



STRUCTURAL GEOLOGY OF THE WESTERN BRANCH OF THE EAST AFRICAN RIFT: TECTONICS, VOLCANOLOGY AND GEOTHERMAL ACTIVITY

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ABSTRACT

The East African Rift System (EARS) is a classic example of continental rifting and provides an excellent framework to study extensional magmatism and the evolution of several central volcanic systems which have formed along the rift from the Tertiary to Recent. Many of the volcanic structures have developed substantial high-temperature geothermal systems where the heat source is magmatic and related to central volcanoes. Detailed studies indicate that the geothermal potential in Eastern Africa is in the excess of 15,000 MW_e. However, despite the high geothermal potential of EARS only Kenya has installed significant capacity of about 570 MW. Magmatism along the EARS is generally believed to be associated with mantle plume activities but the number and nature of mantle plumes is still, however, controversial. EARS is divided into two main branches, the Eastern- and Western rifts and it is well documented that significantly greater volcanism is observed in the older Eastern rift (i.e. Ethiopia and Kenya) compared to that in the younger Western rift, where eruptive activity is, in general, restricted to four spatially distinct provinces along the rift axis. These are the Toro-Ankole in western Uganda, the Virunga and Kivu provinces along the border of the DRC with Uganda, Rwanda and Burundi, and the Rungwe volcanic field in SW Tanzania

1. INTRODUCTION

The East African Rift (EARS) is an active continental rift zone in eastern Africa that appears to be a developing divergent tectonic plate boundary where rift tectonics accompanied by intense volcanism has taken place from the Tertiary to Recent. Large successions of basalts occur along much of the rift system, emplaced over a broad range both spatially and temporally. The East African rift system (Figure 1) shows up at the surface as a series of several thousand kilometres long aligned successions of adjacent individual tectonic basins (rift valleys), generally separated from each other by uplifted ridges.

Each basin is controlled by faults and forms a subsiding graben, or trough, near one hundred kilometres long, a few tens kilometres wide, empty or filled with sediments and/or volcanic

rocks. The rift valleys form two main lines, the Eastern and Western branches of the EARS which become separated at about 5°N.

The Eastern branch (Figure 1) runs over a distance of 2200 km, from the Afar triangle in the north, through the main Ethiopian rift, the Omo-Turkana lows, the Kenyan (Gregory) rifts, and terminates in the basins of the North-Tanzanian divergence in the south. It is part of the Afro-Arabian rift system that extends from the Red sea to Mozambique in the south a total distance of more than 4,000 km.

The Western branch runs over a distance of 2100 km from Lake Albert (Mobutu) in the north, to Lake Malawi (Nyasa) in the south (Figures 1 and 2). It comprises several segments: the northern segment includes Lake Albert (Mobutu), Lake Edward (Idi Amin) and Lake Kivu basins, turning progressively in trend from NNE to N-S; the central segment trends NW-SE and includes the basins of lakes Tanganyika and Rukwa whilst the southern segment corresponds mainly to Lake Malawi (Nyasa) and small basins further to the south.

