Joint Inversion of TEM and MT Data from Paka Geothermal Prospect in Kenya

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ABSTRACT

Joint one-dimensional (1-D) inversion of magnetotelluric (MT) and central loop transient electromagnetic (TEM) data was done by fitting both data sets using the same 1-D resistivity model. It is well known that in the presence of small-scale surface or near-surface resistivity inhomogeneities the magnetotelluric (MT) apparent resistivity can be shifted by a multiplicative factor which is independent of frequency. In this regard TEM has been used to correct for the static shift factor to restore the MT curve where it should have been without the effect of shift for this project.

The 1-D joint inversion results reveals three main resistivity zones, a shallow high resistivity zone ($> 200\ \Omega$m) to about 400 metres below the surface, an intermediate low resistivity zone ($\sim 10\ \Omega$m) to depths of about 1 kilometre and a deeper high resistivity region ($> 50\ \Omega$m), up to 3-4 kilometres depth. Below the high resistivity zone a relatively deeper low resistivity zone at depth is evident possibly indicating a high temperature which is a likely heat source for this field.

Results from this survey will be used to predict the correlation between resistivity structure and hydrothermal alteration and also to infer temperatures to be expected once drilling is carried out. In a high temperature geothermal system low resistivity is dominated by conductive minerals in the smectite-zeolite zone at temperatures of 100-200 ºC. In the temperature range 200-240 °C, zeolites disappear and smectite is gradually replaced by resistive chlorite. At temperatures exceeding 250 °C, chlorite and epidote are the dominant minerals and the resistivity is probably dominated by the pore fluid conduction in the high-resistivity core provided that hydrothermal alteration is in equilibrium with the present temperature of the reservoir.

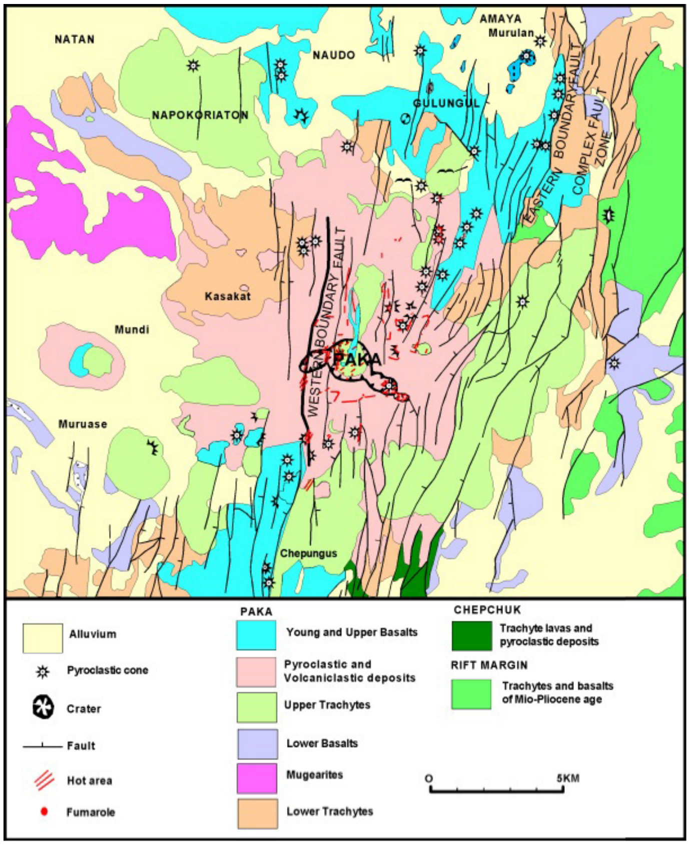

Figure 1. Geological map of Paka Prospect, modified from Darling et al. (1993).

