

Three Dimensional Inversions of MT Resistivity Data to Image Geothermal Systems: Case Study, Korosi Geothermal Prospect

Mathew Arthur

Geothermal Development Company,

P. O. Box 17700, Nakuru, Kenya.

marthur@gdc.co.ke

muthurimathew@gmail.com

ABSTRACT

In real situation the physical Earth is in three Dimensions (3-D), a 2-D and 1-D Earth models may not therefore explicitly explain or represent the 3-D Earth in all situations. This is a simple and obvious reason why one needs a higher dimensional interpretation of MT resistivity data in modelling geothermal reservoirs. 2-D MT interpretation is commonly applied in geothermal exploration and in many cases has successfully provided accurate information of geothermal reservoirs. However, due to complex geological environments, 2-D interpretation sometimes fails to produce realistic models, especially for deeper parts of reservoir. It is also the case in other natural resource exploration and geo-scientific research, such as oil exploration or underground water resources, volcano logical studies etc. In this regard, 3-D interpretation techniques are now in high demanded for understanding of true resistivity structures in various geological applications.

This paper describes (3-D) magneto telluric (MT) inversion for 147 MT data sets obtained from Korosi geothermal prospect. The inversion scheme was based on the linearized least-squares method with smoothness regularization. Forward modeling was done by the finite difference method, and the sensitivity matrix was calculated using the adjoint equation method in each iteration.

The research has proved the practicality of 3D inversion with real field data to recover deeper resistivity structures in Korosi prospect. The results infer two geothermal reservoirs below Korosi - Chepchuk massif.

A close correlation between major surface structures, fumaroles, and the 3D model is observed. Consequently, the extent of geothermal resource at Korosi - Chepchok prospect, the depth of the inferred geothermal reservoirs and possible recharge zones for the system have been inferred.

INTRODUCTION

The MT method is now widely applied to natural resource exploration including geothermal. The resistivity structure of a geothermal reservoir is often characterized by a combination of a low-resistivity clay-rich cap layer on top and a domed relatively high resistivity reservoir zone beneath. This resistivity structure is usually applicable when clay minerals are the dominant hydrothermal alteration product in a geothermal field (e.g. Arnason and Flovenz, 1992; Uchida and Mitsuhata, 1995).

2D inversion has been the standard technique for MT data interpretation in the past decade. It has provided detailed resistivity models in many geothermal fields and has contributed to understanding the resistivity features of geothermal reservoirs. However, because of complicated geological environments, which we often encounter in geothermal fields, 2D interpretation sometimes fails to produce realistic models.

TE-mode data are more sensitive to a deep conductive anomaly in a 2D situation than TM-mode data. However, unless the subsurface structure is almost 2D, we usually cannot achieve a good fit for TE-mode data by a 2D inversion. On the other hand, fitting of TM-mode data in a 2D inversion can be more easily achieved even for a 3D structure. This is why we often utilize only TM-mode data for 2D inversion in geothermal exploration. However, even if the misfit of the TM-mode data is small, the recovered 2D model may be unrealistic or contain false anomalies. In particular, the resistivity distribution in deeper parts of the reservoir is often ambiguous. This situation illustrates the limitation of the 2D MT interpretation in geothermal exploration (Uchinda and Sasaki 2006).

The original Occam's inversion was introduced by Constable et al. (1987) for 1-D MT data. It was later expanded to 2-D MT data by deGroot-Hedlin and Constable (1990). Occam's inversion is stable and converges to the desired misfit in relatively small number of iterations compared to most other methods. They both are based on the model space method. Computational costs associated with construction and inversion of model-space matrices make a model-space Occam approach to 3D MT inversion impractical because all computations depend on the size of model parameter, M (Siripunvaraporn Weerachai, 2006).

These difficulties can be overcome with a data-space approach, where matrix dimensions depend on the size of the data set N , rather than the number of model parameters M . Generally, $N \ll M$ for MT data. As discussed in Siripunvaraporn and Egbert (2000), the transformation of the inverse problem to the data space can significantly improve the computational efficiency for the 2-D MT problem. The WSINV3DMT inversion code is based on the data space approach (Siripunvaraporn et al., 2005). With the

transformation to data space the computational costs (i.e. CPU times and RAM required) are significantly reduced making the 3-D inversion practical for PCs and workstations as used by Geothermal development Company.

