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Summary - This paper presents the results of microearthquake (MEQ) and resistivity studies at the Longonot geothermal prospect in Kenya. The data used was acquired by new MEQ instruments specifically designed to work under the field conditions in Kenya. The results show a good correlation between resistivity, location of microearthquakes, volcanic activity, fluid flow and structures. Analysis of the resistivity data shows high anisotropy close to the boundaries of low and high resistivity anomalies which are also associated with the location of microearthquakes. Based on the data analysis and interpretation, one well has been located in an interpreted fracture zone. The fracture zone is bound by areas of higher resistivity which are attributed to lower fracture porosity and probably lower temperatures. Such areas of deep high resistivity should not be targets for drilling exploration wells. An important finding of these studies that has international implications in the way MEQ data is acquired for geothermal exploration is that MEQ data loggers must be deployed appropriately close to the fracture zone. When the seismometers are located far away from the fracture zone, the MEQ signals are often attenuated before they arrive at the recording stations. This can lead to the erroneous conclusion that geothermal prospects are aseismic.

1.0 Introduction

The Longonot geothermal prospect lies within the Kenya Rift Valley (KRV) which extends from Tanzania in the south to Ethiopia in the north. The KRV is part of the East African Rift Valley (EARV) system that extends from Mozambique in the south to the Red Sea in the north (Figure 1).

The Longonot geothermal prospect is associated with the Longonot Volcano which has a well developed 2 km wide summit crater (with a peak altitude of over 2770 masl) and an interpreted caldera covering about 40 km^2. The caldera is postulated to have been formed by a regional withdrawal of magma along the KRV (Scott and Skilling, 1999). The first volcanic eruptions are postulated to have occurred at about 0.4Ma with eruption of trachyte lava and volcanic ash deposits (Scott and Skilling, 1999). Pumice eruptions also occurred at about 9150±110 ypb followed by trachytic volcanic eruptions at about 5650 ybp. An explosive eruption of volcanic ash and pumice occurred at about 3280±120 ybp (Scott and Skilling, 1999). The eruption of pumice is important because it signifies the interaction of fluids with magmatic sources that could be the heat source for the geothermal system. The geology of the Longonot geothermal system is dominated by trachytic lava flows and pyroclastics.

Existing geophysical models indicate that the upwelling of the asthenosphere provides the driving mechanisms for the lithosphere uplift and extension. Most of the previous geological, geophysical and geochemical studies have been focused on understanding the regional deeper crustal structure and therefore are not relevant to evaluating the reservoir properties of the geothermal systems. The significant finding of most of the studies is that the structure of the KRV varies both along and perpendicular to the rift. Regional seismic tomographic studies show that the Longonot volcanic system is associated with low P-wave velocities in the crust. The areas of low P-wave velocities have been interpreted as zones of partial melt that may form important heat sources for the geothermal systems. Most studies indicate significant spatial variations in magmatism and tectonism along the Rift Valley (Karson and Curtis, 1989). These variations could significantly affect the structures and the fluid flow mechanisms of the geothermal systems that are found along the KRV. The complex geological, structural and volcanic setting provides a big challenge to understanding the hydrothermal systems in the Kenya Rift Valley.

2.0 Previous studies

Previous studies relevant to geothermal exploration at Longonot have been carried out by the British Geological Survey, KenGen and Duke University. The main events of the Longonot volcano include building of an early shield, pyroclastic and lava cone, formation of a summit crater and crater floor lava eruptions.

These rocks have high silica content (≥ 60%). From geological mapping and analysis of incompatible trace elements (ICE), Clarke et al. (1990) noted that:

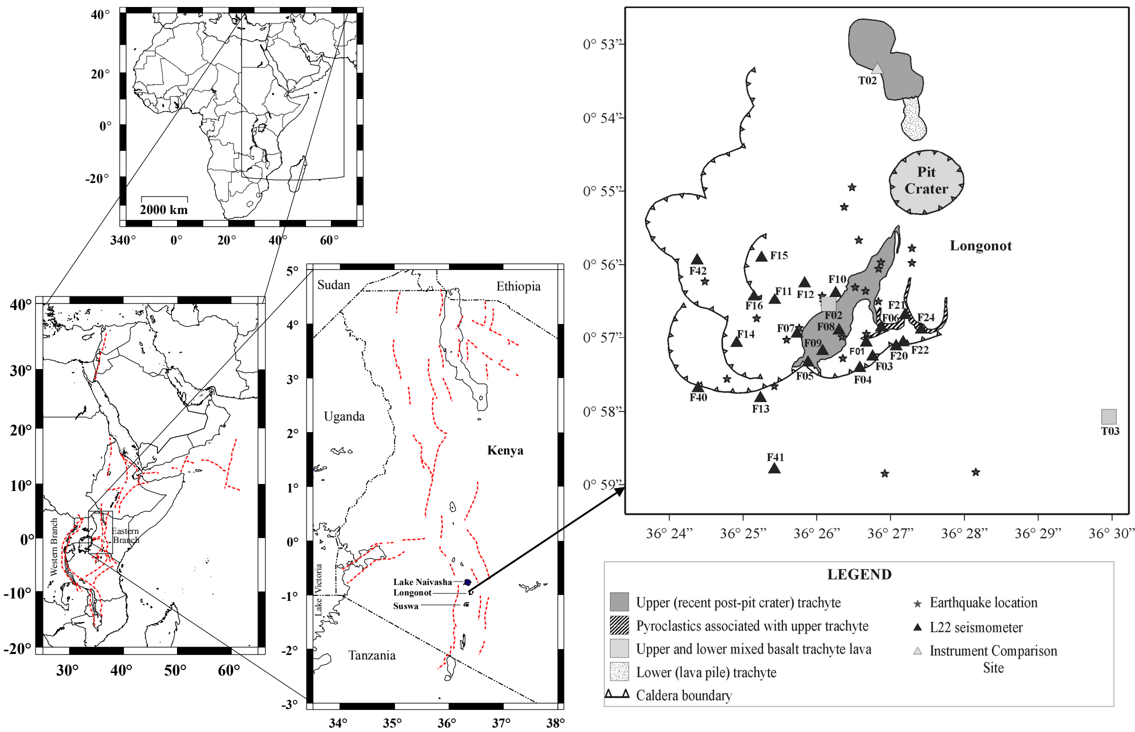

Figure 1: Location of the Longonot hydrothermal system within the Kenya Rift Valley (KRV) which is part of the East Africa Rift Valley (EARV) that stretches from Mozambique in the South to the Red Sea in the north. The KRV is generally a NS trending feature that is bound by NNW and NNE faults. The Longonot Volcanic system is composed of pit crater and a caldera covered by pyroclastic rocks.

(a) Recent volcanic activity tapping a large fractionating magma chamber.

(b) A Tectono-Volcanic Axis (TVA) together with the caldera walls form major structures in this area. However, other structures are probably covered by pyroclastics (600m).

(c) The Longonot crater seems to be at the intersection of NE and NW trending regional faults. These structures may strongly influence the regional hydrogeology while the faults within the KRV may control the local hydrogeology. High permeability shear zones will act as channels of fluid flow. The fault patterns may therefore significantly determine the overall productivity of the wells.

(d) Geothermal fluid indicators include fumaroles and altered grounds. The fumaroles occur within the summit crater, southern part of caldera rim and to the southeast

Based on the above findings, in 2000, Kenya Electricity Generating Company (KenGen) carried extensive geophysical, geochemical and geological studies of Longonot with a view drilling exploration wells to a depth of 2000m.

Between July 10 and September 30, 2000, Duke University and KenGen, conducted a microearthquake monitoring experiment around Longonot volcano (see Figure 1). The study was sponsored by the United States Department of Energy (DOE) geothermal resources program, KenGen, and the Incorporated Research Institutes for Seismology (IRIS) program. The goal was to characterize the geothermal resource by studying the associated microearthquakes (McCausland et al., 2000; Shalev et al., 2000). The choice of MEQ sites was motivated by the results of electrical resistivity surveys (Onacha, 1998), which identified a potentially active geothermal system in the southern part of Mt. Longonot. The monitoring experiment located only 23 microearthquakes during the three months recording.