1.0 Introduction

1.1 Geological and Tectonic Setting

Paka is a small shield volcano whose evolutionary history may be broadly divided into two periods of Trachytic volcanism separated by basaltic activity. Volcanic activity commenced by 390 Ka and has continued to within 10 Ka. Much of the shield forming lavas are covered by Trachytic pyroclastic deposits which are seen to cover the areas around the volcano. The oldest exposed rocks are the Lower Trachytes, which formed an early volcanic shield. Subsequent fracturing of the shield by the NNE-SSW trending faults was accompanied by eruption of the Lower Basalts from fissure sources on the eastern flanks of the volcano. The age of these sequences ranges from the early Pleistocene represented by the shield forming trachytes to a few hundred years BP represented by the pristine less vegetated Young Basalts.

2.0 Resistivity Study of Paka Geothermal Field

2.1 TEM Survey

In this study a total of 73 Central Loop TEM soundings were carried out in the Paka area spread over about 190 km^2. The stations are widely distributed within the prospect area which made it possible to use TEM to correct static shift on MT data.

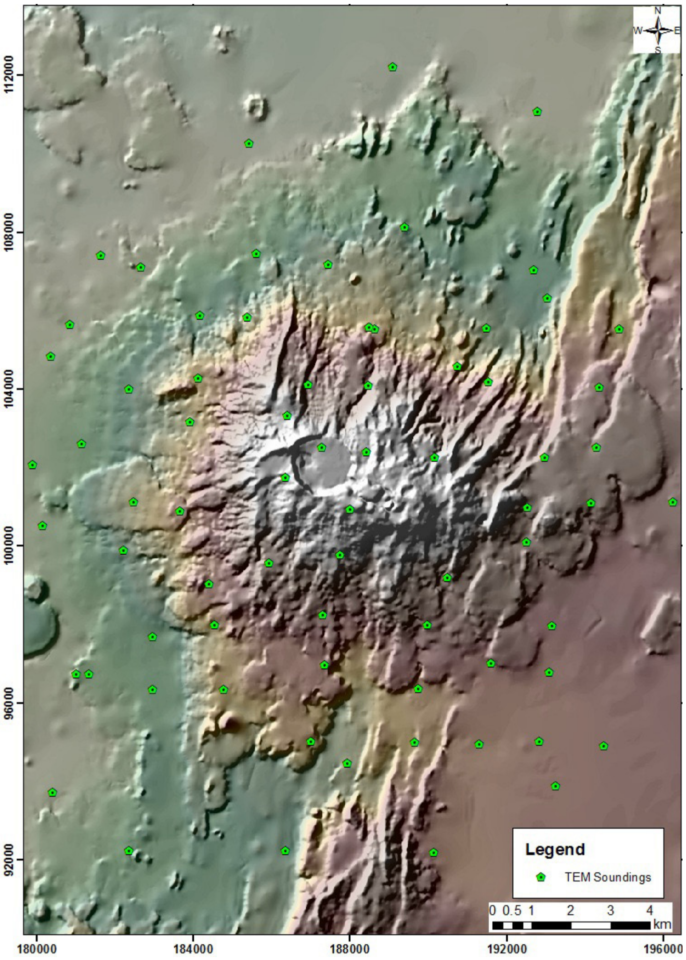

Figure 2. TEM sounding locations.

2.2 TEM Data Processing and 1-D Interpretation

Raw data files were read and downloaded from the GDP-32 receiver using TEM SHRED (a Zonge Geophysics program) and TEM-AVG (also a Zonge Geophysics program) was used to calculate averages and standard deviations of repeated transient voltage measurements and late time apparent resistivity as a function of time. WingLink (Geosystem) interpretation program was used to perform 1-D inversion on the data.

All the TEM soundings in the Paka area have been interpreted by 1-D inversion, using Occam inversion (Figure 3), and using models that were as smooth as possible. In 1-D inversion it is assumed that the earth consists of horizontal layers with different resistivities and thicknesses. The 1-D interpretation seeks to identify the layered model whose response best fits the measured responses.

