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Resistivity Imaging of Geothermal Resources Using 1D and 3D MT Inversion A Case Study of Menengai Geothermal Field in Kenya

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ABSTRACT

This study investigated the geothermal potential over the Menengai Geothermal field through correlation of 1D and 3D resistivity models in order to recover 3D resistivity structures not seen from 1D models which is very important in geothermal systems in order to reduce ambiguities in 1D resistivity models which assumes resistivity varies only with depth as compared to 3D resistivity models where resistivity varies in all directions. Magnetotellurics (MT) and Transient electromagnetics (TEM) is commonly used to analyse the resistivity distribution that can give indications of alteration zones especially the clay capping and to contribute more information to the conceptual model to help target geothermal wells and assess resource capacity in potential areas. MT and TEM data obtained from earlier surveys since 1999 to 2013 has been re-processed and interpreted using 1D and 3D inversions. Usually 1D interpretation is easy to obtain and is always representative to shallow depths while 3D can image resistivity structures at deeper depth. Mainly 1D inversion has always been used due to limitation in computer hardware to perform 3D inversion, but due to developments in computational hardware a workflow for 3D inversion has been set and carried out and the results from the inversion interpreted in form of resistivity maps and cross sections. This has been accomplished using a 3D inversion algorithm.

This research has explained the differences in results between 1D and 3D models and come up with general recommendations for effective MT resistivity imaging of geothermal resources. This has provided reliable information about the presence, location, and size of geothermal system in Menengai Geothermal field. The results from both models correlate quiet well near the surface and then some difference in resolution as you go deeper. 3D models are able to resolve deeper structures quiet well as compared to 1D. So the general recommendation is to interpret MT data using 1D near the surface and rely more on 3D models for the deeper portion to make a conclusive interpretation.

1. INTRODUCTION

Magnetotellurics (MT) and Transient electromagnetics (TEM) is commonly used to analyse the resistivity distribution that can give indications of alteration zones especially the clay capping and to contribute more information to the conceptual model to help target geothermal wells and assess resource capacity in potential areas. The Menengai geothermal field is associated with a trachytic volcano located along the Kenyan rift valley (Figure 1). Geophysical surveys were undertaken in Menengai to give a structural image of the subsurface. The electrical resistivity method was used as its data are strongly affected by geothermal processes and may indicate the presence of a geothermal system. The magnetotelluric (MT) method is prefered for exploration of geothermal. The method is effective for delineating geothermal reservoirs, which are characterized by high-resistivity contrast between the reservoir and the cap rock (clay caps) that are located on top.

The transient electromagnetics (TEM) was used to resolve the static shift problem in MT due to its good resolution near the surface. The hypothesis used is that an increased fluid content due to fracturing, and the development of more conductive alteration clay minerals can give rise to an electrical resistivity contrast which with reliable mapping can increase chances of discovering geothermal resources and defining the extent of geothermal reservoirs. This is done through imaging the controlling structures of geothermal systems, and in locating and characterizing permeable fracture zones. Apparent resistivity data from MT and TEM surveys were analysed to understand the resistivity structure within the prospect.

Surface geology of Menengai volcanic complex is composed of late quaternary volcanics. The formation of Menengai caldera began with the building of a trachyte shield volcano, followed by piecemeal subsidence to produce a caldera of about 84 km^2 that has been largely filled by recent trachytic post caldera lavas. The most recent volcanic eruption is the post caldera lava dating about 1,400 years BP, although the youngest can be assumed to be a few hundred years old according to their pristine nature. Drill cuttings from the wells have yielded important information on the stratigraphy, hydrothermal alteration and the present state of the geothermal system. The wells lithology show close similarity with trachyte being the dominant rock. Syenite intrusives were intercepted intermittently in some wells, indicating shallow magmatic intrusives, which provide for the heat source(s) for the geothermal system. Reaction of geothermal fluid with the host rocks invariably results to progressive hydrothermal alteration with increasing depths.