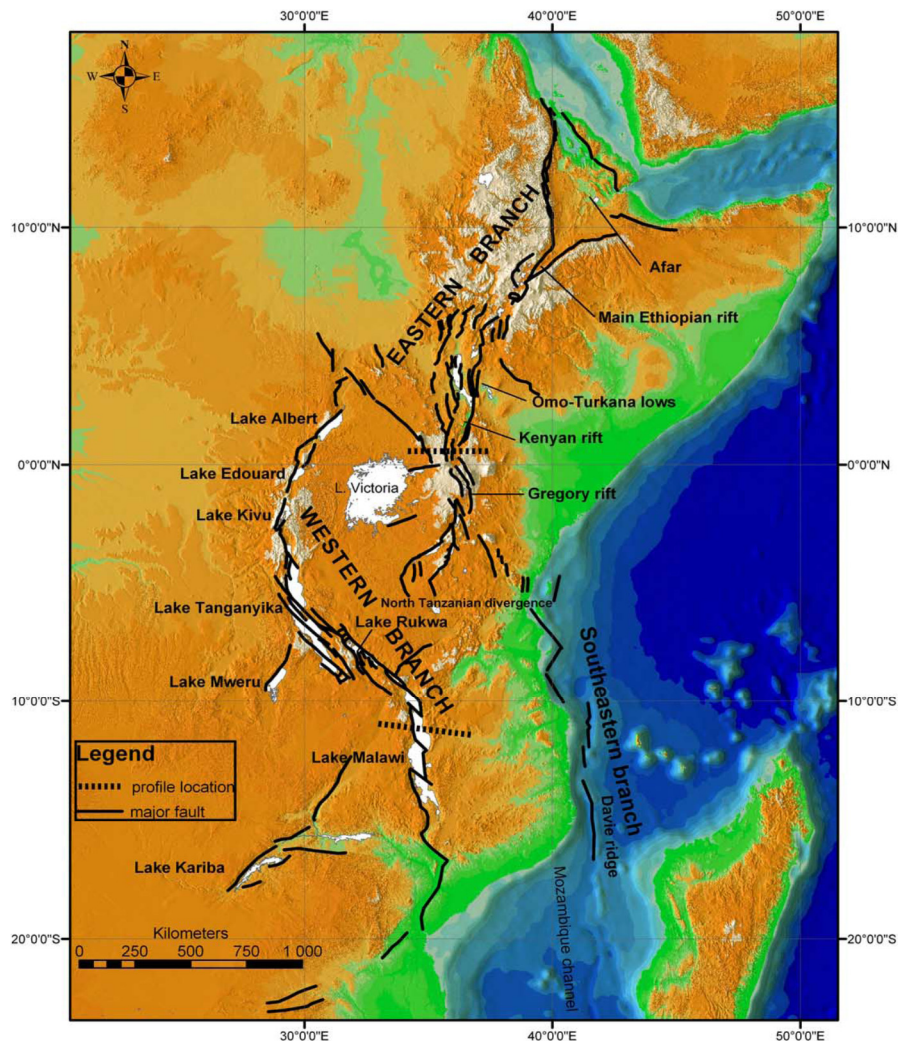


FIGURE 1: Map of the East African rift system. Black lines: main faults, white surfaces: lakes. The East African rift system is a series of several thousand kilometres long aligned successions of adjacent individual tectonic basins (rift valleys), separated from each other by relative shoals and generally bordered by uplifted shoulders. It can be regarded as an intra-continental ridge system comprising an axial rift (Chorowicz, 2005).

The South-Eastern branch comprises N-striking undersea basins located in the Mozambique Channel, west of the Davie ridge. Most of the great lakes of Eastern Africa are located in the rift valleys, except notably Lake Victoria whose waters are maintained in a relative low area between the high mountains belonging to the Eastern and Western branches (Chorowicz, 2005). A further SW branch comprises the Luangwa-Kariba-Okavango rifts (Figures 1 and 2) which run from Lake Tanganyika into southern DR Congo and Zambia and from there to the SW into NW Botswana (Omenda, 2013).

2. VOLCANISM AND TECTONICS OF THE EARS

Development of the EARS was preceded by earlier volcanism in the Turkana region of southern Ethiopia and northern Kenya between 45 and 37 Myr ago and has been linked to mantle plume activity (Furman et al., 2006; Roberts et al., 2012 and references therein). Widespread volcanism with eruption of the Afar plume commenced in central Ethiopia and Yemen around 30 Myr ago, depositing massive flood basalts and rhyolites, accompanied by broad thermal uplift. Volcanic activity (rifting), and the EARS as a whole, slowly propagated southwards through time at a mean rate of 2.5-5 cm/yr (Hoffman et al., 1997; Ebinger et al., 2000; Chorowicz, 2005; Roberts et al., 2012). At present, the EARS is still propagating southward, as revealed by the distribution of seismic activity (Figure 3) (Chorowicz, 2005).

Extension and uplift of rift shoulders began as early as 45-40 Myr ago in northern Kenya and became more widespread between 30 and 20 Myr ago, but may have been more recent (about 18 Myr old) in southwestern Ethiopia (Roberts et al., 2012 and references therein). By 20 Myr ago much of the Eastern branch of the EARS was well established.

It has been argued that volcanic activity in the Western branch is significantly younger, with its development beginning about 13-12 Myr

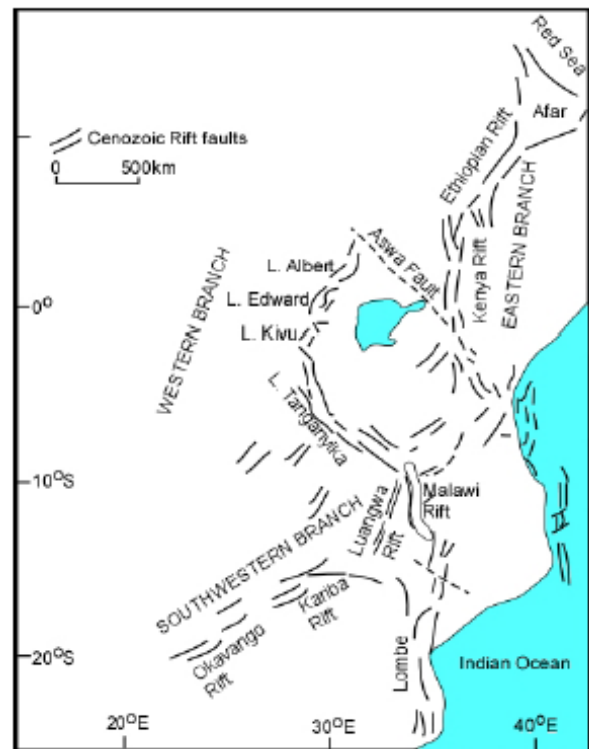


FIGURE 2: Structural map showing the East African Rift System (Omenda, 2013)

