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Resistivity Structure of the Eburru Geothermal Field, Kenya Depicted Through 1D Joint Inversion of MT and TEM Data

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ABSTRACT

Eburru is one of the geothermal fields in Kenya, producing 2.5 MWe from one of the six exploratory wells. In order to drill production wells, a total of 36 additional MT and TEM soundings were carried out in 2013 to delineate the geothermal resource field of Eburru. This report discusses and presents the results of the earlier soundings and soundings from 2013 which brought the total number to 43 MT and 43 TEM soundings. The TEMTD program was used for joint 1D inversion of MT and TEM data, and the program calculates the shift factor. The MT data are therefore, corrected for the static shift. Data used in this report were acquired by KenGen staff team using data logger MTU-5A made by Phoenix Ltd for acquiring MT data and TerraTEM provided by Monex GeoScope Ltd for acquiring TEM data. MT data were processed using SSMT 2000 and MTEditor before jointly inverted with TEM data. The results discussed in this report present 1D joint inversion, resistivity cross-sections and iso-resistivity maps down to several kilometers. The reservoir in Eburru geothermal field is located at about 2500 m b.g.l according to the subsurface resistivity structure.

1. INTRODUCTION

Eburru geothermal field lies in the Great Africa rift system (GARS) which is a major tectonic structure stretching about 6100 km starting from Red Sea in the north to Mozambique in the south. The rift starts from a triple junction which is evident in Ethiopia. At this point two branches are in contact with Red Sea and Gulf of Eden and the third is towards the south passing through Ethiopia. Eburru is located in one of the eastern arms of the GARS stretching though Eritrea, Ethiopia, Kenya and all the way down to Mozambique (Figure 1). Eburru volcano consists of east and west volcanic centres which are composed of pyroclastics, rhyolites, basalts, trachytes, tuffs and pumice (Omenda and Karingithi, 1993). The two volcanic centres are arranged in an E-W trend and extend as far to the west as the Mau escarpment. The structure of the Eburru field is dominated by faults and fractures that trend in N-S direction. Large open fractures and faults are common on the eastern Eburru volcano, forming micro-grabens through the geothermal field and the main outflow path for the geothermal fluids as shown by the abundance of surface manifestations in the form of fumaroles, hot and steaming grounds. The Great Africa Rift system which host Eburru geothermal field was formed in more or less a linear like zone where the continental plate is being pulled apart with the rifting between widened mantle plume probably began creating three arms under east Africa, which are East Africa Rift, Gulf of Eden Rift and Red Sea Rift (Omenda and Karingithi, 1993). The heat flow from the asthenosphere along the rift zones leads to volcanism and formation of domes as can be seen in Olkaria to the south of Eburru (Figure 2).The eastern branch is believed to be much older and considered to have developed about 13 to 23 million years earlier before the western branch and this was supported by the discovery of preserved vertebrate fossils and volcanic ash which are believed to be about 23 million years old (Velador et al., 2002).

The stretching causes fracturing above the ductile brittle boundary leading to the formation of a series of normal faults and hence the graben structure along the rift valley. The continuous stretching process is associated with thinning of the crust and volcanic eruption softly forming caldera as seen in Eburru and lava flow covering large areas with some exposed on the rift valley flanks. The EAR is largely following the ancient continental plates that collided to form African craton billions years ago.

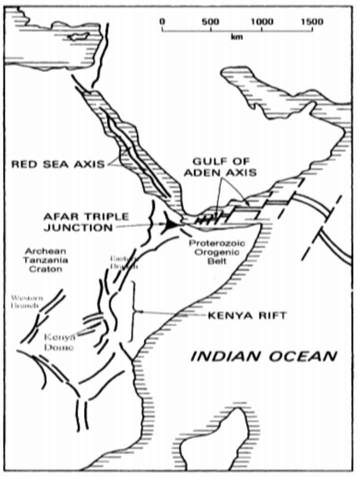

Figure 1: Location map of the Kenyan rift (Clarke et al., 1990)

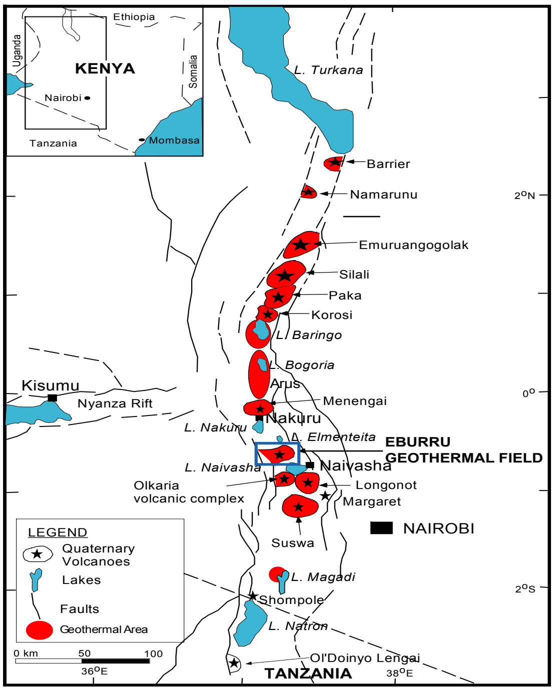

Figure 2: Map showing the loation of Eburru geothermal field (name shown in blue box) in Kenya rift system

