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GEOPHYSICAL METHODS FOR GEOTHERMAL RESOURCE CHARACTERIZATION

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ABSTRACT

The most commonly used methods for geothermal exploration are geological mapping, geochemical studies, geophysical measurements and exploration drilling. There is no one particular method, which can be used on its own to select the best site for drilling with a high rate of success. It is therefore important to carry out a survey using a suite of the above methods and integrate the results in order to select the best site for drilling. It is very important to note here that drilling a successful exploration well is the most critical part of the geothermal development. Moreover, the cost of one exploration well drilling is higher than that of surface exploration. The methods applied to site exploration and production wells should therefore be thorough.

1. INTRODUCTION

The geophysical methods applied usually measure physical properties which are related to geothermal systems. To locate and map a geothermal system, the system must then have anomalous physical properties different from those of the surrounding country rocks.

The most important physical properties are temperature, electrical resistivity, magnetisation, density, and seismic velocity. Derived from these physical properties are then have thermal, electrical, magnetic, gravity, and seismic geophysical methods.

Planning for a geophysical survey is perhaps one of the most important, yet often overlooked, steps. The planning should consider available information, maps, accessibility, security, personnel, equipment and budget. Before a detailed geophysical survey is undertaken, desktop review of all available information from the area is carried out and reinterpretation done if possible. Based on this review, a detailed survey should then be planned to build on the existing data, correct previous errors made and infill gaps that exist. If there is no previous information, then a reconnaissance survey is done before a detailed survey is carried out. There should be no geophysics undertaken in an area without geology because geophysics

depend on the physical properties of the rocks and the structures in an area. The geological information will assist in the interpretation of the geophysical data to a large extent.

The use of modern equipment and data interpretation software is also important in order to take advantage of technology for example the use of GPS to identify measurement locations. The use of computers for data collection, storage and interpretation is central to geophysical surveys. The use of GIS for storage and presentation of geophysical data and information from other exploration methods is becoming increasingly critical. The collected data is reviewed and initial interpretation made where possible as it is collected so that instrumentation or human errors can be corrected while in the field. Discovering these errors in the office would make it impossible to repeat measurements cost effectively.

Local communities should be involved as much as possible in carrying out some of the unskilled work. They can provide very important information such as shortcut routes to use, areas known for geothermal manifestations and security.

Handling of the field data is as important as collecting it. Duplicating data is important so that if one set is lost or damaged, there is another set available.

Having collected geophysical data, the next most important step is to interpret it into something useful. The first objective is to determine whether a geothermal reservoir exists worthy drilling into. This is the most challenging part. It is usually not possible to do this without integrating results from the other exploration methods. Therefore, the interpretation of the geophysical data will develop a geophysical model which can be integrated with other models. The best site for exploration drilling is that location that is supported by many of the other models. By integrating the results of the other disciplines, the survey should therefore come up with a unified geothermal reservoir model on which the best exploration well or wells can be sited. Although KenGen usually has a strategy of three exploration wells if the first one failed, would rather have the first successful exploration well. The second objective is to determine an area large enough for development or certain targets for appraisal and production drilling.

Geophysical methods are grouped into direct and indirect. There are numerous text books and papers on geophysical surveys which the reader can be referred to for example by Keary and Brooks (1992) one report specifically prepared for geothermal exploration by UNU-GTP programme by Hersir and Björnsson (1991). It is therefore not the intention of this paper to go to great details but to give an overview of some important geophysical aspects based on field experiences at KenGen in Kenya.