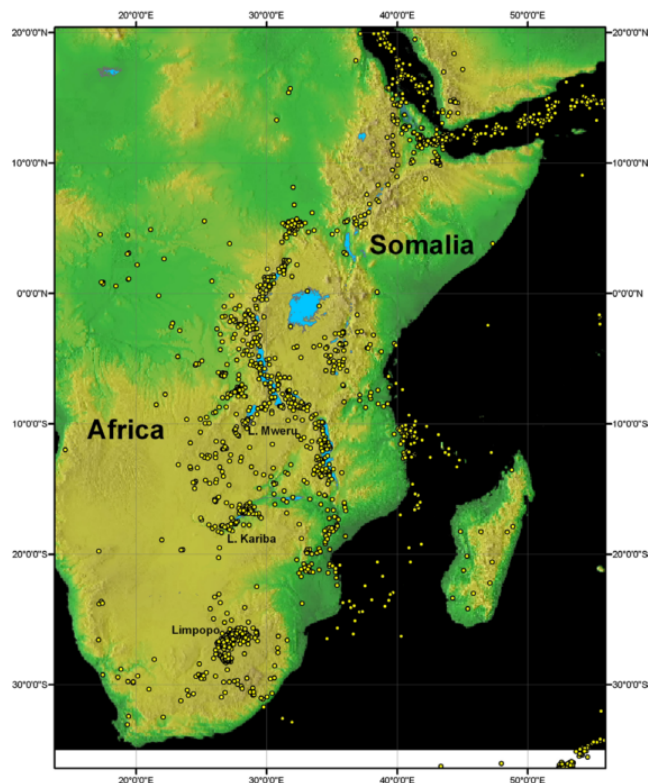


FIGURE 3. Distribution of earthquake epicentres (Chorowicz, 2005)

ago, based on lake-sediment thickness calculations for the Tanganyika Basin and dating in the Toro-Ankole, Virunga, South Kivu, Mwenga-Kamituga and Rungwe volcanic provinces (Bellon and Pouclet, 1980; Ebinger, 1989; Cohen et al., 1993; Pickford et al., 1993; Roberts et al., 2012). However, recent studies indicate that rift-related volcanism and lake development may have begun by about 25 Myr ago (Roberts et al., 2012). Roberts et al. (2012) attribute this more synchronous model of rifting, volcanism and basin development between the two main rift branches of EARS to extensional stresses associated with more widespread plume(s)-related uplift and/or to broad epiorogenic uplift associated with major plate-boundary reorganization.

The earliest rift (extension) manifestations in EARS are the formation of open fractures at 30 Ma in the Afar and Ethiopian plateau, due to hot spot activity, responsible for emission of trap lava flows (Hoffman et al., 1997), accompanied by the initiation of three converging graben structures, forming a triple junction at lake Tana (Chorowicz et al., 1998). Rifting in the Gulf of Aden began at 30-29 Ma, and in the southernmost Red Sea at 27–23 Ma (Hughes et al., 1991). The Afar depression seems to have formed later in the Miocene. At 20 Ma, the first volcanism appearing more to the south at the future triple junction between the northern Kenyan, central Kenyan and Nyanza rifts (Pickford, 1982; Fitch et al., 1985). The main Ethiopian rift, located between these two nucleations, commenced after 11 Ma (Wolfenden et al., 2004), later than the early Miocene volcanic events in the Turkana region (Bellieni et al., 1981).

As discussed earlier, magmatism along the EARS is generally believed to be associated with mantle plume activities but the number and nature of mantle plumes is still, however, controversial. To account for the relationship between African extensive intraplate volcanism, topographic elevation and seismic velocity anomalies, the nature of one or several mantle plumes has been put forward in various models. To the north of the EARS, the voluminous Ethiopian flood basalts and subsequent volcanism (probably more than $1 \times 10^6 \text{ km}^3$ in total), as well as geological, geochemical, and geophysical characteristics of the Afar area, have long been attributed to the activity of a mantle plume (Schilling, 1973; Schilling et al., 1992; Keller et al., 1994; Rogers et al., 2000; Pik et al., 2006 and references therein). However, geochemical identification of such a mantle plume is difficult due to the diversity of the different mantle and crustal sources and variations in their respective contributions through time.

The possible relationship between volcanism in Ethiopia and that in Kenya has been investigated from a geochemical point of view by Rogers et al. (2000), who proposed that two distinct plumes are present under these two bordering volcanic provinces (Figure 4), and by Furman et al. (2004) who instead advocated the occurrence of a unique long-lived plume component under the Ethiopian and Kenyan domes. Others prefer unified mantle plume hypotheses, for example, Castillo et al. (2014), who propose that the observed variation of EARS lavas is mainly due to mixing of material from a Superplume with a compositionally variable lithospheric mantle beneath an isotopically depleted, Late Proterozoic Pan-African mobile belt and isotopically enriched, Early Proterozoic Nubian plate. Hybrid hypotheses have also been suggested (Pik et al., 2006) where the observed geochemical and petrological constraints require the presence of two types of mantle plume under the African plate: (i) a large, deeply sited mantle plume characterized by high- ^3He signature (i.e. originating from the transition zone), which triggered the flood basalts 30 Ma ago and which subsequently interacts with shallower mantle sources to produce the syn-rift volcanism of the Afar province, and (ii) a second order type of shallow mantle upwelling, <500 km as imaged seismically, isolated from the main plume, and disseminated in the African plate under the uplifted and rifted swells.

