



UNITED NATIONS
UNIVERSITY

UNU-GTP
Geothermal Training Programme



EASTERN RIFT STRUCTURAL GEOLOGY – TECTONICS, VOLCANOLOGY AND GEOTHERMAL

Risper J. Kandie

Kenya Electricity Generating Company (KenGen)

Olkaria Geothermal Project (Naivasha)

KENYA

rkandie@kengen.co.ke

ABSTRACT

Eastern rift is a branch of the larger East African Rift (EARS), an extensive continental rift on the Earth's surface that extends from Gulf of Eden/Red Sea in SW Asia and propagates southward through East Africa to Mozambique near Beira. As the EARS propagates southwards from Afar triangle/triple junction, it separates into two branches namely Eastern and Western Branches. The Eastern branch includes the Ethiopian and Kenya rifts that are centered on Ethiopian and Kenyan domal hotspots respectively. Rifting tectonic episode started 30Ma in the Afar region. Magmatic and volcanic activities associated with domal uplift started during Miocene. Volcanism preceded the major rift faulting events and the mechanism of rifting process has been modeled to be as a result of elevated heat flow from the upper mantle that caused a pair of thermal bulge in the central Kenya and the Afar region of north central Ethiopia. The volcanic centres within the Eastern rift have elevated heat flow and fracture networks that has made it possible for existence of low to high geothermal systems.

1. INTRODUCTION

East Africa Rift System (EARS) is an active continental rift zone in which the African Plate is in the process of splitting into two new sub plates or prototypes; Somali and Nubian Plate at Afar triple junction or triangle (Figure 1). The northern portion of the East African Rift System, together with the Red Sea and Aden rifts, forms the Afar triple junction. The East African Rift propagates from the Afar (triangle) Triple Junction in the southward through Eastern Africa. It is believed to run offshore of the coast of Mozambique along the Kerimba and Lacerda rifts or grabens, terminating in the Andrew Basin Fracture Zone complex, where it is believed to have its junction with the Southwest Indian Ridge.

As the East African Rift propagates southwards, it branches into two main branches: the Gregory Rift and the Albertine Rift. These resulted/formed from the actions of numerous normal (dip-slip) faults which are typical of all tectonic rift zones. The Eastern Rift Valley includes the Main Ethiopian Rift, which continues south as the Kenyan Rift Valley. The Western Rift Valley includes the Albertine Rift, and further south, the valley of Lake Malawi. The rifting is believed to have started in the north and in early Tertiary and propagated southwards with time (Saemundsson, 2008).

EARS comprises of rift which are at different stages of development such as Ethiopian and Kenyan rift which are at advanced stage whereas the Afar and Djibouti are at oceanic rift stages. The Asal Rift is tectonically the most active structure in the zone of crustal divergence. The Asal area constitutes a typical oceanic type rift valley, with a highly developed graben structure displaying axial volcanism.

The Asal series are relatively complex in structure, because of different series of active volcanism in recent Quaternary times, each with very different characteristics depending on the sites of appearance (Farah, 2014).

The Western rift arm of EARS includes the Albertine rift and runs < 2100 km from L. Albert in the north to L. Malawi in the south. Unlike the Eastern rift, it is less advanced and is also less volcanically active. The two branches of EARS later converge in south west Tanzania and form a triple junction at the Rungwe volcanic complex in the Mbeya area. The development of the Western branch of the EARS may have developed due to the failure of the Eastern rift to effectively propagate southward as it encountered a rather stable Tanzania craton. The Eastern branch is marked by a number of active volcanos and abundant geothermal features whereas the western Rift shows only a few active volcanos and minimal surface geothermal activity.

The Eastern rift is attributed to existence of notable domes, the Kenyan dome and the Ethiopian domes that are hot spots. The Kenya domal uplift is responsible for the split of the Eastern rift further into three rift arms, two form the main rift and the third the Kavirondo rift (Saemundsson, 2008) (Figure 2). The Gregory rift is endowed with numerous volcanic tectonic features that have been assessed to have geothermal potential. There are sixteen geothermal prospects, with some at exploitation and development stages such as Olkaria, Menengai and Eburru

1.1 Tectonic evolution

The East African Rift is a zone of crustal extension in which part of the Eastern African continent is being split into Nubian and Somalia Plate as it separates from the Arabian plate. The Afar Depression is a plate tectonic triple junction, where the spreading ridges that are forming the Red Sea and the Gulf of Aden emerge on land and meet the East African Rift. The western margin of the triangle extends to