2. THERMAL METHODS

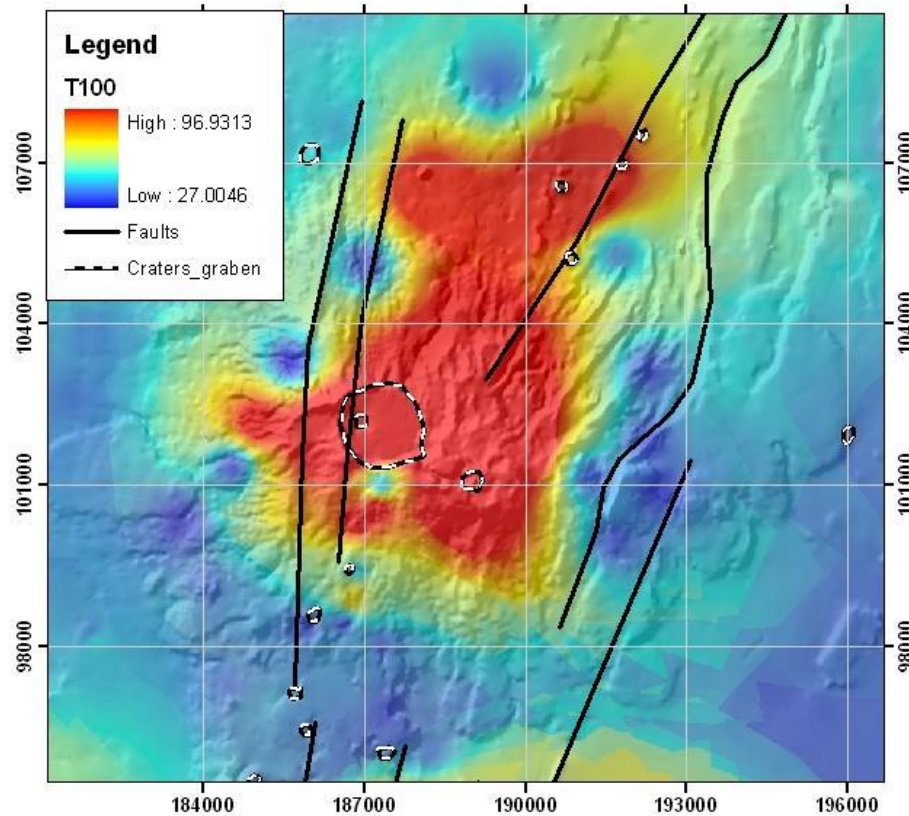
2.1 Introduction

Thermal methods are direct methods that measure temperature and heat. The methods use temperature measurements in soil, temperature gradient in shallow wells, and heat flow calculated from the temperature gradient and thermal conductivity of rocks. The temperature is affected by the method of transfer of heat in rocks and can be through conduction or convection. Convection is very much dependent on fluid movement in rocks through pores and fracture permeability. The data obtained from these methods are often very difficult to interpret and therefore the thermal methods tend to be of limited use particularly in detailed surveys.

2.2 Surface measurements of temperature in soil

Temperature is measured in an augured hole 0.5-1m deep in a grid form. The distance between measurements is dependent on the area to be covered and ranges from tens of meters to hundreds of meters.

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FIGURE 1: Temperature distribution map at 1m depth at Paka Prospect in Kenya (from Mwawongo, 2007)

manifestations like fumaroles, hot springs etc (See Figure 1).

2.3 Infrared (IR) Surveys

This method uses infra-red scanners measured from an aeroplane flying at very low altitude. It detects radiated heat and has been used to detect warm grounds and hot springs over a large area. However, it is possible to miss many hot areas unless the radiation is very strong. Infra red survey was carried out in the early stages of Olkaria (Noble and Ojiambo 1976). Since IR tends to map areas of fumaroles which can be mapped by geology, it is no longer being used.

2.4 Temperature Gradient (TG) Wells

This method measures temperature profiles in shallow wells drilled up to 200-300m using small water well rigs. The temperature gradient can be determined and areas of above normal thermal gradients can be mapped and deeper temperatures can be estimated. An area with ground water wells is good for this survey. However, if no wells are available, some can be drilled quickly based on some other methods like geochemistry and resistivity to increase information base and eliminate some areas before deep 1000m or deeper wells can be drilled. The temperature in the holes is measured using a thermistor every say 5m.

The temperature contour maps are then drawn at fixed heights above or below sea level rather than depths from the surface to reveal areas of high temperature gradient.

The main weakness of the TG method, like IR and soil temperature, is that an area mapped this way could be located in an outflow part of the system and therefore not necessarily located directly above the main upflow zone.

KenGen has never drilled temperature gradient wells as a surveying method although measurements are made whenever there are any available shallow wells in the locality.

2.5 Heat Flow surveys

Heat flow measurements provide the areal distribution of a geothermal field and the total flow of heat from that system. The conductive heat flow is calculated by multiplying the temperature gradient determined from the temperature gradient wells with the conductivity of rocks determined in the laboratory or published. Since the geothermal reservoirs are structurally complex and thermal conductivity quite variable through a system, the thermal heat evaluation is difficult and also makes this method of limited use.

3. ELECTRICAL METHODS

3.1 Introduction

The electrical resistivity methods are the most useful methods for geothermal exploration because resistivity is directly related to temperature, fluid salinity, alteration minerals and permeability of the reservoir rocks. These factors will affect the resistivity in the following manner:

1. The presence of fresh water in a rock will reduce the resistivity to some degree due to conduction of electricity through the water. However, as the salinity of the water increases, this continues to reduce the resistivity of the rock as shown in the graphs given in Figure 3.
2. Temperature: As the temperature of water (even fresh water) decreases the resistivity of rocks up to about 200 °C (Figure 2). This is because the temperature increases the mobility of ions. However above this temperature, a decrease in dielectric permittivity of water increases resistivity. It is usually said that a supersaturated reservoir full of steam would show high resistivity rather.
3. Porosity: It has been observed that the resistivity of water saturated with water varies inversely as the square of porosity. This means that the resistivity decreases as the porosity increases because the water in a more permeable rock will have better movement of the ions. In a reservoir, fluids tend to move more easily in the fractured rocks and at the formation contacts. The conductivity at the contacts and fracture formations would then decrease the resistivity much more than the pores in the rocks.
4. Alteration minerals: Field measurements have shown that at temperatures below 200°C, smectite clay minerals form and dominate the alteration assemblage. Smectites are relatively conductive minerals and therefore reduce the resistivity of the rock formations. Between 200- 250 °C, there is a transition where above this temperature chlorite and epidote, which are high temperature alteration minerals, dominate the alteration assemblage. Chlorite and epidote are resistive minerals and therefore the formation would show an increase in resistivity in very hot reservoirs which would appear paradoxical.

