



Addis Ababa University

School of Earth Science

Assessing Volcanic Hazards from potential future Eruptions of Gebalaytu and Kurub Volcanos in the Tendaho Graben of Afar, North Eastern Ethiopia

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Abstract

The paper assess the potential volcanic hazards pose by a Holocene Gebalaytu and Kurub volcanoes which are situated in the central afar depression at top of Tendaho Graben and adjacent to the active recent Manda-Harraro rift and west of Semera town about 5km and SE of the Manda -Harraro volcanic complex in the South Danakil region respectively.

The petrographic and geochemical analysis of the volcanic rock is used to constraint the volcanic evolution and the origin of magma as a result the high Fe₂O₃ content of Gebalaytu rock tend to show tholeiitic affinity and sub alkaline group while Kurub volcano shows much more high Fe₂O₃ content however the Magma type is MORB at plate divergent and partial melting of the mantle since afar mantle plume is pushing the continental crust in afar. The associated rhyolitic rocks are formed by fractional crystallization of the basalt with little or no crustal contamination.

The volcanoes have proximity to Semera city, Semera University, dry port a geothermal power sites, the Tendaho sugar estate and the Tendaho dam and water reservoir. The main road from Addis Ababa to Djibouti passes through the town and small villages around the volcanoes. The Tendaho graben as a whole is shows a potential of geothermal with different fumarolic activity Gebalaytu and Kurub volcanoes may pose potential hazards to population and important infrastructure.

An assessment of the potential volcanic hazards from future eruption has been attempted based on the volcanoes past eruptive history. Tentative volcanic hazard maps and zones have been produced from four identified vents for Gebalaytu and one central vent for Kurub affecting an area over a moderate distance of 10km radius.

Acknowledgment

First and most, my heart full thanks to almightily GOD, who paved all the ways through which I have travelled to reach at this position.

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Acronyms

DEM Digital Elevation Model

EARS East African rift system

MER Main Ethiopian Rift

GFDRR Global Facility for Disaster Reduction and Recovery

GIS Geographic Information System

GPS Global Positioning System

m.a.m.s.l Meter above Mean Sea Level

WFB Wonji Fault Belt

TG Tendaho Graben

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1. 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, 1987). Yet within the geosciences community, relatively few specialize in Volcanology, the study of the transport and eruption of magma (Sigurdsson, 1987), with emphasis on active or potentially active volcanoes. Since the 17th century, volcanic disasters have killed more than 300,000 people and caused property damage and economic loss in excess of many hundreds of millions dollars (Tilling, 1989). The risk to humankind posed by volcano hazards those affecting people on the ground as well Correspondence as those from encounters between aircraft and drifting volcanic clouds from energetic explosive eruptions will inevitably increase.

Of more than 1300 volcanoes known to have erupted in Holocene time, about half are classified as active (i.e., those that have erupted in recorded history). On average, about 50 of these volcanoes erupt each year, an eruption frequency that appears to be obtained for all historical time. Individual volcanoes, however, may remain in repose for many centuries or even millennia and thus may be classified as dormant (i.e., could become active again) or extinct (i.e., not expected to erupt again).

On a global basis and relative to most other hazards, natural or man-made, volcanic and related hazards occur infrequently and affect few people. Average annual economic loss and human casualty from volcanic hazards are correspondingly low if considered globally, but volcanic disasters like earthquakes can have significant short-term human and economic impact.

Of the 600 active volcanoes known in the world, only a small fraction of them have been, or are being, studied in detail. Economically and scientifically developed countries lack sufficient resolve to study and monitor all of the active or potentially active volcanoes within their borders the situation is even more acute for the developing countries which contain most of the world's

explosive volcanoes many in densely populated regions. Nonetheless, identification of high-risk volcanoes is required to determine which ones should receive the most attention by scientists and public safety officials within the limitations of whatever resources may be available.

During recent years, considerable progress has been made in understanding how volcanoes work, such as magma supply and delivery systems eruption frequency and dynamics and eruptive processes and products (Self and Francis, 1987). This improved understanding has in turn strengthened the basic underpinning for more specialized hazards mitigation studies. Improvements in instrumentation at a collection and transmission and data analysis and interpretation have led to correspondingly more refined techniques of volcano monitoring and eruption forecasting.

Volcanic hazard assessment attention is paid to the geologic (especially stratigraphic), petrologic and geochemical information on the nature, distribution and volume of the eruptive products. From such data it is possible to reconstruct volcano's past events and eruptive behaviour, which in turn provides the basis for assessing potential hazards from future eruption (Tilling et.al, 1989).

Hazards zonation maps at appropriate scales should be an integral part of a hazards assessment, because they represent the pertinent information in a summary fashion readily understood by land use planners and decision makers as well as by scientist.

Seismically and volcanically active rift system has long been a classic area for investigation of rifting and break-up because its sectors encompass basins in all stages of rifting and passive margin development (Yirgu et al., 2006). The Afar depression marks the intersection between the red sea, Gulf Aden and East African systems along the terrestrial portion of the red sea system, which runs inland through Eritrea and Ethiopia, extension, seismicity and volcanism are localized at discrete magmatic rift segments (Hayward and Ebinger, 1996) Hence, Afar depression is considered one of the few places worldwide where the processes of sea- floor spreading are occurring on land.

The extension in Afar is organized along rift segments which result from interactions between dyke injection and volcanism, as observed during the well documented 2005 fissure event at Dabbahu volcano. Several volcano-tectonic events have occurred in Afar and the Main Ethiopian

rift during the last ten years. The most notable volcano-tectonic sequences are; the May-June, 2000, Gewane sequence; the 2003/2004 MelkaSedi/Werer sequence and the Dabbahu-Manda-Hararo sequence that commenced in September 2005, and resulted in fissure eruption at Karbahi in 2007, and 2009 and explosive eruption of Nabro volcano in 2011, Hydrothermal manifestations in Afar rift, and Central MER (particularly at Aluto and Chabbi Volcanoes) and surface deformation of volcanoes such as Aluto, Corbetti, Haledebi (Biggs, 2011) are indicators of magma beneath the Ethiopian and Afar rifts.

1.1 Literature review

There are plenty of research papers have been written concerning the East African rift system in the afar depression which is one of the few places worldwide where the processes of sea floor spreading is occurring on land, affording an opportunity to directly observe and quantify the plate separation. Different local and international geoscientist interested in searching and experiencing this on land plate separation however most of the paper are concentrated on tectonic part and volcanism and none of them are dealing with associated hazards and hazard zonation map as preliminary assessment.

For this work I have been looking different literatures that are related to the title which were done in the study area and some of them are international one.

Megersa G. and Getaneh E. (2006) Discussed the geology of Dubti-Semera area and mapped at a scale of 1:50,000 as cited by lemma et.al (2010).Concerning rift related volcanism of the afar depression David J Ferguson et.al (2010), Ellen Wolfendn et.al (2004), Derek k. et.al (2013) and G.Yirgu, C .J. Ebinger and P.K.H. Maguire (2006) discussed the continental rifting process and the Ethiopian plateau has experienced episode of volcanism and continue to present day. The other paper present on local and regional seismic data constrain the space time history of deformation and likely magma sources for the 2005 diking episode in the Manda-Harraro rift zone of the Afar depression AtalayAyele et.al (2009).

The future activity of Chabbi active volcano of Corbetti caldera discussed by FekaduAdugna (2014) as result he produce tentative hazard zonation map for lava flows and fall and lava flows. Amha A (2010). Paleomagnetism and tectonics of Manda-Harraro rift northern afar he studies about the magnetic and tectonic activity of Manda-Harraro rift system.

MirutsHagos (2010), discuss the Geochemical and Petrographic Studies of the Volcano-Tectonic Evolution of Northern Afar: Implications for the Structural Setup of the Actively Expanding Erta'Ale Depression

L. Field, J. Blundy, A. Calvert and G. Yirgu, discusses Magmatic history of Dabbahu, a composite volcano in the Afar Rift. A new geological map, are used to provide insights into the evolution of the volcano.

Structure of Tendaho Graben and Manda-Harraro Rift: Implications for the evolution of the southern Red Sea propagator in Central Afar which is done by V. Acocella, B. Abebe, T. Korme, and F. Barberi (2008). Mainly they discussed the structure and geology of Tendaho Graben, the red sea propagator in central Afar.

F. Amelung, C. Oppenheimer, P. Segall and H. Zebker (2000) present a paper, the Ground deformation near Gada Ale volcano, Afar, observed by Radar Interferometry. According to the paper 12cm subsidence shown near Gada Ale volcano in north afar, in Radar interferometric measurement of ground surface using ERS, as result data show a change in radar range.

Early continental breakup boundary and migration of the Afar triple junction, Ethiopia presented by S. Tesfaye, J. Harding and T. Kusky(2011). Their finding, On the basis of the location of the paleo-triple junction, deduced from the position of accommodation zones and geomorphic considerations, it is estimated that the Afar triple junction has migrated 1.5 (160 km) in a north-northeast direction with respect to the African (Nubian) plate.

The structure of Afar and the northern part of the Ethiopian Rift is discussed by L. Gibson, H. Tazieff and V. Hepworth (2011). The paper presents the different tectonic elements and structure of afar and northern part of Ethiopian rift.

TadiwosChernet (2005) studies Geological and Hydrothermal Alteration Mapping of the Doffen Geothermal Prospect and Adjacent Western Escarpment. Active hydrothermal manifestations in the study area occur on the northern and southern parts of the DVC, According to him the manifestations on the northern part of the center are hot springs, hot ground and fumarolic activity.

Tectonics of the Afar Depression: a review and synthesis by A. Beyene and M.G. Abedesalam (2005). The article Outline geomorphological and Tectonic elements of Afar Depression and discusses its evolution.

Fault growth at a nascent slow-spreading ridge: 2005 Dabbahu rifting episode, Afar. The paper present a preliminary account of the near-field surface strain associated with a major magmatic rifting episode at a nascent slow spreading ridge in the Afar depression. By J. V. Rowland, E. Baker, C. J. Ebinger, D. Keir, T. Kidane, J. Biggs, N. Hayward and J. Wright (2010).

The northwestern Ethiopian Plateau flood basalts: Classification and spatial distribution of magma types discussed by Raphael P., Catherine Deniel, Christian Coulon a, G. Yirgu c, Corine Hofmann d, DerejeAyalew (1998) as a result Major and some trace element data have been used to identify distinct .Three magma types have been distinguished: two high-Ti groups HT1.

Dereje A., Pierre B. Bernand M. Lauriesberg, Gezahegn Y. and Raphael P (2002).The paper present Source, genesis, and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts.

DerejeAyalew, Sally A. Gibson (2009).present Head-to-tail transition of the Afar mantle plume: Geochemical evidence from a Miocene bimodal basalt–rhyolite succession in the Ethiopian Large Igneous Province

A geological and geophysical study of the Tendaho Graben in the Afar Depression, Ethiopia: insights into transitional continental rifting by David Lee Bridges (2011). A detailed magnetic and gravity study across the Tendaho Graben and proposed a new model for evolution of Tendaho Graben.

Surface geological mapping at Tendaho Geothermal field ,Ethiopia the study present Tendaho is an active site of the present day extension, such fracturing and faulting counteract the sealing effect of hydrothermal activity and The existence of crisscrossing fault structures of MER (NE) and Red Sea (NNW) indicate potential increase in permeability to allow the circulation of fluid in the Graben.

Exploring for Geothermal Sites in Northern and Central Afar presented by J. Varet, Tadiwos C., Girm and K. Arnason(2012). They explore and select new sites of interest for electric power production certainly exist in north and central afar with supporting factor.

Integrated Geophysical Surveys to Characterize Tendaho Geothermal Field in North Eastern, Ethiopia.by Yohannes L., Aklilu H., MohammednurD.,and U. Kalberkamp (2010). This paper presents the boundaries of the geothermal reservoir and geological structures that control flow of geothermal fluids using Magneto telluric (MT) and Transient Electromagnetic (TEM) survey. As a result, the complete Bouguer anomaly map has revealed two distinct broad high (in NW sector) and low (in SE sector) Bouguer anomalies. These contrasting Bouguer anomalies may indicate the presence of ENE-WSW trending regional crustal discontinuity.

Magnetotelluric Exploration at Tendaho High Temperature Geothermal Field in North East Ethiopia Yohannes L., U. Kalberkamp², Fisum A., Kassahun D.1, and Yiheyis K. (2012) study 2D inversion of magnetotelluric (MT) survey data along seven profiles. The 2D inversion of MT data from Tendaho high temperature field revealed three main resistivity structures down to a depth of 10 km: low resistivity surface layer underlain by a resistive layer followed by good conducting structure.

Exploration and Development of the Tendaho Geothermal Field by, MergaTassew(2010). He found that a high temperature underground fluid exists with an evidence of long time residence occupied by high temperature rocks. Of the six deep exploratory wells, four wells are believed productive to supply geothermal fluid for power generation.

Exploration Results in the Tendaho Geothermal Field, Ethiopia by YiheyisAmdeberhan (2005).He compile the geoscientific and engineering studies conducted during the last 35 years. Tests conducted at the shallow productive wells are described. Problems encountered during a production test and measures taken to solve the problems are discussed.

Atlas of igneous rocks and their textures the petrographic property of rocks discussed by W.S.Mackenzie, C. H. Donaldson and C.Guilford.

A preliminary assessment of the potential volcanic eruption impacts in the GFDRR priority countries, assessment of exposure of population and important infrastructure to various volcano

hazards, and an assessment of the national capacities to cope with the volcano risk a valuable work carried out by Aspinall et.al (2011) on a report called volcano hazards and exposure in GFDRR primary countries and risk mitigation.

Cynthia A. Gardner, Kevin M. Scott, C. Dan Miller, Bobbie Myers, Wes Hildreth, and Patrick T. Pringle (1995). Potential Volcanic Hazards from Future Activity of Mount Baker open file report. Preliminary volcano hazard assessment for Redoubt volcano, Alaska BY Christopher F., Joseph M. Thomas P. Christina A., and Robert G. (1998). The other is a Preliminary Assessment of Volcanic and Hydrothermal Hazards in Yellowstone National Park and Vicinity BY Robert L. Christiansen, Jacob B. Lowenstern, Robert B. Smith, Henry Heasler, Lisa A. Morgan, Manuel Nathenson, Larry G. Mastin, L. J. Patrick Muffler, and Joel E. Robinson (2007). Volcano hazards in Mount Hood region, Oregon by W.E. Scott, T.C. Pierson, S.P. Schilling, J.E. Costa, C.A. Gardner, J.W. Vallance, and J.J. Major (1997) and Preliminary Volcano-Hazard Assessment for Mount Spurr Volcano, Alaska by By Christopher F. Waythomas and Christopher J. Nye (2002). All five papers discussed the future activities of the respective volcano hazards on the population, economy and related hazards as a result a tentative hazard zone is mapped.

Volcanic hazards and their mitigation –progress and problems, Robert I. Tilling (1988) discuss the historical aspect and Development in volcanology study and the problem that face in progress.

Robert I. Tilling (2009) discuss Volcanism and associated hazards with the insight of Andean volcanic complex.

The critical role of volcano monitoring in risk reduction by R. I. Tilling (2008) the paper present trole of monitoring in reduction of volcanic risk. In any effective hazards-mitigation program, a basic strategy in reducing volcano risk is the initiation or augmentation of volcano monitoring at historically active volcanoes and also at geologically young, but presently dormant, volcanoes with potential for reactivation.

Quantifying probabilities of volcanic events: The example of volcanic hazard at Mount Vesuvius, by Warner Marzocchi, Laura Sandri, Paolo Gasparini, Christopher Newhall, and Enzo Boschi (2004). They describe an event tree scheme to quantitatively estimate both long- and short-term volcanic hazard.

Automatic GIS-based system for volcanic hazards, by AelicieFelpeto, Joan Martin and Romom Ortiz (2007) this paper present automatic system for the elaboration of volcanic hazard maps and scenarios.

Risk Assessment and mapping for Canlaon Volcano, Philippines by Rowena B. Quiambao The paper present, Risk assessment and mapping for Canlaon Volcano and risk is present as a result of the relationship between the hazards and the human and non-human elements.

Applications of GIS to the Estimation of Lava Flow Hazards on Mauna Loa Volcano, Hawai'i by Jim Kauahikaua, Sandy Margriter, Jack Lockwood, and Frank Trusdell (1995). This paper explores methods by which hazards from lava flows on Mauna Loa volcano can be quantitatively assessed with the aid of Geographic Information System (GIS) software.

1.2 Statement of the problem

The Afar rift is a region where extensional tectonic processes and intense volcanic activity are taking place. Ongoing lithospheric thinning has been generating a regional heat flow anomaly that extends along all parts of the rift with present day volcanic activity and surface hydrothermal activity over large areas. The Erta'ale lava lake, the eruption of Daure volcanic dome (part of Dabbahu volcano) in 2005, Karbahi in 2007, and 2009, the explosive eruption of Nabro volcano in 2011, hydrothermal manifestations in Afar rift, and Central MER (particularly at Aluto and Chabbi volcanoes) and surface deformation of volcanoes such as Aluto, Corbetti, Haledebi (Biggs, 2011) are all indicators of the existence magma beneath the Ethiopian and Afar rifts.

According to Aspinall et.al (2011) a number of active volcanoes of Ethiopia are at close proximity to major cities with 9.5 million people living within 30km of an active volcano. Most of the volcanoes have little or no documented volcanic history or geology and none of the volcanoes is monitored resulting in high uncertainty indices.

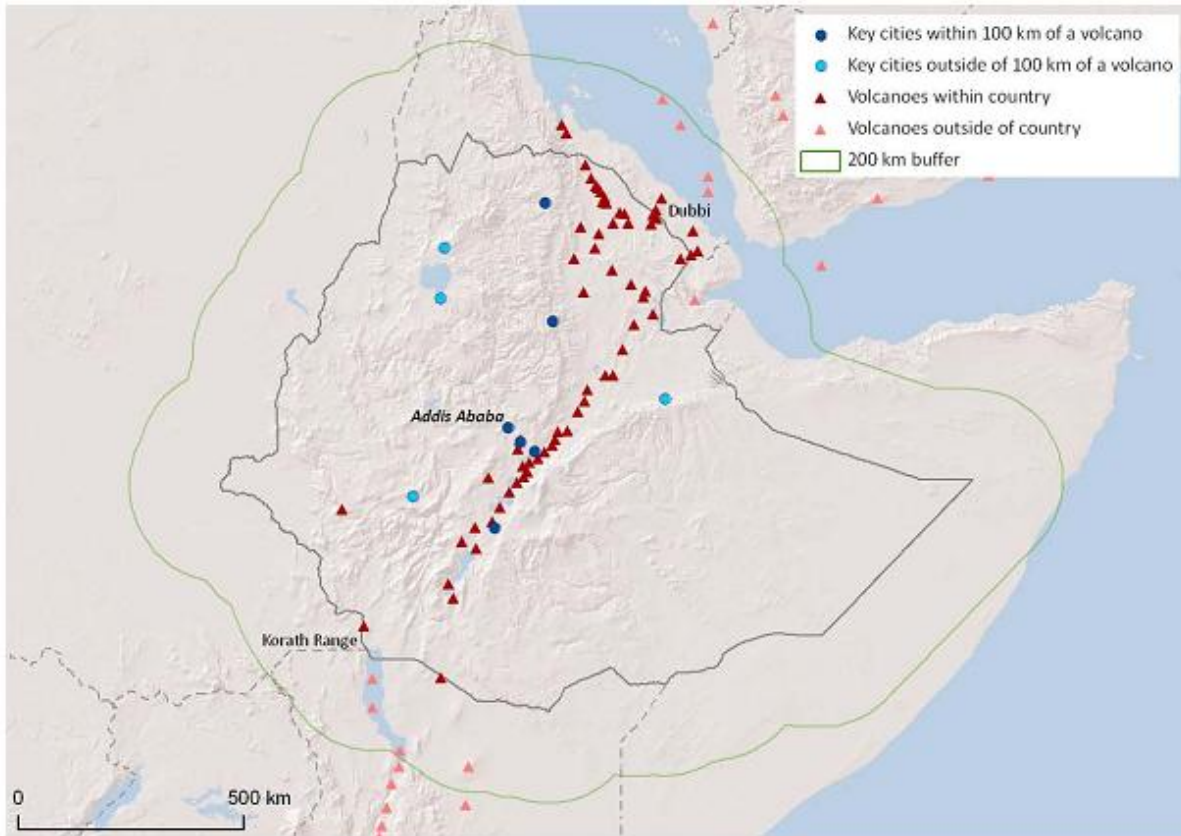


Fig 1.1 Distribution of volcanos in Ethiopia and surrounding counties (Aspinall et.al, 2011)

Afar region is considered to be remote and even inaccessible to experience the inland process of rifting, but now things are different the region is developing more and more specially Semera town having different infrastructures including Semera university and a new dry port a geothermal power site, the Tendaho sugar estate and the Tendaho dam and water reservoir. The main road from Addis Ababa to Djibouti passes through the town.

