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An outline of the East African Rift Volcanism

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1. Introduction

The East African Rift System (EARS) is a more than 3000 km long system of depressions flanked by broad uplifted plateaus. A long record of volcanism in EARS provides invaluable constraints on past and present processes, as well as the various depth levels of magma generation and storage. In this presentation, I outline volcanic processes along the length of the EARS from pre-rift setting through rift initiation to continental breakup.

The volcanic evolution of the EARS reveals consistent patterns in the distribution, volume, compositions and sources of volcanic products allowing its subdivision into volcanic provinces. EARS extends from the Red Sea in the north to Mozambique and beyond. The system is characterized by regional topographic uplift, the Ethiopian dome, the Kenyan dome. The principal rift sectors include the Ethiopian, Eastern and Western rift valleys. The Ethiopian and Kenyan branches of the rift are the site of substantially greater volcanism than is observed at the Western rift.

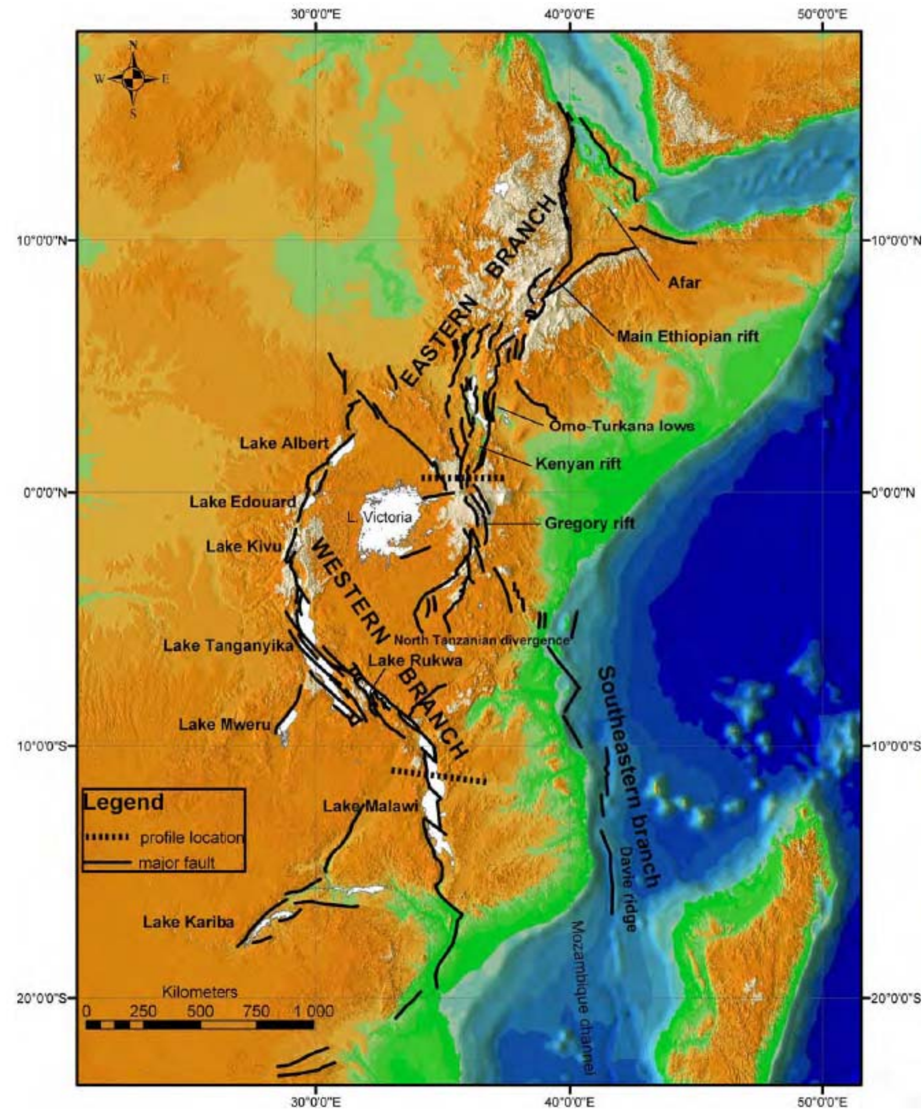

Figure 1 Digital Elevation Model of the East African rift System. Black lines are main faults

2. Volcanic Provinces and distribution

Within Ethiopia, we distinguish three separate volcanic sub-provinces: pre-rift plateau, Afar rift and the Ethiopian rift. The northern Kenya rift comprises the Turkana, Huri Hills and Marsabit regions, as well as the Quaternary central volcanic complexes of Emuruangogolak, Namurunu, Silali, Paka and Korosi Volcanic complexes in central and southern Kenya rift include the within-rift centres Menengai, Eburru, Naivasha, Longonot, Suswa and Lenderut as well as off-rift volcanic field at Chyulu Hills In the Western rift, eruptive activity is restricted to four spatially distinct sub-provinces along the rift axis. From north to south these are: the Toro-Ankole region in western Uganda, the Virunga and Kivu sub-provinces along the border of the Democratic Republic of the Congo with Uganda, Rwanda and Burundi and the Rungwe volcanic field in southwestern Tanzania. The Rungwe Volcanic Province has been a long-lived volcanic area in the past 9 Ma and is developed at a triple junction of the EARS.