2. INSTRUMENTATION OF MAGNETOLELLURIC AND TRANSIENT ELECTROMAGNETIC EQUIPMENTS

2.1 Magnetotelluric (MT) equipment

Magnetotelluric (MT) equipment is used for data acquisition and the main aim is to collect high quality data over abroad period range. The equipment consists of three magnetic sensors, five electrodes, five telluric cables each at least 30 m long, magnetic cables and one data logger. Usually a five channel equipment is used to measure the time components of the electromagnetic field, Ex, Ey, Hx, Hy and Hz. The deployment of MT equipment is done in reference to x and y-axis in magnetic north and east respectively. The E-field is measured as voltage between rounded electrodes about 60 m (2 X 30 m) apart. Electrode at the centre is used to ground data logger (Figure 3). The magnetic coil for Hx is oriented along n-s direction with the connected side facing instrument (Figure 4), Hy oriented along e-w and Hz is the vertical component. The electrodes are connected to MTU data logger too. The electrodes are made of KCl or $PbCl_2$ in solution enclosed in a ceramic container. Wet bentonite is applied on the outside of electrode to ensure good contact with the soil. The three conductive coils measure the natural time varying electric and magnetic fields at the earth´s surface caused by electromagnetic waves radiated from the sun and from distant electrical storm (Vozoff, 1991). The soundings were made by computing the impedance for a range of frequencies ranging from 320 to 0.001 Hz from data acquired in 18-26 hours.

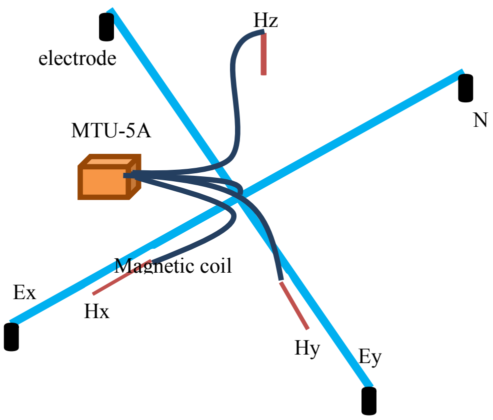

Figure 3: Layout of MT equipment (each electrode is place 30 m from centre of the array)

Figure 4: N-S magnetic coil

2.2 Transient electromagnetic method

The instrument used in the acquisition of the data analyzed was TerraTEM and was developed by Monex GeoScope Pty Ltd. Terratem is made up of transmitter (TX), receiver (RX), a loop of 100x100 m and a battery pack. The transmitter is connected to the loop and the receiver placed at the centre is also connected to the transmitter with a synchronization cable (Figure 5). The data used in this report were acquired according to the method developed by Monex Ltd. The locations of the loops were always chosen depending on area topography, avoidance of cultural interference and the accessibility.

The loop was laid out using compass direction to measure the sides precisely. All the data that were collected by TerraTEM were processed using Terratem software and stored in USF form before taken to TEMTD for inversion.

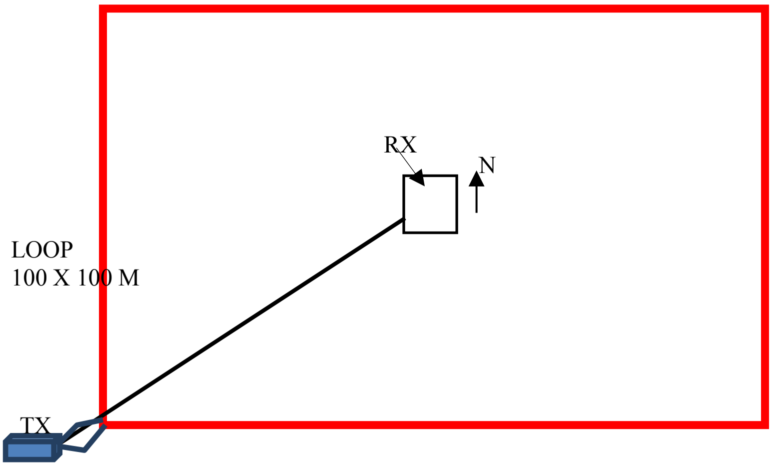

Figure 5: Schematic diagram of terraTEM equipment deployed in the field

3. GEOTHERMAL SURVEY AT EBURRU GEOTHERMAL FIELD

3.1 Geology of Eburru

Eburru geothermal field is located along the Great Rift Valley system to the south of Menengai and north of Olkaria geothermal fields. In 1980's, geoscientific studies were done in Eburru, leading to the drilling of six exploratory wells between 1986 and 1990 with an average depth of 2.5 km below the ground level. The elevation reaches 2800 metres above sea level and is the highest topography within the rift valley floor. Eburru structures are mainly trending N-S direction with west and east volcanic centers. Eburru has been active since pleictocene. Rhyolite, trachytes and basalts are the most abundant rocks in the area and trachytes are mainly pantelleritic. The western older sector of Eburru is covered by upper trachytes which are underlain by lower pantellerite while the caldera of eastern side is composed of upper pantellerite and upper trachytes. The eastern pantellerites are considered as the youngest rocks dating about 400 years (Clarke et al, 1990). The presence of syenite below the entire Kenyan rift has been suspected including Eburru geothermal field and the drilled cores collected from Eburru confirmed syenitic body at about 2400 m below the ground level. The volcanic cones and domes have been referred to as caldera (Omenda 1997).

A total of six wells have been drilled in Eburru (Figure 6). Three out of six wells discharged and one well EW-1, is used for production of 2.5 MWe. The fluid chemistry from the drilled well one (EW-1) indicates that Eburru reservoir is a non-boiling reservoir with high amount of non-condensable gases and high salinity brine. Low magnesium and calcium content in the brine reduces scaling problem in this well with a high chloride level of 956 to 1976 as compared to Olkaria (KPC, 1990).