The rift axis volcanic products Gebalaytu includes late Pleistocene (0.5Ma) pahoaho basalt, Scoria and Rhyolites and Kurub volcanic products include basalt (Megersa and Getaneh, 2006) thus the past eruption shows as that the products are acidic and basaltic which makes the volcanos are explosives and effusive.

Gebalaytu volcano is located approximately 5km north-east of the town of Semera and Kurub volcano is close to villages and settlement areas also found in the area. Future eruptions from Gebalaytu and Kurub active volcanic centres pose potential hazards and threat the population and infrastructure in the nearby towns, villages and settlements areas. Therefore to address this

potential threat from future eruptions of Gebalaytu and Kurub volcanos, it is found to conduct a research on the volcanos.

1.3 Location and Environment of the study area

The study area is located in the central Afar depression, North Eastern part of Ethiopia enclosed between the geographic coordinate of 11°30'-12° (N) latitude and 41°00'-41°30' (E) longitude. That can be accessed via the main asphalt road from Addis Ababa to Djibouti and via foot trail through Gebalaytu and Kurub village. The elevation in the study area varies from 600m above sea level to 320m above sea level. The lowlands of Afar depression are dominated by heat. There is no rain for most of the year and yearly rainfall average ranges from 100 to 200mm. The Awash River flowing North-Eastward via southern Afar provides a narrow green belt and enables life for the flora and fauna and for the inhabitants as well.

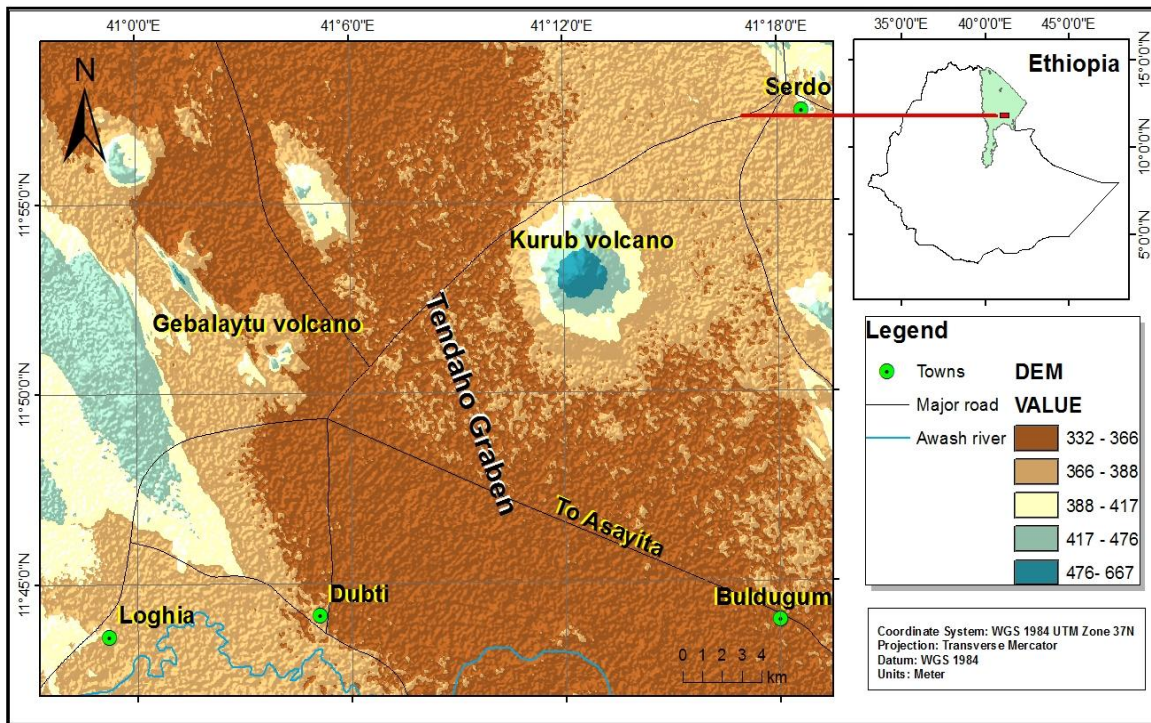


Fig 1.2 Location of Gebalaytu and Kurub volcanos within Tendaho Graben

1.4 Physiography

The triangular shaped Afar depression covers an area of about 200,000km³ and is bounded by marginal escarpments, which close at narrow axial rift zones and ranges. It is flanked by the Ethiopian plateau in the west and the Somalian plateau to the south east. The Ali-sabieh and Danakil blocks bound the eastern and north eastern sides of the Afar depression, respectively. Further south, the north eastern segment of the Main Ethiopian rift separates the Ethiopian and Somalian plateau. The Afar depression is divided into north, central and south sectors on the basis of its geology and geography (Tesfaye et al., 2003).

The northern part of the depression is dominated by axial volcanic ranges (e.g. Erta'ale). The <1m.a. old shield volcanoes of the axial ranges are typically produced by basaltic fissures eruptions aligned in NW to SE belt, parallel to the regional tectonic trend of the Red Sea (Barberi and Varet, 1977; Varet and Gasse, 1978).

The central sector dominated by graben and horst structures and bounded to the west and east by axial volcanic ranges, is occupied by Pliocene flood basalts and quaternary sedimentary rocks. The Tendaho graben is one of the biggest in this part of the Afar depression.

Southern Afar, like central Afar, is dominated by horst and graben structures. Unlike central Afar, however, the graben strike north-north east, and the topography has a mean elevation of 700m. The Tendaho-Gobbad discontinuity separates central Afar from southern Afar (Ebinger and Hayward, 1996).

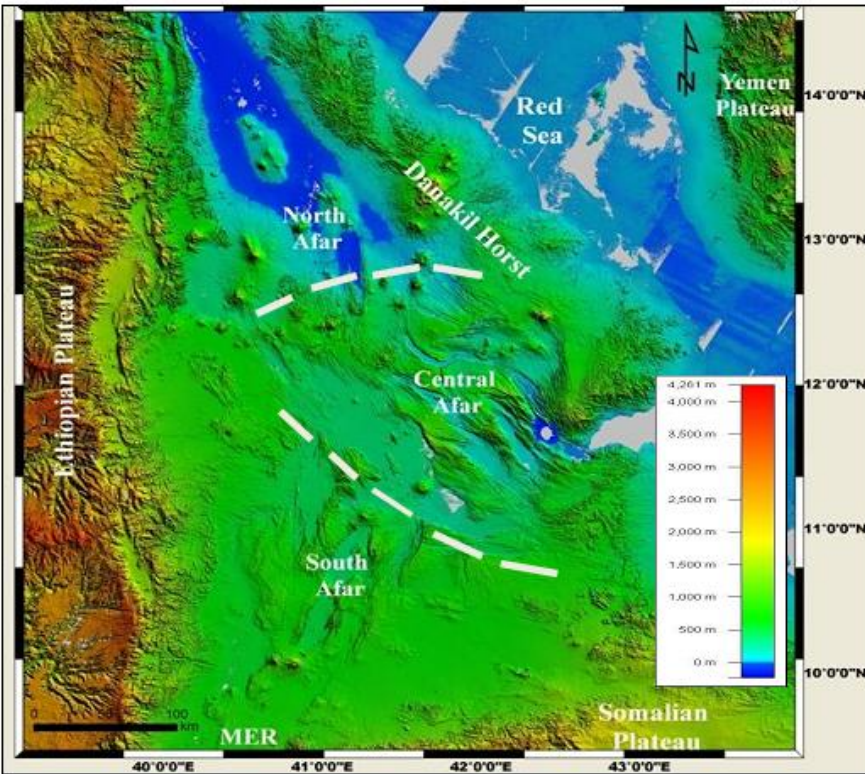


Fig 1.3a 90m resolution digital elevation model showing the physiographic setting and rough classification of the afar depression (after Tesfaye S. et al., 2003)

1.5 Objective of the study

The primary objective of the research is to study the volcanic products of earlier eruptions as well as the current state of Gebalaytu and Kurub volcanos to reconstruct their past history and use that knowledge to assess the potential hazards and threat that could results from future eruptions. As products, a series of volcanic hazard zonation maps will be prepared.

1.5.1 Specific objectives

- Identify and describe the rock types eruptive products and their distribution
- Identify and describe active magmatic vents, manifestation and tectonic structures
- Produce a detail geological map of Gebalaytu and Kurub volcano and surrounding at a scale of 1:25,000
- Attempt to reconstruct the magma genesis and history of Gebalaytu and Kurub volcano

- Assess exposure of the population and infrastructure to volcanic hazards and make a volcanic threat analysis

1.6 Overview of the study

In the thesis that follows, Chapter 2 Methods Chapter 3 mainly focus on volcanoes of Ethiopia and volcanism in Afar depression Chapter 4 the regional geology of the area will be discussed, in detail. Chapter 5 Discuss the local or volcanic geology and geomorphology of the study area. Chapter 6 will present the laboratory result and data analysis, the result and discussion of findings. Finally, Chapter 7 will be conclusion and recommendation.

2. Methods

For the study of this MSc work, quite different techniques were applied, before, during and after the fieldwork. GIS techniques were used to prepare geological and hazard zonation map. For the study of petrography, optical microscopy was used. For the study of whole rock chemistry, X-ray fluorescence (XRF) and ICP-MS and ICP-AES Methods were applied.

2.1 Pre-field work

The pre-field work mainly includes literature reviews, collection of existing data, analysis and study of the Digital Elevation Model (DEM) and satellite imageries. GIS and Remote sensing software packages were used throughout the study. Three Landsat ETM+ scenes were analyzed and processed in order to show the lithological and structural features of the study area; particularly, Tendaho graben.

2.2 Field work

Because of the harsh nature of the Afar depression extended fieldwork is very difficult in the study area despite of the awful condition, I try to explore or understand the past eruptive history of the two volcanoes (i.e. Gebalaytu and Kurub). The Field investigation is held in January 15 to February 1 and most useful activities were done during this time. The extent and distribution and past products were observed. The detail observations of outcrops and collection representative sample were done. The volcanic morphology and lithological units of area is characterized. The product types and contacts were observed. Physical Volcanology characteristics of the eruptive

products including, rock and pyroclastic textures, grain size and degree of welding were determined. Thicknesses of lithological units were measured and flowmorphologies(basaltic flow) were characterized.

2.3 Laboratory analysis

2.3.1 Sampling

Total of 20 samples, each weighing slightly less than a kg, were collected from two volcano-tectonically (Gebalaytu and Kurub) distinct areas in the central Afar. Of these 8 representative samples were selected from the 20 samples and set for the petrographic analyses and 5 representative rock samples were selected and put for geochemical (XRF and ICP-MS) analyses.

Petrographic thin-sections were also prepared for seven samples from each of the basaltic and Rhyolitic rocks mineralogical analyses were made under an optical (petrographic) microscope. For some of the minerals, the semi quantitative modes were determined by visually estimating the mineral proportions in thin sections.

2.3.2 Analytical methods

2.3.2.1 X-ray fluorescence Spectroscopy (XRF)

X-ray fluorescence (XRF) spectrometry is a non-destructive and widely available analytical technique used to determine the concentrations of elements present in all states. The concentrations of major oxides (SiO₂, TiO₂, Al₂O₃, Fe₂O₃, MnO, MgO, CaO, Na₂O, K₂O, and P₂O₅) and minor elements heavier than F (Sc, V, Cr, Cu, Ni, Zn), as well as some trace and rare earth elements can be determined using this accurate technique. Therefore, XRF is not a very accurate technique for light elements having less than atomic number 10.

Major elements were determined by XRF, in Irish company called ALS mineral Global, Ireland. A prepared sample (0.66 g) is fused with a 12:22 lithium tetraborate – lithium metaborate flux which also includes an oxidizing agent (Lithium Nitrate), and then poured into a platinum mold. The resultant disk is in turn analyzed by XRF spectrometry. The XRF analysis is determined in conjunction with a loss-on-ignition at 1000°C. The resulting data from both determinations are combined to produce a “total”.

2.3.2.2 Inductively Coupled Plasma - Mass Spectroscopy (ICP - MS)

Inductively Coupled Plasma - Mass Spectroscopy (ICP - MS) A prepared sample (0.200 g) is added to lithium metaborate flux (0.90 g), mixed well and fused in a furnace at 1000°C. The resulting melt is then cooled and dissolved in 100 mL of 4% HNO₃ / 2% HCl₃ solution. This solution is then analyzed by inductively coupled plasma - mass spectrometry. By this method some base metal oxides and sulfides may not be completely decomposed by the lithium borate fusion. Results for Ag, Co, Cu, Mo, Ni, Pb, and Zn will not likely be quantitative.

2.3.2.3 Inductively Coupled Plasma – Atomic emission spectroscopy (ICP - AES)

Inductively Coupled Plasma – Atomic emission spectroscopy (ICP AES) The lithium metaborate fusion is not the preferred method for the determination of base metals. Many sulfides and some metal oxides are only partially decomposed by the borate fusion and some elements such as cadmium and zinc can be volatilized. Base metals can be reported with ME-MS81 for either an aquaregia digestion (ME- AQ81) or a four acid digestion (ME- 4ACD81). The four acid digestions is preferred when the targets include more resistive mineralization such as that associated with nickel and cobalt

2.4 Remote sensing and GIS

Remote sensing, particularly satellites offer an immense source of data for studying spatial and temporal variability of the environmental parameters (K. Perumal and R. Bhaskaran, 2010).

Geographic information system (GIS) has tools that enable us to map geology of the eruption area and to delineate the vulnerable area for future eruption hazards. Arc GIS version 10 was utilized for the GIS data integration, geologic mapping and delineations of possible hazard zones. Mapping activity is based on ground truth and review of previous works. Using DEM of the study area the elevation profile is delineated. Elevation versus distance profile paves the way to estimate coverage by lava flows. Tentatively possible volcanic hazard for lava flow was estimated and zoned by incorporating the elevation, morphology and magma physical properties.

3. Volcanism and volcanoes of Ethiopia

3.1 Introduction

Volcanic and seismic activity are the most evident expressions of the deformation processes acting at lithospheric plate boundaries; they give rise to the most important geological risks related to the active processes shaping the surface of our planet. Being an area of active deformation, the rift valley is characterized by numerous volcanic edifices, most of which are still active or showing evidences of very recent activity, and by widespread seismicity.

Divergent plate boundaries provide the most suitable site to study how extension occurs in the Earth's crust, including the development of a rift zone and its relationships with volcanic activity. On continents, the most suitable place to investigate divergent plate boundaries is the East African Rift System. In a very similar fashion to oceanic boundaries, this continental rift consists of spaced spreading segments associated with volcanism and tectonic (Ebinger and Casey, 2001). The composition of volcanism varies, from basaltic to rhyolitic, as a function of the crustal thickness (Trua et al., 1999). Nevertheless, the overall deformation pattern, characterized by large extension fractures and open normal faults with tilted hanging-walls, is remarkably similar to that observed along oceanic boundaries (Acocella et al., 2003). Minor differences do exist in the size, aspect ratio and spacing of the faults, as a function of the crustal thickness (Ebinger and Hayward, 1996).

The Ethio-Afar mantle plume is one of the youngest plume structures on earth that continually pours significant amounts of magmatic products to the surface of the earth for the last 30 Ma or more and reshaping the sublithospheric crust of east Africa. As a result of the complex geodynamic nature of the region, the petrologic diversity is very significant, the lavas ranging from basanites to tholeiitic basalts and phonolites to trachytes.

The Afar Depression is an area of active extensional deformation and basaltic volcanism from which the Red Sea, the Gulf of Aden and the MER radiate (Abbate et al., 1995). The Afar Depression, core of the Oligocene-Recent Afro-Arabian continental breakup, is one of the few active tectonic zones in the globe where one can easily study the activities of mantle plume, rift-rift-rift triple junction and Micro plate formation on land (Eagles et al., 2002). Moreover, it is probably the only active intracontinental rift in the globe where both the incipient continental

breakup history and the current seafloor spreading can be observed on the surface (Tesfaye et al., 2003).

3.2 Volcanism in East Africa rift system

The Earliest magmatic activities in the EARS occurred in southwestern Ethiopia at ~45 Ma (Ebinger and Sleep, 1998), followed by widespread flood basalt activities in northwestern Ethiopia, Eritrea, and Yemen at ~30 Ma (Baker et al., 1996). Following the voluminous eruptions of flood basalts and associated felsic rocks, large shield volcanoes developed on the uplifted plateau hundreds of kilometers outside the faulted rift valleys (Kieffer et al. 2004). Recent volcanism is mainly confined to magmatic segments within the Ethiopian rift, and incipient spreading zones in Afar (Boccaletti et al. 1998). Thus, the afar volcanic province has experienced a long, complex history of basaltic and explosive felsic volcanism since 45 Ma, with the volumetrically largest eruptions tied to the onset of rifting of Africa and Arabia at c. 30 Ma (Yirgu et al. 2006). Gass (1975) proposed that the African Plate was motionless for long period in Eocene–Miocene and high heat flux released by the hot mantle plume targeted on the same lithosphere that raised its base (the start of the Ethiopian Dome). The high heat flow beneath the same lithosphere has provoked the production of isolated chambers of magma within the extended anomalous mantle and the major magmatism of the ~30 Ma flood basalt series (Beyene and Abdelsalam, 2005). The spatial and temporal gap between the earliest phase of magmatism and plume-driven volcanic activity represents basic geodynamic controversy surrounding the development of the EARS (Furman et al., 2004).

The contribution of hotspots in the development of the present physiography and dynamics of East African landmass has led to contending models as to the number of distinct plumes that may lie beneath (Rogers, 2006). Ebinger and Sleep (1998) suggested that volcanism across the entire East Africa (i.e., Ethiopia and Kenya) can be elucidated as a result of the outpouring of a single hot mantle plume beneath southwestern Ethiopia ~45 Ma. After the first impact at southwestern Ethiopia, the mantle plume propagated beneath the lithosphere, controlled by the inverse topography at its base, produced during pre-rift extensional structures (Rogers, 2006). In the single plume model, the plume head intrudes the base of the lithosphere beneath southwestern

Ethiopia and then spreads southwards to the current Lake Victoria following the topography of the lithosphere/ asthenosphere boundary (Corti, 2009).

On the other hand, George et al. (1998) and George and Rogers (2002) suggested that two spatially and temporally distinct mantle plumes are required to explain the East African magmatism: one beneath the Ethio-Afar and the other beneath Kenya. In the two-plume model, the southward propagation of basaltic magmatism from southwestern Ethiopia through Kenya into Tanzania reflects the northward motion of the African plate with respect to the stable Kenya plume for the last ~50 My, whereas volcanism in central and northern Ethiopia reflects 30 My of sustained activity of the Afar plume (Furman et al., 2004). The oldest volcanism in southwestern Ethiopia reflects the thermal and mechanical influence of the Kenyan asthenosphere, rather than the Ethio-Afar mantle plume (George et al., 1998). The two-plume model requires that Eocene–Oligocene magmatism in southwestern Ethiopia, a region now within the influence of the Afar hotspot, was originally under the influence of the Kenyan plume (George et al., 1998).

