# Geology and the geothermal systems of the southern segment of the Kenya Rift

John Lagat
University of Iceland, Department of Geosciences, Geology house, Sudurgotu, 101 Reykjavik, Iceland
*Kenya Electricity Generating Company Ltd, P. O. Box 785, Naivasha, Kenya
E-mal: *jlagat@kengen.co.ke, johnl@hi.is
*Permanent address

### Abstract

The Kenya Rift is part of the East African Rift system, which is an active continental divergent zone. The Southern segment of the Kenya Rift Valley is a unique petrographic province comprising of at least four Quaternary to Recent volcanic complexes namely Suswa, Longonot, Olkaria, and Eburru. Although these volcanoes are located only about 40 km from each other, the eruptive products show marked compositional contrasts, requiring differences in magmatic processes. The rocks are characterised by subalkaline/peralkaline trachyte and/or peralkaline rhyolite volcanism with basalts being confined to eruption sites between individual centres. The segment of the Kenya Rift has anomalously high heat flow due to shallow intrusions. Active geothermal systems are associated with the volcanic centres. This paper summarizes the geology of the southern segment of the Kenya Rift and discusses reasons that indicate greater geothermal potential for Olkaria and Eburru and promising geothermal potential for Suswa and Longonot volcanic centres all with an estimated potential of more than 1000 MWe. These include the youthfulness of the volcanic activities, large shallow magma chambers, fractured reservoir rocks, and favourable hydrogeology. Geothermal energy in Kenya is mainly utilized for generation of electricity and to a very small extent in direct use for drying pyrethrum, soil fumigation and in greenhouse heating.

***Keywords:*** *Volcanism, geothermal systems, geothermal potential, Olkaria, Eburru, Suswa, Longonot, Kenya.*

## 1 Introduction

The Kenya Rift valley (Figure 1) is part of the East African Rift system that runs from Afar triple junction in the north to Beira, Mozambique in the south. It is part of an incipient continental divergence zone, a zone where thinning of the crust is occurring and hence eruption of lavas and associated volcanic activities. The development of the rifting within Kenya started during the late Oligocene (30 Ma) and continues to present, with most of the Quaternary volcanism concentrated within the axis of the rift. The southern segment of the Kenya Rift is a unique petrographic province comprising of at least four Quaternary to Recent volcanic complexes. These are, from south to north, Suswa, Longonot, Olkaria and Eburru. The shallow lithosphere-asthenosphere boundary and Moho is responsible for the general high heat flow within the rift with a geothermal gradient of over 200°C/km (Wheildon et al., 1994).

Geothermal systems are confined to these centres, with Olkaria and Eburru having a proven geothermal resource of 173 $MW_e$ and 20 $MW_e$ respectively. The former has been producing electricity since 1981. The total estimated power output from Olkaria and Eburru when both conventional and binary systems are used is over 600 $MW_e$. Detailed scientific studies have been conducted in Suswa and Longonot, and the results indicate good prospects for geothermal resources exploitation with an estimated power output of over 400 $MW_e$. This puts the total estimated power output for this sector of the Kenya Rift at 1000 $MW_e$. Described below is the geology of the volcanic centres from south to north of the sector.

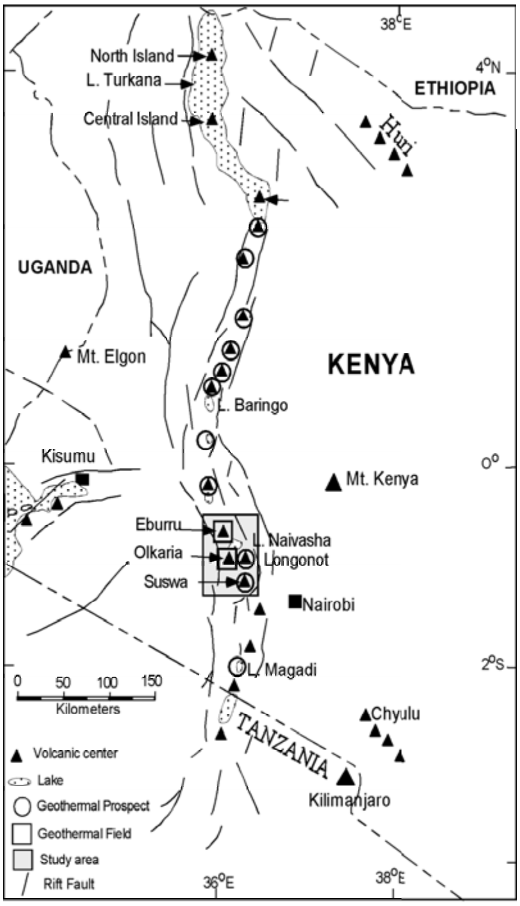


**Figure 1: Map of Kenya Rift showing the locations of Suswa, Longonot, Olkaria and Eburru (Modified from Omenda, 1997).**

