



## THE GEOTHERMAL ACTIVITY OF THE EAST AFRICAN RIFT

**Peter A. Omenda**

Geothermal Development Company  
P. O. Box 100746, Nairobi 00101  
KENYA  
*pomenda@gdc.co.ke*

### ABSTRACT

The East Africa Rift System is a classical continental rift system associated with the world-wide mid ocean rift systems. The rift extends from the Red Sea – Afar triple junction through Ethiopian highlands, Kenya, Tanzania and Malawi to Mozambique in the south. The western branch passes through Uganda, DRC and Rwanda while the nascent south-western branch runs through Luangwa and Kariba rifts in Zambia into Botswana. The volcanic and tectonic activity in the rift started about 30 million years ago and in the eastern branch the activity involved faulting and eruption of large volumes of mafic and silicic lavas and pyroclastics. The western branch, typified by paucity of volcanism, is younger and dominated by faulting that has created deep basins currently filled with lakes and sediments.

Geothermal activity in the rift is manifested by the occurrences of Quaternary volcanoes, hot springs, fumaroles, boiling pools, hot and steaming grounds, geysers and sulphur deposits. The manifestations are abundant and stronger in the eastern branch that encompasses Afar, Ethiopian and Kenya rifts while in the western branch, the activity is subdued and occurs largely as hot springs and fumaroles. Detailed and reconnaissance studies of geothermal potential in Eastern Africa indicates that the region has potential of 2,500MW<sub>e</sub> to 6,500MW<sub>e</sub>.

### 1. INTRODUCTION

The East African rift system is widely recognized as the classical example of a continental rift system which is part of the Afro Arabian rift system that extends from the Red Sea to Mozambique in the south. As the rift extends from the Ethiopian segment southwards it bifurcates at about 5°N into the Eastern and Western branches. The two branches of the rift skirts around the Tanzania craton and formed within the Late Proterozoic belts adjacent to the margins of the craton (Mosley, 1993 and Smith and Mosley, 1993). However, the Eastern Branch that comprises the Ethiopian and Kenya rifts is older and relatively more volcanically active than the western branch that comprises Albert–Tanganyika-Rukwa-Malawi rifts.

In the rift axis of the eastern branch occurs numerous central volcanoes of Quaternary age overlying products of Miocene and Pliocene volcanism. The shield volcanoes are built largely of intermediate lavas and the associated pyroclastics, thus indicating the presence of shallow hot bodies (magma chambers). In the Western Branch, there is paucity of volcanism along the entire length of the rift with the main volcanic areas being Virunga and Rungwe. The geothermal activity in the East African rift

occurs in the form of hot springs, fumaroles, hot and altered grounds is closely associated with Quaternary volcanoes in the axis of the rifts. The association is related to the shallow hot magma bodies under the massifs, which are the heat sources. In the Afar rift where the crust is as thin as 5km, extensive manifestations and high heat flux is due to a combination of mantle heat and magma bodies occurring at shallow depths. In the less magmatic western branch of the rift, heat sources could be combination of buried pluton and high heat flux associated with thinned crust.

Using today's technologies, Eastern Africa has the potential to generate 2500 to 6500 MW of energy from geothermal power (GEA, 1999) which if developed would represent from ¼ to ¾ of current worldwide production from geothermal sources (8,200 MW total installed capacity). Despite this potential, only Kenya and Ethiopia have active geothermal generation of 130 MW and 7.2 MW, respectively. Varying degrees of geothermal exploration and research have been undertaken in Djibouti, Eritrea, Uganda, Tanzania, Zambia and Malawi. The potential to use geothermal energy for grid-connected electrification is greatest in Kenya, Djibouti, Ethiopia, Uganda and Tanzania. In addition, all the countries have the potential to use geothermal energy for grid connected electrification.

## 2. GEOTHERMAL ACTIVITY

### 2.1 General

East African rift system (EARS) is a succession of rift valleys that extend from Beira in Mozambique in the south to Afar triangle in the north; a total distance of more than 4,000-km. The EARS is a continental branch of the worldwide mid ocean rift system that corresponds to the third arm of the Afar- Red Sea – Gulf of Aden triple junction. The rift is assumed to mark the incipient plate boundary between the Somali and Nubian micro-plates and linked to the Afar- Red Sea – Gulf of Aden rift systems (Figure 1). The EARS splits into two at about 5°N to form the Eastern and Western branches. The Eastern branch comprises the Afar, Ethiopian, Turkana and Kenya Rifts while the western branch comprises Albert, Kivu, Tanganyika, Rukwa and Malawi Rifts. The SW branch comprises Luangwa-Kariba-Okavango rifts.

