INVESTIGATION OF GEOLOGICAL STRUCTURES USING ELECTROMAGNETIC DOWN-HOLE TEMPERATURE AND WELL LOGS ON PETREL PLATFORM: CASE STUDY OF EBURRU GEOTHERMAL FIELD

Ammon O. Omiti
Kenya Electricity Generation
P.o. Box 785 – 20117
Naivasha - Kenya
aomiti@kengen.co.ke

ABSTRACT

The objectives of this project was to correlate geological, electromagnetic, down-hole well log temperature, geological and well log information to indirectly image the permeable geothermal reservoir geometry and provide enough information for well siting. This confirmed that reservoir interpretation based on correlating magnetotelluric resistivity, inferred alteration and temperature was possible. The magnetotelluric resistivity maps and cross-sections extended these correlations to undrilled areas, revealing the likely geometry of the geothermal system. Conceptual models based on the resistivity images indicated that major northeast trending structures and confirmed by available well data information. The resistivity data interpretation reveals the heat source location and the major boundaries in Eburru geothermal field, it illustrates areas of target but can be reviewed with respect to engineering and environmental issues. By more efficiently directing well targeting, magnetotelluric resistivity imaging can reduce heating unsuccessful wells which intern can save on cost.

1. INTRODUCTION

1.1 GEOLOGICAL SETTING

Eburru geothermal field lies within 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).The Great Africa Rift system 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 under east Africa creating three arms 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 eruptions often forming caldera as seen in Eburru and lava flow covering large areas with some exposed on the rift valley flanks. The East Africa Rift (EAR) is largely following the ancient continental plates that collided to form African Craton billions of years ago.

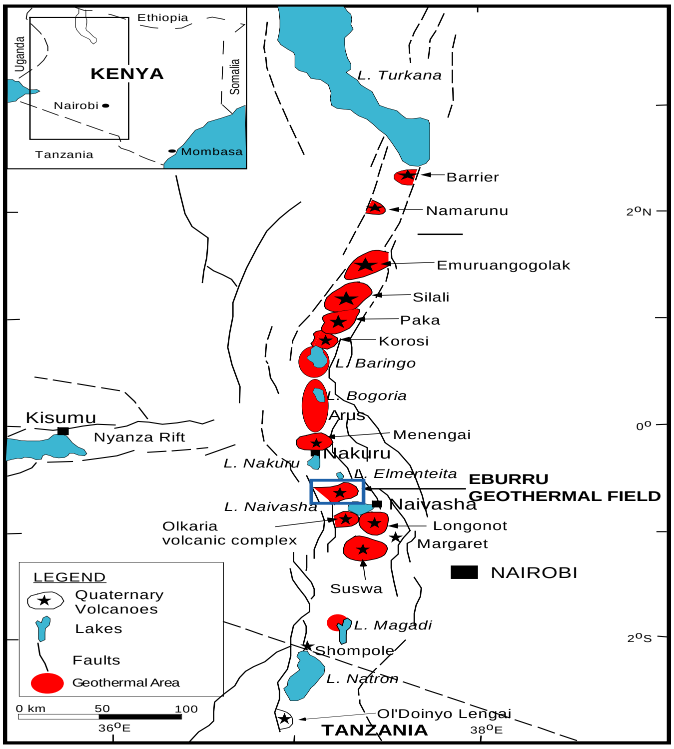

Figure 1: Map showing the loation of Eburru geothermal field in Kenya rift system

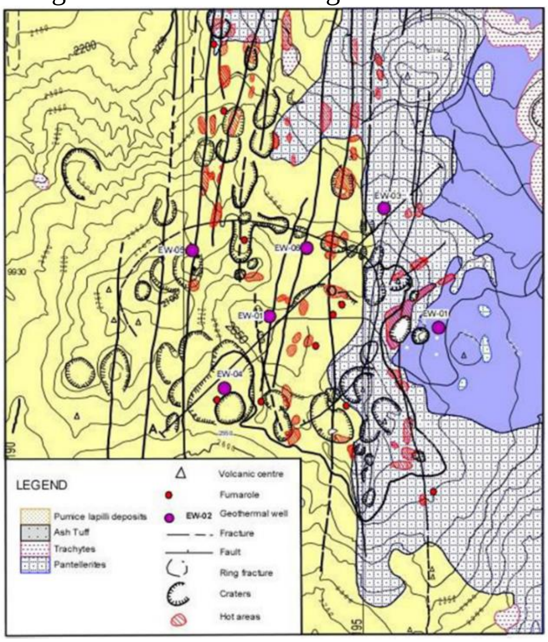

Figure 2: Eburru geological map with structures (Omenda and Karingithi, 1993)

1.2 PURPOSE OF STUDY

This project is aimed at investigation of geological Structures of Eburru geothermal field using Electromagnetic and Gravity Methods on Petrel Platform

1.3 SPECIFIC OBJECTIVES

i. Analyze and interpret all available geophysical and geological data and incorporate this data into a unified conceptual model to identify Geological structures of Eburru and Badlands area.

ii. Interpret resource geometry and average permeability patterns from correlations of the resistivity patterns with existing well data and extend these to exploration and development targets.
iii. Identify the most likely conceptual model for the Eburru and Badlands Geothermal Resource Area.

