# JOINT 1-D INVERSION OF TEM AND MT DATA FROM OLKARIA DOMES GEOTHERMAL AREA, 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 kinds 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 (> 100 Ωm) to about 300 metres below the surface, an intermediate low resistivity zone (10 Ωm) to depths of about 1 kilometre and a deeper high resistivity (> 50 Ωm), up to 3-4 kilometres depth. Below the high resistivity zone a relatively low resistivity zone at depth is evident possibly indicating a high temperature which is a likely source of crustal fluids for this field.

A good correlation is found between the resistivity structure, hydrothermal alteration and reservoir temperatures. The low resistivity is dominated by conductive minerals in the smectite-zeolite zone at temperatures of 100-200°C. In the temperature range of 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.

**Key words**: resistivity, alteration, static shift, joint inversion

## INTRODUCTION

### *Scope of work*

This report presents the geophysical work performed in Olkaria-domes in Kenya. It covers Magnetotelluric (MT) and Transient electromagnetic (TEM) data acquisition, processing and interpretation using a one dimensional joint inversion of those data sets (based on a nonlinear least-squares inversion of the Levenberg-Marquardet code, Árnason, 1989). The result is presented both by iso–resistivity maps at different elevations and resistivity cross-sections along profiles. The goal of this study is to establish the resistivity structure of this field and correlate it with the alteration mineralogy and the reservoir characteristics from wells that have been drilled and suggest possible locations for future drill holes.

An attempt has been made to relate the modelled geophysical parameters to the geological and tectonic structures and the geothermal reservoir characteristics from wells in the area.

### *Geological and tectonic setting*

Olkaria Domes geothermal field is located on the South-eastern part of the Greater Olkaria geothermal area. The area approximately bound by Ol'Njorowa gorge to the west and a ring of domes to the east and south of the field (Figure 1).

The Greater Olkaria volcanic complex is characterized by numerous volcanic centres of Quaternary age and is the only area within the Kenya rift with occurrences of comendite (a type of white rhyolite comprising the minerals amphibole and pyroxene) on the surface (Lagat, 2004). Other volcanoes in Kenya are associated with calderas of varying sizes. Olkaria volcanic complex does not have a clear caldera formation, which might suggest younger in age compared to other volcanic areas in Kenya. However as seen on figure 1, the volcanic domes in the east, south and southwest appear to be located on a ring shaped structure. This observation has been used to suggest the presence of a buried caldera (Figure 1); Naylor, 1972, Virkir, 1980, Clarke et al., 1990, Mungania, 1992). In support of the caldera theory micro-seismic studies have indicated possible attenuating bodies under the ring of Domes (Simiyu, et.al., 1998).

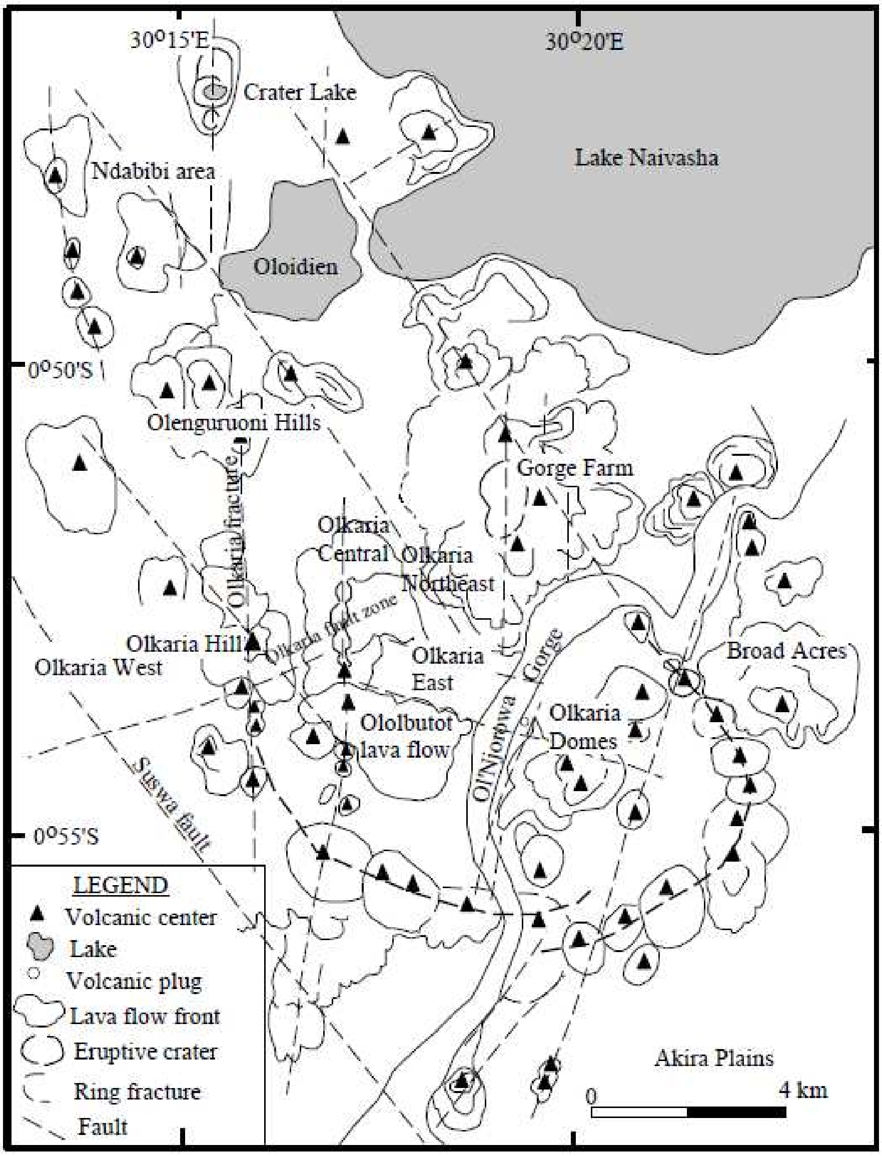


**FIGURE 1**: Volcano-tectonic map of the Greater Olkaria volcanic complex (modified from Clarke et al., 1990)

## RESISTIVITY STUDY OF OLKARIA DOMES GEOTHERMAL FIELD

### *TEM survey*

In this study a total of 52 Central Loop TEM soundings were carried out in the Domes area spread over about 45 km$^2$. The stations are scattered within the prospect area with denser coverage in the areas where wells have been drilled as can be seen on Figure 2.