2. MAGNETOTELLURICS (MT) AND TRANSIENT ELECTROMAGNETICS (TEM)

Magnetotelluric uses natural electromagnetic waves induced by magnetosphere or ionosphere currents. The signals are used to image the resistivity structure of the earth, Vozoff, 1991; Jiracek et al, (1995). Since the source is far away from the earth's surface, MT waves can be treated as planar, Zhdanov and Keller, (1998). The MT wave is comprised of electric and magnetic fields which are recorded orthogonally using two electric and three magnetic channels.

In the TEM method, an electrical current is induced in the ground and the magnetic field created is measured at the surface, from which the resistivity of the subsurface rocks is determined, Arnasson 2008. The current in the ground is generated by a time-varying magnetic field. Yet, unlike MT-soundings, the magnetic field is not the randomly varying natural field, but a field of controlled magnitude generated by a source loop. A loop of wire is placed on the ground and a constant magnetic field of known strength is built up by transmitting a constant current into the loop. The current is then abruptly turned off. The decaying magnetic field induces electrical current in the ground. The current distribution in the ground induces a secondary magnetic field decaying with time. The decay rate of the secondary magnetic field is monitored by measuring the voltage induced in a receiver coil (or a small loop) at the centre of the transmitter loop.

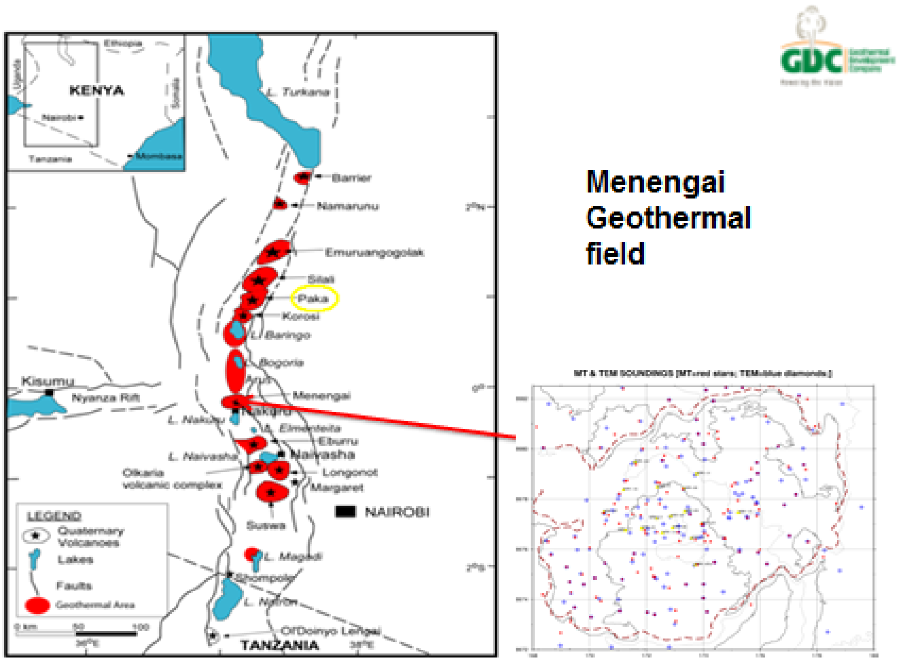

Figure 1: Location map of Menengai Geothermal Field in Kenyan rift valley and MT/TEM coverage respectively.