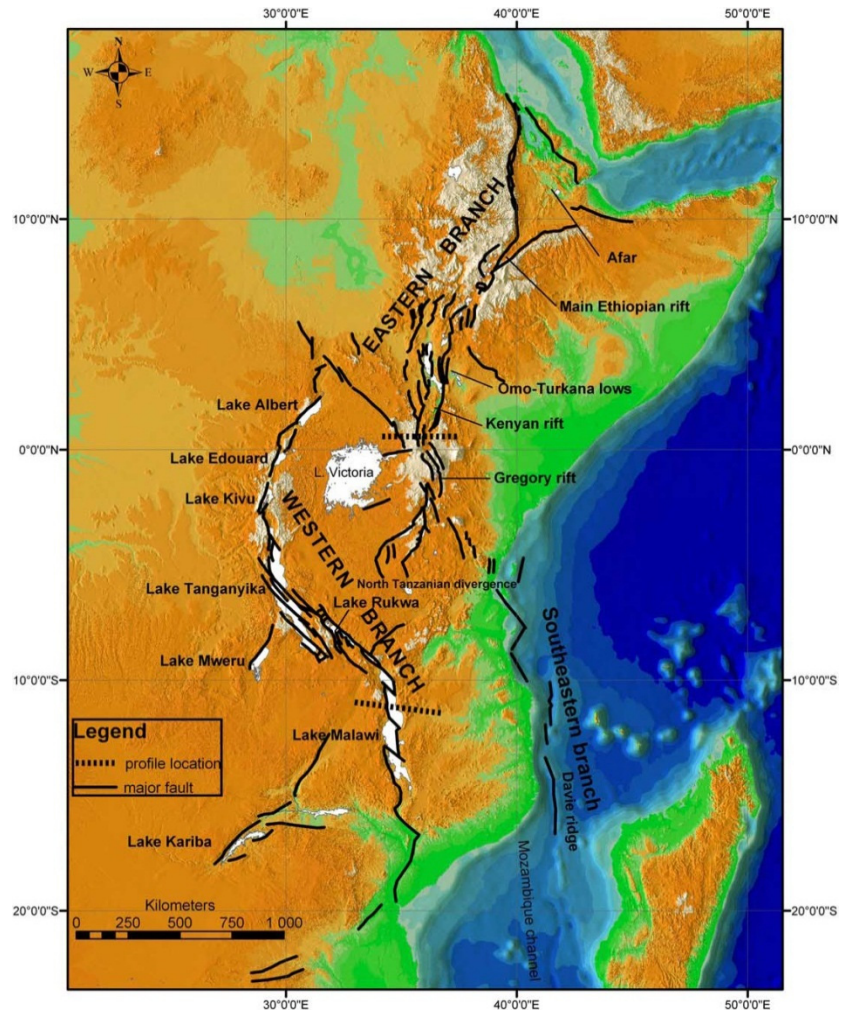


FIGURE 1: Hypsographic DEM of the EARS. Black lines, main faults; white surfaces, lakes; grey levels from dark (low elevations) to light (high elevations). The EARS is a series of several thousand kilometres long aligned successions of adjacent individual tectonic basins (rift valleys), separated from 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 Red Sea, while the south-Eastern part extends to the Gulf of Aden off the Arabian Peninsula. The EARS propagates southwards separating into the Eastern and western branches. The development of the western rift is attributed to resistance of the Tanzanian craton to yield somehow to tectonic stress regimes. This has greatly influenced the structural and tectonic setting of the two branches. While the Western rift is termed as a passive rift having no internal stress field which drives its opening, the Eastern rift is known to be seismically active (Saemundsson, 2008). The rifting at the Kenya Rift started from Turkana and extended southwards towards Magadi to Mozambique.

1.2 Model mechanism of the Eastern Rift formation

The widely accepted model of the formation of the EARS is based on the assumption that there exist elevated heat flow from the upper mantle caused a pair of thermal bulges in the central Kenya and the Afar region of north central Ethiopia. These bulges can be easily seen as elevated highlands on any topographic map of the area. As these bulges form, they stretch and fracture the outer brittle crust into a series of normal faults forming the classic horst and graben structure of rift valleys (Valet, 2013).

Bulges are initiated by mantle plumes under the continent heating the overlying crust and causing it to expand and fracture. Ideally the dominant fractures created occur in a pattern consisting of three fractures or fracture zones radiating from a point with an angular separation of 120 degrees. The point from which the three branches radiate is called a "triple junction", in this case the Afar region of Ethiopia, where two branches are occupied by the Red Sea and Gulf of Aden, and the third rift branch runs to the south through Ethiopia.