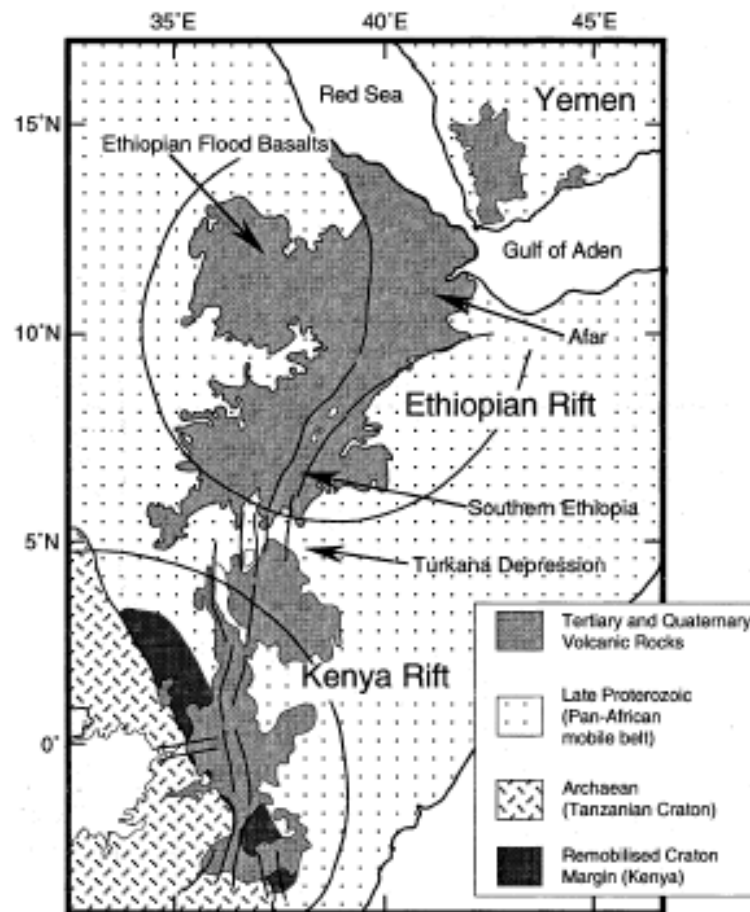


FIGURE 4: Sketch map of the Kenya and Ethiopia rifts, showing the distribution of Tertiary-Recent volcanism, cratonic and mobile belt and the reworked craton margin as mapped out in Kenya. The curved solid lines denote the extent of the Ethiopian and east African plateaus and the faint lines mark the strike of the major border faults of the main rift valleys (Rogers et al., 2000)

The regional gravity study of Ebinger et al. (1989) found that topographic wavelengths >1000 km are overcompensated across the Kenyan dome, suggesting that surface features are maintained by dynamic uplift from the upper mantle. Taken together, these observations suggest that a hot mantle plume is centred beneath the northern part of the Tanzanian craton and Lake Victoria, and model calculations are consistent with a plume head diameter of 600 km (Simiyu and Keller, 1997). Detailed gravity studies (Upcott et al., 1996; Simiyu and Keller, 1997) suggest that the underlying mantle plume has two arms with diameters <250 km that penetrate the lithosphere to shallow levels beneath the Eastern and Western rift branches. The gravity anomaly associated with the Eastern rift is shallowest beneath north central Kenya and deepens rapidly to the north and south (Simiyu and Keller, 1997). In the Western rift, the geophysical data suggest that the greatest extent of lithospheric thinning has occurred just south of the Kivu volcanic province. Experimental investigations of plume dynamics (Griffiths and Campbell, 1991) also suggest that the narrow, arcuate Western rift may reflect subsidence of cold lithospheric mantle near the edge of a plume head. This model is consistent with the low degree of extension estimated for the Western rift ($<15\%$) (Ebinger, 1989), and may be appropriate for parts of the Eastern rift as well. Under this scenario, the post-Miocene alkalic

volcanism throughout the East African Rift system is primarily caused by melting of lithospheric mantle (Furman and Graham 1999). Mid-Miocene to Recent volcanic activity has occurred along the entire length of the Eastern rift, but is restricted to four intra-basinal accommodation zones in the Western rift (Ebinger, 1989).

As plume activity caused flood basalt volcanism in Ethiopia by about 31 – 30 Ma the African plate system was slowly moving over the plume and extensive volcanism affected Kenya down to the border with Tanzania. Because of the northward drift of Africa, the Eastern branch shows this distinct evolution from initial rifting stages in the South (Tanzanian Divergence Zone), via mature stages in the Kenya Rift to incipient continental break-up in the Ethiopian/Afar section. Flood volcanism was preceded by heating and mantle metasomatism along the asthenosphere-lithosphere boundary, which led to the emplacement of kimberlites in Achaean cratons surrounding the rift in the Eocene. The differences in volcanism and uplift/subsidence in the Eastern and Western branch, respectively, undoubtedly reflect different mantle temperatures with temperatures underneath the Eastern branch probably 100-150°C higher than underneath the Western branch (White et al., 1987), which may be mirrored as variances in geothermal gradients.

