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MT and TEM Joint Inversion of Eburru high Temperature Geothermal Field, Kenya

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ABSTRACT

Eburru,is a volcano located north of Olkaria Geothermal Field found in the Kenya Rift south of the equator. The Eburru volcanic complex is known to have the highest peak in the Rift Valley with an elevation of about 2800m. This field has been studied actively by Kenya Electricity generating Company (KenGen) since 1987 and these studies subsequently led to the drilling of 6 exploration wells. This field is currently developed with a wellhead generator of a 2.5 MW installed capacity and is operated by KenGen. Geophysical exploration is part of the on-going geo-scientific studies applied on this field with the main aim of estimating its potential for electricity production using steam and also exploring new methods to facilitate direct utilization of the resource by the local community as well as geo-tourism. The area hosting the resource is very important for the development of the region as it has a significant population. The Eburru field belongs to the complex of volcanoes - Menengai, Olkaria, Longonot, and Suswa - that are centered on the Kenya Dome. Currently Olkaria is the most developed. In Menengai drilling is on-going while Suswa and Longonot are waiting to set the stage for exploration drilling. In Eburru, geophysical techniques employed during the campaign included transient electromagnetics (TEM), magnetotellurics (MT). These were employed to image the subsurface for the existence of electrically conductive zones that could be geothermal reservoirs. The TEM was used to correct the static shift in the MT data. The joint inversion of MT and TEM data indicates that the resistivity structure of Eburru goes to depths in the range of kilometers and also indicates a probable reservoir located at about 1.8km. This paper discusses the results obtained from recent interpretation of 1D inversion of MT and TEM data from Eburru.

1. INTRODUCTION

The East African Rift passes through Kenya (see Figure 1) which is the main reason why the country is vastly endowed with geothermal resources. It was formed by the process of continental rifting, where two continental plates move away from each other. It is a failed arm of these continental rifting and activities that started about 30 million years ago. Magmatic activity is associated with this rifting where the continental crust thinning is the source of the geothermal heat below. The rifting at the Kenya Rift started from Turkana and extended south towards Magadi and north to Mozambique. The molten rock is very close to the surface in the floor of the Rift hence, it heats up the surrounding rock and the water flowing from the highland to the lower rift zone in the hydrological cycle is heated up and transported through convection to the surface as hot springs and geysers.

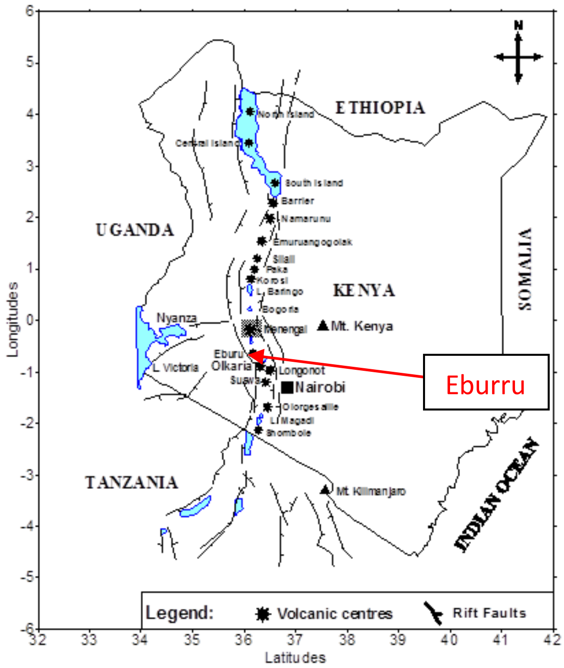

Figure 1: Location map of the East African Rift passing through Kenya and the Eburru Geothermal Field.

Within the Rift Valley spectacular scenes of these geothermal manifestations are common. Eburru is one of the geothermal fields located south of the equator, about 20km north of the Olkaria Geothermal Field in Kenya. The Eburru volcanic complex is located in the Kenyan Rift and is known to have the highest peak in the Rift Valley with an elevation of about 2800m. This field has been studied actively by KenGen since 1987 and these studies led to the drilling of 6 exploration wells. The field is currently under development of a 2.5 MW electrical power plant by KenGen. The area has a population of about 100,000 people and is very important for the development of the region.