3.0 Data Acquisition

Schlumberger DC resistivity, Transient Electromagnetic (TEM), Magnetotelluric (MT) and microearthquake (MEQ) data at Longonot were acquired in different stages between 1998 and 2004.

DC resistivity measurements were acquired for current electrode spacing of 6000m. The TEM measurements were acquired by the central loop configuration with a square loop of 300m. In the MT data acquisition, magnetic coils and potential electrodes were oriented in orthogonal NS and EW directions. The electric field was measured using lead chloride porous pots. Some sites straddled known fractures in order to study the effect of open fractures on the MT data. The ground conductivity was improved by placing the electrodes in a salt water and clay mixture. The Phoenix MTU-5A equipment was used for data acquisition in the frequency range of 400-0.0025 HZ. The telluric lines were typically 50 - 70m. The three MT loggers were deployed everyday in different locations and data was automatically acquired for 17 hours.

MEQ data was acquired by 15 new seismographs designed to record low frequency data. The new seismographs consist of a data logger module, geophone module, and an anti-theft "lock-out lock-down" ground auger assembly. The tri-axis on which the geophones are mounted also contains an opening for a J-hook which anchors onto a ground auger. This mechanism couples the geophones acoustically onto the ground and also provides security against vandalism. The electronics and battery are located inside the logger module, and the GPS antenna is located on top of the logger. The new logger module houses three 1 Hz geophones. The logger is designed to work as an integrated unit with the geophone module and powered by an 11.1V, 59.4A-Hr Lithium-Ion battery.

Data from 100 MT, 88 TEM, 87 DC resistivity soundings and 15 MEQ sites has been used to image the Longonot geothermal prospect. The MT and MEQ data acquisition sites during the 2004 field campaign in 2004 and TEM acquired in 1998 are shown below (Figure2).

4.0 Data Analysis

Occam and layered inversions were performed by the program TEMTD (Arnasson, 2006). 1-D models from TEM data were used to generate equivalent 1-D MT models at the same site. The synthetic 1-D MT models were then used to correct for static shifts (Pellerin and Hohmann, 1990) in both TE and TM modes of the MT data. Resistivity maps were prepared from the results of 1-D Occam's models to show the spatial distribution of resistivity at fixed elevations. 1-D interpretation was carried out both for layered and Occam's inversion using the entire MT data set after rotation to the principal axes. These maps together with the 1-D sections have been used as the basis for the 2-D modeling. 2-D forward and inverse modeling was carried out on two NE-SW trending profiles across the Longonot TVA (see Figure 2) using WinGlink program (Rodi and Mackie, 2001) to determine which features in the inversion models were important.

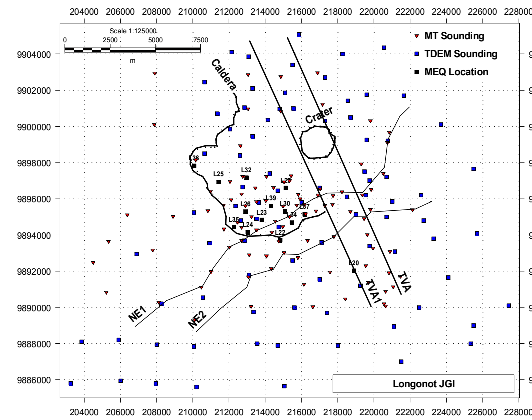

Figure 2: Location of MEQ, TEM and MT stations in the Longonot area. The location of the Tectonovolcanic Axis (TVA) which is an important structural feature is shown. Two NE-SE trending profiles used in the interpretation of MT data are also shown

Locating earthquakes was done by first picking P and S phases with the associated errors. The locations of the MEQ stations required to locate earthquakes were determined from the internal GPS measurements and cross-checked with locations from the hand held GPS. The microearthquakes are located at a reference datum which is the average of the stations.