The Oligocene flood basalt province, within Ethiopia and Eritrea, covers an area of about 600,000 km^2, with an estimated total volume of about 350,000 km^3. The thickness of this lava pile varies, reaching up to 2000 m in northwest Ethiopia and thinning to ~500 m towards both north and south. Well-developed polygenetic calderas are situated in the center of the Main Ethiopian Rift axis. Recent basalts are erupted from within fissures adjacent to and distal from these central volcanoes. Quaternary volcanism covers about two-thirds of the Afar Depression at the northern end of the Triangle. The axial part of Afar is characterized by discrete active magmatic segments (axial ranges) that are considered nascent oceanic ridges in stretched continental lithosphere.

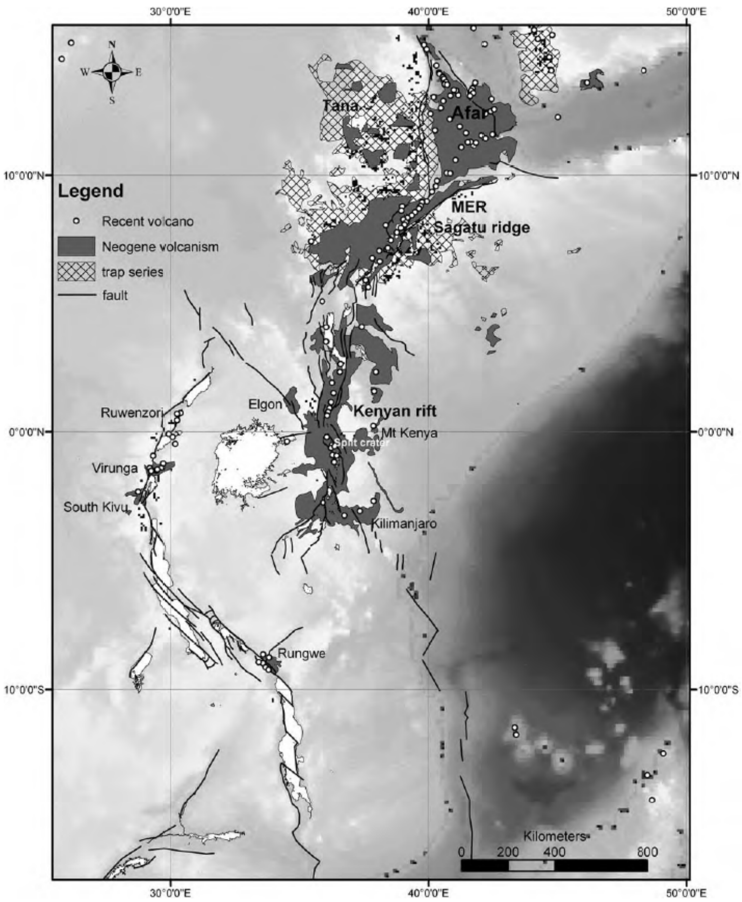

Figure 2 Spatial and temporal distribution of volcanism in the EARS (source, USGS database).

3. Modes of eruption

Volcanism in EARS is emplaced in different styles. Older pre-rift flood volcanics in Ethiopia, Eritrea and Kenya are emplaced in the form of extensive sheets forming piles of flat-lying layers (Figure below). These products are dominantly mafic and alkaline lavas but include sheets of felsic pyroclastic layers produced by explosive eruptions.

Rift-related volcanism dominantly occurs in the form of central edifices made up of mafic or felsic products or both. Silicic units show eruption styles varying from large-volume explosive pyroclastic eruptions producing ignimbrites and tuffs, to smaller volume mixed effusive-explosive eruptions emplacing silicic lavas intercalated with tuffs and ignimbrites. Active volcanoes include lava flows mafic, intermediate and felsic in composition or pyroclastic explosive products.

Examples of flood basalts, stratovolcanoes, short lava flows and scoria cones are shown in the figures below.

Figure 3 Flood basalts, Ethiopian plateau.