The Eburru field belongs to a complex of volcanoes – Menengai, Eburru, Olkaria, Longonot, and Suswa – that are centered on the Kenya Dome. All of these volcanoes are prime targets for the exploitation and production of geothermal energy. Correlation with dated volcanism implies that the activity at Eburru is utmost approximately 500,000 years. The surfaces preserved on the youngest flows suggest that they erupted within the last 1,000 years (Velador et al., 2002).

In this paper the results of the processing and joint 1D inversion of resistivity data, MT and TEM, from Eburru are shown as resistivity cross-sections and iso-resistivity maps. The models reveal the subsurface resistivity structure of Eburru and add further to the understanding of the geothermal system.

2. MT AND TEM SURVEYS

Significant geoscientific work has been done since the mid 1980´s and this culminated in the drilling of 6 exploration wells between 1987 and 1990. The wells drilled are EW-01, EW-02, EW-03, EW-04, EW-05, and EW-06, and have average depths of 2.5km. There has been more recent geophysics work done in 2006 and 2009 and that is MT, AMT and TEM electrical surveys.

The MT and TEM data from these surveys has been processed and analysed by TEMTD program. 14 TEM soundings, covering an area of about 30km^2, were carried out in the Eburru Geothermal Field using Central Loop TEM Array. The equipment used for this survey was the Zonge system GDP 16 receiver.

The current was transmitted using a 300m by 300m^2 loop at 16 Hz and 4 Hz. A total of 14 TEM soundings were processed and used for static shift correction. Processing and 1D interpretation of Eburru TEM data was done using temx software. The results are presented as individual soundings at the appendix and the TEM was used for joint inversion of MT data.

2.1 Data Acquisition

MT and AMT methods were applied to the Eburru Field in two phases: first phase in 2006 and second phase in 2009. The data was distributed over an area of about 56km^2 (Figure 2) and was collected using equipment supplied by Phoenix geophysics, Canada.

A total of 34 MT/AMT soundings were processed and analyzed using a TEMTD program. The TEM data was used to correct the static shift in MT data and this was not enough for all the soundings. Static shift multipliers distribution was plotted and used to determine a factor for the sounding without TEM within the vicinity of 300m.

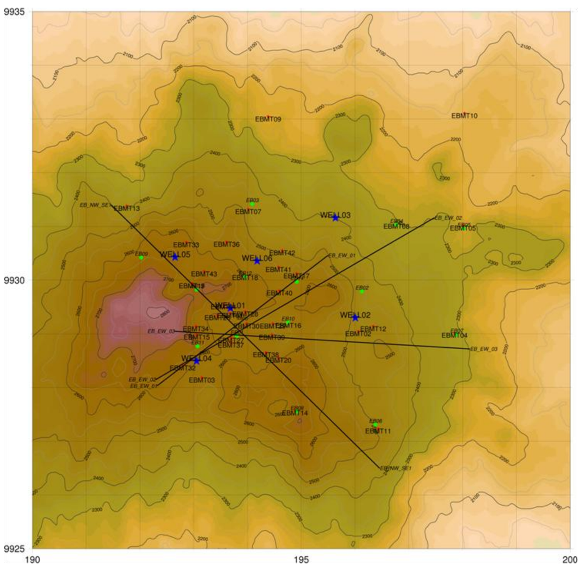

Figure 2: Location map showing MT soundings (shown in red dots), TEM soundings (shown in green dots) and the well locations (blue stars).

2.2 Data Processing

2.2.1 Processing of TEM data

The TEM data was processed by a temx program. The temx software is written in ANSI-C and uses the XForms library (a free software available on the web) for interactive graphics (Árnason, 2006a). The program comes in two versions: temx which reads and processes central-loop TEM data recorded by a PROTEM receiver form GEONICS Ltd. and temxZ which reads and processes central-loop TEM data recorded by GDP-16 receiver from Zonge Engineering & Research Organization, Inc .

The two versions only differ by the routines that read the raw data but data processing and interface is identical. The TemX software reads files with datasets from a sounding. It performs normalization of the voltages with respect to transmitted current, gain and effective area of the antenna and then displays all the data graphically - allowing the user to omit outliers, calculates averages over datasets and calculates late time apparent resistivity (Árnason, 2006a).

The TEM data is then inverted using layered models as well as the Occam inversion and the output looks as shown in Figure 14. The layered model is used as the initial model for the Occam inversion. Occam inversion layers are fixed and we only invert for the resistivity. The model is controlled such that we do not get sharp changes in the resistivity structure unlike in the layered model where no constraint is put in the change in resistivity between layers.