1.4 BENEFITS OF THIS RESEARCH

Improved well targeting leads to fewer wells being drilled, fewer well pads and reduced surface disturbance, as well as reduced costs in future exploration and development in Eburru geothermal field. Permitting costs and times are likely to be reduced in the area. Additionally, a fuller appreciation of the likely geometry of the resource will foster improved long-term land use planning. The advances in technique and knowledge and the experience gained in this project and the demonstration of non-invasive surface geophysical surveys in a sensitive environment are likely to benefit exploration in Eburru geothermal areas. The availability of a public domain data set in industry standard format with well data to provide explicit constraints will provide a basis for researchers to improve the MT imaging of geothermal reservoirs. The direct comparisons of borehole geological data and MT resistivity data performed (as a key component of this project) provided important confirmation of the geological interpretation of geothermal resistivity data at Eburru field, and is transferable on a conceptual basis for improving interpretations of resistivity data at other geothermal fields in Kenya. Lastly, the expansion of Eburru geothermal field resource area are expected to benefit Nakuru County and Kenya as a whole by creating jobs, creating several million dollars in annual property tax revenue, and providing new renewable energy that can help the country meet its vision 2030.

1.5 BACKGROUND INFORMATION

Various geothermal surface manifestations such as fumaroles, geysers, hot grounds and hot springs are eminent along the Kenyan rift. The rift, extending from Lake Turkana to Lake Natron in northern Tanzania, is a part of The East African rift valley system that runs from the Afar Triple Junction at the Gulf of Eden in the north to Mozambique in the south. It is part of incipient continental diverging zone, a zone where thinning of the crust is occurring and hence eruptions of lavas and associated volcanic activities (Lagat, 2003). More than twelve major geothermal prospects have been identified in the Kenyan rift.

Eburru is located north of the Greater Olkaria geothermal field. The two fields are about 40km apart. Surface manifestations evident in the field include fumaroles, hot and thermally altered grounds. Deep drilling of six wells to an average depth of 2500 m was done between 1989 and 1991. Of the six wells drilled, only EW-01, EW-04 and EW-06 were productive, with an estimated capacity of 2.4 MWe, 1.0 MWe and 2.9 MWt respectively, while the rest of the wells could not discharge (Lagat, 2003). The Eburru geothermal power plant, utilizing steam from well EW-01, has been generating 2.5 MWe since 2012 when the plant was commissioned. There are plans by KenGen to drill and develop the field further.

1.6 LITERATURE REVIEW

According to Williams (1972), Baker and Wohlenberg (1971) (Clarke et al, 1990) and Baker et al. (1971), the geological and structural setting of the Kenyan rift is controlled by the Great Africa Rift System (GARS). Eburru-Badlands is located on the eastern arm of the East Africa Rift System (EARS) stretching though Eritrea, Ethiopia, Kenya and all the way down to Mozambique, the information revealed is about the surface geology but there is a knowledge gap on the subsurface structures and possibly the directions.

Early studies conducted in Eburru-Badlands geothermal field by Omenda and Karingithi (1993) established that Eburru volcano consists of east and west volcanic centres which are composed of pyroclastics, rhyolites, basalts, trachytes, tuffs and pumice with a distinct form of tectonics central rift, the south and north with the rift forming faults trending NNW-SSE while the southern and northern segments trend NE-SW. They further proposed that rift floor faults in the central sector, some of which cut through Eburru, trend in a N-S and NNE-SSW direction. Omenda and Karingithi (1993) suggested that the two volcanic centres are arranged in an E-W trend and extend to the west of the Mau escarpment. This study also reveals very important information on the surface geology of Eburru but the subsurface structures were not properly addressed.

2. TIME DOMAIN TRANSIENT EECTROMAGNETICS

2.1 THEORY

In the TEM method, a time varying magnetic field is generated by a controlled artificial source. In this method, a loop of wire is placed on the ground and a constant current is built up in it. The current is turned on and off at predetermined times. When the current is turned off, it causes sudden change in magnetic field which further causes current to flow in the earth. This current creates an image of the loops for a short time. Since there is no source to support the induced current it dies out generating a new time varying secondary magnetic field that consequently induces a new current in the ground. This current density diffuses downwards and outwards into the earth. The rate of magnetic field decay is measured at the centre of the loop by a receiver coil. The current distribution and the decay rate of the secondary magnetic field depend on the resistivity structure of the earth with the decay being more gradual over a more conductive earth (Árnason, 1989).

TDEM system from Zonge Engineering (USA) that is comprised of a transmitter, 24 bit multifunction receiver, voltage regulator, 1.0mm^2 transmitter cable and a receiver coil with a dipole moment of about10000Am^2 was used. In the field setup, a central loop configuration of either a 300 x 300 or a 200x200 transmitter loop was used to transmit the half duty current wave at 16hz and 4Hz depending on the available space. In both cases the transient signal (induced voltage) in the receiver coil at the centre of the loop is measured at several points, or logarithmically spaced- sampling time gates, which are defined relative to the zero time when the current becomes zero (end of TOFF)

The raw TEM data was processed by the program TemxZ for Zonge data (Árnason, 2006). This program averages data acquired at same frequency and calculates late time apparent resistivity as a function of time after turn-off. It also enables visual editing of raw data to remove outliers and unreliable data points before the data can be used for interpretation. 1-D inversion of TEM was achieved by TEMTD software, an inversion algorithm that creates a 1-D horizontal layered earth model that best fits the data (Árnason, 2006a). The best fit is achieved when the misfit function (chi2) which is the mean-square difference between measured and calculated values is the lowest.

The method of Occam inversion that uses a number of layers each of equal thickness (on a logarithmic scale) and only varies the value of resistivity in each layer was chosen as it was the most consistent through a variety of inversion attempts. The forward algorithm calculates the induced transient voltages in the receiver as the sum of the responses from successive current turn-on and turn-off times. The transient responses are calculated both as induced voltages and late time apparent resistivity as a function of time. This program employs the nonlinear least-squares inversion of the Levenberg-Marquardt type as described by (Árnason, 1989).

