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INTERGRATED GEOPHYSICAL METHODS USED TO SITE HIGH PRODUCER GEOTHERMAL WELLS

Anastasia W. Wanjohi,
Kenya Electricity Generating Company Ltd.
Olkaria Geothermal Project
P.O. Box 785-20117, Naivasha
KENYA
awanjohi@kengen.co.ke or amuragz@gmail.com

ABSTRACT

The aim of geophysical exploration is to measure the earth's physical properties in order to delineate geothermal fields, locate aquifers, site wells and provide information on which economical exploitation can be based on. During these measurements, emphasis is put on parameters that are sensitive to rock temperature, permeability, porosity and salinity of the fluids that are contained in the rock matrix.

By use of all geophysical method in one field and integrating all their data in interpretation, we have been able to site deeper wells that are good producers producing up to 16MWe. We have been able to map out various structures such as intrusive rocks (possible heat source), porosity variations, faults and dyke systems. We also liaise with other departments (e.g. geology and geochemistry) so as we can combine notes and come up with a detailed accurate conceptual model of the area.

1. INTRODUCTION

Kenya is endowed with a huge geothermal resource due to the presence of the Kenya rift which is part of the East African rift system (Figure 1). With increased emphasis on geothermal development, new exploration methods are needed in order to improve general understanding of geothermal reservoirs, characterize their extent and assess the potential for sustainable utilization and site high producer wells. Surface investigations geological, geochemical, and geophysical and reservoir studies indicate that the potential is over 7000Mwe if fully exploited. The geothermal activity is attributed to Neogene volcanic activity which has resulted to the presence of near surface heat generating sources. Geothermal fields of the Kenya rift occur in two types of environments. The main geothermal fields are associated with Quaternary volcanoes. The second type is associated with fissures that are related to active fault zones. In either case, these fields are dissected by numerous rift faults that give rise to a number of geothermal springs and fumaroles.

1.1 Objectives

Geophysical exploration is carried so as to answer specific geophysical questions based on literature review or specific interests. The main objectives for carrying out geophysical surveys in geothermal areas are:

