Proceedings of the 4th African Rift Geothermal Conference
Nairobi, Kenya, 21-23 November 2012

Correlating Resistivity with Temperature and Alteration Mineralogy in Menengai Geothermal Field: Case Study of Menengai Well MW-01

Yussuf Noor, Janet Suwai and Deflorah Kangogo

Geothermal Development Company Ltd, P. O. Box 17700, Nakuru 20100, Kenya

ynoor@gdc.co.ke, jsuwai@gdc.co.ke, *dkangogo@gdc.co.ke*

Keywords: Resistivity, geothermal, temperature, alteration minerals, reservoirs

ABSTRACT

Resistivity surveys is one the methods used in identifying deep subsurface structures indirectly from the surface at relatively low cost, in comparison to probing by drilling. The geophysical techniques employed are aimed at mapping electrical resistivity of the earth's matrix beneath the surface to determine geothermal potential areas from the resulting resistivity anomalies. Magnetotelluric (MT) and Transient electromagnetic (TEM) images of the subsurface were applied in Menengai to map the anomalous geothermal reservoirs and electrically conductive heat source and cap rocks. Resistivity cross-section across Menengai geothermal field indicates four distinct anomalies of very resistive top layer of approximately 200m from the surface, followed by low resistivity layer (cap) overlying moderately resistive core (reservoir) underlain by deep low resistivity dense bodies, interpreted to be a heat source. Comparison between the resistivity structure and the subsurface well data, mainly alteration mineralogy and temperature profiles were carried out at the Menengai geothermal field. Results indicate that conductive minerals such as zeolite dominate in the temperature range of 80-200°C representing low resistivity cap between the depths of 400-800m. Between depths of 900-2200m, at temperatures of 200-240°C, zeolites diminishes and is replaced by more resistive clays. Above 250°C epidote dominates the relatively resistive reservoir core, where conductivity is controlled by pore fluids rather than clay minerals. Thus from this correlation it is clear that resistivity data can be interpreted and used in the prediction of pre-drilled well temperature and alteration mineralogy distribution with caution.

1.0 INTRODUCTION

The Menengai geothermal field (Figure 1) has been surveyed extensively for decades until present using resistivity methods among others to identify and delineate high temperature geothermal systems. MT resistivity method is the most preferred due to its ability to penetrate and probe resistivity structures much deeper beneath the surface, while TEM is used as a complementary to MT for static shift correction. The on-going analysis of resistivity data has revealed low resistivity anomaly overlying a moderately resistive sub-stratum at several points which have been the target for drilling exploration wells in Menengai geothermal.

Subsurface well data obtained from well MW-01 have been used to correlate hydrothermal alteration mineralogy and subsurface temperature data with resistivity structures obtained during surface exploration. The geothermal environment is prone to changes in resistivity resulting from geothermal fluids and hydrothermal alteration, forming clay minerals at different temperatures relative to depth. Despite the findings from this research that comes in handy in determining pre-drilled temperatures at different depths by correlating it with resistivity, caution should be taken not to misinterpret the findings since each field is unique and every low resistivity may not necessarily be a drilling target.

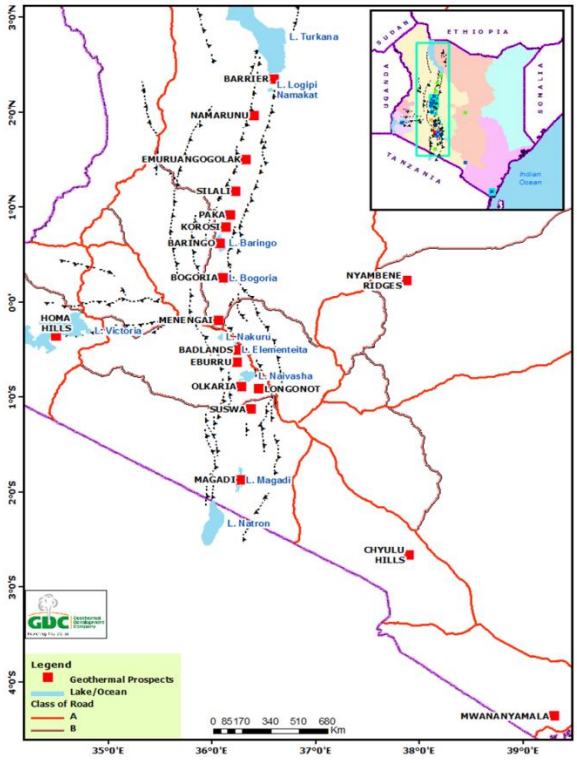

Figure 1: Location of geothermal areas in Kenya including Menengai geothermal field