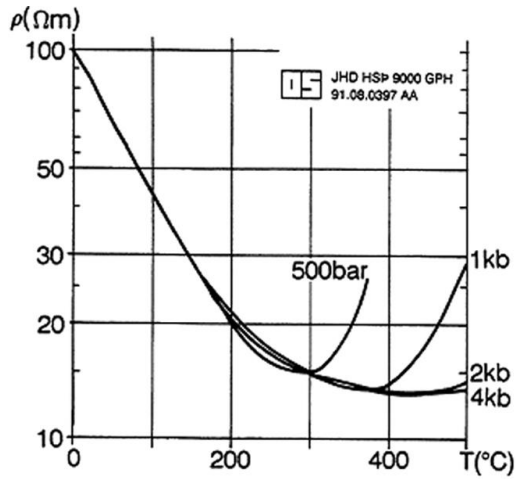


FIGURE 2: Resistivity variation with temperature at different pressures (from Quist and Marshall, 1968)

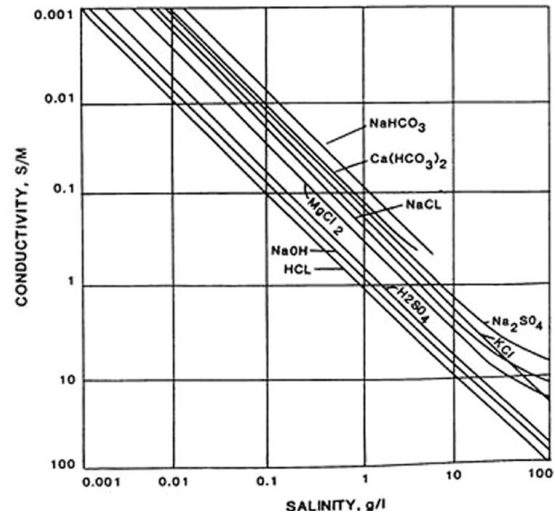


FIGURE 3: Pore fluid conductivity vs.salinity concentrations for different salts(From Keller and Friscknecht, 1966)

The problem, which the Geophysicist has therefore to struggle with, is to determine what parameters are in play in the reservoir and which affect the resistivity being measured on the surface. However, most of the high temperature reservoirs indicate resistivities below 50 ohmm. It is the anomaly of the area relative to the generally resistivity structure that is of importance rather than the absolute resistivity values.

3.2 DC- Resistivity Method

In direct current (DC) resistivity method, a known amount of current is injected at two points and the voltage due to this current is measured in the middle between the injection points. The voltage measured is dependent on the distance between the current injection points, the distance between the voltage measuring points and the conductivity of the rocks through which the current has travelled. Resistivity can then be calculated using well established formulae. In order to determine the variation of the resistivity downwards through several layers of different types of rocks below a fixed point, the current injection distance is increased logarithmically (see field layout in Figure 4). This is called resistivity sounding. The resistivity would then decrease or increase

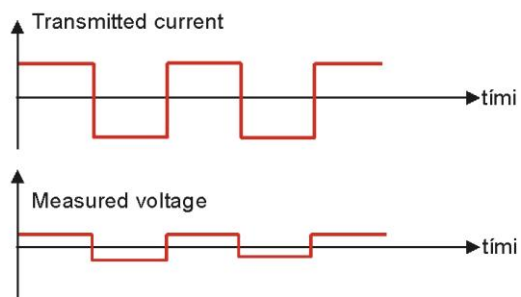
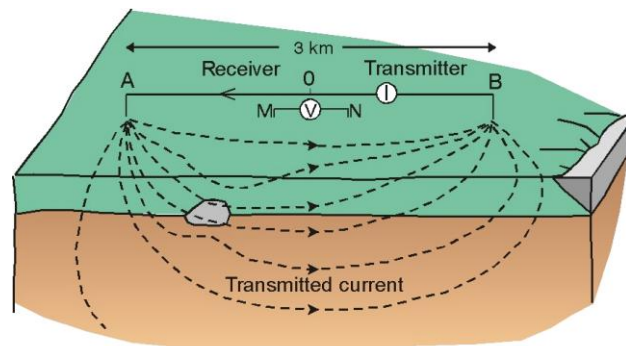


FIGURE 4: Schlumberger DC resistivity layout with transmitted and received current and voltage wave forms (from Hersir and Bjornsson, 1991)

depending on the rock types and factors described above affecting the resistivity in the formation.

A typical apparent resistivity plot is shown in Figure 5. If the resistivity variations at a given depth is to be determined over a large area, then the measurements are done with the fixed length of current injection but the centre is moved around either a long a grid pattern or along the access roads. The resistivity can be plotted to form a map indicating the variation at the same fixed depth. This is known as profiling. It is important to note that the resistivity measured is usually called apparent and one needs to interpret it using now readily available software to determine the true resistivity of the formation. It is therefore important to indicate when plotting maps whether it is apparent resistivity or true resistivity. Apparent resistivity data can be used to create maps similar to the profile maps and the tendency is to make sounding measurements, which can be interpreted into various layers, and also plot apparent resistivity maps without resurveying again.