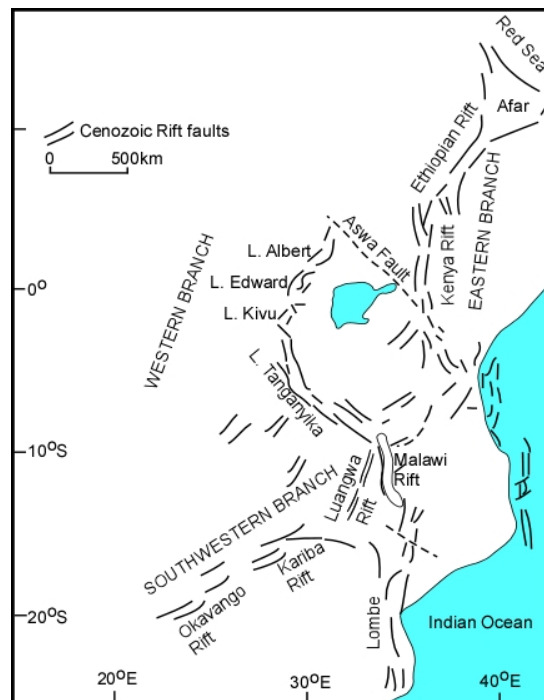


FIGURE 1: Structural map showing the East African Rift System (modified from Atekwana et al., 2004)

The standard model for active rift formation involves lithospheric extension accompanied by upwelling of the underlying asthenospheric mantle (Figure 2). Decompression of the asthenosphere results in large volumes of magma generation. Further brittle extension of the crust results in down-faulting and formation of the graben. In the case of the EARS, extensions is more active in the north being more than 2cm/year in the Red Sea – Gulf of Aden, 1 mm/year in the Main Ethiopian Rift, and further less than 1mm/year in the Kenya Rift and southwards. In response to the increased extension in the EARS, the Moho is at between 5

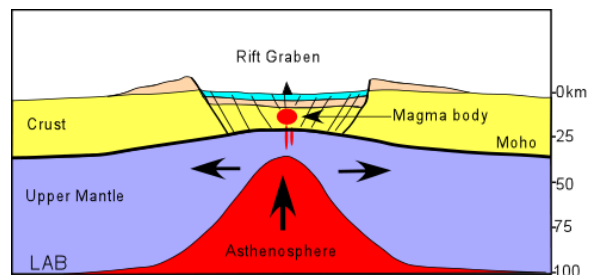


FIGURE 2: Generalized E-W section across a typical continental rift showing late stages of its formation

and 35 km along the axis of the rift.

## 2.2 The Ethiopian Rift

The Main Ethiopian Rift (MER) and Afar Rift represent the northernmost part of the East African Rift (Figures 2 and 3). Volcanic activity in Ethiopia started about 30 million years ago with uplift followed by eruption of large volumes of basalts (Mohr and Zanettin, 1988). However, activity has reduced since the Miocene times with eruptions of bimodal suite of basalts and more alkaline silicic lavas concentrated within the rift zone. More recent activity in the axis of the rift consisted of rhyolite volcanoes and domes as well as ignimbrites and non-consolidated pyroclastics. Studies by Mohr (1992) indicate that over 90% of the eruptives are of silicic composition. In the axis of the rift occurs the Wonji fault belt, which is a region of Quaternary crustal extension. The fault zone is offset in several locations along its length and some of the large volcanoes including Aluto are located at the fault intersections (Figure 3).

The Afar rift is the most active segment of the entire EARS with Erta Ale volcano being presently active. The Afar rift floor is dotted with a large number of rhyolitic volcanoes in the south and more basaltic centres in the north. The surface geology in the south is similar to that of the MER where ignimbrites are abundant while in the north basalt sheets of Quaternary age dominate. The volcanics overlie older sedimentary rocks in the Afar rift zone.

Geothermal manifestations occur as fumaroles, altered grounds, steaming grounds and hot springs in many locations, most of which are associated with young volcanic fields in the rift valley. Hot springs also occur on the flanks of the rift where they are associated with Tertiary faulting episodes. The manifestations are more pronounced and vigorous within the axis of the rifts than on the flanks due to the favourable hydrology and relatively shallow heat sources. The heat sources for the geothermal systems are related to (1) shallow magma chambers associated with the young rhyolite volcanoes that are common in the southern Afar and MER and (2) upper mantle intrusion/upwelling associated with the thin crust in the area that averages between 5 – 20 km. Description of characteristics of geothermal activities in the Ethiopian rift is discussed below.