In 1-D inversion, it is assumed that the earth consists of horizontal layers with different resistivity and thickness and therefore it searches for conductivities of the layers as well as finding the optimal thickness of each layer as well as seeking to determine the layered model whose response best fits the measured responses. As a rule of thumb, interpretation of the TDEM resistivity is based on the fact that the depth of investigation of the TDEM soundings is dependent on the transmission frequency and the resistivity of earth where greater penetration depths are achieved with low frequencies in resistive earth.

3. MAGNETOTELLURIC DATA PROCESSING

3.1 THEORY

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 4).

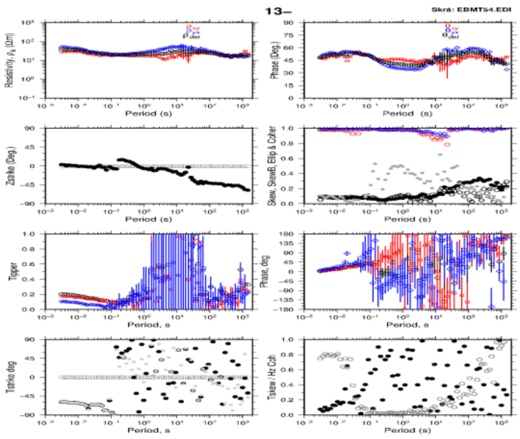

Figure 3: MT parameters as extracted from EDI file (Apparent resistivity, phase in xy, yx direction and the determinant, electrical strike direction Zstrike, coherence, skew, Tipper, tipper phase, Tstrike and Tskew

3.1.1 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 (Figure 4). 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. 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.

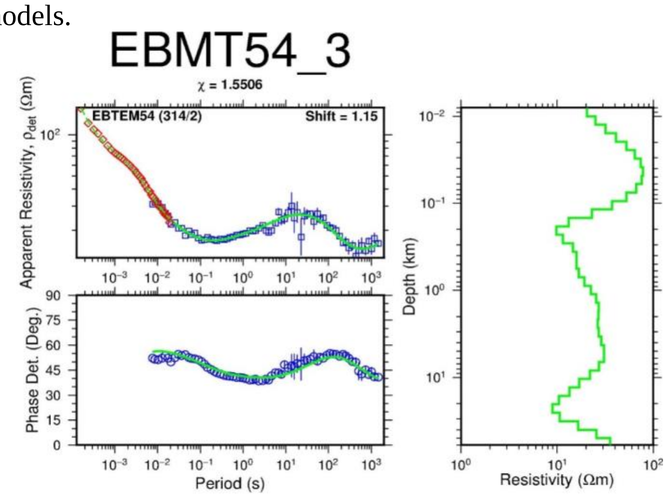

Figure 4: 1D Joint inversion of MT and TEM soundings; red and blue symbols on the top left represent the apparent resistivity from TEM and MT soundings respectively; the bottom panel shows,

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.

3.2 MT FIELD INSTRUMENTATION AND DATA COLLECTION

The resistivity survey carried out in Eburru geothermal area included 100 MT soundings with a maximum spacing of about 1 km but most of the station spaced in less than 0.5 km (see Figure 5). All the 100 soundings are considered in this study for proper and thorough understanding of the deep subsurface resistivity structures and delineation of geothermal area of interest. The data collection was performed using 5-channel MT data acquisition (MTU-5A) from Phoenix Ltd in Canada. It has the capacity of measuring the MT signals in the frequency range up to 400 Hz and down to 0.0000129 Hz (Phoenix Geophysics, 2009).The field work was conducted by KenGen employees under the supervision of KenGen geophysicists.

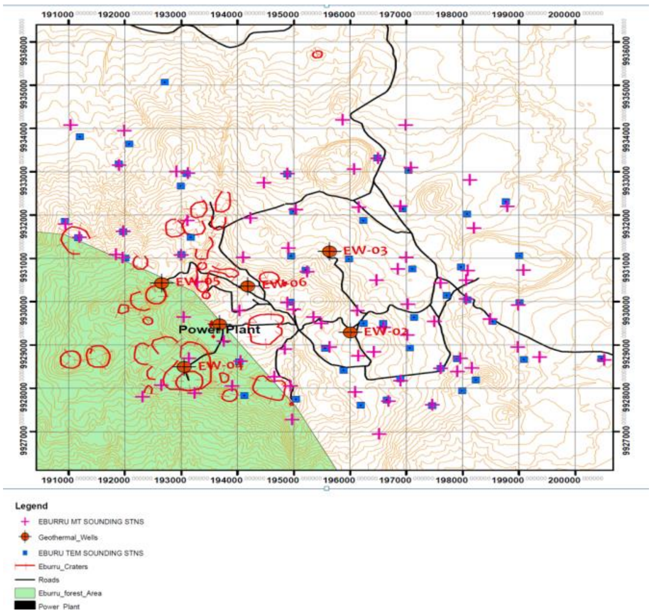

Figure 5: Location map of the Eburru geothermal field showing MT and TEM soundings

4. PETREL PLATFORM

Compilation of already processed data and information is a key to developing a conceptual model. Data considered for compilation included: 1D Geophysical, geological well logs, down-hole temperature and gravity other related information with particular emphasis information on fractures, faults, general tectonic setting, aerial photos and other remote sensing data, borehole information including location, total drilled depth, casing depth, liner information and casing and well diameters. The analysed and compiled data was then presented using Petrel programme, a Schlumberger software platform that provides an integrated solution from exploration to production. It allows the user to interpret Geology, Geophysics, Geochemistry and Reservoir data, perform well correlation, build subsurface models suitable for simulation, submit and visualize simulation results, calculate volumes, produce maps and design development strategies to maximize reservoir exploitation. It addresses the need for a single application able to support the workflow, reducing the need for a multitude of highly specialized tools. By bringing the whole workflow into a single application risk and uncertainty can be assessed throughout the life of the reservoir.