The earliest phase of volcanic activities in southwestern Ethiopia lasted for longer period but with low rates of eruption. Ebinger et al. (1993) have estimated the volume of the Amaro basalts from southern Ethiopia, which erupted in a duration of 10 My, to be at least 30,000 km³, implying an average eruption rate of 0.003 km³/yr. The eruption rates of the Kenyan basalts are also very low, ~0.006 km³/yr (Baker, 1987). These led to a conclusion that eruption rates in Southern Ethiopia in the Eocene period were more comparable with the eruption rate calculated for the Kenyan rift integrated over the past 30 Ma, implying a similar geodynamic condition beneath the lithospheric mantle (George et al., 1998).

The southern Ethiopian (Amaro) basalts, which are spatially and temporally comparable with the Kenyan basalts, are also geochemically analogous. The Amaro basalts were originally recognized as an early phase of Afar-related magmatism (Stewart and Rogers, 1996). Their early eruption has provided a key component for estimating the timing of initial volcanism in East Africa using the single plume model (Ebinger and Sleep, 1998). However, the more detailed geochemical studies of basalts from the southern Ethiopia (George and Rogers, 2002) have shown that they have distinct characteristic signature that enable to differentiate easily from both the Oligocene high-Ti magmas from the northwestern Ethiopian flood basalts and Quaternary Afar basalts but more similar to basalts from Kenya (Rogers, 2006). According to Rogers (2006),

the major and the trace element contents as well as the Sr and Nd isotopes of the Amaro basalts imply marked petrological differences compared with the high-Ti magmas from the northern Ethiopian CFB.

3.3 Volcanoes of Ethiopia

About 50 volcanic edifices in Ethiopia have documented activity during the Holocene. The majority of recent volcanoes are located within the Afar depression; among the active volcanoes, Erta Ale is one of the few volcanoes on the world that have an almost persistent lava lake. It is an isolated basaltic shield volcano, 50 km wide, rising more than 600 m from below sea level in the Barren Danakil depression. The volcano contains elliptical summit crater with several steep-sided pit craters, one of them containing a lava lake. Another larger wide depression, elongated parallel to the trend of the Erta'ale range is located to the SE of the summit and is bounded by curvilinear fault scarps on the SE side. Fresh-looking basaltic lava flows from these fissures have poured into the caldera and locally overflowed its rim. The summit caldera is renowned for one, or sometimes two long-term lava lakes that have been active since at least 1967, or possibly since 1906. Recent fissure eruptions have occurred on the northern flank of Erta'ale. On the same volcanic alignment, the DallaFilla volcano gave rise -during 2008- to the biggest eruption ever recorded in Ethiopian territory in historical times.

Dabbahu volcano whose activity started during September 2005 with a dyke emplacement, a strong seismic swarm and a small eruption, followed by other 14 dyke intrusions and 4 small eruptions, the last of which occurred during May 2010. In June 2011, a major eruption occurred at Nabro volcano, at Eritrea-Ethiopia border; many other volcanoes to the South of the Afar depression, many volcanic edifices have documented historical activity: an example is the Fantale volcano,

Fantale is a large Stratovolcano in the Ethiopian Rift Valley west of Lake Awash; it contains a large spectacular summit caldera. Fantale's historic eruptions produced lava flows that descended to the east side into the valley and Lake Awash. An eruption during the 13th century destroyed a town and church located south of the volcano. In 1820, a 4 km long fissure eruption occurred on the east flank and sent basaltic lava flows both into the caldera and outside, reaching the bottom of the Rift valley. More to the South, obsidian flows from the flanks of the Aluto volcano have been at around 2000 years, this volcano (like many others in the region) is characterized by strong fumarolic activity.

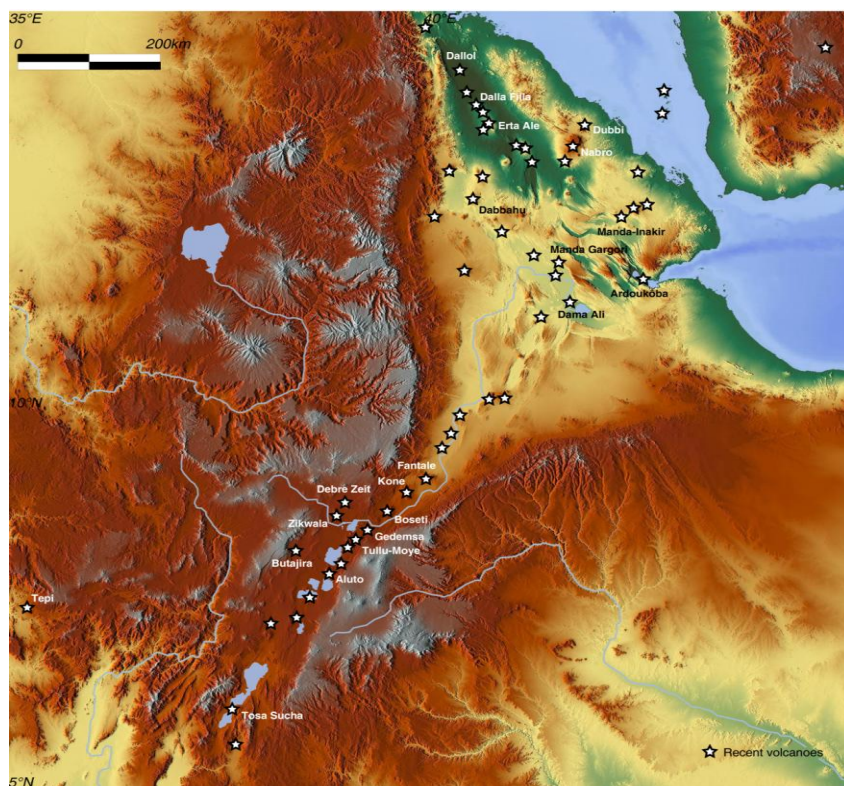


Fig 3.1 Recent volcanoes of Ethiopia

Manda Harraro volcanic complex

Manda- Harraro complex is located on the southernmost axial range of the western Afar triangle, inside the Kalo plain, SSE of Dabbahu volcano. The first historic eruption witnessed at this volcano took place in August 2007, when a series of cracks opened in the ground, some of which erupted basaltic lava flows. The activity was accompanied by an intense seismic activity and many signs of ground deformation typical of rift spreading zones. The massive complex is 105 km long and 20-30 km wide, and represents an uplifted segment of a mid-ocean ridge spreading center. A small basaltic shield volcano is located at the northern end of the complex, south of which is an area of abundant fissure-fed lava flows. Two basaltic shield volcanoes, the largest of which is UndaHararo, occupy the center of the complex. The dominant part of the complex lies to the south, where the Gumatmali-Gebalaytu fissure system is located. Voluminous fluid lava flows issued from these NNW-trending fissures, and solidified lava lakes occupy two large craters. The small Gebalaytu shield volcano forms the SE-most end of the Manda-Harraro complex. Lava flows from Gebalaytu and from Manda overlie 8000-year-old sediments. Hot springs and fumaroles occur around Daorre Lake.

Kurub the small Holocene shield volcano, also known as Kurub Koma, Kurub Koba, or Curub, lies in the Saha Plain, SE of the Manda-Harraro complex in the South Danakil region. The easternmost lava flow of Kurub volcano was potassium-argon dated at about 0.3 million years. Wind-blown sand fills the summit crater of the very recent basaltic volcano. Initial subaqueous activity occurred along NNW-trending fissures. Fumarolic activity observed in the 1930s.the above mentioned volcanoes to see as an example but the most recent volcanoes of Ethiopia are shown in the above figure 3.1

3.4 Volcanism in Afar depression

Magmatic activities in the Afar Depression commenced ~4My after the peak volcanism in the Ethiopian plateau. The Adolei basaltic series, oldest volcanic formation recorded within the Afar Depression, erupted during the late Oligocene–early Miocene, from 27–20 Ma (Audin et al., 2004). They are commonly deposited in the form of dykes with variable orientations that intrude the sedimentary basement rocks of the eastern tectonic domain of the depression (Black et al., 1975). Silicic volcanics in the depression are mainly associated with the shield and composite volcanoes of the area. The origin of these silicic extrusive rocks (i.e., trachytes and rhyolites) in the Afar is attributed to fractional crystallization (FC) of basaltic magmas with no or little crustal contamination (Gibson, 1972; Barberi et al., 1975; Ayalew et al., 2002).

The Mabla series, still minor in the depression, deposited from 25–12 Ma around the eastern tectonic zone of the depression (Ali Sabieh block) and consists of basaltic lava flows, rhyolitic dykes, and some trachytic layers (Audin et al., 2004). Recent volcanism (Pleistocene–Quaternary) is mainly confined to the active tectonic and magmatic segments within the embryonic spreading centers in Afar, and axial zones of MER (Boccaletti et al., 1998; Yirgu et al., 2006). Thus, the Afar Depression has experienced a 30My history of mafic, felsic and pyroclastic volcanism since Oligocene, with the voluminous eruptions (i.e., Stratoid series) tied with the initiation of seafloor spreading in the Gulf of Aden and Red Sea (Yirgu et al., 2006).

Magmatic activities have been bimodal in Afar Depression at least for the last 4My, but with basaltic rocks predominating over silicic products (Lahitte et al., 2003b). The silicic shield volcanoes (ignimbrites to pantellerites) emerge locally from the upper part of the Stratoid series and some younger volcanic formations (Lahitte et al., 2003a). In the northern Afar Depression, zone of active extensional deformation, magmatism is marked by bunches of volcanic edifices and extensive fissure-fed transitional–tholeiitic basalt (Corti, 2009). These axial range basalts, which are the replica of the mid oceanic ridge basalts (Barberi et al., 1972), are also called the ‘Aden Series’ basalts.

The Afar Stratoid series with an aerial exposure of ~55,000 km² covers approximately two-thirds of the low-lying Afar Depression and has been dated at 3.5–0.6 Ma (Thurmond et al., 2006). This series consists largely of fissure-fed trap-like basaltic flows and significant proportion of interbedded felsic lavas (Thurmond et al., 2006). This important volcanic deposit in the central and northern Afar Depression, both in volume and surface area, is not found within the eastern part of the depression (Audin et al., 2004). Towards the axial zone, the Stratoid series is gradually substituted by the youngest transitional–tholeiitic basalt called the ‘Erta’Ale axial range basalts.

The Erta’Ale Range, in the Danakil Depression, is one of the volcano-tectonically active segments of the EARS. The range is composed of seven shield volcanoes that are aligned parallel to NNW-SSE–trending Red Sea rift. These are from south to north HayliGub, AleBagu, Erta’Ale, Borale’Ale, Dalaffilla, Alu, and Gada’Ale (Barrat et al., 1998). Erta’Ale, the only active shield volcano in the region, is ~60-km-long and 30-km-wide and rises nearly 700 m above the low-lands of the Danakil Depression (Barberi et al., 1972; Oppenheimer and Francis, 1997). At the summit of the shield volcano, there are two active craters that have been erupting lavas continuously for the last 100 years (Thurmond et al., 2006). The Erta’Ale Range basalts, derived from the modern Afar plume, have slightly lower Sr isotopic composition than the Oligocene Ethiopian HT flood basalts, although the Nd isotopic compositions of these two magma series overlap (Furman et al., 2004). It could be deduced that the plume tail undergoing melting is now compositionally different from the plume head that gave-rise to the production of HT basalts (Furman et al., 2004). Compositionally, the Afar Depression basalts are dominated by transitional-tholeiites, falling within the subalkaline field/olivine tholeiites (Rogers, 2006). This characteristic extends to the Ethiopian HT flood basalts, making them unusual amongst other flood basalt provinces generally which are most frequently quartz-normative tholeiites (Rogers, 2006).

In September 2005, the largest dyking episode occurred in the Dabbahu magmatic segment of the Afar depression. In this dyking episode, ~2.5km³ of magma was injected as near vertical dykes in the upper ~10km of crust beneath the entire ~60km length of the Dabbahu magmatic segment and caused as much as ~8m of horizontal opening (Yirgu et al., 2006).

Preliminary petrographic study of Yirgu et al. (2006) from the lava dome indicates heating of the source magma chamber with an influx of hotter basaltic magma.

4. Regional geology

4.1 An overview of Afar Depression

The Afar Depression, a diffuse triple junction where the Gulf of Aden, the Red Sea and the MER radiate, covers an area of ~250,000 km² and is encircled by steeply inclined fault escarpments, which close at the Alid graben north of Dallol Depression (Abbate et al., 1995; Beyene and Abdelsalam, 2005). The depression is bordered on the west by the Ethiopian escarpment, on the east and northeast by the Danakil Microplate, and on the south by the Somalian Plateau. The elevation drops radically from the rift bounding Ethiopian plateau that stands well above 3500 meters above sea level to the lowest point in northern Afar Depression (Dallol Depression) at ~146 meters below sea level (Tesfaye et al., 2003). On the basis of its Physiography and tectonic domains, the Afar Depression is divided into northern, central, and southern sectors (Fig. 4.1).

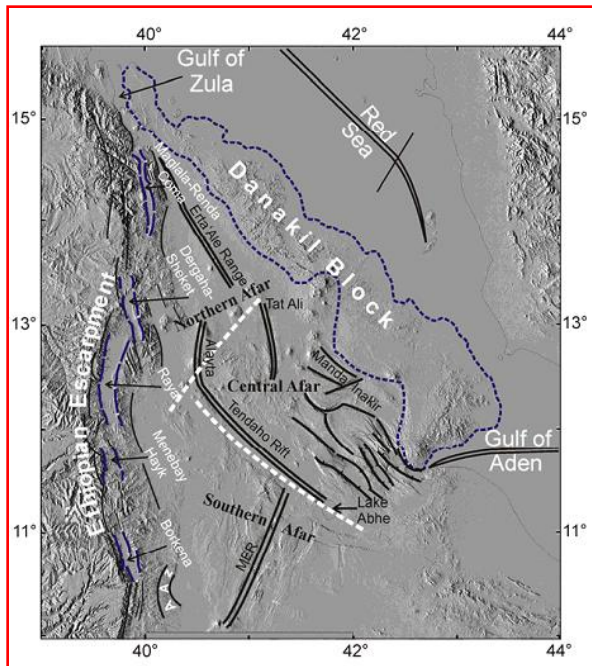


Figure 4.1 Shaded relief image of Afar Depression and the surrounding marginal area and plateaus produced from Digital Terrain Elevation Data (DTED; modified after Tesfaye et al., 2003). Tectonic zones and marginal basins of the depression are separated by white and blue dashed lines, respectively. The white dashed lines separate the northern, central and southern Afar Depression. Double black lines represent the active spreading ridge segments of Afar Depression, the Red Sea, and Gulf of Aden (after Mirtus H. et al., 2011)

The northern Afar Depression, alternatively known as the 'Danakil Depression', is a low-lying region bounded by the Ethiopian escarpment on the west and the Danakil Microplate on the east (Beyene and Abdelsalam, 2005). The depression, with a mean elevation of ~200 m, is

characterized by NNW-SSE-trending elevated axial volcanic range (Erta' Ale Range). Elevation at the peak of the range rises to ~1150 meters above sea level making a remarkable topographic contrast with the nearby deepest sub-aerial depression on earth (i.e., the Dallol Depression). The northern Afar Depression gets progressively deeper and narrower towards a northern zone within the depression known as Dallol (Beyene and Abdelsalam, 2005). The Quaternary volcanic edifices of the depression are usually produced by basaltic fissure lavas and some felsic derivatives aligned in a NNWSSE-trending axial zone, which is parallel to the regional tectonic trend of the Red Sea rift (Tesfaye et al., 2003). The deepest parts of the depression are commonly filled with recent lacustrine sediments, evaporite beds and floored by fissure-fed basaltic lava flows. The earliest sedimentation started in the Oligocene-Miocene along the newly developed marginal grabens with the clastic 'Red Series', and continued in the Pliocene-Recent by Piedmont sediments and shallow water carbonates (Barrat et al., 1998). According to these authors, the northern Afar Depression became arid after its isolation from the Red Sea by the Alid volcanic centre at lat 15°N.

The central Afar Depression, corrugated by grabens and horsts and few local high relief peaks representing volcanic shields, is a typical physiographic feature in the region hosting the only active sub-aerial triple junction in the globe. The Tendaho rift is one of the largest axial structures in the central sector of the Afar Depression marking the south western limit of the region. The NE and SW graben margins of the Tendaho rift, marked by prominent fault scarps with a maximum throw of ~100 m, show the highest topographic gradients (Acocella, 2010). Northwest-striking parallel sets of grabens and horst are characteristic features of the region accumulating a mean elevation of ~450 m (Tesfaye et al., 2003).

The southern Afar Depression (northern extension of the MER), like central Afar, is characterized by horst and graben morphologic features (Tesfaye et al., 2003). Unlike central Afar, however, it is dominated by a series of NNE-trending right-stepping horsts and grabens (Beyene and Abdelsalam, 2005). The ~700 m mean elevation of the southern Afar Depression gets progressively lower towards the Tendaho graben. The well-known NNE-trending discontinuous but en-echelon arranged grabens at the center of southern Afar are the northward propagation of the Wonji Fault Belt (WFB), active extensional rift zone of the MER (Tesfaye et al., 2003)

The low-lying Afar Depression is separated from the Ethiopian highland by the N-S–running Ethiopian escarpment, N-S trending marginal grabens and half-grabens of tilted fault blocks constituting the western margin of the Afar Depression (Beyene and Abdelsalam, 2005).

This margin is bordered by a seismically active, right-laterally offset, en-echelon arrangement of grabens that extend from 14°30'N to 10°30'N (Tesfaye et al., 2003). These grabens, typical physiographic features of the western margin, are Maglala–Renda Coma, Dergaha–Sheket, Guf–Guf, Menebay–Hayk, and Borkena (Tesfaye et al., 2003; Beyene and Abdelsalam, 2005). The marginal grabens, developed at the foot of the Ethiopian escarpment, average 30-km-long and 5-km-wide and are associated with transtensional faulting initiated during the middle Oligo–Miocene (Beyene and Abdelsalam, 2005). Systems of en-echelon strike-slip faults are also aligned parallel to the marginal grabens (Chorowicz et al., 1999). Reactivated deformational features associated with magma injection constitute the western Afar margin (Beyene and Abdelsalam, 2005). The western Afar margin was formed by down-warping of the Afar Depression and consequent antithetic and synthetic faulting and eastward tilting of faulted blocks (Zanettin and Justin-Visentin, 1975).

The Afar Depression is separated from the eastern plateau by the E-W–trending Somalian escarpment. It is characterized by a mosaic of closely spaced synthetic and antithetic normal faults. Unlike the Ethiopian escarpment, the southern Afar margin has no dilatational grabens developed adjacent to the Somalian highland. Instead series of half-grabens and some felsic volcanic centers are aligned along the lower and upper parts of the southern margin, respectively, where they are more concentrated towards the eastern accommodation zone (Tesfaye et al., 2003) of south western Afar Depression(Beyene and Abdelsalam, 2005).