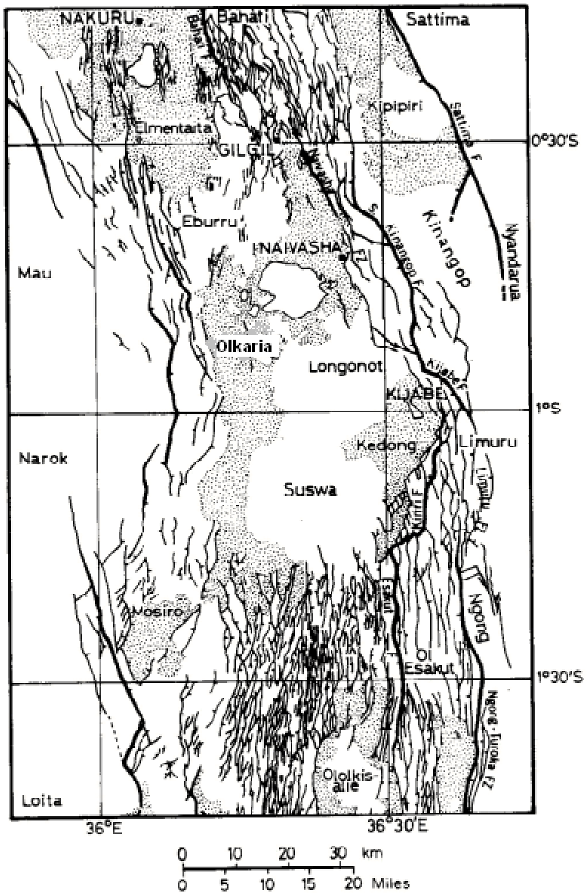


**Figure 2: The structural map of Kenya Rift (From Baker et al 1988).**

# 2 Geology

## 2.1 Suswa

Suswa is made up of two calderas; the inner (younger) and the outer caldera. The outer caldera measures about 12x10 km in diameter and has a general orientation of ENE-WSW. The inner caldera has a diameter of about 4 km and the central resurgent block measures about 3 km in diameter. The rock outcrops in Suswa and the adjacent areas can be divided into four main groups: Pre-Suswa volcanics, pre-caldera trachytes, syn-caldera trachytes, and phonolites. The Pre-Suswa volcanics, which comprise of Limuru Trachytes and Plateau Trachytes, have been dated at 2.0-1.7 Ma and 1.3-1.9 Ma respectively and they predate the rift block faulting. The pre-caldera trachytes can be divided into two groups: the faulted, shield-building group and the late non-faulted shield building lavas. The early trachytes are the oldest group dated 0.4±0.01 Ma and is the onset of volcanic activity at Suswa. The late phase, non-faulted trachytes typically overlie the faulted group. Syn-caldera rocks include ignimbrites and trachytes (Baker et al., 1988). Most of these lavas contain xenoliths of syenite and hydrothermally altered rocks most likely torn from the roof and volcanic conduits. Some of the vesicles are lined with magmatic calcite. Post-caldera (I)

Phonolites lavas were erupted in two distinct episodes, both post-dating caldera (I) formation, however, one group predates caldera (II) and the other postdates caldera (II) formation. The youngest flow in Suswa occurs within the annular trench. The lava flow has scarce vegetation cover, attesting to its youthful age. Torfason (1987) suggested that this flow may be about 200 to 400 years BP, but no dating has been done to obtain the actual age. The geothermal system in Suswa developed prior to caldera collapse as hydrothermally altered lithics with alteration minerals indicating temperatures of >250°C occur within the syn-caldera sequences. Fumarole geothermometry studies indicate temperatures ranging from of 270°C to >300°C (Arnorsson, 1989).

Detailed scientific studies were carried out by KenGen in 1992-1993 in Suswa and indicated the volcano as a good prospect, which possibly has a shallow heat source under the caldera (Omenda, 1993). Three exploration wells were sited and exploratory drilling is envisaged in the near future. Estimated power stored in Suswa geothermal field is put at approximately 200 $MW_e$.