### 2.2.1 Djibouti

Djibouti lies at the Afar triple junction of three active, major coastal spreading centres: (a) the Eastern Africa Rift zone; (b) The Gulf of Aden Rift; and (c) and the Red sea Rift (Figures 1, 3 and 4). In Djibouti, areas of strong manifestations are located within the Asal and Hanle rifts in the Afar Depression (Mohamed, 2004). According to a recent study by the Geothermal Energy Association (GEA, 1999), the geothermal potential in Djibouti is between 230-860 MW<sub>e</sub> from a number of prospects including: Lake Abbe, Hanle, Gaggade, Arta, Tadjourah, Obock and Dorra.

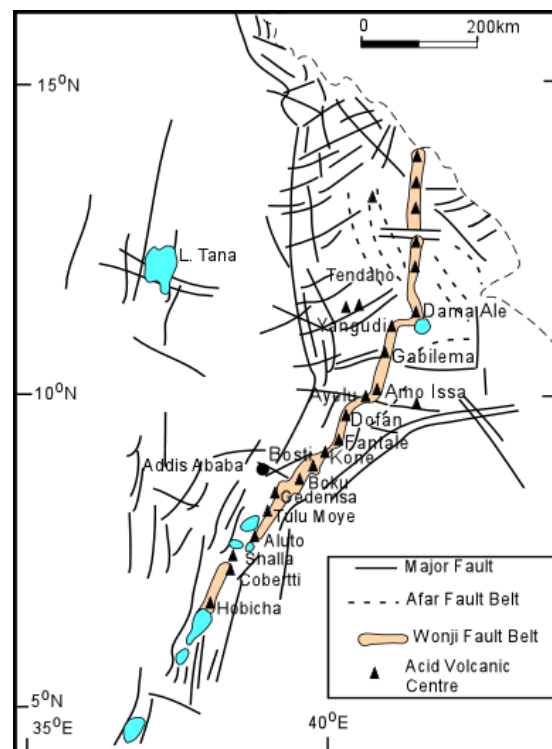


FIGURE 3: Structural map of the Ethiopian Rift showing locations of Quaternary volcanoes (From Abebe, 2000)



FIGURE 4: Map of Djibouti showing geothermal areas

**2.2.2 Eritrea**

In 1973 the United Nations Development Programme (UNDP), identified a potentially significant exploitable geothermal resources in Eritrea. In 1995 with help of USGS, Eritrea identified the Alid geothermal prospect area for follow up detailed investigations. This area is located about 120km south of Massawa (Figure 5)

Alid Volcanic centre is the better studied of all geothermal areas in Eritrea. The geothermal prospect lies within the Danakil Depression and is characterized by a rhyolitic domal intrusion which is considered to be the main heat source for the geothermal system. Manifestations occur in the form of boiling pools, hot springs, and fumaroles (Woldegiorgis et al., 2003). Detailed geoscientific investigations revealed a reservoir temperature of about 250°C.

**2.2.3 Ethiopia**

Ethiopia started a long-term geothermal exploration undertaking in 1969. Over the years a good inventory of the possible resource areas has been built up and a number of the more important sites have been explored in the Ethiopian Rift Valley. Of these areas, about sixteen are judged to have potential for high temperature steam suitable for conventional electricity generation (Figures 3 and 6).

Exploration work peaked during the early to mid-1980s when exploration drilling was carried out at the Aluto-Langano geothermal field, Lakes District Eight deep exploratory wells were drilled to a maximum depth of about 2500m, and four were found to be productive with a maximum geothermal reservoir temperature of about 350°C.

Much effort has been expended in Djibouti since the 1970's, in view of the country being deficient of indigenous energy resources. Djibouti's current energy production is by fossil fuels. The first concerted effort to assess and explore Djibouti's geothermal resources took place in the Assal area from 1970-83 and funded by the French government. About six exploratory wells were drilled in the Assal geothermal fields. While a very high temperature system has been successfully located, problems related to high salinity of the discovered fluids, which is due to the close proximity of the field to the Gulf of Aden, has delayed resource development and exploitation (Teklemariam, 2005).