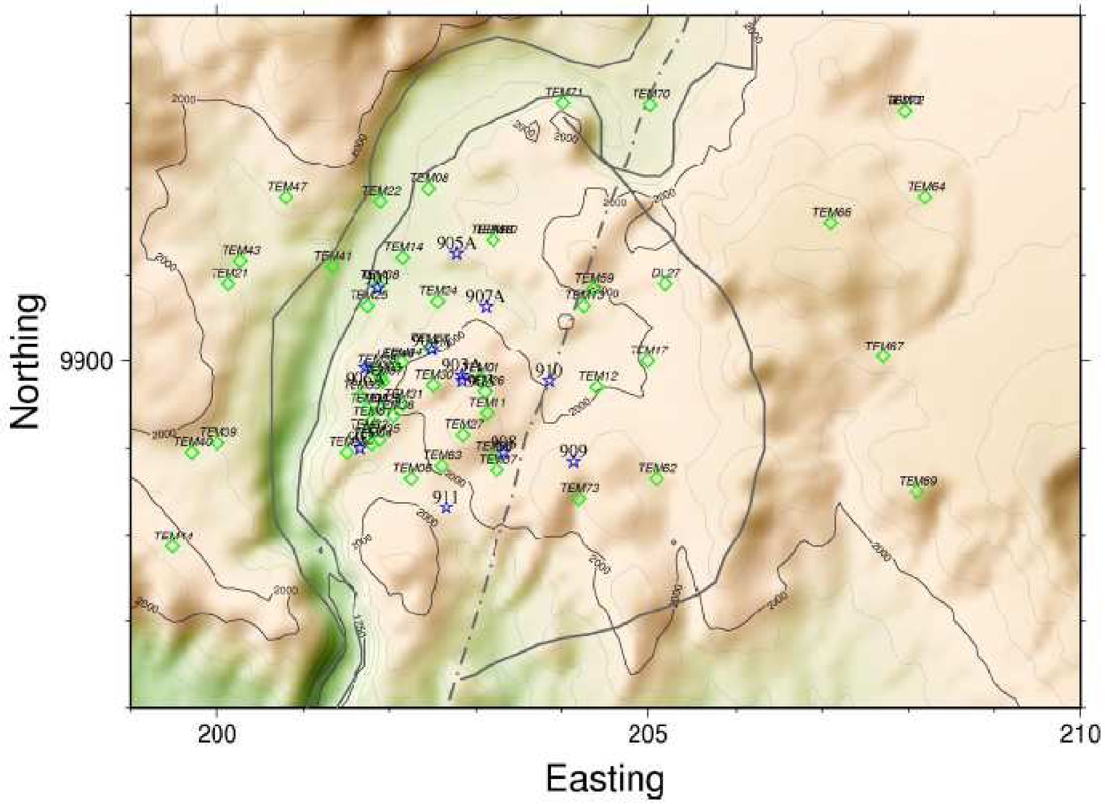


**FIGURE 2**: TEM sounding locations

### *TEM data processing and 1-D interpretation*

The raw TEM data was processed by the program TemZ, a modified version of Temx to handle Zonge data (Árnason, 2006). This program averages data acquired at same frequency and calculates late time apparent resistivity as a function of turn-off time. 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 is achieved by software called TEMTD a UNIX program. This software assumes that the source loop is a circular source field and that the receiver coil/loop is at the centre of the source loop. Practically a square loop is used with equal area to that of the circle. The current waveform is also assumed to have equal current-on and current-off time segments. The transient response is calculated both as induced voltage and late time apparent resistivity as function of time.

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

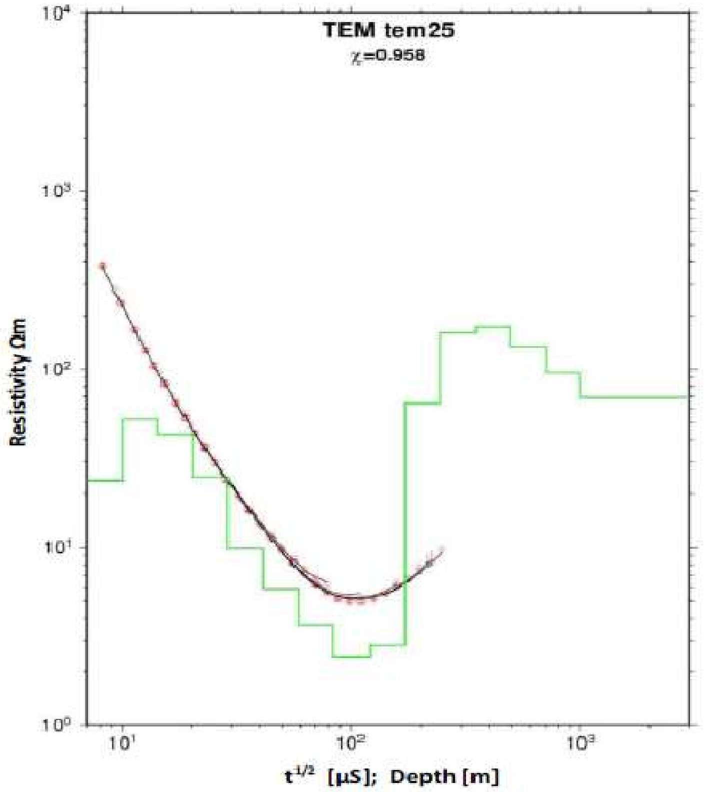


**FIGURE 3**: TEM sounding from Domes area and its 1-D inversion. It illustrates the TEM apparent resistivity curve and its interpretation.

### *MT survey*

A total of 70 MT soundings are considered for interpretation in the Domes prospect covering an area of about 45 km$^2$ as can be seen in (Figure 4). The data was acquired using 5-channel MT data acquisition system (MTU-5A) from Phoenix Geophyics.