The plume activity obviously affected the two branches in a different fashion. A possible reason for this might be the pre-existing heterogeneities at the lithospheric level. The Eastern branch developed in the Pan-African Mozambique Belt, which was a typical subduction/collision orogeny in the Cambrian. Much of the Western branch formed in older, early to middle Proterozoic Belts that, at least in part, characterized by regionally widespread granulite-facies metamorphism, which cause regional dehydration of rocks and made the crust strong. It appears conceivable that the Mozambique Belt lithosphere (Eastern branch) was prone to delamination/gravitational removal or easier to thermally erode than the older lithosphere beneath large parts of the Western branch. Therefore, thickness gradients underneath the Eastern branch were greatest, channelling the plume material along the rift axis and causing distinctly higher degrees of partial melting (Ring, 2014 and references therein).

The morphotectonics of the EARS are under control of divergent movements, inducing localized extensional strain in the continental lithosphere. The brittle crust has reacted by faulting and subsidence, forming elongate, narrow rifts, while the lithospheric mantle is subjected to sharply defined ductile thinning, inducing ascension of asthenospheric mantle (Chorowicz, 2005). The most characteristic features in the rift system are then these narrow elongate zones of thinned lithosphere related to deep intrusions of asthenosphere in the upper mantle. This hidden part of the rift structure is expressed on the surface by thermal uplift of shoulders, and argued by geophysical data. On the surface, the main tectonic features are normal faults, but strike-slip, oblique-slip and sometimes reverse faults are commonly observed. Extension produces widespread open fractures, comprising tension gashes. Most of the fractures are syn-depositional, and when volcanism occurs, it is closely related to the tectonics (Chorowicz, 2005). All of these fundamental elements, mentioned above, relate to the nature of the geothermal activity in the EARS.

Spreading in the EARS (Figure 5) decrease from north to south from about 2.6 cm/yr in the Red Sea to about 1 cm/yr in Afar to 0.7 cm/yr in the Ethiopian Rift and 0.5 mm/yr combined in the Western and Eastern rifts across the Kenya Dome and gradually decreasing from there to the south (Chorowicz, 2005; Saemundsson, 2008).

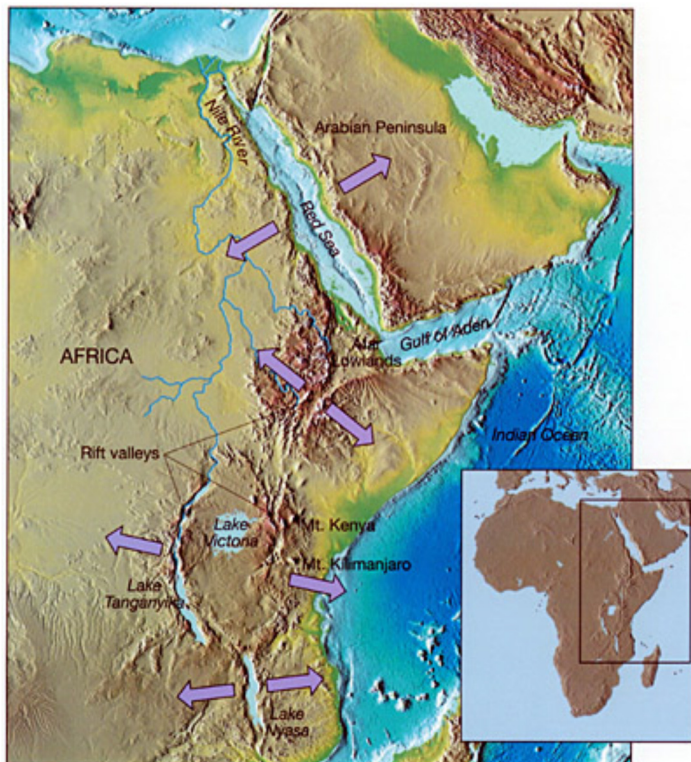


FIGURE 5: Spreading rates along the EARS decrease from north to south (Saemundsson, 2008)

In response to increased crustal spreading the Moho is at about 5-35 km depth along the axis of the rift (Omenda, 2013). Studies reveal that the crust under the EA rift ranges between 5 km (Afar) and 35 km (Kenya) in thickness in the axis of the rift as compared to regions outside of the rift where the thickness is typically more than 45 km (Prodehl et al., 1997; Simiyu and Keller, 1997; Omenda, 2013). The thin crust and upwelling asthenosphere directly under the rift has resulted in generally high heat flow arising from high geothermal gradient within the entire length of the rift (Wheildon et al., 1994). However, the importance of asthenospheric heat would be most important in the vicinity of the Afar triple junction where the crust is less than 5 km thick (Omenda, 2013).

The scenario of north to south propagation of plume/rift activity is consistent with the thin lithosphere shown by a large N–S trending gravimetric negative Bouguer anomaly in eastern-central Africa, and may explain the differences in volcanism between Western and Eastern rifts, and differences from north to south (Simiyu and Keller, 1997).