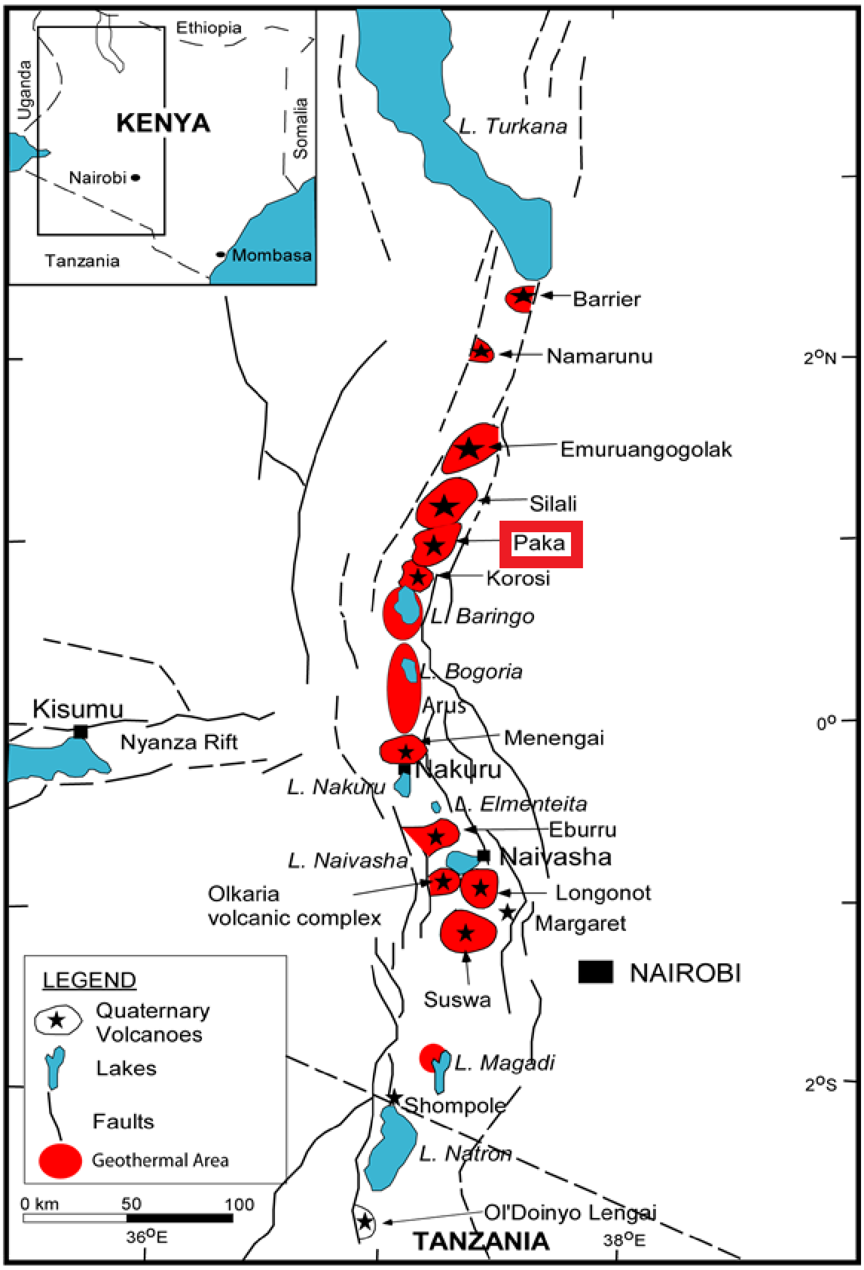

FIGURE 1: Map showing location of geothermal area along the Kenyan rift valley.

- To detect and delineate geothermal resources
- To identify and locate exploitable reservoirs
- Estimate geophysical properties of the geothermal system
- To get a conceptual model that will assist in siting of the drill holes through which hot fluids at depth will be exploited
- Drill a productive well

2. GEOPHYSICAL EXPLORATION

Geophysics is the study of the earth by the quantitative observation of its physical properties and its surroundings by methods such as seismic, electrical and electromagnetic, magnetic and radioactivity methods. In geothermal geophysics, we measure the various parameters connected to geological structure and properties of geothermal systems. In lay man's language, geophysics is all about x-raying the earth and involves sending signals into the earth and monitoring the outcome or monitoring natural signals from the earth.

Geophysical methods play a significant role in the investigation of geothermal prospects because they are the only means to finding deep subsurface structures at much lower costs than the most direct method, drilling. A relatively wide area can be surveyed within a short time using geophysical techniques. Geophysical exploration does not overrule the need for drilling but, if properly applied, it can optimize exploration programs by maximizing the rate of ground coverage and minimizing the drilling requirement. Geophysical methods are widely used in terms of siting drilling targets.
A wide range of geophysical surveying methods exists for exploration of geothermal energy as well as monitoring of geothermal reservoirs under exploitation (Ndombi, 1981; Mariita, 1995; Simiyu and Keller, 1997). The type of physical property to which a method is sensitive to assists in deciding the method to be used in a particular survey depending on the outlined objectives.

2.1 Electrical/ electromagnetic methods

Electrical/electromagnetic methods are methods where the variation in physical properties is directly related to the geothermal system (e.g. temperature). They include thermal and electrical methods (DC and AC methods). These methods utilize direct currents or low frequency alternating currents to investigate the electrical properties of the subsurface. There are many electrical methods used in electrical prospecting depending on the source field. Some make use of naturally occurring fields within the earth while others require the introduction of artificially generated currents into the ground (Kearey and Brooks, 1994).

2.1.1 Thermal methods

Thermal methods directly measure temperature and heat (temperature surveys). No other methods have such a good correspondence with the properties of the geothermal system. There are approximately four sub-categories: temperature alone (direct interpretation, mapping); geothermal gradient (vertical variation of temperature measured in soil or drillholes); heat flow (calculated from the product of gradient and thermal conductivity); heat budgets (measuring spring flow and steam output and/or integrating heat flow). Measuring the temperature alone or the geothermal gradient is of direct significance in local geothermal work, while measuring the heat flow is more of a regional or global interest.