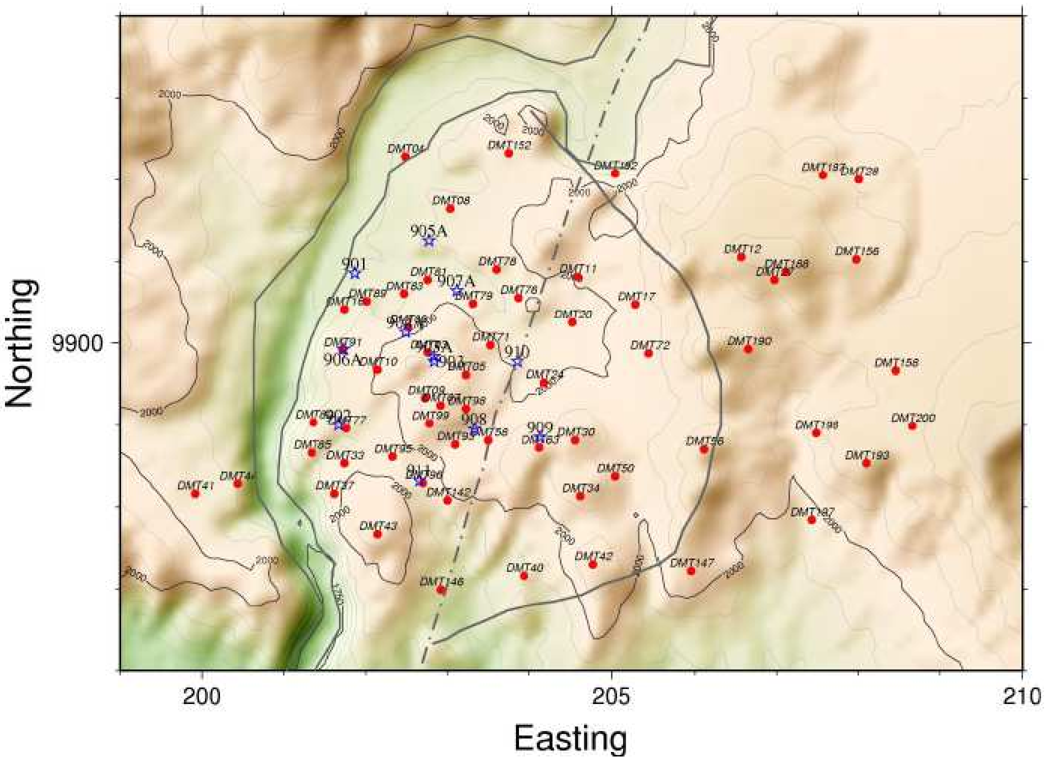


**FIGURE 4**: The MT sounding distribution over the prospect area

### *The MT static shifts*

The MT method suffers from the so called static shift problem. This phenomenon is caused by local resistivity inhomogeneities which disturbs the electrical field. The main cause is the accumulation of charges at resistivity boundaries causing the Electrical field not to be continuous close to 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 big problem in volcanic environments where resistivity variations close to the surface are often extreme. These parallel shifts in apparent resistivity curve can lead to large errors in inverted data.

In this interpretation Central loop-induction TEM sounding have been used to correct for static shift in MT data by jointly inverting both MT and TEM data. This is based on the fact that, for TEM measurements at late time there are no distortions due to near surface inhomogeneities since they do not involve measuring 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 environment.

### *Static shift analysis of MT data in Domes*

Static shift analysis of the 62 MT sounding was done in the Domes area where shifts factors in the range of 0.2 to 2.1 have been observed. This outcome indicate that about 57% of all the MT determinants were shifted down whereas 23% were shifted up with only 20% not showing any static shift (Figure 5). Therefore if interpretation was to be done without the static shift correction then we would have an error of 80% in resolving the resistivity structure for this field.

Figure 6 shows the spatial distribution of the shift multipliers in the Domes area. The map shows that there are some large areas where the MT apparent resistivity is consistently shifted downwards and other areas where it is shifted upwards. The orientation of shift spread could probably be used to infer certain geological structures since the shifts are as a result of near surface inhomogeneities.