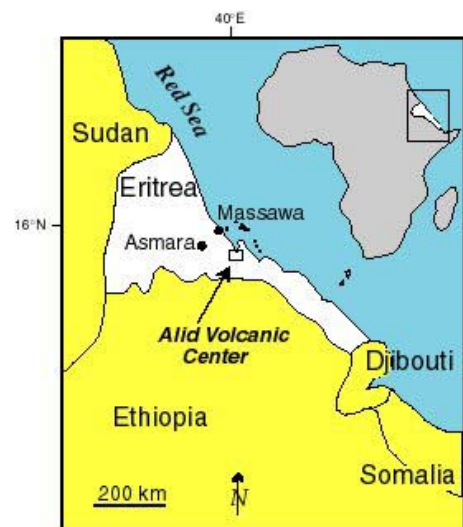


FIGURE 5: Map showing the location of Alid volcanic centre in Eritrea

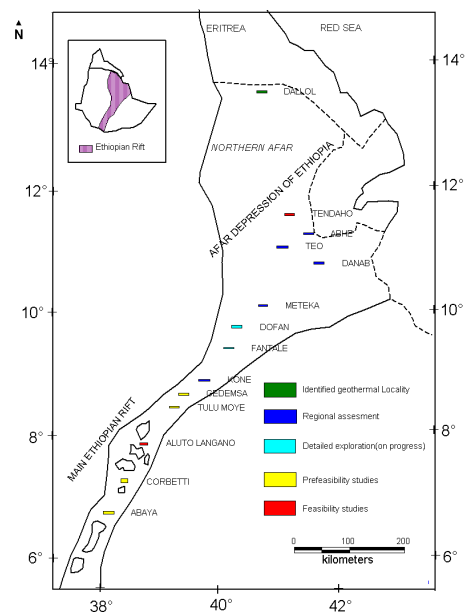


FIGURE 6: Location map of the geothermal areas in the Ethiopian Rift

During the early 1990s exploration drilling was also carried out at Tendaho (Northern Afar). Three deep (2100m) and three shallow wells (500m) confirmed the existence of a high temperature (270°C) reservoir. The Aluto-Langano geothermal field was handed over to the Ethiopian Electric Power Company (EEPCo) for development in the year 1996 but utilization was delayed until 1998 when the first 7.2MW<sub>e</sub> pilot power plant was built.

### 2.3 The Kenya Rift

The Kenya rift is the segment that extends from Lake Turkana to northern Tanzania. The formation of the Kenya rift started about early Miocene in the north around Lake Turkana and migrated southwards being active from about middle to late Miocene in the central segment. The development of the rift occurred largely within the Late Proterozoic basement of Mozambique belt and close to the eastern margin of the Tanzania craton.

The formation of the rift started by up doming and volcanism on the crest of uplift and followed by faulting to form a half graben. The formation of a full graben occurred during the early Pleistocene, on the floor was erupted lava flows of basaltic and trachytic composition, and intercalated with tuffs. Subsequently, sheet trachytes were grid faulted with dominant north-south closely spaced faults. The Quaternary times saw the development of many large shield volcanoes of silicic composition in the axis of the rift.

Activity in the southern extreme of Kenya and northern Tanzania segment of the Kenya rift is dominated by alkaline and carbonatitic volcanism of which Ol'Doinyo Lengai is well known. Prevalence of the carbonatites in the region is attributed to deep source of the lavas occasioned by the thick cratonic crust in the region. Alkaline lavas are predominant in the areas around Kilimanjaro where micro- rift grabens occur near Arusha and further south.

The entire length of the Kenya rift from Lake Turkana in the north to northern Tanzania has young volcanoes dominantly of silicic composition in its axis. The youthfulness of the volcanoes attests to active magmatism under the rift. Similarly, geothermal manifestations are more abundant and stronger within the rift and in many cases they are associated with the young Quaternary volcanoes (Figure 7).

Geothermal manifestations in the Kenya rift include fumaroles, hot springs, spouting springs, hot and altered grounds and solfatara (sulphur deposits). Fumaroles commonly occur on the mountains while hot springs and geysers are common on the lowlands. Sulphur deposits have been observed at several geothermal areas including Olkaria, Paka and Barrier volcanoes where it is indicative of the presence of a degassing magma body at depth. Extinct manifestations in the form of travertine deposits, silica veins and chloritized zones are common in the Lakes Baringo – Bogoria regions indicating long-lived geothermal activity in the rift.