In Kenya, the East African/Gregory Rift depicts "continental rifting" and this provides a glimpse into what may have been the early development of the Ethiopian Rift. The rifting of Eastern at this level is complicated by the fact that two branches developed, one to the west which hosts the African Great Lakes, referred to as kavirondian rift and another nearly parallel rift about 600 kilometers to the east which nearly bisects Kenya north-to-south before entering Tanzania where it seems to die out. Lake Victoria sits between these two branches. These rifts are generally following old sutures between ancient continental masses that collided billions of years ago to form the African craton. The split around the Lake Victoria region occurred due to the presence of a small core of ancient metamorphic rock. The Tanzania craton was too hard and immobile for the rift to tear through/ go straight through this area instead it diverged around it leading to the development/formation of two branches that can be seen today.

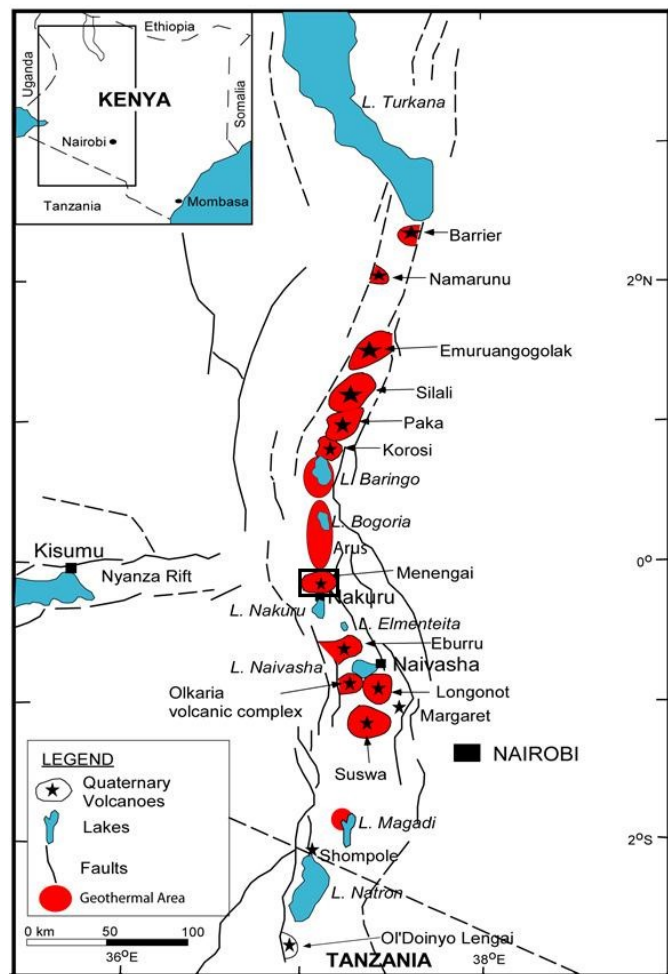


FIGURE 2: Apex of Gregory Rift domal uplift with two volcanically active rift branches and a third E-W branch dying. (Nyanza rift) Stratovolcanoes are shown. Fissure swarms have not been identified as integral parts of the volcanic systems (Mwawongo, 2004)

1.3 Geological evolution

The East African rift is an intra-continental divergent type of rift basins whose development was initiated in the Gulf of Aden in Miocene about 30 Ma. Its evolution was structurally controlled with the rift faults exploiting the weak collisional zone at the contact between the Archean Tanzania craton and Proterozoic orogenic belts (Smith and Mosley, 1993). The Eastern branch of EARS developed in Neoproterozoic orogenic belts (referred to as East African Orogen) whereas the western rift developed in Paleoproterozoic and Mesoproterozoic orogenic belts which host the Western Rift that is much older, thicker and stronger. The difference in the orogenic belt settings has given rise to differences in modes of upward transfer of mantle mass and heat and character of hydrothermal features and of the indicated geothermal resources in the western and Eastern arm of the EARS (Valet, 2013)

The basin formed as regional extensional tectonics that rifted and dislocated the crust of the African shield into a step faulted ridge and trough. The consequences of extensional/ pull apart rift tectonic forces led to crustal thinning accompanied by intense volcanism that dates back from late Tertiary to Recent volcanic eruptions that resulted to the formation of present day volcanic features and geology. Within the EARS are two domal features, the Ethiopian and Kenya dome. Domal uplift and extension caused the brittle crust to fracture into a series of normal faults giving the classic horst and graben structure of rift valleys. In Djibouti and Ethiopia volcanic and rifting episodes are known to have occurred involving magmatism and widening of discrete volcanic systems. (Saemundsson, 2010).