5. RESULTS

5.1 Cross-sections

Resistivity cross-sections are plotted for results obtained from 1-D inversion by petrel program, developed by Schlumberger (https://www.software.slb.com/products/petrel). The program calculates the best line between selected soundings on a profile, and plots resistivity iso-lines based on the 1-D model for each sounding. It is actually the logarithm of the resistivity that is contoured so that the color scale is exponential and numbers at contour lines are the actual resistivity values. Several cross-sections were made through the survey area and are presented below.

The comparison between the geological well log (Figure 6), 1D model resistivity, down-hole temperature and pressure from OW-1 reveals a lot of information structurally. The geology of OW-1 from the well logs indicates the presence of Pyroclastic rocks to a depth of about 600 m below ground level which is underlain by a thin layer of trachyte. The trachyte is again underlain by this layer of pyroclast believed to be tuffs which forms the cap rock of the reservoir. The well experienced loss of circulation of about 650 m thickness believed to be due to lose formation possibly the feed zone. This zone is underlain by fractured rhyolite alternating with trachytes and some basaltic intercalation forming reservoir rocks. The temperature log shows cold inflow at depth but the temperatures are above 260°C considered to be high temperature zone.

The resistivity profile trend in the WE (Figure 6) direction and shows the variation of conductivity from West to East at different depths above sea level as shown in Figure 20. The resistivity structures generally show a four-layer high-low-high-low resistivity trend. The topmost >100Ωm resistivity layer coincides with the unaltered formation and the superficial deposit on the surface. Beneath this thin high resistivity layer is a thick layer of a very conductive >6 Ωm making a dome-like layer west of OW-1 that extends up to 1600 m.a.s.l to the west but deeper to the East but disappears to the far east. This layer is presumed to be dominated by low temperature conductive alteration minerals such as smectites and zeolites that defines the clay cap and it is less than 1 km thick. Beneath the base of this conductor is a resistive >15-50 Ωm which is thought to be associated with the high temperature secondary minerals such as epidote, chlorite and biotite present in the reservoir. Beneath the resistive layer is another low conductive layer extending to about 6,000 m bsl and could be associated with the heat source.

The very steep increase in temperature from less than 40°C at 100 m depth to over 177°C at 450 m depth implies that this interval has very low permeability. This also correlates with the highest relative values of smectite in the argillic alteration zone and the underlying transition from smectite to higher temperature minerals. The smectite component of the mixed layer smectite-illite clay characteristic of the transition zone is seldom detected using XRD. As expected, smectite rapidly decreases in the transition zone, as temperature rises above 180°C and smectite is progressively converted to illite. The propylitic alteration zone that typically corresponds to the top of the geothermal reservoir is encountered at the interpreted maximum temperature of 238°C at 1000 m depth. The comparison of the above results of OW-1 indicates that hot inflow is between 1200 -1700 m bgl, this information is confirming that the loose of circulation zone in geology is the hot recharge zone (Figure 7).

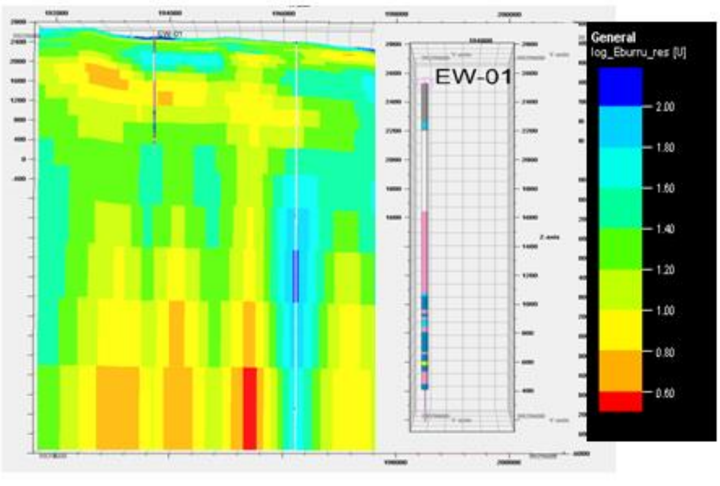

Figure 6: EW Profile crossing EW-1

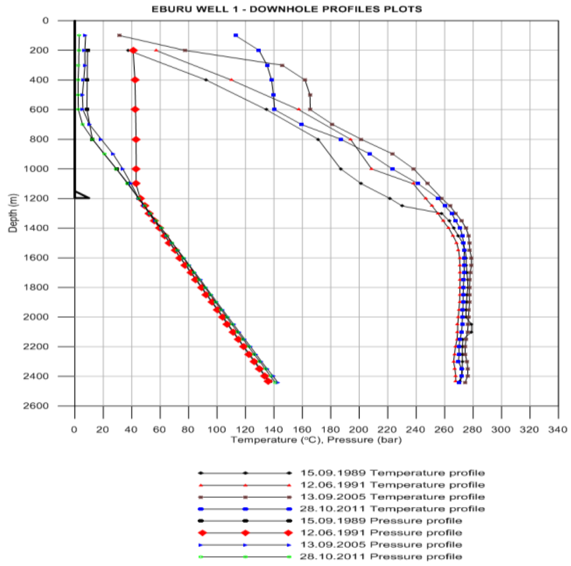

Figure 7: Down-hole Temperature and pressure profiles for EW-1

The geology of EW-2 is different with geology of EW-1 near surface. The well logs indicate the presence of tuffs alternating with rhyolite and trachyte on the entire well profile. There is no circulation loss recorded in EW-2 well log (Figure 8).

Down-hole temperature profile movement resembles EW-1 but the temperatures recorded are low as compared to EW-1. The maximum temperature recorded according to data collected in 2005 is 140 °C which is way far below what was collected in EW-1. The profile indicates a hot inflow between 800 m bsl to 1200 m bsl (Figure 9). The resistivity data indicates the presence of high temperature geothermal field with high-low-high-low resistivity profile. There is an indication from the profile that the heat source is to the western side of EW-2. Far East seems to posse's resistivity outside a geothermal system (Figure 8).

