DYKING PROCESSES AT ARUS-BOGORIA GEOTHERMAL PROSPECT IN KENYA REVEALED USING GRAVITY AND MICROSEISMIC DATA

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ABSTRACT

Arus-Bogoria geothermal prospect, located in the central Kenya rift valley (KRV), encompasses several features of geological significance that are indicators of possible geothermal potential. These include surface manifestations, such as fumaroles, steam jets, mud pools, hot springs, spouting geysers, and high rate of micro-seismic activity of about 500 earthquakes recorded within a period of three months in comparison to other geothermal fields and prospects along the Kenya rift valley (KRV).

A comparison of the results of gravity survey, undertaken between 2005 and 2006 for geothermal resource evaluation of Arus and Lake Bogoria geothermal prospects, to results of micro-seismic monitoring undertaken in 1985 during the Kenya Rift International Seismic Project (KRISP 85) was undertaken to map the existence of heat source(s), presumably due to dyking, and define the brittle-ductile transition zone. The results indicate that the heat source is due to a series of north-south trending dyke injections occurring at depths of ~3 – 6 km in the vicinity of the Arus steam jets. The geothermal prospect is seismically active and approximately 95% of the seismic activity is probably associated with tectonic activity due to reactivation of north-south trending faults.

Further, only ~5% of micro-earthquakes can be correlated with the geothermal activity such as dyking, as mapped using gravity data, and hydrothermal processes. The change in seismic activity at Arus-Bogoria geothermal prospect occurs at a depth of 8 – 15 km with a peak in micro-seismic activity at 12.5 km depth. We therefore conclude that 8-15 km represents the brittle-ductile transition zone in Arus-Bogoria geothermal prospect.

1. INTRODUCTION

Arus-Bogoria geothermal prospect is located on the eastern floor of the central Kenya rift valley (KRV) in Baringo-Bogoria basin (BBB), about 250 km north of the city of Nairobi and about 100 km north of Menengai geothermal field. The area of study within the geothermal prospect is bound by latitudes 0^o and 0^{o}30'N and longitudes 35^{o}45' and 36^{o}15'E within the rift graben (Figures 1 and 2). The geothermal prospect is characterized by spectacular geothermal surface manifestations which include hot springs and spouting geysers on the shores of Lake Bogoria. Other geothermal surface manifestations discussed elsewhere by Karingithi (2006) and, Karingithi and Wambugu (2007) include fumaroles and steam jets on the banks of Molo river, Loboi and Maji Moto areas, anomalous hot ground water in boreholes in Mugurin and Emining areas, and some CO_2 emitting holes in Esageri area (Karingithi and Wambugu, 2007). The study area is overlain by Miocene lavas, mainly basalts and phonolites, and Pliocene to recent sediments and Pyroclastics such as tuffs, tuffaceous sediments, superficial deposits, volcanic soils, alluvium and lacustrine silts (Baker and Wohlenberg, 1971; Smith and Mosley, 1993.

Extensive faulting accompanied by block tilting characterize the terrain and these form numerous N-S ridges and fault scarps. According to Baker and Wohlenberg (1971), Baker (1986) and Baker et al., (1972, 1988), this complex network of faults and fractures suggests that tensional strain oblique to the primary rift axis is still occurring.

The central Kenya rift valley and particularly Arus-Bogoria geothermal prospect has been the target of a number of geophysical and geological investigations summarized in two special volumes (Prodehl et al. 1994, 1997).

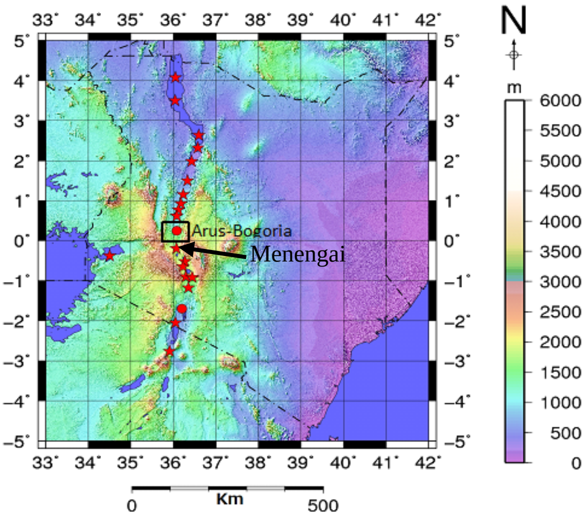

Figure 1: Volcanic centers along the Kenya rift valley. Arus-Bogoria geothermal prospect is outlined by the rectangle (After Mulwa, 2011).