Heat can be exchanged in different ways such as by conduction (transfer of heat through a material by atomic vibration (often in steady-state); convection (transfer of heat by motion of mass, i.e. liquid, natural circulation of hot water); and through radiation (does not play any significant role in geothermal exploration). Conduction plays a significant role in the transfer of heat in the earth's crust. Thermal convection is usually a much more effective heat transfer mechanism than thermal conduction and is most important in geothermal systems

2.1.2 Electrical resistivity methods

An electrical method is either a sounding method or a profiling method, depending on what kind of resistivity structure is being investigated. Sounding method is used for mapping resistivity as a function of depth while profiling method maps resistivity at more or less constant depth and is used to map lateral resistivity changes. Electrical methods can either be DC or AC. In DC-methods, a constant current $\boldsymbol{I}$ (independent of time) is introduced into the ground through a pair of electrodes at the surface of the earth. The current creates a potential field in the earth. By measuring the electrical field $\boldsymbol{E}$ (potential difference over a short interval), the subsurface resistivity can be inferred. Schlumberger soundings, head-on profiling, dipole soundings and profiling are useful DC-methods.

For AC, transient electromagnetic method (TEM), magnetotellurics (MT) and audio-magnetotellurics (AMT) methods are common. In magnetotellurics (MT) and audio-magnetotellurics (AMT), fluctuations in the natural magnetic field of the earth and the induced electric field are measured. Their ratio is used to determine the apparent resistivity. The time domain or transient electromagnetic method (TEM) is a method where a magnetic field is built up by transmitting a constant current into a loop or grounded dipole; then the current is turned off and the transient decay of the magnetic field is measured. It is used to determine the resistivity.

Measuring the electrical resistivity of the subsurface is the most powerful prospecting method in surface geothermal exploration since resistivity is directly related to the properties of interest, like salinity, temperature, porosity (permeability) and alteration mineralogy. To a great extent, these parameters characterise a reservoir (Hersir and Björnsson, 1991). The specific resistivity, ρ, is defined through Ohm's law, which states that the electrical field strength $\boldsymbol{E}$ (V/m) at a point in a material is proportional to the current density $\boldsymbol{j}$ (A/m^2):

$$\boldsymbol{E} = \rho \boldsymbol{j}$$

The proportional constant, ρ, depends on the material and is called the (specific) resistivity and measured in Ωm. The reciprocal value of resistivity is conductivity ($1/\rho = \sigma$). Resistivity can also be defined as the ratio of the potential difference ΔV (V/m) to the current I (A); across material which has a cross-sectional area of 1 m^2 and is 1 m long.

$$\rho = \frac{\Delta V}{I}$$

2.2 Structural methods

Structural methods are also called indirect exploration methods. In these methods, physical properties investigated do not directly relate to the geothermal system since the anomaly is caused by associated geological formations or structures (e.g. fault, dykes). These methods are gravity, magnetic and seismic.

2.1.1 Magnetic methods

Magnetic methods in geothermal exploration are applied in mapping geological with an aim of locating and determining depth of concealed intrusives, tracing dykes and faults, locating buried lava, determining depth to basement, locating hydrothermally-altered areas, and paleomagnetism.
Magnetic method is a passive potential method that measures naturally occurring phenomena i.e. small, localized variations in the Earth's magnetic field. In magnetic surveying, we measure the strength of the earth's magnetic field, which will vary locally depending on the amount of magnetic material in the underlying rocks. Where the rocks have high magnetic susceptibility, the local magnetic field will be strong and such areas will show up as areas of high magnetic field strength. The magnetic properties of naturally occurring materials such as magnetic ore bodies and basic igneous rocks, allows them to be identified and mapped by this method. Strong local magnetic fields or anomalies are also produced by buried steel objects. The depth of penetration of magnetic surveys is unaffected by high electrical ground conductivities, which makes them useful on sites with saline groundwater, clay or high levels of contamination where the GPR and Electromagnetic methods struggle.