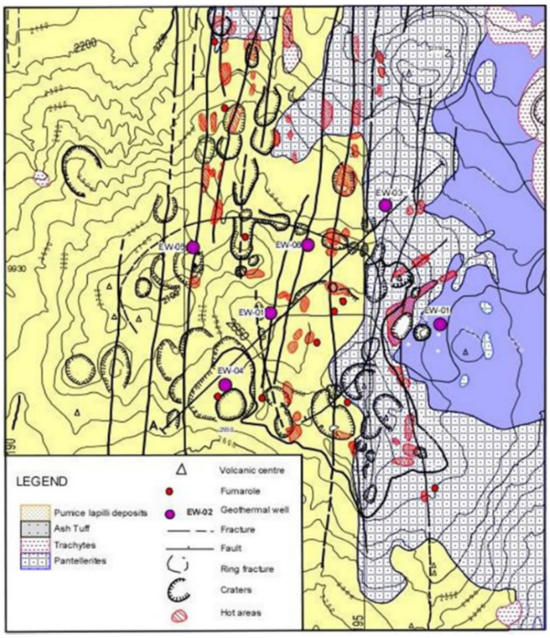

Figure 6: Eburru geological map with structures (Omenda and Karingithi, 1993)

3.2 The resistivity survey

The geophysical methods applied during the early 1980's include DC sounding (Schlumberger) and gravity leading to the sitting of the exploratory wells. In 2006 to 2007 the more advanced geophysical methods comprising of transient electromagnetic (TEM) and magnetotelluric (MT) methods were applied where a total of 7 TEM and 7 MT soundings were carried out using Zonge TEM system and MTU-5A Phoenix MT equipment respectively (Figure 7). The latest survey of April 2013 added 36 MT and 36 TEM soundings using two sets of TerraTEM system and four MTU-5A Phoenix MT equipments.

A total of 43 TEM and 43 MT soundings were analyzed to improve the conceptual model of Eburru geothermal field.

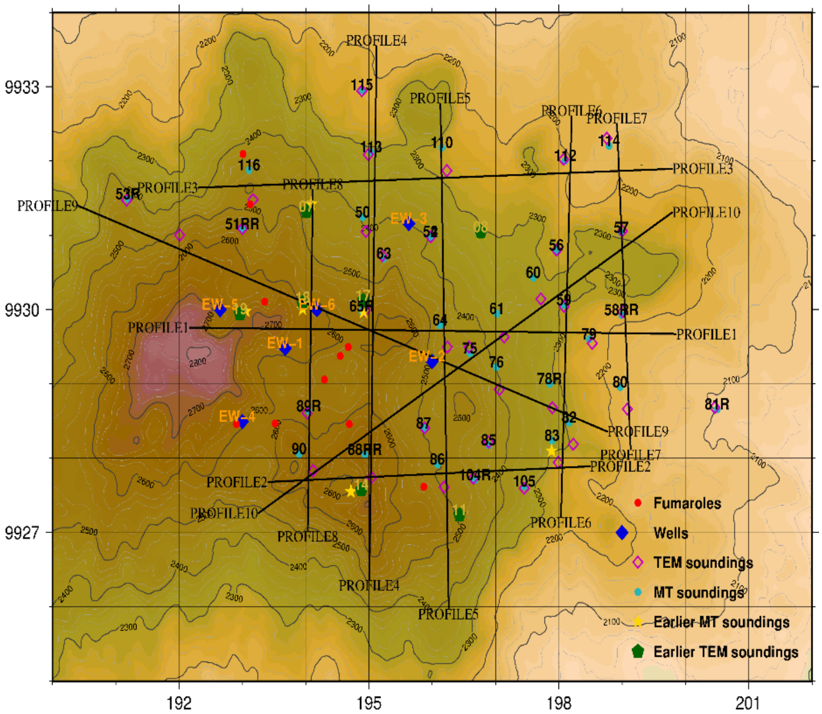

Figure 7: Location of MT soundings (black dots), TEM soundings (inverted triangles) and the black lines are the cross-sections used in interpreting the resistivity structure of Eburru

4 PROCCESSING AND INVERSION OF EBURRU FIELD DATA

MT and TEM data processing is specifically done to suppress various types of noise that affect measurements. It was found that the method used in processing this data can recover response functions from noisy field data. The processed data used in defining the resistivity structure beneath Eburru geothermal field were high quality data except for some few which were used as bench marks to test the quality of the software in case the field data are noisy.

4.1 Transient Electromagnetic data processing

The TerraTEM data collected in Eburru were processed by TemxUSF, a new version of temx for TerraTEM equipment. The program read the USF file output of TerraTEM and enables visual edit of data by throwing out the outlier points before the data is used in TEMTD for inversion (Árnason, 2006a).

TEMTD program was used for the Eburru data to perform 1D inversion. In 1D inversion it is assumed that the earth consists of horizontal layers with different resistivity and thickness (Figure 8). The program runs on a Linux operation system and can be used for joint inversion of MT and TEM, inversion of MT or TEM alone. In case of joint inversion, the program is used to determine the best static shift for MT data and indicate the static shift value, hence solving the shift problem.1-D interpretation calculates the layered model and determines where it best fits the measured response.

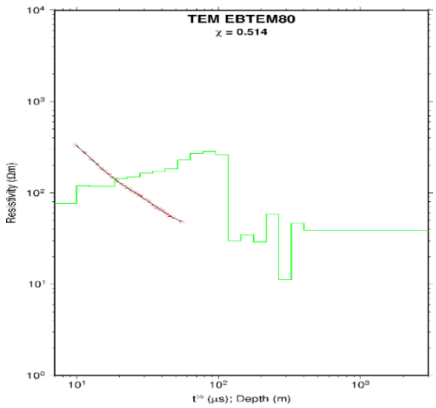

Figure 8: 1D inversion of TEM sounding with x shows the fit between measured data and calculated data

4.2 Magnetotelluric data processing

The MT data analyzed in this report were acquired by magnetotelluric equipment MTU-5A made by Phoenix geophysics Canada. Data were acquired by three different sets of equipment. The initial processing is done by SSMT2000 from Phoenix Geophysics (2005) software provided by equipment manufacturer. This involves the editing of the parameter file to reflect the setup of the data acquisition and furrier transform of the resulting time series data to frequency domain. MTEditor program was then used to display the phase curves, the apparent resistivity and the cross powers used to calculate each point of the curve. The program was also used to edit or smoothen the data further by removing outliers considered as noisy data points on the phase or apparent resistivity curve. The final result from MTEditor was stored in EDI format (Electromagnetic data interchange) ready for inversion in TEMTD program (Figure 9).