Other geophysical investigations include those by Simiyu and Keller (1997, 2001); Mariita (2003); Swain et al. (1981, 1994); Swain (1992), Fairhead (1976); Hautot et al., (2000); Rooney and Hutton (1977); Young et al. (1991); Tongue (1992); Tongue et al. (1992, 1994) among others.

Regional gravity analysis by Simiyu and Keller (2001) and Mariita (2003) indicate no existence of volcanic heat sources in Arus-Bogoria geothermal prospect despite the associated geothermal surface manifestations. This is probably attributed to occurrence of thin dykes which could not be mapped by gravity data at such a regional scale. Gravity analysis by Simiyu and Keller (2001) along an axial rift profile shows a series of positive gravity highs at

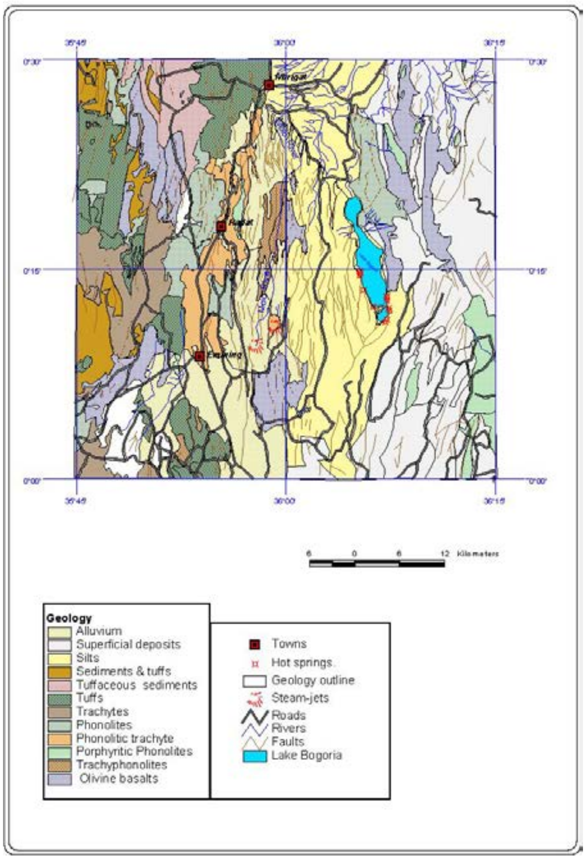

Figure 2: Geology and geological setting of Arus-Bogoria geothermal prospect (After Mulwa et al. 2009 and Mulwa, 2011).

Menengai, Eburru, Olkaria and Suswa geothermal fields (Figure 1). The gravity highs have been modeled as resulting from volcanic centers underlain by discrete mafic bodies having a density of $2.9x10^3$ kg m^{-3} which are presumed to be the heat sources for these geothermal fields. Cross-rift gravity model by Mariita (2003) along a profile at latitude 0.6^o N shows that this area is underlain by about 2-4 km thick of low density ($2.3x10^3$ kg m^{-3}) Miocene lavas and sediments but there no evidence of volcanic intrusives which could be possible heat sources. According to Fairhead (1976), the Kenya rift valley is characterized by localized positive anomalies due to dyke injections.

Magnetotelluric studies by Rooney and Hutton (1977) however, show that a low resistivity anomaly ($\rho_a \cong 2 - 20$ Ωm) at shallow depths (< 8 km) exists along the Kenya rift, including Arus-Bogoria geothermal prospect. According to Rooney and Hutton (1977), the low resistivity anomaly is probably due to high temperature and water saturation. Hautot et al. (2000) have identified a thick succession of well defined tectonostratigraphic units in Baringo-Bogoria basin and downward continuous layer related to dyke injections.

Young et al. (1991); Tongue (1992); Tongue et al. (1992, 1994) identified Arus-Bogoria geothermal prospect as an area characterized by relatively high frequency of seismic activity and low magnitude (< 3) seismic events in comparison to other geothermal areas along the KRV. They attributed this to intense surface faulting and multiple episodes of dyke injections.