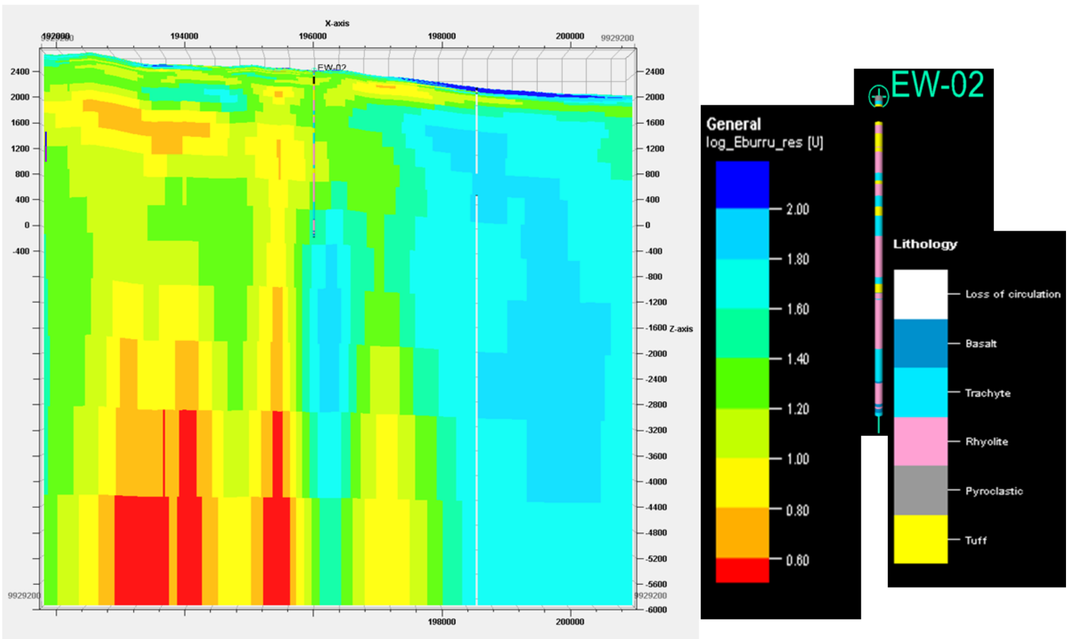

Figure 8: W-E Profile crossing EW-2

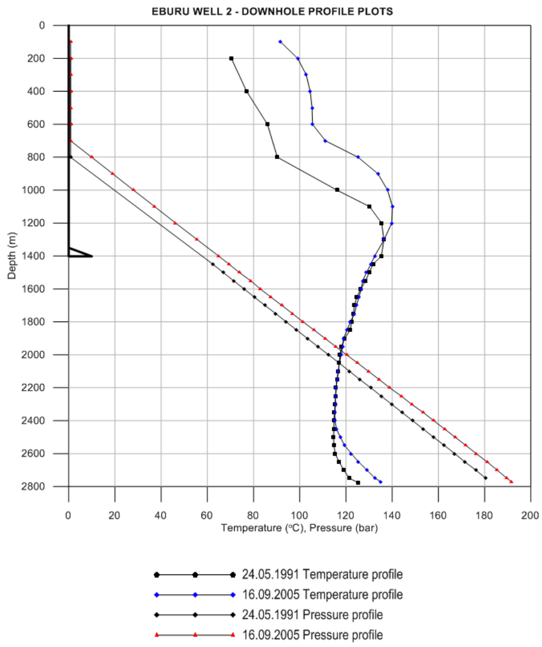

Figure 9: Down-hole Temperature and pressure profiles for EW-2

The geological information of EW-3 is very scarce and the available information can only be used for the interpretation of up-to 1400 m asl (Figure 10). Pyroclasts covers near surface for about 300 m bgl with a thin layer of rhyolite in between. It is underlain by trachytes and tuffs alternating to about 1400 m asl. The geological log information to the bottom of the well is not available. Temperature profile indicates hot fluid inflow between 600 m bgl to 1000m bgl. A temperature of up-to 162 ^{o}C was recorded. The well discharged but could not be used for generation but it is can still be used under direct use of geothermal system. The hot fluids were encountered in trachytes alternating with tuff formation. Below this layer is a cold inflow area with fluids of less than 100 ^{o}C are encountered since not suitable for high temperature gothermal production (Figure 11).

