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STRENGTHS AND WEAKNESSES OF GRAVITY AND MAGNETICS AS EXPLORATION TOOLS FOR GEOTHERMAL ENERGY

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ABSTRACT

There are many different geophysical techniques available to the earth scientist, each with its own strengths and weaknesses. Some aspects of geophysical surveys still prohibit wide application of these techniques. 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.

This paper describes procedures for planning and executing specialized geophysical work in geothermal-resources investigations. It covers the potential field's methods of gravity and magnetics. The general physical principles underlying each method and its capabilities and limitations are described. Possibilities for non-uniqueness of interpretation of geophysical results are also noted. Examples of actual use of the methods are given to illustrate applications and interpretations in selected case examples of geothermal areas in Kenya. The objective of the paper is to provide the potential or young geophysicist with a sufficient understanding of the capabilities, limitations, and relative cost of gravity and magnetic geophysical 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. Results are usually confirmed by drilling.

Gravity, seismic refraction & reflection, and electrical resistivity delineate bedrock valleys concealed by sediments or volcanic materials. 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.

Techniques for geophysical detection and mapping of permeable fractures have been developed, tested and applied. In addition to the surface techniques briefly outlined here, some subsurface conditions can be resolved by geophysical measurements involving boreholes. Geophysical techniques do not eliminate the need to drill and sample. However, geophysical prospecting can reduce the overall costs and improve the overall quality of a site investigation by:

(1) Targeting anomalous areas where sampling is most likely to encounter extreme values;
(2) Providing physical evidence needed to justify interpolation of subsurface conditions between sample locations;
(3) Providing physical evidence that areas not directly sampled are unlikely to conceal unexpected conditions.

Proper application of geophysical measurements can significantly reduce the number of wells needed to characterize a prospect while improving the confidence of interpretations based on direct borehole measurements. Geophysical techniques become increasingly cost-effective as the area and depth to be investigated increase. One limitation, however; certain routine geophysical methods 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 (see Figure 1) preferably by a combined team of earth scientists and engineers are often required prior to finalizing plans for a geophysical prospecting project.

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

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, where 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.

Geophysical investigations can be a timesaving and cost-effective method for providing both qualitative and qualitative subsurface information for a site. They can be used for screening large areas for potential geothermal reservoirs, for focusing resources for intrusive investigation activities on the anomalous areas, and for identifying or confirming the presence and extent of heat sources. Buried hot rocks will (most likely) exhibit different bulk material properties than the surrounding native country rock. This will typically allow geophysical instruments 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 in order to more correctly assess the site. Non-intrusive geophysical methods can be utilized as preliminary screening before performing intrusive investigations, they may be implemented as the primary investigative technique, they may be used in combination with intrusive investigation methods such as bore holes or test pits, or they can be used in combination with other non-intrusive geophysical methods. Understanding the specific strengths and weaknesses of each method will allow the investigator to decide how to best utilize geophysical investigation.

The results obtained from a geophysical investigation are subjective and rely on geologic interpretation. Geophysical techniques do not directly measure the parameter needed to solve the problem but instead measure contrasts in material properties. For example, seismic methods measure velocities of seismic waves through the subsurface material recorded by the receivers, called geophones, and correlated to the material properties of the subsurface. Careful analysis can tell us whether it is a direct surface wave, one reflected from a subsurface geologic interface, or a wave refracted along the top of a geologic interface. Although geophysical interpretations are not always perfectly accurate, 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 coupled with an intrusive investigation, large volumes of material can be explored accurately and cost-effectively. In the discussions that follow each of the major geophysical methods will be briefly described with emphasis on the applications and limitations in geothermal energy investigations.

2.1 Overview of the Magnetic Method

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 by the earth's magnetic field during some process in the history of formation of the mineral) or induced magnetization created by the presence of the earth's magnetic field. In most rocks both are present.

The goal of the magnetic method is to map changes in the magnetization which are in turn related to the distribution of magnetic minerals.

Instruments used to measure the magnetic field are called magnetometers. An important distinction between the magnetic and gravity methods is that magnetization depends on the inducing field so that the resulting field from an object depends, in a rather complex way, on how the induced field interacts with the inducing field to alter it and hence to change the magnetization. These are the so called demagnetization effects. For gravity the effect of a body is simply the Newtonian gravitational attraction of the point masses which make it up - the force of attraction has no effect on the density. Fortunately, for most practical situations the magnetization of rocks is weak and a simple approximation does allow magnetic anomalies to be calculated in a manner equivalent to the linear summation used in gravity.

