Presented at Short Course VI on Exploration for Geothermal Resources,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 27 – Nov. 18, 2011.

GEOTHERMAL TRAINING PROGRAMME

Kenya Electricity Generating Co., Ltd.

APPLICATION OF GEOPHYSICAL METHODS TO GEOTHERMAL ENERGY EXPLORATION IN KENYA

Nicholas O. Mariita
Kenya Electricity Generating Company Ltd-KenGen
Olkaria Geothermal Project
P.O. Box 785, Naivasha
KENYA
nmariita@kengen.co.ke

ABSTRACT

For earth scientists, a wide range of geophysical, geo-chemical and geological surveying methods exist for geothermal energy investigations. For each of these methodologies, there is a typical physical/chemical property to which the technique is sensitive to. For geophysics, location of a geothermal reservoir may be determined by use of seismic velocity, electrical conductivity, magnetic or/and gravity methods. Effects of exploitation of a geothermal reservoir can be monitored using micro-seismic, micro-gravity, geo-chemical and temperature/pressure techniques. Though these may require complex methodology and relatively advanced mathematical treatment in interpretation, much information may be derived from simple qualitative assessment of the survey or monitoring data. Often many of these methods are used in combination to obtain a plausible inference. 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. This article provides a general introduction to the most important methods of geophysical exploration that have been employed at Olkaria Geothermal field, Kenya. The occurrence of surface manifestations in the country's rift valley regions encouraged various people to carry out various geophysical investigations to establish the subsurface structure with a view of establishing its geothermal potential. Various levels of success have been achieved with each of the techniques. The activities resulted in the construction and commissioning of Africa's first geothermal power plant at Olkaria with 45 MW capacity between 1981-1985. Changes in technology saw the deployment of modern geophysical techniques that included transient electromagnetics (TEM) and magnetotellurics (MT) which made it possible for shallow and deep conductors to be accurately imaged and thus more accurate geothermal models developed.

1. INTRODUCTION

The objectives of the surface field investigation of a geothermal prospect are:

- To determine the geothermal potential of the prospect by studying the structural patterns, lithologic outcrops, stratigraphy, volcanology and geothermal manifestations,
- To determine whether a resource exists and propose sites for exploratory drilling, and
- To develop a geothermal conceptual model of the area.

In this, the common geo-science disciplines used are geology, geophysics and geochemistry. This article provides a general introduction to the most important methods of geophysical exploration that have been employed at Olkaria Geothermal field, Kenya. These methods are a primary tool for carrying out investigation of the subsurface in prospecting for natural resources such as geothermal energy. Since this is an introductory discussion we shall not attempt to be completely comprehensive in our coverage of the subject. Geophysics is a highly mathematical subject; however we shall attempt to keep the discussion qualitative. The science of geophysics applies the principles of physics to the study of the earth's subsurface by taking measurements at or near the earth's surface that are influenced by the distribution of the physical properties in the subsurface.

An alternative method of investigating subsurface conditions is by drilling bore-holes, but these are expensive and provide information only at discrete locations. Geophysical surveying, although sometimes prone to major ambiguities in interpretation, provides a relatively rapid and cost-effective means of getting a really subsurface information. Geophysical surveying does not dispense with the need for drilling but, properly applied; it can optimise exploration programs by maximizing the rate of ground coverage and minimizing the drilling requirement.

The general problem in geophysical surveying is the ambiguity in data interpretation of the subsurface geology. This arises because many different geologic configurations could reproduce similar observed measurements. This basic limitation is brought about from the unavoidable fact that geophysical surveying attempts to solve a difficult inverse problem. In spite of this limitation, however, geophysics is an important tool in the investigation of subsurface geology.

2. THE SURVEYING METHODS

Geophysical surveying methods can be divided into two broad groups, i.e., those that use natural fields of the earth and those that require input of artificially generated energy into the ground. The natural field methods include gravity, magnetics, and Magnetotelluric (TM). Artificial methods involve the generation of electrical, electro-magnetic or seismic energy whose propagation and transmission paths in the subsurface provide information on the distribution of geological boundaries at depth.

A wide range of geophysical surveying methods exists for exploration for geothermal energy as well as the monitoring of geothermal reservoirs under exploitation (Ndombi, 1981; Mariita, 1995; Simiyu and Keller, 1997). The type of physical property to which a method responds dictates the application. At Olkaria we employ seismic, gravity, magnetics, electrical resistivity, Transient Electromagnetic (TEM) and Magnetotelluric (MT). Often we use these methods in combination. For example, magnetics is done along with gravity. 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.