2. HEAT SOURCE MAPPING

In an attempt to map the heat source in Arus-Bogoria geothermal prospect, we used standard gravity survey and data reduction techniques as discussed by various authors e.g. Hinze et al. (2005); Li and Götze (2001); Kane (1962); Bible (1962); Hammer (1939); Nettleton (1939); Nagy (1966a, b); Woollard (1979); Fairhead et al. (2003); LaFehr (1991a), and Chapin (1996). We constrained our density values in our starting models using seismic velocities by converting P-wave seismic velocities to densities using the expression by Gardner et al. (1974). We finally applied 2D, 2.5D and 2.75D modeling to our Bouguer anomaly. The gravity results indicate that Arus-Bogoria geothermal prospect is characterized by a Bouguer anomaly having an amplitude of ~40 mGals aligned in north-south direction and approximately centered along longitude 36^oE (Figure 3). However, more gravity infill gravity data will be required to precisely define the dimensions of the anomaly.

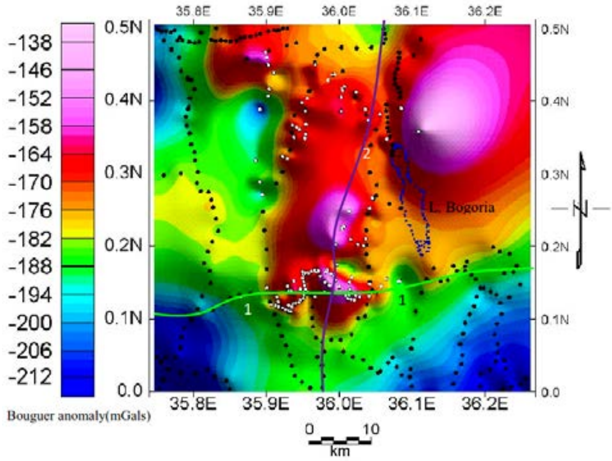

Figure 3: Complete Bouguer anomaly map of Arus-Bogoria geothermal prospect and, east-west (1) and north-south profiles (2) used in modeling of gravity anomalies (After Mulwa et al. 2009 and Mulwa, 2011). The dots represent distribution of field gravity stations.

Gravity models along two profiles in east-west (profile 1) and north-south (profile 2) directions show that the heat source in Arus-Bogoria geothermal prospect is due basic intrusions (ρ = 2.9 g/cc), herein considered to be multiple dyke injections presumed to be cooling, at depths varying between 3-6 km below the ground surface (Figures 4 and 5). The study area is overlain by low density (2.4 g/cc) volcanic soils and sediments whose thickness varies from 2-6 km. These are underlain by upper crustal basement rocks (2.7 g/cc). Further, the middle and lower crustal rocks are characterized by densities of 2.85 g/cc and 3.05 g/cc respectively. The lowermost upper mantle layer has a density of 3.15 g/cc.

3. MICROSEISMIC MONITORING

Young et al. (1991) operated a 15 station short period seismic array for a period of three (3) months in Arus-Bogoria geothermal prospect. This project was part of the 1985 Kenya Rift International Seismic Project (KRISP 85) survey. A total of about 572 earthquakes, 81% with M_L<1.0 were located. Figure 6 shows the distribution of macro- and micro-earthquakes in Arus-Bogoria geothermal prospect.

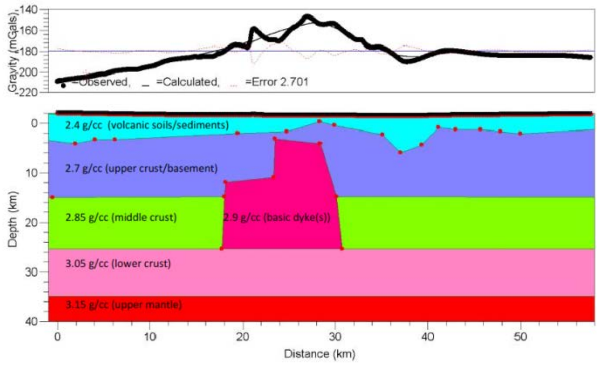

Figure 4: East-West gravity model along profile 1 in figure 3. The values indicate densities of subsurface rocks in g/cc and the fitting error is in mGals (After Mulwa et al. 2009 and Mulwa, 2011).