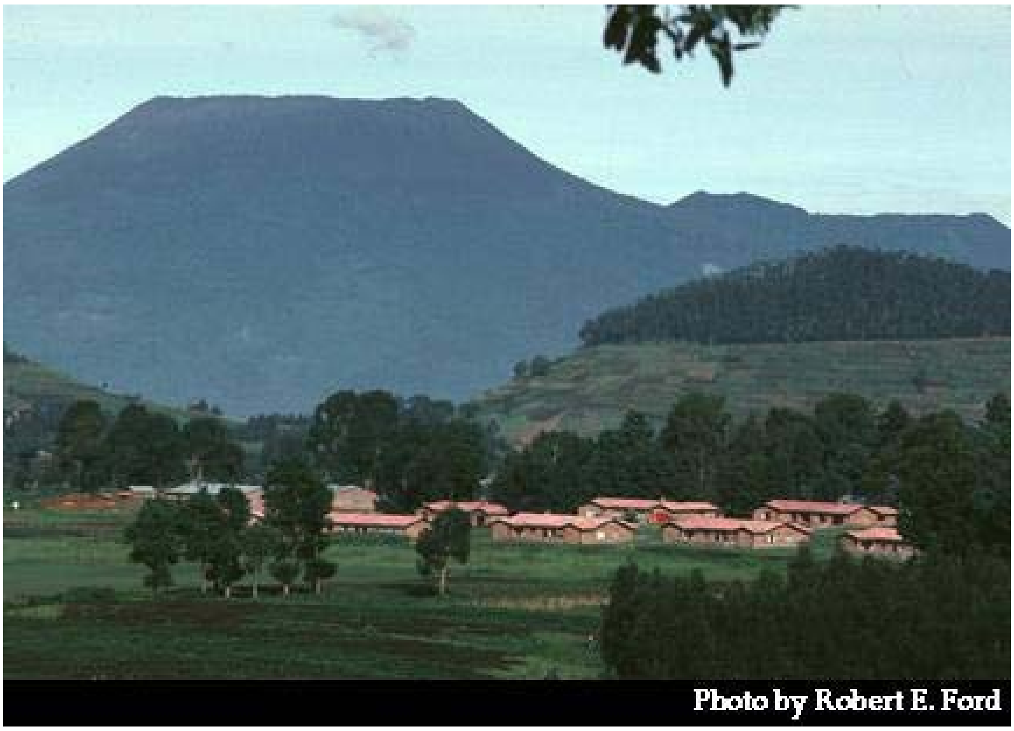

Figure 4 Nyiragongo volcano

Figure 5 Stratovolcano (Fantale) in the Main Ethiopian rift.

Figure 6 Young basaltic lava flows and associated scoria cones in the main Ethiopian rift.

4. Timing and duration of volcanism

The earliest recorded volcanic activity in the EARS region took place 40-45 Ma in southernmost Ethiopia/northern Turkana depression. Then, flood basalts, forming the Ethiopian and Eritrean plateaus erupted apparently in short time interval (<5 Ma) with the greatest eruption rates during 31 to 28 Ma. This event was followed by shield-volcano-building episodes, (23 to 11 Ma) on the northwestern and southeastern Ethiopian plateaus.

The magmatic activity in the Main Ethiopian rift was episodic rather than continuous with lesser amount of magma relative to the ~30 Ma flood basalts. In southwestern Ethiopia volcanism started in the early Miocene around 20–21 Ma and reached the central and northern portions of the Main Ethiopian rift ~11 Ma. This was followed by the eruption of voluminous ignimbrites in the Central MER during the Pliocene (5–3 Ma).

Magmatic activities in the broad rift zone of Turkana Depression are episodic. Three discrete volcanic episodes have been described as (1) prerift late Eocene–early Oligocene magmatism (32–40 Ma) in the south central portion of the rift (Kajong area and Mount Porr), (2) more voluminous synrift magmatism at 26–16 Ma in the western and eastern part of the rift (Lodwar and Jarigole area), and (3) Plio-Pleistocene to present eruption of axially aligned composite volcanic centers. Since the earliest volcanism in the Turkana region, the onset of magmatism has also migrated southward through central and southern Kenya, finally reaching northern Tanzania some 5–8 Ma.