The configuration commonly now used to make resistivity measurements is called Schlumberger array as shown in Figure 4. In order to penetrate very deep say 2000m which is the depth of most geothermal reservoirs, the current injection array need to be at least 4000m apart which is quite wide? This then creates a practical problem of laying the current cables across such a large span. Also the amount of current required is large for it to effectively penetrate to the desired depth and this creates a problem with the type of instrumentation to be procured and if the equipment has to be carried in inaccessible terrain, this can be a limiting factor.

The other problem of Schlumberger resistivity measurements is that since resistivity variation is logarithmic, the resolution decreases with depth and therefore introduces errors in the interpretation of the various layers at large depths. Therefore the method is sensitive to shallow layers than the deeper layers. It has also very poor resolution in generally low resistivity environment for example areas with sea water or shall clay layers and therefore prevents current penetration.

3.3 Electromagnetic Resistivity Methods

The electromagnetic methods use alternating current which induces an electromagnetic field. The electromagnetic field then induces a secondary current within the rocks proportional to the field and the conductivity of the rocks in which that secondary current is moving. The source of the current can be artificial as in TEM or can be the natural earth magnetic field as in MT.

3.3.1 Transient Electro Magnetic (TEM) Method

The field layout for TEM measurements is shown in Figure 6. A loop of wire is placed on the ground about 300m by 300m and a constant magnetic field of know strength is generated by passing a constant current in the loop. The current is then switched off and the decaying magnetic field induces a secondary current in the ground. The current distribution in the ground in turn induces a secondary magnetic field, which decay with time. The decay rate of the secondary magnetic field is measured by measuring the voltage induced in another small loop of some 10m x 10m located at the centre of the big current loop. The decay rate of the voltage in the small loop is recorded as a function of time after the current is switched off. From these measurements, apparent resistivity is determined. A typical log-log plot of apparent resistivity against depth is given as Figure 8.

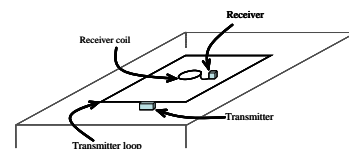


FIGURE 6: Central loop time domain TEM layout

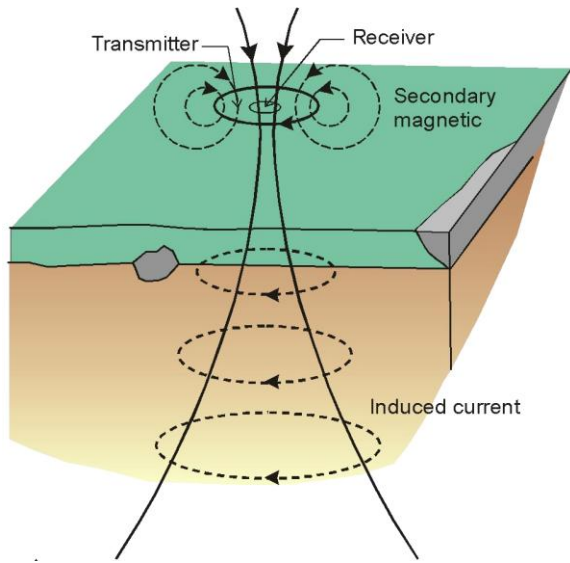


FIGURE 7: Transient current flow in the ground and current voltage signal (from Hersh and Björnsson, 1991)

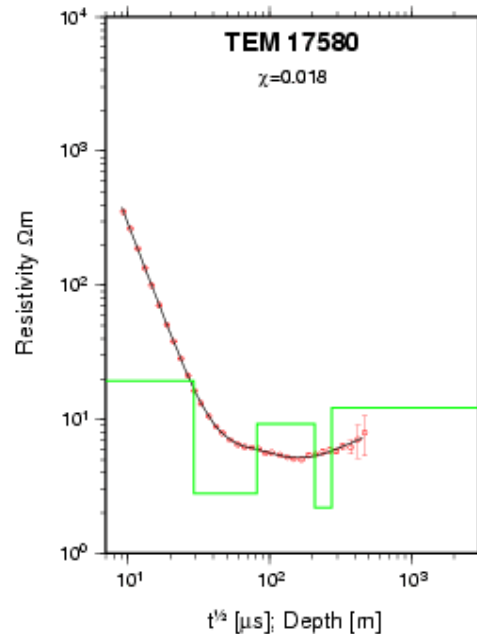


FIGURE 8: TEM resistivity curve with several interpreted layers.

TEM measurements penetrate to a limited level as Schlumberger DC resistivity method. TEM measurements can be interpreted using readily available software to determine the various resistivity layers in the earth. A typical cross-section of TEM interpretation is shown in Figure 9.

