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THE GEOLOGY AND GEOTHERMAL ACTIVITY OF THE EAST AFRICAN RIFT SYSTEM

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ABSTRACT

The East Africa Rift System is a classical continental rift associated with the world-wide mid ocean rift systems. The rift extends from the Red Sea - Afar triple junction through the Ethiopian highlands, Kenya, Tanzania and Malawi to Mozambique in the south. The western branch passes through Uganda, DRC and Rwanda. 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, however, is younger and is dominated by faulting that has created deep basins currently filled with lakes and sediments. Minor volcanics dated at less than 12Ma occur in the Virunga and Rungwe fields.

Geothermal activity in the rift is manifested by the occurrences of Quaternary volcanoes, hotsprings, fumaroles, boiling pools, hot and steaming grounds, geysers and sulphur deposits. The manifestations which occur in all forms 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, hot grounds and fumaroles. In the eastern branch of the rift, the manifestations are dominantly associated with Quaternary volcanoes while in the western branch they are associated with faults and fractures.

1. INTRODUCTION

The East African rift system is widely recognized as the classical example of a continental rift system which is a part of the Afro Arabian rift that extends from the Red Sea to Mozambique in the south (Figure 1). As the rift extends from the Ethiopian segment southwards it bifurcates at about 5^{o}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; 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 Albertine–Tanganyika-Rukwa-Malawi rifts.

In the rift axis of the eastern branch occurs numerous central volcanoes of Quaternary age occur 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 volcanoes, hot springs, fumaroles, hot and altered grounds and sulphur deposits. The manifestations dominantly occur proximal to Quaternary volcanic centres and along fault zones with the most active areas being the rift axis. Occurrences on the rift flank have been reported.

2. GEOLOGICAL SETTING

The 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 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, extension 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 and 35 km along the axis of the rift.

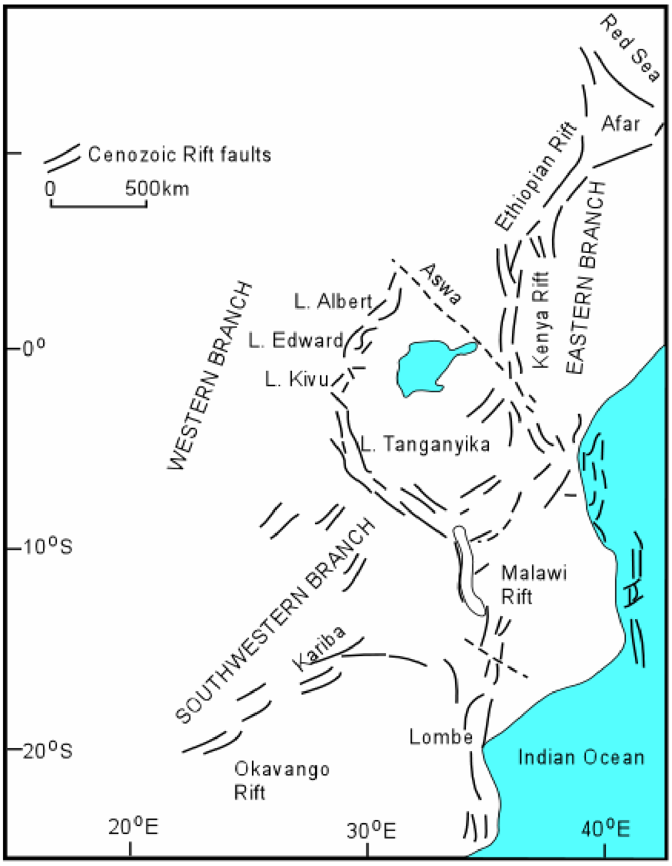

FIGURE 1: Structural map showing the East African Rift System (from Atekwana et al., 2004)