In this paper 3D inversion has been applied to 147 MT soundings obtained from Korosi – Chepchok Geothermal prospect. The main objective of this work was to prove the practicality of 3D inversion with real field data, to recover 3D resistivity model of Korosi geothermal prospect which was not clear when resistivity models were recovered using a lower dimensional inversion, to estimate the extent of geothermal potential of Korosi prospect and to infer the depth of geothermal reservoir and possible recharge zones for the system.

KOROSI GEOTHERMAL AREA



Figure 1: Map of Kenya geothermal resources areas with inset Korosi geothermal prospect.

Korosi geothermal prospect is located in the northern segment of Kenyan rift valley. It is bound by latitudes $0^{\circ} 40' N$ and $0^{\circ} 53' N$ and longitudes $36^{\circ} 00'$ and $36^{\circ} 13'$ within the rift graben. The geology of Korosi is mainly dominated by the intermediate lavas mainly trachytes and trachy-andesite which cover the central and eastern sectors of the prospect area and basalts dominating the south, north and western sectors. The south western plain is however, dominated by fluvial and alluvial deposits whereas the air fall pumice deposits dominate the western plains. Seven fumaroles were mapped in the previous exploration studies. The area within the prospect is highly fractured with several major and minor faults striking NNE-SSW.

Between the year 2006 and 2016 several entities have obtained resistivity data from the Korosi /Chepchok geothermal prospects including KenGen and GDC. Only 147 MTs were considered in this paper.

INVERSION METHOD AND PREPARATION OF 3D INPUT FILES

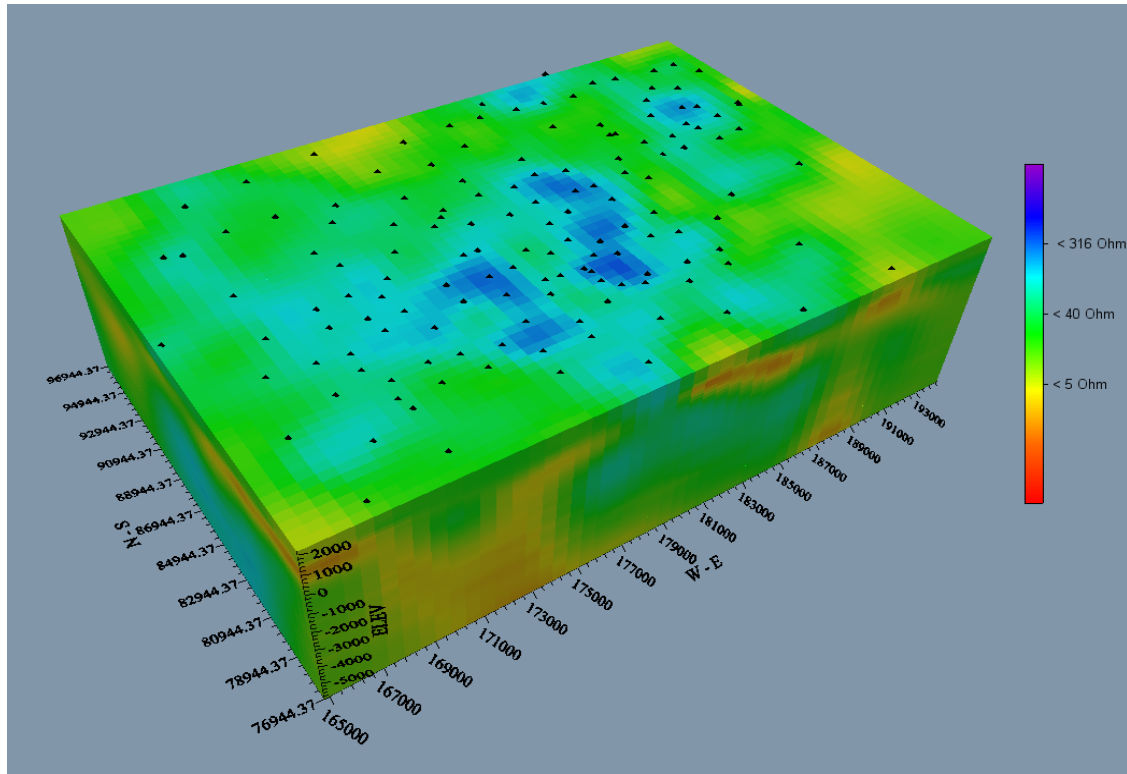


Figure 2: A block resistivity model of Korosi – Chepchuk is shown with MT/TEM soundings overlaid (the black triangles indicate density of MT/TEM soundings)