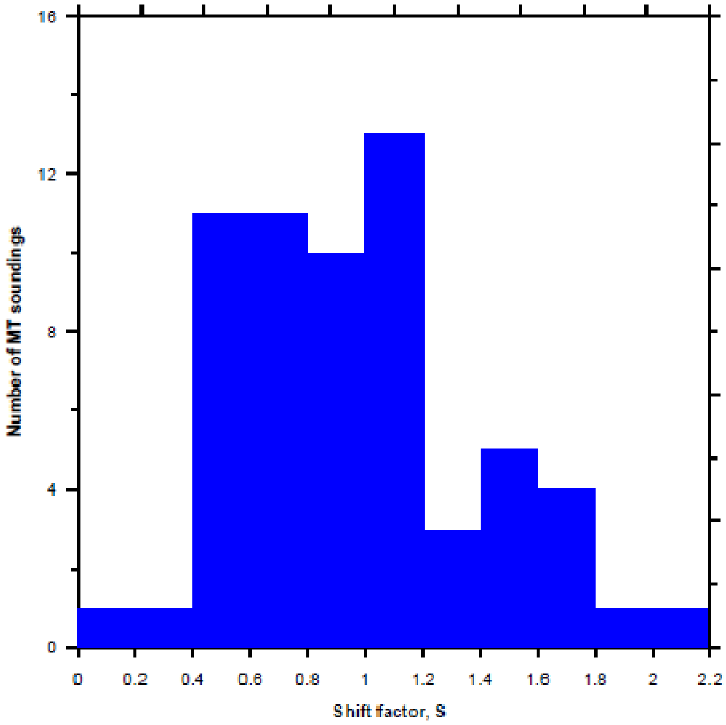


**FIGURE 5**: Histogram of static shift parameters for determinant apparent resistivity in the Domes area.

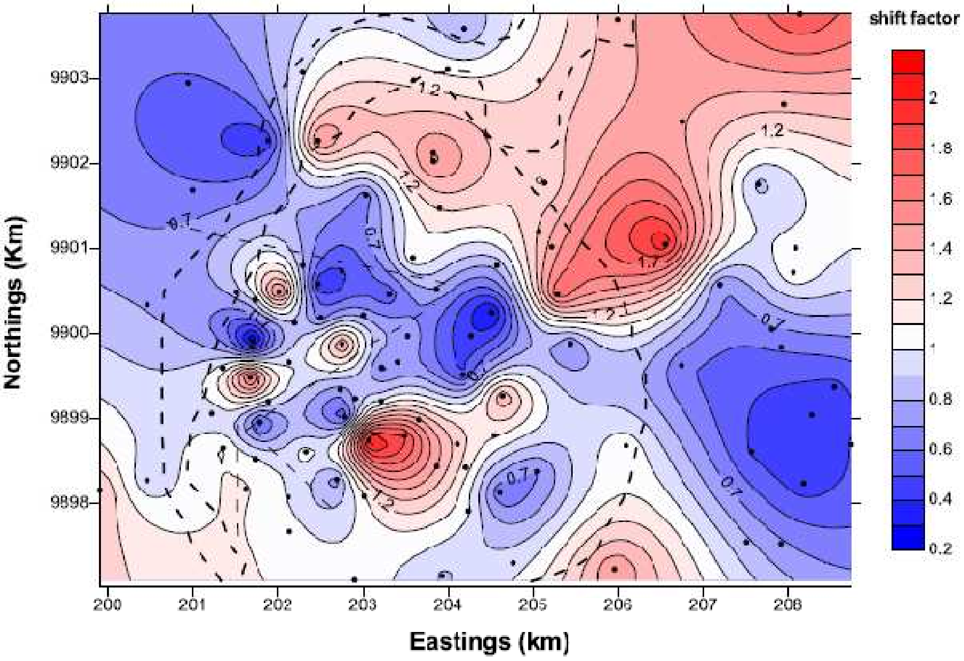


**FIGURE 6**: Spatial distribution of static shift parameters for determinant apparent resistivity in the Domes area.

## 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 use of an algorithm which determines the appropriate shift factor to be used to constrain the MT data to fit the TEM response. 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 TEMTD program was used to invert MT apparent resistivity and phase derived from the rotationally invariant determinant of the MT tensor elements. In the joint inversion, one additional parameter was also inverted for, namely a static shift multiplier needed to fit both the TEM and MT data with the response of the same model, (Árnason, 2006).

An example of a 1-D joint inversion of MT and TEM data is shown on Figure 7, where the red diamonds are measured TEM apparent resistivities and blue squares are the MT apparent resistivities and phase. Solid lines show the response of the resistivity model to the right. The shift multiplier is shown in the upper right hand corner of the apparent resistivity panel.

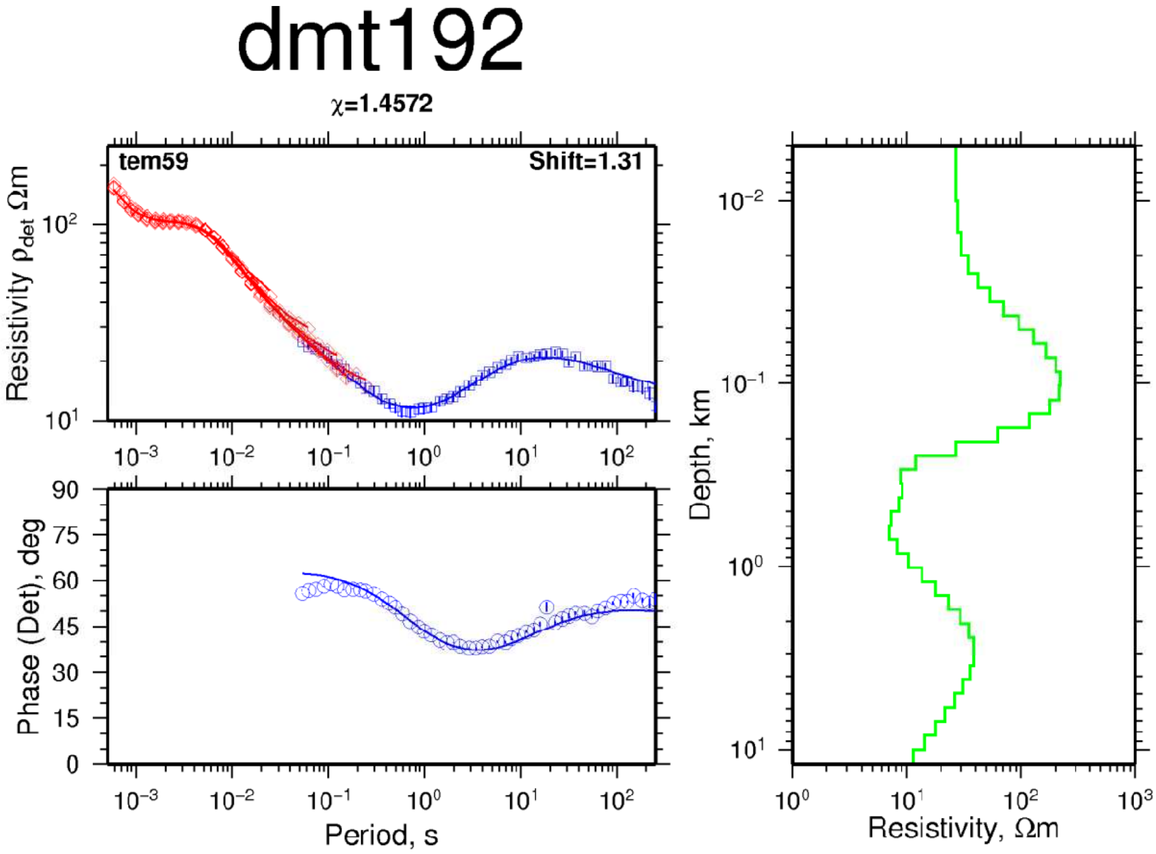


**FIGURE 7**: Typical result of a joint 1-D inversion of TEM and MT soundings

### *Cross-sections*

Resistivity cross-sections are plotted from 1-D inversion results by a program called TEMCROSS (Eysteinsson, H., 1998). The program calculates the best line between selected stations on a profile, and plots resistivity isolines based on the 1-D model generated for each sounding. Several vertical cross-sections were made through the survey area and their locations are shown on Figure 8. A sub-program called MAXDEPTH has been used to clip soundings to match their longest periods so that they do not give misleading depths of penetration.