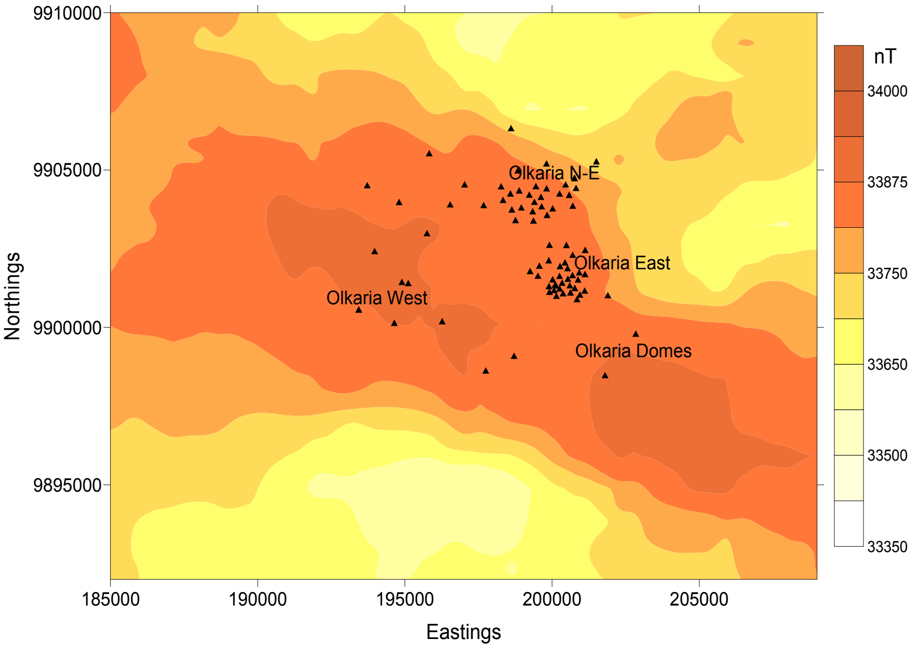

FIGURE 2: Magnetic anomaly over Olkaria geothermal field, Kenya. It is obvious that the anomaly trends in a NW-SE direction

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^{o}C). Ground magnetic measurements do provide more detailed information on sub-surface structures that could act as heat sources in comparison to aeromagnetic data. Figure 2 is an example of aerial magnetic measurements of Olkaria geothermal field, Kenya.

2.2 Overview of the Gravity Method

Gravity meters measure the *difference* in gravity between a base station (where the absolute value of gravity is known) and a series of field stations. Most base stations are established by measuring the difference in gravity between the new base and an already established base station. Many base stations trace their origin back (through a line of base stations) to Potsdam, Germany, where physicists attempt to measure "g" to a precision of one part in a million.

Many workers prefer the LaCoste and Romberg meter over others that have been used. Once the gravity at a new field site is known, theoretical gravity is calculated. Theoretical gravity depends on latitude, elevation, and on the surrounding topography. Many of the commonly applied equations can be found good geophysics textbooks or by taking a class in gravity field methods. The difference between the observed and theoretical gravity is called the Bouguer anomaly. If the Bouguer anomaly is negative, it means the observed gravity is less than the theoretical.

Because the force of gravity is proportional to the mass responsible for the gravitational field and inversely proportional to the square of the distance between any part of that mass and the observation point, a local lack of normal mass (say, a thick layer of low-density sediments instead of heavy igneous rocks of negligible porosity) will result in a local gravity low. A mass of unusually dense rock (gabbro intruding sedimentary rock or acidic volcanics) will generate a gravity high.