Apart from employing the above mentioned techniques to carry out survey for a geothermal energy resource, we employ some of them also for reservoir monitoring. In the recent past Olkaria has experienced difficulty in maintaining its designed output of 45 MW. Under these circumstances it is necessary to monitor which part of the field is being affected most by fluid withdrawal and to recommend re-injection strategies. Long-term changes, which evolve over months and years, are being monitored by employing micro-gravity and micro-seismicity methods.

2.1 Seismic surveying

In seismic surveying, we send seismic waves through the earth and the travel times are measured of the waves that return to the surface after refraction or reflection at the geologic boundaries. We then convert these travel times into depth values and, hence, the distribution of the subsurface interfaces of geologic interest are mapped. At Olkaria, we have used active seismicity to map faults for possible drilling targets (Hamilton *et al*., 1973). We have further utilized earthquakes caused by 45 blasts from nearby road construction quarry.

2.2 Seismic monitoring

Since 1996 we have run a continuous micro-seismic monitoring network at Olkaria to study the earthquake distribution and wave properties across the geothermal field (Mariita *et al.*, 1996; Simiyu *et al.,* 1997, Simiyu, 1999). We have also set up seismic stations at the nearby geothermal prospects of Olkaria Domes, Longonot and Suswa. The main objectives are to carry out an analysis of the wave parameters so as to determine earthquake location and to relate these locations to the presence of structures that allow reservoir fluid flow patterns (Figure 1). Finally, these seismic properties are related to the directly physical parameters of pressure and temperature. We have used this technique in our interference tests for wells under discharge; location of feeder zones in wells and barriers that control fluid flow. As part of an investigation of re-injection of wastewater from some of our wells, investigation of any associated seismic activity has been carried out and data is being analysed.

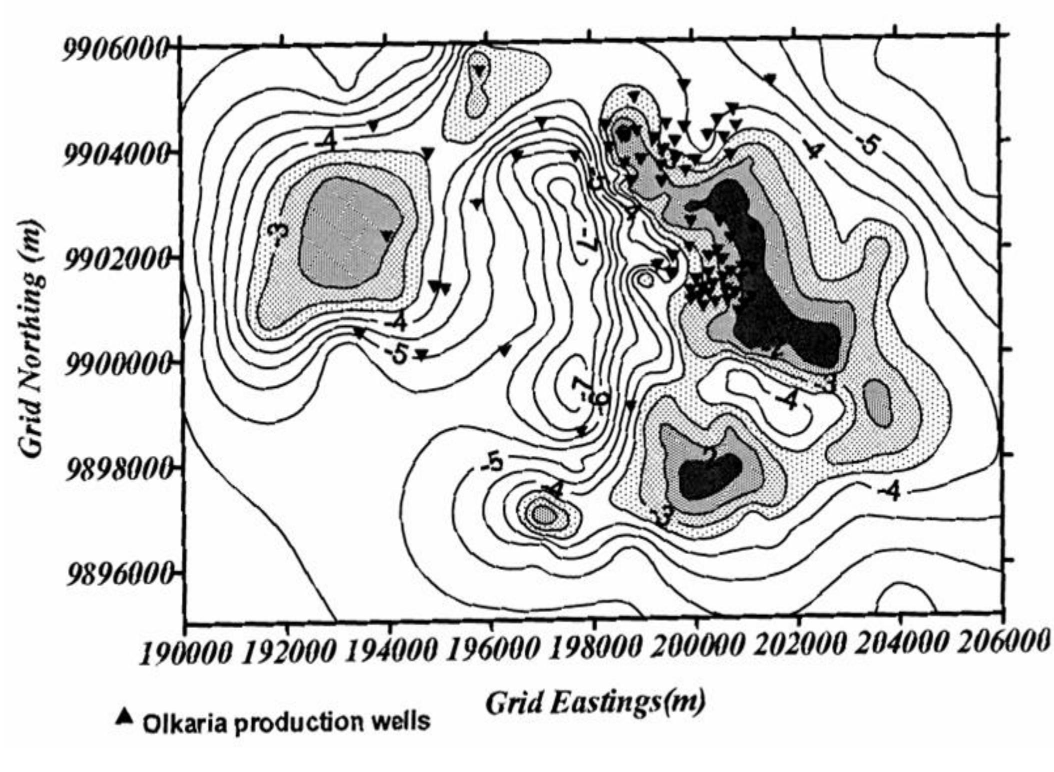


FIGURE 1: Contour map of average seismic event depth (km) distribution across the greater Olkaria geothermal field. Note that the production fields (Olkaria East, West, NE and Domes) overlie regions of shallow events