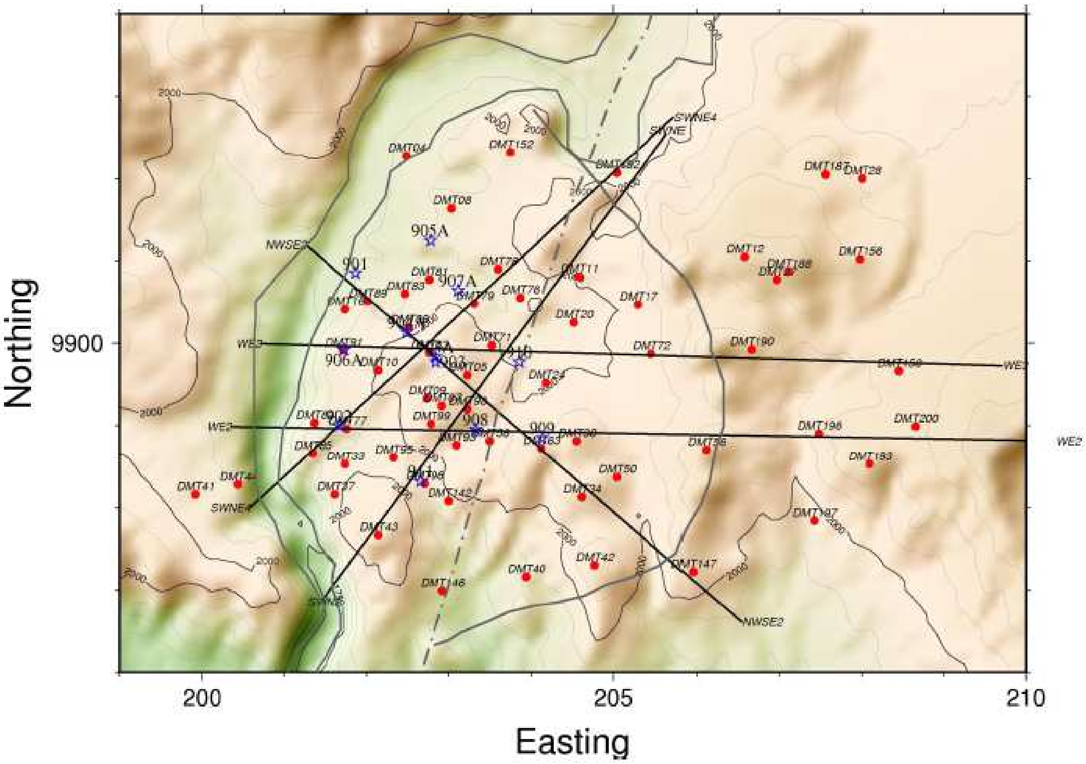


**FIGURE 8**: Domes profile map, red dot show location of MT stations and the blue stars are location of wells.

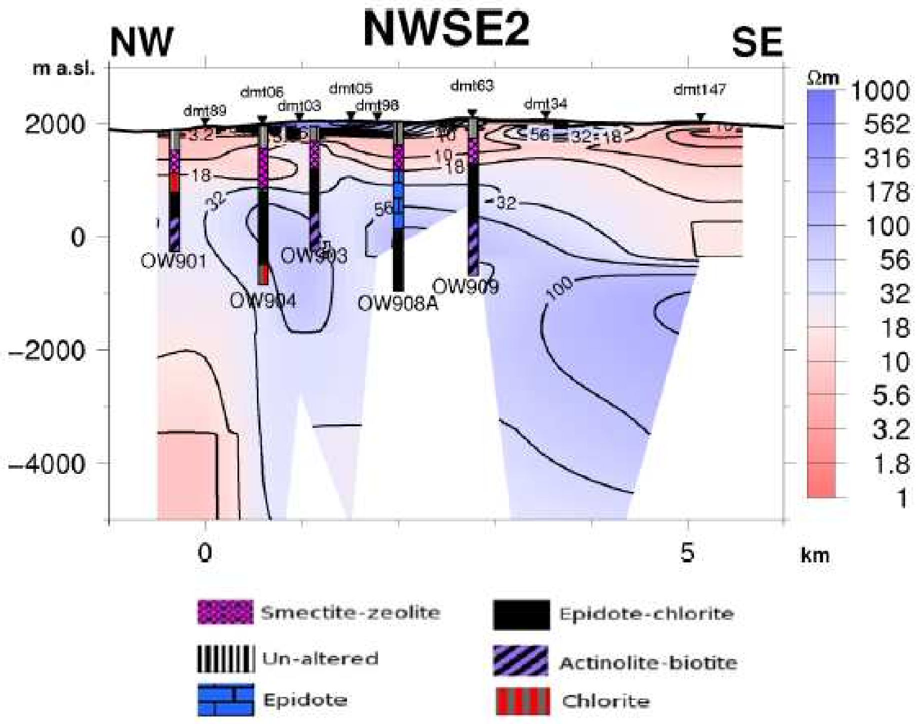


**FIGURE 9**: Resistivity Cross-section NWSE2 according to joint 1D inversion of TEM and determinant MT data.

**Cross-section NWSE2** is shown on figure 9; cutting through wells OW901, OW904, OW903, OW908A and OW909. A high resistivity (> 100 Ωm) occurs close to the surface below some of the sites, overlaying a low resistivity extending down to 0.5 to 1 km. This high resistivity could be reflecting unaltered rocks near the surface. The low resistivity (< 10 Ωm) here correlates well with the alteration clay minerals as seen in the wells close to the profile. Below the low resistivity zone is a high resistivity, with resistivity close to 50Ω m and increases to above 100 Ωm and stays relatively high in the chlorite and chlorite-epidote zones as evidenced from the drill holes.

**Cross-section SWNE** is shown in Figure 10. It shows a high resistivity in the uppermost 300 metres. The uniformly low resistivity layer of about 10 Ωm correlates well with the smectite zone as seen in the alteration mineralogy of well OW910. Below the low resistivity layer is a high resistivity layer reaching 100Ω m at about 2 kms depth. To the south west of well OW909 a low lateral resistivity discontinuity can be seen protruding up to depth of 1000 m.bsl below soundings dmt93. This low resistivity anomaly could be reflecting a fault-like structure. Also below OW909 a low resistivity can be seen at about 6 km depth which could probably be related to the heat sources for this part of the field.