2.1.2 Gravity method

Gravity Method involves measurements of the gravitational field at a series of different locations over an area of interest. The objective is to associate variations with differences in the distribution of densities and hence rock types. It is relatively cheap, non-invasive, non-destructive remote sensing method. Gravity method is a passive method, meaning no energy is needed to be put into the ground in order to acquire data thus the method is suited to populated area. Porosity and pore fluid content are probably the most important factors affecting density in the shallow sub-surface.

In geothermal exploration, the gravity method is used to detect geological formations with different lateral densities. Different types of rocks in the crust and mantle have different densities, hence different gravitational forces. The gravity force between two masses, m_1 and m_2, at a distance r apart, is given by Newton's law of gravitation (m_1 is the first mass and m_2 is the mass of the earth):

$$F = G\frac{m_1 m_2}{r^2}$$

where G is the universal gravitational constant, $G = 6.670 \times 10^{-11}$ Nm^2/kg^2.

Gravity variations are measured with a gravimeter. These are very sensitive mechanical instruments which measure the change in acceleration (g) at one place relative to another reference place (relative measurement). The unity for acceleration is m/s^2. A gravity unit (g.u.) is equal to 10^{-6} m/s^2. One g.u. is equal to 0.1 mgal. The sensitivity of gravimeters is about 0.005 mgal.

In order to obtain information about the subsurface density from gravity measurements, it is necessary to make several corrections to the measured gravity values before they can be represented in terms of geological structures. The final corrected value for the gravity anomaly is called the Bouguer anomaly.

2.2.3 Seismic method

Seismic method is a used for studying seismic energy propagation through the earth. This method is used to study seismic velocities of rock units in the subsurface with an aim of sub-surface strength, horizontal and vertical discontinuity of the sub-surface and structures hosting ground water, minerals etc. Depending on the instrumentation used and scope of the study, this method is capable of resolving depth of up to 10 km. The method can either be active or passive.

Active seismic measurement involves injecting sound into the ground and recording the energy that reflects back at different times and locations on the surface using geophone receivers. Processed seismic data can give information about subsurface geology, including rock types and fault structures. It can also be correlated with gravity surveys to define more accurate velocity models which provide more accurate depth estimates hence can assist in locating drilling locations. Passive seismic method makes use of natural induced micro-earthquake activities and can be used to delineate permeable fractures acting as a flow path for geothermal fluids and to delineate the brittle-ductile zone and also to monitor useful indicators in natural or induced reservoir phase changes during exploitation of a geothermal field (Simiyu et al, 1998).

3. INTEGRATED INTERPRETATION

Proper interpretation of geophysical data is paramount. It should be noted that there is no superior method thus integration of different geophysical techniques has been effective in mapping defined structures in tectonic regimes where geothermal resources are found. Exploration of the Olkaria geothermal resource started in 1956 with deep drilling commencing in 1973 (Ouma, 2010). In those days, geophysical methods used were not advanced in technology and were not many as is these days. DC methods were used for exploration of the Olkaria field. Wells X1 and X2, which were not productive, were sited using the results of the surface exploration.

Currently and for the past decade, geophysical methods have greatly revolutionised and technology grown tremendously. In Olkaria field we commonly carry out a variety of geophysical measurements such as MT, TEM, gravity, magnetic and seismic and use the results jointly to interpret and come up with the geophysical conceptual model.

Often we use these methods in combination. For example, magnetics is done along with gravity. Since geophysics is highly mathematical, it is sometimes prone to ambiguities in interpretation. At the interpretation stage, ambiguity arising from the results of one survey may often be removed by consideration of results from a second survey method. Furthermore, although many of the geophysical methods we employ require complex methodology and relatively complex mathematics in processing and interpretation of data, we derive much information is derived from a simple assessment of the survey data.

Figure 2 shows MT/TEM map at sea level showing the resistivity structure. High resistivity anomalies have been observed in a north west - south east trend from Olkaria west to Olkaria domes.