Station corrections were incorporated to account for the elevation differences with respect to the average elevation. Station corrections are computed by locating many earthquakes with zero corrections and then assigning the average time errors as station corrections. The location of microearthquakes was carried by the Hypoinverse-2000 code (Klein, 2000) with a parameter input interface in Matlab. The initial velocity model was obtained from the velocity structure previously used to locate events in the area of Longonot (Simiyu and Keller, 2000).

S-wave splitting of microearthquakes was carried out and the results compared to the polarization directions of MT data at collocated sites (Onacha, 2006). S-wave splitting, which is sometimes referred to seismic birefringence, is probably the most diagnostic and measurable property of seismic anisotropy (Crampin 1985). Anisotropy is usually interpreted as a characteristic of fluid-saturated, stress-aligned cracks. (Crampin, 2005; Elkibbi and Rial, 2005). S-wave splitting was done by searching for the angle that maximizes the amplitude ratio of the horizontal components of the S-waves. After rotating the S-waves to the direction parallel and perpendicular to this angle, the time delay was obtained by cross correlation of the amplitudes.

5.0 Results

The regional DC resistivity map at 1000masl derived from 1-D models (Figure 3) shows that the Olkaria and Longonot geothermal areas are defined by a low resistivity anomaly while the Suswa field shows higher resistivity may be due to a lower degree of hydrothermal alteration and lower permeability. The map at 1800masl (Figure 4) derived from Occam 1-D invariant MT models shows a NE-SW trending low resistivity anomaly at the intersection of the NW-SE trending caldera boundary and the TVA. This map probably shows the near surface alteration patterns which seem to correlate with the area of recent volcanic activity. The MT resistivity at 3000mbsl (Figure 5) probably shows the heat source for the geothermal system to the south of the Longonot crater. The deep low resistivity coincides with the southern extension of the TVA that is aligned by recent volcanic centres. The TVA therefore correlates with the surface alteration and the postulated fracture zone that may be buried by recent volcanic activity. The maps show considerable spatial variations in resistivity.

A common feature in the interpretation of resistivity from Mt. Longonot is the existence of a high resistivity surface layer of recent volcanic rocks or pyroclastics with variable resistivity depending on the age of the rocks and proximity to the fracture zone. The second layer with extensive low resistivity is associated with an interpreted smectites-zeolite clay layer. The base of the clay cap probably correlates with a geothermal reservoir at a temperature between 200 and 240˚C. This is likely to be the case because a shallow well drilled to the SW part of the Longonot caldera struck steam that has geochemical indicators of a hydrothermal reservoir at 240˚C. The 2-D resistivity model (Figure 6) shows a deep low resistivity zone, which is interpreted as the heat source for the geothermal system at a depth of more than 5km.

Analysis of S-wave splitting shows that station L37 recorded 49 S-wave splitting events while station L34 recorded only 12 events. The field deployment was only for about three weeks. The S-wave splitting again shows dominant polarization of the fast S-wave in the NE-SW direction and in the NW-SE direction (Figure 7). The S-wave splitting directions are similar to those recorded by the MT data strike directions (Figure 8).

