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# APPLICATIONS OF POTENTIAL FIELD METHODS FOR GEOTHERMAL EXPLORATION – A CASE FOR OLKARIA AND MENENGAI GEOTHERMAL FIELDS, KENYA

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**ABSTRACT**

Many different geophysical techniques are available to the earth scientist, each with its own strengths and weaknesses. Some problems encountered are shallow depth penetration ability of the instruments, interpretation of data can be difficult and results ambiguous, and instrumentation can be expensive. The techniques can be divided into the two broad categories: passive and active methods. Passive methods detect anomalies or changes in the Earth without introducing any energy. These include magnetometry, gravity and magnetotellurics. Active methods introduce some sort of energy into the ground and then detect subsurface responses. Active techniques include resistivity and electromagnetics.

Magnetometry and gravity are often referred to as the Structural Methods. In this paper we discuss procedures for executing magnetic and gravity methods in geothermal-resources investigations. The general physical principles underlying each method and their capabilities and limitations are described. Possibilities for non-uniqueness of interpretation of results are also presented. Examples of actual use of the methods are given to illustrate applications and interpretations in selected case examples of the geothermal fields of Olkaria and Menengai in Kenya. The objective of the paper is to provide the reader with a sufficient understanding of the capabilities, limitations, and relative cost of magnetic and gravity methods to make sound decisions as to when use of these methods is desirable.

## 1. INTRODUCTION

Geophysical techniques are often useful for discovering unknown subsurface conditions. Most of these techniques are classified as non-invasive, requiring only minimal disturbance of surface cover. Projects involving successful application of exploration, monitoring or geophysics in geothermal industry include:

Micro-seismic event mapping for an irregular concealed erosional contact such as a fault. Results are used to reduce the number of drilled holes needed to design for a geothermal power plant or other direct uses. Magnetic survey supplements gravity studies to locate heat sources. Electromagnetic conductivity and DC resistivity profiles maps can be used to infer the presence of a heat source and geothermal reservoir. The integrated interpretation of geophysical and hydrogeological information suggests that geothermal wells drilled into the centre of such anomalies are more likely to encounter substantial steam or hot water than wells drilled at random or wells drilled based on an incomplete knowledge of the anomaly location.

In geothermal energy exploration the potential fields of Gravity and Magnetics have been used to delineate bedrock valleys concealed by sediments or volcanic materials and mapping of permeable fractures during the early stages of investigations. These measurements can significantly reduce the number of wells needed to characterize a prospect while improving the confidence of interpretations. Gravity and Magnetics techniques are cost. One limitation, however, is that they sometimes cannot be used due to cultural noise (electrical power lines or transformers, heavy vehicular traffic, buried pipes, pavement) or natural conditions. The experienced geophysicist knows how to recognize and minimize any influence due to such noise. Site visits (Figure 1) preferably by a combined team of earth scientists and engineers are often required prior to finalizing plans for a gravity or /and magnetics prospecting project.

FIGURE 1**:** A team of earth scientists making site visits to a potential geothermal prospect

This paper is a brief review of the gravity and ground magnetics methodologies used as part of surface geophysical exploration and their application in geothermal energy investigations with particular reference to Olkaria and Menengai geothermal fields in Kenya. It explains the capabilities of these methods and, in a general way, the processing and interpreting the data. No mathematics is employed, and the scope is limited to an elementary discussion of theory, a description of the methods, and examples of their applications. It is in no way intended to be an exhaustive discourse on applications of these potential fields. Rather its aim is to provide the general geothermist with a rudimentary under-standing of how surface measurements may be of help.

## 2. SELECTION OF GEOPHYSICAL METHODOLOGIES FOR GEOTHERMAL ENERGY PROSPECTING

Geophysical prospecting of high temperature geothermal reservoirs aims at identifying either fluid trapping structures or anomalies related to the properties of the hydrothermal fluid and rock to fluid interactions. Two types of reservoir environments can be characterized: (i) sedimentary reservoirs when a carbonate reservoir is generally capped by a dominantly argillaceous, hydraulically impervious and thermally insulating cover, and (ii) volcanic and volcano-sedimentary reservoirs associated with hydrothermally altered areas.

Based on the aforementioned exploration goals and reservoir settings, a wide spectrum of geophysical methods can be applied whose selection is largely commanded by local geological conditions and expected reservoir morphology. For example, detection of a geothermal heat source is best carried out by using a combination of gravity and magnetic measurements, while reservoir characteristics are best imaged by use of electric or electromagnetic techniques.

Buried hot rocks will (most likely) exhibit different bulk material properties (such as density and magnetisation) than the surrounding native country rock. This will typically allow gravity meters and magnetometers to distinguish geothermal reservoir from relatively cooler surrounding areas.