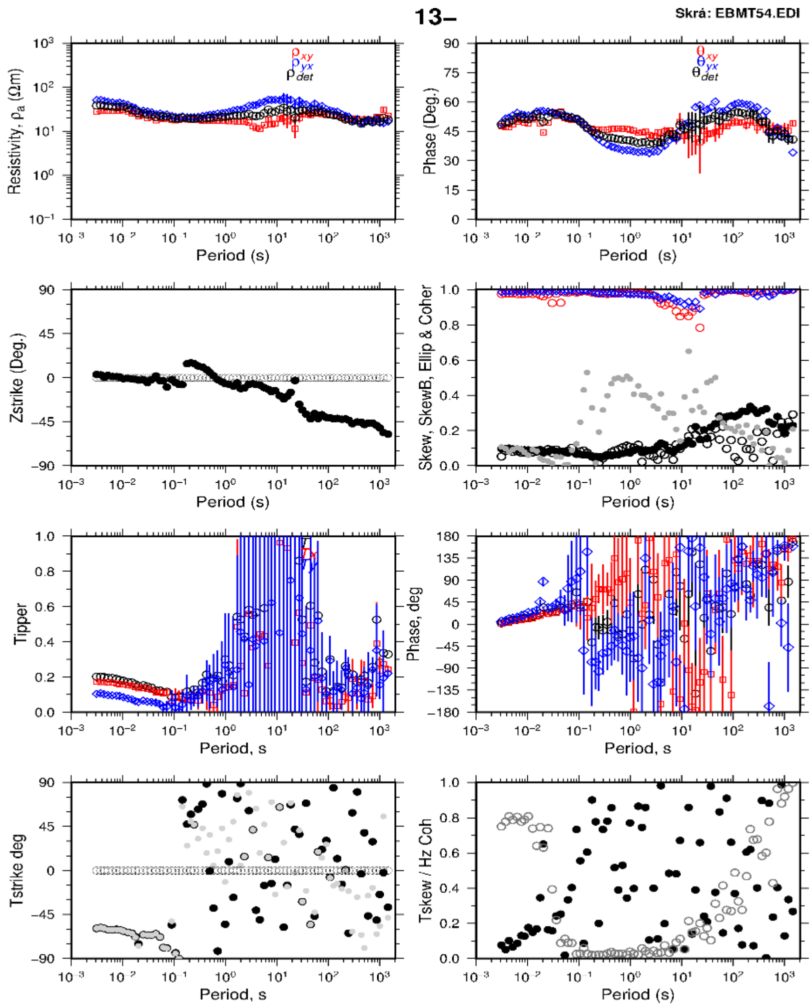

Figure 9: MT parameters as extracted from EDI file (Apparent resistivity, phase in xy, yx direction and the determinant, electrical strike direction Zstrike, coherence, skew, Tipper, tipper phase, Tstrike and Tskew

4.3 Eburru Strike analysis

Rose diagrams for the electrical strike based on tipper strike for different period ranges were analyzed in this report. Tipper strikes at shallow depths (0.001-1s), and greater depths (1-1000s) are shown in Figure 10 and 11. The Tipper strike confirms the results of 1D joint inversion models with the low resistivity at the centre and the alignment of tipper strike around the low resistivity.

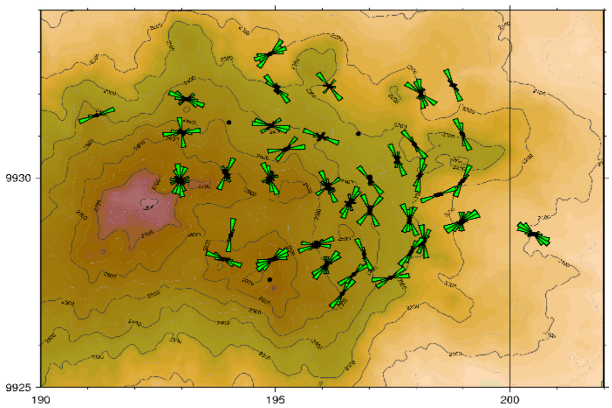

Figure 10: Rose diagram for the electrical direction based on the Tipper

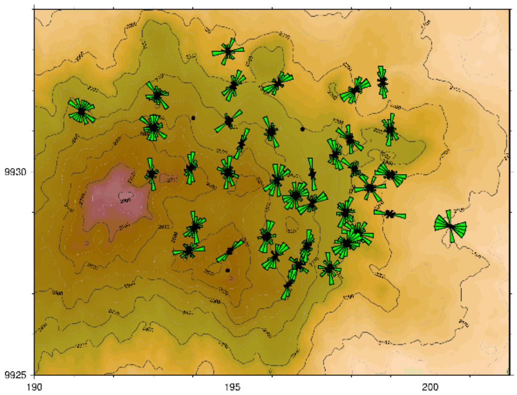

Figure 11: Rose diagram for the electrical direction based on the Tipper strike at 1-1000 s

4.4 TEMTD 1-D Inversion

TEMTD is a program used for 1-D inversion of MT data and joint inversion of MT and TEM data. TEMTD program was written by Knútur Árnason of ISOR (Árnason, 2006b). The program is capable of inverting phase derived from MT off-diagonal element tensor (yx and xy modes) and the apparent resistivity. It is also able to invert for static shift multiplier needed to fit both the TEM and MT data with the same model in joint inversion (Figure 12). It is capable of doing smooth Occam inversion with increasing but fixed layered thickness with depth as well as with inverting for resistivity values and thickness of layered models. TEMTD program inverts the determinant of the impedance, and the apparent resistivity and phase are calculated from the rationally invariant determinant of the MT impedance tensor as a function of the period.