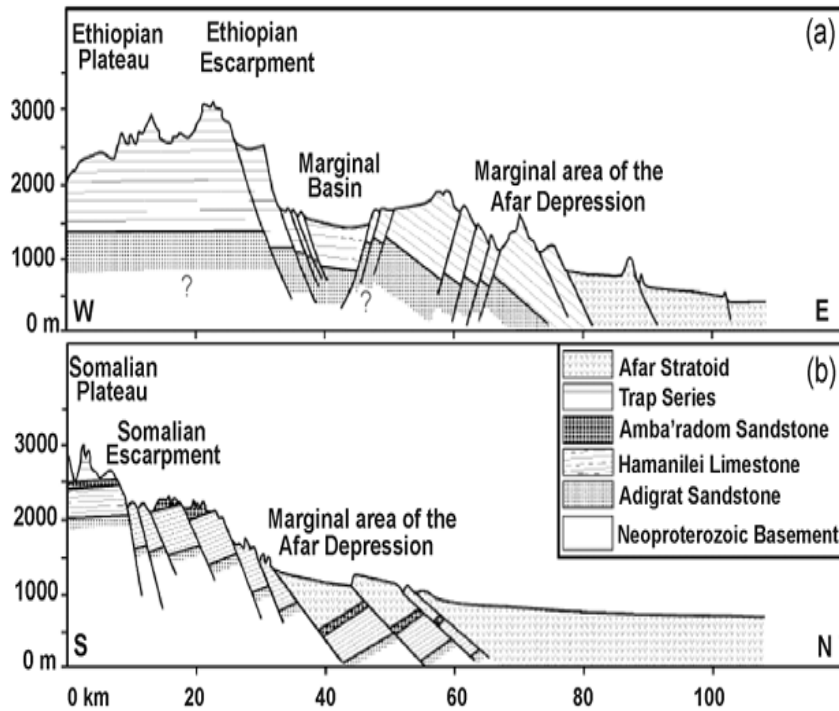


Fig 4.2 Schematic geological cross-sections showing the nature of crustal deformation across the Ethiopian and Somalian margins of Afar (a) Antithetic and synthetic faults bounding the marginal basins of the western margin. (b) book-shelf type faulting and associated half-grabens dominate the southern/Somalian margin (after Beyene and Abdelsalam, 2005).

4.2 General Geology of Afar and Tectonic Elements

The geology of the Afar Depression and its margins is of great interest because it may represent the complete sequence of rocks spanning from the Late Proterozoic to the present. The Afar Depression is not only a site of volcanism; it is also an excellent site of depositional environment. In addition to the Miocene to Holocene basalts and their felsic derivatives, late Miocene– to late Pliocene syn-rift Red Series sandstones, evaporites, and shales were deposited in newly developed basins in the northern Afar Depression (Redfield et al., 2003). However, these formations are not precisely mapped, because they are completely covered by the vast exposure of Pliocene–Pleistocene Afar Stratoid series and Quaternary sediments of the region. The geological formations of the Afar Depression and its marginal areas and surrounding plateaus can be divided into four broad divisions (Fig. 5.4): (1) Pre-rift complexes; (2) Syn-rift igneous rocks; (3) Pliocene–Pleistocene volcanic rocks; and (4) Quaternary volcanic and sedimentary rocks (Beyene and Abdelsalam, 2005; Bosworth et al., 2005).

Pre-rift complexes: These complexes consist of the Neoproterozoic crystalline basement rocks (Arabian-Nubian Shield), the Paleozoic–Mesozoic sedimentary sequences, and the Eocene–Oligocene volcanic rocks, which are exposed along the peripheries and plateaus surrounding the Afar Depression and within the Danakil and Ali-Sabieh micro blocks (Kazmin et al., 1978; Vail, 1985) (Fig. 5.3). The Arabian–Nubian Shield (ANS) also called the ‘low-grade basement complex’ covers a wide region to the west and northwest of the Afar Depression (Vail et al., 1985). These weakly metamorphosed crystalline rocks of the shield also constitute lower parts of the Ali-Sabieh and Danakil Microplates (Beyene and Abdelsalam, 2005). The ANS are overlain by thick successions of Mesozoic and in some places by Paleozoic sedimentary rocks and Tertiary volcanic rocks. The oldest clastic sediments (Lower Sandstone) are generally early Triassic or possibly Permian overlying the basement complexes, with younger formations (Upper Sandstone) extending into the early Cretaceous (Bosworth et al., 2005). These Paleozoic–Mesozoic sedimentary successions correspond to a major transgressive–regressive cycle, which has been assigned to the Adigrat–Amba-Aradom formations. The Mesozoic sedimentary rocks of the western (Ethiopian) Plateau comprise early Jurassic Adigrat Sandstone, middle–late Jurassic Antalo Supersequence and Agulae shale, and early–middle Cretaceous Amba-Aradom Formation (Varet and Gasse, 1978). The Mesozoic sedimentary successions of the eastern (Somalian) Plateau comprise early Jurassic Adigrat Sandstone, early–middle Jurassic Hamanileifossiliferous Limestone, late Jurassic Urandabgypsiferous Limestone, and early Cretaceous Amba-Aradom formation (Fig. 4.3b; Beyene and Abdelsalam, 2005). On the Ethiopian Plateau, the upper surface of the Mesozoic successions is marked by a great unconformity, over which the Oligocene Ethiopian volcanic rocks or ‘trap series’ were extruded (Bosworth et al., 2005). The Ethiopian volcanic rocks cover an area of ~600,000 km², with a layer of basaltic lavas and interbedded felsic and pyroclastic products constituting ~2000 m thick (Kieffer et al., 2004). The flood basalt was commonly extruded onto the lateritized sandstone surface and sometimes found inter-fingered with the Oligocene lacustrine, fluvial origin sedimentary rocks near or above sea level (Beyene and Abdelsalam, 2005)

Syn-rift igneous rocks: Flood and shield basalts of ~25–15 Ma are found both on the Ethiopian plateau and within the Afar Depression. In the Afar Depression, the oldest volcanic rocks are assigned to the Adolei, Mabla, and Dahla series (Fig. 4.4.; Varet and Gasse, 1978). However, these intensely faulted and deeply weathered Miocene basalts occur in limited areas around the

eastern peripheries of the Afar Depression (Gulf of Tadjoura and Ali-Sabieh Microplate). Alkaline to peralkaline granites were also intruded into the Neoproterozoic basement, Jurassic limestone and the pre-rift flood basalts along the western and eastern margins of Afar Depression (Beyene and Abdelsalam, 2005).

Pliocene–Pleistocene volcanic rocks: More than two-thirds of the Afar Depression is covered by Pliocene–Pleistocene volcanic rocks. These widely distributed fissure-fed units are commonly assigned to the Afar Stratoid series (Fig. 4.4; Varet and Gasse, 1978). They are the most important volcanic formation in the depression in terms of aerial coverage, volume, and preservation of volcanic structures and tectonic features (Beyene and Abdelsalam, 2005). The Stratoid lavas may be a manifestation of the commencement of ridge spreading in central Afar Depression at 4 Ma (Wolde, 1996), also roughly contemporaneous with the initiation of oceanic spreading in the south central Red Sea (Eagles et al., 2002). The massive outpouring of lava, mode of eruption and structuring of the Afar Stratoid series represent the transition of the central Afar Depression from continental rifting to incipient seafloor spreading (Barberi et al., 1975). Pliocene–Present fluvial and lacustrine sedimentary rocks interbedded with basaltic lava flows and felsic–pyroclastic products fill extensional grabens in central and southern Afar Depression (Tesfaye et al., 2003).

Quaternary volcanic and sedimentary rocks: Wide-spread fissure-fed basaltic flows and basaltic shields, scoria cones, and alkaline to peralkaline silicic rocks were erupted along the actively expanding axial ranges in the Afar Depression over the past 1 Ma (Varet and Gasse, 1978; Tefera et al., 1996). The transitional–tholeiitic axial range basalts are injected along the NNW–trending fissures displaying symmetric magnetic character that are underlain by very young and thin oceanic-type lithosphere, and get increasingly older and colder towards the marginal areas (Beyene and Abdelsalam, 2005). Because of these unique characteristics, Barberi and Varet (1977) considered the axial basaltic ranges to be sub-aerial equivalents of mid-oceanic spreading ridges, linked by transform faults. South of the Tat’Ali and Alyata, NE aligned volcanic centers, which are thought to be similar with the transform faults, transverse the NNW–SSE–trending basins found along the eastern and western Afar margins (Fig. 4.1; Beyene and Abdelsalam, 2005).

Because of the unique physiographic feature, the Afar Depression also hosts lacustrine deposit dominated Quaternary sedimentary rocks. Significant shallow water sedimentary rocks were deposited along the newly developed grabens (i.e., MandaHararo–Goba’ad, MandaInakir and Dobe rift basins) in the central Afar between ~12 and 1 ka (Beyene and Abdelsalam, 2005). Evaporites and lacustrine sedimentary rocks of several hundred m thick cover the Dallol Depression in the north and Awsa plain in the east central Afar, respectively (Varet and Gasse, 1978).

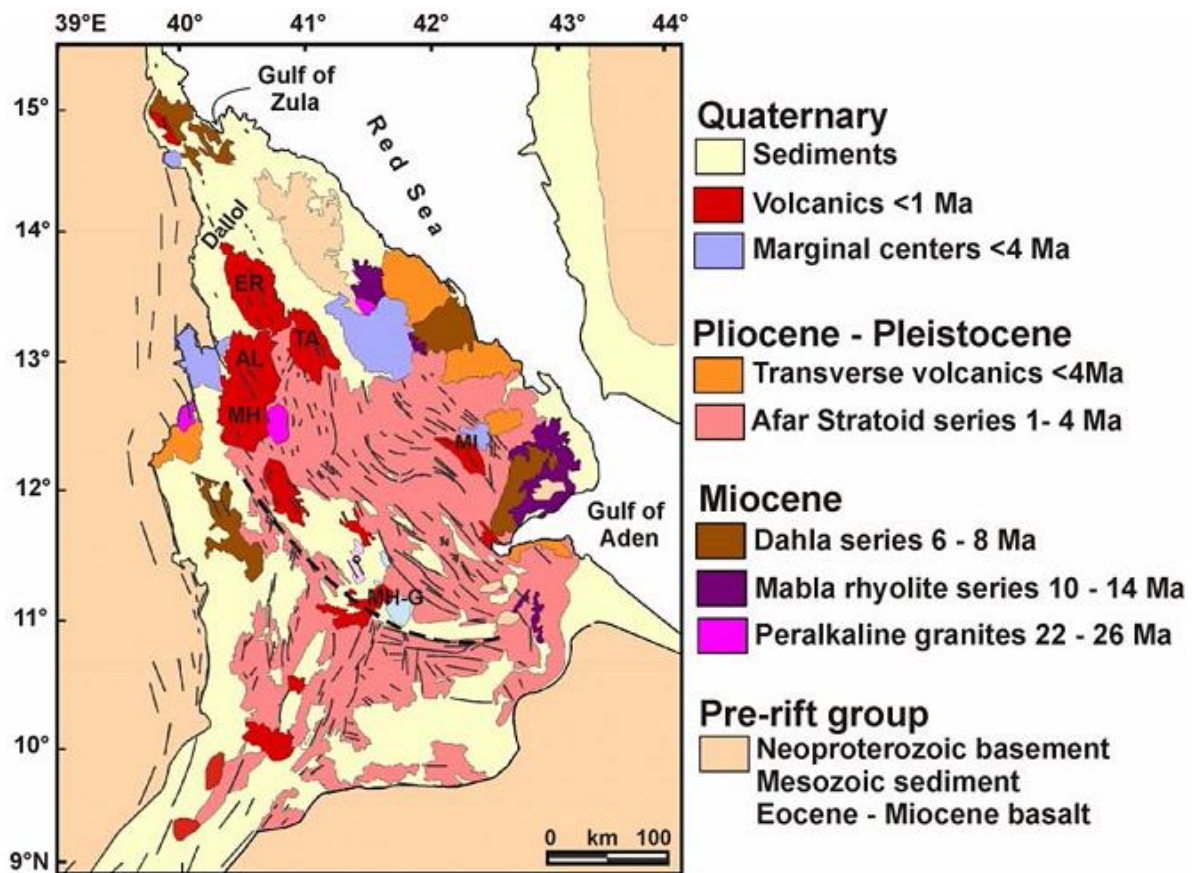


Fig 4.3 Geological map of the Afar Depression and the surrounding plateaus Active axial ranges are represented by: ER – Erta’ Ale Range; TA – Tat’ Ale; AL – Alyata; MH – MandaHararo; MI– MandaInakir; MH-G – MandaHararo-Goba’ad (after Beyene and Abdelsalam, 2005).

4.3 Tectonics elements of Afar depression

The Afar Depression is part of the East African Rift system, which is part of Afro Arabian Rift System. This system extends from southern Africa, through the East African Rift System, Afar Depression, Red Sea, Dead Sea, through the Jordan Valley and terminates in Syria. The Red Sea, Gulf of Aden and Main Ethiopian Rift form a so-called rift-rift-rift triple junction between the Arabian, Nubian and Somalian Plates (Beyene and Abdelsalam, 2005). The major tectonic elements associated with the Afar Depression include the Dankil, Ali-Sabieh and East Central Blocks; the MandaHararo-Gobaad, and Asal-MandaInakir; detailed description of the above elements follows.

Danakil block

The elevated Danakil block region within the Afar depression, which consists of pre-rift geological units, has been referred to as a block, a horst, or a microplate reflecting the various views held as to its origin. Souriot and Brun (1992) indicated that the Danakil Block has rotated 100° in the last ~7Ma and also indicated that the anti-clockwise rotation of the Danakil Block caused concentrated extension in the Northern Afar, clockwise rotation and diffused extension in the central Afar, oblique extension in the Tajura area and dextral strike-slip faulting in the southern Afar. Collet et al., (2000) argued that the Crank arm model does not support the left lateral strike slip motion observed on the western Afar margin. Furthermore, Collet et al., (2000) hinted that the stress field required for the anti-clockwise rotation of the Danakil block is incompatible with sinistral strike-slip motions observed on the northern Afar.

The Danakil Block is interpreted as a micro-plate that extends into the Red Sea (Chu and Gordon, 1998). According to Eagles et al. (2002), the most recent, statistically significant, independent movement of the Danakil microplate can be related to the onset of ocean type accretion in Afar that promoted the ongoing propagation of the neighboring plate boundaries.

Ali-Sabieh Block

The region that extends from the Somalian plateau along the Ayshaarea towards the Afar depression is referred to as the Ali-Sabieh Block. This region has been characterized as strongly attenuated autochthonous continental block that remained attached to the Somalian plate during the Nubian and Somalian plate separation (Christiansen et al., 1975). The Ali-Sabieh Block was thought to have rotated 90° clockwise at a rate of 4.5° per Ma concurrent with the Danakil Block for the last 20Ma in a 'Saloon Door' fashion contributing to the opening of the Afar Depression (Manighetti et al., 2001). Furthermore, Manighetti et al., (2001) observed that the western side of the Ali-Sabieh Block is marked by spatter cones that are aligned at $\sim 90^{\circ}$ to the E-W trending Somalian escarpment, along sinistral strike-slip faults that might have developed due to the clockwise rotation of the block. Evidences from Paleomagnetism on the Dahla basalts and Mabila rhyolites indicate clockwise rotation of about 15° (Audin et al., 2004).

East Central block

The SE-propagating MandaHararo-Gobbad and the NW-propagating Asal-Manda-Inakir overlapping rifts in the southwest and northeast, respectively bound the East Central Block. The overlapping and propagating rifts are believed to have induced dextral shearing that has caused clockwise rotation of the Central Block about a vertical axis due to differential

spreading rates. The extension within the East Central Block is localized in some major grabens such as the Dobi graben.

The MandaHararo-Gobbad rift

The Red Sea spreading ridge south of 17°30'N branched into a SE and SSW trend (Chu and Gordon, 1998). The SE trend continues along the Red Sea axis and terminates in a seismically quiet zone around the Hanish-Dubbi area (Barberi&Varet, 1975). The SSW trend runs along the Gulf of Zula, steps onto land within the Danakil Depression and continues south along the Erta'ale axial volcanic ranges to central Afar. The SSW-trend in turn splits south of Erta'ale into Tat'ale-Dadar trend in the east and the Alyata-MandaHararo trends in the west. The propagation along the Erta'ale-Dadar trend probably stopped as the Tat'ale axial range reaches the 100ka Dadar graben (Lahitte et al., 2003). Propagation along the Alyata-MandaHararo axial zone continues southward in to the Tendaho-Gobbad Discontinuity. The southward advance of the SSW-trend along Erta'ale-MandaHararo is broken into shorter rift and magmatic segments that are arranged into rift-in-rift structure as they approach the Tendaho and Gobbad axial ranges further south (Tazieff and Varet, 1972).

The Asal- MandaInakir rift

The Aden ridge propagating westward into the Afar Depression via an overlap zone bounded by the Gulf of Tajura in the north and the Asal-Ghoubbet rifts in the south. The opening of the Gulf of Tajura changed courses from NE-SW and proceeded along the Ghoubbet-Asal-Manda-Inakir rift in a NW direction (Dauteuil et al., 2001). The Asal -MandaInakir trend is characterized by rift propagation and spreading whereas the area to the southwest as far as the Tendaho -Gobbad Discontinuity is dominated by NE-SW extension and clockwise rotation.

Rift propagation and spreading along the Asal-MandaInakir rifts are episodic and occur in intervals of 106 and 105 years, indicating alternative effusive and tectonic events (Courtilot et al., 1984). Further Courtilot et al. (1984) suggested that at ~4Ma the Aden ridge reached the Gulf of Tajura, at ~2Ma propagation reached up to Arta-Tajura, and at ~1Ma began to open the Ghoubbet-Asal-MandaInakir rift.

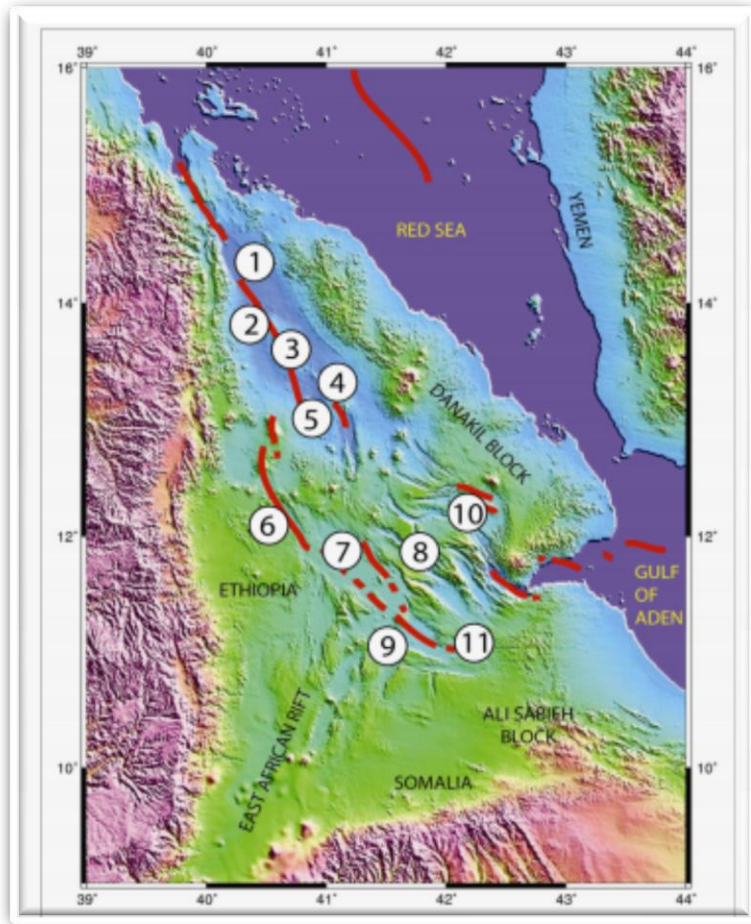


Figure 4.4 Topographic relief map of the Afar Depression with important structures 1= Danakil Rift. 2= Red Sea Trend. 3= Erta Ale Volcano. 4= Alyata Volcano. 5= Tat Ale Volcano. 6= Manda Harraro -Gobaad Rift. 7= Awsa Plain. 8= Dobi Graben 9= Tendaho Gobaad Discontinuity. 10= Asal -MandaInakir Rift. 11= Gulf of Aden Trend (After Beyene and Abdelsalam, 2005)

4.4 Structure and evolution of Tendaho graben

The TG is located in central Afar and terminates the NE extension of the MER structures. It is bounded to the east by the East Central Block and to the west by the marginal blocks created by normal faulting associated with the Ethiopian Plateau escarpment. The TG is an extension of the MandaHararo rift segment to the northwest of the Goba Ad structure, a half-graben, to the southeast (Abbate et al., 1995)

The TG is the largest rift basin in the central Afar (Acocella et al., 2008). It is typically 50 km in width (Abbate et al., 1995) and extends a few hundred kilometres in the NW-SE direction. Its flanks primarily consist of Stratoid basalts and younging axial Volcanics toward the center of the graben (Lahitte et al., 2003). The floor consists of young Volcanics in axial ranges and lacustrine deposits. The TG hosts historically active Kurub and Dama Ali volcanoes (Simkin and Siebert, 1994). The relief from flanks to basin bottom is a few hundred meters however the sediment thickness exceeds 1600m in places and could be much thicker based on data from the Tendaho Geothermal Project (Aquater, 1996a). Geochronological data suggests that the opening of TG was initiated as early as ~ 2.0Ma Acton et al., 2000). The youngest Volcanics are found along the MandaHararo rift axis at ~ 0.03 Ma (Lahitte et al., 2001).