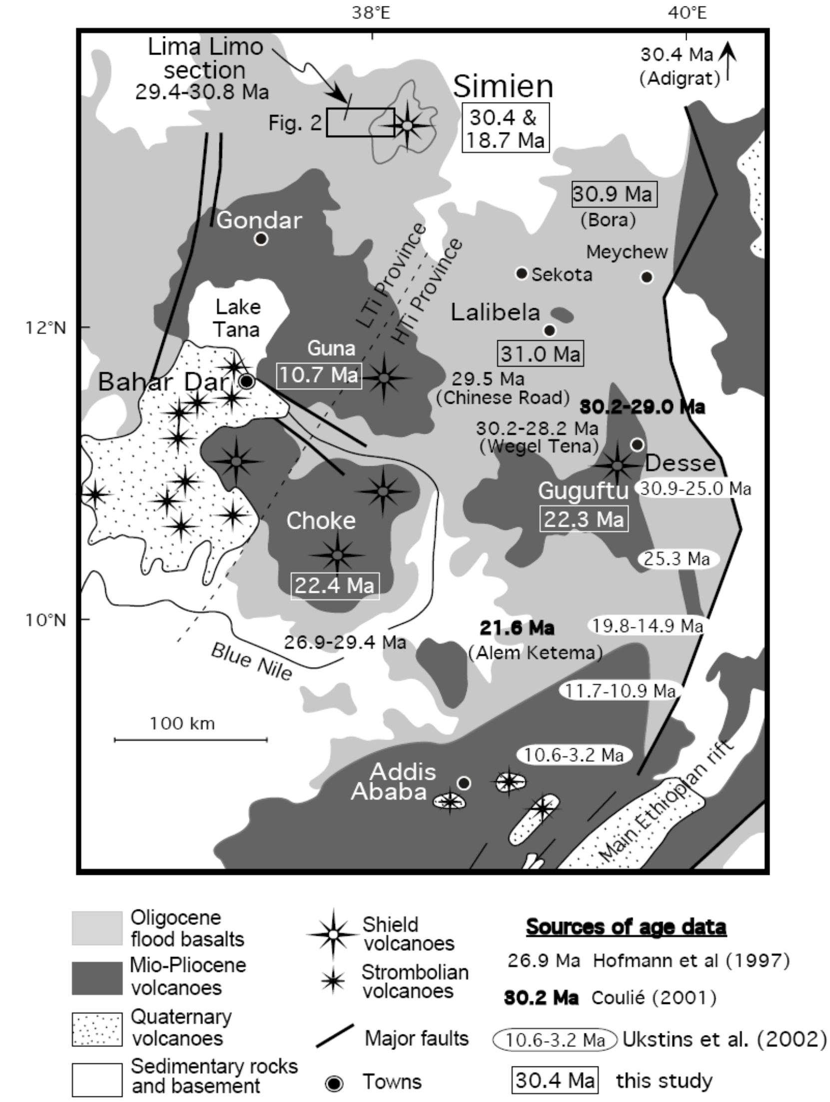

Figure 7 Map of the northern part of the Ethiopian plateau: showing flood volcanism and shield volcanoes

Duration of volcanism in various sectors of EARS may be summarized as follows.

In Ethiopia,

- In southwestern Ethiopia: 19-17 Ma;
- In southern Afar, volcanic events occurred at 14–11;

In the northern Kenyan rift,

- Basalts and rhyolites were emplaced at 33–25 Ma;
- Then nephelinites and phonolites at 26–20 Ma; 15 Ma
- Beginning of the Pliocene, trachytic, phonolitic, nephelinitic rocks, and basaltic volcanism were accompanied with some rhyolitic activity

In the central Kenyan rift,

- Flood basalts erupted between 20 and 16 Ma,
- Large volumes of trachyte and phonolite between 5 and 2 Ma;
- Carbonatite and nepheline-phonolite volcanoes around 1.2 Ma

In the Western rift branch

- In the north (Ruwenzori), volcanism began at 12 Ma
- In the Virunga, massif fissure volcanism started between 11 and 9 Ma,
- Large Pliocene-Pleistocene central volcanoes were formed,
- In the Rungwe province activity began at 8.6 Ma

5. Magma Compositions and Petrogenesis

Lavas erupted along the EARS display a wide range of geochemical compositions that reflect heterogeneity in both magmatic processes and mantle sources. The Ethiopian Oligocene flood basalts are primarily tholeiitic-transitional in their petrology. The southwest Ethiopia volcanic province is characterized by episodic volcanism that becomes increasingly silica-saturated through time, ranging from essentially tholeiitic compositions 40-45 Ma to nepheline-normative basalts since ~19 Ma. These features are similar to those displayed by contemporaneous lavas from the Turkana region which is located immediately to the south. Within Ethiopia, the MER basalts are transistional-tholeiitic overall, with evolved products encompassing primarily rhyolites and trachytes. The northern Kenya rift mafic lavas associated with central volcanoes are transitional-tholeiitic basalts; the corresponding felsic lavas are dominantly trachytic in composition. Volcanic complexes in the axial part of the central and southern Kenya rift are dominantly trachytic to pantelleritic with little to no exposure of basalts. Where present the basalts are dominantly transitional-tholeiitic, although the Chyulu Hills lavas are markedly silica-undersaturated. The lavas in the Western rift are characterized generally by silica-undersaturated mafic volcanoes the products of which include ultrapotassic, hypersodic and carbonatitic compositions.