Smoothing of the raw MT data was performed to get rid of outliers and fit the observed data to the calculated mathematical model. MT soundings and Time domain EM obtained from the same location were first marched at relatively high frequencies and a preliminary static shift correction was obtained. Since Time domain EM is not the ultimate static shift correction as a result of lateral ground elevation variations. Time domain resistivity values obtained from ground peaks suffers static shift and thus cannot be used for optimal static shift correction as shown in figure 3. A static shift value was obtained and a mathematical model was formulated to obtain final static shift by using the special filtering method as in figure 4. The impedance elements were obtained and formed part of the 3D input files. Design of other parameters that form input files was performed and a 3D inversion was done using data space approach. Using a high end 64 GB RAM, 1TB ROM, 16 Core computer with hyper threading capability, the inversion took 36 hours for the first run and 34 hours for the second confirmation run. The minimum RMS of 1.3171 was obtained at iteration 12 above which the RMS started to increase. Model results of iteration 12 were taken as the best solution and imaged to obtain the 3D resistivity model.

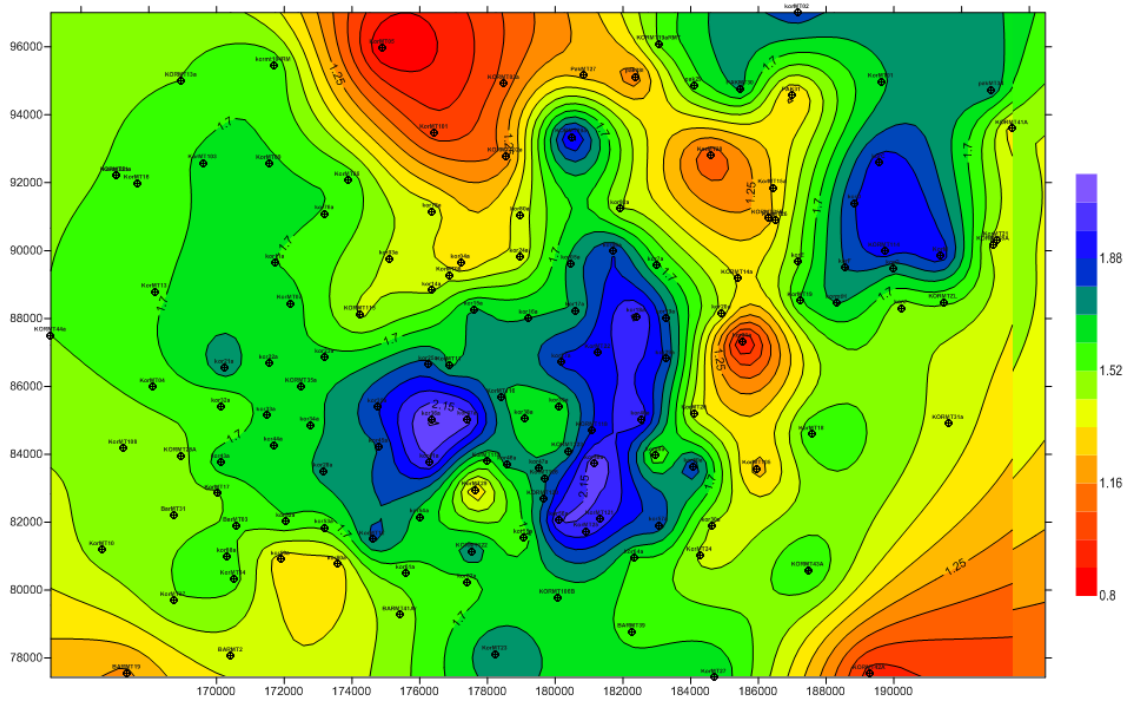
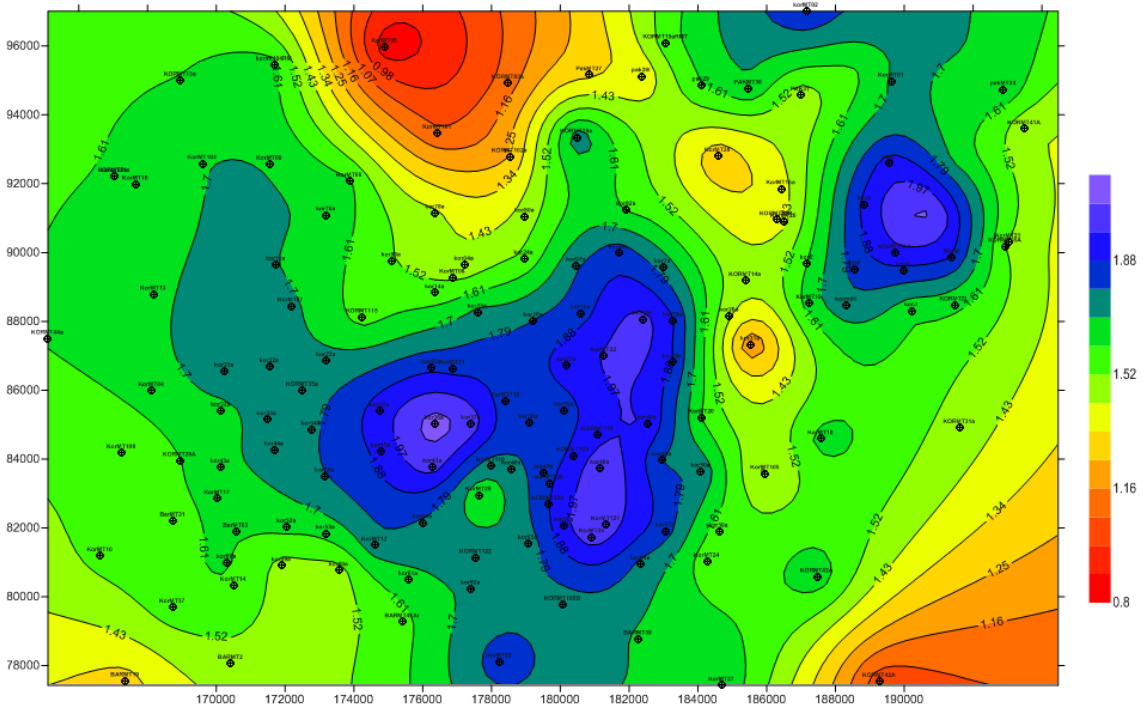