4.4.1 Joint Inversion of MT and TEM

As discussed in the next section, MT apparent resistivity is frequently shifted by multiplicative factor. The shift is constant at all frequencies with no effect on the phase data (Jones, 1988). The amount of static shift depends on the resistivity characteristics beneath the area of study (Berdichevsky and Dmitriev, 1976).

TEMTD software was used for jointly inverting MT and TEM data for correction of static shift. Joint 1D Occam inversion of MT and TEM data was performed and the best multiplicative factor or shift parameters of all the MT soundings in Eburru were determined.

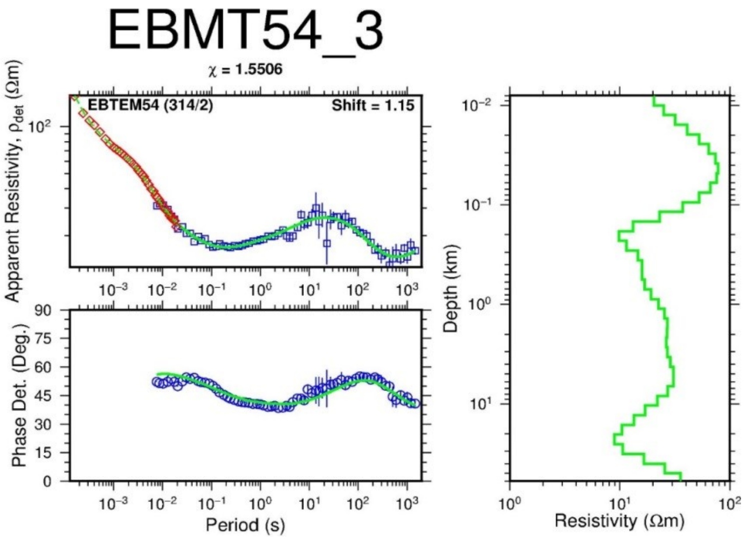

Figure 12: 1D Joint inversion of MT and TEM soundings; red and blue symbols on the top left represent the apparent resistivity from TEM and MT soundings respectively; the bottom panel shows, the detetminant of the MT impedance tensor; the right box shows the results of 1 D resistivity inversion model. The green line is the fit of TEM and MT.

5. RESULTS AND DISCUSSION

Resistivity interpreted from electromagnetic methods or direct current method has been used for hydrothermal exploration for several years. Correlation of resistivity against drilling results has been done in many drilled geothermal field and it is shown that resistivity method can be used to study the earth subsurface. (Árnason et al., 2000). The indirect correlation of temperature and resistivity is controlled by degree of hydrothermal alteration. High temperature geothermal systems are normally associated with low resistivity resulting from mineral alteration (Árnason et al., 2000). The possibility of using resistivity method to interpret temperature, permeability and alteration in geothermal system resolves the geometry of geothermal reservoir.

The study of low resistivity zones is very essential in delineation of high temperature zones as targets for geothermal drilling. The interpretation of Eburru data will take into consideration the structures, the geological setting and alteration pattern that might influence the area resistivity distribution.

5.1 Cross-Section

Several cross-sections were made in the area as shown in Figure 13. Three cross-sections are along east-west direction, five along north-south direction, one in northeast-southwest direction and the last one along southeast to northwest direction but only five profiles are described on this paper. The cross-sections were plotted by TEMCROSS programme (Eysteinsson, 1998) developed at ISOR – Icelandic GeoSurvey. The program plots the resistivity obtained from 1D inversion. The final models are presented here in two different ways, as a resistivity map (Iso-resistivity map) for different elevations (depths) and resistivity cross-sections.

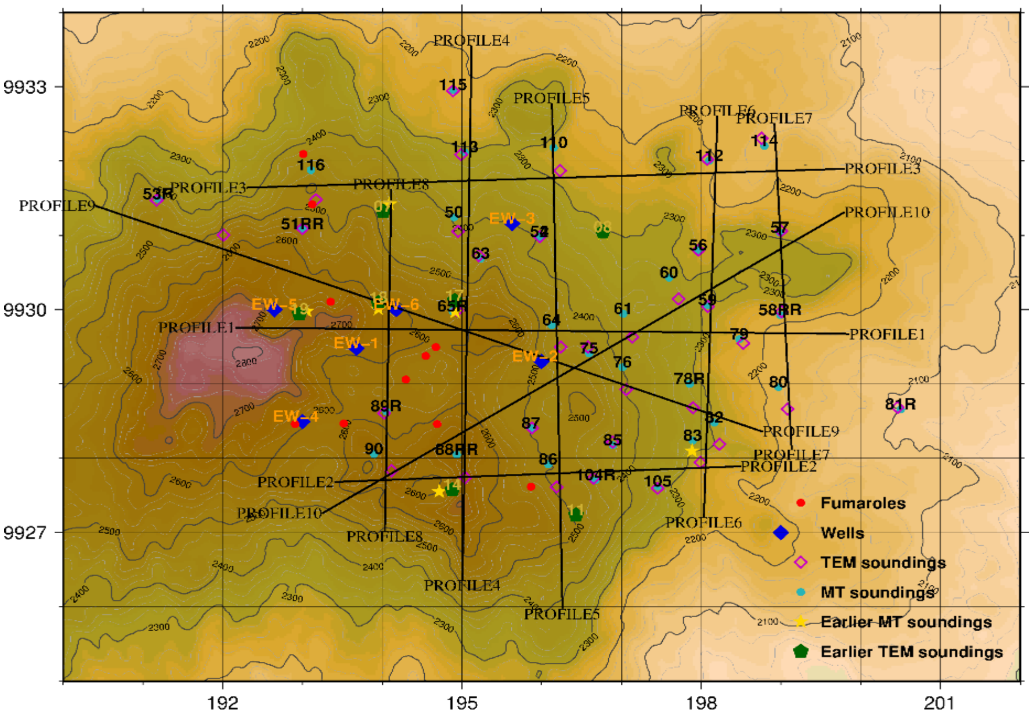

Figure 13: Location of MT soundings (black dots), TEM soundings (inverted triangles) and the black lines are the cross-sections used in interpreting the resistivity structure of Eburru