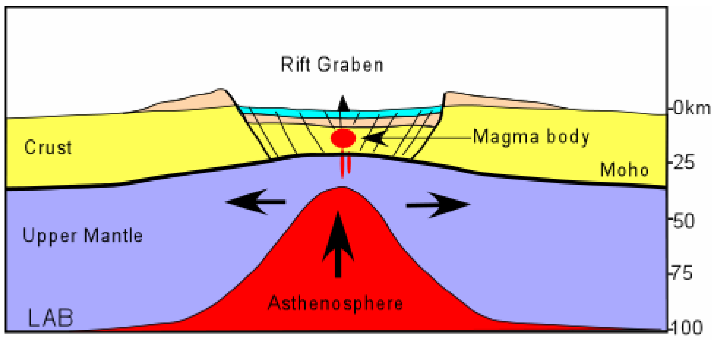

FIGURE 2: Generalized E-W section across a continental rift showing late stages of its formation

2.1 Ethiopian Rift

The Main Ethiopian Rift (MER) and Afar Rift represent the northernmost part of the East African Rift (Figures 1 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). The activity has continued since the Miocene times with eruptions of bimodal suite of basalts and 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.

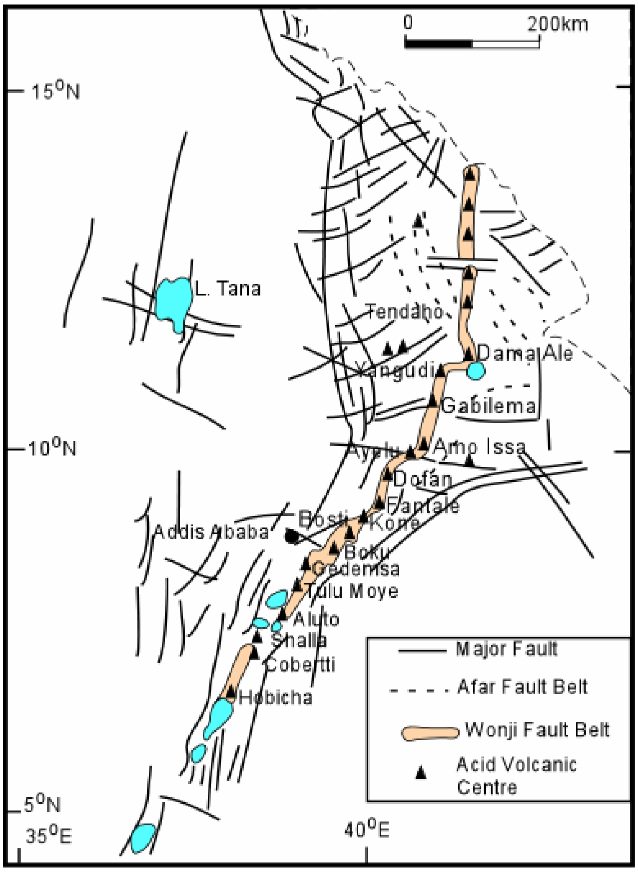

FIGURE 3: Structural map of the Ethiopian Rift showing locations of Quaternary volcanoes. (From Abebe, 2000)

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.

2.2 Kenya Rift

The Kenya rift is the segment that extends from Lake Turkana to northern Tanzania (Figures 1 and 4). The magmatism in 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 the Mozambique belt and close to the eastern margin of the Tanzania (Nyanza) 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 were 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 caldera 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.

2.3 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 4). The geography of the western branch is typically half grabens characterized by high angle normal rift faults. The rift is characterized by paucity of volcanism relative to the Kenyan and Ethiopian rifts. Whereas the volcanism and tectonic activity in the eastern branch commenced about 30 million years ago, the volcanic activity in the western branch commenced about 12 Ma in the Virunga Province and about 7 Ma at Rungwe 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 in early Miocene and is dominated by a 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 basalts, 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.