3. THE WESTERN BRANCH OF EARS

Until recently the Western branch of EARS has received less detailed attention than the Eastern branch. The geography of the Western branch is typically half grabens characterized by high angle normal rift faults and by paucity of volcanism relative to the Kenyan and Ethiopian rifts (Omenda, 2013). Whilst rifting volcanism and tectonic activity in Eastern branch commenced about 30 million years ago in the Eastern branch of the EARS, it has generally been argued that volcanic activity in the Western branch started much later, or at about 13-12 Ma (Bellon and Poulet, 1980; Ebinger, 1989; Cohen et al., 1993; Pickford et al., 1993; Roberts et al., 2012). However, as mentioned in the previous section, recent studies indicate that rift-related volcanism and lake development may have begun by about 25 Myr ago (Roberts et al., 2012). This more synchronous model of rifting, volcanism and basin development between the two main rift branches of EARS has been attributed to extensional stresses associated with more widespread plume(s)-related uplift and/or to broad epiorogenic uplift associated with major plate-boundary reorganization (Roberts et al., 2012).

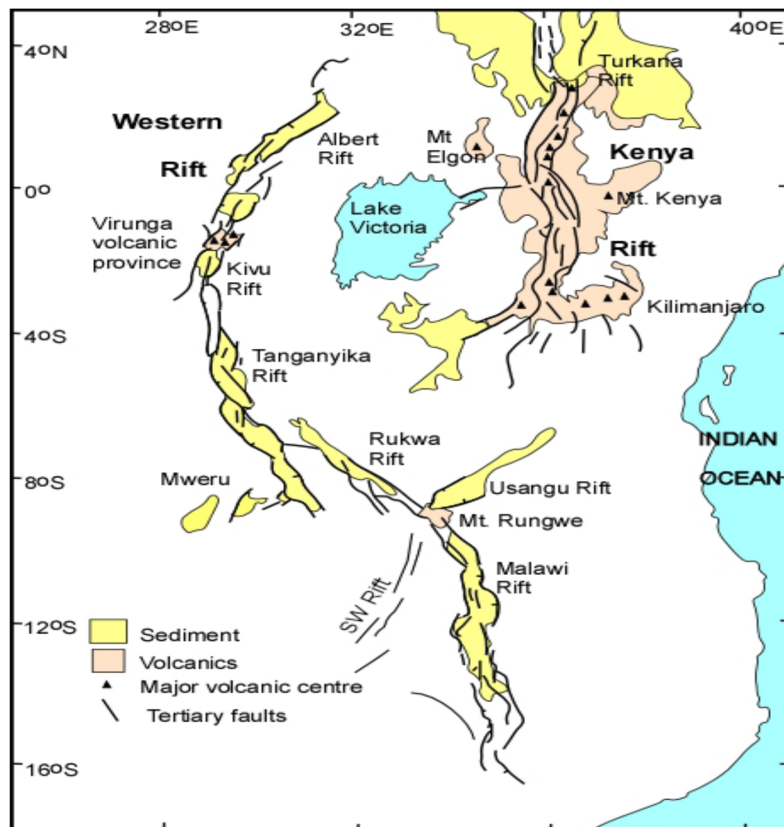


FIGURE 6: Map showing the structural relationship between the Eastern (Kenya) and Western branches of the EARS (Omenda, 2013)

The Western branch extends over a distance of about 2100 km from Lake Albert in the north, to Lake Malawi in the south (Figure 6). In the north it is linked to the Eastern branch through the Aswa fracture zone (Figure 2) and to the south in SW Tanzania (Figure 7). The trend of the rifts is less continuous than in the Eastern branch, with a number of apparent gaps, together with some clear offsets (Macgregor, 2015). Regional doming/uplift is much less pronounced than in the Eastern branch, and parts of the Western branch show the greatest absolute subsidence on Earth as expressed by deep rift lakes whose bottom is at or below sea level. Furthermore, rift flank uplift is, at least in part, pronounced. The most striking example is the Rwenzori Mountains, which are a promontory of the Eastern rift shoulder in Uganda and rise to more than 5 km above sea level (Pickford et al., 1993; Rosenthal et al., 2009; Ring, 2014). The Rwenzoris are the highest rift mountains on Earth.

The individual rift basins are long (~100-150 km) and narrow (~50-70 km) and are in the process of linking up. Volcanism occurs in four main isolated centres, which are from N to S, the Toro-Ankole, Virunga, South Kivu and Rungwe volcanic fields (Figure 6). The smaller Mwenga–Kamituga province is located southwest of the South Kivu field. The volcanic centres are confined to the rift zones proper and limited age data suggest that magmatic activity occurs periodically rather than continuously (Delvaux et al., 1992; Ebinger et al., 1993). Volcanism and rifting in the Western rift lacks the southward age progression typical of the East African Rift as a whole, perhaps because magmatism seeks its way through the weakest points of the basement complex (Rosenthal et al., 2009).