The domal uplift within the Kenyan dome is attributed to anomalous hot mantle upwelling that caused brittle crust to fracture into series of normal faults giving the classic horst and graben structure of the rift valleys that is approximately 40-50 km wide and endowed with volcanoes and eruptive centres that are hydrothermally active and regarded as geothermal prospects. The development of the rift within Kenya started during the late Oligocene (30 Ma) in the area known as the Turkana rift (Smith, 1994). Volcanism associated with rifting started during the Miocene. The magmatic activity was accompanied by domal uplift of about 300 m on the crest of which erupted phonolites (Hay and Wendlandt, 1995). Most volcanic centers have had more than one explosive phase including caldera collapse. Prospects from south to north are L. Magadi, Suswa, Longonot, Olkaria, Eburru-Badlands, Menengai, Lake Bogoria, Korosi, Paka, Silali, Emuruaogolak, Namarunu and Barrier towards L. Turkana. The rifting also provided the troughs that formed the lakes that are alkaline and the geology is comprised of Precambrian basement and Tertiary rift volcanics that are covered by sedimentary deposits that thicken heading north towards L. Turkana. The geology ranges from recently erupted basalts as observed in the Ethiopian Rift to Late Tertiary and Quaternary volcanics that overlie the proterozoic basement.

1.4 Structural geology

The tectonic and geological setting of Eastern rift provides suitable/ conducive environment for the occurrence of geothermal system characterized by high heat flow on the upper zone of the crust. Factors controlling the locations of these systems and the regional heat flow variations have been known for a long time (Koenig and McNitt, 1983). Structural patterns show complexities that could be attributed to the magnitude of the tectonic events and also the repetitiveness of the episodes. Structural deformation probably took place between Tertiary and Early Quaternary, it initiated with normal type of faulting that is characterized by steep dips that are commonly near vertical to as low as 60 degrees. The fault planes are almost slightly curved and may be arcuate.

1.5 Rifting, volcanicity and geothermal implications

The East African Rift Zone includes a number of active as well as dormant volcanoes, among them: Mount Kilimanjaro, Mount Kenya, Longonot, Menengai, Karisimbi, and Nyiragongo. The Ol Doinyo

Lengai volcano remains active, and is currently the only natrocarbonatite volcano in the World. Erta Ale is a continuously active lava lake in a basaltic shield volcano in the Afar (NE Ethiopia). The volcanic system within the rift are also hosts to geothermal resource. The volcanoes and volcanic centres in Eastern rift are regarded as geothermal prospects. This has been proven with an estimated geothermal potential in excess of 10,000MWe in the prospects situated within Kenyan Rift whereas for Ethiopia and Djibouti it is estimated to be over 10,000MWe. Existence of geothermal potential in these areas has been made possible courtesy of extensional forces that resulted to thinning of continental crust. The thinning of crust gave rise to elevated heat flow that causes thermal bulges. The consequence of this is a relatively shallow heat source. The extensional forces were responsible for the formation of fracture network when the brittle crust yielded to stress/ extensional tectonic forces.

1.6 Geothermal resource potentials

Geothermal resource potential in Eastern branch of the EARS is controlled by the geological and structural setting with the highest geothermal potential expected in Ethiopia and Kenya. Several of these geothermal areas are related to the magmatic activity and associated volcanic activities that have occurred in more than one episode since 30 Ma ago. The Eastern rift area is characterized by active volcanism, hydrothermal activity and geological structures like faults, fractures and fissures, a recipe for high, medium and low enthalpy geothermal resource types (Figure 3).

There is comparable difference between the geothermal potential of the Eastern and the Western branches of East African Rift System. It estimated that the geothermal potential of the Eastern branch is about ten times higher than the geothermal potential of the western branch (Hochstein, 2005).

What favours existence of geothermal resources within the Eastern rift is an elevated heat flow that is attributed to continental crust thinning, and extensional tectonic forces that cause stretching and fracturing of the brittle crust. Stretching and fracturing is accompanied by upwelling of upper mantle and upward mass and heat transfer. Based on global seismic tomography studies, two localized zones of elevated mantle plumes within the EARS have been identified namely; the Ethiopia and Kenya domes.