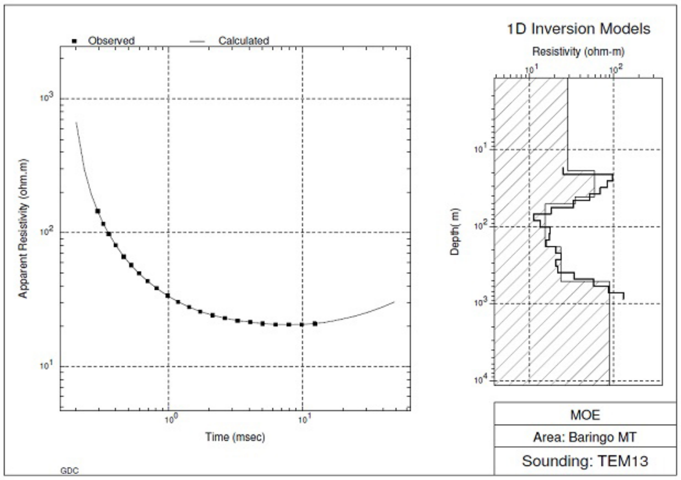

Figure 3. TEM sounding from Paka area and its 1-D inversion, showing the TEM apparent resistivity curve and its interpretation.

2.3 MT Survey

A total of 107 MT soundings are considered for interpretation in the Paka prospect covering an area of about 190 km^2 as can

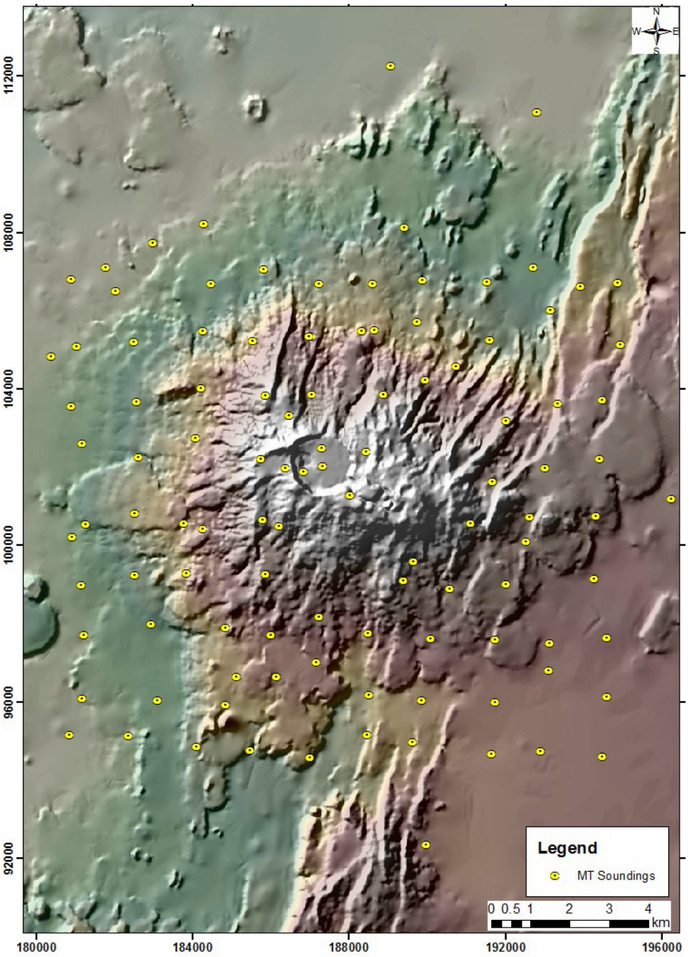

Figure 4. The MT sounding distribution over the prospect area.

be seen in Figure 4. The data was acquired using 5-channel MT data acquisition system (MTU-5A) from Phoenix Geophysics.