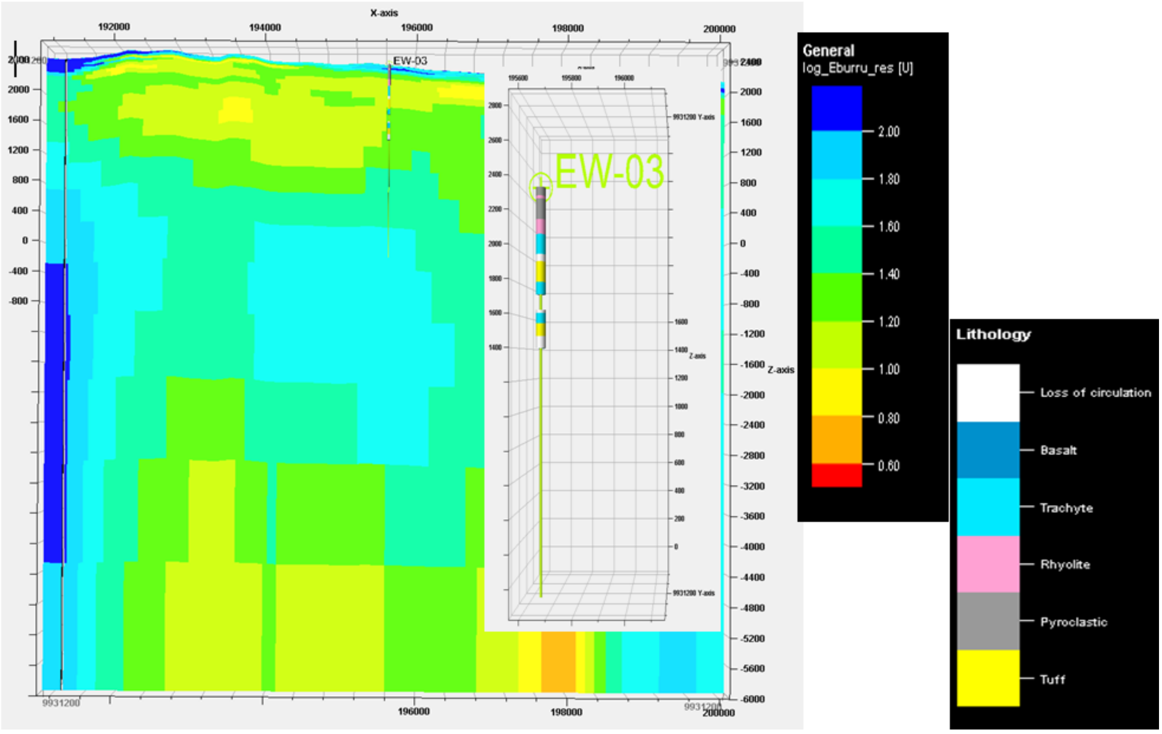

Figure 10: W-E Profile crossing EW-3

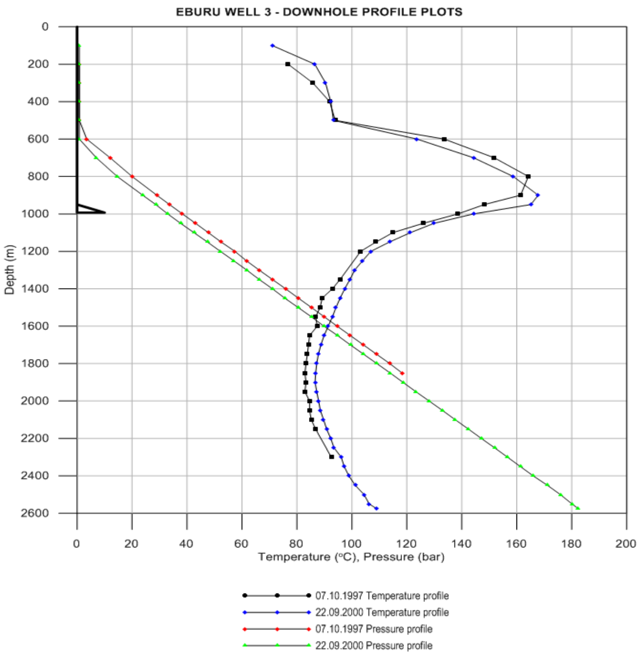

Figure 11: Down-hole Temperature and pressure profiles for EW-3

5.2 Iso-resistivity maps

Iso-resistivity maps are made by the same petrel program which generates iso-resistivity maps at fixed elevations derived from the 1-D Occam models (Eysteinsson,1998). The resistivity is contoured and colored in a logarithmic scale. The general elevation of the area is about 2400 a.s.l. In the following section, Iso-resistivity maps are presented from 200 m a.s.l down to 6000 m b.s.l. The maps show that resistivity varies considerably both laterally and with depth.

Conductance at 1200 m asl

In studies of high temperature geothermal fields, maps of conductance are often used as a surrogate estimate of total hydrothermal smectite clay content over a particular depth interval. Maps of conductance are particularly useful for mapping the results from 1D layered resistivity inversions. Because conductance maps illustrate an average over a depth interval, they are less prone to distortion. The type of 1D MT inversion presented in this report is inherently smooth and experience shows that realistic resistivity slices can be made through the model at a particular elevation, the 1D MT conductance at 1200 m asl in Figure 35 is provided as a direct comparison to the alteration geology. Also, it is inherent to all MT and TEM inversions that the total conductance of a very conductive layer is better resolved than its thickness or its conductivity, so this is the most reliable parameter to display in a map. The conductive minerals encountered are interpreted to be due to the presence of low temperature alteration minerals like smectite (Figure 12).