The interpretation of geophysical contacts is based on geologic assumptions: (1) earthen materials have distinct subsurface boundaries, (2) a material is homogeneous (material properties are the same throughout) and (3) the unit is isotropic (material properties are the same in all directions). Since these conditions rarely occur in nature, and almost never occur in volcanic environments, geophysical methods are most often used in conjunction with other intrusive methods (where signal are 'injected into the ground) in order to more correctly assess the site. Non-intrusive geophysical methods (such as gravity and magnetics) can be utilized as preliminary screening before performing intrusive investigations; they may be implemented as the primary investigative technique. Understanding the specific strengths and weaknesses of each method will allow the investigator to decide how to best utilize geophysical investigations.

The results obtained from a gravity or magnetic investigation are subjective and rely on geologic interpretation. These techniques do not directly measure the parameter needed to solve the problem but instead measure contrasts in material properties. Although geophysical interpretations are not always perfectly accurate, the geophysical equipment is very precise. That is to say that the measurements obtained from non-intrusive geophysical techniques are very exact. The raw data is good data. The problem resides in the geophysical interpretation of the data, which are often educated estimations and/or calculated correlations and can lead to inaccuracies. However, when the appropriate geophysical technique is applied, large volumes of material can be explored accurately and cost-effectively.

Several minerals containing iron and nickel display the property of ferromagnetism. Rocks or soils containing these minerals can have strong magnetization and as a result can produce significant local magnetic fields. The magnetization can be either remanent (a permanent magnetization created. 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. Used with gravity, this method can be used to infer heat. Positive anomalies are generally interpreted to occur in demagnetized zones corresponding to heat sources with a temperature above the Curie Point of magnetite (575°C). Ground magnetic measurements do provide more detailed information on sub-surface structures that could act as heat sources in comparison to aeromagnetic data. In the discussions that follow we briefly describe Magnetic and Gravity methods with emphasis on the use and limitations in geothermal energy investigations as experienced at Olkaria and Menengai Geothermal Fields.

## 2.1 Application of the magnetic method over Olkaria

An aeromagnetic survey was flown in 1987 for the National Oil Corporation of Kenya (NOCK). Maps prepared from these data have been used to corroborate the gravity interpretation for a qualitative assessment of the shapes and trends of the anomalies, in conjunction with the geologic map of Kenya. Results from the larger rift indicate that the axis of the rift is marked by a series of high amplitude magnetic anomalies whose wavelengths are less than 2.5 km, with the positive anomalies coinciding closely with known Quaternary volcanoes. The residual aeromagnetic data shows that the Greater Olkaria Geothermal Area has a positive anomaly that has a NW-SE trend. The positive magnetic anomaly separates two negative anomalies to the south and the north. The negative anomalies correspond to normally magnetized rocks. The positive anomaly occurs in a demagnetized zone corresponding to the heat source that is silicic origin. This provides some evidence for heat source at a temperature above the Curie point of Magnetite (above 575°C) close to the surface. The occurrence of magnetic and gravity anomalies at the intersections of NE and NW rift faults, is an indication of distinct near surface heat sources controlling the reservoir characteristics of the geothermal systems at Olkaria. Figure 2 is an example of aerial magnetic measurements over Olkaria geothermal field, Kenya.