The basin of TG primarily consists of alluvial and lacustrine plains with NW-SE elongated basalt outcrops. Ten km southwest of Kurub, NW striking faults are present in the sediments indicated by aligned steaming grounds, fumaroles, hydrothermal deposits and faults steps (Abbate et al., 1995).

Acocella et al. (2008) studied the structure of the MandaHararo rift (Semera Plateau) in the TG in detail. The southern geomorphologic expression of this young rift is a basalt plateau (Semera Plateau) oriented NW-SE. It is dominantly recent axial basalts surrounded by lacustrine deposits and subordinate interbedded Volcanics. The plateau itself is highly fractured by vertically displaced faults that are not expressed in the surrounding sediments. Acocella et al. (2008) divided the plateau into two domains, a mostly untilted domain to the west and a domain to the east characterized by NE-dipping blocks that decrease in dip to the east. The untilted domain is characterized by opposite facing, nearly vertical scarps with vertical displacements ~1 to 10 m high forming mini grabens. The eastern domain is much more complicated where the north eastern dipping blocks are interrupted by regularly spaced SW-dipping normal faults.

Lastly, thick (>1000 m) sequences of volcanics and sediments are present within TG and the young (~ 300 to 0.030 Ma) volcanics a few km east of Semera represent the current MandaHararo rift axis (Lahitte et al., 2001). The antithetic nature of the fault blocks along with the topographical escarpments (>200 m) contribute to the ~ 1600 m vertical displacement of the TG (Acocella et al., 2008).

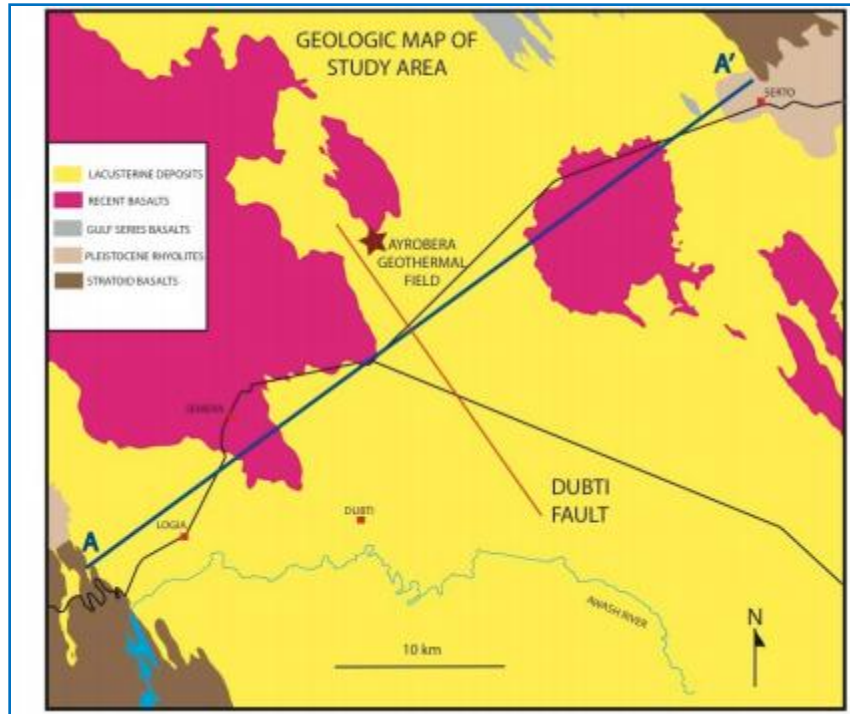


Fig 4.5 General Geology of the Tendaho Graben, The red line shows the linear known extent of Dubti fault and associated hydrothermal activity. The maroon star marks, the Ayrobera geothermal field(after David L.Bridges et.al 2011)

4.4.1 Structure of Tendaho graben

TG is bordered by NW-SE trending faults, at all scales. According to Acocella et al. (2008) remote sensing and field data show that the overall architecture of TG is characterized by the following features. The NE and SW shoulders consist of sub horizontal Stratoid layers, often dissected by NW-SE trending faults. At the NE and SW graben margins, marked by the highest visible scarps, the sub horizontal Stratoid layers end, forming inward dipping Stratoid blocks arranged in a domino configuration inside the margins. The dominos, usually 1 km wide, are bordered by NW-SE trending faults which dip away from the graben axis; the displacement of these faults decreases toward the graben axis, in a similar fashion to the amount of tilt of the blocks that they bound (between 30 and 5). Stratoid in the inner portion of TG are deformed into a broad NW-SE trending syncline-like structure formed by the tilted blocks separated by the NE-SW trending faults.

Therefore the syncline is fault controlled and its axis represents the axis of TG. Thick (1000 m) volcanic and sedimentary sequences are present within the TG. The youngest basalts outcropping in its NE part marks the present active axis of MHR (Lahitte et al., 2001). The spatial coincidence between the sharp topographic variations at the sides of TG (scarps >200 m high), the locations of the tilted blocks, and sporadic hydrothermal activity suggest the presence of master faults bordering Tendaho Graben. The foot-wall of the master faults is made up of Stratoid with sub horizontal attitude, whereas the hanging-wall is made up of tilted Stratoid blocks. Their vertical displacement does not only result from topographic variations, but also from the tilt of the blocks on the hanging-wall. This accounts for a significant part of the 1600 m of vertical displacement calculated by means of drill data in the Dubti area (Battistelli et al., 2002).

The active normal faults in TG are characterized by a significant dilatational component, with dragged hanging-wall. These features are identical to those of the normal faults observed along the axial part of rifts at divergent margins, including the northern portion of the Red Sea Propagator (Acocella, 2008), MER and Iceland (Gudmundsson, 1992).

4.4.2 Evolution of Tendaho Graben

Several models for the evolution of the TG have been proposed (Acton et al., 1991; 2000; Thurmond, 2007 and Acocella et al., 2008). David L. et al (2011) argued and propose a new model for the evolution of TG (fig 5.6). Common to all models is the emplacement of the Stratoid Basalts between 3.5 and 0.6 Ma (Lahitte et al., 2003). Much of central Afar is covered by ~ 2 Ma Stratoid (Lahitte et al., 2003) and for all models this represents the initial formation deformed by the initiation of the TG.

Most of the previously mentioned models have the initiation of the TG ~ 1.8 Ma and are based on the Acton et al. (1991) model. Acton et al. (1990) arbitrarily chose 1.8 Ma, for the initiation of the TG due to Stratoid series blanketing all older formations and structures. Rotation of the East Central Block, which forms the NE footwall of the TG, started ~ 2.0 Ma (Kidane et al., 2003). This would more likely be the correct initiation time of the TG and thereby the date chosen for the proposed model for the new work.

The next event with an age control is the emplacement of the rhyolites presently near Serdo and to the W of Loggia (Figure 4.6c). Dating by Lahitte et al. (2003) reveals similar dates of emplacement (1.320 and 1.269 Ma). These silicic domes were likely emplaced when the TG was only 6.5 to 10 km wide. A modern analogue is the Imino Graben to the NE. The Dobe Graben, in the East Central Block, is another analogue that may be currently at the stage where the Tendaho Graben was around the emplacement of the rhyolites. The master faults of the graben were the focuses of melt ascent and emplacement. The previous models of Acton et al. (1991; 2000) and Thurmond (2007) have the rhyolites as precursors to rift initiation; however, this does not fit the geochronologic data. The large fissure flows of Gulf Series basalts were emplaced ~ 1.1 Ma (Lahitte et al., 2003) and filled the floor of the young TG (Figure 4.6d). These fissure basalts likely exploited syn-faulting that was occurring along the graben margins associated with the continuing extension of the upper crust.

According to the newly acquired magnetic data and additional constraint in the proposed evolution of TG model, Around 0.78 Ma, accommodation of extension in the TG moved from the margins towards the center axis of the graben (Figure 4.6e). Due to the dominantly reversed polarity Stratoid blocks on the margins of this central axis, the exact transition time cannot be constrained with magnetic and field data alone. This transition from mechanically stretched crust to magma assisted extension could have occurred not long after the major pulse of Gulf Series basalts were emplaced. On the other hand, this transition could have happened after 0.78 Ma depending on the recent spreading rate of the Graben. Nonetheless, forward modelling has shown that a 10 km section of dominantly normal polarity dikes would fit the observed magnetic data. Based on regional spreading rates (e.g. Chu and Gordon, 1998), placing the initiation of diking around the change from the Mataysuma to Bhruneschron (0.78 Ma) is appropriate.

The present TG width of ~50 km is the result of both brittle deformation and magma emplacement (Figure 4.6f). Diking and geothermal activity is concentrated in the centre of the graben forming the Ayrobeara geothermal field in the NW to a large plantation to the SW. The Dubti Fault controls this activity. The extension rate of the TG has slowed considerably from 1.64cm/yr from rift initiation to 0.78 Ma to 0.64 cm/yr from 0.78 Ma to present. This would suggest that the extension across the central Afar Depression is being accommodated somewhere in the East Central Block or possibly the Gulf of Aden propagator. This evolution is unique in

that it records the transition from mechanical stretching of the upper crust to a magma assisted extension regime.

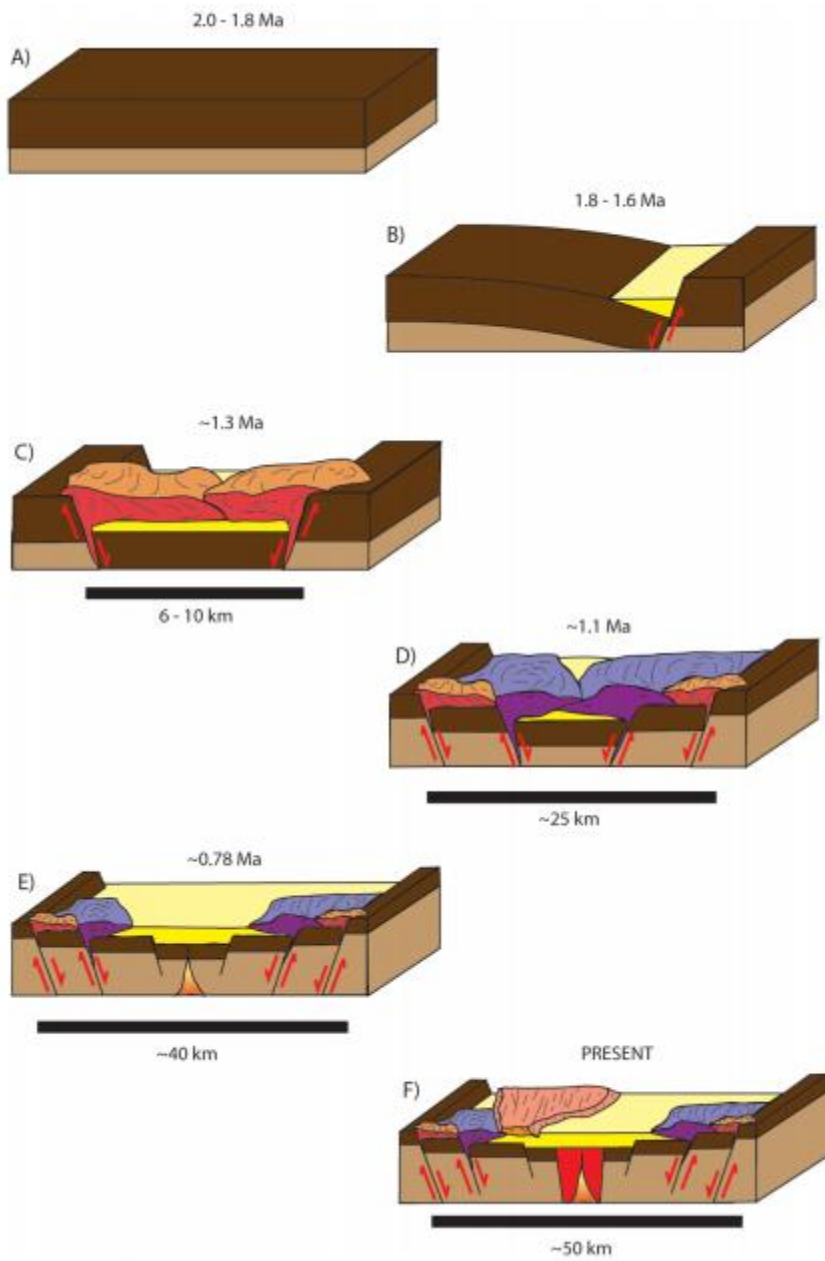


Fig 4.6 Proposed Evolution of the Tendaho Graben, A) Emplacement of Stratoid Basalts (dark brown) overlying unknown pre-Pleistocene surface (Light Brown) B) Continuing mechanical stretching creates a half graben to form along with sediment deposition. C) As extension continues, formation of a full graben along with high asthenospheric heat flow creates melts of rhyolitic composition that are emplaced along the master faults of the graben. D) The Tendaho Graben is now ~25 km wide and the Gulf Series basalts are emplaced again mainly focused along the crustal weakness zones create by normal faulting. E) Extension moves from the margins and border faults to the center of the graben and mechanical crustal thinning has been replaced by magmatic diking near the center of the graben. F). Present day scenario with ~ 10 km zone of dominantly normal polarity dikes. (after David L brdiges et al 2011)

5 Geology and Geomorphology of the study area

5.1 Geomorphology of the study area

A small Holocene Gebalaytu volcano is situated in the central afar depression at top of Tendaho Graben and adjacent to the active recent Manda-Harraro and west of Semera town about 5km. Since it lays the on top graben (Gebalaytu plain to East and Inkisa-Gentu plain to south) surrounded by alluvial sediments. The complex nature of the volcano makes the slope is widely different and depends on the types of the volcanic product. The volcano is characterized by mainly gentle slope and relatively stiff cliff at the summit.

The Holocene Kurub shield volcano, lies in the central Afar depression on top of Tendaho graben, in the Saha Plain, SE of the Manda-Harraro volcanic complex in the South Danakil region. Kurub has maximum height which is about 625m.m.a.s.l /2015 ft. Kurub is an isolated central volcano standing on western portion of the study area with a maximum relief of 260m from the surrounding plain land. It seems slightly elongated along NW-SE. The top most part of the volcano is a flat-laying depressed land filled by thin layer of sediments/soil (fig5.1). This land has an elliptical shape having maximum longitudinal length of 300m, small width of 250m and depth of approximately 10m.



Plate 5.1 volcanic centre of Kurub volcano which show elliptical shape and filling sediment

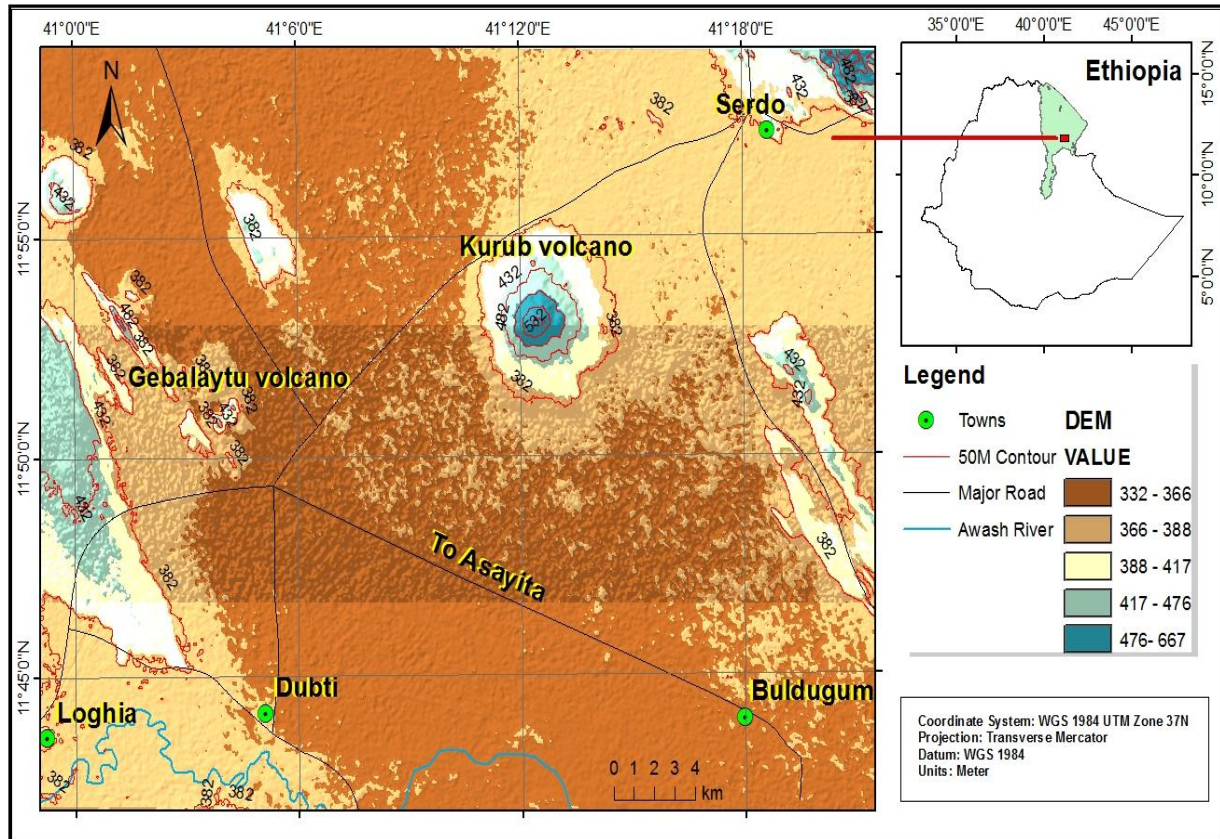


Fig 5.1 Topographic map of Tendaho graben and Gebalaytu and Kurub volcanos

5.2 Volcanic products of Gebalaytu and Kurub

For some one observing the region at semi detail scale, geomorphology and local geology shows slight variation due to the fact that the presence of Tendaho Graben filled by soft Fluvo-Lacustrine sediments and resistant topography formed by basic lava flows and minor axial Felsic lava, though the regional geological setting of the area is similar for the entire region. The present study is located on center of the Tendaho Graben and covered by volcanic group (basic to Felsic) and sedimentary sequences. The Afar Stratoid Series constitutes the borders of the Tendaho Rift; the rift is filled with Lacustrine and Fluvial deposits and with post-Stratoid basaltic flows. Even younger products, such as scoria cones, fresh Pahoehoe basaltic flows, occur in the Gum'Atmali-Gebalaytu. The volcanic and sedimentary units of the Tendaho Graben are the products of the Upper Pliocene to present time. The older products in this area are the

lava pile out cropping the graben edges; whereas the most recent activity, both linear and central, is concentrated within the graben.

Pre-rift stratified volcanic rocks along the rift margin and post-rift recent volcanic product and basin filling sedimentary sequence in the rift floor mainly cover Semera-Dubti area. The volcanic rocks have a composition ranging from basaltic to Rhyolitic. Basalt is the most common rock type that occurs as broadsheet of flood basalts believed of fissural origin and also younger flow from central volcanoes. Whereas, the sedimentary sequence consist of alluvial, lacustrine and Aeolian deposits. Based on morphology and structure, the study area is grouped in to two morph structural complexes: the Rift Margin and the Rift axis.