2.3 Gravity surveying

In gravity surveying, subsurface geology is investigated on the basis of variations in the earth's gravitational field generated by differences of density between subsurface rocks. A subsurface zone whose density is different from that of the surroundings causes a localized perturbation in the gravitational known as a gravity anomaly. Volcanic centres, where geothermal activity is found, are indicators of cooling magma or hot rock beneath these areas as shown by the recent volcanic flows, ashes, volcanic domes and abundant hydrothermal activities in the form of fumaroles and hot springs. Gravity studies in volcanic areas has effectively demonstrated that this method provides good evidence of shallow subsurface density variations, associated with the structural and magmatic history of a volcano (Ndombi, 1981). There is a correlation between gravity highs with centres of recent volcanism, intensive faulting and geothermal activity. Olkaria, Domes and Suswa geothermal centres are located on the crest of a gravity high (Figure 2). Gravity data is collected, processed (Figure 3), interpreted and results used in conjunction with seismic data to locate the heat source and permeable zones as drilling targets.

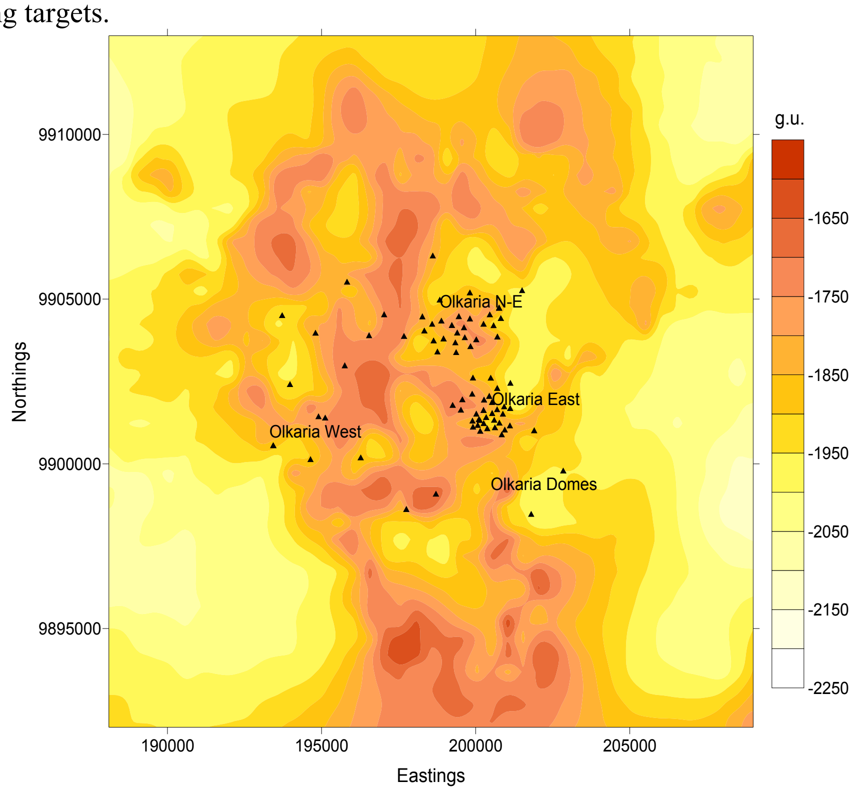


FIGURE 2: Bouguer gravity distribution over the greater Olkaria geothermal field and surrounding areas