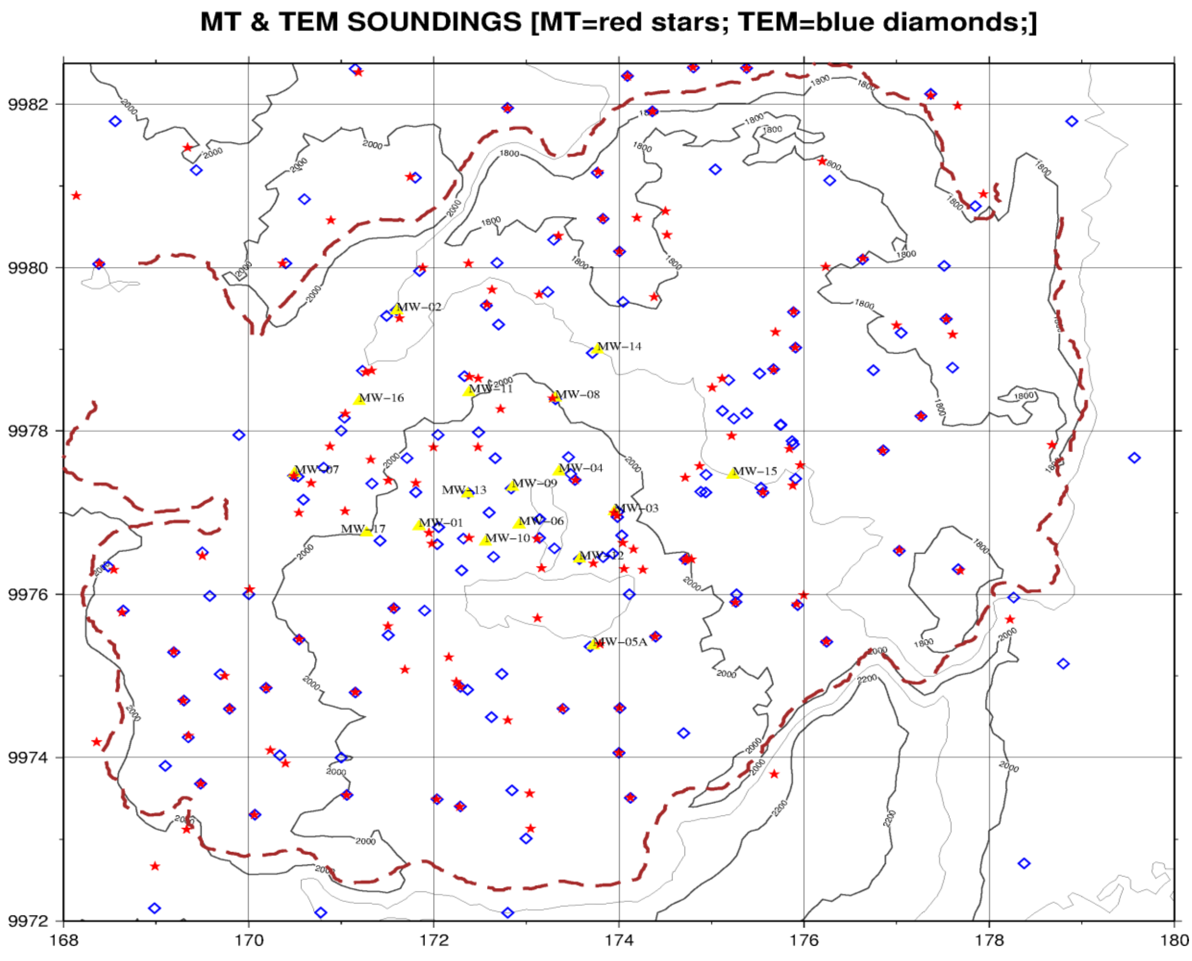

Figure 2: Location of MT and TEM soundings in red stars and blue diamonds respectively

2.1 TEM and MT joint inversion

The joint 1-D inversion of TEM and MT sounding data was designed to solve the static shift problem in MT data in the volcanic environment of the Menengai Geothermal field, Stenberg 1988. In joint 1-D inversion of TEM and MT data, one more parameter is inverted for, in addition to the layered model resistivity and thickness parameters, namely a static shift multiplier by which the apparent resistivity has to be divided so that both the TEM and MT data can be fitted with the same model (Figure 3). The program can do both standard layered inversion (inverting resistivity values and layered thicknesses) and Occam inversion with exponentially increasing layer thicknesses with depth. A joint 1-D Occam inversion was performed for the rotationally invariant determinant apparent resistivity and phase of the Menengai MT soundings and the associated TEM soundings as seen in Figure 4.