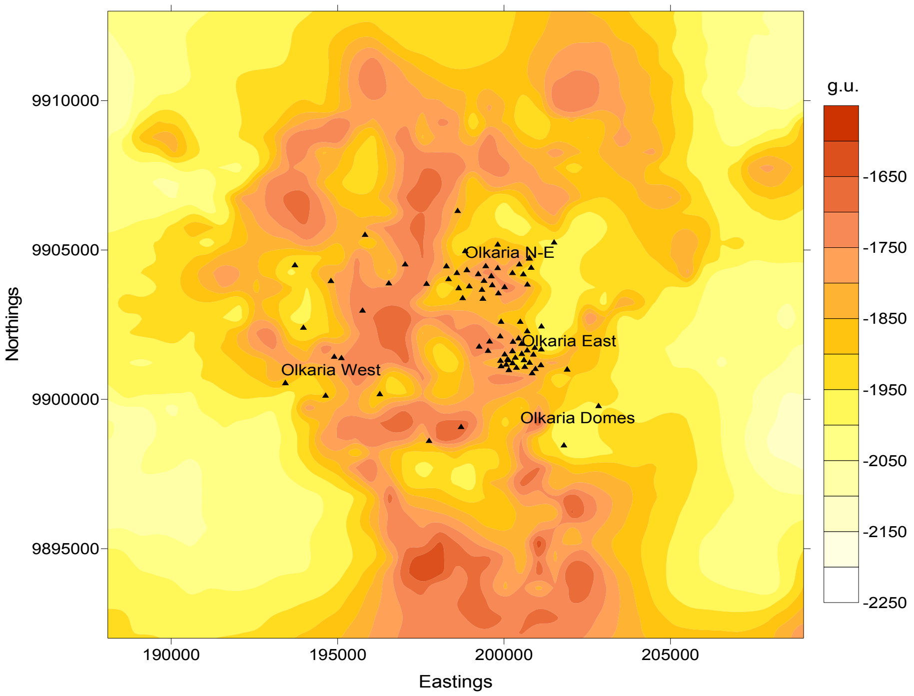

FIGURE 3: Gravity anomaly over Olkaria geothermal field in Kenya

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 2 is an example of a gravity anomaly over Olkaria geothermal field in Kenya.

By now it is obvious that many geophysical methodologies are available to the geophysicist. But which ones are applicable to geothermal energy prospecting? Table 1 is a summary of the advantages and disadvantages of the common methods that have been used in exploration for geothermal energy.

TABLE 1: Strengths and Weaknesses of common geophysical methods used in exploration for geothermal energy

Method	**Strength**	**Weakness**
Seismic Refraction		
Conventional reversed profiles:	Classical engineering method. Reveals general layering in the subsurface. Relatively short processing time in lab compared to other seismic methods. Excellent complement to DC resistivity and GPR surveys for depth to the water-table or depth to bedrock.	If structure is not dipping planar, then more refined methods should be (have been) used, such as the delay time method (below). Somewhat more time intensive in field than above conventional refraction method, and considerably more time intensive in lab.

Delay time or time term method:	In principle, since each geophone or shot position can lead to an estimate of the local depth to the refractor beneath the respective "station", this procedure can result in a highly detailed configuration of the refracting surface, e.g. bedrock.	General to both refraction methods: While a layer may be detected at depth, its seismic velocity may not be an unambiguous discriminator between bedrock and the groundwater table. Low velocity layers, sandwiched between higher velocities, are masked and total depths are biased. Complementary data may be required.
Seismic Reflection	Often, good resolution of layering from depths of 20 m to more than several hundred meters. For decades, the favoured tool of the oil industry for deep exploration, but has fewer proponents or service providers for shallow (<100 m) investigations.	Labour intensive both in the field and by skilled interpreters in the lab. Cost is usually justified when information from depths of 100 m or so is needed. Extracting precise interval velocities from multilayered media is sometimes difficult.
Gravity	The method "weighs" the earth directly beneath a field site. Because of the density difference between unconsolidated sediments and surrounding bedrock in a sediment-filled valley, for example, the technique is very effective for gross characterization of depth to bedrock beneath 10's to 100's of meters of sediments. Effective in culturally developed areas where buried water mains and utility lines, overhead wires, pavement, etc., may "mask" other geophysical signatures.	Relatively time intensive for a trained interpreter in the field and lab. Needs to be "calibrated" at one or more control points using complementary well data or other geophysics (e.g. seismic refraction/reflection).
DC Resistivity (four electrode "sounding" or "profiling" methods: Wenner, Schlumberger, Dipole-dipole.)	Direct indicator of electrical conductivity, which, in turn, is an indirect indicator of soil moisture or percent saturation. Good for determining depth to the water table. Good indicator of bedrock at depth. Very effective complement to seismic refraction or GPR data.	Vertical resolution in the best of cases is somewhat coarse. Method needs special care when lateral features are encountered, adding greatly to acquisition cost and interpretation. Requires a lateral clearance for a horizontal array that may be 10 times the depth of resolution.
Electromagnetic *"Active" Sources*: Frequency domain (FDEM) Time domain (TDEM)	Very effective for the rapid reconnaissance of an area for mapping depth to bedrock, depth to water-table, detecting clay lenses. Also effective for mapping infrastructure hazardous to drilling or excavation. Several light-weight FDEM and TDEM units are available for use by single operators for rapid reconnaissance. Active source (horizontal loop) methods can be specially deployed to map features at several 100 m's depth. TDEM appears to have good potential for vertically probing in areas of restricted horizontal access. Whereas TDEM has been used by the mineral industry for deep exploration for many years, it has few service providers for shallow (<100 m) investigations.	Topography can be a problem in interpreting FDEM data. TDEM is not widely used for shallow studies (less than 20 m) in resistive terrains, except for shallow (1 or 2 m) metallic infrastructure investigations. In some cases, source effects can be significant.
Electromagnetic "*Distant" or "Passive" Sources*: VLF (Very Low Frequency) Method(s) Controlled Source Audio Frequency Magnetotellurics Magnetotellurics Tellurics Magnetic variations	Particular methods are effective for mapping depth to bedrock, depth to water-table, detecting clay lenses, and for delineating fracture patterns in bedrock, sometimes to may 10's of meters.. Generally, these methods are very cost effective for large scale reconnaissance studies, or in areas of rugged terrain. Also effective for mapping infrastructure hazardous to drilling or excavation. Various methods can be used in "profiling" or in "sounding" modes, and in some cases lead to	Conventional VLF sometimes has difficulty receiving multiple stations. In some cases, interpretations of local structure are distorted by 2D and 3D effects beyond the immediate survey area. While VLF instruments are relatively inexpensive, the technique is not highly developed. Other instrumentation is relatively expensive, and requires some expertise in interpretation.