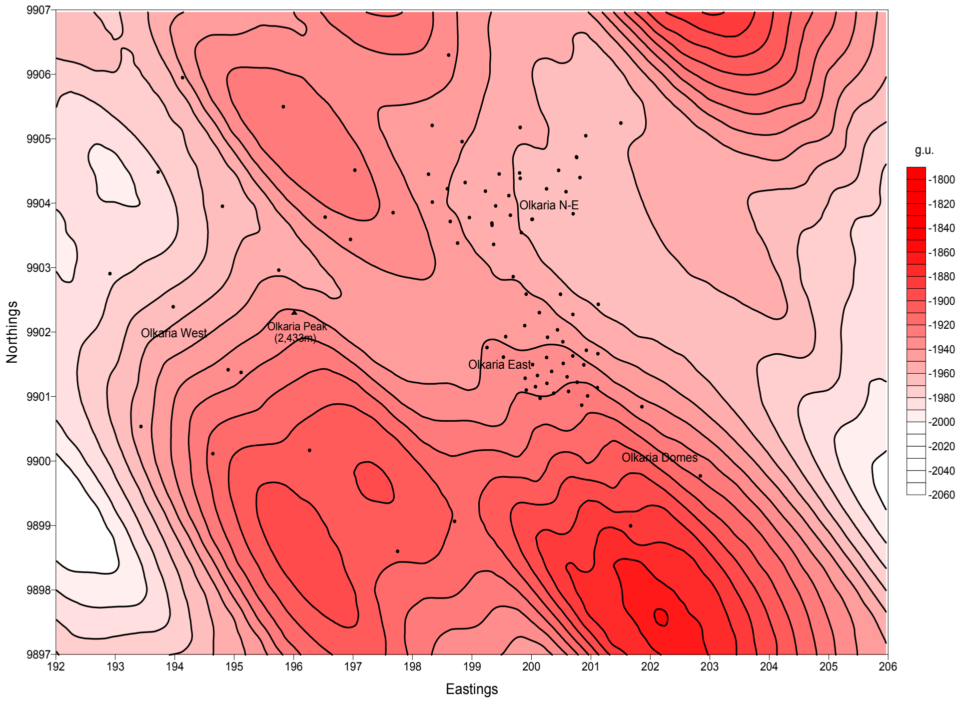


FIGURE 3: Directionally filtered gravity data of the greater Olkaria geothermal field. This procedure highlights the NW-SE trend of the gravity anomaly through Olkaria, not seen in the Bouguer data in Figure 2

2.4 Micro-gravity monitoring

Reservoir engineering calculations of mass and energy balance on producing geothermal reservoirs require information about in- and out-flows from the reservoir. Such information is usually available for surface flows, such as production and re-injection. Values for subsurface in- or out-flows are difficult to get. One method used is a history matching process whereby reservoir performance is computed for various strengths of influx and the matched against observed performance.

A more direct and independent method is through repeat micro-gravity over a producing field. As mass is removed from a geothermal reservoir the gravity field above the reservoir will change. For an influx it will increase while for a loss it will decrease. By measuring the surface gravity field at two points in time the change in gravity over the reservoir during the time interval can be determined. When such surveys are carried out with appropriate accuracy, they allow an estimate of mass loss or influx to be made without any drill-hole information. Precision gravity surveys at Olkaria Geothermal Field began in 1983 to monitor gravity changes as a result of geothermal fluid withdrawal. A review of the observed gravity data over each benchmark indicates changes over the years during monitoring (Figure 4). Maximum gravity changes show a constant trend in time, but different characteristic distributions from zone to zone. This information has been correlated with production data (enthalpy and mass output) from nearby wells as well as assisting in identifying zones for re-injection.

2.5 Magnetics

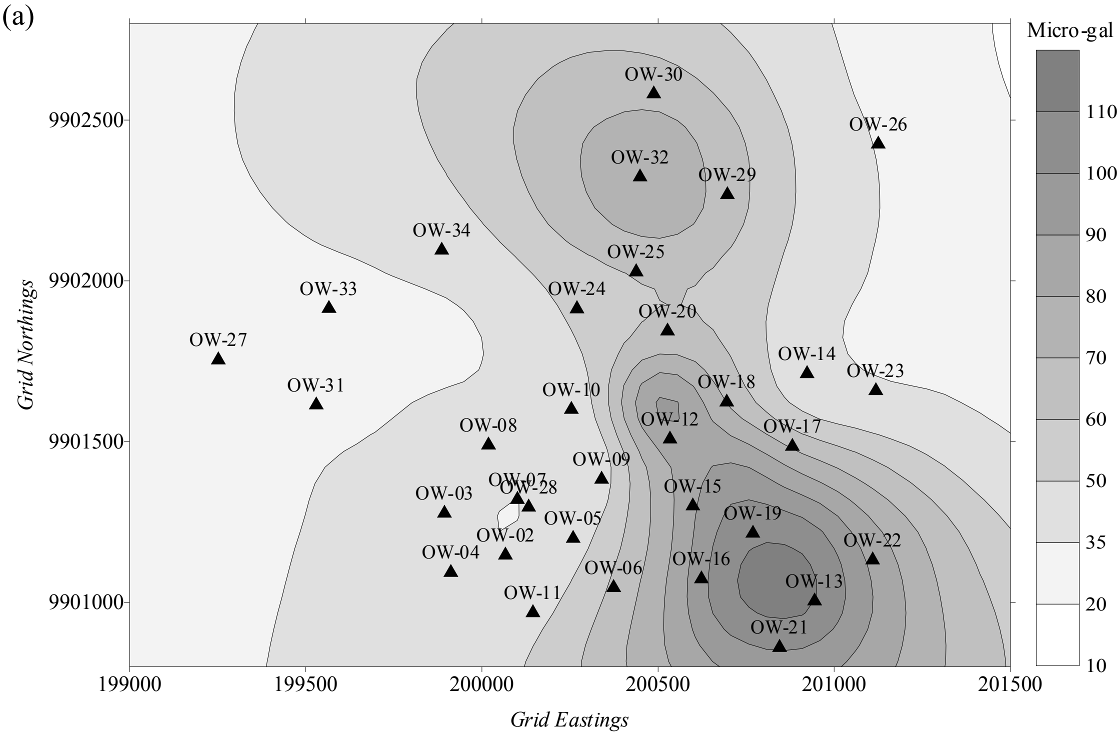
The aim of a magnetic survey is to investigate subsurface geology on the basis of the anomalies in the earth's magnetic field resulting from the magnetic properties of the underlying rocks. In general, the magnetic content (susceptibility) of rocks is extremely variable depending on the type of rock and the environment it is in. Common causes of magnetic anomalies include dykes, faults and lava flows. In a geothermal environment, due to high temperatures, the susceptibility decreases. It is not usually possible to identify with certainty the causitive lithology of any anomaly from magnetic information alone. Interpretation of aeromagnetic anomalies over a geothermal area can be further complicated by the presence of magnetic effects caused by volcanic terrain, concealed lavas with a strong magnetisation or reversely magnetised rocks. Conversely, there are examples in the world (e.g., over Iceland) where hydrothermal demagnetisation causes distinctive negative magnetic anomalies over geothermal fields.