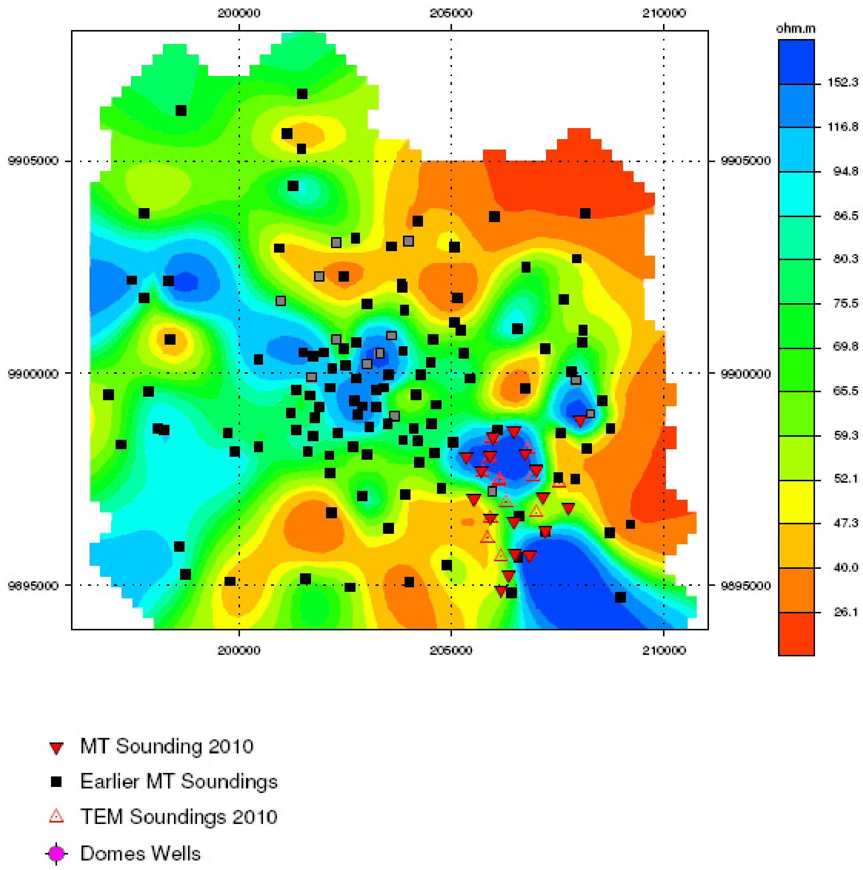

FIGURE 2: Map of the greater Olkaria area (GOGA) showing resistivity at sea level (approx. 2.5 km depth).

The resistivity anomaly can be well supported by the results of seismic studies in the area (Figure 3) where earthquakes tend to occur in a similar trend as the resistivity. Plot b shows the depths of events and can be used to map heat sources in Olkaria.