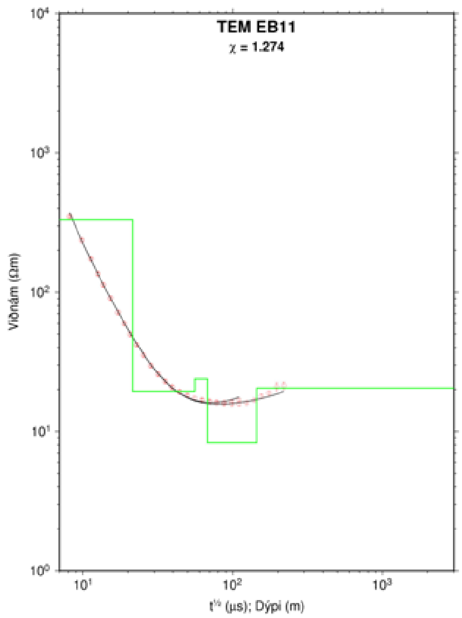

Figure **3: Layered model of TEM sounding EB11. In the layered model there is no constraint on the resistivity differences between layers.**

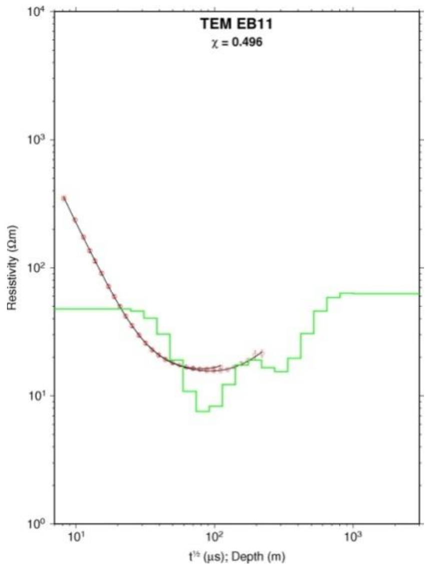

Figure 4: Occam model of TEM sounding EB11In the Occam inversion, the thicknesses are fixed and the resistivity between layers is constrained.

2.2.2 Processing of MT data

The MT data was processed using a ssmt 2000 software from phoenix geophysics which is part of a suit of processing software that is supplied with the MT equipment. The time series data was Fourier transformed then processed and edited in the mteditor program.

In this program data is edited or sort of cleaned up (removal of outliers) and at the end converted to EDI files. EDI stands for Electrical Data Interchange standard, which is an approved data format for MT data.

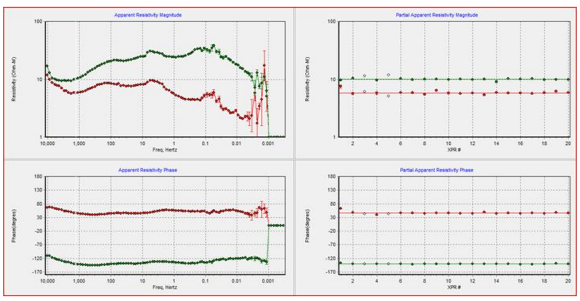

Figure 5: An example showing plot of apparent resistivity vs frequency and also the phase for MT sounding EBMT40. The outliers on the right hand window have been removed to clean the curve. At the end of the curve the low frequency part is usually noisy and also can be cutoff.

This program takes as input the MT plot files created by SSMT2000 and displays the resistivity and phase curves as well as the individual cross powers that are used to calculate each point on the curves (Figure 5). Cross powers that were affected by noise can be automatically or manually excluded from the calculations.

The program also allows one to display a variety of parameters of the plot files such as tipper magnitude, coherency between channels and strike direction. The output is industry-standard EDI files suitable for use with geophysical interpretation software. The files with a .edi extension which have been processed, have an apparent resistivity curve plotted against period and there are two apparent sets of resistivity, that is, the $\boldsymbol{\rho}_{xy}$and $\boldsymbol{\rho}_{yx}$..These are the blue and the red curves in the left top panel of Figure 6.

