclastic deposits are derived from felsic lava.

Shield Volcanics (Megezez Formation, above 2800 masl)

Shield-forming basalt lavas are found above the upper ignimbrite unit, known as the short fissural-type volcanic eruption (Megezez formation). Field observations reveal that this rock unit is characterized by the presence of aphyric and porphyritic basalt flows, volcanic agglomerates, and basaltic scoria. Only one sample was considered for petrographic analysis, which revealed that the bottom part of the Megezez flows is characterized by an aphanitic texture with minor plagioclase and oxide minerals. The groundmass of this sample shows a trachytic texture.

The lower basalt and upper basalt are separated by a layer of clastic sediments, indicating a time gap between the two flood basaltic units. These units differ in geomorphological manifestations: the lower basalt unit forms a relatively gentle topography, while the upper basalts form steep cliffs, often separated by paleosol horizons.

5.3 Composite Stratigraphic Section and Correlation

The volcanic stratigraphy of the Upper Kesem River section is summarized in Table 1 and shown in the composite stratigraphic sections (Figs. 12 and 13). These sections include detailed descriptions of each litho-stratigraphic unit in the study area, including shield basalt, upper rhyolitic ignimbrite,

upper flood basalt, lower rhyolitic ignimbrite, and lower flood basalt. The correlation of these units to previous works from other areas within the North-Western Ethiopian Plateau is also provided.

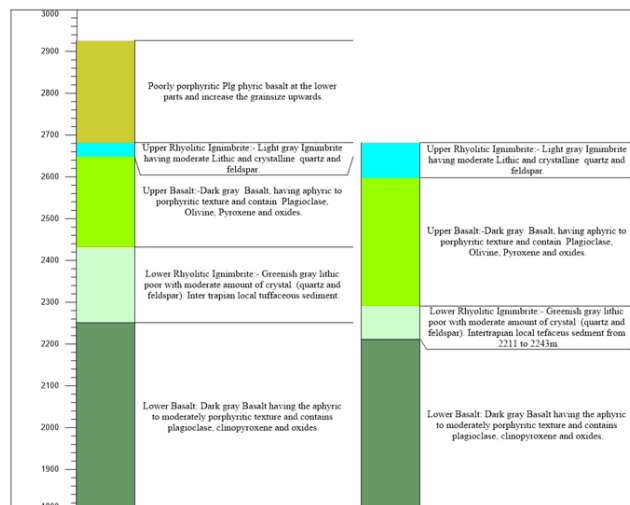
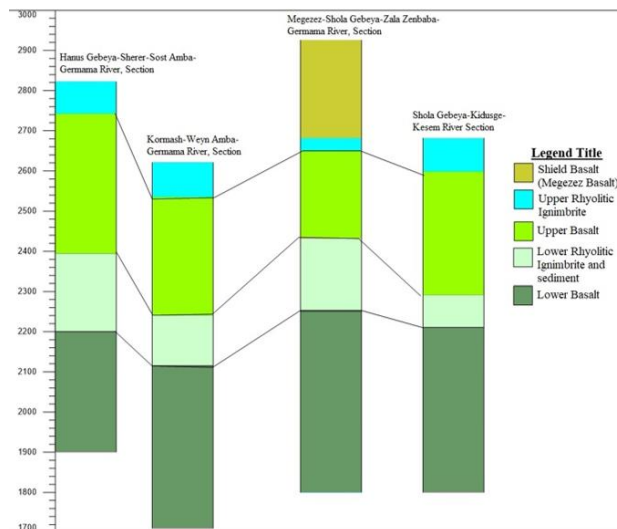


Figure 12. Volcanic stratigraphic log section of the Upper Kesem river section (a) the two sections are from Hamus Gebeya -Koremash Germama river section and (b) the two sections are from Shola Gebeya Kesem section.

Figure 13. Correlation of local volcanic stratigraphic sections of the study



are (a and b) from Koremash section and (c and) from Shola Gebeya section.

Table 1. Composite volcanic stratigraphy of the Upper Kesem River section with summary note.

	Litho-stratigraphic Unit with approximate thickness	Summary description of litho-stratigraphic units
3000 2900 2800 2700 2600 2500 2400 2300 2200 2100 2000 1900 1800 1700	Shield basalt (Megezez basalt) (>400m);	The unit consists of tens of basalt lava flows and interbedded scoraceous layers. The lower flows are largely poorly porphyritic to sparsely Plg phyric and degree of porphyricity increases upwards.
	Upper rhyolitic ignimbrite (~80m);	This felsic unit consists of several separate pyroclastic flow and fall deposits. The overall color varies from light to medium grey, is massive, and contains moderate amounts of lithics and crystals (quartz and feldspar).
	Upper flood basalt (~400m)	The unit consists of tens of thin (~37.5m) basalt flows. Basaltic lava flows are intercalated with minor felsic-pyroclastic layers. Most individual basalt flows typically show flow top, flow core and flow bottom features. They are aphyric to porphyritic in texture and contain phenocrysts of plagioclase, olivine, clinopyroxene and opaque oxides in various proportions.
	Lower rhyolitic ignimbrite (~150m)	This pyroclastic unit consists of several separate pyroclastic flow and fall layers. It varies in color from light grey to greenish gray, is massive, welded, lithic poor, contains moderate amounts of crystals (quartz and feldspar) and includes thin tuffaceous sediment layers.
	Lower flood basalt (~450m) Lower contact with Mesozoic sediments are not exposed	This consists of three of thick (~150m) basalt flows are highly fractured and weathered; aphyric to moderately porphyritic with plagioclase, clinopyroxene and opaque oxides in to holocrystalline groundmass.