Figure 3: Preliminary static shift with TEM data. The scale in this figure is in log scale with 0.8, 1.16, 1.52, 1.88 representing 6.309, 14.45, 33.11, 75.85 ohm-m



INTERPRETATION OF THE FINDINGS

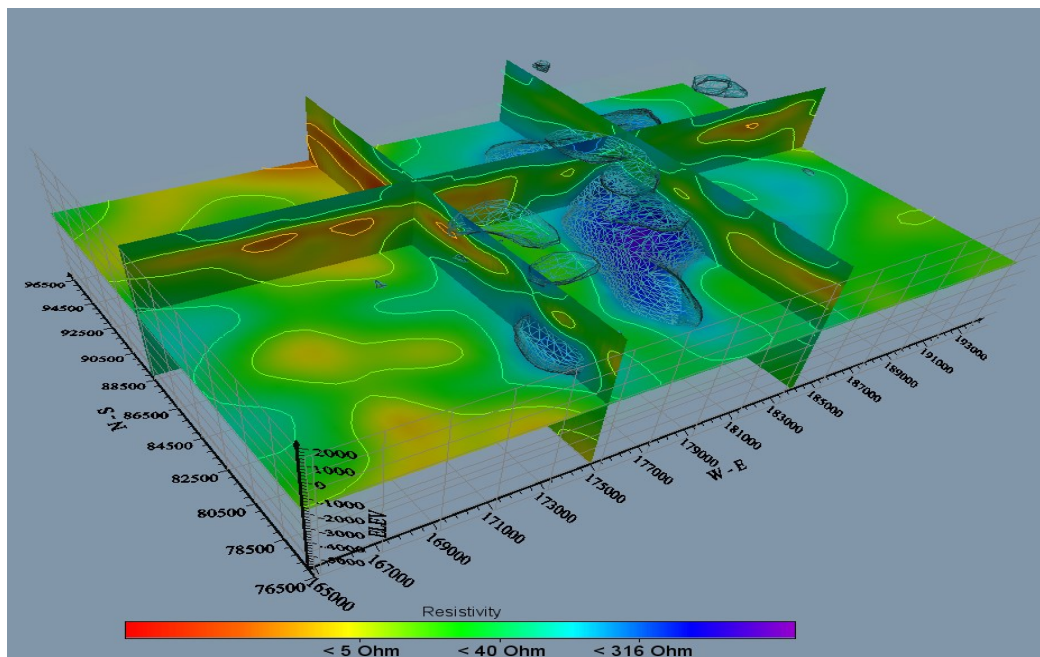


Figure 5; W-E and N-S and ISO resistivity sections of Korosi geothermal prospect. (The first N-S section from left cut through the inferred smaller reservoir and the second N-S section from left cut through the second inferred larger reservoir)