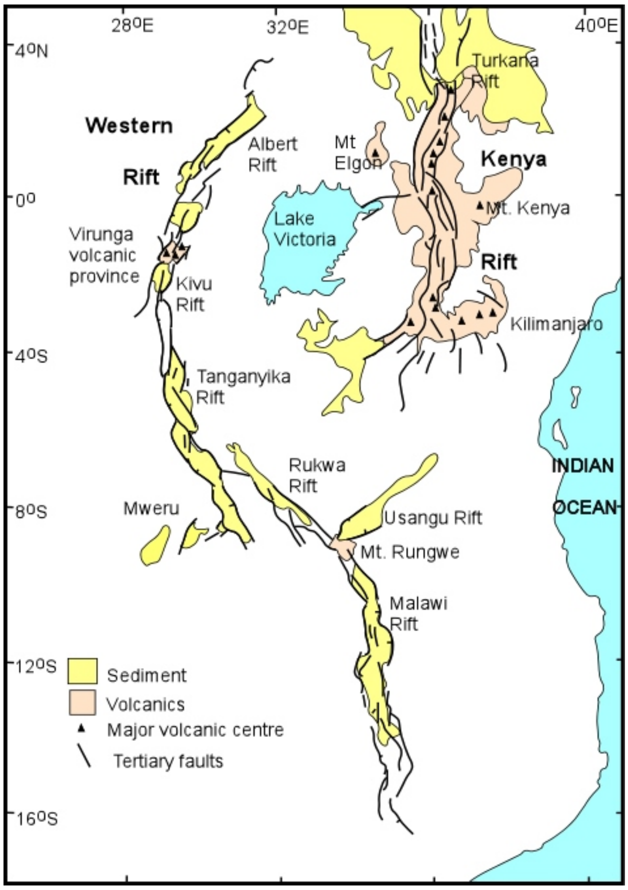

FIGURE 4: Map showing the structural relationship between the Eastern (Kenya) and Western branches of the EA Rift system

The Tanganyika–Rukwa-Malawi (TRM) segment of the western branch follows the fabric of the basement Precambrian metamorphic rock structures inherited from the Proterozoic period (Figure 4). The rift is characterized by normal boundary faults, which define half grabens, horsts and step faults with riftward tiled blocks and monoclinal 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 with volcanic fields being only at Rungwe between lakes Tanganyika and Rukwa. Late Cenozoic volcanism started about 7-9 Ma ago in the Rungwe volcanic province where the rift follows the NE-SW trend of the Usangu Rift (Figure 4). The volcanic products include Quaternary mafic and felsic rocks.

2.4 Southwestern Branch

The southwestern branch of the western rift follows geological structures along mobile belts from Lake Tanganyika in southern DR Congo and NW Zambia then southwestward into the nascent Okavango rift in northwest Botswana (Figures 1 and 4). The rift is non magmatic in its entire length, however, faults are evident along the entire length of the rift. Near Lake Tanganyika, the rift faults cut through the Nyasa craton to form the Lake Mweru basins (Figure 4). However, rift structures in the Okavango have been identified only through geophysical techniques (Atekwana et al., 2004).

3. GEOTHERMAL ACTIVITY

The geothermal resources are frequently indicated by the occurrence of visible geothermal activity/manifestations that include hot springs, fumeroles, steam vents, geysers, hot and altered grounds and to some extent volcanoes. Geothermal activity is often the first major indication of higher temperatures in the subsurface than the normal. In the EARS, the majority of the high temperature (>150°C) geothermal resources in the rift are closely associated with Quaternary silicic volcanic centres (<2 Ma) located in the axis of the rift, while low temperature (<150°C) resources are associated with fault zones within and on the flanks of the rifts.

3.1 Ethiopia Rift

The Ethiopian Rift, which comprises the Main Ethiopian (MER) and Afar rifts have major silicic Quaternary volcanoes on the floor of the rifts. On the floor also occur extensional faults along which the volcanoes erupted. The Afar rift hosts some of the most active volcanoes in the entire EARS with Erta Ale volcano being presently active. 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. Hotsprings 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. In Djibouti, areas of strong manifestations are located within the Asal and Hanle rifts in the Afar Depression (Mohamed, 2004) while in Eritrea, the most intense manifestations occur within the Danakil Depression as associated with the rhyolite domal intrusion. Here, boiling pools, hot springs and fumaroles occur (Woldegiorgis et al., 2003).