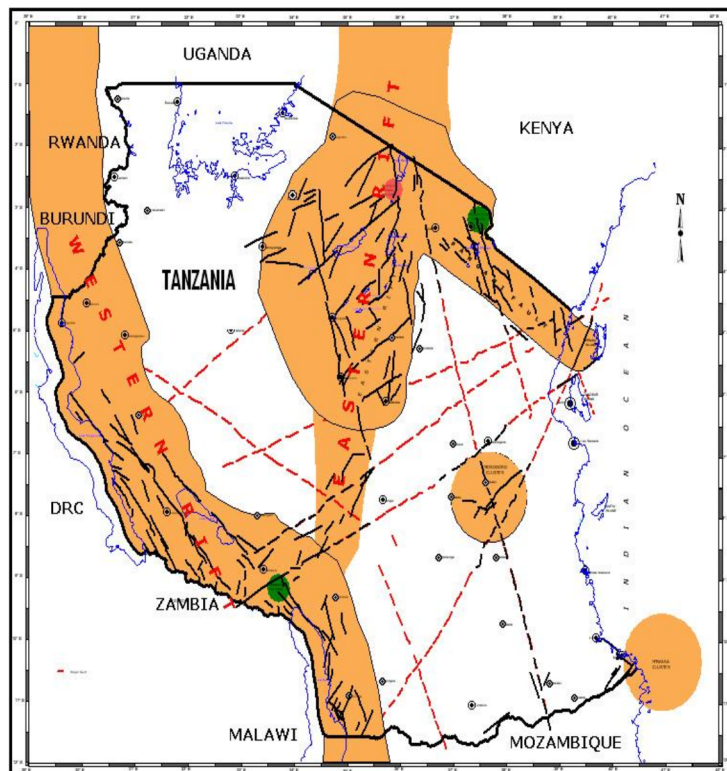


FIGURE 7: The two branches of EARS converge to the south in SW Tanzania and form a triple junction at the Rungwe volcanic complex in the Mbeya area. The conditions for high-enthalpy resources are particularly favourable in this region due to the presence of active faults and young volcanic heat sources

The northern zones of the rift comprise several basins that define the Albertine Graben near Lake Albert. The Lake Albert rift was initiated early Miocene and is dominated by thick sequence of sediments and is largely non magmatic except for the southern basins where volcanic products occur (Omenda 2013). The Tanganyika Rukwa-Malawi (TRM) segment of the Western branch follows the fabric of the basement structures inherited from the Proterozoic period. The rift is characterized by normal boundary faults, which define half grabens, horsts and step faults with riftward tiled blocks and monoclinical structures. The Malawi segment extends south to the Urema and Lebombo grabens in southern Mozambique. Within the rifts occur lakes Tanganyika and Malawi, which are deep sedimentary basins. The rift segment is largely non-magmatic during the Quaternary times with volcanic fields being only at Rungwe between lakes Tanganyika and Rukwa (Omenda, 2013). Even though the area is not volcanically active at present geothermal activity is evident in many localities. The manifestations in the Tanganyika-Rukwa-Malawi Rift include hot springs and fumaroles at temperatures of up to 86°C which occur at Mbeya where they are closely associated with the Quaternary Rungwe volcanic field. The area is also characterized by high seismicity signifying that the area is still tectonically and magmatically active (Omenda, 2013). Other hot springs occurring in Malawi, Zambia and Mozambique are fault controlled, the hot springs being associated with deep circulation of ground waters through rift structures (Omenda, 2013).

The youngest and most northerly volcanics of the Western branch of the EARS are strongly silica-undersaturated, potassic, and calcium-rich kamafugites and carbonatites (Figure 8) indicating deep melting. They represent the initial stage continental rifting, and are reminiscent of ultramafic lamprophyres formed in similar regions of erosion of subcratonic lithosphere from

below. The strongly potassic character of kamafugites may be explained by melting phlogopite-bearing veins at >100 km depth. Towards the south, melting occurs at shallower levels, involving amphibole and phlogopite to produce olivine melilitites and basanites (Virunga), and amphibole alone further south to produce tholeiites in the Kivu field (Furman and Graham, 1999; Rosenthal et al., 2009).

There is a systematic decrease in SiO₂ and increase in K₂O and CO₂ from south to north. Interestingly, the geochemistry of Rungwe volcanics does not keep to this trend. Volcanics in the Virunga province range from silica undersaturated to slightly silica-oversaturated with numerous intermediate compositions in terms of SiO₂ (Rogers et al., 1998; Furman, 1995), whereas, the Rungwe field features trachyphonolites, alkali basalts, basanites, nephelinites, and picrites (Furman, 1995). During the Late Quaternary, volcanism with a broad spectrum of compositions was active simultaneously in Toro-Ankole, Virunga, South Kivu, and Rungwe (Furman, 1995). The volume of volcanics in the Western rift is estimated at ~100 000 km³, considerably less than in the Eastern rift branch of >900 000 km³ (Rosenthal et al., 2009).