Cross-section along profile 1 (Figure 14) has six soundings and is about 7 km long (cut across EW-5, EW-6 Eburru well) It shows a thin resistive layer near the surface along the profile interpreted as unaltered formations underlain by low resistivity less than 10 Ωm due to the effect of geothermal manifestations such as fumaroles. Below this at 900-1800 m a.s.l is a conductive cap beneath sounding 19, 18 and 17 of 6.3 Ωm interpreted as hydrothermal alteration minerals like zeolite and smectite with temperature range of 100-230^{o}C. It is underlain by resistive body interpreted as high temperature alteration minerals associated by chlorite and epidote with formation temperature range between 250-300^{o}C. Up doming low resistivity at 3000 m b.s.l below sounding 19, 18 and 17 is associated with heat source of Eburru geothermal field. Sounding 59 and 58RR mark the eastern boundary of Eburru geothermal field A thin conductive layer near the surface is interpreted as due to the presence of sediments and groundwater and is not associated with geothermal activity. The underlying high resistivity is described as the normal resistivity outside a geothermal field

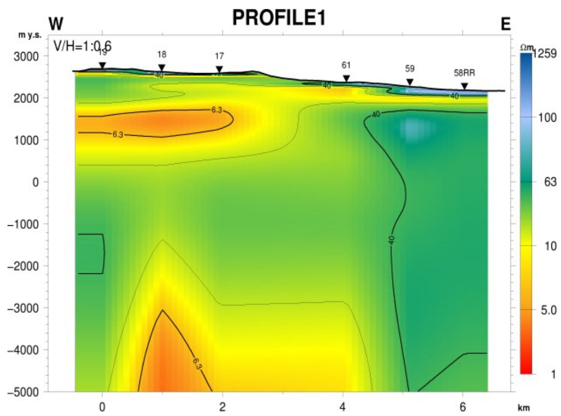

Figure 134: Resistivity cross-section in Eburru along profile 1 based on 1 D joint inversion of MT and TEM data

The second cross-section (Figure 15) is to the south of EW-4, 2 km south of profile 1 and cuts across five soundings and extends for 5 km. The resistivity distribution of the top layer varies from west to east with a medium resistivity of 10-30 Ωm seen near the surface beneath sounding number 90, 88R and 86 interpreted as near-surface alteration and a bit resistive layer of 100 Ωm beneath sounding 85 and 83 interpreted as unaltered formation near the surface. The low resistivity to the west continues downwards and is underlain by a bit resistive body of about 50Ωm at 900 m a.s.l to 2100 m b.s.l interpreted as chlorite epidote zone due to high temperature geothermal alteration. The Eastern part below sounding 85 and 83 possesses a very thin layer of low resistivity at about

2200 m a.s.l interpreted as due to sedimentary deposits and groundwater effect. It is then underlain by high resistivity down to depth beyond 10,000 m b.s.l interpreted as normal resistivity outside geothermal field hence the boundary of the resource area to the east.

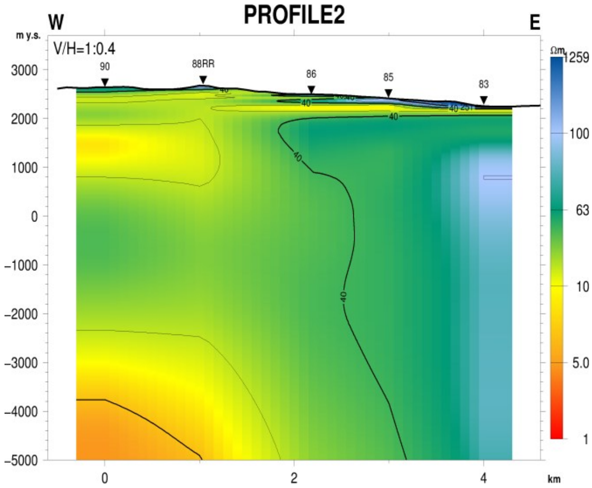

Figure 145: Resistivity cross-section in Eburru along profile 2 based on 1 D joint inversion of MT and TEM data

Profile 3 cross-section (Figure 16) dissects the area in west east direction cutting across six soundings in the northern part of the study area and close to EW-3. The resistivity pattern of the area indicates closeness to northern boundary of the geothermal field, low and high temperature alteration mineral are not as well evident in the western side of the cross-section as in profile 1. Eastern side possesses a normal resistivity outside geothermal field indicating the boundary.

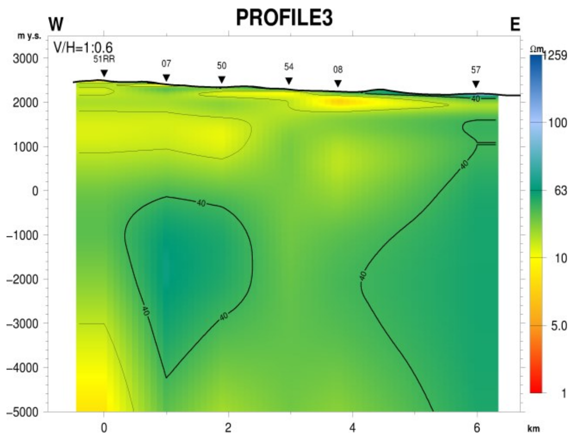

Figure 156: Resistivity cross-section in Eburru along profile 3 based on 1 D joint inversion of MT and TEM data

Profile 4 cross-section (Figure 17) cuts the area in north-south direction. It is about 6 km long and cuts across seven soundings. The resistivity pattern shows the northern boundary below sounding 115 and 113. Southern part has a thin layer of high resistivity near the surface indicative of unaltered minerals overlying a uniform fairly low resistivity of about 10 Ωm indicative of altered minerals due to steam condensate from a hot up flow from the underlying resistive layer interpreted as high temperature altered rock.