Resistivity cross sections derived from the inversion results at iteration 12 are observed. Near the surface, < 1000m from surface, a low resistivity is evident inferring possible clay cap. On the surface a high resistivity overburden is seen probably as a result of volcanic lavas as evident on the surface. Uplifted high resistivity zone at depth could infer hydrothermally altered zone formed under high temperature condition, necessitated by remarkably low resistivity zone distributed above the uplifted high resistivity zone. The resistivity discontinuities often reflect fractured zones along fault lines as shown in figure 7. An extensive low resistivity is evident western side of the prospect; this low resistivity could be as a result of sedimentation.

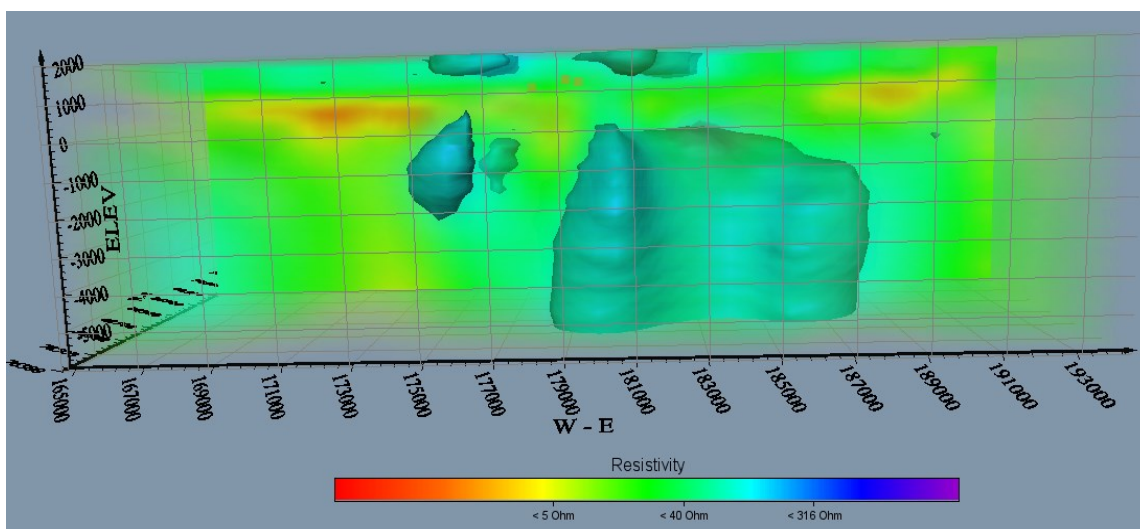


Figure 6: Line of constant resistivity of about 125 Ohm- m surface inferring possible reservoir locations in the prospect. Volumetric block resistivity distribution is shown.

A line of constant resistivity of 125 Ohm-m is shown mapping out low resistivity area. This isolates the near surface anomalies as a result of resistive overburden giving a resistivity of several tens of ohm-m to some few hundreds of ohm-m. This overburden is composed of resistive rocks such as muguerite lava, trachyte lava and basalt (Simiyu, 2010). The lower resistivity immediately below this overburden could infer lower temperature mineralogy of clay minerals. This zone appearing at about 1000 masl could infer clay capping of the geothermal reservoir. An up domed high resistivity zone below zones this capping could infer a high temperature where alteration processes may increase the resistivity of some rocks by changing the resultant secondary minerals such as smectite to illite or chlorite which can be interpreted as a geothermal reservoir.