## 2.2 Longonot

The activity directly associated with Longonot started 0.4 Ma BP and can be described in three main periods namely pre-caldera, syn-caldera and post-caldera. A series of arcuate ridges on the northern, western and the southern parts of the summit crater indicate existence of a caldera. Due to wide spread cover of the area by post caldera pyroclastics and lavas, pre- and syn-caldera rocks are not extensively exposed. Pre-caldera rocks, which include trachytes, have been encountered in shallow boreholes on the northern and western flanks of the Longonot volcano (Clarke et al., 1990). Syn-caldera activity includes layers of ignimbrite and pumice lapilli and ash deposits. Lower and upper mixed basalt/trachyte lavas and trachyte lavas were erupted during this period. The most recent activity is emission of trachyte lava on the north and the southwest flanks of the cone and mixed basalt/trachyte lava on the crater floor and are estimated at about 200 yrs BP (Clarke et al., 1990). Trace element of studies done on Longonot volcanics indicate that they are comagmatic, thus suggesting the presence of a large, highly evolved and long lived magmatic system under the caldera (Clarke et al., 1990). Presence of hydrothermally altered lithics indicates that the geothermal system under the volcano must have attained >250°C (Geotermica Italiana, 1989).

KenGen did detailed scientific work at Longonot volcano in 1998 and the results indicated a prospect area of about 60 $km^2$ and three exploration wells were sited in the area. Drilling of the exploration wells will be conducted in the near future when funding is secured. Estimated power output from the Longonot geothermal field is approximately 200 $MW_e$ (KenGen, 1998).

## 2.3 Olkaria

Olkaria volcanic complex is characterized by comendite lava flows and pyroclastics on the surface and basalts, trachytes, and tuffs in the subsurface. The litho-stratigraphy of the Olkaria geothermal area as revealed by data from geothermal wells and regional geology can be divided into six main groups: Proterozoic "basement" formations, Pre-Mau Volcanics, Mau Tuffs, Plateau Trachytes, Olkaria Basalt and Upper Olkaria volcanics. The Pre-Mau formation is not exposed in the area, but outcrop on the rift scarps in the parts of the Southern Kenya Rift. Mau Tuffs are Pleistocene in age and are the oldest rocks that crop out in the Olkaria area. The Upper Olkaria formation consists of comendite lavas and their pyroclastic equivalents, ashes from Suswa and Longonot volcanoes and minor trachytes and basalts (Omenda, 1997; Clarke et al., 1990; Thompson and Dodson, 1963). The youngest of the lavas is the Ololbutot comendite, which, has been dated at 250±100 yrs BP using $^{14}C$ from carbonized wood obtained from a pumice flow associated with lava (Clarke et al., 1990). The geothermal system in Olkaria is bound by the ring structure which is thought to be a caldera marked by numerous volcanic cones and domes to the east and to the south, the western edge being marked by Olkaria hill.

The geothermal system at Olkaria has been used to generate power since 1981. The proven resource is 173 MWe. The Olkaria East field is currently generating 45 MWe, Olkaria North East field has a power station of 64 MWe under construction and will be producing electricity later this year, and Olkaria West field which is being developed by an IPP and will have a capacity of 48 MWe when completed in 2004. Olkaria Domes is still under exploration and is estimated will host a 64 MWe power station and this would bring the total power for the Greater Olkaria Geothermal Area to 237 MWe. The area is capable of producing more power (>400 MWe) if the available resource is used optimally and combined cycle and binary systems are used.

## 2.4 Eburru

Eburru volcano forms the highest topography within the entire rift floor at elevation of about 2800 m while the surrounding area average 1900 m. The Eburru massif consists of east and west volcanic centers. The volcano is made up of basalts, trachytes, rhyolites, tuffs, and pumice and has possibly been active since early Pleistocene. Cores and cuttings from wells up to 2700 m deep drilled for geothermal exploration in the area revealed more information on the volcanologic history of the volcano. The western older sector of Eburru is composed of lower pantellerite and overlying faulted lower trachyte. The eastern sector with a caldera is composed of upper trachytes and upper pantellerite. Some of the phases might be contemporaneous but the last phase of the eruption is pantellerite. The trachytes are mainly pantelleritic. The occurrence of syenite below the volcanoes within the Kenya Rift, including the Eburru area, has been suspected given the common occurrence of syenitic xenoliths within pyroclastic deposits. Drill cores from Eburru confirmed the presence of a syenitic body below about 2400 m depth. The Eastern Eburru pantellerites are the youngest rocks and are dated about 400 yrs BP (Clarke et al, 1990). The east ring structure bound by numerous volcanic cones or domes has been referred to as a caldera (Omenda 1997).