Over Olkaria both ground and aero-magnetic data (Figure 5) have been used to investigate the presence of a geothermal resource in combination with gravity (Bhogal and Skinner, 1971). From the aero-magnetic maps several of the anomalies can be clearly correlated with surface expressions of volcanism such as craters, domes or cones, localised basaltic lavas or plugs. From these maps most of the volcanic centres tend to lie in areas with magnetic highs (positives). Sometimes a superimposed magnetic low (negative) exist; but this is generally weak or zero.

2.6 Electrical and electromagnetic surveying

There are many methods of electrical and electromagnetic surveying. Some use naturally occurring fields within the earth while others require introduction of artificially generated currents into the ground. In some resistivity methods, artificially-generated electric currents are introduced into the ground and the resulting potential differences are measured at the surface. Deviations from the pattern of potential differences expected from a homogenous ground provide information on the form and electrical properties of subsurface inhomogeneities such horizontal and vertical discontinuities as well as bodies of anomalous electrical conductivity. The objective of resistivity data interpretation is to delineate the resistivity variation with depth assuming that the earth is electrically homogeneous and the resistivity only varies with depth and relate them to hydrogeological and thermal structures associated with geothermal reservoirs. From several of these soundings a 2-dimensional model is constructed by use of computer inversion programs.

(a)



(b)

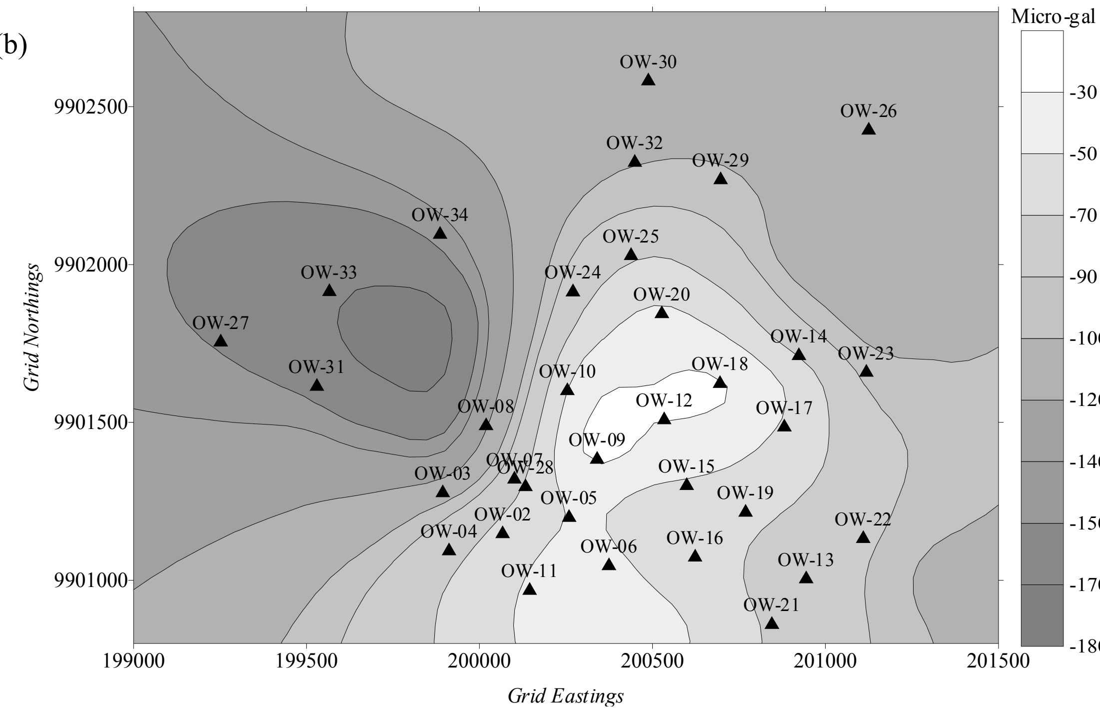


FIGURE 4: Gravity changes over Olkaria 1 geothermal field between 1983 and 1988 (a) and between 1988 and 2000 (b).