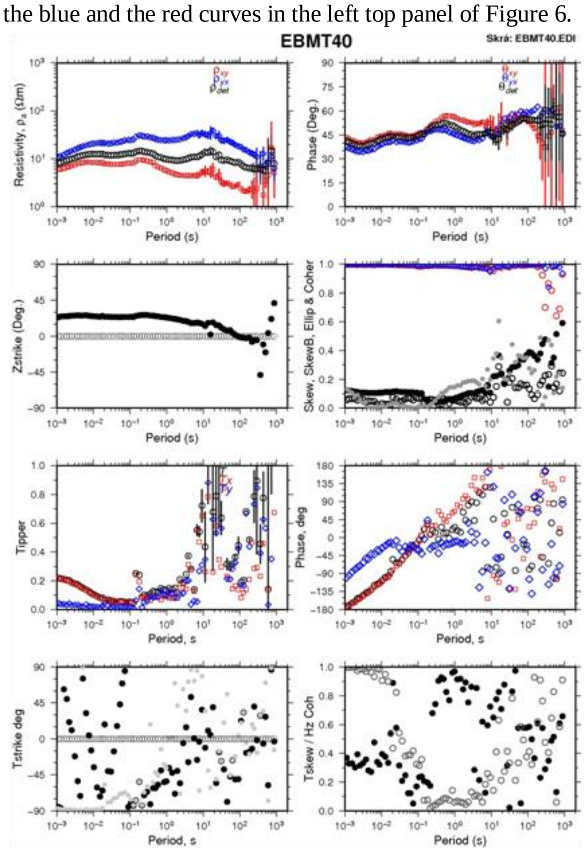

Figure 6: Joint 1D inversion of TEM and MT soundings. Red symbols are measured TEM apparent resistivity and blue symbols are measured apparent resistivity and phases derived from the determinant of MT impedance tensor. Green lines show the response of the resistivity model to the right. The shift multiplier is shown in the upper right hand corner of the apparent resistivity panel.

The determinant of the apparent resistivity curves is used for inversion. The Z strike shows the dimensionality of the ground and it will show 1D case if the pattern is continuous without major changes. Figure 19 shows a 1D case at shallow shorter periods; at about 10 seconds there is change to a 2D case. The EDI file can be used to check the coherency of the data. This is about the data quality and when the data is of high quality the coherency is near 1. For each site MT parameters are shown in the example of station EBMT40 in Figure 6.

Apparent resistivity for both main modes ($\rho_{xy}$and ρ_{yx}) is calculated in the measured directions i.e. **x** is magnetic north and **y** magnetic east. Black circles denote the apparent resistivity derived from the rotationally invariant determinant of impedance tensor. Apparent phase ($\theta_{xy}$and θ_{yx}) is calculated in the measured directions. Black circles denote the apparent phase derived from the rotationally invariant determinant of impedance tensor.

1. Z strike or the Swift angle gives the electrical strike, (the horizontal rotation which maximizes$|Z_{xy} + Z_{yx}|$) for each frequency and is shown by filled circles. The direction used for calculating apparent resistivity and phase is shown by unfilled circles. For two dimensional electrical structures a constant value of electrical strike would be observed.
2. Three dimensional indicators:

   Skew=$\frac{|Z_{xx}+Z_{yy}|}{|Z_{xy}-Z_{yx}|}$. Swift skew is shown by filled circles. It is rotationally invariant and should be zero for 1-D and 2-D earth.

   SkewB=$\frac{\sqrt{|\mathrm{Im}(Z_{xx}Z_{yy}^{*}+Z_{xx}Z_{yy}^{*})|}}{|Z_{xy}-Z_{yx}|}$ or Bahr skew is shown by unfilled circles. It is rotationally invariant and should be close to zero for both 1-D and 2-D earth.

   Ellip=$\left|\frac{Z'_{xx}-Z'_{yy}}{Z'_{xy}+Z'_{yx}}\right|$or ellipticity is shown by gray circles. It is calculated in the principle rotational coordinates and gives the axis rotation of the electrical field ellipse. A value of zero for both skew and ellipticity is a necessary and sufficient condition for two-dimensionality of the data.
3. In red and blue colors on the Skew, SkewB, Ellip & Coher graph show the multiple coherenc of the electrical fields with respect to the horizontal magnetic fields, in the measuring coordinates (Personal comment from Hersir, 2011).