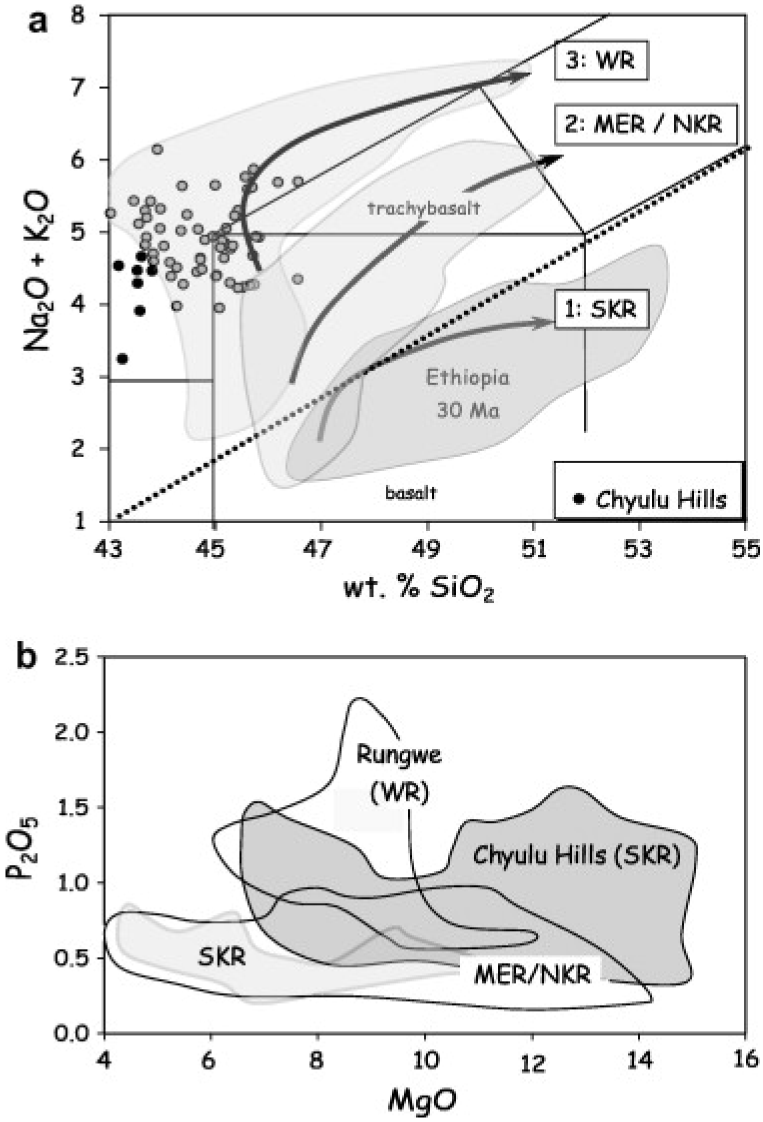

Figure 8. Major element variations in African Rift mafic lavas. (a) Within-suite variations in total alkalis against silica define consistent regional patterns. The dotted line is the alkaline-tholeiitic division of Macdonald and Katsura (1964).

Trend 1: Silica-saturated lavas from Naivasha in the southern Kenya Rift (SKR) overlap the field of quartz- and hypersthene-normative 30 Ma Ethiopian flood basalts (shaded). Trend 2: Lavas from the northern Kenya Rift (NKR; Turkana, Emuruangogolak, Silali, Huri Hills) as well as basalts from the Main Ethiopian Rift (MER) define a transitional-tholeiitic sequence. Trend 3: The most highly silica-undersaturated samples are found in the Western Rift (WR; e.g., Rungwe, Muhavura) and southern Kenya (Chyulu Hills). (b) Variations in P_2O_5 against MgO show similar regional trends. Tholeiitic basalts from the southern Kenya Rift (SKR: Ol Tepesi, Singaraini, Kirikiti) have the lowest overall incompatible element contents.

Transitional tholeiites from Turkana, Huri Hills and the northern Kenya Rift (NKR) and Main Ethiopian Rift (MER) have higher incompatible element abundances, and silica-undersaturated lavas from Chyulu Hills and the Western Rift (WR; here represented by the Rungwe province) have the highest incompatible element contents. Source: Furman 2007.

The EARS magmas are widely variable from alkaline to hyperalkaline, with widely varying geochemical and isotopic compositions. Extensive polybaric fractionation within the upper mantle and lower crust accompanied by crustal assimilation. Fractionation generated a wide range of mugearitic, trachytic, peralkaline rhyolites and phonolitic magmas. Crustal anatexis has locally resulted in the formation of peralkaline rhyolites.

The southwest Ethiopia volcanism ranges from essentially tholeiitic compositions 40-45 Ma to nepheline-normative basalts since ~19 Ma. MER basalts are transistional-tholeiitic overall, with evolved products encompassing primarily rhyolites and trachytes.

The northern Kenya rift mafic lavas are transitional-tholeiitic basalts, the corresponding felsic lavas are dominantly trachytic in composition. Central and southern Kenya rift volcanics are dominantly trachytic to pantelleritic. The basalts are dominantly transitional-tholeiitic

Oldoinyo Lengai (N Tanzania) is the only active carbonatite volcano, typically involving extreme low viscosity magmas. The origin of its unique natrocarbonatites remains a key topic for debate.

Western rift mafic lavas are silica-undersaturated including ultrapotassic, hypersodic and carbonatitic compositions. Virunga volcanics show silica undersaturated, ultraalkaline, alkalic-mafic compositions.

6. Melting conditions (depth and extent of melting)

Available trace element data in the East African Rift lavas show general patterns in the extent of melting and source mineralogy. Turkana basalts and Main Ethiopian Rift lavas record the highest degrees of melting and, correspondingly, the lowest proportion of amphibole in the source rock. Similarly mafic lavas from most sub-provinces of the Western Rift, as well as lavas from throughout Kenya and the Turkana areas, derive by higher degrees of melting of amphibole lherzolite, On the other hand the silica-undersaturated lavas of the Chyulu Hills province are derived by the lowest degrees of melting of amphibole-bearing source material (i.e., lowest K/Th); Nyiragongo lavas formed at greater depths by low degree partial melting of a garnet, clinopyroxene, and phlogopite-bearing carbonated mantle, while the Nyamuragira lavas are products of larger degree partial melting at comparatively shallower mantle depths with a recycled crustal component.