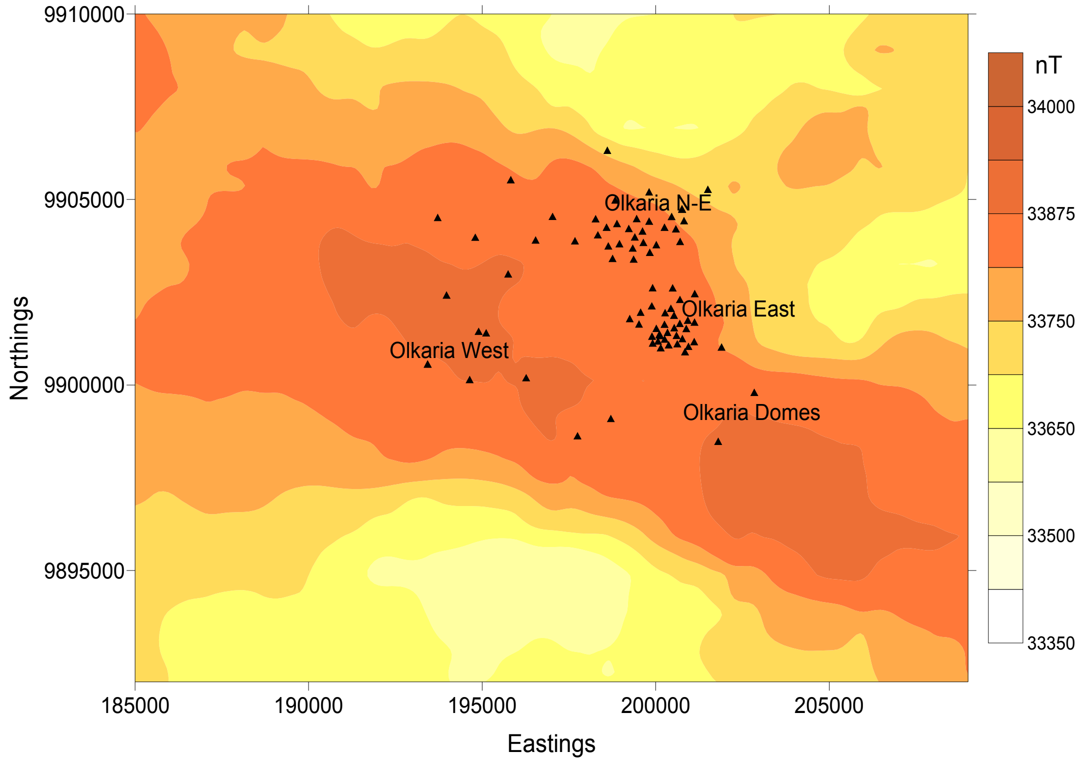


FIGURE 5: Total magnetic intensity over Olkaria and surrounding areas

A resistivity survey of a geothermal field reflects the thermal alteration of the field, hence the temperature. Elevated temperatures lead to increasing alteration of minerals in the rocks of the subsurface leading to a lowering of resistivity.

At Olkaria direct current resistivity methods (Onacha, 1993) have been used for reconnaissance mapping, location of faults for drilling targets and to define the boundaries of geothermal reservoirs. In recent years we have favoured Transient Electromagnetic (TEM) and Magnetotelluric (MT) sounding methods (Meju, 1996). In the TEM technique an artificial transient electromagnetic field is induced in the ground and secondary fields are measured at the surface. The sounding results are normally presented by late time apparent resistivity as a function of time, which is then used in an inversion computer program. The depth of penetration of TEM soundings is not very great, being limited by the frequency range that can be generated and detected. It is also dependent on the geology of the field under investigation and how long the signal received can be traced in time before it is drowned by noise. For the Olkaria situation (Onacha, 1990) our experience is that the maximum depth is about 500 m to 1 km (Figure 6).