2.4 The MT Static Shifts

The MT method suffers from the so-called static shift problem. This phenomenon is caused by local resistivity inhomogeneities in the shallow sub-surface which disturbs the electrical field. The main cause is the accumulation of charges at resistivity boundaries causing the electrical field to be discontinuous near this boundary. The static shift is expressed by scaling of the apparent resistivity by an unknown factor (shifted on log scale). This shift is independent of frequency, at least for those frequencies generally used in MT soundings (Jones, 1988). The static shifts can be a major problem in volcanic environments where resistivity variations close to the surface are often extreme. These parallel shifts in the apparent resistivity curve can lead to large errors in inverted data.

In this interpretation Central loop-induction TEM soundings have been used to correct for static shifts in MT data by jointly inverting both MT and TEM data. This is based on the fact that, for TEM measurements at late times there are no distortions due to near surface inhomogeneities since they do not involve measuring the electrical field. This has been tested by model calculations (e.g. Sternberg et al., 1988) and shown to be a useful method to correct for static shifts in MT soundings, at least for 1-D resistivity environments.

2.5 Static Shift Analysis of MT Data in Paka

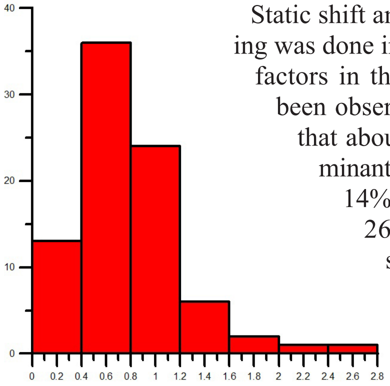

Figure 5. Histogram of static shift parameters for determinant apparent resistivity in the Paka area. x-axis shows the shift factors with y-axis showing the number of soundings.

Static shift analysis of the 92 MT sounding was done in the Paka area where shifts factors in the range of 0.1 to 2.8 have been observed. This outcome indicate that about 60% of all the MT determinants were shifted down whereas 14% were shifted up with only 26% not showing any static shift (Figure 5). Therefore if interpretation had been done without the static shift correction then we would have an error of 76% in resolving the resistivity structure for this field.

3.0 Joint 1-D Inversion of TEM and MT Soundings

The one-dimensional joint inversion is performed simultaneously for both TEM and MT data by fitting one inversion on both data sets to obtain one model. This is achieved by shifting the TEM curves to fit them to the TEM 1-D inversion. Both the MT and TEM data collected on approximately the same location are brought together in a joint inversion where TEM 1-D inversion obtained earlier was used for static shift correction on MT data.

The Winglink program was used to invert MT apparent resistivity derived from the rotationally invariant determinant of the MT tensor elements.

An example of a 1-D joint inversion of MT and TEM data is shown on Figure 6, where the red diamonds are measured TEM apparent resistivities and blue squares are the MT apparent resistivities. Solid lines show the response of the resistivity model to the right.

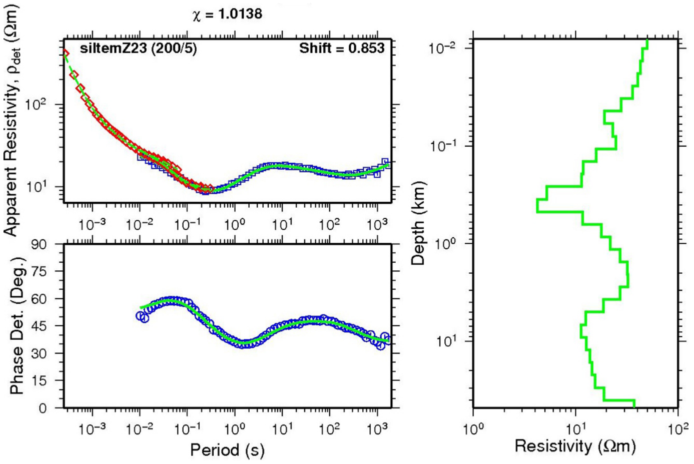

Figure 6. Typical result of a joint 1-D inversion of TEM and MT soundings.