Of these areas, Olkaria has been developed for electricity generation (130MW<sub>e</sub>) while a pilot plant is planned for Eburru (2.5MW<sub>e</sub>). Both the Olkaria and Eburru geothermal systems are volcano hosted resources and thus, the heat driving the systems are associated with hot intrusive bodies under the

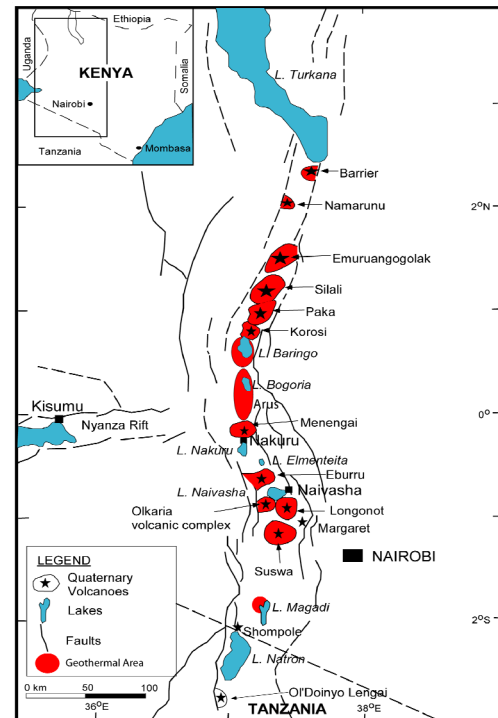


FIGURE 7: Map of the Kenya rift showing the locations of geothermal areas

volcanic complexes. Gravity has imaged dense bodies under the volcanoes which are probably magma bodies (Figure 8).

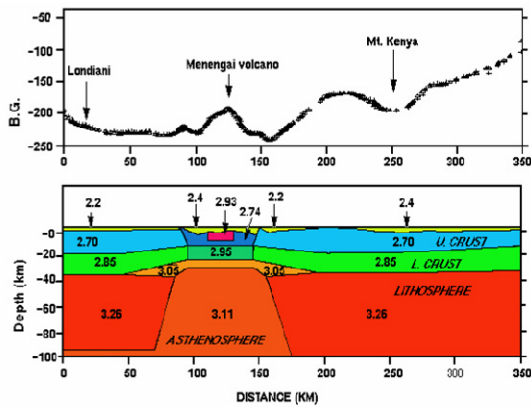


FIGURE 8: E-W Gravity model across Menengai volcano (after Simiyu, 1996)

Detailed investigations recently concluded in Menengai, Korosi, Paka and Lakes Baringo and Bogoria geothermal prospects reveal the possible existence of geothermal systems. High temperatures systems possibly exist at Menengai, Paka and Korosi while low to medium temperatures resources could be associated with the systems around Lakes Baringo and Bogoria. Exploratory drilling is planned for Suswa, Longonot and Menengai prospects from the year 2008. It is estimated that over 3,000 MW<sub>e</sub> can be generated from the geothermal systems in the Kenya rift. It is notable that in Kenya other than electricity production, geothermal water and carbon dioxide are used in an extensive complex of green houses for growing roses at Olkaria.

### 2.4 Western Branch

The western branch of the rift runs along the western side of Lake Victoria and along the edge of the East African plateau (Figure 9). The geography of the western branch is typically half grabens characterized by the high angle normal rift faults. The western branch of the rift is characterized by paucity of volcanism relative to the Kenyan and Ethiopian rifts. Whereas the volcanism and tectonic activity in eastern branch commenced about 30 million years ago in the eastern branch of the rift, volcanic activity in the western branch commenced about 12 Ma in the north near Lake Albert and about 7 Ma in the Tanganyika rift (Ebinger, 1989).

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. The Albertine basin is also thought to have petroleum potential. The western branch is characterized by the abundance of potassic alkaline rocks that consists of carbonatites, ultrapotassic mafic rocks and potassic mafic-felsic lava. Volcanic activity is more intense in the Virunga volcanic field where Nyiragongo and Nyamuragira in the DR Congo are active with basaltic eruptives.