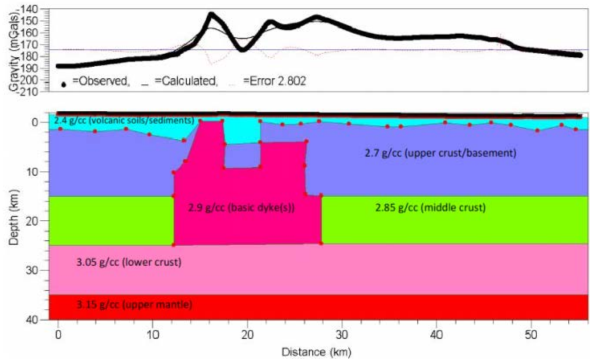

Figure 5: North-South gravity model along profile 2 in figure 3. The values indicate densities of subsurface rocks in g/cc and the fitting error is in mGals (After Mulwa et al. 2009 and Mulwa, 2011).

The macro-earthquakes are for the period 1906-2012 and include the two strongest earthquakes in Kenya, that is, the January 6, 1928 M_s=6.9 Subukia earthquake and the M_s=6.0 aftershock four days later (Ambraseys, 1991).

Consistent with the results of Young et al. (1991), ~95% of the micro-seismic activity in Arus-Bogoria geothermal prospect forms a somewhat linear N-S feature to the east and southeast of Lake Bogoria. This linear feature follows the trend of, and on the contrary, does correlate with the north-south trending Bogoria-Emsos-Legisianana fault and to a lesser extent the Laikipia-Marmanet-Chui fault scarp to the east of Lake Bogoria, where apparently the main shock due to the January 6, 1928 earthquake occurred. Apart from this significant earthquake in the Kenyan history, the macro-seismic activity, however, does seem to correlate with and represents a deep active and probably buried NE-SW trending fault.

Elsewhere, numerous micro-seismic studies undertaken by Giampiccolo et al. (2007), Simiyu (2000), Simiyu and Keller (2000), Foulger et al. (1989), among others, have shown that recent intrusions are associated with high levels of earthquake activity. This is, however, contrary to the distribution of earthquake activity in Arus-Bogoria geothermal prospect. Apart from the area around Arus steam jets, ~95% of seismic activity within the geothermal prospect is most likely neither related to the occurrence of dyking processes nor to the geothermal activity but rather to re-activation of the north-south trending faults to the east and SSE of Lake Bogoria within the study area.

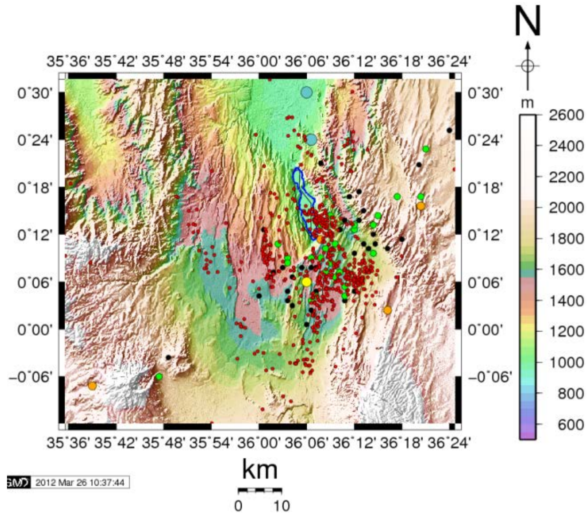

Figure 6: The distribution of earthquakes in Arus-Bogoria geothermal prospect and adjacent areas. The red filled circles show distribution of micro-earthquakes while the black, green, orange and yellow filled circles show macro-earthquake distribution. The light blue filled circles show the epicenters of the January 6, 1928 main shock (south) and aftershock (north).

4. DYKE MAPPING IN ARUS-BOGORIA GEOTHERMAL PROSPECT

Out of the 572 well located micro-seismic events, only ~5% of the micro-seismic activity does correlate with geothermal activity (e.g. dyking and hydrothermal processes) within the geothermal prospect. This group of events is approximately centered along latitude 36^{o}E (Figure 6). The epicenters coincide with the location where gravity high, herein interpreted to be a series of dyke injections presumed to be the heat source mapped using gravity technique occurs at the shallowest in the subsurface near Arus steam jets (Figures 3, 4 and 5). Figure 7 shows the hypocentral distribution of well located, i.e. occurring within 10 km of the nearest recording station (Young et al. (1991)), micro-earthquakes between longitudes 35.80^o and 36.11^o E.