7. Source regions of magmas

Many researchers have suggested one or more mantle plume models that they consider consistent with the geophysical features and with the geochemical and geological evidences. High He isotopic values (9 and 19R_A) in Oligocene flood basalts as well as in young mafic lavas from the Main Ethiopian Rift require a contribution from an undegassed lower mantle source region, i.e., an upwelling plume. In addition, interaction of mantle plume-derived magmas with various proportion of upper mantle (DM) and lithospheric mantle and/or continental crust sources were suggested for the genesis of EARS lavas on the basis of trace elements and Sr-Nd-Pb-He isotopic compositions. Recently, *Furman* [2007] provided petrological, geochemical and geodynamic overview of the plume-related magmatism of the EARS and concluded that three distinct source components (or domains) control magmatism throughout the broad area from the Afar triangle in northern Ethiopia to the Rungwe province in southern Tanzania:

(1) the subcontinental lithospheric mantle, which is the ultimate source of ultrapotassic and other silica-undersaturated lavas erupted in the Western and Southern Kenya Rifts;
(2) a plume source with high-μ (HIMU) Sr-Nd-Pb-He isotopic affinities and is present in all volcanic systems within and south of the Turkana Depression; and
(3) a plume source with nonradiogenic Sr-Nd-Pb isotopic values but radiogenic He isotopic signature, analogous to those observed in some ocean islands, and is recorded in all Oligocene flood basalts and younger volcanic systems throughout the Main Ethiopian Rift and northward to the Afar region.

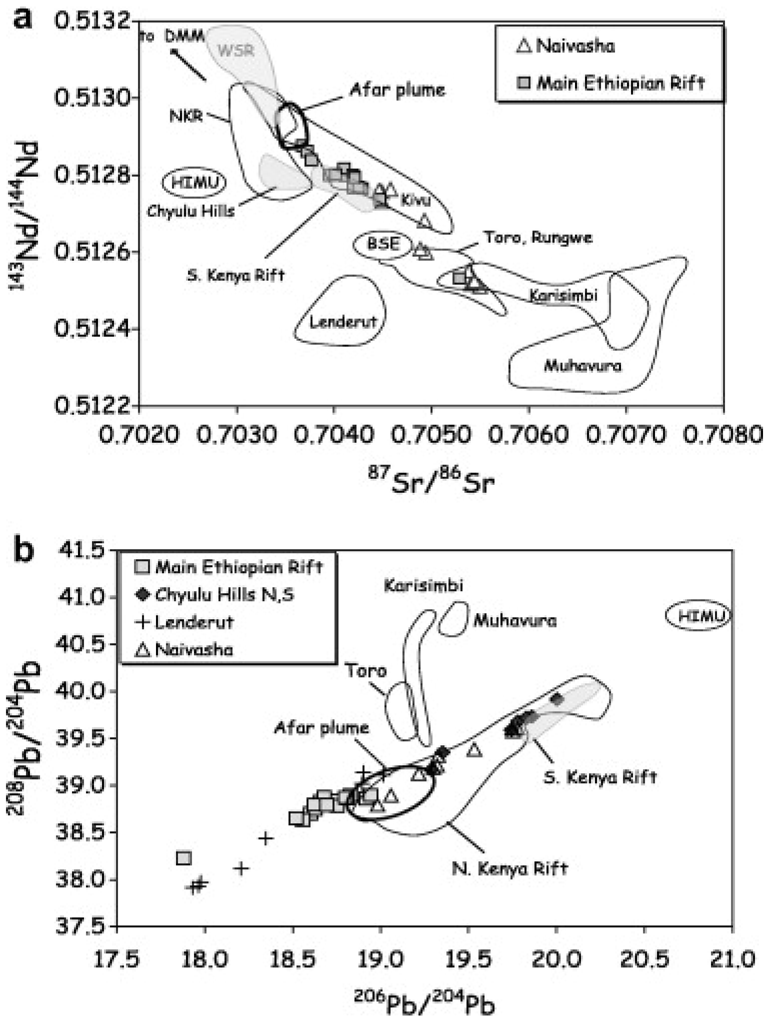

Figure 9. Radiogenic isotopic variations in African Rift mafic lavas. Source: Furman, 2007.

Furthermore, *Furman* [2007] integrated the geochemical observation and geophysical features and proposed a modified one-plume model that allows for multiple plume stems arising from a common large plume at depth. The plume stems are proposed to contain lenses of isotopically distinct materials that record large-scale heterogeneity within the South African Superplume. Much recently, the geochemical variations have been reinterpreted to reflect the involvement of at least four mantle plume components as sources for the northeastern Africa magmatism (Meshesah and Shinjo, 2008). The debate on the number of mantle plumes existing under the East African rift system remains to be resolved.