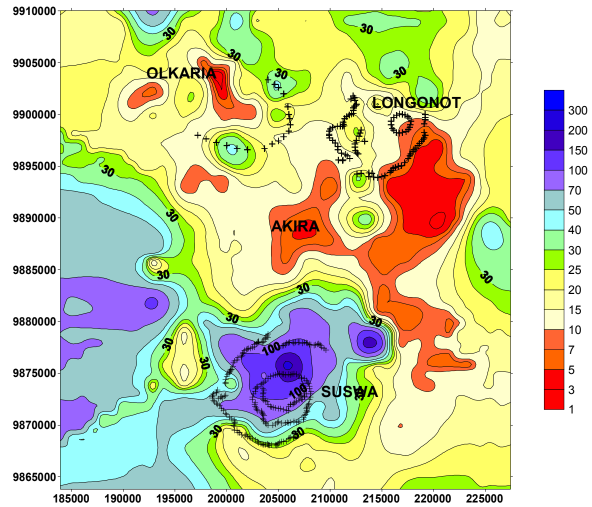

Figure 3: Regional DC resistivity at 1000masl

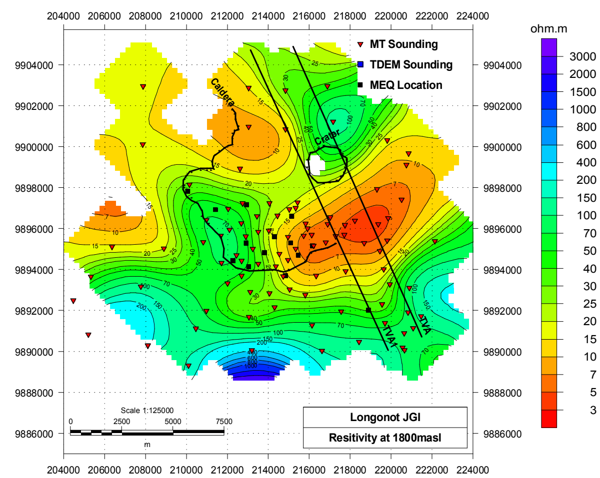

Figure 4: Resistivity at 1800masl from TEM and MT data

6.0 Discussions

The main objective was to explore a new area for exploration drilling in the KRV. In this study, the MT data set provided suitable information for targeting geothermal wells below the clay cap within a NW-SE trending fracture zone that coincides with a Tectonovolcanic axis associated with recent volcanic eruptions.

The low seismic activity may be attributed to the deployment of the MEQ stations far away from the fracture zone imaged by the interpretation of resistivity. This reasoning is supported by the observation that two of the stations located close to the interpreted fracture zone recorded the highest number of microearthquakes with significant S-wave splitting. From similar studies at Krafla in Iceland (Onacha, 2006), it has been established that the network should be located close to the source of earthquakes.

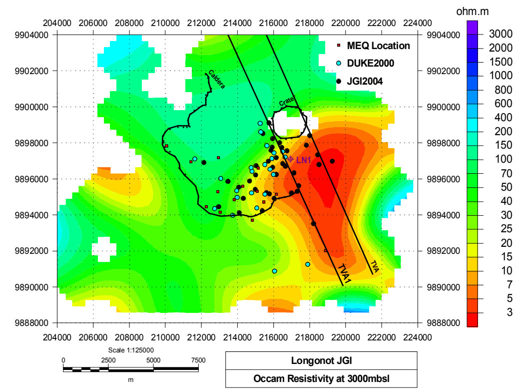

Figure 5: Resistivity at 3000mbsl. The location microearthquakes and the proposed exploration well (LN1) are shown.

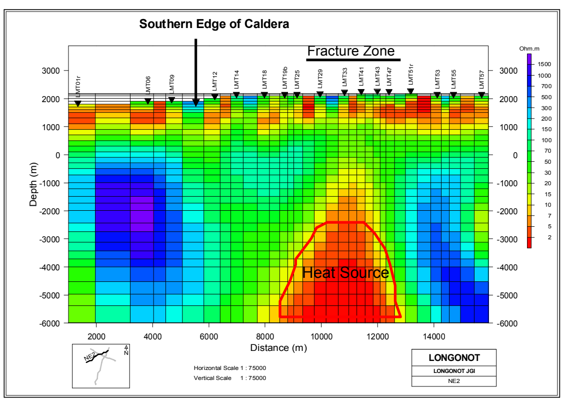

Figure 6: 2-D resistivity model along a NE-SW profile across the Mt. Longonot hydrothermal system in Kenya. The model shows an interpreted heat fracture and heat source.

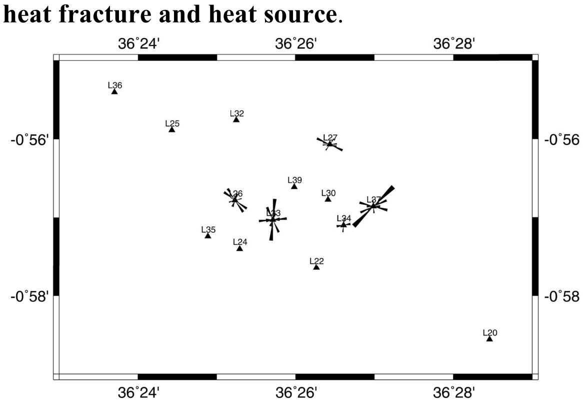

Figure 7: The main directions of S-wave splitting are in NW-SE and NE-SW. S-wave polarization length and thickness are proportional to the number of events.