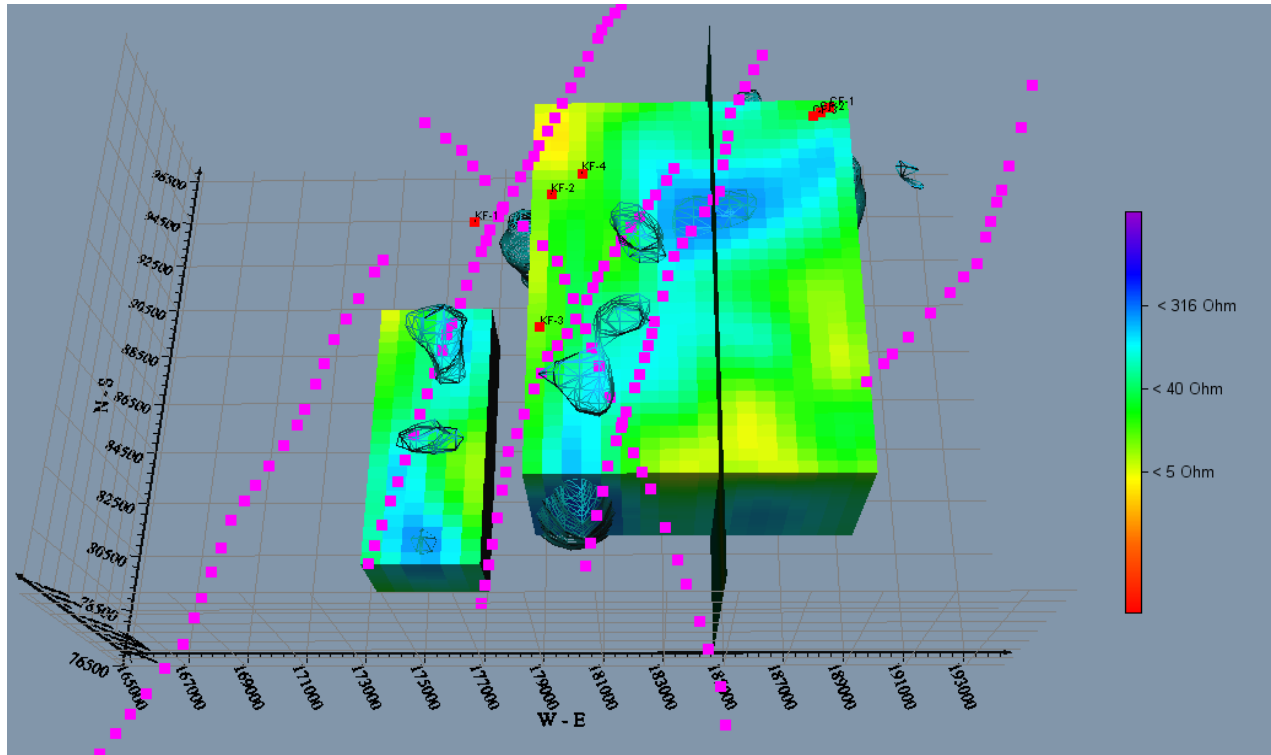


Figure 7: Relationship of the inferred reservoir and the the regional structures and fumaroles. Red squares are fumaroles. The light purple square lines are regional structures evident on the surface. The two blocks are the two inferred geothermal reservoirs.

Two reservoirs are inferred both which are slightly above sea level with the left smaller reservoir superficial relative to the left larger reservoir. The general orientation of the regional structure is evident on the topographic map as NNE-SSW. These form conduits through which hotter fluids transmission is possible to the fumaroles. All the fumaroles KF1-KF4 and CF1-CF3 indicated by red squares are of about 70°C and above indicating some permeability as evident by micro faults shown in figure 8 below.