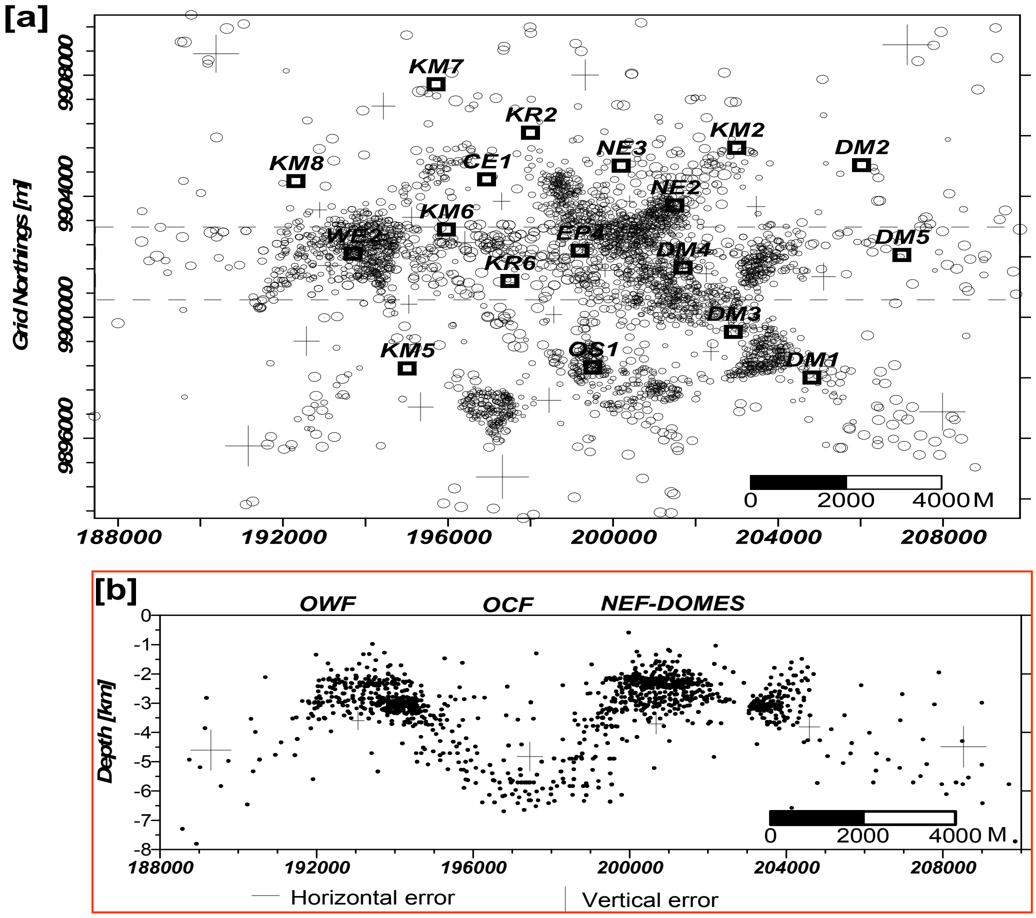

FIGURE 3: Plots with event distribution in Greater Olkaria area (GOGA) (Simiyu and Keller, 1997)

Figure 4 shows the total magnetic intensity over Olkaria and also shows high magnetic intensity is a NW-SE trend. This is much in line with the resistivity and seismic anomalies. Figure 5 shows a cross-

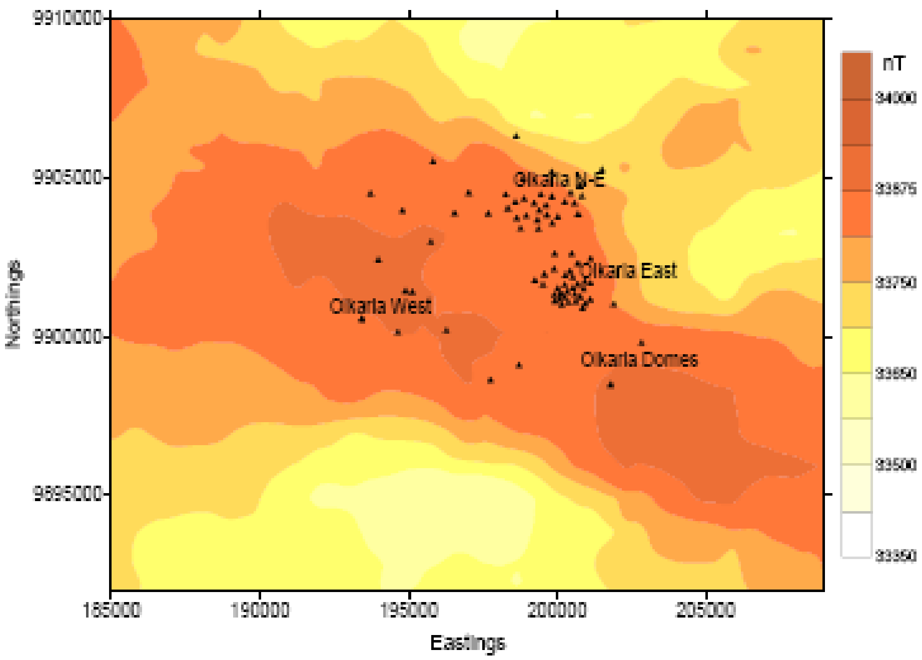

FIGURE 4: Map showing total magnetic intensity over Olkaria (Mariita, 1975)

section in Domes area oriented NW-SE. Alteration mineralogy has been integrated in this profile so as to aid in the interpretation. The alteration mineralogy and temperatures from geology are in line with the results obtained earlier.