2.0 VARIATION IN RESISTIVITY

Despite the insulator property of rocks in natural condition, several physical parameters such as porosity, salinity of saturating fluid, temperature and alteration mineral determine its conductivity in water-saturated rocks (Arnason et al., 2008). This property is summed up by Archie's formula (Archie 1942) for water saturated rocks as shown below:

$$\rho = \rho\omega \cdot \alpha \cdot \Phi^{-n}$$

ρ is the bulk resistivity, $\rho\omega$ is the fluid saturated resistivity,Φ porosity, n and α are the empirical coefficient

A study by Zulfadhli et al, (2010) correlating subsurface and laboratory resistivity of granite rock indicates field measurements with lower resistivity than laboratory analysis, suggesting the presence of water in the pores and

cracks of subsurface rocks. Thus the true resistivity of rocks is higher than the apparent resistivity attributed to the moisture content from water and minerals in the subsurface rock. A resistive sub-stratum overlain by a conductive zone consisting of altered minerals makes a drilling target for geothermal prospect (Mulyadi et. al., 1998). Mulyadi (1998) further attributed decrease in resistivity to increase in clay content, geothermal fluids, altered minerals, change in acidity and decrease in silica content.

3.0 VARIATION IN ALTERATION MINERALOGY

Metamorphism of minerals occurs under high pressure and temperature which tend to increase with depth as indicated by the expression;

$$p = \rho h g$$

Where p is pressure, ρ is the density, h is depth and g is the gravity

Other factors that alter minerals include hydrothermal interaction with the rock matrix that changes the chemical composition and mineralogy of the host rock. Alteration may further be accelerated and magnified by the pH nature of geo-fluid composition, while the result of the alteration is manifested in the clays and alteration minerals formed. Pri Utami (2000) revealed the existence of hydrothermal mineral assemblages of acidic nature that occupies the shallower level of the system characterized by the presence of Kaolin with or without smectite, alunite, quartz and pyrite. In the deeper level of the system, geo-fluid composition is neutral in pH resulting in the formation of epidote, wairakite, calcite, chlorite and interlayer clays.

4.0 TEMPERATURE VARIATION

Temperature is the key element in a geothermal system that determines the use of its output effectively, in that, high enthalpy system is used for electricity generation while low enthalpy is best suited for direct utilization. Temperature varies with depth in geothermal system where at shallow depth clay minerals such as kaolin and smectite dominate and stabilizes at ambient temperatures of about 80°C, while epidote, wairakite and laumonite are used as high temperature indicators (Pri Utami, 2000). However, at any stage in the system, temperature may change due to an encounter with cold recharge or thermal instability during measurement. Temperature also tends to increase with depth, as demonstrated by MW-01 temperature profile in this paper (Figure 4).

5.0 RESULTS

5.1 Resistivity Profile

To determine the resistivity of Menengai (MW-01) exploration well, cross section of MT 68 and TEM sample Mntem-66 profile conducted at the well pad (Figures 2, 3 and 4) was individually interpreted to correlate with well data. From the surface to about 200m (1800 masl) the resistivity is high (>1000 Ω.m), indicative of unaltered rocks extending from the surface. Low resistivity (<20 Ω.m) dominates from 1400-800 masl and is attributed to low temperature clay minerals such as zeolites detected. The low resistivity could have been influenced by other factors such as permeable fracture zones loaded with saline hydrothermal fluids, before the gradual rise in resistivity to a moderately high resistivity (>40 Ω.m) between 800 masl-200 mbsl. This is correlated with high temperature alteration minerals such as epidote. Highly conductive convex structures exist below 4000 mbsl (Figure 2) which is the heat source for the Menengai geothermal system not covered in this paper.