Rift Axis Complex

The Rift Axis complex covers much of the study area and characterized by flat depressed land. Volcanic activities of this complex is first characterized by linear/fissured/ basaltic eruption overlaying the basin filling sedimentary sequence and then eruption through structurally controlled vents which produced recent basaltic, scoriaceous, hyaloclastitic and rhyolitic rocks.

Gebalaytu Rhyolitic Rocks

This unit is found in the rift axial range of the study area, west of (locally named) “KEYAFER”, forming dome structure. It represented by mainly by acidic rocks (Dacite/ rhyolite). Obsidian is rarely seen in the dome. Generally, this unit represents the latest Felsic volcanic activity of the Axial Rift Volcanic of the area.

Rhyolites and/or dacite are a felsic volcanic rock and typically occur as viscose flow and forming dome in Gebalaytu area. It is light gray; medium grained banded rock and weakly weathered. It is commonly found with perlite and obsidian and has blocky lava flow appearance. Outcrop is highly affected by NW-SE trending faults and fractures. Perlite dominates over obsidian in Gebalaytu rhyolitic lava dome. Both obsidian and perlite represent acidic lava that has chilled quickly after eruption. The different between the two is in the depositional environments. Obsidian represents chilling of acidic lava under sub aerial conditions where as perlite cooled under water with absorption of some water.

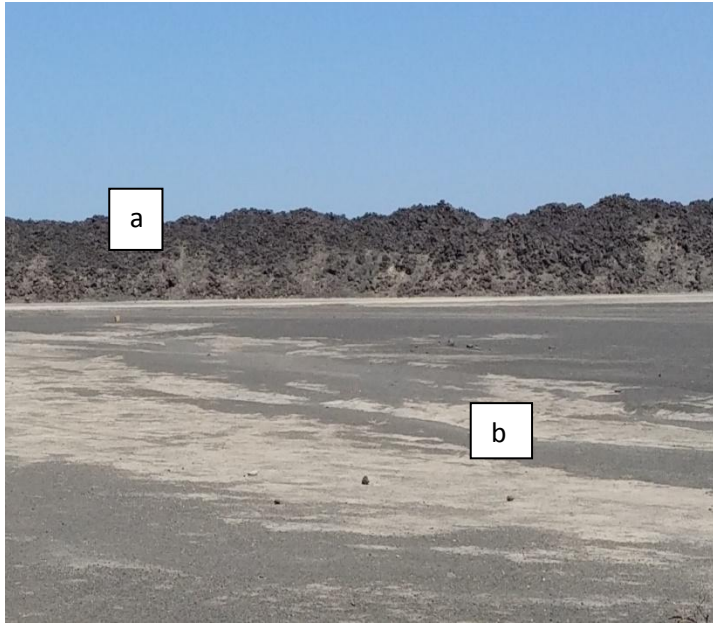


Plate 5.2 (a) Gebalaytu rhyolitic rocks (b) rift floor or Fluvo-Lacustrine sediments

Gebalaytu Scoria

This unit is locally named as “KEYAFER” and commonly used for making gravel road in different parts of the study area. It is dissected by young NW-SE trending faults in which very recent axial basalt extrude and flow on it. The Gebalaytu Scoria forms an elongated ridge, in the direction of NW-SE. It is a friable pyroclastics fall and differs from the pyroclastics falls (pumice, tuff and ash) by its basic composition. But, in the study area, it is totally oxidized and its darker color is changed to red/reddish brown. Its grain size varies from fine to gravel.

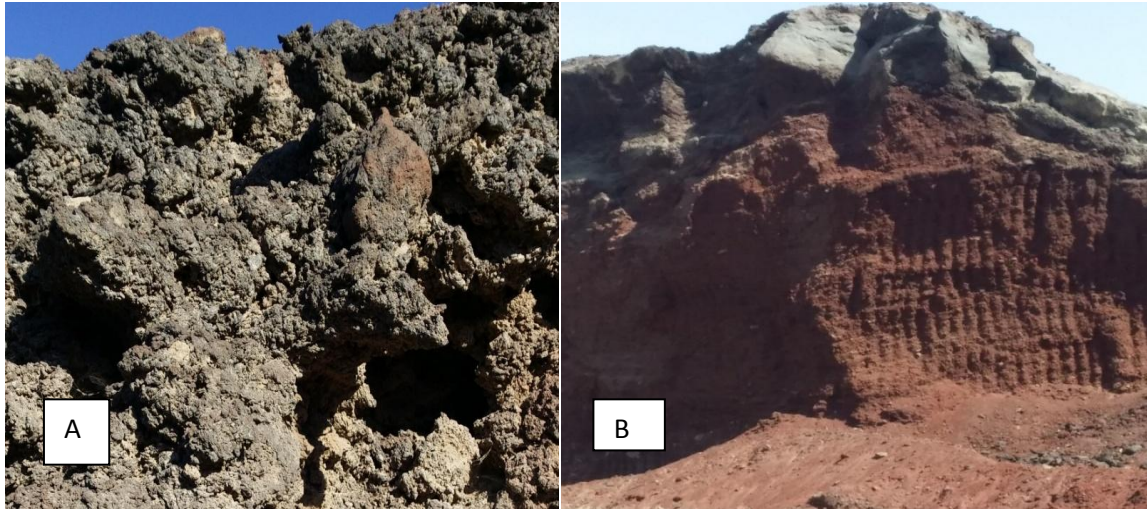


Plate 5.3 Gebalaytu scoria (A) black colour scoria (B) basalt flow over the oxidized scoria

Pahoehoe Basalt

The very recent basaltic lava outcropping around Gebalaytu ridge, central part of the mapped area, extruded through NW-SE trending axial faults forming pahoehoe lava flow type. It flows in different direction surrounding the Gebalaytu rhyolitic rocks. At least three volcanic centres (aligned in NW-SE direction) are seen during the field survey around Gebalaytu area. The main rock is dark gray vesicular porphyritic basalt forming mainly pahoehoe lava flow structure. It is fresh with low degree of weathering. Near the source of the lava, billow, hummocky or ropy lava surface and vesicular glassy skin with rough but glistening appearance (plate 5.4 c and d) are the common features. Vesicles, in few outcrops, are uniform and aligned in one direction, forming flow banding. Minor vesicles are filled with weathered, friable and whitish material which can be seen with hand specimen.

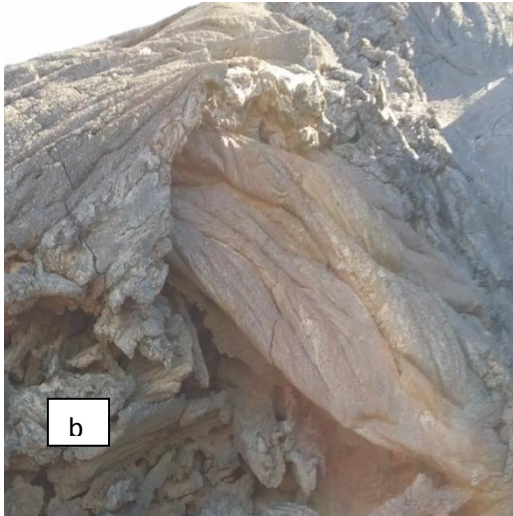


Plate 5.4 some features of lava flow of Gebalaytu (a) and (b) ropy lava surface (c) and (d) Blistering in lava flow

Rift Axis Sedimentary Sequence

Fluvo-Lacustrine and Aeolian Deposits

Recent sediments are commonly found at river courses and flood plains, the origin of the deposits could be fluvial and/or lacustrine. Recent sediments are commonly found in the Tendaho Graben & minor depressed land: at river courses and flood plains (such as Gebalaytu plain, Kurub plain, Saha plain, Inkisa-Gentu plain, Dubti plain) and very wide coverage, more than 50 percent. Genetically, it comprises of alluvial, lacustrine and Aeolian and minor residual

sediments. Since these sediments, surficially, mixed with one another, it is impossible to map separately. The following sediments are generally observed in the area; light gray to gray Aeolian sand and sandy soil, dark gray and fluvial soils. The top most part of the graben is dominantly covered by material that area transported and deposited by wind. It is constituted by gray to light gray, fine to medium grained sand with silty material resulting from Aeolian activity. Based on previous subsurface exploration (drilling), the thickest part of the NW Tendaho graben (underneath the surficial Fluvo-Lacustrine and Aeolian Deposit) is comprises by sedimentary sequence with intercalation of thin volcanic flows. Siltstone, sandstone and intercalation of these are the dominant sedimentary rocks



Plate 5.5 Alluvial deposit

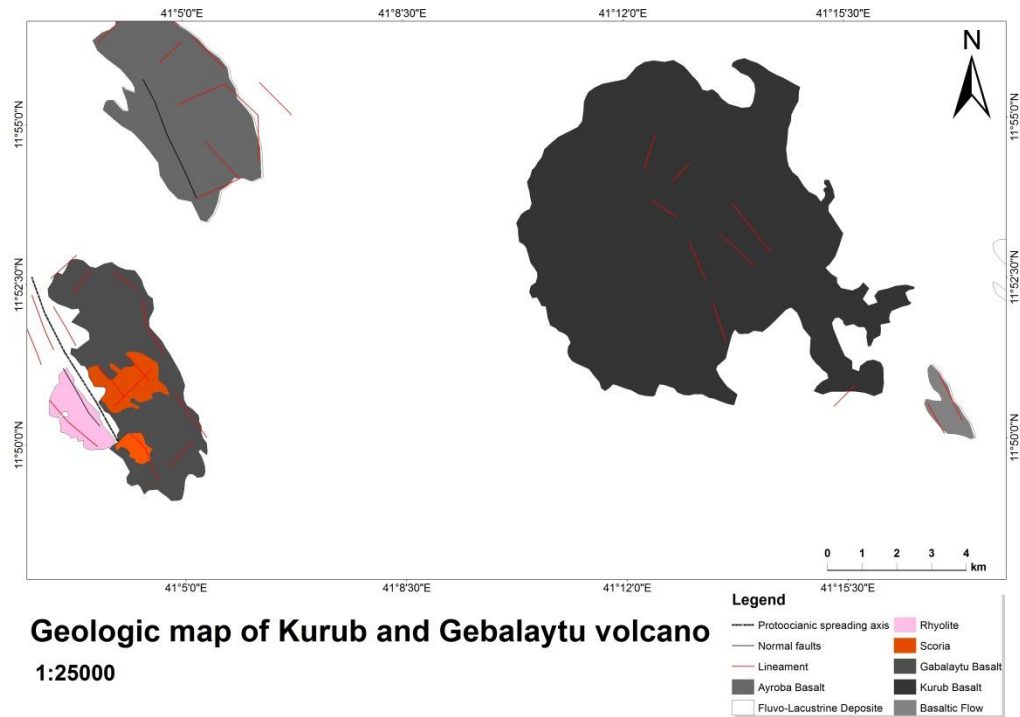


Fig 5.2 Geological map of Kurub and Gebalaytu and their surrounding

Kurub basalt

Kurub is an isolated central volcano standing on western portion of the study area. It seems slightly elongated along NW-SE direction; small-elongated cracks trending in the same direction are seen on its flanks. The top most part of the volcano is a flat-laying depressed land filled by thin layer of sediments/soil.

Volcanism in Kurub was probably initiated by an extrusion of olivine-phyric basalt and then by plagioclase bearing. Its bottom part (thin lava flow on plain land) is dominated by olivine phyric and its top part is mainly characterized by plagioclase phyric, porphyritic basalt, which might suggests deep-seated differentiation process. Porphyritic basalt form gentle slope having blocky lava flow appearance due to intense cracks, fractures and joints. It is highly vesicular, dark gray porphyritic basalt. This rock is dominated by large vesicles (up to 1cm length) filled by weathered whitish material, probably calcite. Porphyritic basalt with plagioclase phenocryst: steep slope forming having blocky lava structures. Outcrops is highly fractured and jointed with NW trend. This rock, in the bottom part, characterized by both olivine and plagioclase phyric dark gray basalt, where as the top part is dominated by plagioclase phenocryst. It is also

vesicular, but size of vesicles is small.. Olivine phenocryst and minor darker minerals is also seen in hand specimen. On the top most part, on depressed land and wall, it is common seeing lava tubes on big blocks of basalt. Exposure in this area is bulged/inclined outward from the central (flat-laying land) to outside in all direction.

5.3 Tectonic Structure of the study area

According to (abbate et al., 1995) Tendaho Graben joins with the Main Ethiopian Rift (MER) marked by volcanic centers and transecting faults. The Tendaho graben is a major structure in the area trending in NW direction and bounded both by inward dipping (synthetic) and outward dipping (antithetic) faults. The width of the graben varies with an average of 50km with decreasing towards its north and south. The graben is bounded by high angle faults with throw ranging from 500m-1000m and larger throw observed on the east bounding faults. Open fissures, fractures were also observed at rift floor. Previous work by (abbate et al., 1995), showed the presence of sinistral strike slip faults at various locations of the graben.

The study area is part of the Tendaho rift/Graben, which is located in one of the major graben of Afar Depression. It is formed predominantly by tensional faulting with main trend in NW-SE direction. NNE-SSW trending fault system is also affecting the southern portion of the mapped area, easily seen in aerial photographs and field survey. The former faults are cut by those of the NNE-SSW trend and vice versa, both are considered recently active. The axial range of NW Tendaho Rift, mapped area, and its product, is part of southern portion of the Erta Ale-Manda-Hararo Rift System of the northern Afar rift, which extends the active tectonics of the Red Sea to South. Different geologic structures (joints, faults, fissures or micro-rift and lineament) affect the different volcanic and sedimentary rocks of the study area.

NW-SE and NNE-SSW trending geologic structures have nearly vertical dip. Rift axis volcanic group is affected mainly by NW-SE trending geologic structure.

5.4 Eruptive vents and their description

During the field at least three eruptive vents are seen in Gebalaytu which are aligned NW-SE direction and all of the vents are in dormant stage and they are filled with soil/sediment and also Kurub has summit/central vent as in the Gebalaytu, the top part is filled with windblown sediment.

The vent in north and south part is mostly covered by basaltic lava flow and the pyroclastic fall of Gebalaytu scoria in the central and north vent while the west vent is mostly covered by rhyolitic product.

Kurub vent is totally covered by basaltic lava flow and it seems slightly elongated along NW-SE. The top most part of the volcano is a flat-laying depressed land filled by thin layer of sediments/soil (fig 5.1)a

5.5 Thermal manifestation

In the afar depression the central and northern part there has been investigation of the huge geothermal resource with indicating active thermal manifestation. Specially, the Tendaho graben could be mentioned as the best site for geothermal resource.

In the rift system fumaroles and hot springs are most commonly associated with manifestation of recent volcanicity, ranging in observed temperature from 28⁰C to 130⁰C (average is about 60⁰C). Geysers are observed a few localities in the rift valley such as Alalobeda in Afar depression and Kulito area (the MER).

Along the axial range, the present day eruptive activity occurs, including recent basic and acidic central volcanoes and active thermal manifestations are also found along the rift axis geological structures (fig4.1). Distribution and type of the thermal manifestations of the Tendaho graben might relate to two different heat release origins. High temperature manifestations within the axial ranges could be due to a rise of upper mantle material beneath. The second type of surface

heat manifestations could be related to the presence of magma pockets located at the intersection of two tectonic directions.

Based on temperature measurement and the intensity of alteration the most promising and prominent area for high enthalpy geothermal resource are the Dubti and Ayrobera. The Alalobeda area is the best of all sites, Areas around southern Ayrobera ridge, northeast Dubti plantation, Alalobeda and Logiya have been strongly affected by surface hydrothermal manifestations and alteration. The surface hydrothermal manifestations are mainly geyser, hot springs, hot water pool (elliptical & polygonal), muddy-water ejecting vents, fumaroles/fumarole's vents, mud pools, muddy hot water pool, hot ground and steaming ground. The measured surface temperature on these manifestations mainly falls in the ranges from 65 to 100.3°C (Megersa and Getaneh, 2006).



Fig 5.3 a small geyser around Alalobeda area south west Dubti town (After Megersa and Getaneh, 2006)

6. Results and Discussion

6.1 Petrology and Geochemistry

6.1.1 Petrology

The petrographic description of seven selected samples of the volcanic rocks of Gebalaytu (5) and Kurub (2) presented as follow in tabular format

Sample No.	Petrographic description	Whole rock texture
GE-01	The specimen is medium grained porphyritic rock dominated by plagioclase phenocryst (6%), olivine(2%) and pyroxene ~1% and set in fine grained ground mass composed of 20% plagioclase opaque mineral(10%) olivine (8%) volcanic glass(5%) 45% of vesicles and secondary mineral (3%).the plagioclase mineral is lath like crystal habit and elongated fine grained. Vesicles are filled by Secondary mineral.	porphyritic
GE-02	Porphyritic textured rock with plagioclase phenocryst 7% olivine 2% and pyroxene 3% set in fine grained ground mass 15% plagioclase and 8% olivine and pyroxene 3% intersistal volcanic glass 25% vesicles 35% .plagioclase is elongated equigranular-inequigranular in grain size, and some plagioclase phenocrysts have Carlsbad twining. Olivine has euhedralsubhedral crystal habit. Pyroxene and plagioclase phenocrysts form a clot or aggregated. The specimen show some oxidized minerals with vein like structure.	porphyritic
GE-03	This rock is characterized by phenocryst of 10% feldspar, 5% rock fragment and 5%quartz set in a fine-grained groundmass of glassy matrix Composed of about 60% volcanic glass (rhyolite), 5% quartz, 5% rock fragment, and 2% opaque. It has the ignimbrite texture but compositionally rhyolite. Plagioclase is elongated and some plagioclase phenocryst shows Carlsbad twining and the rock is oxidized which can be seen in hand specimen.	Vitrophyric
GE-04	The rock characterized with 10% feldspar phenocryst 4% quartz set in glassy matrix composed of 80% volcanic glass opaque mineral 6% .the rock is oxidized and forming vein like structure. Plagioclase is alteration shows dark dirty appearance and under PPL it likes empty space.	Vitrophyric
GE-05	The specimen is characterized by porphyritic texture with 10% plagioclase 3% olivine set in fine grained ground mass 12% plagioclase intersestal volcanic glass 35% and vesicles 40% Plagioclase The Carlsbad twinning and lath like crystals of plagioclase is common. Olivine has euhedral to subhedral crystal habit. Vesicles are black oval feature typical scoria mostly found In singe somewhat rounded and some of them are found in contact with each other.	Porphyritic
KU-01	The specimen has Glomeroporphyritic texture which crystal cloths of plagioclase olivine enclosed by fine grained intergranular and intersertal textured ground mass. The phenocryst with plagioclase 15% Olivine 3% pyroxene 2% set in	Glomeroporphyritic

	fine grained ground mass volcanic glass (35%) plagioclase (20%) olivine (10%) opaque mineral (15%). The plagioclase mineral are found in clots or aggregate with olivine and pyroxene and some of plagioclase elongated and show Carlsbad twining.	
KU-02	The specimen is fine grained porphyritic texture and highly vesiculated (70%). The vesicles are very large (1cm) and some of them are filled with secondary mineral (calcite?). The plagioclase is the dominant mineral (12%) and there are medium to fine grained olivine (3%) and hematite (15%)	porphyritic

6.1.2 Geochemistry

According to total alkali silica (TAS) classification (Cox-Bell-Pank 1997) the volcanic rocks from the two volcanoes are basalt except G1 is rhyolite (fig) the mafic rocks are fall in the basalt for classification using the mafic lavas plot in the sub alkaline field. The volcanism in the Tendaho Graben which in the view of Gebalaytu the volcanic rocks form the analysis are bi-modal (basalt and rhyolite, even if the samples are few).