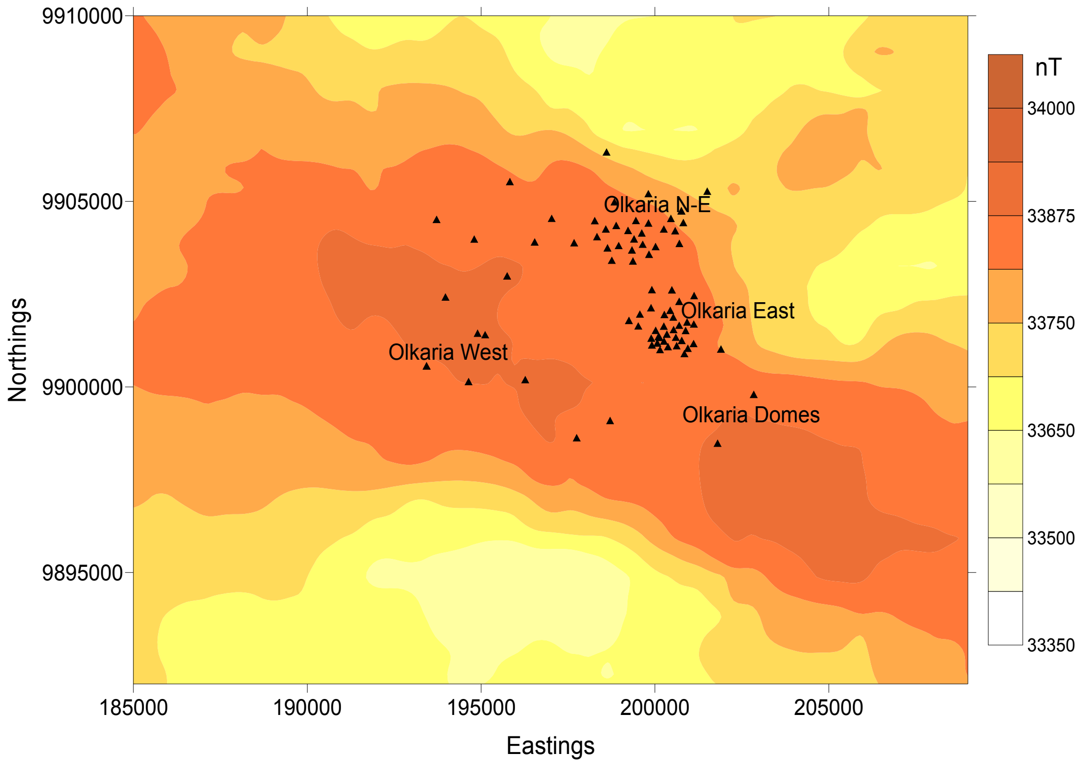


FIGURE 2: Total magnetic intensity over the Greater Olkaria area over Olkaria geothermal field, Kenya. It is obvious that the anomaly trends in a NW-SE direction

Studies of residual magnetic anomalies indicate that different anomaly patterns are associated with subsurface outflows and reservoirs hosted in both normally and reversely magnetised rocks. Several of these anomalies can be clearly correlated with surface expressions of volcanism such as craters, domes or cones, localised basaltic lavas or plugs. 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. The central geothermal area has a positive magnetic anomaly trending NW-SE. This anomaly is superimposed on a broad regional negative anomaly that covers the entire southern Lake Naivasha region (Bhogal and Skinner 1971). Finally, a rather subdued and almost featureless pattern occurs over a few areas where rocks lying outside the reservoir have lost their magnetisation by interaction with acidic, steam-heated water.

### 2.2 Application of the magnetic method over Menengai

Both the aeromagnetic survey flown in 1987 data for the National Oil Corporation of Kenya (NOCK) and results from ground magnetic investigations, that have be carried out by various workers and organisations (Geotermica, 1987; Gislason, 1989), including the Geothermal Development Company (GDC), have been used to study the geothermal potential of Menengai. The work of Kemei et al (2011) suggest that the northern part of Menengai geothermal field is demagnetized indicating a zone of possible high temperature and higher degree of hydrothermal alteration and intruded with high density bodies in the upper crust. This zone is large and extends beyond the area investigated towards the north. Used in conjunction with gravity data the magnetic signatures over Menengai area suggest the presence of a heat source and a geothermal reservoir hosted within the fractured/faulted brittle trachytic lavas of the rift floor to the north and northeast of Menengai caldera.

The aero-magnetic contour map (Figure 3) indicates a circular positive anomaly coincident with the Olrongai area. Positive magnetic anomalies are normally interpreted as being caused by changes in the magnetisation of rocks. This anomaly is probably caused by demagnetisation due to heating of the rocks above the Curie Point of the magnetite in the rock which is about 575 degrees Celsius at depths of between 3 to 4 km. If this interpretation is correct, then the area with the highest porosity is the Olrongai-Menengai extending to the Solai Axis and to the south-east.

The crater tends to interrupt the NW-SE trending anomaly which suggests structures in this direction which would control any possible geothermal fluids. This positive anomaly also coincides with a resistivity low.