In the MT method (Dimitrios, 1989), use is made of natural current fields induced in the earth by time variations in the earth's magnetic field. Both the electric and magnetic fields are measured. Due to this, the technique does provide more information on subsurface structure, as its depth of penetration is much larger than TEM. The depth is dependent on frequency and the resistivity of the substrate. Consequently, depth penetration increases as frequency decreases and the apparent resistivity varies with frequency. The calculation of the apparent resistivity for a number of decreasing frequencies thus provides resistivity information at progressively increasing depths (Figure 7).

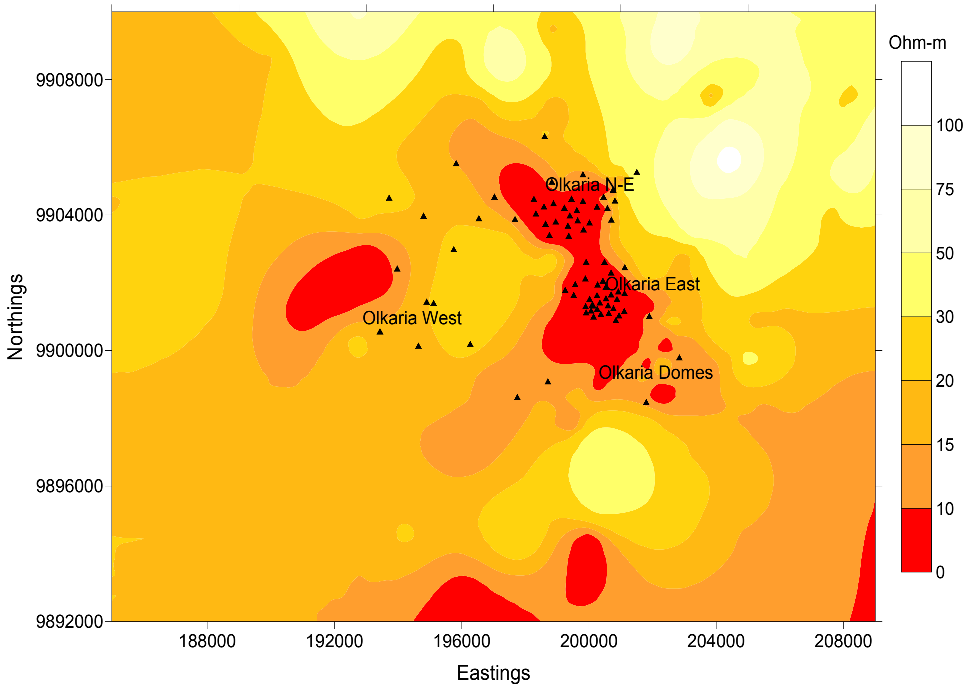


FIGURE 6: TEM Resistivity distribution at 1400 masl over the greater Olkaria geothermal field and surrounding areas. Note that the present production fields are underlain by a low resistivity anomaly