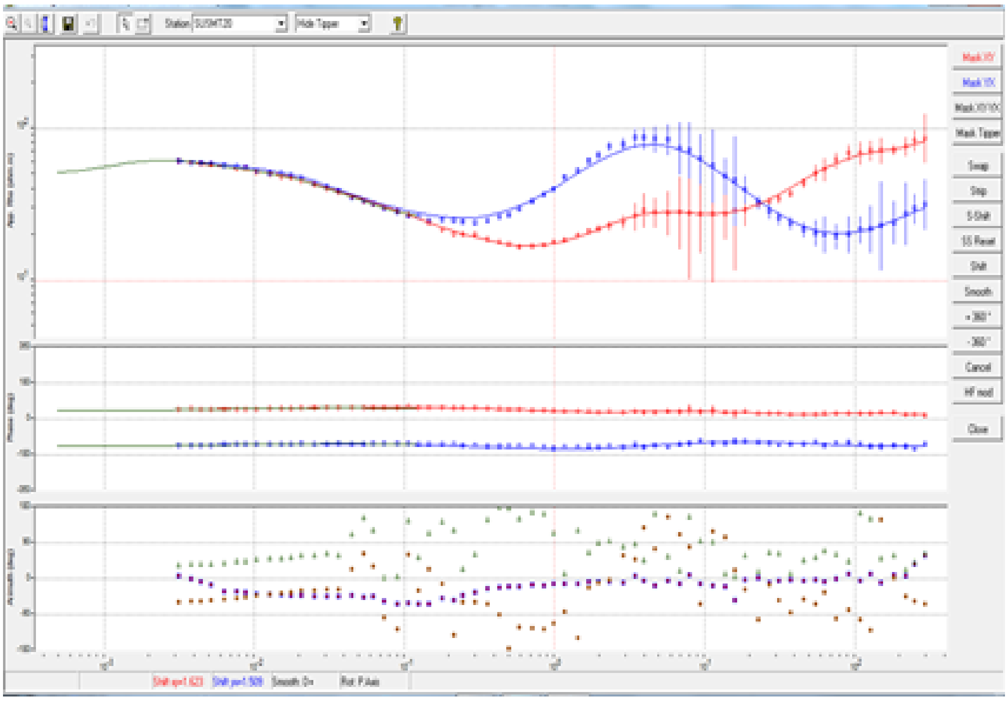

Figure 3: Joint 1-D inversion of TEM and MT soundings.