3.1 Iso-Resistivity Maps

Resistivity 500 m Above Sea Level

At 500 masl (Figure 7) a high resistivity anomally (> 30 ohm.m) aligns itself in the direction of major structures NNE as a result of un-altered formations at about 500 meters below surface, the eastern part of the plot a low resistivity anomaly persists due to conductive clays, even though it is not well constrained further east due to scarcity of data.

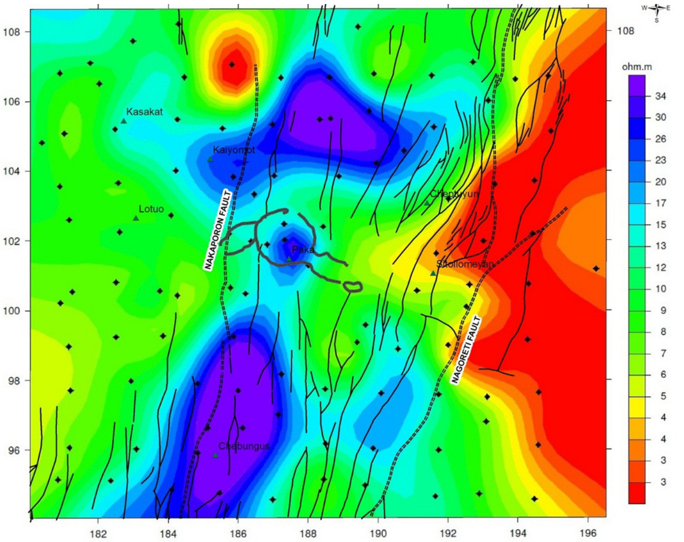

Figure 7. Resistivity 500 m above sea level.

Resistivity at Sea Level

At sea level (Figure 8) low resistivities are evident in the NW, SE and NE of the prospect area which could be associated with the conductive alluvial sediments. In the central part of the prospect a resistivity anomaly of less than 52 ohm-m is evident aligning in NE-SW direction which can be interpreted as a probable reservoir

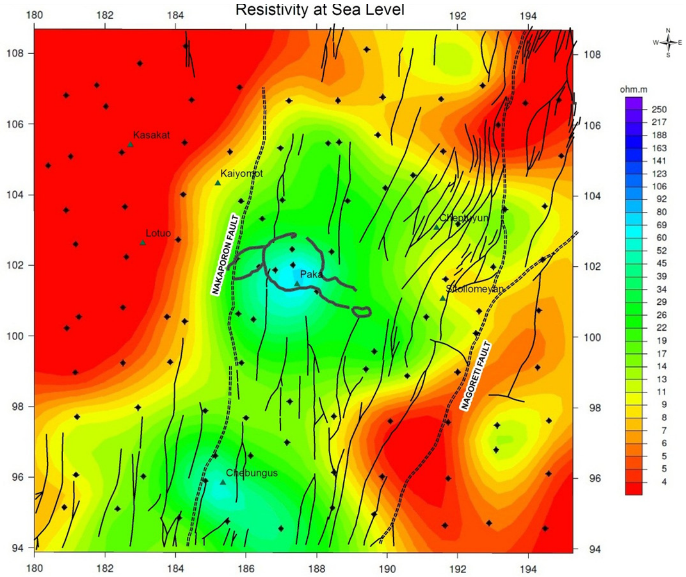

Figure 8. Resistivity at sea level.

zone for this prospect area and is characterised by high temperature alteration minerals such as chlorites and epidotes.

Resistivity 1000 m Below Sea Level

A high resistivity anomaly (Figure 9) is oriented NNE along the Nakaporon fault. This feature could be related to the high resistivity core representing the reservoir of this prospect which is likely to be steam dominated. The low resistivity on the eastern and SE side could be the remnant of the conductive alluvial sendiments.