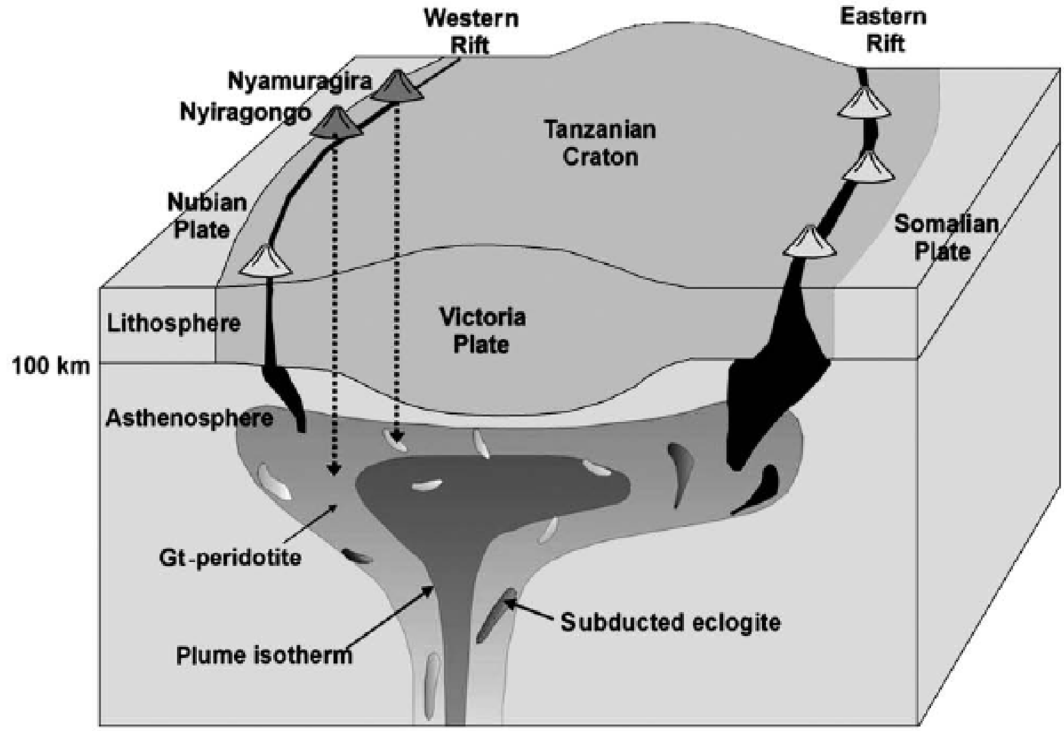

Figure 10. Diagram showing the proposed model for the genesis of the Virunga volcanics in the west rift (Chakrabarti et. al., Chemical Geology 2009)

Geodynamic Implications

1. EARS volcanism is supported by two distinct regions of upwelling at upper mantle levels, both probably connected to deeper mantle reservoirs
2. A super plume with multiple plume stems appears consistent with South African Superswell
3. The South African Superswell controls magmatism throughout the African Rift
4. Sea-floor spreading could be initiated (in Afar) above a mantle plume

8. Active volcanism in the East African rift system

There exist more than 20 historically active volcanoes or volcanic fields located across Africa, notably along the East African Rift System (EARS).

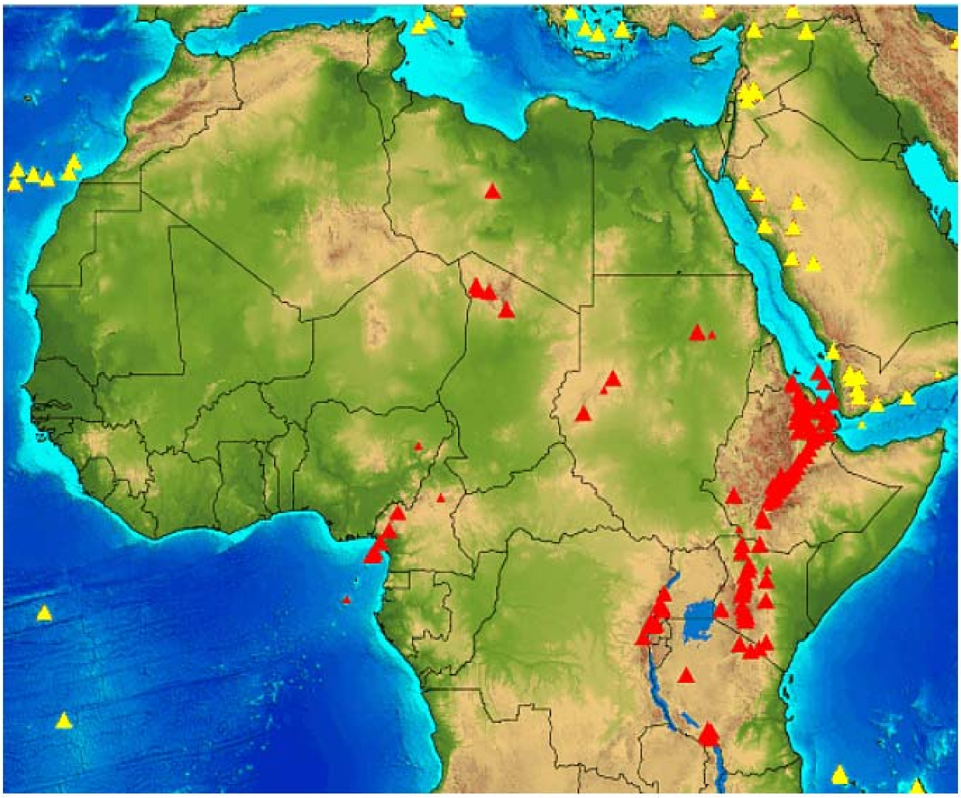

Figure 15 Location of volcanoes in East Africa (Source: www. http://Smithsonian/GlobalVolcanismProgram/)