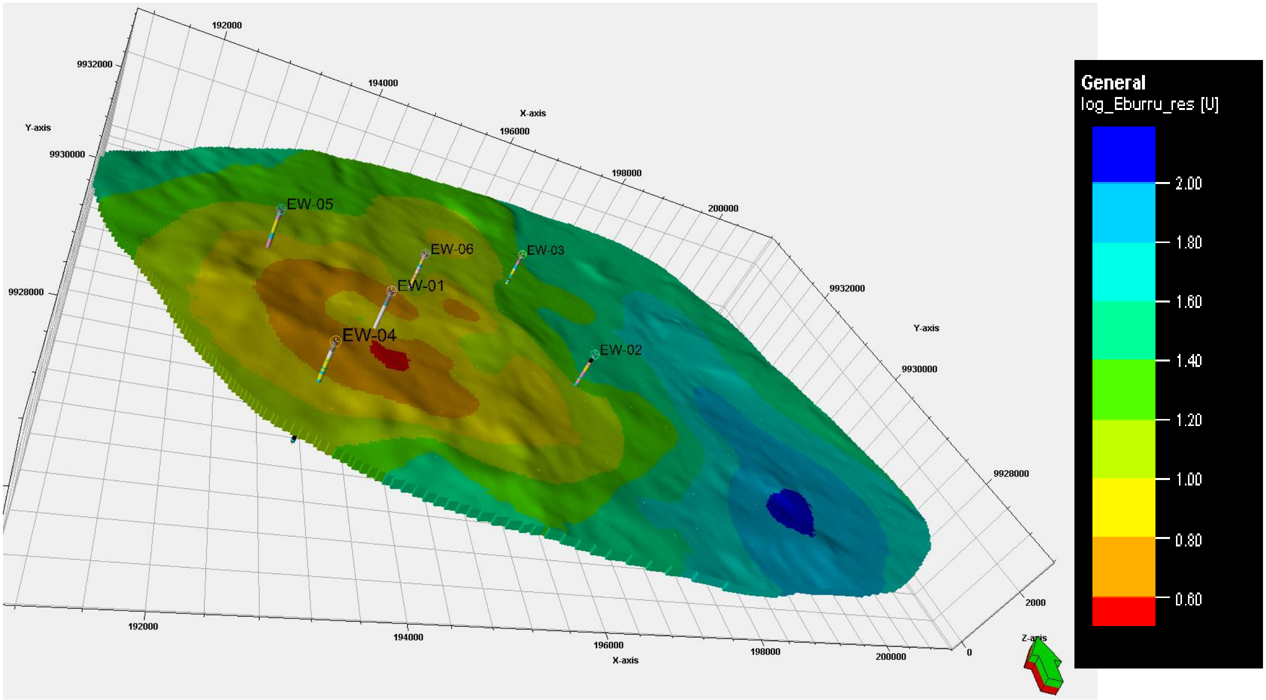

Figure 12: MT Resistivity Iso-map at 1200 m asl from 1D Inversion Interpreted Jointly with Eburru Wells

The Iso-map below dissects the resistivity model at 0 m asl about 2200 m depth. This is considered as the main reservoir where high temperature minerals were encountered. The resistive formation is not showing a definite structure as compared to conductive minerals (Figure 13).

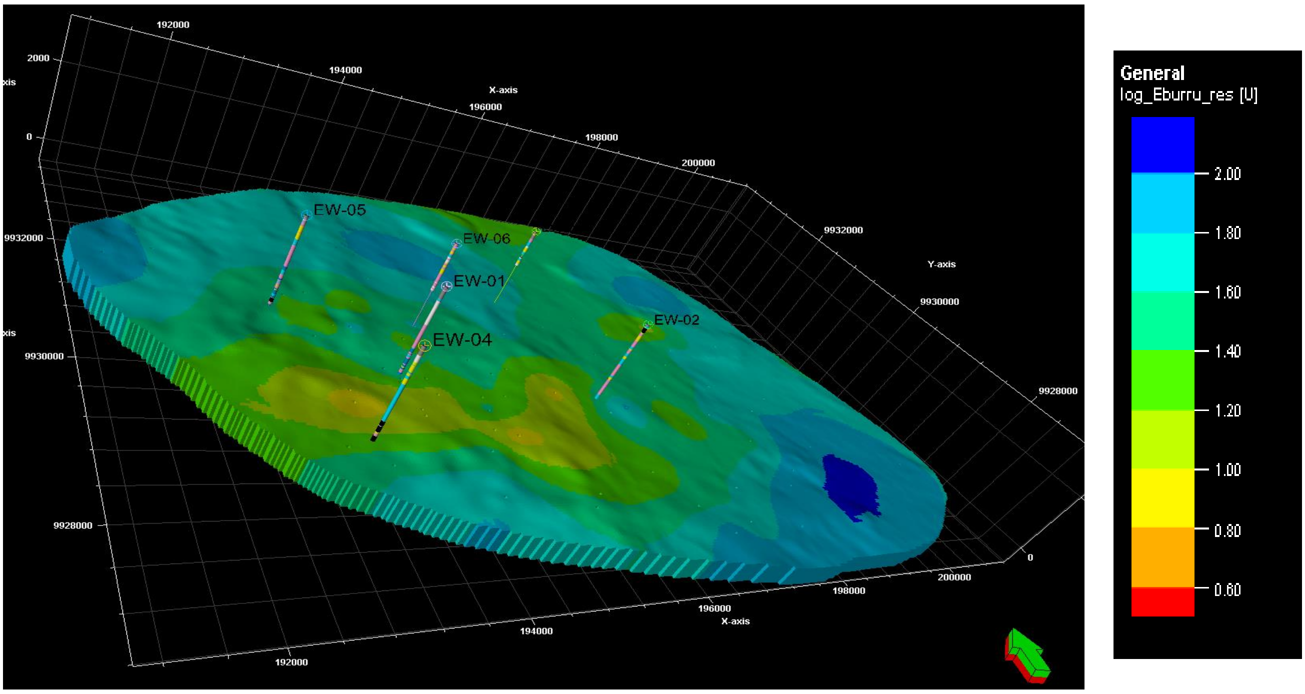

Figure 13: MT Resistivity Iso-map at 0 m asl from 1D Inversion Interpreted Jointly with Eburru Wells

The Iso-map cutting the resistivity model of Eburru at 2300 m bsl is showing the location of Eburru heat source and it's very evident that EW-4, EW-1 and EW-06 are located close to the heat source. EW-3 and EW-5 were drilled away from the heat source (Figure 14).