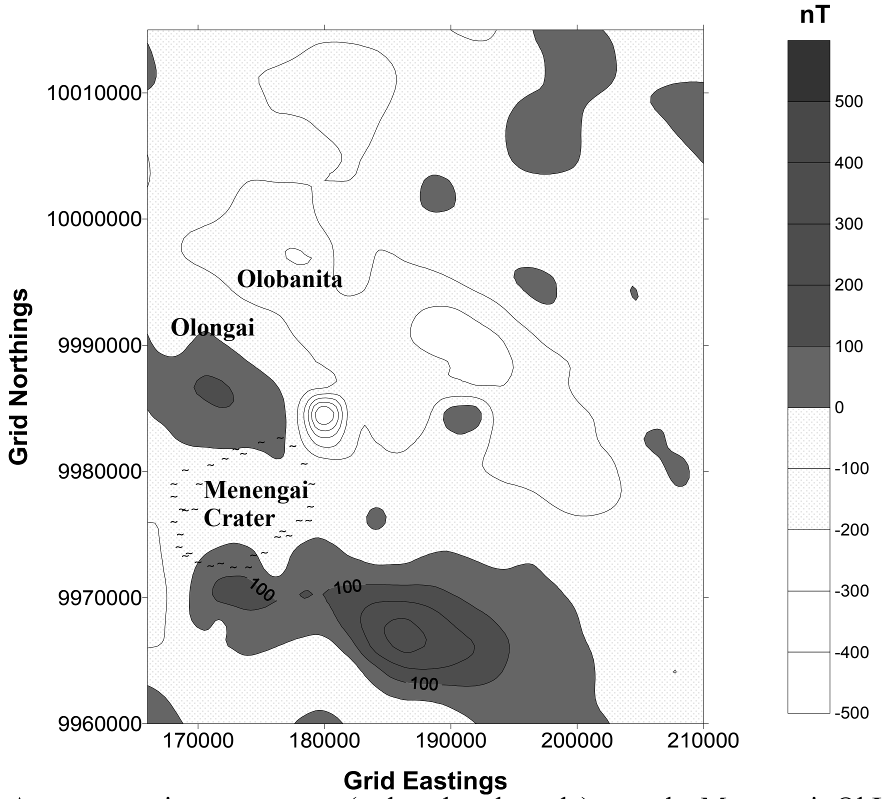


FIGURE 3: Aero-magnetic contour map (reduced to the pole) over the Menengai- Ol Longai - Olbanita geothermal areas, Kenya. Note the NW-SE trending anomalies

Experience of using the magnetic method over both Olkaria and Menengai Geothermal Fields is that it needs to be used in conjunction with gravity. Both fields are slowly getting populated accompanied by increasing human activity which introduces cultural noise (power lines, piping etc) into the data. This necessitates extra computing time to process the data so as to remove the cultural noise and to produce a 'clean' baseline data set against which the products of quicker automatic and semi-automatic intelligent routines of deculturing can be compared. Hence it is important to communicate the scale of the problem encountered and to show that by applying considerable care, it is possible to attain high-quality data.

## 2.3 Application of the gravity method over Olkaria

Volcanic centres, where geothermal activity is found, are indicators of cooling magma or hot rock beneath these areas as shown by volcanic flows, ashes, volcanic domes and abundant hydrothermal activities in the form of fumaroles and hot springs. Gravity studies in volcanic areas have effectively demonstrated that this method provides good evidence of shallow subsurface density variations, associated with the structural and magmatic history of a volcano. There is a correlation between gravity highs with centres of volcanism, intensive faulting and geothermal activity. During interpretation, to reduce ambiguity, use is made of seismic data to constrain the models generated. Figure 4 is an example of a gravity anomaly over Olkaria geothermal field in Kenya.