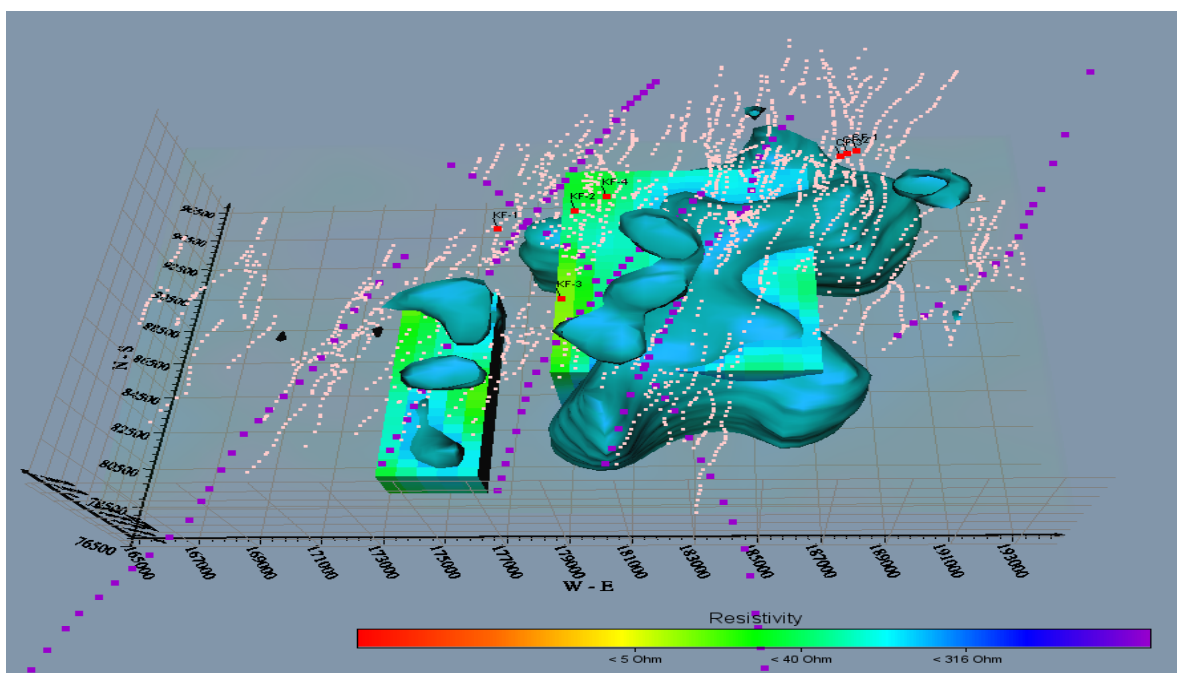


Figure 8: Regional structures shown by purple squares and micro faults are indicated by pink dotted lines.