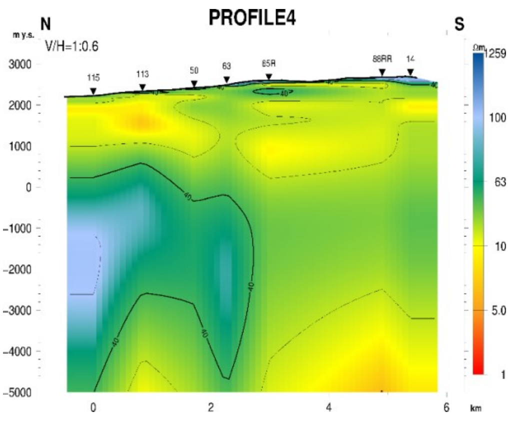

Figure 167: Resistivity cross-section in Eburru along profile 4 based on 1 D joint inversion of MT and TEM data

Cross-section along profile 8 (Figure 18) is about 4.5 km long. It cuts across four soundings in north-south direction and passes close to EW-1 and EW-6. The distribution of the resistivity in this cross-section clearly depicts resistivity of a high temperature field. At the top is a thin layer of high resistivity near-surface signifying the unaltered rocks overlying the low resistivity of about 10 Ωm interpreted as a result of geothermal manifestations like fumeroles and a pocket of low resistivity (< 5Ωm) below sounding 18 and 89R interpreted as smectite zeolite zone which could indicate low temperature alteration from a hot up flow condensate from underlying resistive layer interpreted as chlorite epidote zone associated with high temperature alteration minerals is in agreement with EW-1 temperature log. EW-4 temperature disagreement with geophysics resistivity is due to fossil effect in the reservoir towards southern boundary indicating cooling of the reservoir.

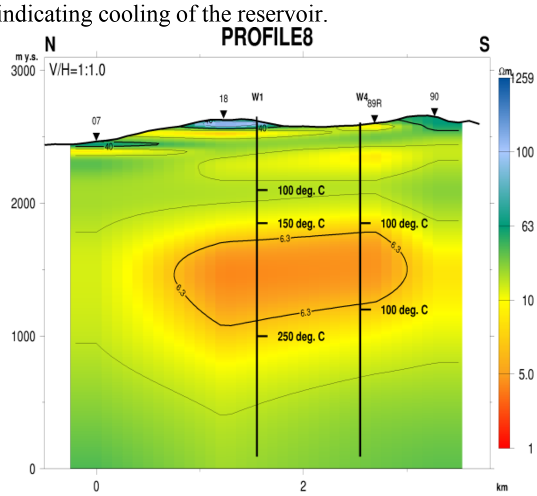

Figure 178: Resistivity cross-section in Eburru along profile 8 based on 1 D joint inversion of MT and TEM data

5.2 Iso-resistivity maps

Iso-resistivity maps were constructed from TEMMAP program (Eysteinsson, 1998) to display the resistivity at different depths in Eburru. Analysis of the conductance which is a product of the resistivity and thickness was also done.

Resistivity map at 2000 m a.s.l.(Figure 19) about 500m below the ground level shows a fairly uniform resistivity of about 10 Ωm. The fairly low resistivity can be interpreted as due to hydrothermal alteration fluid filled fractures rock associated with fumaroles. Low resistivity on the eastern, northern and northwestern boundaries are due to sediments and groundwater effect.

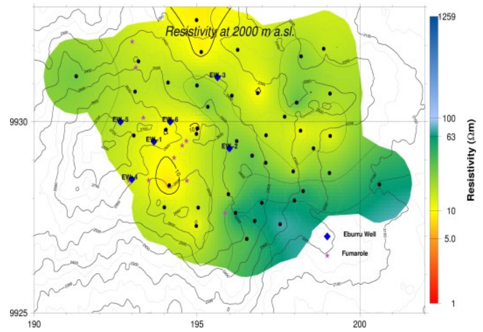

Figure 189: Resistivity Iso-map of Eburru geothermal field, black dots denotes MT soundings

Resistivity map at 1500 m a.s.l.(Figure 20) about 1500m below the ground level shows a fairly low resistivity (< 10Ωm) except for the eastern boundary. The fairly low resistivity is interpreted as low temperature alteration minerals like smectite, zeolites and also confirms the presence of geothermal fluid.

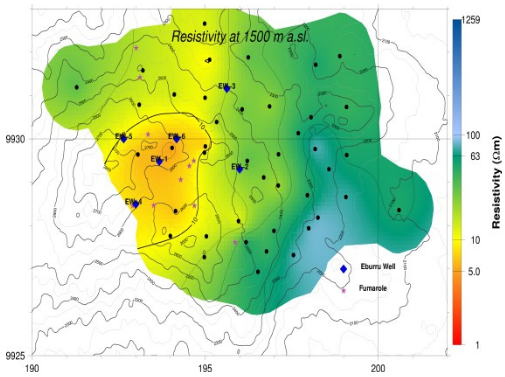

Figure 20: Resistivity Iso-map of Eburru geothermal field, black dots denotes MT soundings

Resistivity map at 500 m a.s.l.(Figure 21) about 2500 m below the ground level shows high resistivity defining the reservoir of Eburru. The high resistivity of over 40 Ωm at the central part is interpreted as high temperature alteration minerals chlorite and epidote. The southeastern, northeaster and northwestern very high resistivity of over100 Ωm defines areas outside the geothermal system.