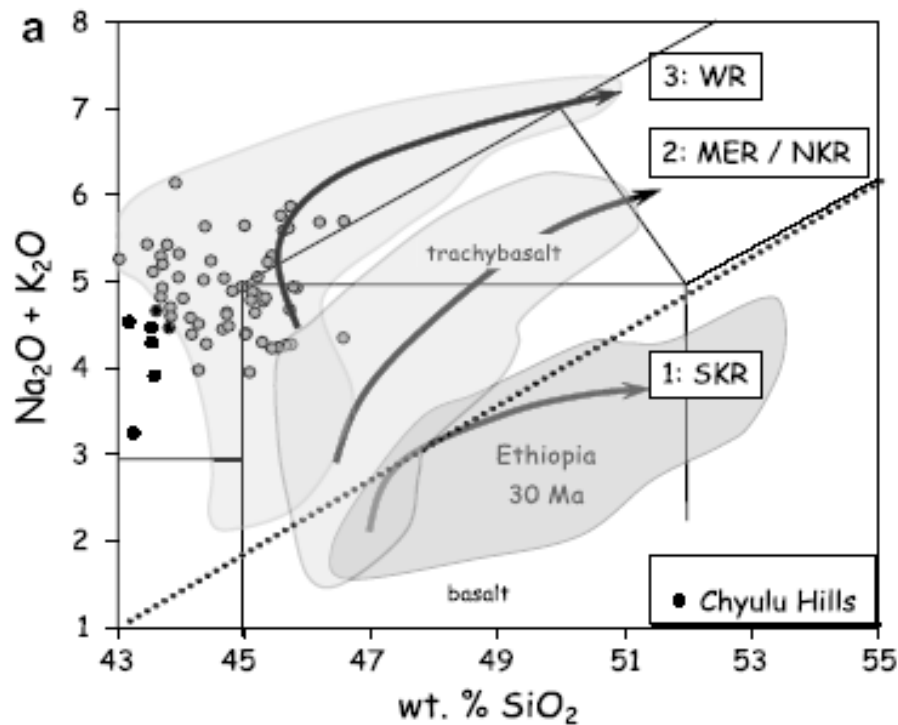


FIGURE 8: Total alkali content plotted against wt% SiO₂. SKR=Southern Kenya rift, NKR=Northern Kenya rift, MER=Main Ethiopian rift, WR=Western rift (Furman 2007). The diagram indicates smaller degree melts and deeper melting in the Western rift compared to the Kenyan rift

Geothermal activity in the East African rift generally occurs in the form of hot springs, fumaroles, hot and altered grounds closely associated with Quaternary volcanic systems in the axis of the rifts. The association is related to the shallow hot magma bodies under the central volcanoes, which are the main heat sources for the high temperature geothermal activity in the Eastern branch of the rift system. In the less magmatic Western branch of the EARS, heat sources could be a combination of buried plutons and moderately high heat flux associated with thinned crust (Omenda, 2013). Sections of the Western branch pass through Uganda, Rwanda, Burundi, DR Congo, Tanzania, Zambia and Malawi (Omenda, 2013). Geochemical studies in

some areas in these countries indicate that the geothermal activity in the Western branch is dominated by low temperature activity (<150°C reservoir temperature) but in a few places higher temperature might be found, or up to about 250°C. Reconnaissance surveys, geological, geophysical and geochemical, have been conducted in and around many geothermal fields. Several relatively shallow wells have been drilled and two deep wells (in the order of 3000 m) in Karisimbi, Rwanda. At present, geo-scientific results seem to indicate that reservoir temperatures in geothermal systems in the Western branch of EARS, might be in some instances, suitable using binary technologies, for the production of electricity. Several systems may, however, be relevant for other applications.

4. SUMMARY

- Magmatism along the EARS is generally believed to be associated with mantle plume activities but the number and nature of mantle plumes is still controversial.
- The Western branch of EARS runs over a distance of around 2100 km from Lake Albert (Mobutu) in the north, to Lake Malawi (Nyasa) in the south.
- It has been argued that volcanic activity in the Western branch is significantly younger, with its development beginning about 13-12 Myr ago. However, recent studies indicate that rift-related volcanism and lake development may have begun by about 25 Myr ago.
- The volume of volcanics in the Western rift is estimated at ~100 000 km³, considerably less than in the Eastern rift branch of >900 000 km³.
- The trend of the Western branch is less continuous than in the Eastern branch, with a number of apparent gaps, together with some clear offsets.
- The volcanic centres in the Western branch are confined to the rift zones proper and limited age data suggest that magmatic activity occurs periodically rather than continuously.
- The volcanics of the Western branch are mostly strongly silica-undersaturated, potassic, and calcium-rich kamafugites and carbonatites indicating deeper melting than in the Eastern branch.
- Heat flow is higher in the Eastern branch because of more advanced rifting, magmatic intrusions and thinner crust.
- High temperature geothermal activity in the Eastern branch is closely associated with Quaternary volcanic systems in the axis of the rifts. The association is related to the shallow hot magma bodies under the central complexes. In the less magmatic Western branch of the EARS, heat sources could be a combination of buried plutons and moderately high heat flux associated with thinned crust.
- At present, geo-scientific results seem to indicate that reservoir temperatures in geothermal systems in the Western branch of EARS, might be in some instances, suitable using binary technologies, for the production of electricity. Several systems may, however, be relevant for other applications.

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