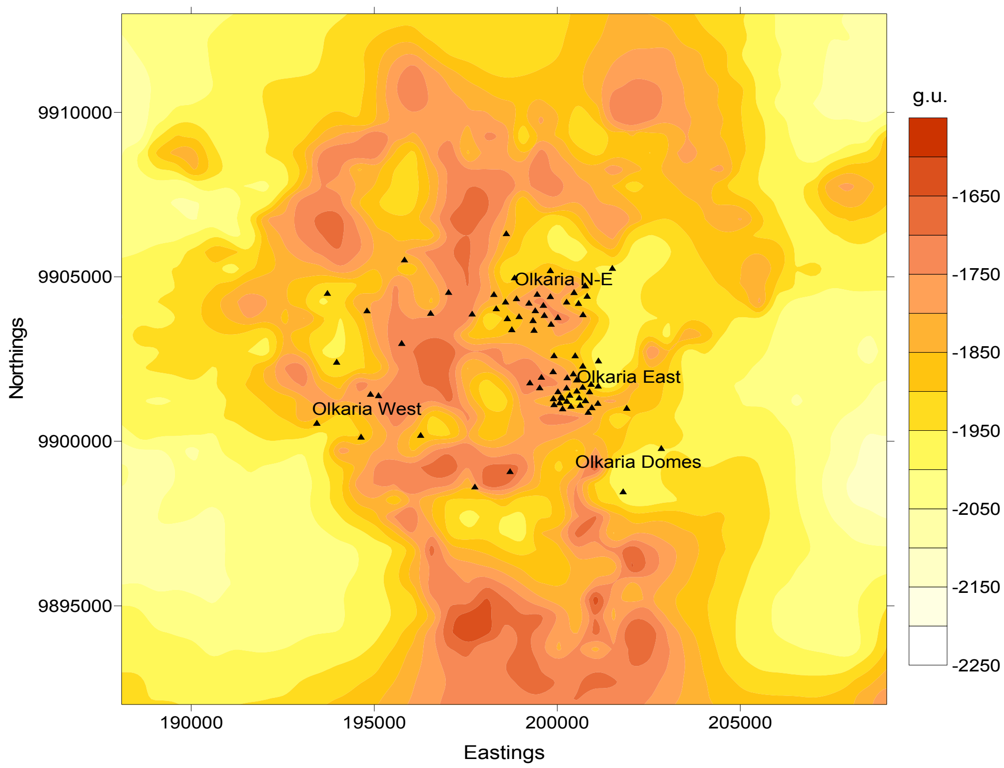


FIGURE 4: Gravity anomaly over Olkaria geothermal field in Kenya

Geological observations indicate that the Olkaria area is underlain by an intrusive mass, part of which still contains residual magma. North-South fracturing in the area has provided loci for eruptions of pleistocene to Recent volcanics, including a number of rhyolitic domes, comenditic flows,pumiceous obsidian flows and dykes. The line of white ash and pumice eruption,phreatic explosion vents, and Ololbutot flow of magma in Olkaria along the north-south Ololbutot fracture. A two-dimensional geologic model of Olkaria is constructed and updated regularly using newer geological and gravity data and the seismic results from current and previous works (Figure 5). Two-dimensional modelling of the gravity data shows that the western part of the Olkaria area is down-faulted relative to the eastern part and the Olkaria area lies partly on a graben structure and partly on a horst structure. Further interpretation of gravity data within the Greater Olkaria Area shows that a dense body occurs at the southern part of Olkaria (Ndombi, 1981). The Olkaria West, EPF and NE fields occur within gravity lows. The major north-South fractures, most of which lie on the horst structure, have been intruded by dyke-like bodies of ryolitic composition. The largest intrusion has occurred along Ol Olbutot fault zone. This intrusion is still in magmatic state and appears to be the main heat source for the present geothermal phenomena at Olkaria. Our interpretation indicates that this system of dikes is a significant hydrogeological barrier between Olkaria West and EPF/NE. The geothermal field has been well delineated by aid of resistivity data. It is contained within a roughly north-south trending zone,up to an average of 2 km on either side of the Ololbutot fracture line , and is bounded by the north-south Olkaria and OI'Njorowa faults.

The Menengai-Olbanita area is located in a region of intracontinental triple junction where the Nyanza rift joins the Kenya rift and is considered to overly a mantle plume (Burke and Dewey, 1973; KRISP Working group 1994). The surface is comprised of several eruptive volcanoes with caldera collapses and concentration of tectonic grid faulting. The Menengai complex is dominated by a central volcano with a large caldera of about 12km in diameter. The Olbanita volcanic complex consists of the remnants of an old caldera 8 km north of Menengai. The surface in both areas is covered by mainly pyroclastics, tuffs and minor occurrence of trachyte and basalt.