TEM method has advantages over DC Schlumberger method in the following ways:

1. No current is injected into the ground overcoming the problem of current injection in dry fresh lavas experienced in DC resistivity measurement
2. The magnetic field measured is not affected by surface conditions at the measuring point which usually distorts DC measurements which introduces errors in interpretation of the data
3. It is less sensitive to lateral variations of the resistivity structure
4. TEM signals are stronger in the low resistivity regimes unlike in the DC measurements where the signals are so low in low resistivity areas typical of geothermal reservoirs and therefore make measurements in DC difficult.
5. The field measurements are easier to make as cables are fixed once in the beginning of the measurements.

Because of the above obvious advantages of the TEM measurement, KenGen has discontinued taking DC resistivity measurements in its exploration campaigns.

3.2 Magnetotelluric (MT) Method

Magnetotelluric resistivity methods use the natural earth's electromagnetic field as the source of energy instead of the artificial energy used in the TEM methods.

The natural magnetic field has waves with a wide range of frequencies ranging from 0.0001 to 10 Hz. In order to penetrate deep into geothermal reservoirs (Deeper than TEM or DC resistivity methods), the

measurements are usually taken in the lower frequencies rather than the higher (>10HZ) which would usually be useful for shallow investigations.

The natural magnetic field B_p of the earth creates an electric field E and a current I in the ground. The current depends on the primary magnetic field and the resistivity of the ground. The current I induces a secondary magnetic field B_s . The total magnetic field $B = B_p + B_s$. The magnetic field B is measured with magnetometers and E is measured with a voltmeter as a potential difference between V between a pair of electrodes fixed at a distance L . The relationship is usually $E = V/L$.

During field measurements (see Figure 10), the magnetic fields are measured in the x (H_x), y (H_y) and Z (H_z) directions and the induced electric fields are also measured in the x (E_x) and y (E_y) directions forming 5 components. These measurements are taken over different frequencies or time periods. The resulting data is Fourier transformed and apparent resistivities in the two directions are calculated as a function of frequency or period T .

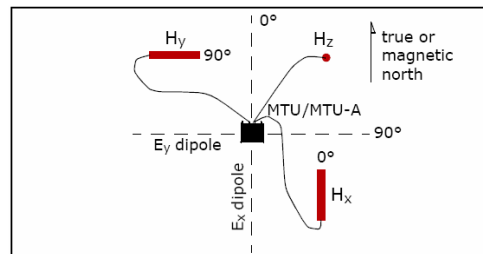


FIGURE 10: Field array for a 5-channel MT data acquisition system (from Wameyo, 2005)

The apparent resistivity measurements can be interpreted in one-dimension or two dimensions. Software exists to do this. Figure 11 is a 2-D interpretation of MT data from Menengai geothermal prospect in Kenya along the same line as the TEM given in Figure 9. Softwares exist to do this. Two dimension modelling takes considerable time.

MT measurements are also easier to make in the field and are capable of measuring much deeper than TEM or DC resistivity methods. However, if TEM and MT are done at the same location because TEM is able to resolve the shallow layers while MT would provide the deeper information. The TEM resistivity values are found to be higher or lower than those of MT (static shift) and therefore are used to shift the MT curves upwards or downwards (shift correction). KenGen has now made MT and TEM the resistivity measurement of choice.

4. MAGNETIC METHOD

Magnetic method is an indirect method and is widely used for geothermal exploration to map geological structures like faults, dykes, and intrusives or indicate areas of large demagnetisation.

It is well known that the earth behaves like a large bar magnet. Therefore there is magnetic field all over the world. However this magnetic field is not the same throughout on the earth's surface. For example it is about 60,000 gamma at the north and south poles and about 30,000 gammas around the equator. The field also changes in both the intensity and in location of the poles. These variations have been studied extensively in the field of Paleomagnetism.