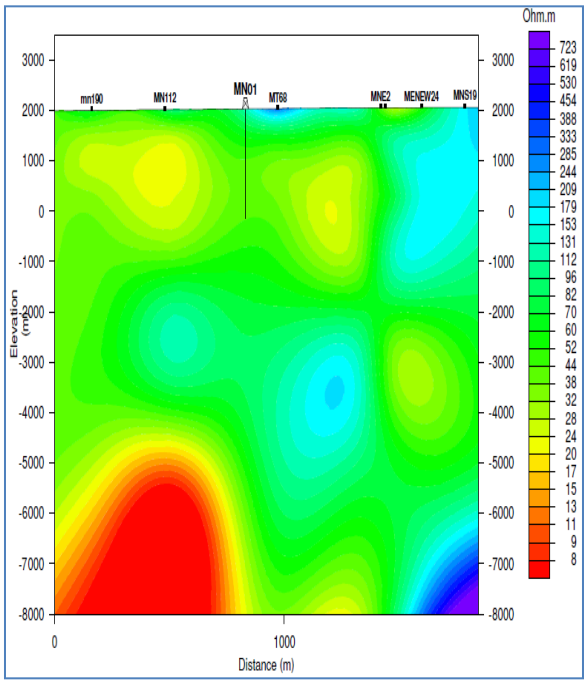

Figure 2: Resistivity cross-section of MW-01

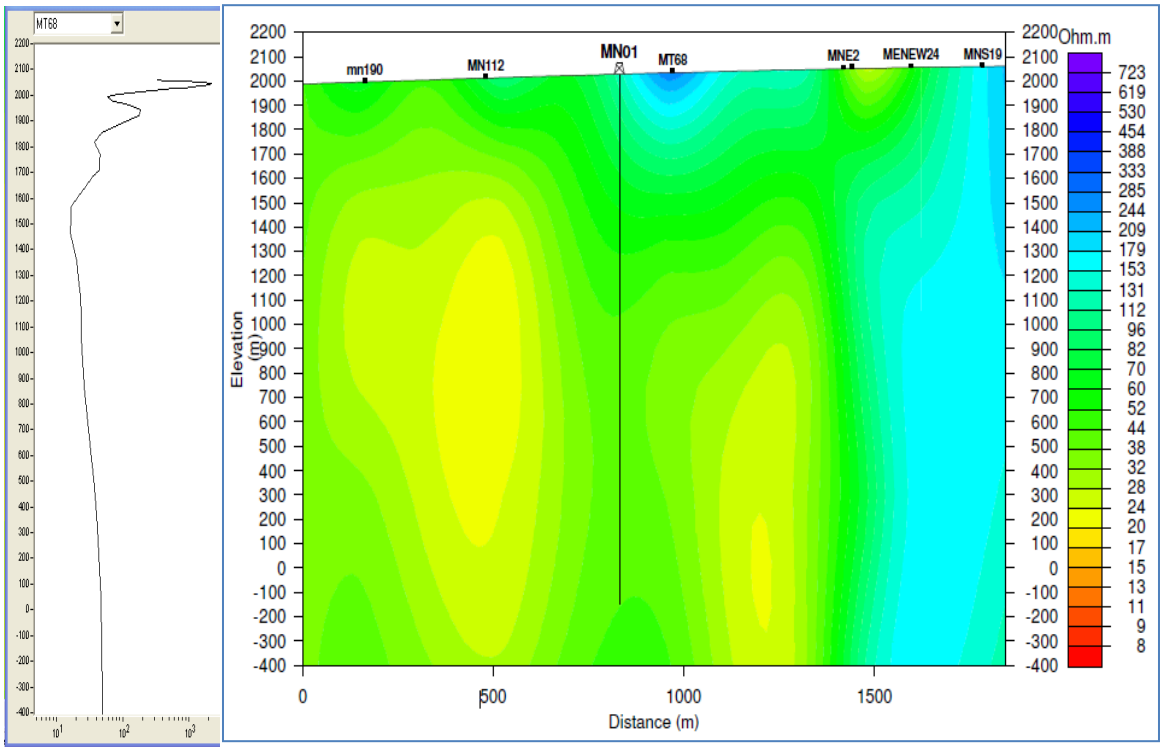

Figure 3: Resistivity cross-section of MW-01 and MT68 I-D Occam profile

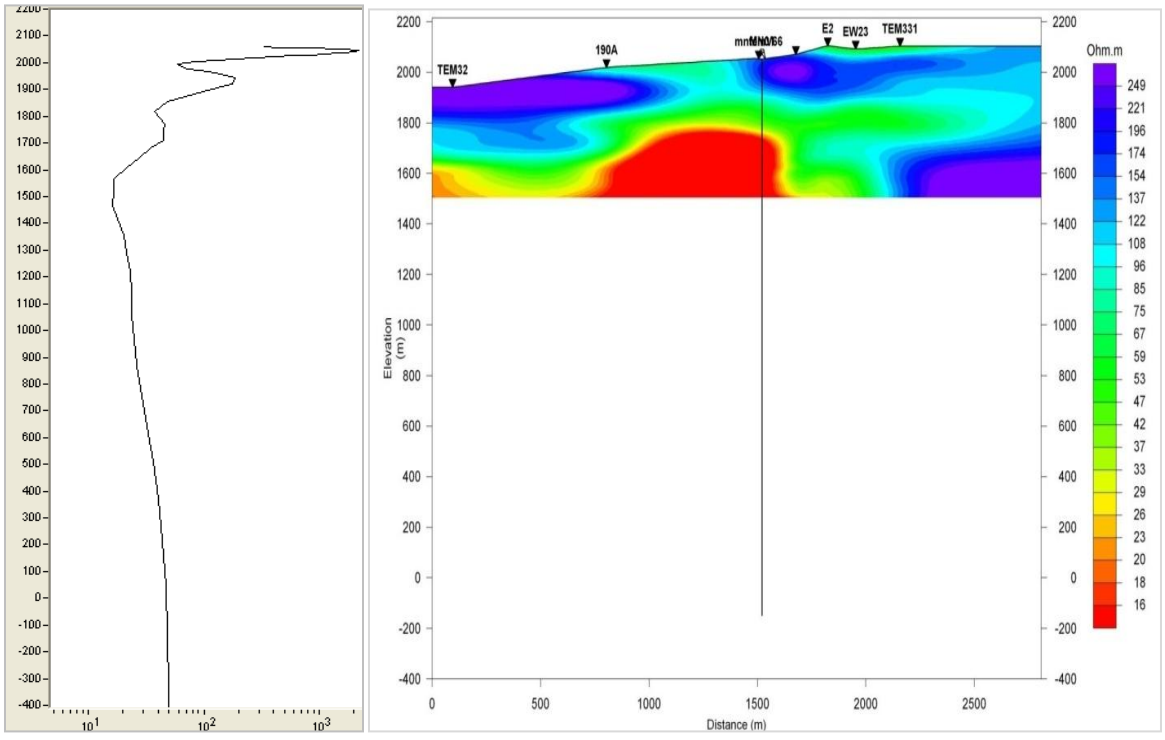

Figure 4: TEM resistivity cross-section through MW-01 and MT-68 I-D Occam profile

5.2 Temperature Logs

Several heat up temperature tests were done to appraise the recovery trend of wells caused by cooling effects during the drilling process. These recovery temperature logs are used to locate feed zones and evaluate formation temperature. Major feed zones are encountered at around 800m and below 1800m depth in MW-01.

The temperature in the upper formation (200m) is low (<50°C) coinciding with the resistive cold rock structure. However, between 200 and 400m a sudden drop in temperature correlates with a cold permeable zone indicated by total circulation loss. Above the depth of 500m, the alteration is non-existence to minimal indicative of less fractured system with low geo-fluid permeability. Temperature increases to a mid-level high between 500-900m to over 180°C. This middle depth zone is characterized by moderate alteration and intense drilling fluids loss of circulation, signifying a highly permeable zone due to feed zone around this horizon (Figure 5). Alteration minerals associated with this zone are zeolite and probably smectite, though undetected in the analysis of MW-01. This correlates well with conductive zone (<20 Ω.m) encountered in the apparent resistivity profile between 400 and 800m from the surface that makes cap rock in this system. Flowing profile indicates temperatures of over 270°C from the well bottom. This correlates well with temperature estimated from gas geothermometers for reservoir beneath Menengai and at Ol Rongai >270°C (Lagat et al., 2010). The high temperature zone is also characterized by secondary minerals such as epidote, albite, illite and quartz associated with moderate to high temperature formations (Anderson et al., 1999, Ussher et al., 2000). Resistivity profile in this region is in the range 45 Ω.m supporting the high temperature mineral formation that correlates very well with well temperature above 250°C (Figure 4). This agrees with resistive unaltered rock formation at the top, conductive cap rock and moderately resistive reservoir zone respectively.