3.2 Kenya Rift

The entire length of the Kenya rift from Lake Turkana in the north to northern Tanzania has young volcanoes most of which are of silicic composition. 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 volcanoes (Figure 5). The youngest of the volcanoes include Barrier (100 yrs BP), Olkaria (250 yr BP), and Ol Doinyo Lengai in northern Tanzania, which last erupted in 2004.

The geothermal manifestations associated with the Rift include fumaroles, hot springs, spouting springs, hot and altered grounds and sulphur deposits. Fumaroles commonly occur on the mountains while hotsprings and geysers are common on the lowlands. Sulphur deposits have been observed at Olkaria and Barrier volcanoes where it is indicative of the presence of degassing magma bodies. Extinct manifestations in the form of travertine deposits, silica veins and chloritized zones are common in the Lakes Baringo – Bogoria regions suggesting that the geothermal activity in the rift is long-lived.

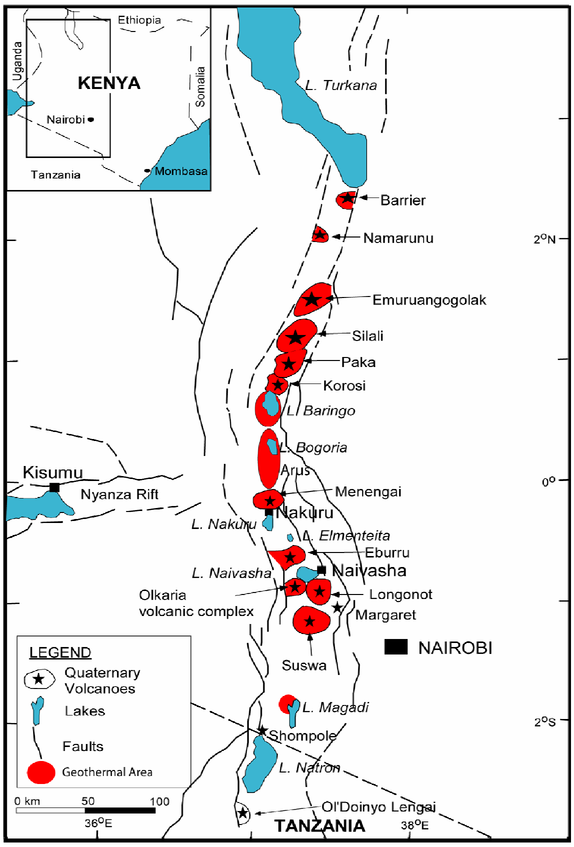

FIGURE 5: Map of the Kenya rift showing the locations of geothermal areas

Detailed investigations recently concluded in Lakes Baringo and Bogoria geothermal prospects reveal the possible existence of low to medium temperatures resources. The system around Lake Baringo, has very few manifestations and no central volcano in the immediate vicinity. A borehole drilled there to 140 m for ground water discharged fluid at boiling point (98^{o}C) with the source at probably more than 200^{o}C as inferred from geothermometry. Together with the many medium temperature boreholes (>30^{o}C) that have been drilled in the area, this is an indication of pervasive high heat flow within the rift.

3.3 Western Branch (Albertine Rift)

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 young volcanoes. Geothermal manifestations occurring outside of the rift in Uganda tend to have lower surface temperatures (Data and Bahati, 2003).

3.4 Tanganyika-Rukwa-Malawi Rift

Whereas there is a paucity of recent volcanism in this segment of the rift, geothermal activity is still evident in many localities. The manifestations that include hot springs and fumaroles at temperatures of up to 86^{o}C 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 and Mozambique are fault controlled and are associated with the border faults.