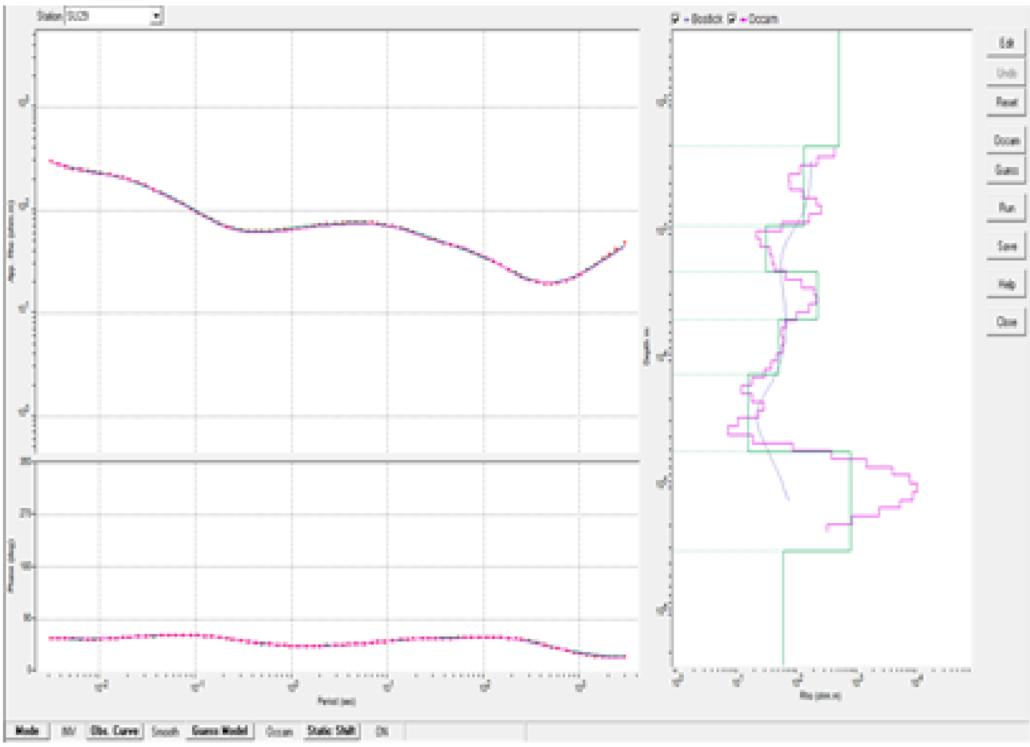

Figure 4: Shows the results of the 1-D resistivity inversion model.

2.2 MT 3D inversion

The objective of a 3D MT inversion is to produce a 3D resistivity model consistent with MT data that require it. There are a variety of MT parameters that roughly indicate whether the 3D signal is significant. From a 1D/2D perspective, these signals are distorted. They are seldom significant at geothermal fields above the base of the clay cap, except near lateral discontinuities.

The effective depth of investigation of the 3D inversion is not limited by geometric assumptions as is the case with 1D and 2D inversion. It is, however, limited by the frequency range of the reliable data used in the inversion, the average resistivity of the model, and the width (or aperture) of MT station coverage. At Menengai volcano, resolution was assumed to be limited to 4000 m because frequencies at less than 0.1 Hz were probably distorted by regional power lines.

Restricting the 3D inversion to frequencies greater than 0.1 Hz allowed for a greater number of frequencies from 0.1 and 300 Hz to be included in the 3D MT inversion, improving the resolution of finer details in the clay cap and reservoir.

3. 1D and 3D resistivity imaging at shallow depth (300m)

The resistivity results at shallow depth in Figure 5 and 6 show a very close correlation for 1D and 3D analysis. Both plots are dominated by fairly low resistivities indicating a zone of low temperature alteration minerals like smectites formed as a result of water rock interation in the geothermal field. This gives a very good indication of permeability evidenced by shallow structures in the Menengai field.

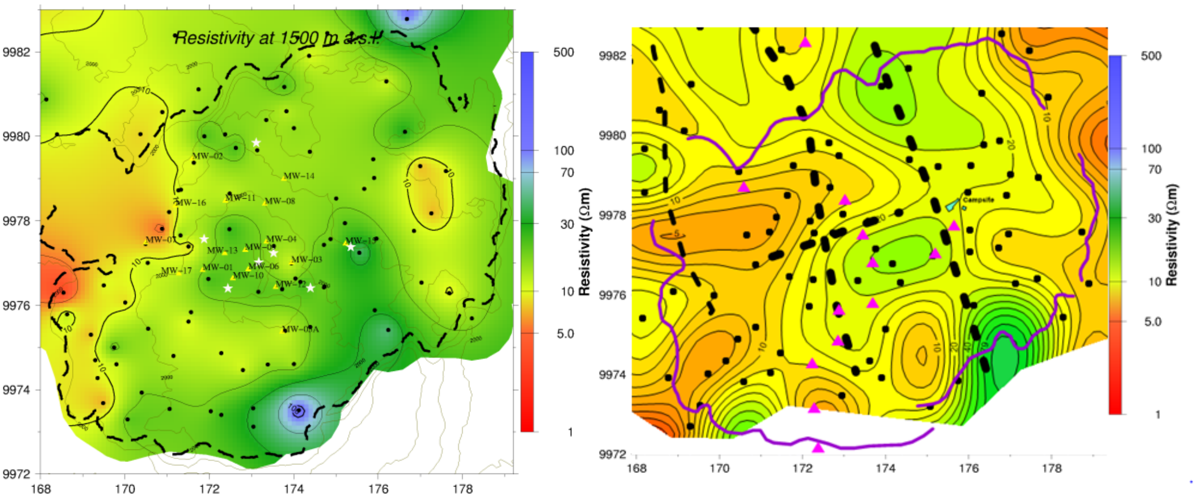

Figure 5 and 6: Shows the results of the 1D and 3D resistivity inversion models at 1500 m.a.s.l shallow depth respectively.