Detailed geo-scientific survey was carried out by the Kenya Electricity Generating Company, Ltd in 1989, which included geophysical survey of the Eburru geothermal field, geologic mapping of eastern Eburru, chemical characterization of the fumaroles, and drilling of six thermally anomalous areas. The wells drilled were EW-01, EW-02, EW-03, EW-04, EW-05, and EW-06, and have average depth of 2.5 km. From those wells, only EW-01 EW-04 and EW-06 were thermally productive with produced 2.4 MWe, 1.0 MWe and 2.9 $MW_t$ respectively. The other wells EW-02, EW-03 and EW-05 recorded maximum temperatures of 131°C, 161°C and 156°C respectively. The exploration campaign indicated that Eburru volcanic complex has about 2 $km^2$ high enthalpy area that can support a 20 MWe power station.

# 3 Structures

High plateaus composed of lavas and pyroclastics flank the central south sector of the Kenya Rift. The flanking plateaus reach elevations of 3280 m and 2870 m at Mau and Loita in the west and average 2300 m to the east. The main marginal escarpments are

70 km apart and are formed by en echelon normal faults with displacements greater that 500 m. The rift floor lies at an elevation of about 2000 m in the Naivasha-Nakuru region, descending southwards to 800 m near Ololkisalie. Faults are not well exposed within the southern-central sector of the Kenya Rift due to the thick lava and pyroclastic cover blanketing the area (Figure 2). The most prominent faults and fracture patterns are N-S trending ones and are common along the floor of this sector of the rift. An extensive fault fracture network is also common and cut through mostly the Plio-Pleistocene lavas. Several volcanic alignments running roughly N-S are common in the portion of the rift floor with the prominent one being the NNW-SSE volcanic alignment that starts south of Mt. Longonot and runs all the way to the Crescent Island in Lake Naivasha. Suswa and Longonot have clear caldera structures, but Olkaria and Eburru have their calderas inferred by alignment of volcanic centres.

# 4 Hydrogeology

The hydrogeology of central to southern portion of the rift valley is mainly controlled by the rift flanks faults, the grid faulting and the tectono-volcanic axis along the rift floor. Fluids are recharged laterally from the high rift flanks and axially along the rift floor southwards as indicated by the piezometric map of the study area in Figure 3. Analysis of the elevation of the ground water in the boreholes in the area done by Clarke et al. (1990) shows that the water table is shallowest around Lake Naivasha getting deeper towards the south with those drilled between Longonot and Suswa never encountering water at drilled depth. The grid faulting act as channels for ground water or they provide permeable barriers to lateral flow. A microseismic study has shown that the grid faulting unlike the escarpment faulting is quite active suggesting they are open (Allen et al., 1989). Thus the faulting causes the ground water to flow from the escarpments to the center and then follow longer flow paths reaching greater depths, and aligning their flow within the rift along its axis. Due to the southward sloping of the rift floor, the axial flow from Lake Naivasha could also be an important source of recharge in the area south of the lake. The N-S normal faults could be very instrumental in channelling the fluids to the area. In Olkaria and Eburru where drilling has been carried out, the geothermal reservoirs are hosted by the faulted Plio-Pleistocene Plateau Trachytes, which are common within the floor of the southern Kenya Rift valley. It is therefore probable that the reservoirs of Suswa and Longonot are hosted in the same formation.