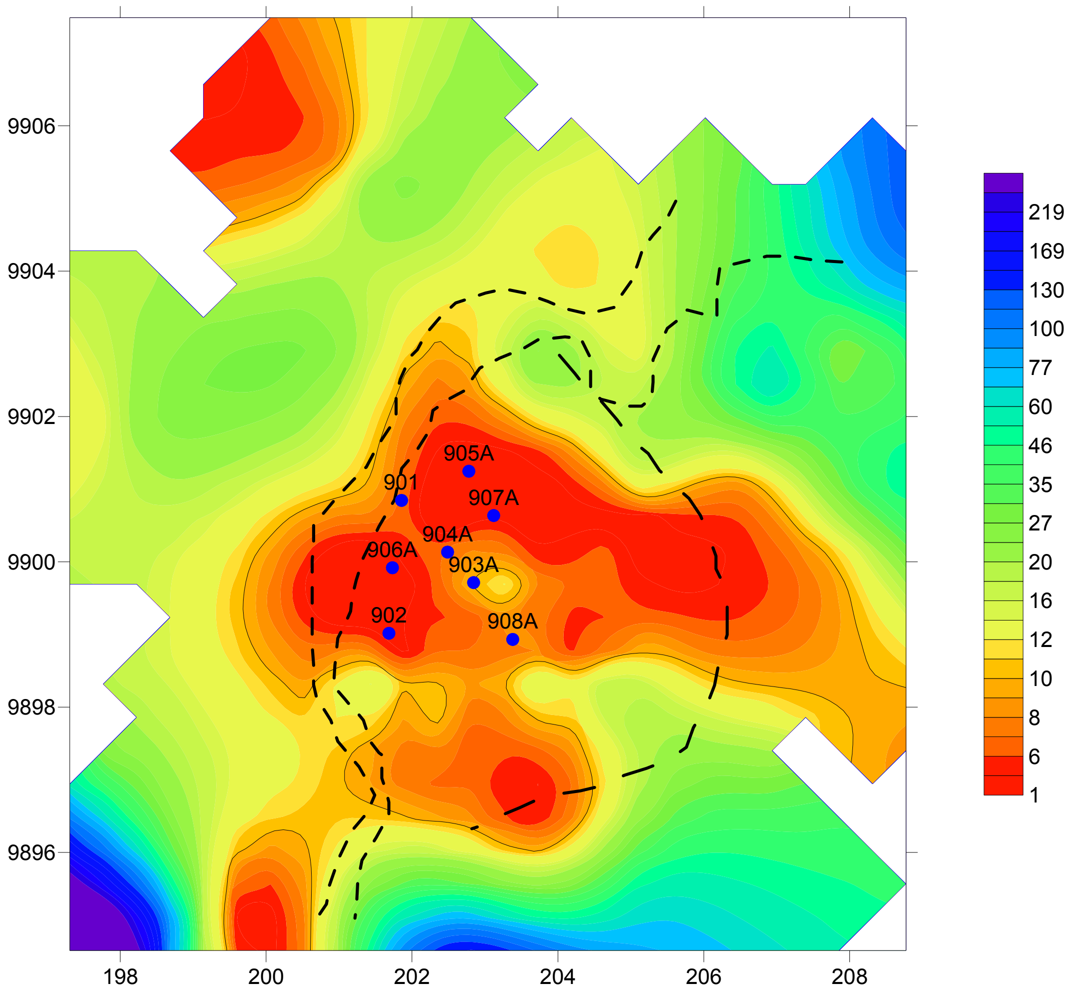


FIGURE 7: MT Resistivity distribution at 1000 m bsl around Olkaria-Domes geothermal field and its surroundings.

3. CONCLUSIONS

The geophysical methodology includes, among others, measurements in gravity, seismic and resistivity. Gravity is important in determining the occurrence of a magmatic heat source at reasonable depth reachable by meteoric waters. It is also useful in mapping structures although it has been very difficult in the rift structure unless there rocks of very contrasting densities. Micro-earthquake mapping can be useful in mapping active fractures that allow upward flow of geothermal fluids. At Olkaria, the resistivity methods have been the most consistent and extensively used geophysical method with very good results. Initially the DC resistivity type was employed. However, this has been abandoned in preference to TEM and MT methods due to the efforts required to penetrate depths greater than 1 km. Resistivity methods are capable of mapping the reservoir itself and that makes it more attractive to use. A large number of measurements are required covering large areas initially at intervals of 1km and later at even lesser spacing.

REFERENCES

Bhogal P. and Skinner M., 1971. *Magnetic surveys and interpretation in the Olkaria geothermal area.* Report prepared for the Kenya Power Company Ltd., 15 pp.

Dimitrios G. 1989: *Magnetotelluric studies in geothermal areas in Greece and Kenya*. Ph.D. Thesis, Univ. of Edinburgh.

Hamilton, R. M., Smith B. E., and Knopp F., 1973. *Earthquakes in geothermal areas near Lakes Naivasha and Hannington (Bogoria), Kenya*. Unpublished report to the UNDP/EAP&L.

Mariita N.O., 1995. *Exploration for Geothermal Energy in Kenya – A Historical Perspective*. Kyushu University, Japan, Geothermal Research Report, report No. 5.

Mariita, N.O., Otieno, C.O. and Shako, J.W., 1996. *Micro-seismic monitoring at the Olkaria geothermal field, Kenya*. KenGen Internal Report. 15 p.

Meju, M.A., 1996. Joint inversion of TEM and distorted MT soundings: some effective practical considerations. *Geophysics 61, 56-65*.

Onacha, S. A. 1990. *Use of Transient Electromagnetic Sounding method in the Greater Olkaria geothermal area*, KPC internal report.

Onacha S.A., 1993. *Resistivity studies of the Olkaria-Domes geothermal project.* KenGen internal report.

Ndombi, J.M., 1981. The structure of the shallow crust beneath the Olkaria geothermal field, Kenya, deduced from gravity studies. *J. Volcanol. Geotherm. Res. 9,* 237-251.

Simiyu, S.M., and Keller, G.R., 1997. Integrated geophysical analysis of the East African Plateau from gravity anomalies and recent seismic studies. *Tectonophysics, 278,* 291-314.

Simiyu, S.M., Mboya, T.K., Oduong, E.O, and Vyele, H.I. 1997. *Seismic monitoring of the Olkaria geothermal area, Kenya.* KPC internal report.

Simiyu, S.M., 1999. Seismic application to geothermal evaluation and exploitation, Southern Lake Naivasha. *24th Workshop on Geoth. Res. Engineering, Stanford, SGP-TR-162.*