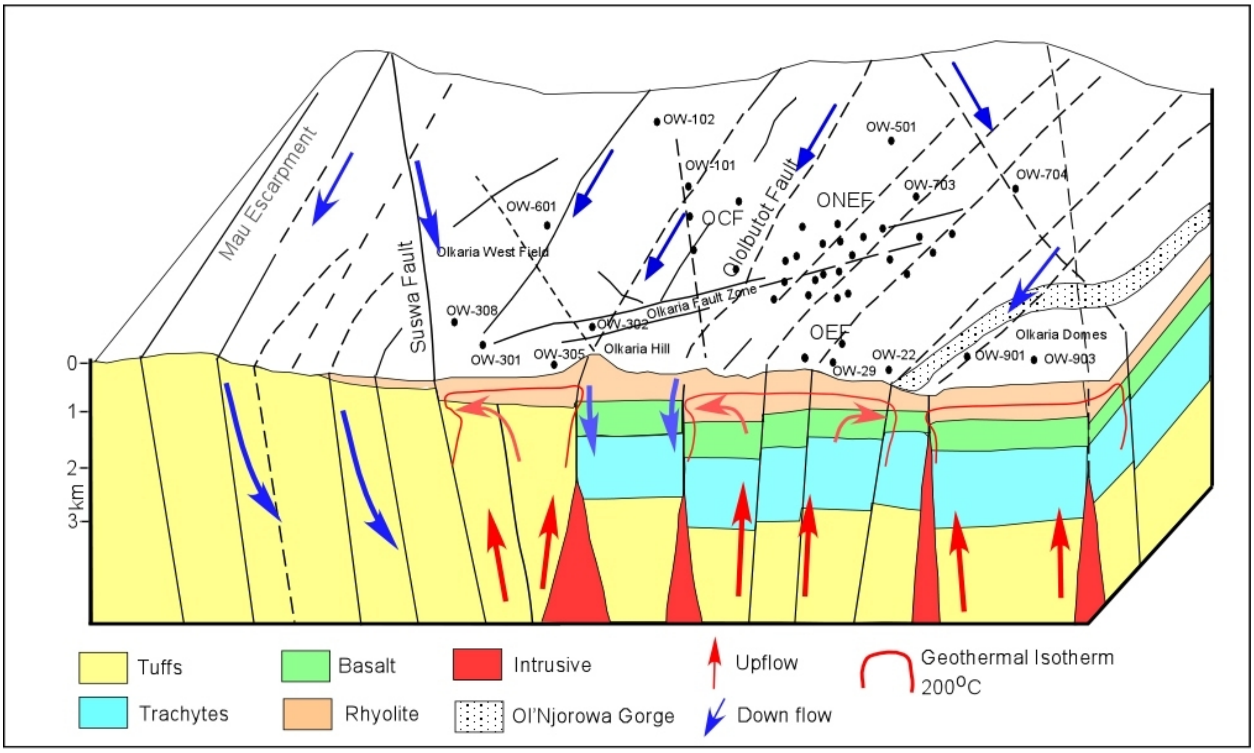


FIGURE 5: An integrated geophysical model of Olkaria geothermal field

Gravity studies by Geotermica Italiana (1987) collected some 1400 data points. Later KenGen and the Geothermal Development Company in-filled more gravity stations in and around the Menengai Caldera. Analysis of this data shows a large positive anomaly, located in the central part of the area. This is interpreted as being related to a dense body located some 3.5-4 km deep and a density of 2.8 gcm-3 that could a heat source for the geothermal system. This anomaly coincides with the Molo Volcanic Axis (Figures 5 and 6).

Data from the Solai area showed that the N-S trending anomaly, which reaches a maximum in the Molo Volcanic Axis, is less prominent within the Solai fault zone. Despite the Solai fault zone having relatively intense tectonic activity, it is less volcanically active than the Molo axis system due to relatively few eruptions of lavas. However, the intense tectonic activity may likely result in high permeability giving rise to some likelihood of cold waters from the eastern escarpment infiltrating any possible geothermal reservoir in the area.

Gravity data interpretation by KenGen (Mariita et al., 2004) by analysis of profiles through the caldera indicate the presence of a high density body with peaks beneath this structure (Figure 8). Since the volcano is relatively young this body could still be hot, the heat being conducted to near surface regions by dykes.