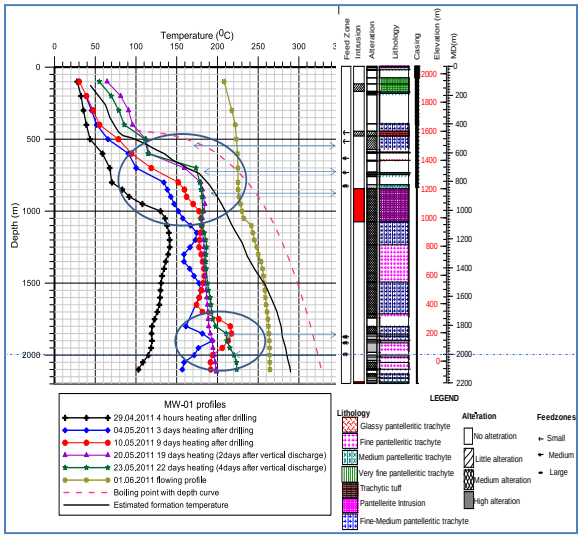

Figure 5: Temperature profiles in MW-01. Circles shows location of feed zones (Omondi, 2011)

5.3 Hydrothermal Alteration Mineralogy

Hydrothermal alteration is the replacing of primary minerals by secondary minerals due to changes in prevailing rock conditions. This is dependent on rock chemistry in addition to temperature, pressure, permeability, hydrothermal fluid and gas composition. The end products from alteration of primary minerals into secondary ones are used as temperature and permeability indicators. Alteration minerals in MW-01 are calcite, illite, quartz, albite, epidote and pyrites (Figure 6). The presence of pyrite and calcite from 500-2206m depth at the bottom of the well is an indication of good permeability, resulting from highly fractured reservoir. Above 200m, alteration level is minimal indicated by the presence of high resistivity impermeable cold rock formations. A low temperature indicator - zeolites - is seen above the depth of 500m. Illites dominate the lower depth of the well as the main clay minerals. Pyrite in particular indicates permeable zones through which hydrogen sulfides gas penetrates (Omondi, 2011). Chalcedony appears between 800-1100m, usually found in veins and fracture fillings. Quartz forms at the minimum temperature of 180°C (Omondi, 2011) and dominates from 800m to the bottom of the well. Albite dominates from 1300m to the bottom of the well indicating temperatures above 180°C. The main hydrothermal index mineral is epidote observed at a depth of 1100m to the bottom of the well usually implies the existence of minimum temperatures between 240-250°C. Therefore it is clear that hydrothermal alteration minerals display a gradual increase of temperature with depth. Whereas zeolites and calcites dominate the low temperature profiles, Illite/quartz and epidote persist in high temperature region.

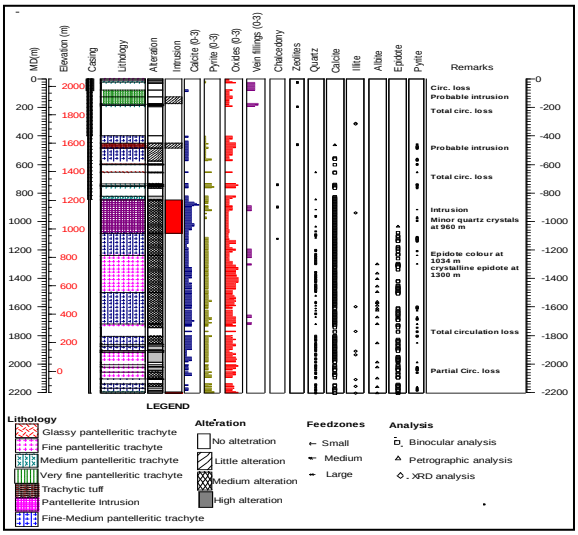

Figure 6: Lithology (and/or stratigraphy) and distribution of alteration minerals in well MW-01 (Omondi, 2011) NB: 0-3 shown in the calcite, pyrite, oxide indicate scale variation between 0 and 3 on the graph