6. Conclusions

The volcanic sequence exposed along the Upper Kesem River has an estimated total thickness of about 1080 m. The basal contact between the volcanic rocks and the underlying Mesozoic sedimentary formations is not exposed.

The volcanic succession has been subdivided into several stratigraphic and lithological units: Lower Basalt (Ashenghe Formation), Lower Rhyolitic Ignimbrite, Upper Basalt (Aiba Formation), Upper Rhyolitic Ignimbrite (Alaji Formation), and Shield Basalt (Tarmaber Formation). These units are separated by distinct contacts defined either by contrasting lithologies (differences in magma composition) or by paleosol horizons, which represent significant pauses in volcanic activity and magma supply. Petrographic analyses indicate that the volcanic pile consists exclusively of basalts and felsic volcanic rocks, with no intermediate compositions identified, suggesting a bimodal petrological distribution.

Earlier studies interpreted the Upper Kesem River section as a single flood basalt succession referred to as the Kesem basalt unit. However, the present study identifies a thick felsic unit—the Lower Rhyolitic Ignimbrite—that separates two distinct flood basalt sequences: the Lower Basalt and Upper Basalt units. The Lower Basalt unit comprises at least three lava flows separated by paleosol layers. In contrast, the Upper Basalt unit contains numerous lava flows, each ranging from 20 to 55 m in thickness, with intervening paleosol horizons 2–3 m thick.

Both felsic units (the Lower and Upper Ignimbrite units) consist of widespread sheets of pyroclastic deposits and volcanic lavas. The large volumes of these volcanic products suggest that flood basalt volcanism was associated with the formation of large, shallow magma chambers where basaltic magmas were stored and underwent extensive fractionation and evolution. The presence of both effusive and explosive eruptions indicates that large, long-lived silicic volcanic complexes, likely with substantial calderas, developed above the flood basalt sequences. However, the locations of these volcanic centers remain unidentified because younger

basaltic lava flows have buried the felsic units.

Changes in the volcanic plumbing system through time are reflected in the petrography and stratigraphy of the lava flows. The transition to shield volcanism indicates a gradual decrease in magmatic flux. Petrographic analysis shows that the Lower Basalt unit displays aphyric and phyrlic intergranular textures, with modal compositions of aphyric and plagioclase–clinopyroxene–phyric basalts. In contrast, the Upper Basalt unit exhibits aphyric microcrystalline and intergranular textures, as well as glomeroporphyritic features, with modal compositions dominated by plagioclase–phyric and plagioclase–clinopyroxene–olivine–phyric basalts. Variations in modal mineral assemblages among the basalt flows suggest the presence of a polybaric magma plumbing system, where multiple

Declaration of competing interest

The authors declare that they have no competing interests.

Acknowledgement

ML gratefully acknowledges Addis Ababa University (AAU) for providing a scholarship, and the School of Earth Sciences at AAU for granting unrestricted access to field and laboratory facilities. ML also extends sincere thanks to Mr. Assnake Bekele and the communities of Koremash and Shola Gebeya for their generosity and support. Appreciation is further extended to all individuals who have contributed directly or indirectly to this work.

References

- [1] G. Yirgu, Magma-crust interaction during emplacement of Cenozoic volcanism in Ethiopia: geochemical evidence from Sheno-Megezez area, central Ethiopia. *SINET: Ethiop. J. Sc.* 20 (1) (1997) 49–72.
- [2] T. Rooney, T. Furman, I. D. Bastow, D. Ayalew, G. Yirgu, Lithospheric modification during crustal extension in the Main Ethiopian Rift. *Journal of Geophysical Research*, 112 (2007) B10201. <https://doi.org/10.1029/2006JB004916>.
- [3] T.O. Rooney, The Cenozoic magmatism of East-Africa: Part I—Flood basalts and pulsed magmatism. *Lithos* 286 (Supplement C) (2017) 264–301.
- [4] I.A. Ukstins, P.R. Renne, E. Wolfenden, J. Baker, D. Ayalew, M. Menzies, Matching conjugate rifted margins: $^{40}\text{Ar}/^{39}\text{Ar}$ chronostratigraphy of pre- and syn-rift bimodal flood volcanism in Ethiopia and Yemen. *Earth and Planetary Science Letters* 198 (2002) 289–306.
- [5] D. Ayalew, P. Barbey, B. Marty, L. Reisberg, G. Yirgu, R. Pik, Source, genesis, and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts. *Geochimica et Cosmochimica Acta* 66(8) (2002) 1429–144.
- [6] B. Kieffer, N. Arndt, H. Lapierre, F. Bastien, D. Bosch, A. Pecher, G. Yirgu, D. Ayalew, D. Weis, D.A. Jerram, Flood and shield basalts from Ethiopia: magmas from the African superswell. *J Petrol* 45 (2004) 793–834.
- [7] C. Natali, L. Beccaluva, G. Bianchini, F. Siena, Rhyolites associated to Ethiopian CFB: Clues for initial rifting at Afar plume axis. *Earth and Planetary Science Letters* 312 (2011) 59–68.
- [8] C. Natali, L. Beccaluva, G. Bianchini, F. Siena, The Axum–Adwa basalt–trachyte complex: a late magmatic activity at the periphery of the

magma chambers at different crustal depths experienced independent recharge and fractional crystallization processes.