	direct estimates of the subsurface resistivity. Distant source methods - whether the signal source is controlled, uncontrolled, or natural - have the advantage that the roving field instrumentation is light-weight and portable, and that the interpretation of field data is, in ideal cases, relatively free of source effects.	
Magnetics	Often useful to delineate geologic features related to hydrogeology, e.g. bedrock lineations, intrusives, geologic contacts, heat sources etc. Very effective for identifying infrastructure hazardous to drilling or excavation. One of the most cost-effective techniques for screening an area for steel USTs, buried drums, water mains, etc.	Local traffic and other magnetic disturbances often require gradient (two sensor) techniques. Lower cost proton precession units tend to be more unstable than more expensive alkali-vapour units in the presence of high magnetic field gradients typical of many industrial sites. Depth resolution is poor except for small, shallow targets.

3. OVERVIEW OF DESIGN OF GEOPHYSICAL SURVEYS

Geophysical surveys can be useful in the study of most subsurface geologic problems. Geophysics also can contribute to many investigations that are concerned primarily with surface geology. However, geophysical surveys are not always the most effective method of obtaining the information needed. For example, in some areas auger or drill holes may be a more effective way of obtaining near-surface information than geophysical surveys. In some investigations a combination of drilling and geophysical measurements may provide the optimum cost-benefit ratio. Geophysical surveys are not practical in all ground-water investigations, but this determination usually can be made only by someone with an understanding of the capabilities, limitations, and costs of geophysical surveys.

A clear definition of the geologic or hydro-logic problem and objectives of an investigation is important in determining whether exploration geophysics should be used and also in designing the geophysical survey. The lack of a clear definition of the problem can result in ineffective use of geophysical methods. The proper design of a geophysical survey is important not only in insuring that the needed data will be obtained but also in controlling costs, as the expense of making a geophysical survey is determined primarily by the detail and accuracy required. In this, the geophysicist plays a great role:

- The geophysicist in normally the one who designs the geophysical survey (written and oral presentation) including which instruments to use and why, what are the survey characteristics (providing guidelines for survey time constraints)
- The geophysicist discusses and debate the merits of the various proposed geophysical techniques and survey characteristics
- The geophysicist and technicians carry out the field geophysical survey as teams
- The geophysicist and technicians use computers to process, display, model and interpret the geophysical data they collect
- The geophysicist must create models of expected anomalies for each of the different instruments proposed
- Results are then presented of the investigations both orally and in a written form (e.g., technical report, scientific paper, scientific poster, etc. depending on project requirements).

4. COLLECTION AND REDUCTION OF GEOPHYSICAL DATA

Some simple geophysical surveys can be made by individuals with little previous experience and with an investment in equipment of only a few hundred dollars. Other surveys require highly skilled personnel working with complex and expensive equipment. Good equipment and technical expertise are essential to a high quality survey. Attempts to use obsolete or “cookbook” interpretation methods in geophysical surveys often increase the total cost of the survey and result in an inferior product. Some geophysical data can be used directly in geologic interpretations. Other geophysical data require considerable processing before the data can be interpreted, and the cost of data reduction is a major part of the total cost of the survey. Many data processing operations in use today require the use of electronic computers.

Interpretation of geophysical data 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. Although some individuals are both skilled geophysicists and geologists, a cooperative effort between geologists and geophysicists is usually the most effective approach to the interpretation of geophysical data.

5. 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, e.g. gravity and magnetometry. Experience from geothermal exploration suggests that both self potential and seismic surveys are probably not the best methods to utilize as first choices. These methods are often difficult to carry out and not generally regarded as the best methods. These methods should only be used when there are special circumstances or targets that these methods are specifically suited for. Besides, seismics are very expensive because field logistics are difficult to implement.

Strong support for the use of a certain method comes from surveys conducted elsewhere for geothermal energy exploration. Resistivity, gravity and magnetic methodologies have been widely applied. 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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