Dubbi volcano, located in the northeast part of the Afar triangle, erupted explosively in May 1861, with the activity switching to basaltic fire-fountaining focused along a 4-km-long summit fissure that fed several lava flows that traveled as far as 22 km. The volume of lava flows alone, 3.5 km^3, makes this the largest reported historical eruption in Africa. Mount Nyamuragira and Mount Nyiragongo (D. R. Congo) are amongst the most active volcanoes on the continent. Nyiragongo is one of very few volcanoes regularly hosting a lava lake. Oldoinyo Lengai (N. Tanzania) is the only active carbonatite volcano, typically involving the ascent and eruption of extreme low viscosity magmas.

Oldoinyo Lengai is the only know active carbonatite volcano in the world.. Rising over 2200 meters from the valley floor, the bulk of this volcanic cone is composed phonolitic tephra. However, its upper portion is dominated by *natrocarbonatite* lava flows. Historic eruptions of natrocarbonatite have filled much of the summit crater.

Western rift branch

Two active volcanoes of Virunga: Nyiragongo and Nyamuragira.

Nyiragongo regularly hosts a lava lake; spectacular eruption in January 2002

Figure 11. Nyiragongo lava lake, 1994

In the Eastern branch

- Dubbi volcano, in the northeast part of the Afar triangle, erupted explosively in May 1861. The volume of lava flows alone, 3.5 km^3, makes this the largest reported historical eruption in Africa.
- The Erta Ale 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.
- An additional extensive basaltic eruption occurred on the Erta Ale range in November 2008.

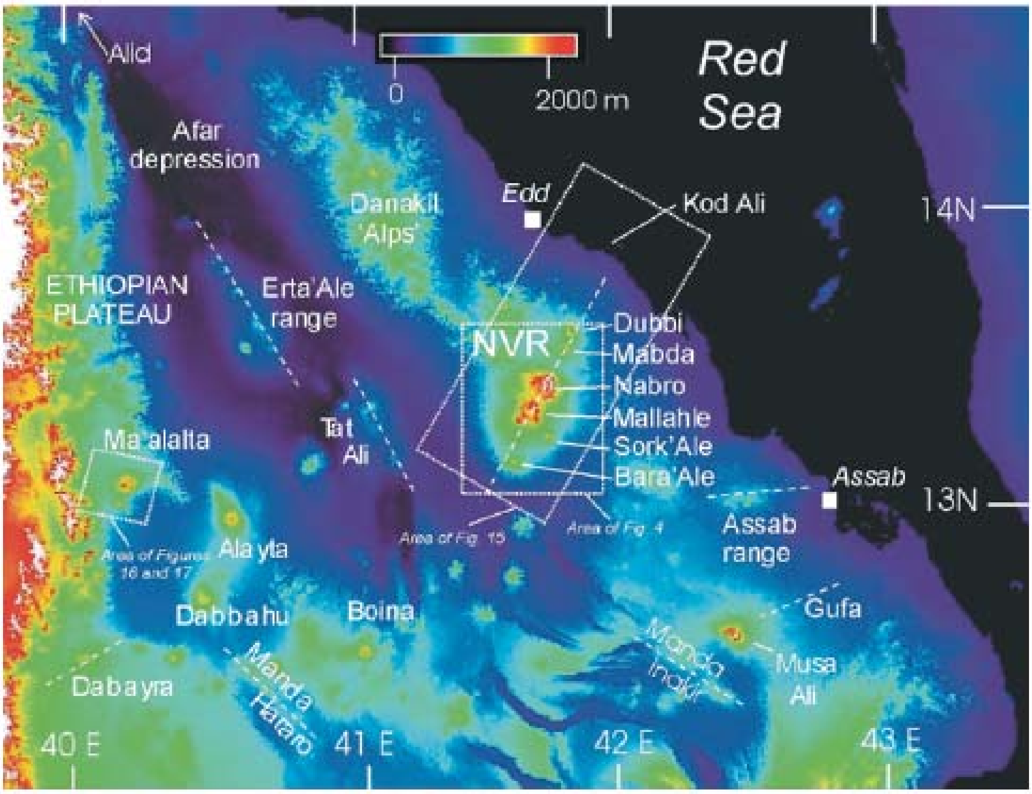

Figure 12. Active volcanoes in Afar

Figure 13. Erta Ale lava lake

In September 2005, an 8-m wide magmatic intrusion was emplaced at shallow crustal depth along a 60-kilometer-long fracture on the Dabbahu magmatic segment in north-central Afar. Subsequent to this major dyke intrusion, 13 separate intrusive events have been documented so far, three of which also erupted on the surface. An additional extensive basaltic eruption occurred on the Erta Ale range in November 2008. The Erta Ale 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.

Figure 14. Newly opened Da Ure volcanic vent

Figure 15. Basalt eruption in June 2009