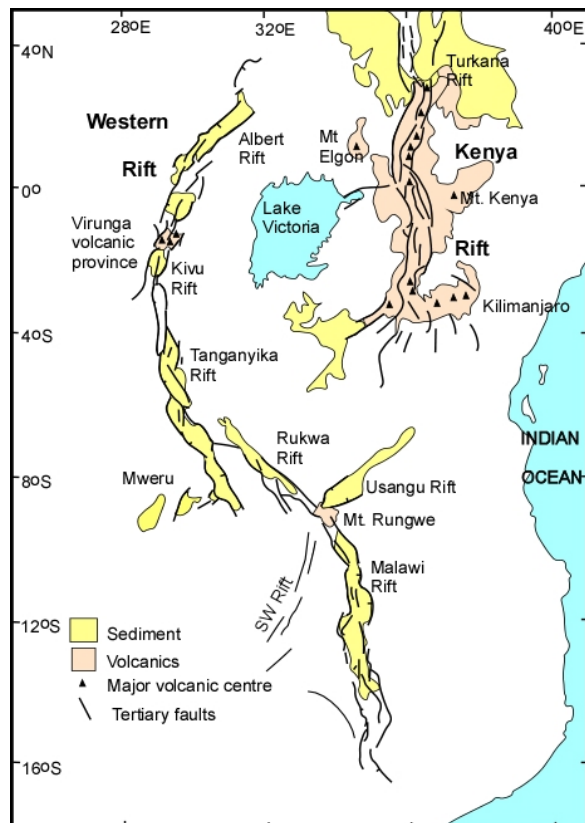


FIGURE 9: Map showing the structural relationship between the Eastern (Kenya) and Western branches of the EA Rift system

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 rift-ward 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. Late Cenozoic volcanism started about 9-7 Ma ago in the Rungwe volcanic province where the rift follows the NE-SW trend in line with the Kenya rift. The volcanic products include Quaternary mafic and felsic rocks.

Whereas there is paucity of recent volcanism in this segment of the rift, geothermal activity is still 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. Other hot springs occurring in Malawi, Zambia and Mozambique are fault controlled and are associated with the border faults. The hot springs are probably due to deep circulation of ground waters through the rift structures.

**2.4.1 Tanzania**

Geothermal exploration in Tanzania was carried out between 1976 and 1979 by SWECO, a Swedish consulting group, in collaboration with Virkir-Orkint (Iceland), with financial support from the Swedish International Development Authority (SIDA). Reconnaissance studies for surface exploration were carried out in the north (near Arusha, Lake Natron, Lake Manyara and Maji Moto) and in the south (Mbeya region). Geothermal work in all locations in Tanzania is at the surface exploration stage.

Two potential target areas for geothermal exploration singled out so far are: (a) Arusha region near the Kenyan border in the North; and (b) Mbeya region between Lake Rukwa and Lake Nyasa in the southwest. Another potential area (Luhoi) was prospected during 1998-2002 by First Energy Company of Tanzania. It conducted important project definition and reconnaissance evaluation work. This area is located 160 km south of Dar es Salaam. The work conducted so far indicates the existence of a possible geothermal system with reservoir temperature greater than 200°C. In northern Tanzania, geothermal activity occurs mainly along the southern extension of the Kenya rift into L Eyasi, Ngorongoro, L. Natron, Ol'Doinyo Lengai and Arusha areas. Other low temperature manifestations occur in central and south east Tanzania in Singida and Rufiji areas.

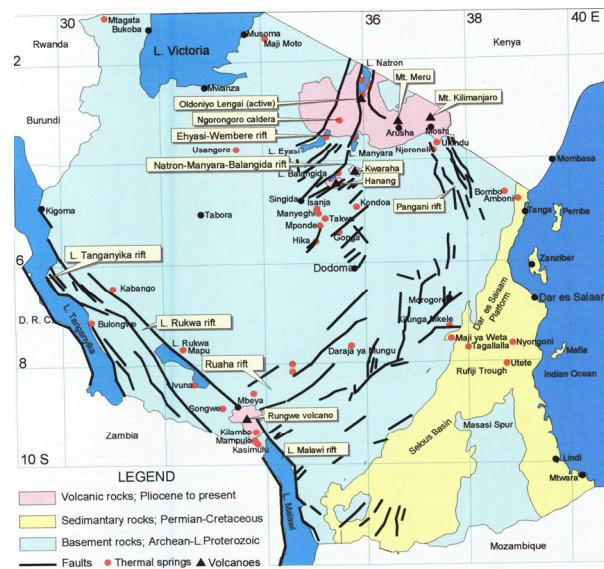


FIGURE 10: Map of Tanzania showing the location of geothermal areas

**2.4.2 Uganda**

In Uganda, geothermal activity is restricted largely to the areas within the western rift valley. Geothermal manifestations in the form of fumaroles and hot springs occur along some of the border faults of the rift valley and within the volcanic fields.