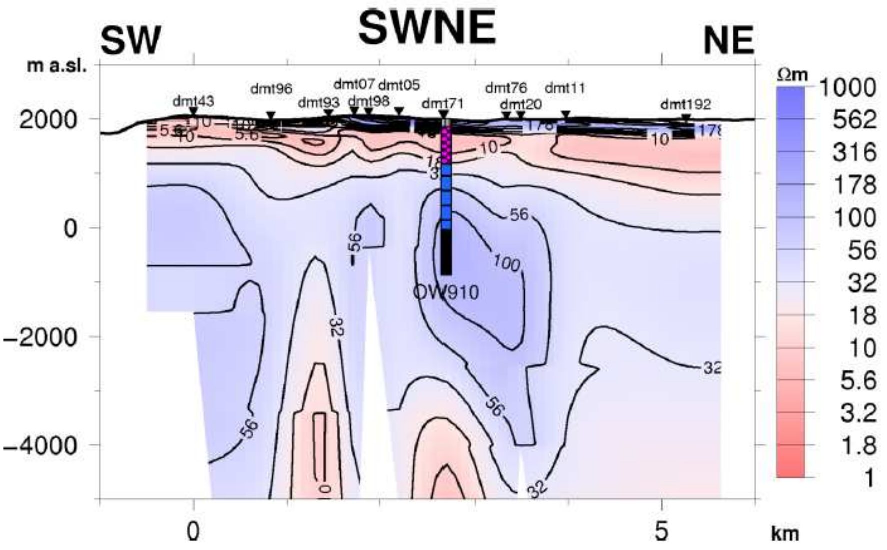


**FIGURE 10**: Resistivity Cross-section SWNE according to joint 1D inversion of TEM and determinant MT data

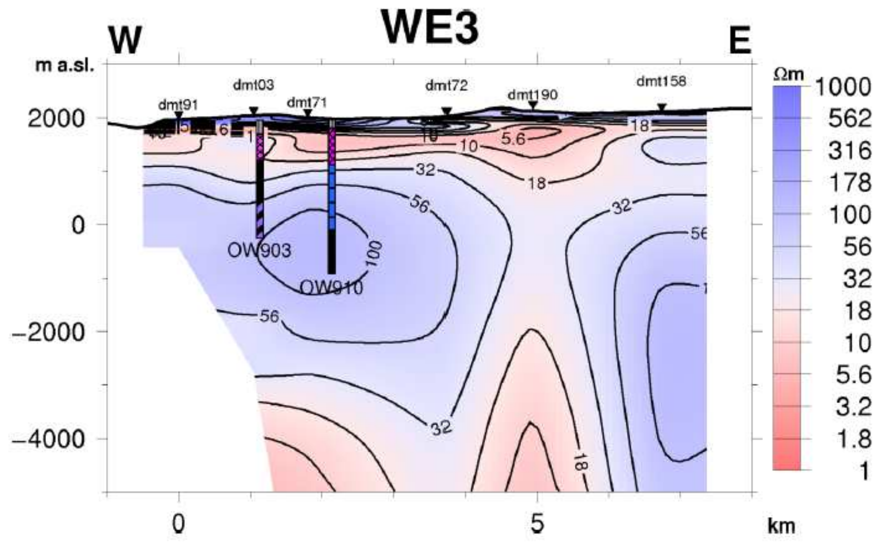
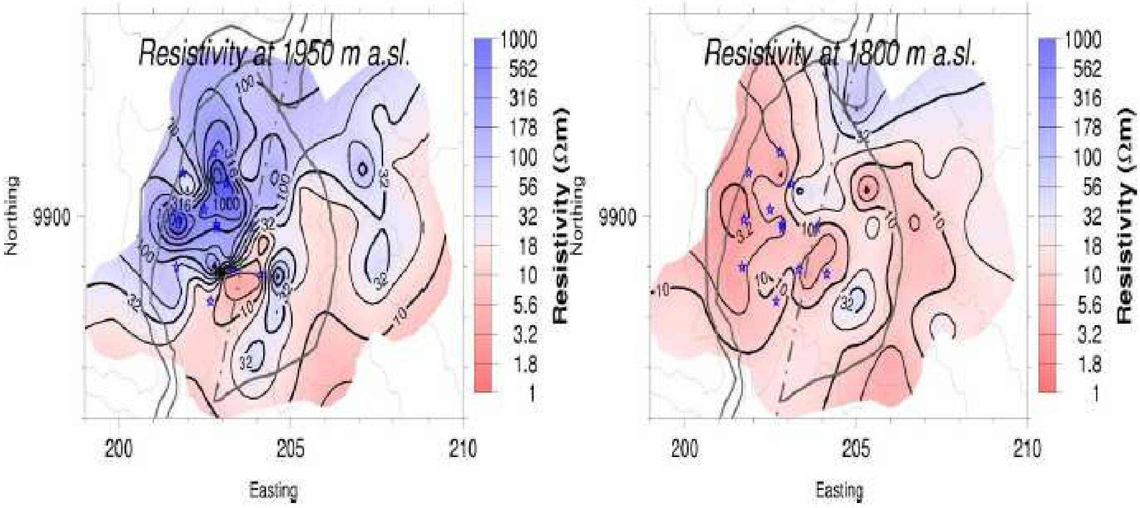


**FIGURE 11**: Resistivity Cross-section WE3 according to joint 1D inversion of TEM and determinant MT data

**Cross-section WE3** as shown in Figure 11 presents a typical resistivity phenomenon expected in a high temperature geothermal system. Where at the top of a high enthalpy geothermal system a clay cap with expandable clay minerals occur. Its resistivity is generally lower than in the overlying rocks exposed to lower subsurface. At depths of 4000 m.bsl, a low resistivity is emerging below the wells, this is the same low resistivity seen from cross-section SWNE and could probably be the heat source for this field though it's not well resolved at depth. To the east of the well OW910 and below sounding dmt190 another low resistivity can be clearly seen at depths of 4 km below the surface. This low resistivity body could be a magmatic intrusion earlier inferred by seismic studies as an attenuating body below the ring structure (Simiyu, et.al., 1998).