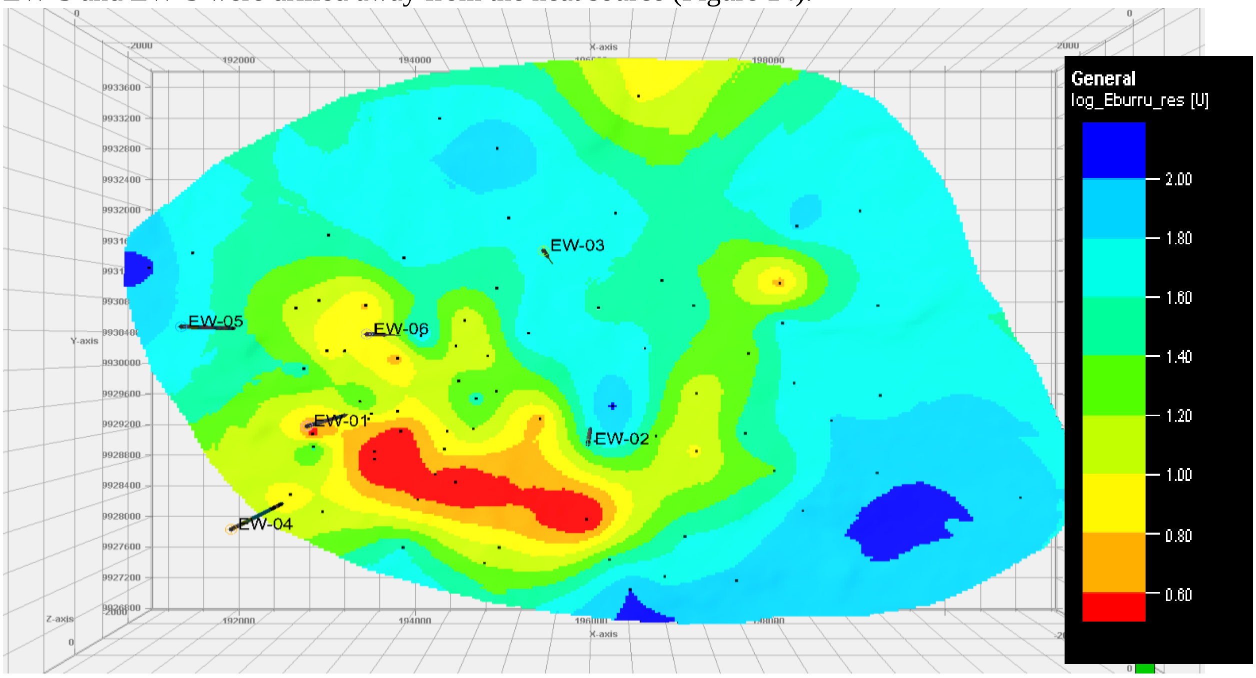

Figure 14: MT Resistivity Iso-map at 2000 m bsl from 1D Inversion Interpreted Jointly with

6. CONCLUSION AND RECOMMENDATION

The 1D MT inversions produced resistivity images that matched the intensity and geometry of the temperature-sensitive smectite clay alteration in the wells. A borehole log from all the wells provided a direct confirmation of the MT resistivity imaging. Three conceptual cross-sections including resistivity and interpreted temperature extend the conceptual interpretation through the survey area.

Although this study concludes that the lowest risk drilling targets are south east of EW-1 area, further work can be done at relatively low cost to refine the targeting and better constrain the relative risks between this area and the other drilling target areas. The well should target not less than 3000 m depth.

The main strategy for targeting wells at Eburru should be targeting the highest temperature upflow zone south east of EW-1 and considering the areas with evident heat source beneath. The relative risks of these targets can be constrained by geological analyses of alteration and other parameters that would promote conceptual comparisons to other geothermal. Further interpretation by reservoir engineering analysis that considers the MT results with respect to the well test data could further characterize the relative economics of the targeting strategies in Eburru geothermal field.

REFERENCES
Árnason, K., 1989: Central-loop transient electromagnetic sounding over a horizontally layered earth. Orkustofnun, Reykjavík, report OS-
89032/JHD-06, 129 pp.

Árnason, K., 2006. TEMTD, a programme for 1-D inversion of central-loop TEM and MT data. Short manual. Iceland GeoSurvey - ISOR,
internal report, 17 pp.

Árnason, K., 2006a: TemXshort manual. ÍSOR – Iceland GeoSurvey, Reykjavík, internal report, 17 pp.

Árnason, K., 2006b: TEMTD, a programme for 1D inversion of central-loop TEM and MT data. Short manual. ÍSOR – Iceland GeoSurvey, Reykjavík, internal report, 17 pp.

Baker, B. H. and Wohlenberg, J. 1971. Structure and evolution of the Kenya rift valley. Nature 229, 538-542

Baker, H. H., Willtams, L. A. J., Miller, J. A. and Fetch, F. J. 1971 Sequence and geochronology of the Kenya rift volcanics. Tectonophysics 11, 191-215.

Clarke, M.C.G., Woodhall, D.G., Allen, D., and Darling G., 1990: Geological, volcanological and hydrogeological controls on the occurrence of geothermal activity in the area surrounding Lake Naivasha, Kenya, with coloured 1:100 000 geological maps. Ministry of Energy, Nairobi, 138 pp.

Omenda, P.A., and Karingithi, C.W., 1993: Hydrothermal model of Eburru geothermal field, Kenya. Geoth. Res. Council, Trans., 17, 155-160.

Eysteinsson, H., 1998: TEMMAP and TEMCROSS plotting programs. Iceland GeoSurvey - ÍSOR, Unpublished programs and manuals.

Lagat, J.K., 2003: Geology, hydrothermal alteration and fluid inclusion studies of the Olkaria Domes geothermal field, Kenya. University of Iceland, MSc thesis, UNU-GTP, Iceland, report 2, 71 pp.

Velador, J.M., Omenda, P.A and Anthony, E.Y., 2003: An integrated mapping and remote sensing investigation of the structural control for the fumarole location in the Eburru volcanic complex.

Williams, L. A. J., 1972; The Kenya rift volcanics: a note on volumes and chemical composition. Tectonophysics 15, 83-96.