2.3 Joint Inversion of TEM and MT Data

A total number of 3 cross-sections were made to display the result of the 1D inversion of the MT and Tem soundings. The programme TEMTD performs 1D inversion with horizontally layered earth models of central-loop Transient Electro-Magnetic (TEM) and Magnetotelluric data. It can be used to invert TEM or MT data separately and also for joint inversion of TEM and MT data, in which case it determines the best static shift parameter for the MT data. For TEM data, the programme assumes that the source loop is a square loop and that the receiver coil/loop is at the centre of the source loop. The current wave form is assumed to be half-duty bipolar semi-square wave (equal current-on and current-off segments), with exponential current turn-on and linear current turn-off. For MT data, the programme assumes standard EDI for of impedance and/or apparent resistivity and phase data. The programme is written in ANSI-C and runs under UNIX/LINUX operating systems. It uses the gnu plot graphics programme for graphical display during the inversion process (Árnason, 2006b).

The results are discussed individually as shown below.

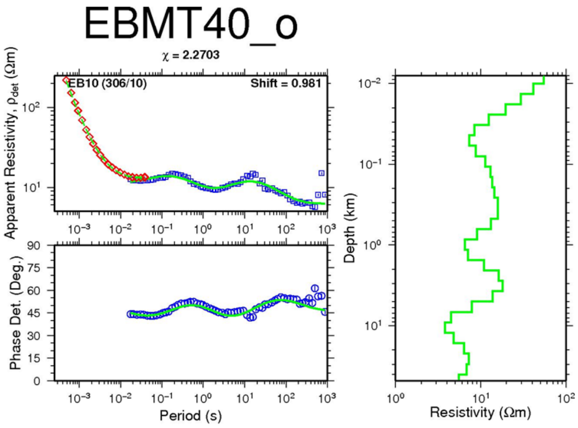

Figure 7: Example of processed data for MT sounding EBMT40.

Soundings once prepared are jointly inverted. This is important because it not only solves the problem of static shift in MT but also helps resolve the upper most layer close to the surface because TEM is mainly 1D and therefore gives accurate 1D information on the earth directly beneath. The TEM curve when jointly inverted generates a model which is a logarithmic scale of resistivity plotted with depth. The programs allow for iterations in order to obtain the best fit in the TEM and MT curve. The shift factor is determined and it is printed in the plots with values ranging from 0.1 to 2. A value of 1 means that the MT curve is not shifted and it does not suffer the shift. Values as low as 0.1 means that the shift factor is high and the shift was much greater. The plots also show the distance of the TEM and the MT as well as the difference in elevation and the chi square which is the percentage error in the fit. When the data is fitted it is also good to ensure that the phase is smooth and fitted well. The final plots give depth vs the resistivity. These are then later used to make cross-sections and iso-resistivity maps to show the 1D model of an area.

TEMTD allows for inversion on MT alone. The soundings that were inverted alone were the TEM soundings that did not have a TEM station nearby. Therefore, a static shift map was made to estimate the shift factors to be input when inverting the MT soundings. The map tries to assist in correcting for the static shift in MT but does not successfully do the proper correction. It should be emphasized that MT cannot be corrected by itself and will need to be within a radius of 300m to a TEM station.

2.4 Results

2.4.1 Cross-sections

This resistivity contrast makes it relatively easy to delineate a resistivity anomaly caused by geothermal activity (Hersir and Björnsson, 1991). To represent the resistivity structure of Eburru, a cross-section of the 1D inversion data was plotted to evaluate how the resistivity changes with depth and in one direction.

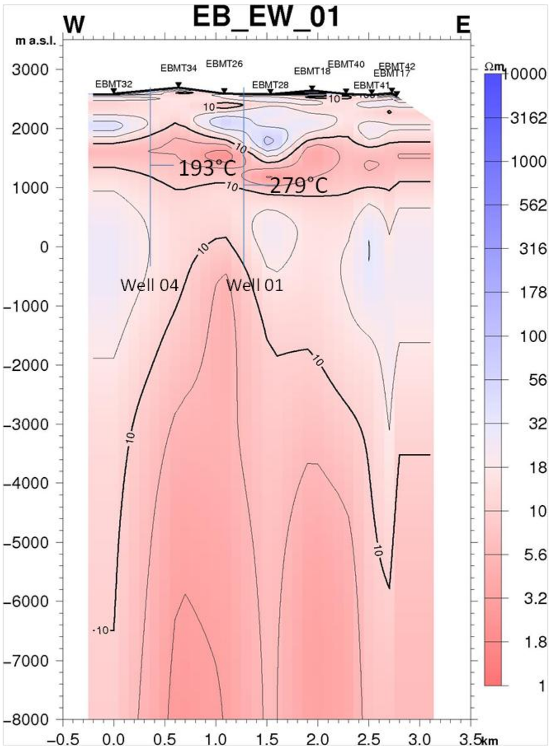

Figure 8: Resistivity cross-section from joint 1D joint inversion of TEM and MT data down to a depth of 8000m b.s.l.