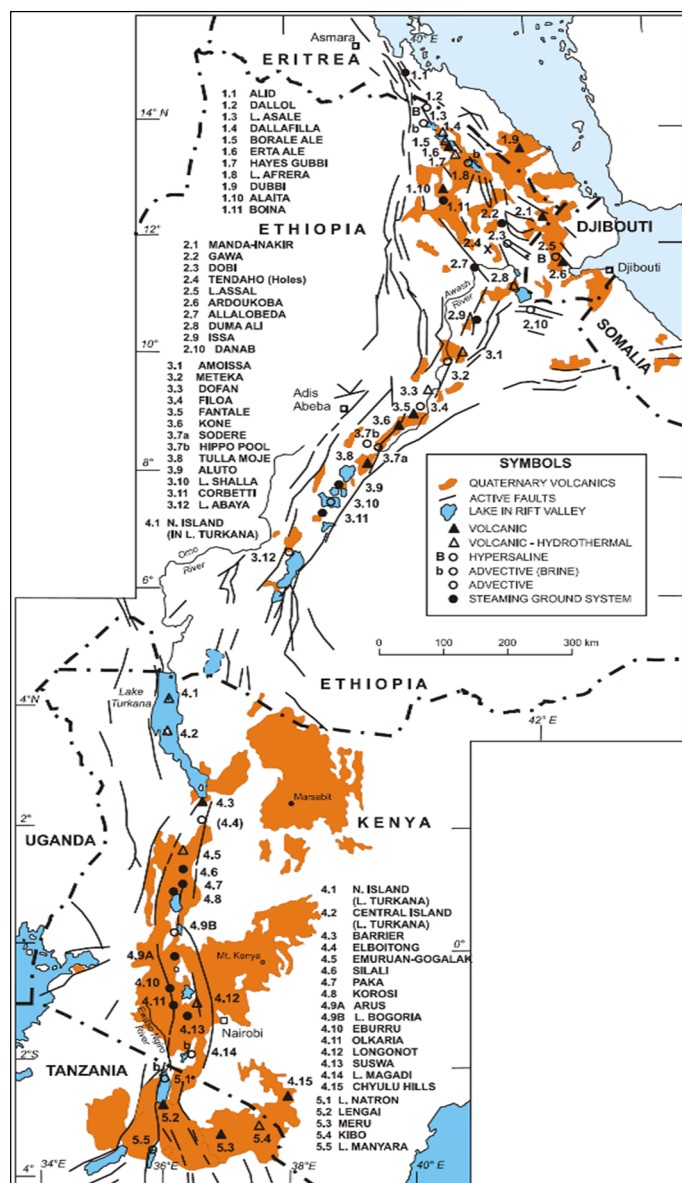


FIGURE 3: Location of major geothermal systems along the Eastern Branch of the East African Rift System (Hochstein, 2005).

REFERENCES

- Chorowicz, J., 2005: The East African rift system. *J. African Earth Sci.*, 43, 379–410.
- Farah, O.F., 2014: Problems encountered while drilling and completion stages in Asal Rift wells, *Djibouti Proceedings, ARGEO-C5 Arusha Tanzania*.
- Hay, D.E., and Wendlandt, R.F., 1995: The origin of Kenya rift plateau type phonolites: Results of high pressure and high temperature experiments in the systems, phonolite-H₂O and phonolite-H₂O-CO₂. *J. Geophys. Res.*, 100, 401 - 410.
- Hochstein, M.P., 2005: Heat Transfer by Hydrothermal Systems in the East African Rifts, *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey*.
- Koenig, J.B., and McNitt, J.R., 1983: *Controls on the location and intensity of magmatic and non-magmatic geothermal systems in The Basin and Range province*. Geothermal Resource Council Special Report 13, 93 p.
- Mwawongo, G.M., 2004: *Infield re-injection strategies in Olkaria, Kenya based on tracer studies and numerical modelling*. UNU-GTP, Iceland, report 12, 239-266.
- Saemundsson, K., 2010: East African Rift System - An Overview. *Presented at Short Course V on Exploration for Geothermal Resources, organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 29 – Nov. 19, 2010*.
- Smith, M. and Mosley, P., 1993: Crustal heterogeneity and basement influence on the development of the Kenya rift, East Africa. *Tectonics*, 12, 591-606.
- Smith, M., 1994: Stratigraphic and structural constraints on mechanisms of active rifting in the Gregory Rift, Kenya. In: Prodehl, C. Keller, G.R. & Khan, M.A. (eds.): Crustal and upper mantle structure of the Kenya rift. *Tectonophysics*, Vol. 236, 3-22 pp.