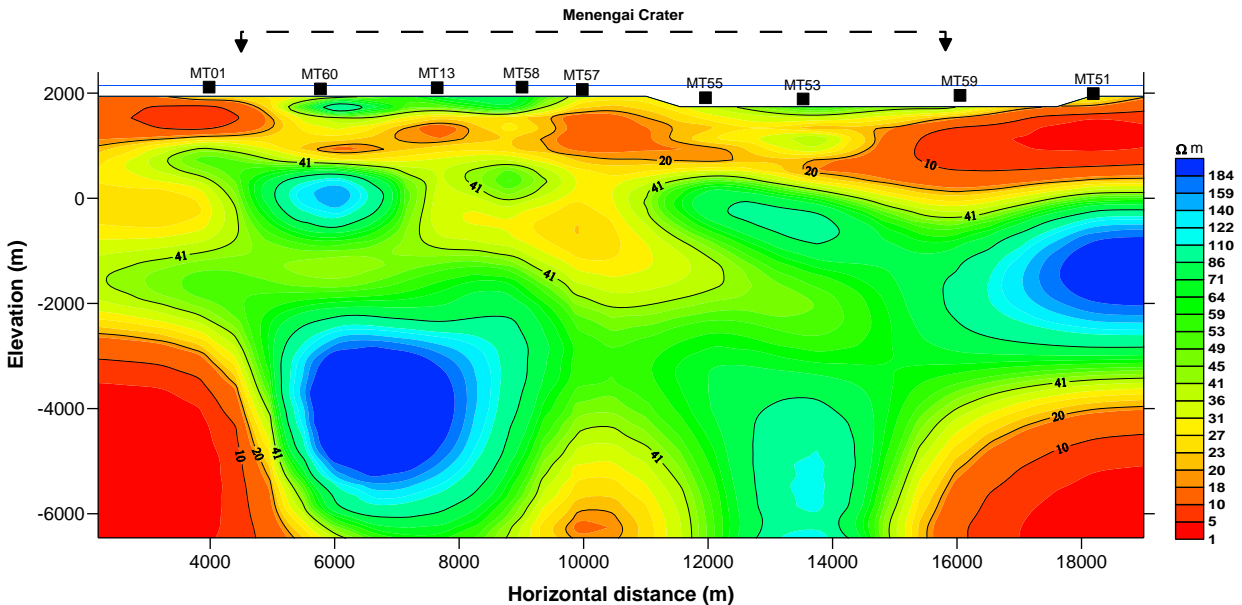


FIGURE 11: MT resistivity cross-section through Menengai prospect (from Wameyo, 2005)

The earth's magnetic field is capable of magnetising the earth's rocks depending on the susceptibilities of those rocks. Therefore by measuring the magnetic field over an area, the magnetic field of the earth will be modified by the secondary magnetic field (induced magnetisation) created due to magnetised rocks. If the rocks in the area are not susceptible to magnetisation by the earth's field, then the measured field is that of the earth in that location. It is therefore clear that variations of the earth's magnetic field across an



FIGURE 12: Magnetic data collection using a magnetometer

area will depend on the rocks being traversed. Some rocks are capable of being magnetised permanently (permanent magnetisation) when they are being formed and therefore attain paleomagnetism. The study of paleomagnetism indicates how the earth's magnetic field has been changing over the years. There are also some variations caused by solar winds. Daily variations can be between 100 and 500 gamma. The existence of paleomagnetism in the rocks and also daily magnetic variations can complicate the interpretation of magnetic data when collected and they need to be considered very carefully.

The total magnetic field data is collected along profiles using a portable magnetometer (see Figure 12) at equal intervals in a grid format or along access roads. The distances between the stations depend on the targets being investigated. If for example a dyke measuring 5 meters is to be investigated, the interval can be as small as 0.5m. If a large geothermal anomaly is being investigated, then measurements can be made every 0.5km. A quicker method of collecting magnetic data is using a plane fitted with magnetometer sensor at the tail end of the plane. The plane would then fly at a fixed altitude and cover a large area.

Before the data can be used, the daily variations and broader anomalies need to be removed so that the local anomalies of interest can be interpreted. One of the most useful ways of looking at the data is by drawing contour maps or stacking data along profiles. This way, structures like dykes or intrusives or different type of rocks can be clearly mapped provided they display magnetic anomaly. The other important use for magnetic method is its capability to map an area that is demagnetised although this can also mean the existence of non-magnetic rocks or reversely magnetised rocks from permanent magnetism. For example Figure 13 shows the aeromagnetic map of Olkaria which indicates a large positive anomaly trending NW- SE which has been interpreted to map a demagnetised area that defines Olkaria field.

5. GRAVITY METHOD

Gravity method is based on the fact that the gravity is not uniform everywhere although the average is known to be about 9.81m/s^2 . The existence of different rocks affects the gravity because of different densities of these rocks. The density of the rocks depends on the porosity, density of fluids filling the pores and the minerals forming the rock. In this regard, high density rocks affect the gravity more.

Although there are now instruments that measure true gravity, most of the instruments measure gravity changes from one station to the other (Figure 14). These are very small changes and are therefore measured in mGal ($1\text{mGal} = 10^{-3} \text{m}^2/\text{s}$)

Gravity measurements must be corrected for changes due to 1) height variation, 2) tidal effect, 3) excess mass above sea level (Bouguer correction, 4) near topographical correction and 5) normal reference according to an international formula. In order to correct for height variation, the height of each station must be determined either by theodolite or GPS depending on the accuracy required.

he corrected data is then plotted in order to reveal trends that might be associated with structures or deep intrusives an example of which is shown as Figure 15 from Olkaria geothermal field. Shallow anomalies may be interpreted by removing the regional anomaly effects.



FIGURE 14: Gravity measurements using a La Coste gravimeter at Olkaria Geothermal field.