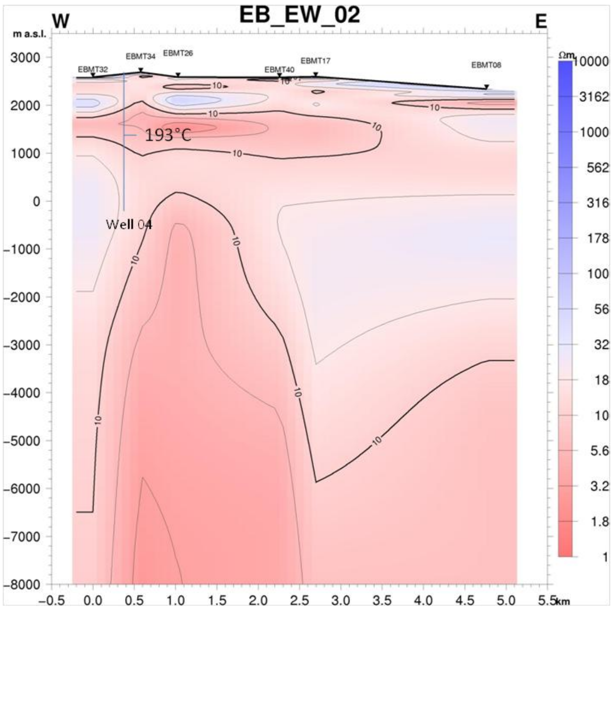

Figure 9: Resistivity cross-section from joint 1D joint inversion of TEM and MT data down to a depth of 8000m b.s.l. The well one is placed directly above the conductive structure. The well indicate is within an up flow zone.

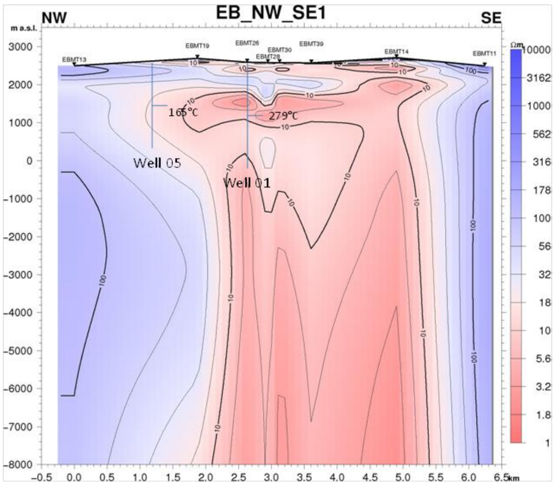

Figure 10: Resistivity cross-section from joint 1D joint inversion of TEM and MT data down to a depth of 8000m b.s.l.

The cross-sections are EB_EW_01, EB_EW_02 and EB_NW_SE 1 as seen in Figures 8, 9 and 10 respectively. The spatial locations of the cross-sections' locations are shown in Figure 2. The profiles EB_EW_01 and EB_EW_02 show similar resistivity structures. The conductive cap, the smectite zeolite zone, is seen at the depth of 2100m above sea level and is well delineated in both cross-sections. It is somewhat thinned and underlying this zone is a resistive zone which is forming as a layer and is persisting for a depth of more than 2km. This is interpreted as the chlorite epidote zone which is overlying a conductive structure which extends to great depths of 8000 below sea level. The Eburru area is host to intrusive bodies and this seems to be a hot intrusive body which acts as the heat source. Well 01 of Eburru with recorded temperatures of above 270 °C seems to be right on top of this zone. The heat source in the Eburru volcanic complex is most probable from a localized intrusive of syenitic composition (Omenda and Karingithi, 1993).

Iso-resistivity maps were also drawn at respective depths. At the surface the resistivity varies: it is high in some places where there are unaltered rocks, and at some points in the surface there is very low resistivity - interpreted as the place with geothermal manifestations like fumaroles which are very abundant in the area (Figure 11).