3.5 Southwestern Rift

Geothermal activity in Zambia and southern DR Congo occurs within the southwestern rift. The geothermal manifestations that include hotsprings occur at Kapisya that discharge at 85^{o}C near Lake Tanganyika. Other springs occur at Chinyunyu (60^{o}C) near Lusaka, Lake Mweru and several other localities in Zambia. The hot prings are all related to the rift faults.

4. DISCUSSION

The geothermal activity in the East African rift system is closely related to the occurrence of Quaternary volcanoes located within the axis of the rift. The shield volcanoes are largely made of trachytes, rhyolites and associated pyroclastics. The presence of the silicic products attests to the occurrence of shallow molten or fossil magma bodies that are considered the most important heat sources for the associated geothermal systems (Figure 6). This is based 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. More 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 and Menengai geothermal areas in Kenya where seismic waves show “gaps” at shallow levels (Figure 7). The seismic “gaps” signify the presence of molten/viscous body at about 6-18 km of the surface. All the volcano hosted geothermal areas in the EARS are anticipated to have magma bodies/intrusions as the main heat sources.

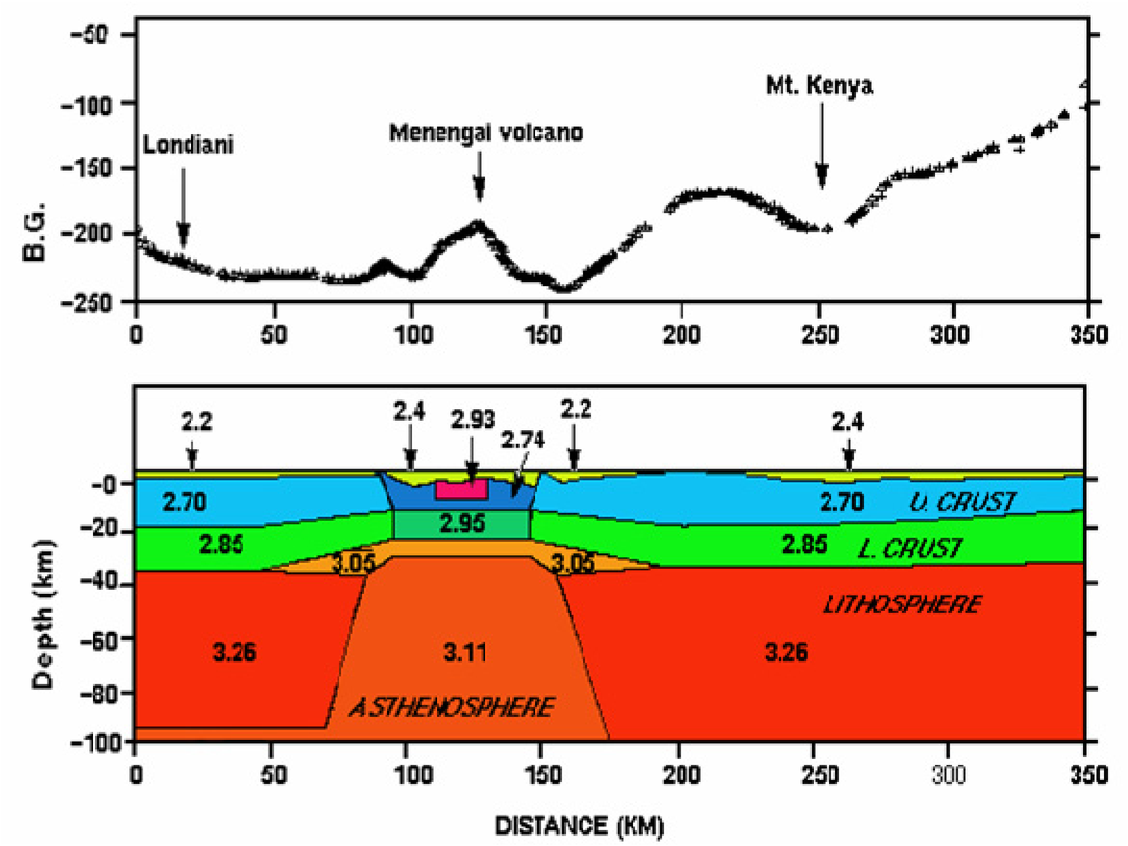

FIGURE 6: Gravity model across the Kenyan rift through Menengai volcano. Density values in kg/m3. The rift axis corresponds with the zone with asthenospheric up-welling (Simiyu, 1996)