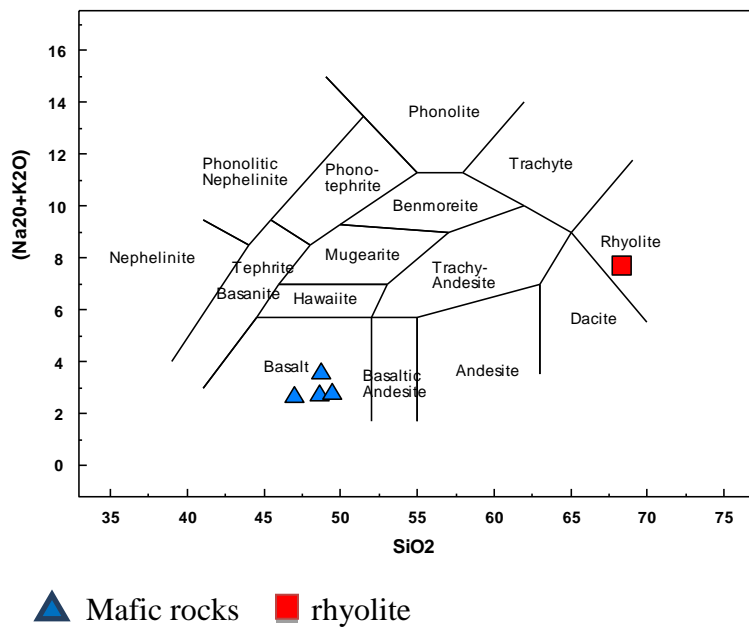


Fig 6.1 Total alkalis-silica (TAS, Cox-Bell-Pank, 1997) classification diagram for volcanic rocks, showing the bimodal basalt-rhyolite association and tholeiitic affinity of the mafic lavas

The samples analyzed in this study SiO₂ have restricted range from 46.06-48.43 wt% and GE-1 is 68.2 wt%. The Representative major-element whole rock analyses are given in Table 1(annex) and plotted as Harker diagrams in (Fig6.2) The abundance of Fe₂O₃, CaO, and tend to decrease with increasing SiO₂, whereas TiO₂, Al₂O₃ and MgO show less variation. Na₂O and K₂O have an inverse relationship and show large variations.

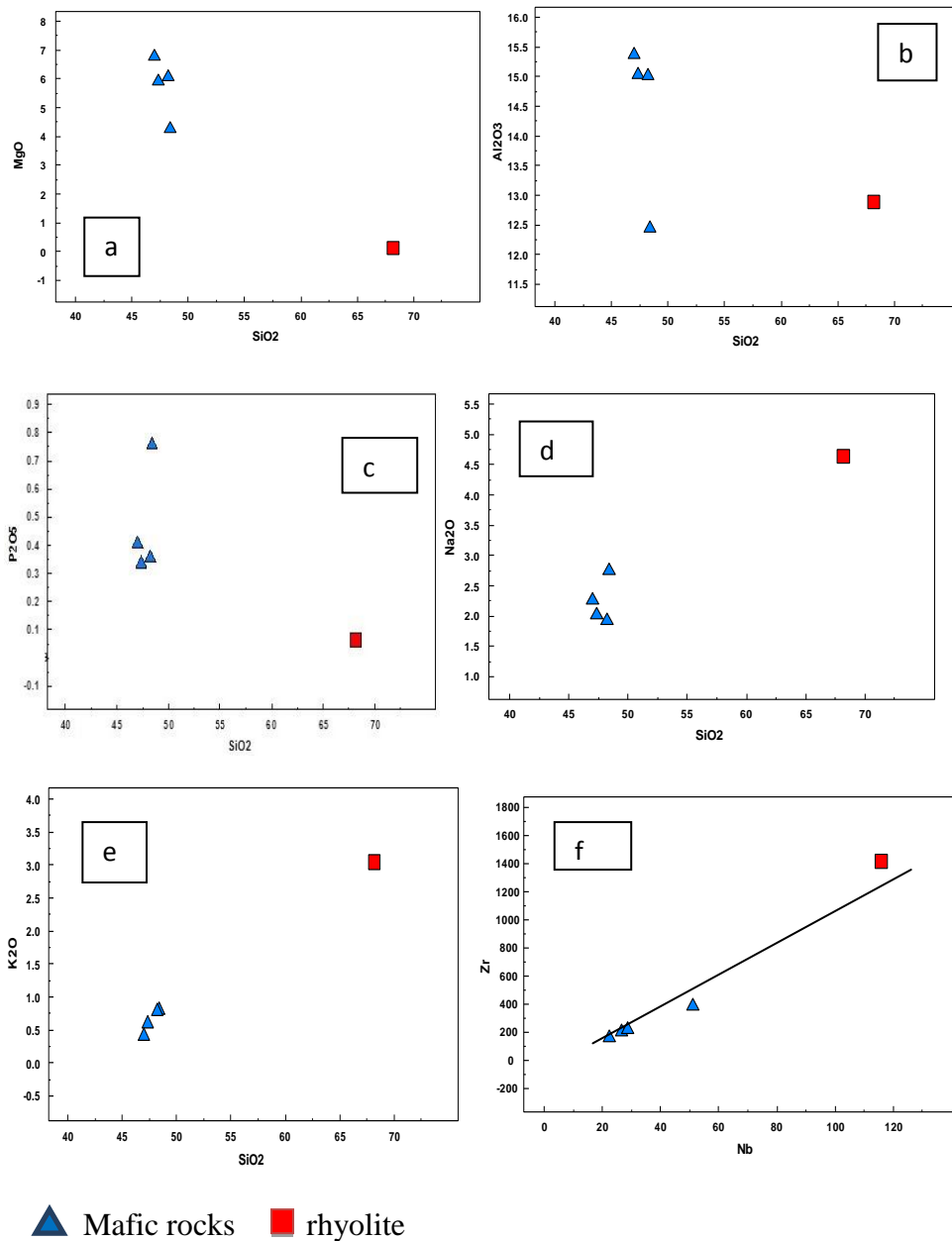


Fig 6.2 some major and trace element plots for the volcanic suites

Tectonic discrimination

According to the triangular plots of Th-Hf/3-Ta, Trace element tectonic discrimination (wood et.al 1980) for the samples of the volcanic rock fall in E-type MORB within plate theolites (fig 6.3)

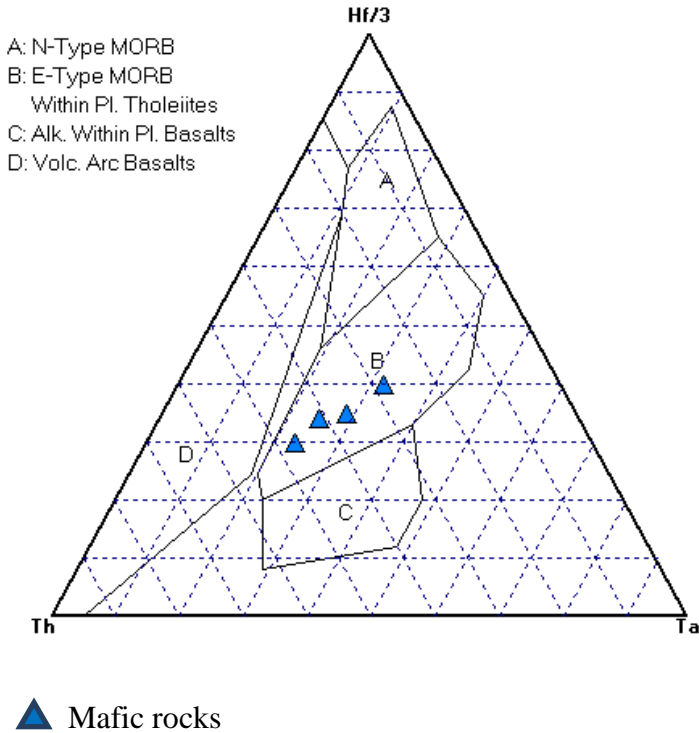


Fig6.3 Triangular plots of trace element (Th-Hf/3-Ta after wood, 1980) Tectonic discrimination of samples from the two volcanic districts

Trace element

The rhyolite is variably enriched in the whole range of incompatible element such as Rb, Th, K, LREE, Nb, Ta, Zr, Hf compared to primitive mantle (fig 6.4). It presents marked troughs in Sr, P and Ti which indicative of feldspar, Apatite and Ti-Fe oxide (Ayalew D. et al 2002). The spatial relation of rhyolite with the mafic rocks can be explained Zr vs Nb plot shows single trend, even if the sample is less (fig 6.2 f)

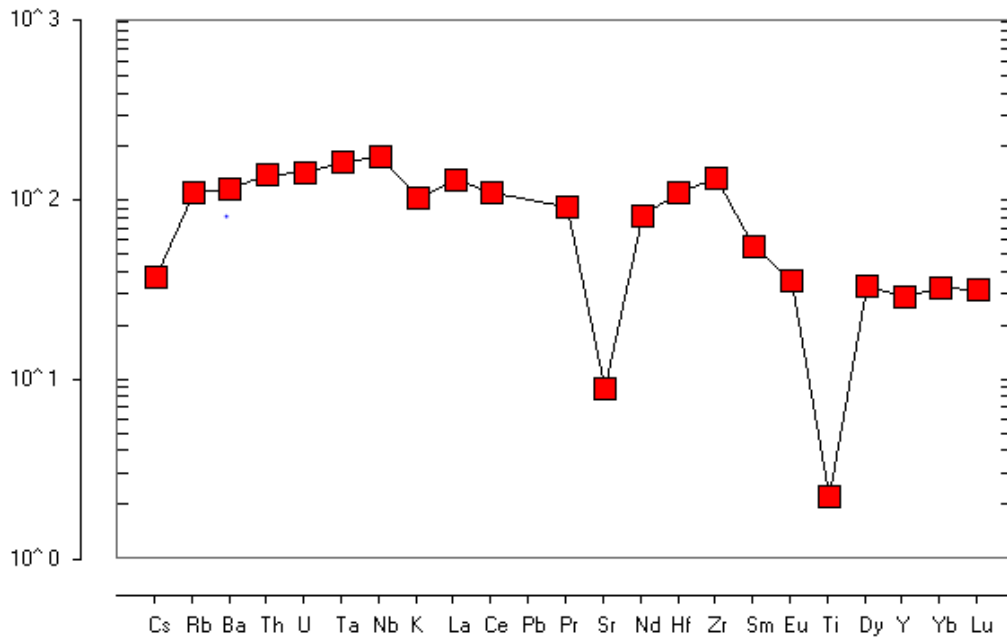


Fig 6.4 Primitive mantle normalized multi-element and chondrite-normalised REE patterns for the Gebalaytu rhyolites. Normalization values are from McDonough and Sun (1995).

Tholeiitic basalts modest enrichment in incompatible trace element and pronounced Ta and Nb anomalies (fig6.5)

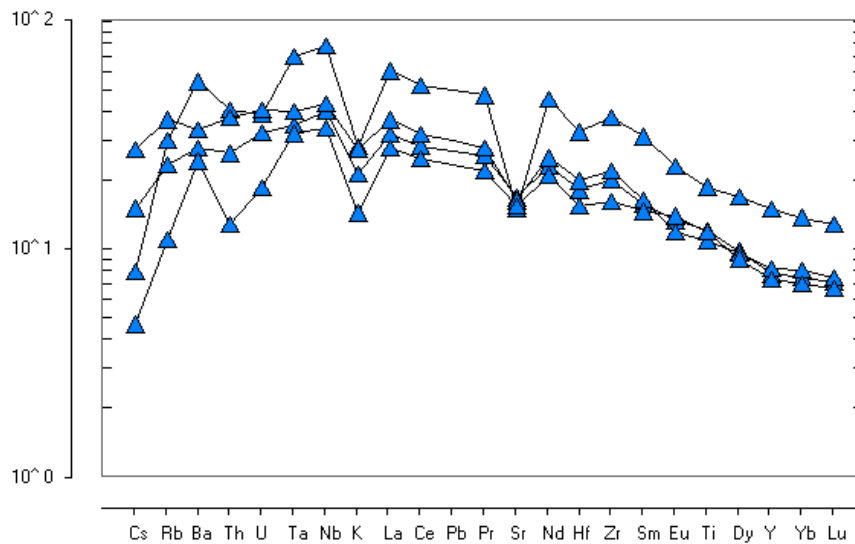


Fig 6.5 Primitive mantle normalized multi-element and chondrite-normalised REE patterns for the mafic rocks. Normalization values are from McDonough and Sun (1995).

Chondrite normalized REE plots of the volcanic suites shows in fig 6.6 relatively flat and enriched in LREE and MREE while depleted in HREE.

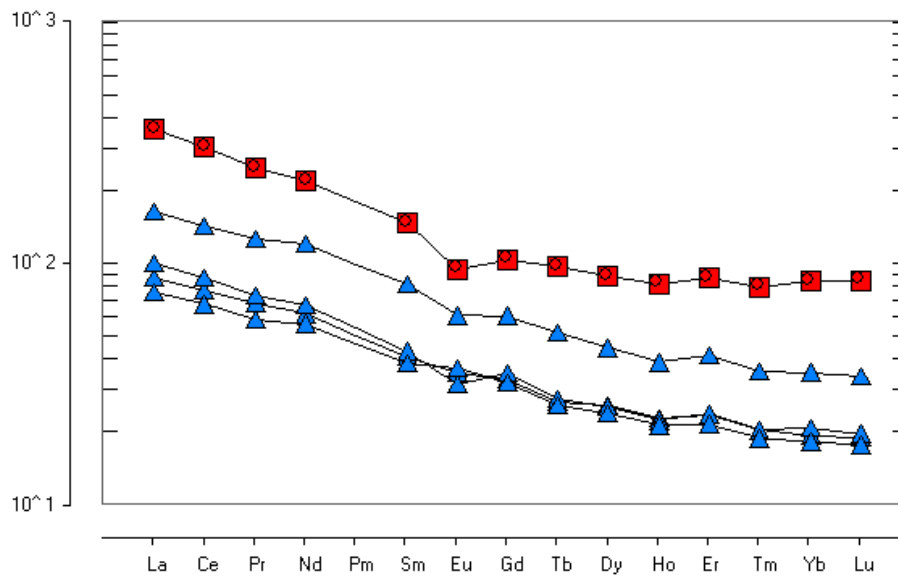


Fig6.6 Primitive mantle normalized multi-element and chondrite-normalised REE patterns for the mafic and rhyolite rocks for comparisons. Normalization values are from McDonough and Sun (1995).

6.1.2.1 Magma Evolution and Genesis

Variations in the major- and trace-element geochemistry, taken together with the observed phenocryst phases in these rocks, can help constrain the differentiation history of the volcanic rocks. The decrease in Al_2O_3 , Sr, and CaO with increasing SiO_2 and degree of differentiation, as well as relatively the negative Eu anomaly (especially the rhyolite), indicate fractionation of plagioclase, which was the major phenocryst phase found in all rock types. The decreases in MgO most likely reflect olivine fractionation in mafic rocks.

The geochemistry of the volcanic rocks from the two volcanic places important constraints on their origins. The tholeiitic characters of most of these rocks are a typical feature of mid oceanic ridges, at plate divergent zones since the thin afar crust is like oceanic crust.

There are two possible interpretations for enrichment in Th, LREE, and MREE in the mafic rocks. First, they could reflect derivation from an enriched OIB- or plume-type of source. It has been shown that large-scale upwelling of plume material has been occurring in the depression during late Oligocene-early Miocene from 27-20Ma (Audin et al., 2004)

Basalt magmas are partial melts of peridotite (olivine and pyroxene) produced by decompression melting in the Earth's mantle. As magmas cool, they precipitate out significantly more iron and magnesium. The tholeiitic magma, as it cools and preferentially produces magnesium-rich crystals, the magnesium content of the magma plummets, causing the magma to move away from the magnesium until it runs low on magnesium and simply moves away and loses iron and any remaining magnesium.

Theolites formed from high-degree (>10-20%) melting of mantle rocks that contain amounts of silica where quartz can exist under equilibrium conditions (Foulger, G.E. 2010). Tholeiitic basalts are found within the Mid Ocean Ridge (MORB) at plate divergent zones, and are depleted due to ancient melting at its source (asthenospheric mantle) during the formation of continental crust. Lherzolite, a fertile mantle peridotite, is a source of partial melting leading to theolite.

6.2 Assessments of Potential volcanic hazard

6.2.1 An overview hazard Assessment

Hazards assessments are generally predicated on the assumption that the same general areas on a volcano will most likely be affected by the same kinds of eruptive events at about the same average frequency in the future as in the past. Obviously, this assumption may not always be complete. The eruptive behaviour, vent locations, and topography of a volcano all may change with time.

Hazards zonation maps at appropriate scales should be an integral part of a hazards assessment, because they represent the pertinent information in a summary fashion readily understood by land use planners and decision makers as well as by scientists.

Volcanic hazard zone maps are perhaps the most easily understandable resources that public officials and citizens can use in planning for volcanic emergencies. The most common means by which a volcano's history and potential for future activity can be presented is a map outlining areas of risk from a particular kind of volcanic. The hazard zones must outline an area likely to be affected by an event, an alert issued immediately after the onset of any eruption could provide enough time for the people to escape, if they are informed and prepared in advance. Additionally, government authorities must evaluate volcanic hazard zone maps, along with socio-economic and political factors, to develop long-range land-use plans.

Hazard maps play an important role in identifying the location and countermeasures to be taken during volcanic crisis. Moreover, hazard maps allow all sectors in their responsible participation in the disaster mitigation process.

Volcanic hazards assessments and/or hazards zonation maps are now available for a number of the world's high-risk volcanoes or volcanic regions. For this study I have tried to assess the possible hazards and zonation maps are delineated.

6.2.2 Assessment of potential volcanic hazards from future eruption of Gebalaytu and Kurub

As I have discussed earlier volcanic hazard assessment and zonation started from the assumption that future volcanic eruption will have similar scenario of its past volcanic evolutions. Furthermore, it has been established that Gebalaytu and Kurub volcanoes are an active volcano with a recent history of both effusive and somewhat explosive eruption styles. It has been mentioned that no recorded eruption history exists and hence the time intervals between eruptions are not well known. However, the two volcanoes are currently in a dormant state, the very young age of the eruptive products together with the present thermal manifestations (the existence of numerous fumaroles, hot grounds, high temperature at the surface and shallow depths) are strong indications that it may turn into an eruptive phase in the future.

Because of the lack of volcano monitoring practice in many developing country like Ethiopia it is reasonable to assume that future eruptions from active volcano will follow similar eruptive characters and patterns that occurred in its recent activity. Hence the future eruption activity of Gebalaytu and Kurub volcano follows the same trend as in the past. Hence, a potential future eruption may take either an effusive or explosive character and will possibly mainly lava flows and may include explosive. The different types of volcanic products existing at different places on Gebalaytu and Kurub volcanoes and surrounding areas are indicative of the areal extent that resulted from the past eruptions. Based on the variety of past eruptive products described in earlier sections as well as eruption types inferred from them, the types of main potential volcanic hazards that may occur from the possible future eruption are

- Rhyolite lava flows and domes
- Possible Large volume of basaltic eruption in the form of lava flow and pyroclastic material(scoria)

Flow hazards

Flow hazards might result from both of lava and pyroclastic flows products. The lava flow hazard will be controlled by viscosity of magma, volume of magma chamber, vent orientations and slope of the surface. Viscous lavas such as dacite and rhyolite which are typically erupted

at low rates form short stubby lava flows or steep sided domes that cover only a few square kilometres (Scott, W. E. 1989a).

The two biggest factors in a lava flow is the topography in the area and the thickness of the magma coming from the underground. Therefore, such a lava flow map has to be delineated mainly by using a Digital elevation model. (Jensen 2010)

To be able to map lava flow it is necessary to know the dynamics of lava and how it behaves. In general, it can be said that lava flow is 'partially molten rock that cool as they flow, in some cases melting the surface over which they flow but in all cases gradually solidifying until they come to rest.' (Griffiths 2000) Lava flow has a behaviour that is instable and depends 'on the properties of the erupted magma, the effusion rate, the ground topography over which the lava flows, and its new environment (which primarily determines the rate of heat loss).' (Griffiths 2000) This might eventually lead to a halt of the flow front, sometimes even before the eruption stops. (Griffiths 2000).