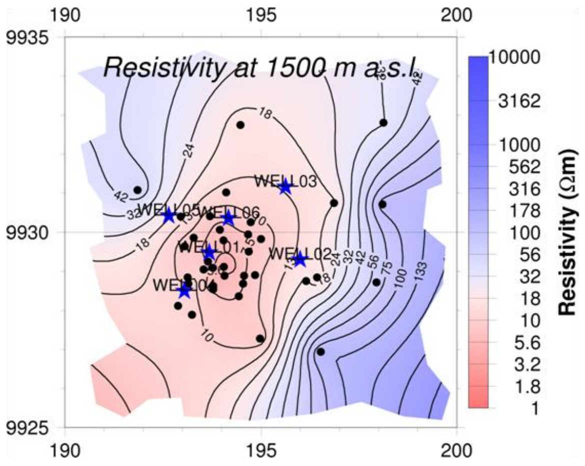

Figure 11: Iso-resistivity map at a depth of 1500 m a.s.l. Black dots denote an MT sounding and the blue dots indicate the wells.

Below at about 1500m a.s.l. a conductive cap is seen and is interpreted as the smectite zeolite zone (Figure 12). At about 1000m a.s.l. is the mixed clay zone and below this zone is the epidote and chlorite zone indicated by the high resistivity.

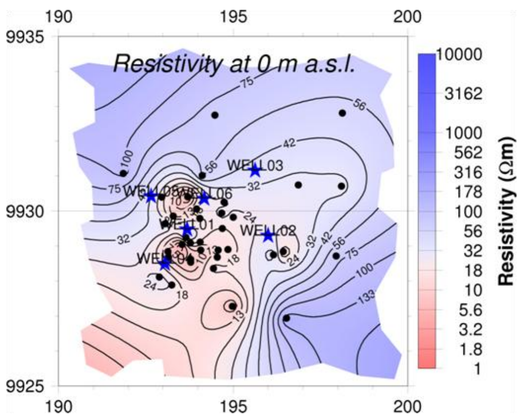

Figure 12: Iso-resistivity map in m at sea level. Black dots denote an MT sounding and the blue dots indicate the wells.

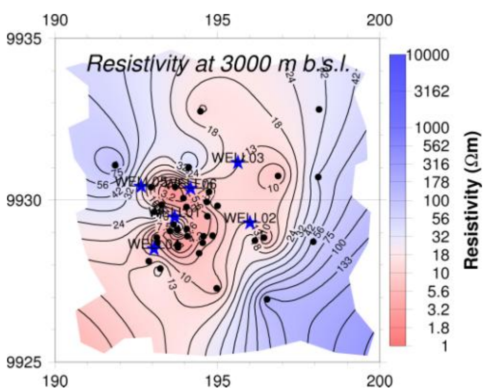

Figure 13: Iso-resistivity map at a depth of 3000m b.s.l. Black dots denote an MT sounding and the blue dots indicate the wells.

The iso-resistivity maps show the resistivity variation at uniform depth. They are drawn at depths which show the interesting variations and this are at 1500m a.s.l, 2000m, 3000m, and 6000m b.s.l. The iso-resistivity indicates the low resistivity conductive cap of the smectite zeolite zone at a depth of 1500m above sea level. The resistivity is very low at < 10 Ω m indicating the zone of conductive clay surface. The resistivity starts to decrease at 2000m b.s.l. This is attributed to the formation of chlorites and epidote which are high resistive minerals. The iso-resistivity maps best display the location of the wells. The well 04 and well 01 are tapping at this zone and the temperatures are at 193° C and 279° C respectively. The resistivity then lowers at the great depths of 3000m below sea level and a perceived heat source is proposed.

4. CONCLUSIONS

- The resistivity cross-sections of joint 1D inversion of MT and TEM data show a geothermal system with three major resistivity zones delineated. The upper surface shows high resistive zones >70Ωm which is interpreted as the unaltered rock at the surface.
- Eburru is home to many geothermal manifestations and the low resistivity pockets noted at the surface about 10Ωm are indicative of these surface alteration. These are the conductive clays and low temperature alteration minerals deposited at the surface.
- The intermediate zone is a very conductive layer of <10Ω m and is the smectite zeolite zone. This is the conductive clay cap to the geothermal system. Below this layer is the mixed clay zone and the chlorite epidote zone indicating a temperature of greater than 230^0C.
- Below is a conductive body to depth which is seen as the heat source for this geothermal system. The drill holes in Eburru were used in comparison with the alteration temperature interpreted from the joint inversion and a close correlation which indicates that the well 01 has temperatures above 270^0C.

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