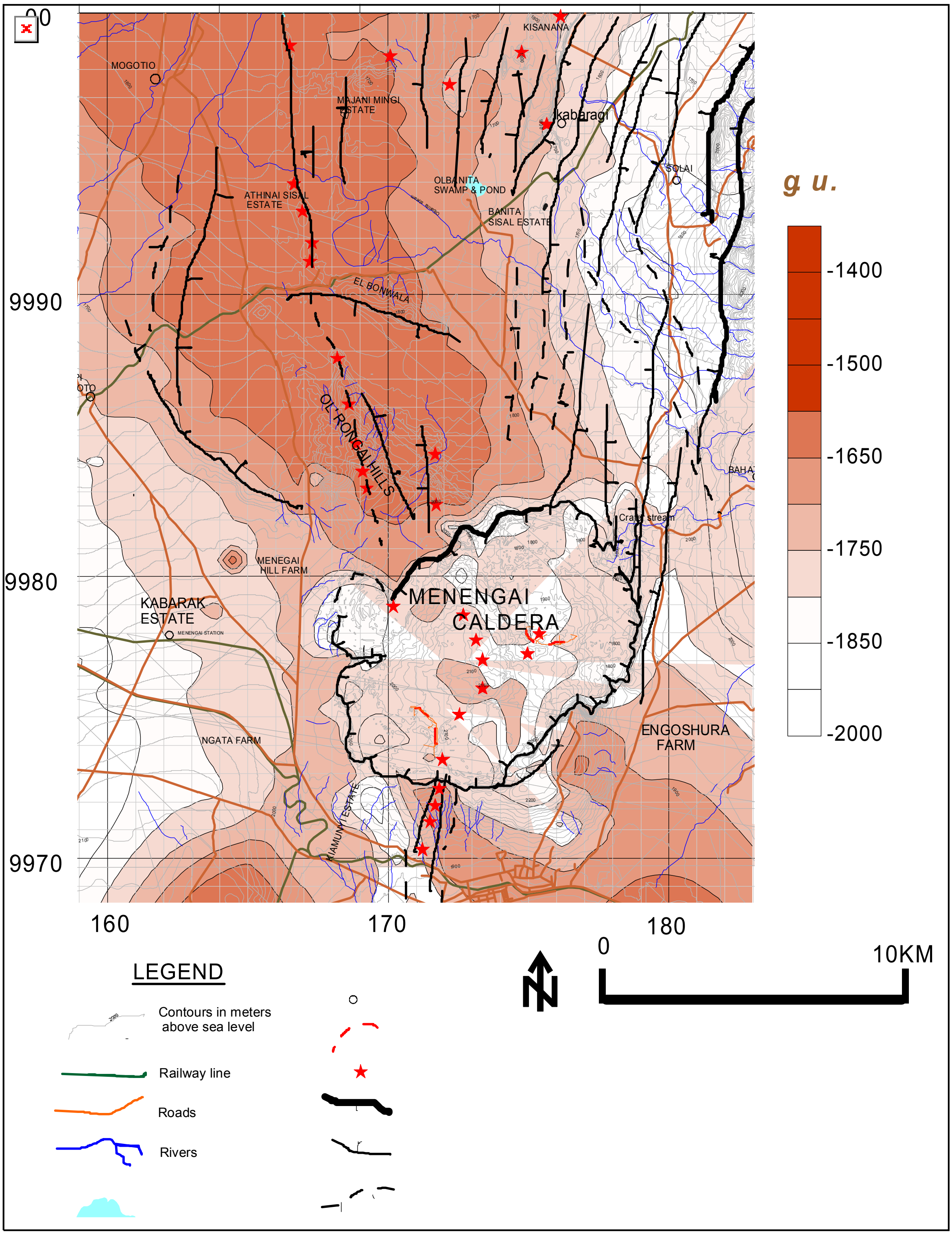


FIGURE 6: Gravity contour map of Menengai - Ol Banita geothermal prospects using Bouguer density of 2.3 gcm$^{-3}$

As shown in Figure 6, gravity high runs through the central part and trends NNW-SSE. This coincides with the Molo Volcanic Axis. A NE-SW trending low gravity anomaly interrupted by Menengai caldera can be seen (Figure 7). This low corresponds to a NE-SW tectonic structure that seems to define the shape of Menengai caldera. This low gravity might be due to fracturing thus lowering the bulk density, indicating presence of high permeability. Within the caldera (Figure 8), the influence of the surficial lavas is seen corresponding to relatively higher gravity, however, the NNW-SSE gravity high still exists.