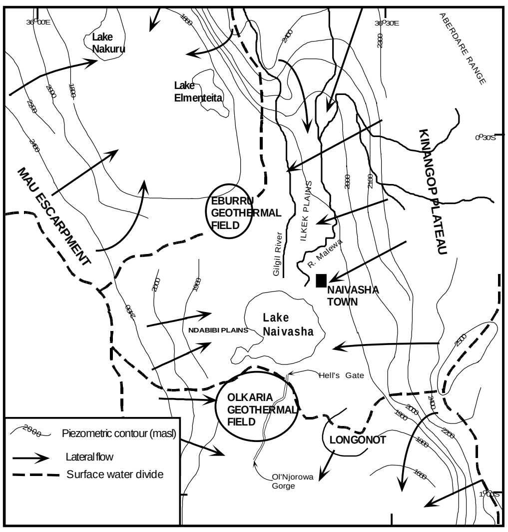


**Figure 3. The piezometric map of Southern Kenya Rift (From Clarke et at., 1990).**

# 5 Geothermal manifestations

Thermal surface signatures in this southern sector of the rift valley are marked by active and extinct geothermal manifestations. The active manifestations occur in form of fumaroles, altered grounds, warm grounds, and sulphur or silica deposition. Extinct manifestations are indicated by presence of altered grounds to brick red/grey clays and silica deposition. These manifestations are mainly structurally controlled, occurring along faults and fractures. Other areas with subsurface information include the boreholes drilled, which tapped low-pressure steam, and hot water. A well drilled to 55 m depth about a half a kilometer south of Longonot recorded a bottom hole temperature of 200$^{o}$C (KRISP, 1985). Geotermica Italiana (1987) studied xenoliths showing high alteration temperature mineral assemblages which suggest hydromagmatic eruptions must have encountered geothermal reservoirs with temperatures of over 250°C.

# 6 Geothermal utilization in Kenya

The geothermal energy in Kenya is mainly used for production of electricity, however minimal direct uses are in drying of pyrethrum, soil fumigation and greenhouse heating. In 1981, a 15 MW power plant was commissioned at Olkaria East field (Olkaria I) followed by the second and third units with the same capacity in 1982 and 1985 respectively. A second 64 MW power station is being constructed at Olkaria Northeast field (Olkaria II) and will be commissioned towards end of year 2003. OrPower 4 an IPP (a subsidiary of Ormat International) is developing Olkaria Northwest field (Olkaria III) and are at the moment generating 12 MWe. When completed in 2004 Olkaria III will produce 48 MW.

Tapped steam has been used to dry pyrethrum at Eburru, but on a small scale. Well OW-101 at Olkaria Central field has been used for soil fumigation for use in horticultural farming. Steam from the well is also used to heat fresh water through heat exchangers and the water is then circulated to heat the greenhouses and hence utilizing the 1.28 MWe from the well effectively.

# 7 Discussion and conclusions

The Kenya Rift is part of an active continental divergent zone, the shallow lithosphere-asthenosphere boundary and Moho is responsible for the general high heat flow within the rift with a geothermal gradient of over 200°C/km. The southern Kenya Rift Valley is a unique petrographic province comprising of at least four Quaternary to Recent Volcanic complexes that host important geothermal prospects. Although these volcanoes are near apart, the eruptive products show marked compositional contrasts with subalkaline/peralkaline trachyte and/or peralkaline rhyolite volcanism with basalts being confined to eruption sites between individual centres.

Magmatic activity associated with these volcanic complexes commenced during late Pleistocene and has been continuous to very recent times. Suswa and Longonot volcanoes are clearly associated with caldera structures whereas Olkaria and Eburru have inferred caldera structures. Presence of very young lava flows indicate that the magma chambers of these volcanic complexes are still active and or hot magmatic intrusions underlie these calderas as evident by the strong thermal surface manifestations present in all the centres. Fumaroles, hot springs, altered grounds and high temperature boreholes are the common geothermal manifestations in most of these prospect areas. Xenoliths showing high mineral alteration temperatures suggest hydromagmatic eruptions encountered geothermal aquifers with high temperatures in most of these prospect areas. In Olkaria and Eburru geothermal systems, high temperature hydrothermal alteration minerals were encountered in well drill cuttings. It is therefore possible that geothermal systems are associated with Longonot and Suswa volcanic centres because of presence of hydrothermally altered lithics with high temperature signatures in pyroclastics from these centres.

The main marginal rift escarpments are 70 km apart and are formed by en echelon normal faults with displacements of greater than 500 m. The rift floor is cut by numerous minor faults that rarely exceed 150 m in displacement. The extensive fault/fracture network evident in this part of the rift provides hydraulic connection and flow towards the rift axis. The rift floor in this central sector of the rift valley is at very low altitude relative to the rift scarps. The flanks, which are wet high altitude areas, therefore provide deep recharge into the floor of the rift due to its great hydraulic gradient between the floor and the flanks. It is therefore possible that surface waters percolate downwards through deep rift structures.

Utilization of geothermal in Kenya has been restricted mainly to production of electricity; direct uses are, however, being applied on a small scale. Direct use should however be boosted especially in farming and industry to make use of wasted energy heat.

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