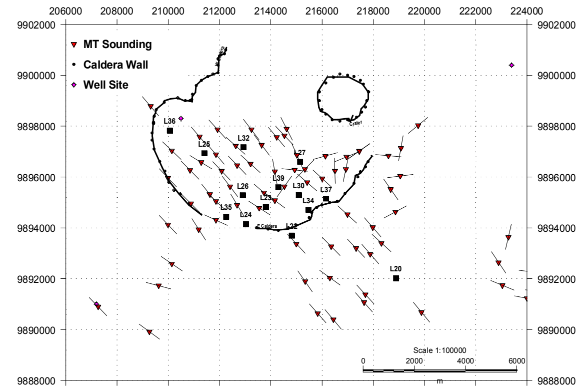

Figure 8: Average MT strike direction at each of the sites at the Longonot hydrothermal system for the frequency range of 320-100 Hz. The locations of the caldera and crater boundaries are shown. There are 2 main strike directions in the NW and NE directions. The NW direction is the dominant strike direction.

The earthquake monitoring network recorded only 38 events located mainly on the boundary between the deep low and high resistivity close to the interpreted fracture zone above the interpreted heat source. This suggests that the earthquakes are probably generated by a combination of fluid movement and tectonic activity. The clay cap is probably formed by the interaction of meteoric water and gases from the deep hot geothermal reservoir. The interaction of the gases and meteoric water may form acidic condensates that alter rocks into clays. The recharge and outflow directions in the Longonot geothermal system are probably controlled by the regional NW-SE and NE-SW faults.

The resistivity is probably consistent with alteration mineralogy patterns and therefore it can be used to infer reservoir temperatures. The near surface high resistivity can be attributed to altered pyroclastics and lava rocks. The second low resistivity layer may be interpreted as a smectite-zeolite zone (<200°C) up to an elevation of 1500masl. A mixed-layer clay zone (200-230°C) probably occurs up to an elevation of 1000masl. The higher resistivity below 1000masl in the interpreted fracture zone is attributed to a chlorite-epidote zone (230-280°C). The deep higher resistivity on both sides of the interpreted fracture zones is attributed to lower formation temperatures and lower permeability.

The interpretation of the 2-D model obtained from MT data after static stripping and using the existing TEM data to correct for the static shift shows a deep low resistivity zone below an interpreted fracture zone. The deep low resistivity is interpreted as a partially molten magma that could be the heat source for the geothermal reservoir at Longonot. This is supported by the location of the microearthquakes above the low resistivity indicating that the low and high resistivity boundary might be the transition to partially molten rocks.

The interpreted fracture zone above the heat source has been proposed as a target for drilling exploration wells. However, it is also noted that the areas with very low resistivity within the interpreted fracture zone could be the core of the fracture zone and therefore a less attractive drilling target because the low resistivity could be as a result of fault gauge and clay which could be impermeable.

7.0 Conclusions

- The study has demonstrated that joint interpretation of MEQ, S-wave polarization and splitting magnitude, resistivity, and magnetotelluric (MT) strike directions can be used to identify fracture zones and heat sources for the geothermal systems.
- Strong evidence exists for correlation between MT strike direction and anisotropy and MEQ S-wave splitting at sites close to fluid-filled fracture zones.
- Resistivity is lowest within the core of the fracture zone and partially molten magma chamber.
- Inappropriate deployment of MEQ can lead to the wrong conclusion that hydrothermal systems are not seismically active, for instance at Mt. Longonot and Krafla.
- Analysis of all earthquake events recorded in Longonot during the 2004 deployment show S-wave splitting at sites close to the interpreted fracture zone.

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