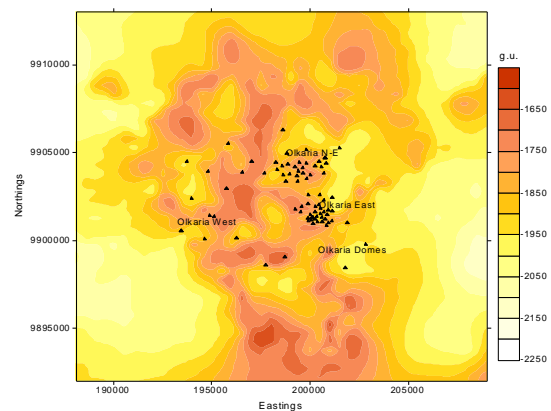


FIGURE 15: Bouguer anomaly of Olkaria Geothermal Field, Kenya

Therefore, in geothermal exploration, the gravity method can be used to map different geological formations with different densities buried below the surface and also detect faults provided the faults have

affected the formations to create contrasting densities i.e. fault movement has placed a denser rock against a less dense one. Otherwise faulting in the same rock formation of the same density does not create an anomaly and therefore cannot be “seen” by the method. Gravity is particularly useful in defining magmatic intrusive bodies acting as heat sources in many geothermal fields. Basaltic intrusives are very easily mapped because the basalts are the densest volcanic rocks and tend to create the largest contrast among most of the other rocks. Gravity measurements have also been used to monitor the reservoir under exploitation. This is because as the fluids are removed from the rocks, the density of the rock formation changes causing changes in gravity. However, if the reservoir receives recharge as the abstraction takes place, no gravity changes would be detected.

6. SEISMIC METHODS

Explosion, earth vibrators or sudden fracture in the rocks produces seismic waves. These waves travel at different speeds in different rocks. Consequently, by measuring the different velocities of the seismic waves, the rocks through which the waves have travelled can be determined. There are two important types of waves generated. The P waves, which travel in the same direction as the wave and are generally faster and the S waves travel perpendicular to the wave direction and are slower than the P waves.

The seismic methods are grouped as active or passive. The active methods are not used routinely in geothermal exploration but are extensively used in petroleum exploration and are fairly expensive. The two types of active seismic methods are reflection and refraction seismic. They are also suitable for well-layered sedimentary type of formations rather than the volcanic formations. The passive methods use naturally occurring earthquake waves while the active method uses the artificially generated vibrations from explosions or vibrators. Geothermal exploration has principally used the passive method by

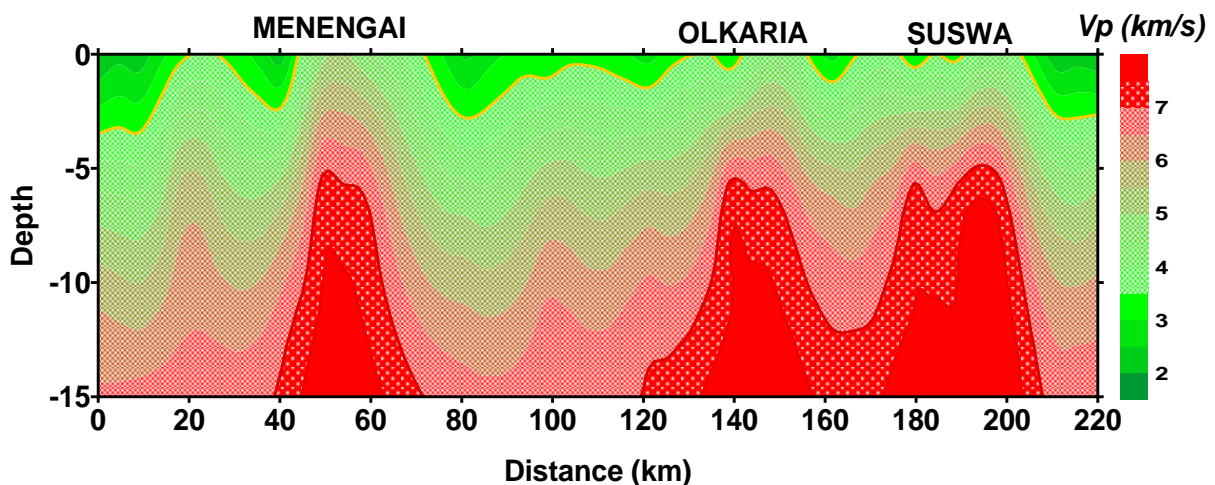


FIGURE 16: Refraction seismic model along the Kenya Rift valley (from Simiyu and Keller, 2000)

recording earthquakes or micro-earthquakes. Teleseismic from long distance earthquakes can also offer some information on attenuation of waves as they pass through very hot molten rocks.

By monitoring for a long period of time the micro-earthquakes, the stress field and the tectonic nature of the region can be studied. The location of the hypocenters and the epicentres are determined from the

arrival times of the P and the S waves at several seismometer locations spread out in the area under exploration. P velocities V_p and S velocities V_s are determined.

The mapping of the micro-earthquake epicentres in a linear manner can indicate existence of fractures or faults that are usually lubricated by flowing geothermal fluids and therefore generating numerous micro-earthquakes (Figures 17 and 18). These fractures are suitable targets for geothermal wells because of high permeabilities in them. Micro-earthquakes are also associated with tensile cracking of cooling intrusions therefore can be used to map their existence and depth at which they occur. Where S waves have been heavily attenuated, this may indicate the presence of partially molten magma chamber. P waves may also be delayed as they pass through hot intrusions beneath a geothermal system.