### *Iso-resistivity maps*

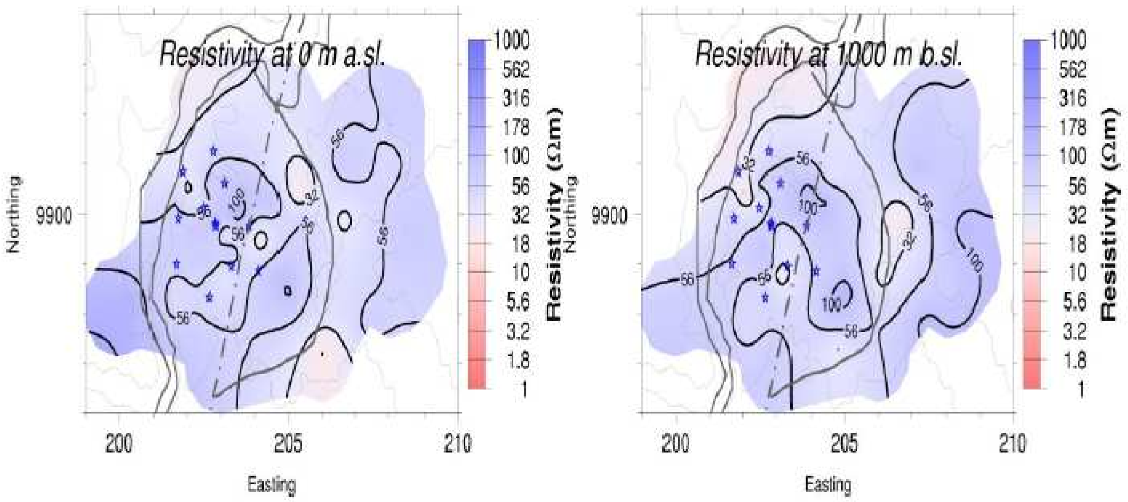
Iso resistivity maps are made by the TEMRESD program, which generates iso-resistivity maps at different elevations from the 1-D Occam models (Eysteinsson, H., 1998). In this report Iso-resistivity maps are presented from 1950 m a.s.l down to 5000 m.bsl, with the upper isomaps reflecting the TEM resistivity structure and the deeper ones representing the depth of penetration of the MT soundings.



**FIGURES 12 and 13**: Resistivity in the Domes area at 1950 and 1800 m a.s.l respectively, the blue stars shows the drilled wells and the black dots are the MT stations.

Resistivity map at 1**950 m a.s.l,** is shown on figure 12. This elevation is generally between 50 to 250 m below the surface within the study area. The map shows high resistivity (100 to about 1000 Ωm) on the western and northern sectors of the study area, the high resistivity is probably due to un-altered formations that overlay the low resistivity region. Low resistivity anomalies are seen one along the ring of Domes from the south and the other in the middle of the study area in NNE-SSE direction superimposed between high resistivity zones.

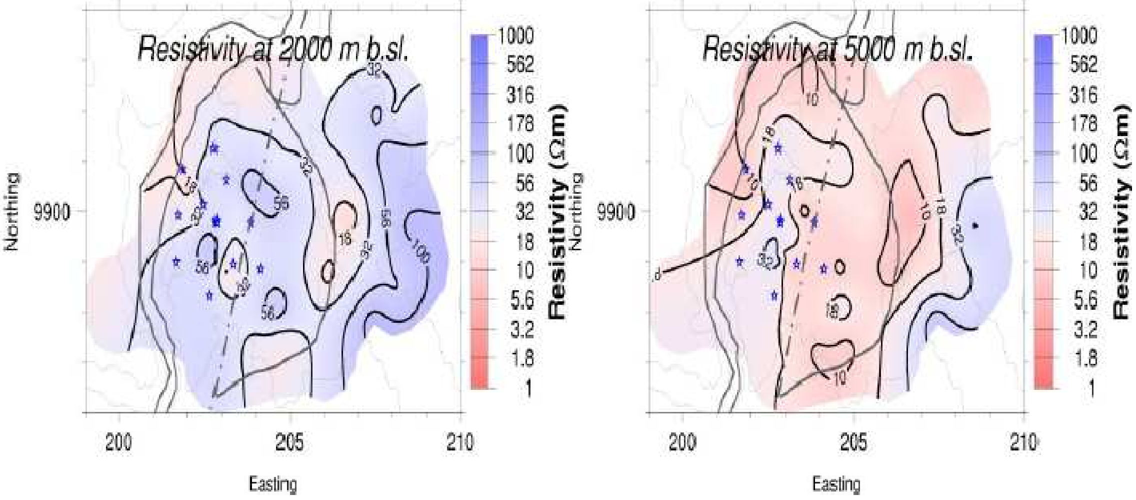
Resistivity map at **1800 m a.s.l,** is shown on figure 13. This elevation is at about 400 m depth from surface. The low resistivity appears on the eastern and central part with a linear low resistivity (< 10 Ωm) anomaly aligning N-S in the eastern portion of the map. These low resistivity spread over the area are associated with the alteration low resistivity clay region overlaying the high resistivity core of the geothermal system. The high resistivity anomaly patches seen in the middle portion of the map are probably remnants of the un-altered zone at this depth.



**FIGURES 14 and 15**: Resistivity in the Domes area at sea level and 1000 m.bsl respectively

Resistivity map at **sea level,** at this depth the high-temperature alteration (resistive zone) has fully set in with more dominance in the central Domes area where wells have been drilled and to the eastern sector of the survey area. This high resistivity perhaps reflects relatively high temperature zone where geothermal fluids may be prevalent. Superimposed between the high resistivity core is a lower resistivity aligned in NE-SW direction, this could probably be a zone of high permeability where hydrothermal alteration is not advanced, suggesting a possible up-flow zone beneath. A medium to low resistivity anomaly is starting to show up between Easting 205 and 207 aligned in North-South direction along the Domes ring structure.

Resistivity map at **1000 m.bsl,** is shown on figure 15. The resistivity is still high in most of the survey area. The low resistivity anomaly seen in the previous elevation is still present along the geological ring structure. A relatively low resistivity is also seen in the north-western sector of the study area, along the northern part of the Ol'Njorowa gorge.



**FIGURES 16 and 17**: Resistivity in the Domes area at 2000 and 5000 m.bsl respectively

Resistivity map at 2**000 m.bsl,** is shown on figure 16. The high resistivity is still dominant in the central sector of Domes field and to the East. The low resistivity anomalies seen 1000 m.bsl are more expressed here, one to the west of the field running in NNE-SSW along the Ol'Njorowa gorge and the other aligning in N-S direction along the Domes ring structure.

Resistivity map at 5**000 m.bsl,** At this depth the low resistivity is seen in almost the whole study area with the lowest resistivity (< 10 Ωm) aligning in NNE-SSW direction. This low resistivity could be reflecting the heat source. However it is not well observed in many MT sites due to lack of long enough period data.

### *Correlation of the resistivity structure with well temperature data and alteration*

This section describes observed relationship between electrical resistivity, alteration mineralogy and reservoir temperatures. The data presented is temperature logs from wells

901 through 910 and lithology from wells 901, 902, 903, 904, 908A, 909 and 910. A resistivity cross-section passing through wells 901, 904, 903, 908A and 909 is shown on Figure 18 with alteration mineralogy and temperature from those wells.