Fault controlled manifestations occur at Buranga at the foot of Ruwenzori massif as well as at Kibiro near Lake Albert. The manifestations at Buranga discharge at boiling point while travertine deposits have also been noted in several localities (Bahati, 2003). Hot springs also occur in the Katwe-Kikorongo and Virunga volcanic fields where they are associated with the young volcanoes. Geothermal manifestations occurring outside of the rift in Uganda tend to have lower surface

temperatures (Data and Bahati, 2003). Reconnaissance survey has been carried out on geothermal areas of Uganda since 1935 when the first documentation of hot springs was made (Bahati and Tuhumwire, 2002).

**2.5 South-western Branch**

The south-western branch of the western rift follows geological structures along mobile belts from Lake Tanganyika into southern DR Congo and Zambia then south-westward into the Okavango rift system in northwest Botswana. The rift is non magmatic in its entire length, however, faults are evident along the entire length of the rift. However, rift structures in the Okavango have been identified only through geophysical techniques (Atekwana et al., 2004).

Geothermal activity in Zambia and southern DR Congo occurs within the south-western rift. The geothermal manifestations that include hot springs occur at Kapisya that discharge at 85°C near Lake Tanganyika and also near Lake Mweru. Other springs occur at Chinyunyu (60°C) near Lusaka (Figures 1 and 12).



FIGURE 11: Map of Uganda showing the location of geothermal areas

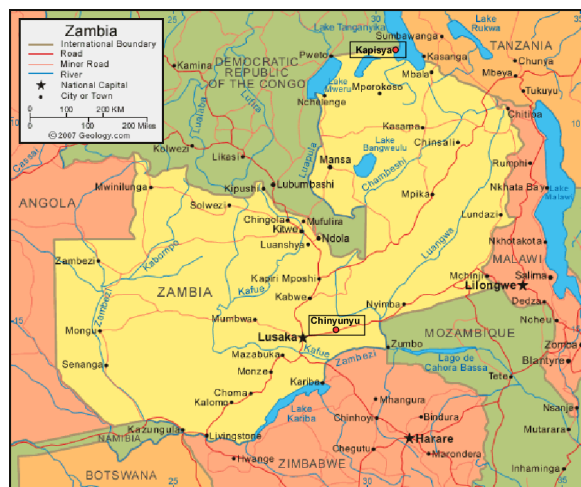


FIGURE 12: Map of Zambia showing the location of Kapisya and Chinyunyu geothermal areas

The Italian government in 1987 funded a mini geothermal pilot power plant (200 KW) at Kapisya hot springs located at the shores of Lake Tanganyika. The plant was installed on the basis of limited exploration work, and it never became operational. ZESCO has signed an MOU with KenGen to assist in refurbishing and commissioning of the plant after being idle for 20 years. As part of the agreement, KenGen and ZESCO carried out detailed scientific investigations at Kapisya and Chinyunyu which revealed that the geothermal systems follow the fault plane model where the heat is due to deep circulation along the rift structures (Figure 13). It is estimated that each of the prospects can generate up to 2MW<sub>e</sub> using binary technology (Omenda et al. 2007).

**3. DISCUSSION**

The geothermal activity in the East African rift system is closely tied to the occurrence of Quaternary volcanoes located within the axis of the rifts. The shield volcanoes are largely made of trachytes, rhyolites and associated pyroclastics. The presence of the silicic products attests to the occurrence of shallow magma (fossil) bodies that are considered the most important heat sources for the associated geothermal systems. This is premised on the fact that since the eruptives are products of mainly protracted fractional crystallization, massive heat must have been conductively transferred to the upper



reservoirs. Further, heat would be transferred where assimilation of crust occurs to a significant level as has been demonstrated at Olkaria (Omenda, 2000, Macdonald et al 1987).

Evidence for the occurrence of shallow magma bodies has been demonstrated at Olkaria, Suswa, Longonot and Menengai geothermal areas in Kenya where seismic waves show “gaps” at shallow levels (e.g. Figures 8, 14 and 15). The seismic “gaps” signify the presence of molten bodies at about 7-10 km of the surface. Therefore, shallow magma bodies are the single most important heat sources for the volcano hosted high temperature geothermal resources in the East African rift.