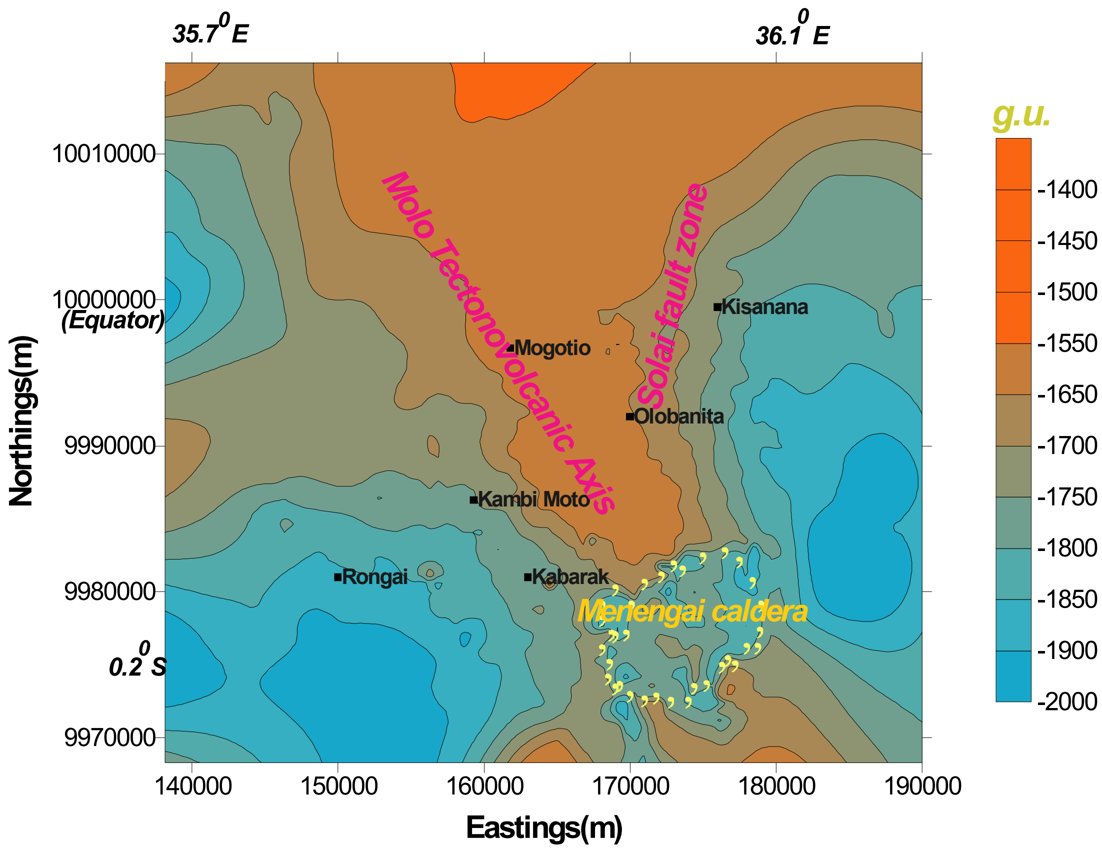


FIGURE 7: Menengai Bouguer gravity map

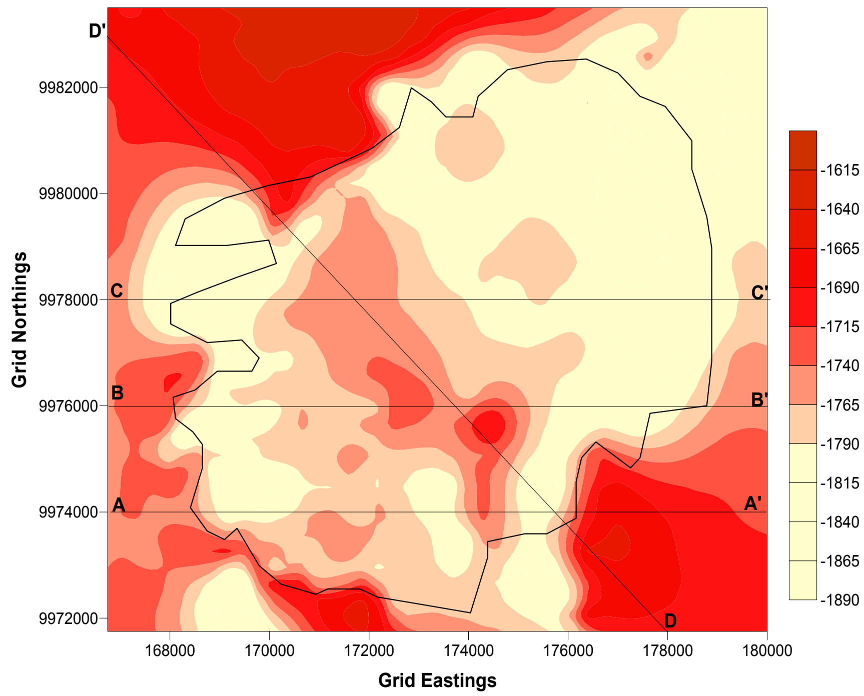


FIGURE 8: Bouguer anomaly map and analysed profiles through Menengai caldera

Parts of Olkaria and Menengai geothermal fields have ragged terrains with few or no access roads. The Menengai caldera is particularly challenging, the near fresh lavas making collection of data difficult or even dangerous.

Gravity data requires a lot processing techniques before being ready for interpretation. Interpretation can be completely objective or highly subjective. It can range from a simple inspection of a map or profile to a highly sophisticated operation involving skilled personnel and elaborate supporting equipment. Some interpretations require little understanding of the geology, but the quality of most interpretations is improved if the interpreter has a good understanding of the geology involved. Gravity data is also known for its ambiguity in interpretation unless compared with results from other methods such as seismology.

## 3. CONCLUSIONS

Given the site conditions and targets of investigation, the choice of a geophysical surveying method for geothermal energy should bear several factors in mind. First, the technique must be suited to detecting the necessary targets at the site imaged as anomalous features. Second, the technique must be appropriate for the conditions of the area, especially the subsurface geology and ground surface. If a particular method is conducted, it would best be used to complement it with another method of geophysical survey. Experience from geothermal exploration using magnetics and gravity around Olkaria and Menengai fields do suggest good indications of the likelihood of a geothermal resource and are best suited the methods to be utilized as first choices. These methods are often easy to carry out and are cost effective.

Gravity data is often complex and may not be interpretable. It could mean the data is possibly erroneous, but could also be accurate data requiring more sophisticated processing and interpretation. When this distinction is made, other reasons ruled out and no anomaly is seen then it can be concluded that the survey was not successful.

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