4. 1D and 3D resistivity imaging at deeper depth (2000m)

The resistivity imaging at deeper portion as seen in Figure 7 & 8 shows notable differences in the inversion results. A look at 1D resistivity imaging shows a fairly high resitivity associated with high temperature alteration minerals within the caldera at taht depth with a low resitivity zone emanating from the southern portion which is as a result of a deep seated structure given the eruption centers at the surface around that region. The 3D resistivity image has clear distintion between the high resistivity bodies seen on the western and eastern part of the caldera and a low resitivity anomaly outside the caldera and the central portion which generally shows areas of very high conductivity due to structures which mimic the regional trend as seen from surface geology. The resitivity discontinuities mapped by black dotted lines in the 3D inversion are very important when it comes to mapping vertical permeability for the field and this is seen quiet well in most wells drilled in the field.

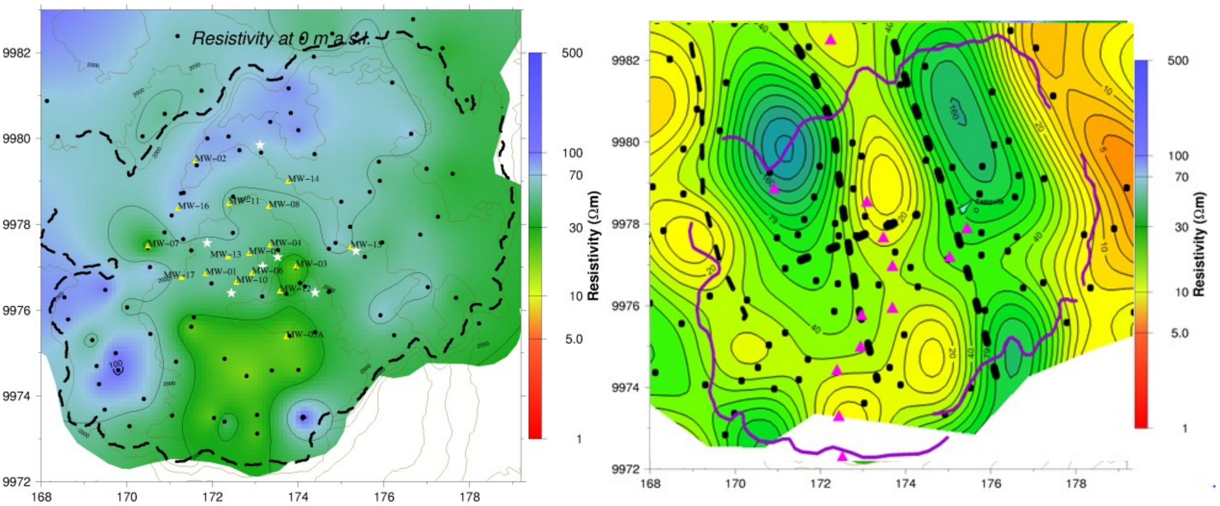

Figure 7 and 8: Shows the results of the 1D and 3D resistivity inversion models at 0 m.a.s.l deeper depth respectively.

5. CONCLUSION

From the resistivity images both 1D and 3D a shallow conductive layer is evident which is likely to be the capping for the Menegai geothermal system. As you go deepe the structures which control the fluid flow at deeper portion are clearly evident from the 3D plot both within the caldera and outside nad are mainly controlled by the regional structures mapped in the Menengai volcanic complex.

This paper has explained the differences in results between 1D and 3D models and the general recommendations for effective MT resistivity imaging of geothermal resources. This provides reliable information about the presence, location, and size of geothermal system in Menengai Geothermal field. The results from both models correlate quiet well near the surface and then some difference in resolution as you go deeper. 3D models are able to resolve deeper structures quiet well as compared to 1D.

The general recommendation is to interpret MT data using 1D for near surface structures and rely more on 3D models for the deeper portion to make a conclusive interpretation due to the better resolution at depth as compared to 1D inversions.

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