Refraction seismic has been done along the Kenyan Rift valley revealing existence of high velocity intrusions beneath several of Kenya's geothermal systems (Figure 16). Micro-earthquakes have also been used in Olkaria to map the existence of the hot magma body at about 6km. Figure 17 is a section showing hypocenter location at Olkaria showing shallow micro earthquake at the hottest parts of the reservoirs while Figure 17 is the map of Suswa geothermal prospect showing buried faults. Since the Olkaria geothermal field has been associated with low permeability, KenGen has recently been concentrating in carrying out experiments using both resistivity and micro-earthquakes to map suitable fractures which could be suitable targets for much higher producing wells (Onacha, 2006).

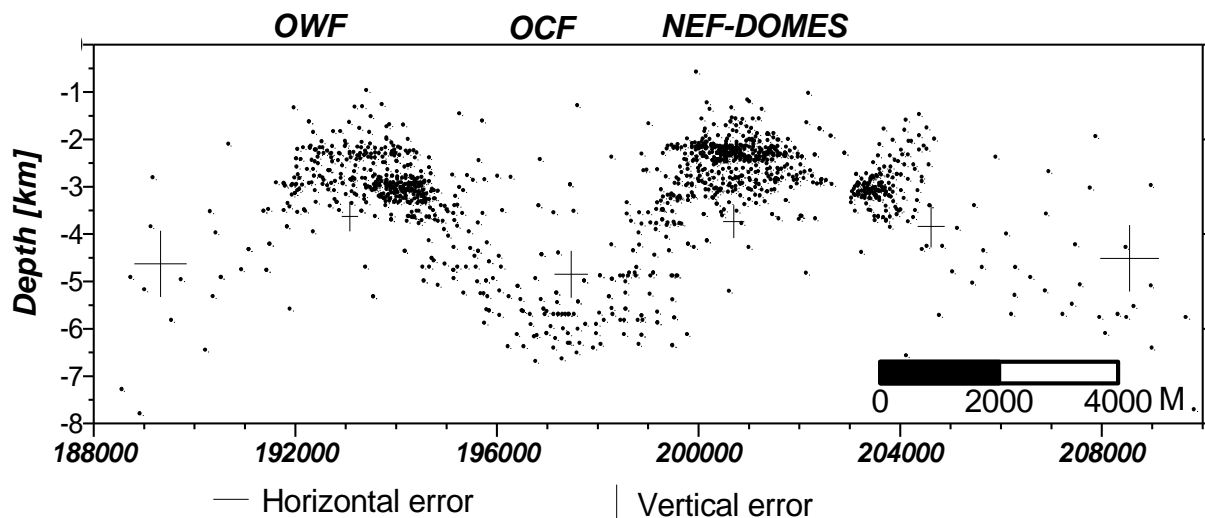


FIGURE 17: Hypocenter locations of micro earthquakes at Olkaria Geothermal field, Kenya (from Simiyu, 1999)

7. CONCLUSION

Geophysical prospecting is very important in geothermal exploration and siting of geothermal wells. Although it should not be used in isolation, it nevertheless contributes significantly. There are several geophysical methods which have become industry standard for defining structures and the reservoir however resistivity method is by far the most useful. This is because it relates directly to the characteristics of geothermal reservoirs. In addition, because of the rough volcanic terrain of most geothermal prospects and the deep nature of the reservoir, TEM combined with MT resistivity methods are becoming the methods of choice for geothermal exploration.

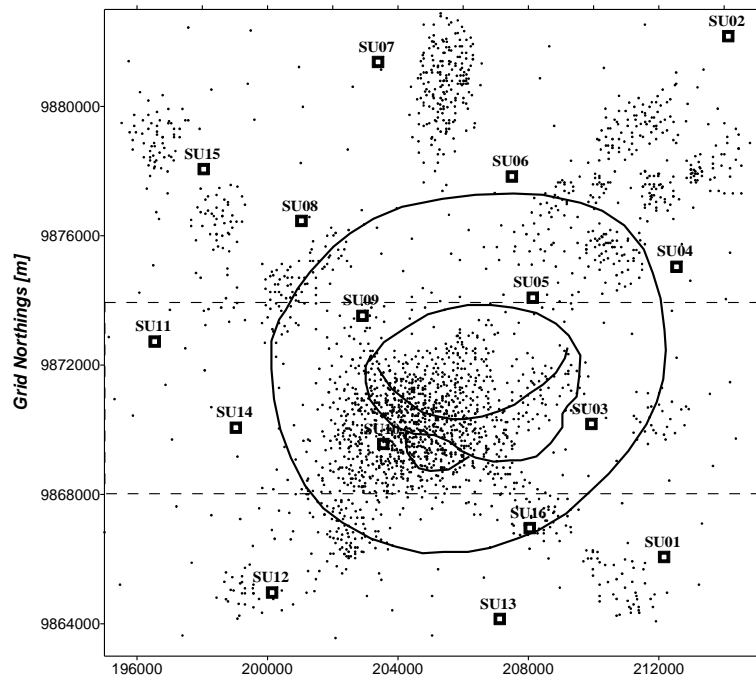


FIGURE 18: Micro earthquake locations at Suswa geothermal prospect (From Simiyu, 1999)

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