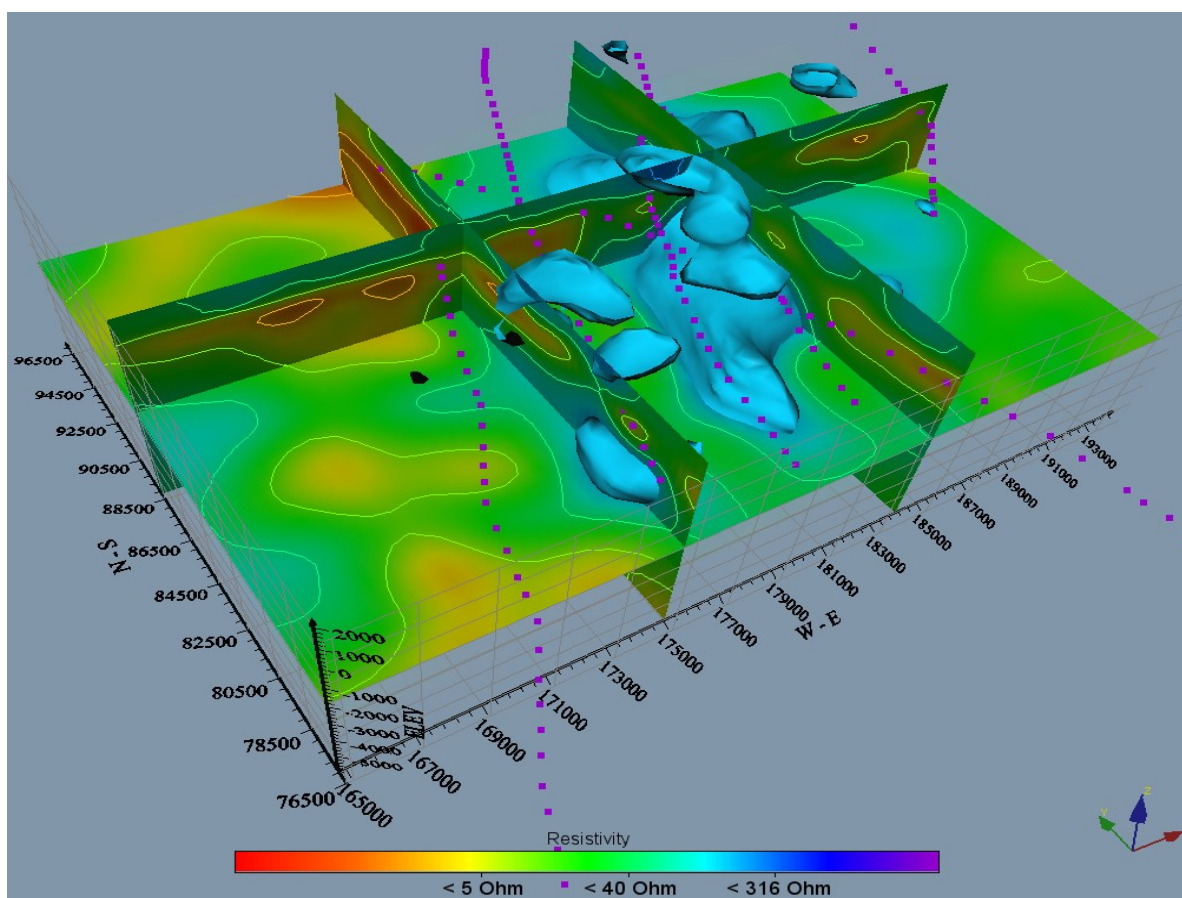


Figure 9: Two N-S, one W-E sections speculating the order of resistivity from surface to deeper portion. An ISO resistivity map cut longitudinally across the reservoirs. The solid bodies (in cyan color) indicate the location of the inferred reservoir.

Arthur

A line of constant resistivity of 125 Ohm-m is shown in figure 9 indicating boundaries of possible high temperature zones. Major structures (purple squares) deduced from topographic map are also overlaid to indicate fault lines evident on the surface. The W-E cross section and N-S cross sections map out the clay cap. The up domed relatively high resistivity could infer geothermal reservoirs.

CONCLUSION AND DISCUSSION

MT data inversion results indicate that there exists a typical geothermal system in Korosi – Chepchok geothermal prospect. Thick clay capping of about the geothermal reservoir is evident to the east of the Korosi towards Chepchok. The results further infer possibility of existence of two geothermal reservoirs within the prospect. A low resistivity structure exists between the inferred reservoirs thus dividing it into two. The left smaller reservoir is superficial relative to the larger right reservoir. The reservoir depth is estimated to be about 0 Masl.

ACKNOWLEDGEMENTS

The author wishes to acknowledge GDC for purchasing a high end, high speed computer that made this research possible. The author also wishes to acknowledge the Honda Mitsuru, Deputy Manager West Japan Engineering Consultants Inc for his untiring support and guidance.

REFERENCES

- Arnarson knutur and Flovenz, O. G. (1992). Evaluation of physical methods in geothermal exploration of rifted volcanic crust. *Geothermal resource council transactions*, 16,207-214.
- Constable, C.S., Parker, R.L., Constable, C.G., 1987. Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data. *Geophysics* 52, 289–300.
- deGroot-Hedlin, C., Constable, S., 1990. Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics* 55, 1613–1624.
- Egbert, W. S. (2000). An efficient data-subspace inversion method for 2-D magnetotelluric data. *Geophysics*,65, 791-803.
- Mackie, R. S. (1994). Three-dimensional electromagnetic modeling using finite difference equations: the magnetotelluric example. *Radio Sci.* 29, 923–935.
- Silas M. Simiyu. (25-29 April 2010). Status of Geothermal Exploration in Kenya and Future Plans for Its Development. Bali, Indonesia,: Proceedings World Geothermal Congress.
- Siripunvaraporn W., G. E. (2005a). Three-Dimensional Magnetotelluric: Data Space Method,. *Physics of the Earth and Planetary Interiors*,150, 3-14.
- Toshihiro Uchida*, T. J.-R., & Yutaka Sasaki, K. (2001). Three-dimensional inversion of magnetotelluric data at the Bajawa geothermal field, eastern.
- Uchida Toshihiro, M. Y. (1995). Two-dimensional inversion and interpretation of magnetotelluric data in the Sumikawa geothermal field, Japan:. *Geological Survey of Japan,Report No. 282.*, 17–49.
- Uchida, T., and Y. Sasaki, 2006, Stable 3D inversion of MT data and its application to geothermal exploration: *Exploration Geophysics*, 37, no. 3, 223–230, doi:10.1071/EG06223.
- W. Siripunvaraporn., G. E. (2002.). Numerical accuracy of magnetotelluric modeling: a comparison of finite difference approximations. *Earth Planets Space* 54,, 721–725.
- Wirachie 2005 And 2