Figure 7 shows that hypocentral distribution of micro-seismic activity, which does correlate with geothermal activity, in Arus-Bogoria geothermal prospect, is highly variable but most of the activity occurs at a depth of ~12.5 km. Young et al. (1991) defined the brittle-ductile transition zone to be 12 km. However, on the basis of our joint interpretation and analysis of gravity and micro-seismic results in the present study, we would like to point out that the change in seismic activity occurs at a depth of 8 – 15 km with a peak in micro-seismic activity at 12.5 km depth. We therefore conclude that 8-15 km represents the brittle-ductile transition zone in Arus-Bogoria geothermal prospect. Micro-seismic activity at depths of less than 8 km is purely due to tectonic activities such as faulting and re-activation of existing faults.

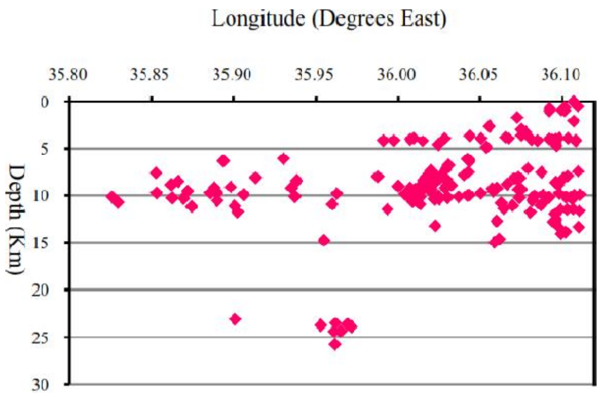

Figure 7: Hypocentral distribution of micro-earthquakes between longitudes 35.80° and 36.11°E in Arus-Bogoria geothermal prospect.

Furthermore, Young et al. (1991) attributed micro-seismic activity deeper than 12 km to be due to magma movement owing to the low frequency of the seismic signals. In Figure 7, such events at depths >15 km which may be correlated to magma movement and coincide with the mapped dyke injections in Arus-Bogoria geothermal prospect are between longitudes 35.9° and 36.1°E.

5. CONCLUSION

An axial rift gravity high, which is approximately centered along longitude 36° E, is evident in Arus-Bogoria geothermal prospect. The gravity high is characterized by an amplitude of ~40 mGals and is attributed to multiple dyke injections in this geothermal prospect. The dyke injections, occurring at depths of ~3 – 6 km, are presumed to be the heat source(s) in Arus-Bogoria geothermal prospect. The distribution of micro- and macro-earthquakes in Arus-Bogoria geothermal prospect shows that only ~5% of the micro-earthquakes can be correlated with the geothermal activity such as dyking and hydrothermal processes. These micro-earthquakes are approximately centered along longitude 36°E in the north-south direction and their epicenters coincide with the location of the axial rift gravity high. They are therefore attributed to episodes of dyking in this geothermal prospect. ~95% of the micro-earthquakes form a somewhat north-south linear feature to the east and southeast of Lake Bogoria. This north-south feature is consistent with the trend of the Bogoria-Emsos-Legisianan fault and as such, the micro-earthquakes are attributed to tectonic activity along this fault and to a lesser extent the Laikipia-Marmanet-Chui fault, both to the east of Lake Bogoria. Apart from the two strongest earthquakes in the Kenyan history, i.e. the January 6, 1928 M_s=6.9 Subukia earthquake and the M_s=6.0 aftershock four days later, the macro-seismic activity in Arus-Bogoria geothermal prospect probably represents a deep active and buried fault trending in northeast-southwest direction.

As part of recommendation to this study, there is need to undertake detailed gravity survey to the east of Lake Bogoria so as to ascertain whether or not the high micro-seismicity in this region is due to tectonic or geothermal processes. In addition, waveform modeling of short period seismic events would enable accurate determination of fault plane solutions (focal mechanism) for categorization of the seismic events due to tectonic processes.

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