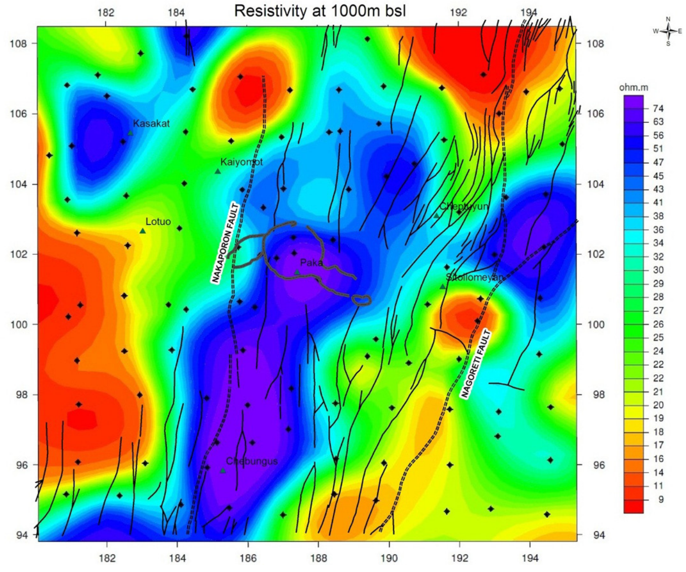

Figure 9. Resistivity 1000 m below sea level.

Resistivity 5000 m Below Sea Level

At this level the high resistivity still persists and it seems to be bound by the two major structures which are believed to be controlling the geothermal activity in this prospect. This high resistivity could still be reflecting the steam dominated reservoir.

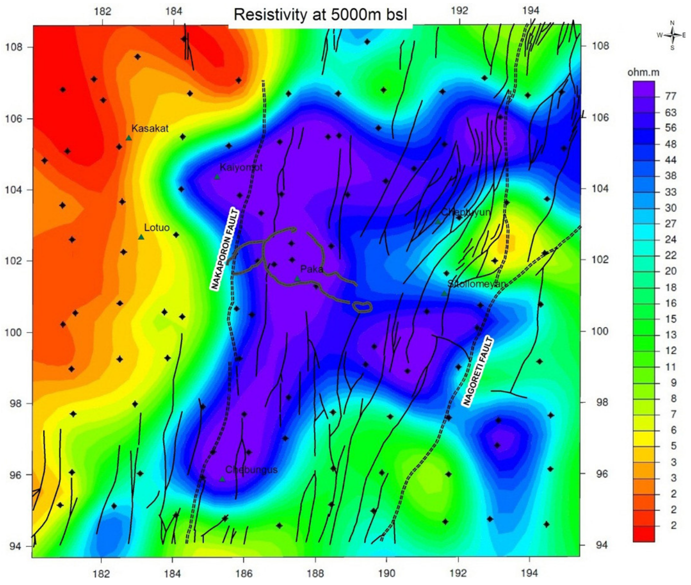

Figure 10. Resistivity 5000 m below sea level.

The eastern sector of the prospect exhibits a low resistivity which could be as a result of saline sediments.

3.2 Cross-Sections

Resistivity cross-sections are plotted from inversion results obtained by use of Winglink software. The program calculates the best line between selected stations on a profile, and plots resistivity isolines based on models generated for the entire profile. Several vertical cross-sections were made through the survey area and a few of them are presented in this paper.