In the case Kurub volcano is basaltic lava flow is the main product, Depending on the topography and thickness of the lava flow may cause the possible prone area from the existing vent is delineated using basaltic magma rheology(fig6.6)

While In the case of Gebalaytu volcano the same method is followed because some products of the volcanos are lava flow type and the acidic product of the volcano which is rhyolite the same theory is governed. Even though rhyolite lava flow may cover limited square km. It can cause ruthless hazards within some tens km radius. Using, the possible flow prone area from existing vents is delineated using rhyolite magma rheology (fig6.6)

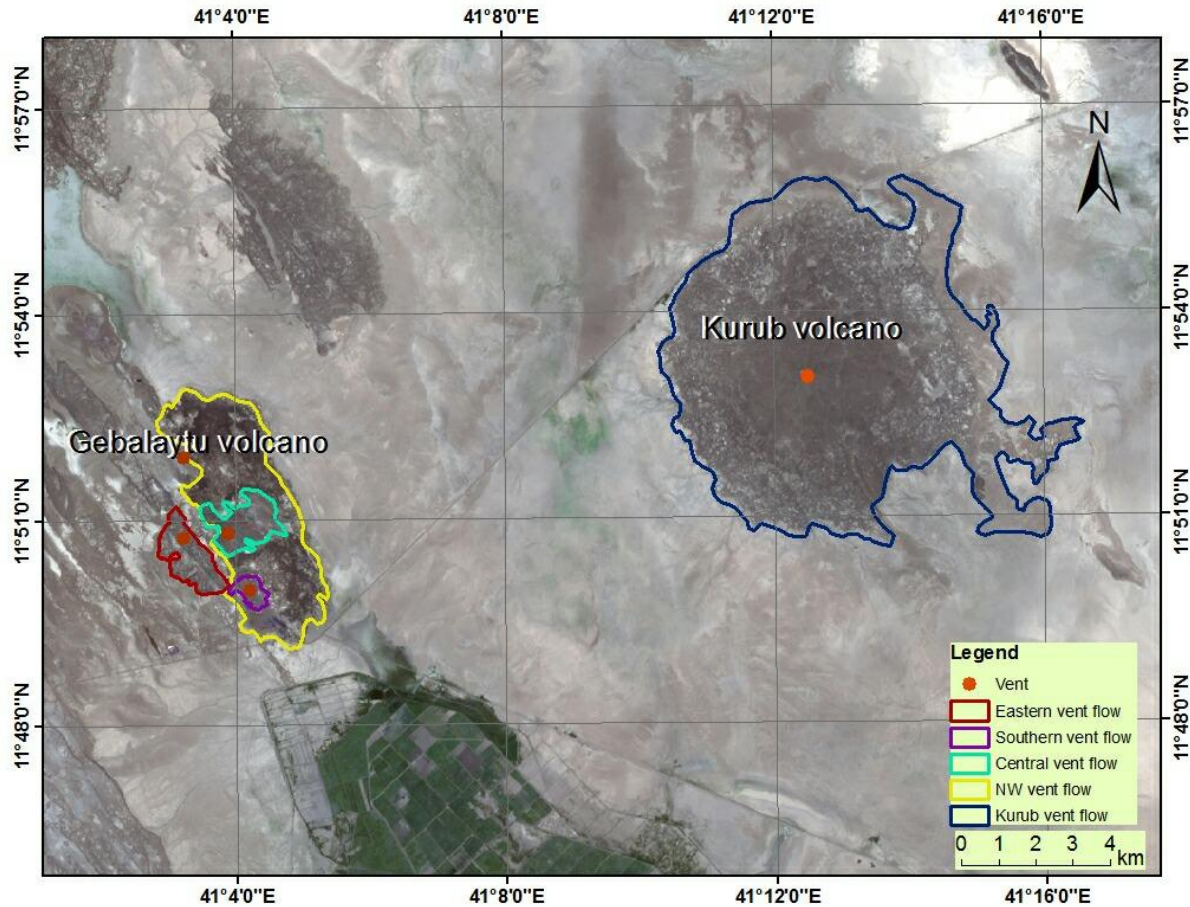


Fig 6.7 possible lava flow of Gebalaytu and Kurub volcanoes

Lava flows generally will be based on topography, flow path, magma nature, volatile content vent orientation, and vent diameter and slope percent. From elevation profile of the volcano, the lava flow will follow the down slope of volcano in all direction. Because Kurub volcano is in the center of the Tendaho graben the lava can flow in every direction and it has steep slope angle.

The vent elevation which 532m.a.m.s.l (Land Sat 50m). The bottom of Kurub volcano the elevations fall to in the range 322-366m.a. m. s. l.

In case of Gebalaytu, from elevation profile of the volcano, the lava flow will follow the down slope of Gebalaytu, south and east of the volcano is low land and has relatively steep slope angle,

especially to the east (Gebalaytu plain) the south (InkisaGentu plain) while the west and north is restricted because of the topography (i.e. rift margin basalt block the movement).

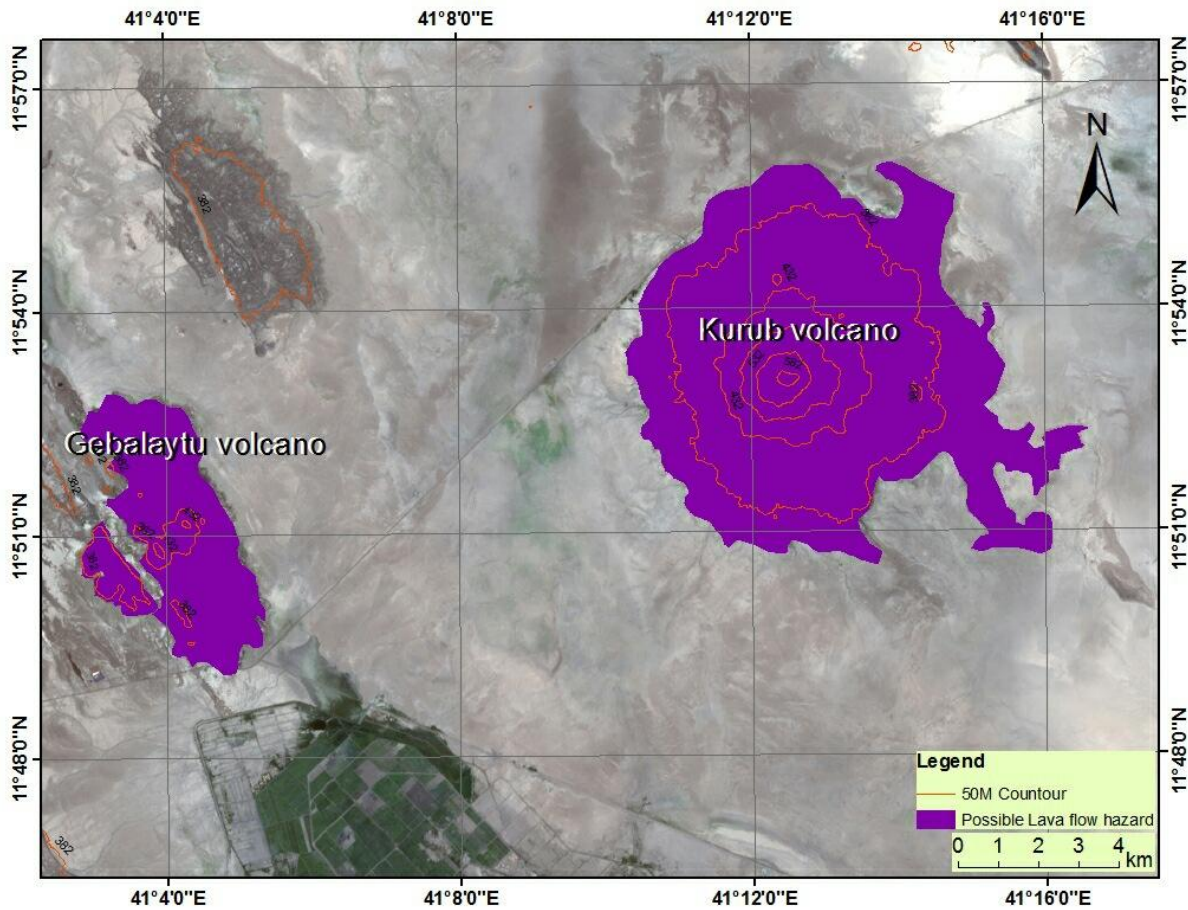


Fig 6.8 possible lava flow hazards from both volcanoes from each vent

6.2.2.1 Tentative volcanic hazard map of Kurub and Gebalaytu volcano

A Holocene Gebalaytu volcano known by, dominantly lava flow some acidic flow of rhyolitic rocks and somewhat a pyroclastic eruption of scoria. The volcanic eruption style is also estimated to Hawaiian or Icelandic eruption style, Based on interpretation of its earlier products. Gebalaytu has effusive eruption and somewhat explosive history.

After incorporation of all methodology and criteria, tentative hazard zone map could be produced using GIS and Remote sensing approach, a method called buffer analysis. The area is divided in to two zones based on earlier product evolution and thickness of deposits coverage and elevation profile. The tentative map of the hazard zone is primary that limited to about 10km radius .

Therefore from the observed past volcanic products, possible future eruption and current manifestations the future possible volcanic hazard of Gebalaytu can be categorized into two major hazard zones: high hazard zone and low hazard zone.

Flowage-hazard zone

Zone 1 represent the area vulnerable to passage of high-concentration of flows including lava flows, and rhyolitic lava flow. The possible future flowage hazards lava flow perpendicular down to the vents. This zone might have area coverage of about 47.45km²; it is hazardous of both lava flow and rhyolite flow. The region is covered with lava flows rhyolite and scoria fall products which is about 10m thick in average. Thus this area has very high probability to be affected by all volcanic hazard types. The elevation difference might facilitate for lava flow

Zone 2 is assigned Low hazard zone that is assumed to be of lava flow hazards is completely be stop by topographic features and magma nature.

Kurub isolated volcano also entirely basaltic lava flow and based on the earlier product the tentative map is produce as in Gebalaytu after incorporation of the relevant data to GIS environment the possible or tentative map is generated. The area is divided in to two zones based on earlier product evolution and thickness of deposits coverage and elevation profile. The tentative map of the hazard zone is primary that limited to about 10km radius.

Tentative volcanic hazard map of Kurub

Kurub isolated volcano also entirely basaltic lava flow and based on the earlier product the tentative map is produce as in Gebalaytu after incorporation of the relevant data to GIS environment the possible or tentative map is generated. The area is divided in to two zones based on earlier product evolution and thickness of deposits coverage and elevation profile. The tentative map of the hazard zone is primary that limited to about 10km radius.

Flowage hazard zone

Zone one represents the passage of high concentration of lava flow and that follow perpendicular down to the slope of the vent and the area coverage is 70.56km²; it is hazardous

Zone two represents relatively low flow even if the topographic feature is plain towards all direction it may be controlled by magma viscosity

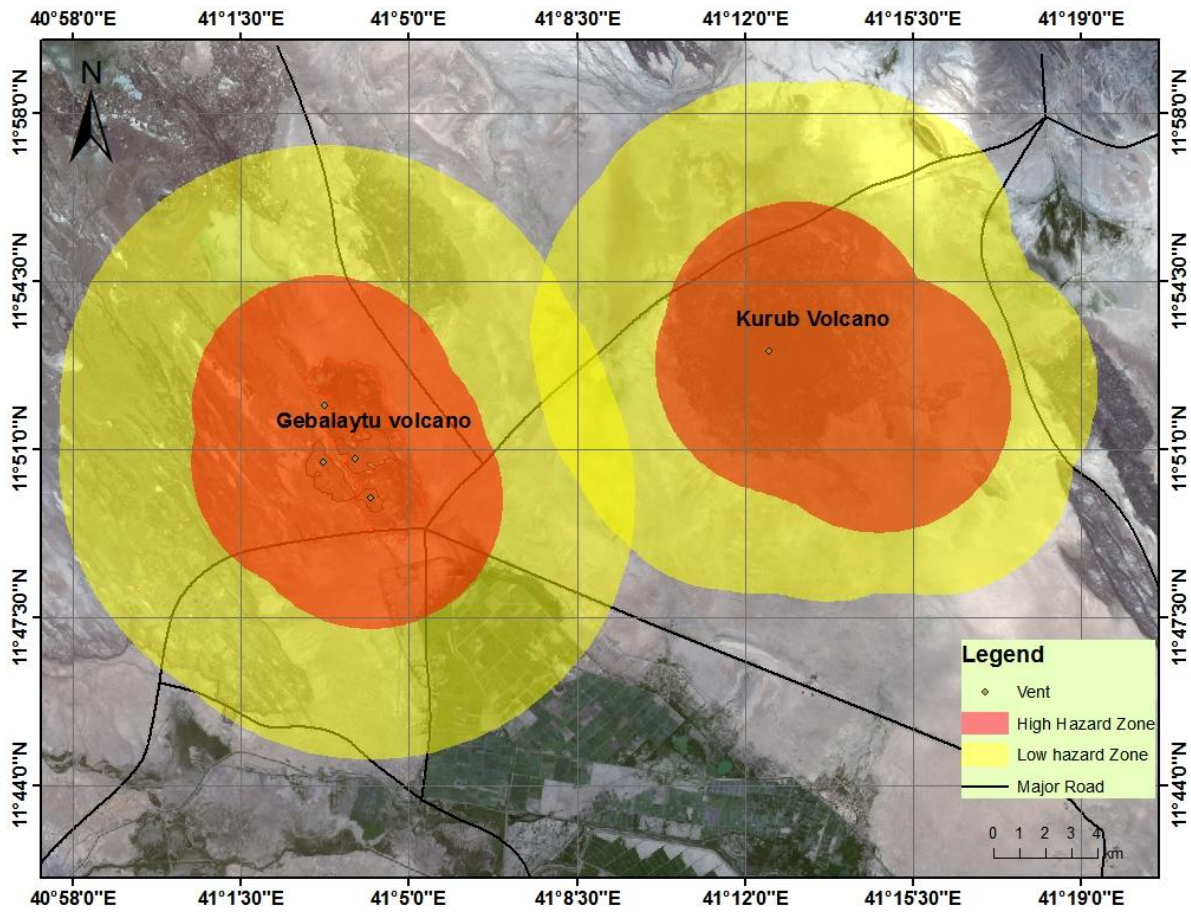


Fig 6.9 Tentative Lava flow Hazard Map of Gebalaytu and Kurub volcano 5km buffer from each vent

7. Conclusion and Recommendation

7.1 Conclusion

Gebalaytu and Kurub Holocene volcanoes are active volcanoes. Geological manifestations are indicators for its activeness and the re-eruption of the volcanoes in near future might be expected.

Gebalaytu and Kurub volcanoes are evolved from partial melting of asthenosphere mantle and associated silicic rocks are evolved from fractional crystallization of partially melted mantle. Gebalaytu volcanic rocks show tholeiitic affinity sub alkaline nature which is found in divergent plate boundaries the continental rift which has an oceanic crust type may produce tholeiitic magma. Kurub volcano shows a tholeiitic nature but the Fe₂O₃ content is high.

The petrography of Gebalaytu volcano show moderate to highly phenocryst (5%-20%) most of the phenocryst is plagioclase and shows Carlsbad twining in most of the sample. Rhyolitic rocks are plagioclase phenocryst and volcanic glass. While Kurub volcano shows Glomeroporphyritic texture and plagioclase dominated phenocryst and olivine dominated phenocryst with small vesicles and large vesicle up to 1cm in diameter.

The geomorphic and volcanic map of the volcano is produced. From earlier products of both volcanoes probably Hawaiian eruption style, were non explosive and somewhat explosive eruptions. Kurub volcano form shield type volcanic land form.

Magnitude of hazard and probable area of coverage for flow products hazards are assessed, delineated and tentatively zoned as its brutality. There were two zones delineated within 10km from all vents at GIS environment. Its earlier products for geological mapping and current coverage area are used to produce hazard zones.

The first zone is prepared within 5km labelled high hazard zone which is considered as very high hazard zone for non-explosive eruption.

Second zone is labelled is low hazard zone which has radius 10km from each vent in all directions. This zone is described as moderately hazardous for non-explosive. This hazard zone has low probability to be covered with lava flow.

7.2 Recommendation

Based on the experience gained from this study and review of different journal articles, I recommend the following points.

- ✚ Volcanically and seismically active tectonic region like Afar it is obvious that various natural hazards are evolved: including volcanic and seismic hazards, however the region lack any attention concerning the natural hazards because the region is desert, now there are some progress in economic activities as a result to protect and save a damage both property and human life it needs much attention.
- ✚ Most peoples are living near active volcano, however there is a lack of volcanic awareness and early warning system in developing countries like Ethiopia; government should use society awareness creation about volcano for those living nearby it.
- ✚ In developing country like Ethiopia volcanic hazards assessment and monitoring practice is poor so as to decrease the fatality, the monitoring practice should be started because most of active and explosive volcanoes found in the region.
- ✚ Finally Scientists and researcher should also participate in assessing the future activity of the many active volcanoes of the region using the current technological equipment and methods to come out the possible prone area map for the community and land use plan.

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Appendices

sample no	Al2O3	BaO	CaO	Cr2O3	Fe2O3	K2O	MgO	MnO	Na2O	P2O5	SO3	SiO2	SrO	TiO2	LOI 1000
Ku-1	12.46	0.04	8.85	<0.01	16.76	0.82	4.31	0.28	2.78	0.76	0.11	48.4	0.04	3.79	0.37
GE-01	12.88	0.09	2.61	<0.01	7.53	3.03	0.12	0.22	4.62	0.06	0.03	68.3	0.02	0.46	-0.07

GE_02	15.05	0.03	10.3	0.03	13	0.62	5.97	0.2	2.05	0.34	0.1	47.4	0.04	2.44	2.67
G3-03	15.04	0.03	10.2	0.03	12.4	0.8	6.1	0.19	1.95	0.36	0.04	48.3	0.04	2.21	2.39
G4-04	15.4	0.03	12	0.04	12.96	0.42	6.81	0.21	2.29	0.41	0.07	47.1	0.04	2.41	0.17

Ba	Ce	Cr	Cs	Dy	Er	Eu	Ga	Gd	Hf	Ho	La	Lu	Nb	Nd	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Th	Tm	U	V	W	Y	Yb	Zr
361	88	<10	0.17	12	6.98	4	24	13	9	2	39.4	0.9	51.3	56.9	12	18.2	12.8	3	303	2.6	1.96	3.3	0.9	0.8	368	1	65	6.12	398
781	189	10	0.8	23	14.6	6	28	22	32	5	85.7	2.2	116	104	24	67.5	22.7	7	180	6.1	3.67	11	2.1	2.9	<5	2	128	14.5	1410
184	48	220	0.32	6.7	3.99	2	20	6.9	5	1	20.9	0.5	26.6	29.3	6.6	14.2	6.41	2	338	1.3	1.02	2.1	0.5	0.7	293	1	34	3.36	213
221	54	210	0.58	6.6	4.01	2	21	7.3	6	1	24.1	0.5	28.7	31.7	7.1	22.3	6.71	2	328	1.5	1.05	3	0.5	0.8	297	1	36	3.6	233
162	42	250	0.1	6.2	3.64	2	19	6.7	4	1	18.2	0.5	22.4	26.6	5.6	6.7	6.01	1	311	1.2	0.98	1	0.5	0.4	346	<1	32	3.16	171

DECLARATION

I, the undersigned, declare that this is my work and that all sources of materials used in the thesis are dully acknowledged.

Yonas Teshome

Signature.....

This Thesis has been submitted for examination with my approval as research advisor.

Dr. Asfawossen Asrat

Signature.....

Addis Ababa, June 2015