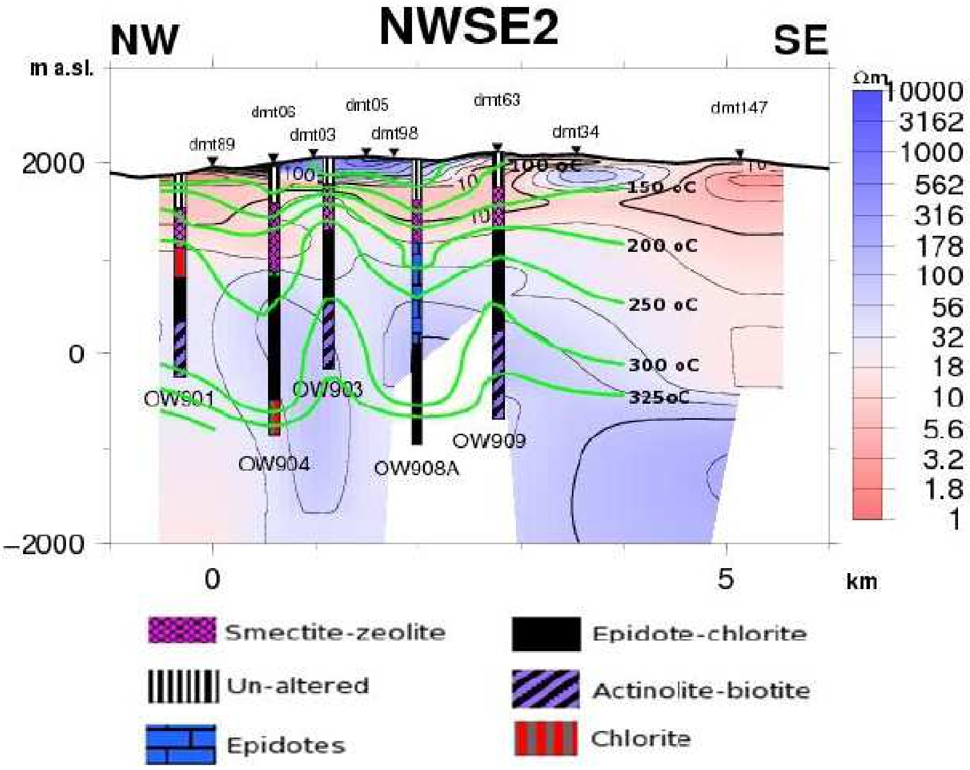


**FIGURE 18**: Resistivity cross-section, alteration zoning in wells and well log temperature.

A low resistivity zone of the order of 10 Ωm is observed between the surface high resistivity and the higher resistivity below at about 1-2 km depth. Five wells have been drilled along this profile showing the zones of dominant alteration minerals. Formation temperature isotherms, based on temperature logs from the wells are also projected into this profile. The figure shows very good correlation between the resistivity, temperature and alteration for the wells 904, 903, 908A, and 909. The resistivity is high in the cold, unaltered rocks outside the reservoir and decreases considerably as geothermal alteration, in the smectite-zeolite zone sets in. The bottom of this region correlates with temperature of about 100 °C and resistivity of about 10 Ωm. At around the 200°C isotherm the smectite-zeolite zone is slowly disappearing and is replaced by the mixed-layered clay zone, with resistivity in the range of 30 Ωm after which the resistivity increases considerably again and stays relatively high in the chlorite and chlorite-epidote zones at temperatures exceeding 250°C.

On the other hand well 901 show a very consistent correlation between the alteration mineral zones and resistivity. The low-resistivity cap (resistivity lower than 10 Ωm) coincides with the smectite-zeolite zone, which extends to about 800 m below the surface. In the chlorite-epidote zone also there is good correlation between resistivity and alteration though the resistivity is not as high as in the high resistivity core to the SE. The correlation with

temperature in the well (and partly also in well 904) is not as good, thus the alteration mineralogy is not in equilibrium with present temperature in the system which probably could be as result of cooling having occurred in that zone.

Studies have shown that the appearance of hydrothermal minerals can be used as indicators of past or present temperature and at the same time becomes an indicator of the impermeable behaviour of geological units because of the sealing of open fractured spaces. Therefore, hydrothermal mineralogy can be used as a support in defining the extent of the reservoir.

## DISCUSSION

In the Olkaria-Domes study area, the results show fairly good correlation with the available geological information. The compiled resistivity model from the 1-D inversions reveals that Domes 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 pyroclastic cover from the adjacent Longonot volcano. Below that is a low resistivity layer of about 10 which correlates very well with the mineral alteration of smectite-zeolite zone of the geothermal reservoir. This zone also correlates very well with the temperature in the range of 100-200 oC.

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, which has been confirmed by the drilled wells. Alteration mineralogy also is in agreement with resistivity structure confirmed by the presence of Epidote-chlorite zone. In the region around well OW901 the reservoir temperature is not in equilibrium with the alteration of the rocks.

The low resistivity seen at sea level in the middle zone of domes may be due to the low resistivity fluid in the pore spaces. Moreover, there is a consistency between the distribution of the relatively low resistivity zone at depth (>2 km bsl.) and the ring of domes alignment in the Domes sector. Therefore, this relatively low resistivity zone at depth possibly indicates a high temperature zone representing a major source of crustal fluids.

Comparison of well data with the resistivity structure shows a good correlation between the resistivity and alteration mineralogy. The low resistivity is dominated by conductive minerals in the smectite-zeolite zone at temperatures of 100-200 oC. In the temperature range of 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.

## CONCLUSIONS AND RECOMMENDATION

For geothermal exploration, MT method targets deep brine reservoirs and hot rocks that act as the heat source for a geothermal system under survey.

Results from the resistivity cross-sections derived from the 1-D joint MT and TEM inversions in Domes area reveals three layers namely: a very shallow high resistivity layer of > 100 Ωm, an intermediate low resistivity layer of > 10 Ωm underlying the upper high resistivity layer, and a deep high resistivity layer with values greater than 50 Ωm underlying

the low resistivity layer. MT resistivity cross-section also shows low resistivity at few kilometres depth below sea level that could be related to heat sources for this part of the field.

Based on these results it can be concluded that the Domes geothermal field host a much larger geothermal system than previously thought. The system appears to cover much larger area than the coverage of soundings. If there is equilibrium between the hydrothermal alteration of the rock and the present temperature in the reservoir, then the temperature in the high resistivity core is expected to be more than 250 °C as evidenced from the well data.

It is recommended that more long period MT and TEM data at the same location be acquired in order to define the extent of this field

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