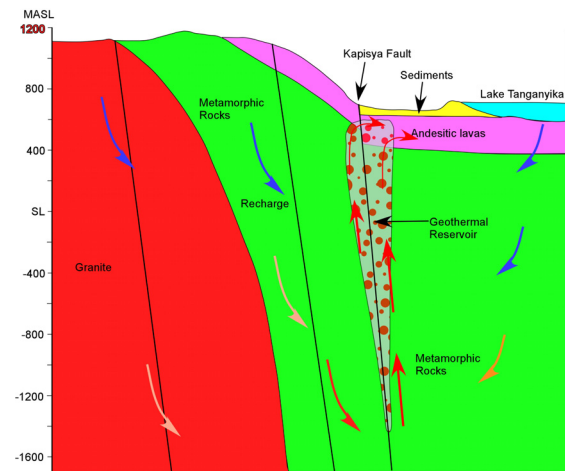


FIGURE 13: Geothermal model of the Kapisya geothermal system in Zambia

Studies reveal that the crust under the EA rift ranges between 5km (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 45km (e.g. Prodehl et al., 1997; Simiyu and Keller, 1997; Figure 2). 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). Importance of asthenospheric heat would be more important in the Afar triple junction where the crust is less than 5km thick.

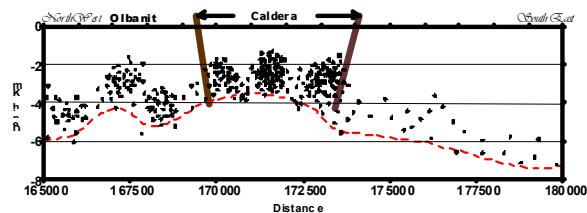


FIGURE 14: Seismic section across Menengai volcano (after Simiyu and Keller, 1997)

Deep circulation of ground waters through the master rift faults would mine heat from the rocks and upflow through the axial regions of the rift. Deep circulation has been indicated by the elevated boron contents of the fumaroles in some prospects in Kenya (Clarke et al., 1990, Dunkley et al, 1993, Geotermica Italiana, 1987). This deep groundwater circulation coupled with enhancement by young dike intrusions or plutons could explain some of the geothermal resources that occur outside of the Quaternary volcanic centres in the rift and those in old terrains as in Kapisya and Chinyunyu in Zambia and western Uganda geothermal areas (Figure 13).

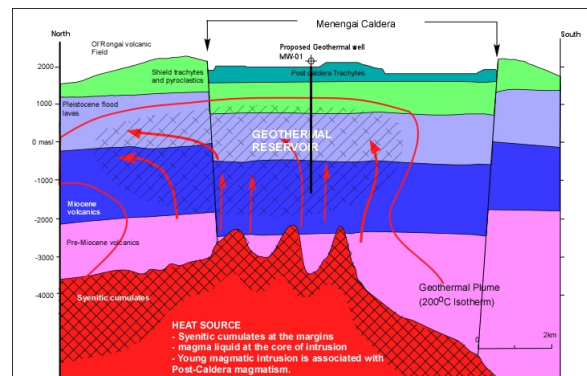


FIGURE 15: The W-E conceptualized geothermal model of Menengai geothermal prospect based on geology, gravity, seismics and MT data.

The main recharge for the geothermal systems in the East African rift, as has been determined by stable isotopes, originates largely from the flanks of the rifts. These regions are generally at higher elevations, wetter and are cut by faults parallel and oblique to the rift structural trends. Recharge would, therefore occur via the rift master faults and channelled to the rift axis by the oblique faults that cut through the rift faults (Abebe, 2000, Omenda, 1998, 1994). The high elevation ensures deep circulation through the master faults to the hot rocks. However, studies at Olkaria indicate that rift

axial recharge is also important but mainly affects the upper parts of the geothermal reservoirs i.e. less than 1,000 m depth (Omenda and Karingithi, 2004).

Geothermal reservoirs in the Ethiopian and Kenya Rifts are mainly hosted within the faulted and layered Plio-Pleistocene rift volcanics. The permeability in such systems is due to fractures/faults and lithologic contacts. It is also thought that fractures caused by domal intrusion could also be important in enhancing permeability in some fields (Woldegiorgis et al. 2003). However, for the case of the geothermal resources in western branch of the rift, the reservoirs are largely hosted within the Precambrian metamorphic rocks where secondary permeability associated with faults and fractures are important.

The capping formation for the volcano hosted geothermal systems in the rifts is often a combination of lava flows and pyroclastics and shales and other sediments form capping formations in the Afar region where the volcanic products overlie sedimentary formations (Mohamed, 2003).

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