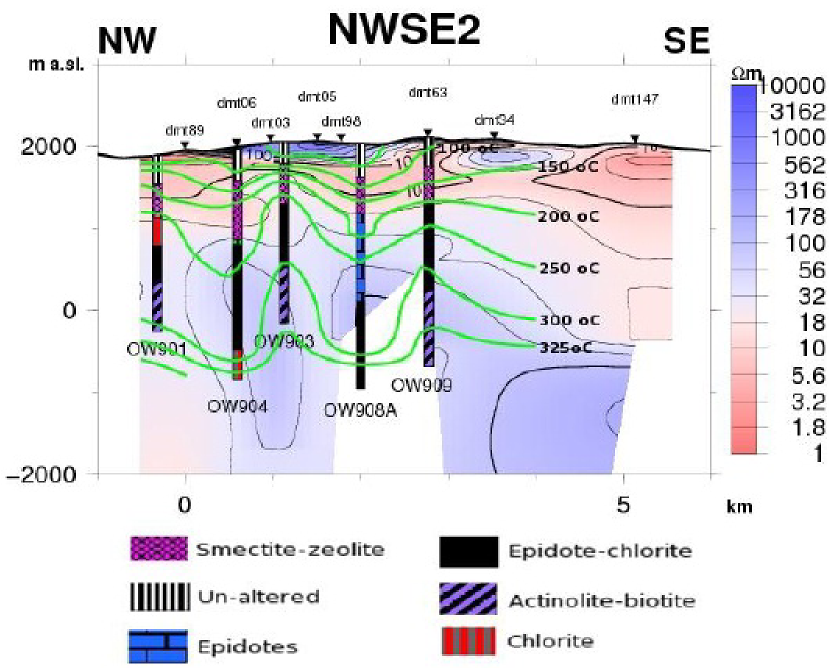

FIGURE 5: MT resistivity profile map across NW to SE in domes. Resistivity varies laterally and vertically.

By integrating results from all geophysical methods together with information from other geoscientific disciplines such as geology and geochemistry, we have been able to site with wells confidently and with accuracy.

3.1 Siting high producer wells

In the earlier days, geothermal wells were being drilled to a depth of about 2000 m. We are now able to drill wells up to a depth > 3000 m since the dynamics of the geothermal system are well understood. Intersection of faults is normally targeted during siting of wells since we expect good permeability. This information is provided by structural methods. Earlier sited wells produce an average of 3 MW while current wells produce and average of 9 MW. This has greatly reduced the cost of drilling since the number of well have been reduced by more than 50%.

By use of results of one geophysical method say MT and TEM, we may be able to site a well. Resistivity results will highlight reservoir zones and the heat source. For a complete geothermal system, we need to have all elements of a geothermal system i.e. heat source, reservoir, fluid channels, and a cap rock. We now need some geophysical results that can give information on the remaining parameters. We normally combine these results with seismic and magnetic results to be able to confidently site a high producer well.

4. CONCLUSION

Costs of geothermal power plants are heavily weighted toward early expenses such as well drilling and pipeline construction. During this stage, resource analysis of the drilling information is carried out. The risks of development and the time for construction can tremendously be reduced if the total number of production wells can be reduced by half. Well output variability exists in the Olkaria Geothermal field where two wells produce about 19 MWe contrary to earlier 6 wells that could produce the same output. If these high production wells were drilled at the beginning of the project, there would have been tremendous savings on the infrastructure and the total costs of developing the geothermal power plants. On average it takes about 45-60 days to drill wells to a depth of 3000 m. The time taken to develop Olkaria field would have been greatly reduced and at the same time realize greater output. Reducing the number of wells by half, the project costs and therefore the cost of steam per KWh will be reduced significantly and increase the number of plants that can be constructed.

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