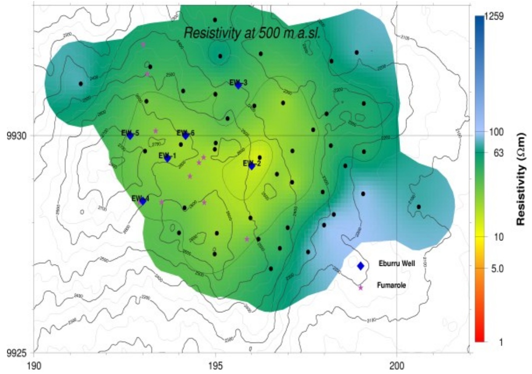

Figure 21: Resistivity Iso-map of Eburru geothermal field, black dots denotes MT soundings

Resistivity map at 1500 m b.s.l (Figure 22) about 4000 m below the ground level shows that low resistivity is spreading from south west which is interpreted to be connected to heat source of Eburru geothermal field. The high resistivity on the outer layer persists downward indication of the boundary and areas outside geothermal system.

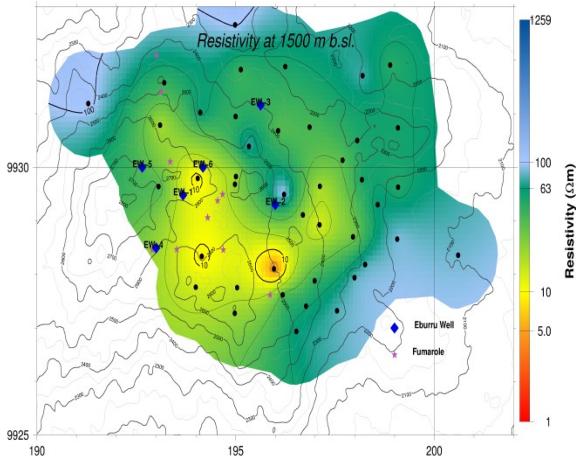

Figure 22: Resistivity Iso-map of Eburru geothermal field, black dots denotes MT soundings

As one can see from the resistivity map at 2500 m b.s.l(Figure 23) about 5000 m below the ground level, the central delineated low resistivity is associated with the heat source of Eburru geothermal field. The boundary of the resource is evident in the boundary between the low resistivity and high resistivity with the outside very high resistivity defining areas outside the geothermal system.

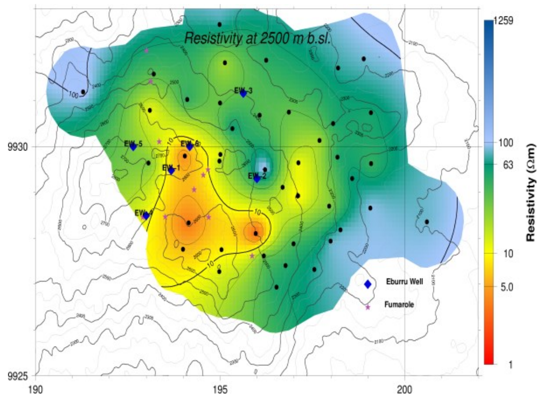

Figure 23: Resistivity Iso-map of Eburru geothermal field, black dots denotes MT soundings

In the resistivity map at 10,000 m b.s.l. (Figure 24) about 12,500 m below the ground level, there is no much change as compared to Figure 23 except for the persistent decrease of resistivity at south-western side of the centre, which is an indication of increase in conductor downwards towards the suspected deep seated heat source(magma chamber) within the volcano. Three wells drilled close to the heat source discharged (EW-1 EW-6 and EW-4) and the remaining three wells drilled outside the heat source did not discharge, indicating the importance of geophysical survey before exploration drilling.

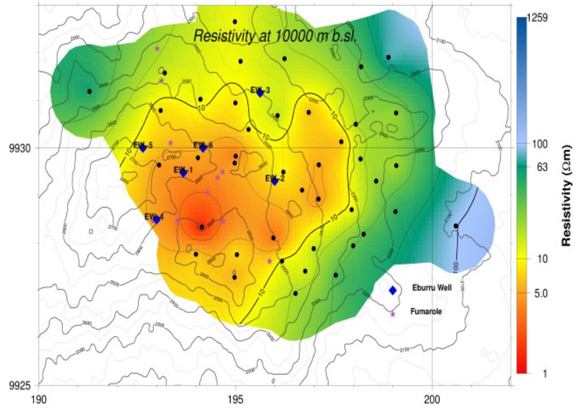

Figure 24: Resistivity Iso-map of Eburru geothermal field, black dots denotes MT soundings

6 CONCLUSIONS AND RECOMMENDATIONS

With Eburru integrated data interpretation from 1D joint inversion of MT and TEM, the following resistivity layers were observed in cross-sections and Iso-maps:

(1) A very thin layer of high near-surface resistivity (> 63Ωm) covering almost the entire area is interpreted as unaltered formations and superficial deposits.

(2) It is followed by a uniform near-surface low resistivity layer (< 10 Ωm) resulting from geothermal manifestations like fumeroles.

(3) A second layer of low resistivity (< 10 Ωm) is evident in the central, southwestern and part associated with smectite and zeolite formed as a result of hydrothermal alteration.

(4) It is followed by a low conductive layer (> 63Ωm) at about 2500 m b.g.l associated by resistive high temperature alteration minerals like epidote and chlorite which define the geothermal system of Eburru.

(5) A good conductor (< 10Ωm) indicating the heat source of Eburru geothermal field is very evident in south west towards the centre.

The interpreted data are clearly delineating Eburru geothermal resource boundary except to the southwest where the resource seems to be close to the surface. It is therefore recommended that more MT and TEM data should be collected towards the western and the southwest of the study area to be able to delineate the exact boundary of the resource field.

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