6.0 DISCUSSION

Analysis and interpretations from subsurface apparent resistivities, hydrothermal alteration mineralogy and well temperatures are useful in establishing a relationship to characterize Menengai geothermal system. From Figure 6, three distinct regions clearly emerges from correlated parameters. At shallow depth above 200m below the surface, resistivity is high (>1000 Ω.m) corresponding to low temperature zone (<40°C) with negligible hydrothermal alteration minerals - these are unaltered cold rock formations.

The low resistivity (<20 Ω.m) encountered between 400-800m correlates with medium temperatures (about 200°C) and moderate hydrothermal alteration level that resulted in the formation of conductive clay minerals such as zeolites detected in MW-01 profile. In general, the low resistivity could have been due to hydrothermal fluids in a highly fractured formation supported by high permeability alteration mineral indicators such as the calcite, pyrites and conductive clays indicated. The conductive portion of this system represents the cap rock composed of clay minerals such as zeolites that overlies the reservoir.

Below the depth of 800m to the bottom of the well, resistivity increased gradually with depth to a moderate value (<45 Ω.m). The moderately high resistivity sub-stratum correlates well with high temperature formations. This could have been due to less clay content corresponding to resistive epidote presence indicating temperatures above 240°C. The zone is highly altered and permeable indicated by calcite and pyrite to the bottom of the well.

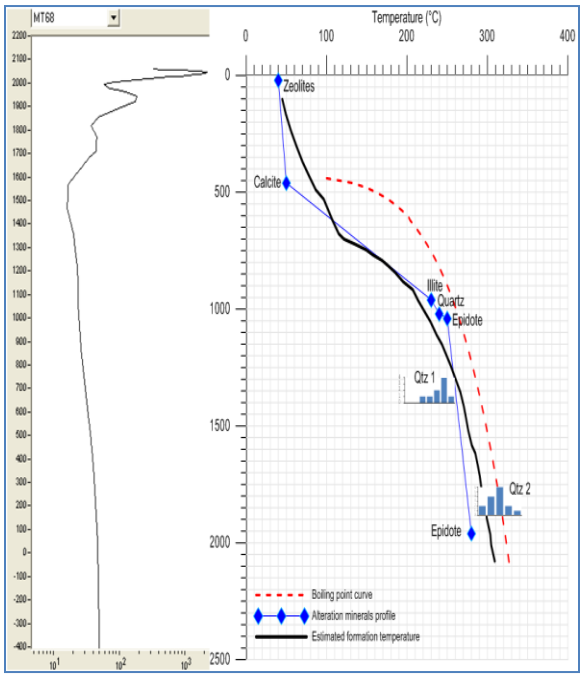

Figure 6: Profile of resistivity correlation with estimated formation temperature and alteration minerals (modified from Omondi, 2011)

Fluid inclusion temperatures indicate that the system in Menengai is at equilibrium since the homogenization temperature correlates well with the hydrothermal alteration and the measured temperatures (Figure 6).

7.0 CONCLUSION

1. The geothermal system of Menengai reveals cool, impermeable highly resistive sub-stratum 200m below the surface overlying a low resistivity zone in the middle, highly altered with clay mineral presence and medium temperature.
2. The reservoir zone is characterized by a high temperature downhole profile supported by elevated temperature indicators from alteration mineralogy presence of epidote indicating temperature above 240°C.
3. There is evidence that the Menengai geothermal field is highly fractured and permeable below 500m indicated by intense alteration with calcite and pyrite abundance in to the bottom of the well.
4. Temperature, alteration mineralogy and resistivity correlate well especially from MW-01 data, thus MT/TEM resistivity survey data can be used to infer pre-drilled well temperature and secondary hydrothermal alteration minerals with careful interpretations.

ACKNOWLEDGMENT

The authors would like to thank Geothermal Development Company and the entire team of geoscientist and technicians who made the data available for this manuscript. Special thanks to Joseph Moore for his resourceful critique and review of this paper.

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