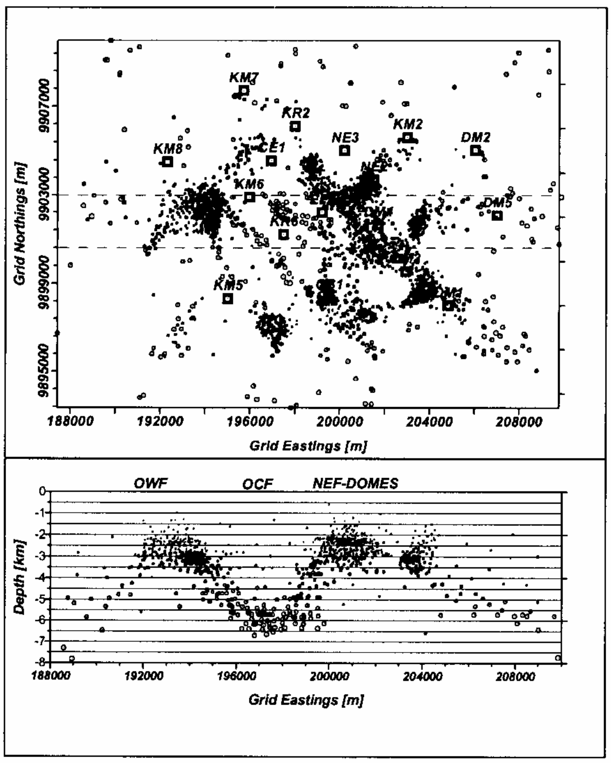

FIGURE 7: Micro-earthquake event location around Olkaria geothermal field

Studies reveal that the crust under the EA rift ranges between 5 and 35 km 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). The thin crust and up-welling lithosphere-asthenosphere boundary directly under the rift has resulted in generally high heat flow arising from high geothermal gradients within the entire length of the rift (Wheildon et al., 1994). Mantle heat is expected to play an important part in geothermal prospects in the Afar rift where the Moho is at less than 5km. 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).

The 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 EARS.

The main recharge for the geothermal systems, 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 by 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 at 4—5km depth. 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 intrusions could also be important in enhancing permeability in some fields (Woldegiorgis et al. 2003). However, for the case of the geothermal resources in the western branch of the rift, the reservoirs are mainly hosted within the Precambrian metamorphic rocks where secondary permeability associated with faults and fractures are important. The fluid types in most of the geothermal prospects in EARS are expected to have low TDS due to the low reactivity of the reservoir rocks e.g. Olkaria and Eburru in Kenya and Aluto in Ethiopia. However, higher TDS (salinity) occur in fields located within sedimentary formations, e.g. in Eritrea and Djibouti.

The capping formation for the volcano hosted geothermal systems in the rifts is often a combination of inter-layered lava flows and pyroclastics. In the Olkaria East Field, the capping formation has been identified as a Basalt-Tuff formation occurring at 400-600m depths while shales and other sediments form capping formations in the Afar region where the volcanic products overlie sedimentary formations (Mohamed, 2003). However, fields lacking capping formations could still be exploited, although, they tend to have depressed isotherms e.g. Olkaria West field while some might be too “leaky” to support viable geothermal systems.

5. CONCLUSIONS

1. The high temperature geothermal manifestations commonly occur within the axis of the rift in association with Quaternary volcanoes where the heat sources are magmatic bodies. High temperature resources are more abundant in the eastern arm than the western arm of the rift.

2. Low temperature resources are largely due to deep circulation of fluids and enhanced by high geothermal gradients within the rift associated with upwelling of the Moho. Other low temperature resources occur between volcanoes as outflows from the massifs.

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