North-South Cross-Section

This section cuts through the paka massif in the N-S direction, In the upper kilometer or so a relatively low resistivity is evident probably as a result of the low temepereture hydrothermal alteration. Underlain is a higher resistivity zone still below the massif and spreading for several kilometers depth. This is a zone where high temperature clay minerals are pres-

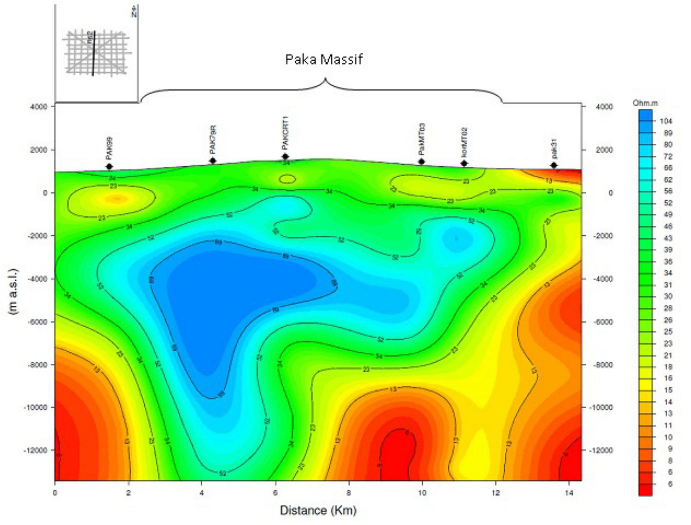

Figure 11. Resistivity cross-section along N-S.

ent and probably an host for the geothermal reservoir. At 8km below sea level deeper conductor a seen which could be the heat sources for this field.

South West - North East Crossection

This profile presents a zone of low resistivity about 14 ohm-m in the top 700m or so. this is a zone where alteration is present. Underrlain is a zone of risistivity of about 51 ohm-m spread almost entire section below the Paka massif, this is a probable reservoir zone for this field. At depth conductive zone are evident which could be related to the heat sources for this field. In the North-East sector of the section a continous low resistivity is evident probably reflecting a fault like structure.

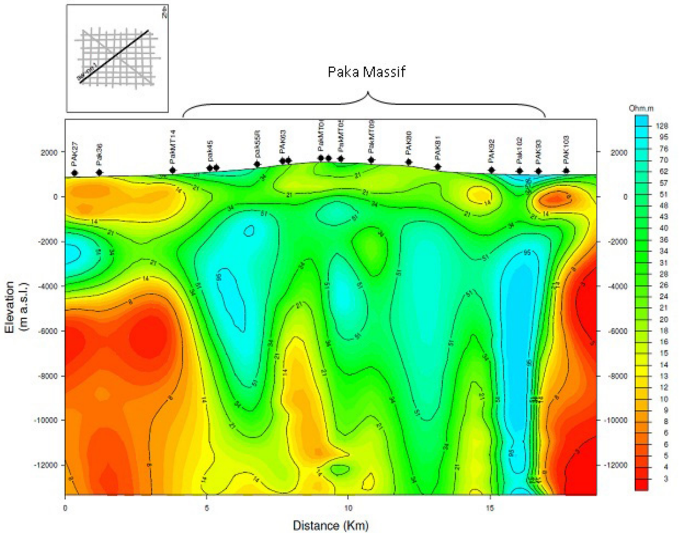

Figure 12. Resistivity Cross-Section along SW-NE.

4.0 Discussions

In the Paka geothermal prospect results show fairly good correlation with the available geological information. The prospect seems to be constrained by the two major structures running in the NNE direction. The resistivity model compiled from the 2-D inversions reveals that the Paka geothermal area is generally characterized by a high-resistivity surface layer (>100 Ωm), which is interpreted as fresh un-altered rocks possibly due to the thick eruptive materials. Below that is a low resistivity layer of about 10 Ωm which correlates very well with the mineral alteration of smectite-zeolite zone of the geothermal reservoir.

Underlain below the low resistivity cap is the high resistivity core which is evident in all the cross-sections within the study area. The existence of a high resistivity core indicates reservoir temperatures exceeding 250°C (Arnason 2000), This high resistivity persists to greater depths and has been used to suggest the presence of a steam dominated reservoir within the Paka prospect.

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