The Upper Kesem volcanic sequence suggests that the Ethiopian volcanic plateau was formed by multiple volcanic centers characterized by variable magma compositions and lava thicknesses. Differences in eruption ages inferred from the paleosol horizons further support this interpretation. The overall geometry and petrological features of the volcanic succession described here are broadly comparable to those observed in other sections of the north-western Ethiopian Plateau, such as Sela Dingay. Consequently, the Upper Kesem River volcanic sequence can be considered the southernmost extension of the north-western Ethiopian volcanic sub-province.

Afar plume. *Contrib Mineral Petrol* 166 (2013) 351–370.

- [9] K. Kabeto, Geological and geochemical variations in Mid-Tertiary Ethiopian Flood Basalt Province, Maychew, Tigray Region, Ethiopia. *MEJS* 2(1) (2010) 4–25.
- [10] R. Pik, C. Deniel, C. Coulon, G. Yirgu, C. Hofmann, D. Ayalew, The Northwest Ethiopian plateau flood basalts: classification and spatial distribution of magma types. *Journal of Volcanology and Geothermal Research* 81 (1998) 91–111.
- [11] L. Beccaluva, G. Bianchini, C. Natali, F. Siena, Continental flood basalts and mantle plumes: a case study of the northern Ethiopian plateau. *Journal of Petrology* 50 (2009) 1377–1403.
- [12] A. Peccerillo, M.R. Barberio, G. Yirgu, D. Ayalew, M. Barberi, T.W. Wu, 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) 2003–2032. Doi: 10.1093/petrology/egg068.
- [13] E.M. Peccerillo, E. Justin-Visentin, B. Zanettin, J.L. Joron, M. Treuil, Geodynamic evolution from plateau to rift: major and trace element geochemistry of the central eastern Ethiopian Plateau volcanics. *Neues Jb. Geol. Palaont. Abh.* 158 (1979) 139–179.
- [14] P. Mohr, Ethiopian flood basalt province. *Nature* 303, (1983) 177–584.
- [15] P. Mohr, B. Zanettin, The Ethiopian food basalt province. In: Macdougall, J.D. (Ed.), *Continental flood basalts*. Kluwer Academic Publishers (1988) 63–110.
- [16] B. Zanettin, E. Justin-Visentin, M. Nicoletti, E.M. Peccerillo, 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 (1980) 231–52.
- [17] C. Hofmann, V. Courtillot, G. Féraud, P. Rochette, G. Yirgu, E. Ketefo, R. Pik, Timing of the Ethiopian flood basalt event and implications for plume birth and global change: *Nature* 389 (1997) 838–841.
- [18] M. Tefera, T. Chernet, W. Haro, Explanation of the Geological Map of Ethiopia. Ethiopian Institute of Geological Surveys, Addis Ababa 3 (1996) 79.
- [19] D. Ayalew, G. Yirgu, Crustal contribution to the genesis of Ethiopian plateau rhyolitic ignimbrites: Basalt and rhyolite geochemical provinciality. *Journal of the Geological Society*, 160 (2003) 47–56. Doi: 10.1144/0016-764901-169.
- [20] D.F. Hailemariam, R. Shinjo, H. Kitagawa, D. Meshesha, E. Nakamura, Petrologic and geochemical characterization of rift-related magmatism at

the northernmost Main Ethiopian Rift: Implications for plume-lithosphere interaction and the evolution of rift mantle sources, *Lithos* 282–283 (2017) 240–261.

[21] B. Girum, Petrology and Geochemistry of mafic volcanics rocks in Kesem-Megezez section western rift escarpment, central Ethiopia, Master's thesis, Addis Ababa Science and Technology University unpublished report (2022).

[22] D. Ayalew, I.S. Gibson, 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 (2009) 461–476.

[23] F. Sefa, Petrostratigraphic Study of Volcanic Rocks in Sela Dingay Area, Northshewa, Central Ethiopia [Master thesis, Addis Ababa University] (2021). URL:<http://etd.aau.edu.et/handle/123456789/29028>

[24] K. Yimenu, Stratigraphy and Petrography of Flood Basalt Succession At Debre Libanos Area, Central Ethiopia, Addis Ababa Science University (2022) unpublished report.

[25] K. Hefferan, J. O'Brien, *Earth Materials*. Wiley-Blackwell, (2010) 624 Pages. ISBN: 978-1-444-33460-9.
www.wiley.com/go/hefferan/earthmaterials.