Presented at SDG Short Course II on Exploration and Development of Geothermal Resources,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Nov. 9-29, 2017.

Geothermal Development Company
Powering the Vision
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UNU-GTP
Geothermal Training Programme
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GRAVITY AND MAGNETIC METHODS

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ABSTRACT

Gravitational method is the study of the distribution of mass in the subsurface with the observation point at the earth's surface. The gravity technique provides information regarding the density distribution in the subsurface and can identify anomalous geological features (of varying density) in order to detect structural or lithological contrasts in the subsurface. The success of the gravity method depends on the different earth materials having different bulk densities (mass) that produce variations in the measured gravitational field. These variations can then be interpreted by a variety of analytical and computers methods to determine the depth, geometry and density that causes the gravity field variations. The gravity method produces an ambiguous, non-unique solution for the subsurface structures. Therefore precise gravity interpretation require a number of data reductions methods so as to eliminate all other effects and only be left with those that are caused by geological variation in the sub-surface. On the other hand magnetic method is a geophysical exploration method used in the study of the distribution of magnetic minerals in the upper sub-surface of the earth's crust. Magnetic method may also be used to estimate the thickness of the crust or to constrain temperatures in the crust using the Curie isotherm (the temperatures at which minerals lose their strong magnetic properties), whichever is shallower. It can also be used to record variations in the magnetic field due to lateral variability in the magnetization of the crust. These lateral variations may produce anomalous regions which are indicative of structural or lithological contrasts in the subsurface.

1. GRAVITATIONAL METHOD

Gravitational method is the study of the distribution of mass in the subsurface with the observation point at the earth's surface. The gravity technique provides information regarding the density distribution in the subsurface and can identify anomalous geological features (of varying density) in order to detect structural or lithological contrasts in the subsurface. Gravity measurements can be recorded from the earth surface, from an airborne platform, aboard a marine vessel, or in a borehole. The gravity method involves measuring the gravitational attraction exerted by the earth at a measurement station on the surface. The strength of the gravitational field is directly proportional to the mass and therefore the density of subsurface materials. Anomalies in the earth’s gravitational field result from lateral variations in the density of subsurface materials and the distance to these bodies from the measuring equipment (Figure 1).

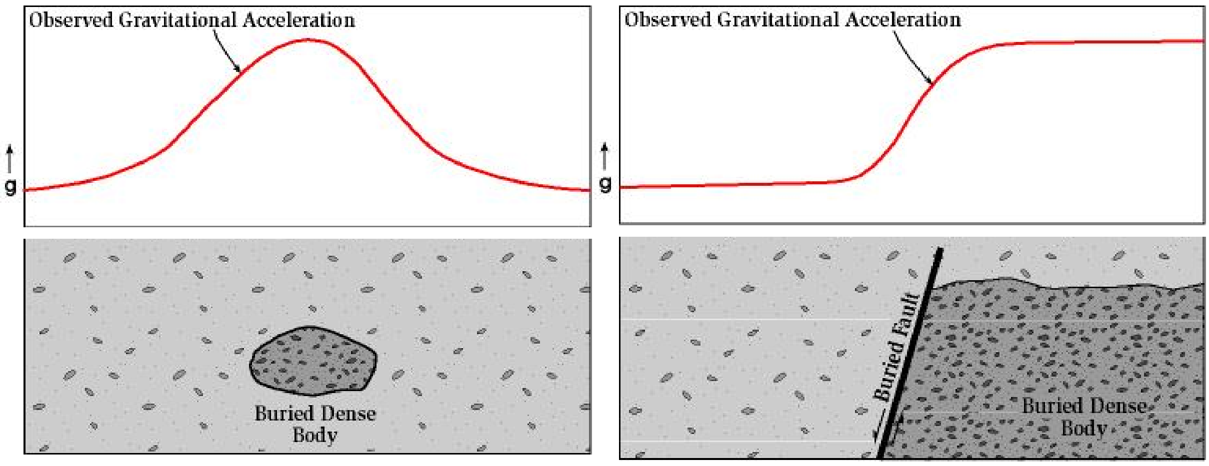

FIGURE 1: Illustrations showing the relative surface variation of Earth's gravitational acceleration over geologic structures

1.1 Application of gravity in geothermal exploration

Gravimetric studies may provide a constraint on the structure and extent of the geothermal reservoir, to a depth of ~2km. Fault location, dip and offset, as well as depth to basement, are commonly interpreted from a gravity survey. Changes in density may also be related to zones of hydrothermal alteration, intrusions, highly fractured rock or deposition of silicates in the vicinity of hydrothermal activity. Additionally, examining components of the gravity field can be useful in geothermal exploration. For instance, the horizontal gravity gradient enables identification of regions with the greatest contrast in density, such as at fault contacts. Gravity techniques are also applied towards reservoir monitoring for subsidence and mass gain or loss within a geothermal reservoir using the microgravity technique.

1.2 Physical properties

The fundamental physical laws defining the behavior of the gravitational field are Newton's Law of Attraction and Newton's Second Law. The gravitational field at a point is measured in milligals (mGal). The total gravity field and directional gradients of the gravity field can be measured.

$$1\ \mathrm{Gal} = 1\ \mathrm{cm/s^2} = 1000\ \mathrm{mGal}$$

Density is the physical property of interest for a gravity survey. Density is an intrinsic property of a material and is measured in mass per unit volume (kg/m^3).

1.3 Potential limitations

The gravity method produces an ambiguous, non-unique solution for the subsurface structures. The density distribution is the product of the mass and the volume of the body in the subsurface. Therefore, many combinations of mass and volume may result in the same anomaly as portrayed in the gravity data. Additional geophysical techniques or geological evidence may be required to reduce the ambiguity and further constrain the gravity model.

1.4 Information derived from gravity technique

Lithology: Distribution of density in the subsurface that enables inference of rock type.

Stratigraphic/Structural: Delineation of steeply dipping formations, geological discontinuities and faults, intrusions and large-scale deposition of silicates due to hydrothermal activity.

Hydrological: Density of sedimentary rocks is strongly influenced by fluid contained within pore space. Dry bulk density refers to the rock with no moisture, while the wet bulk density accounts for water saturation; fluid content may alter density by up to 30%. (Sharma, 1997).

Thermal: Determination of potential heat source of the system related to the low density signature of molten intrusions.

1.5 Field procedures

A ground gravity survey is a passive, low impact, non-invasive geophysical technique. An instrument called a gravimeter is used for the measurement. A relative gravimeter, commonly used for exploration, is transportable by one person with a backpack and weighs roughly 8kg. The instrument is carried to the measurement station, placed on the ground surface, and levelled. The gravity measurement takes a few minutes (depending on the type of gravimeter), and then the gravimeter can be picked up and transported to the next station. Some of the gravity meters types used are shown below.

1.6 Data access and acquisition

There are two types of gravity instruments: an absolute and a relative gravimeter. An absolute gravimeter is a highly precise tool applied to reservoir monitoring and subsidence studies usually used in microgravity study. The commonly used gravimeter in geophysical exploration applications is the relative gravimeter. The LaCoste and Romberg and Scintrex instruments are the most commonly used gravimeters (Figure 2).

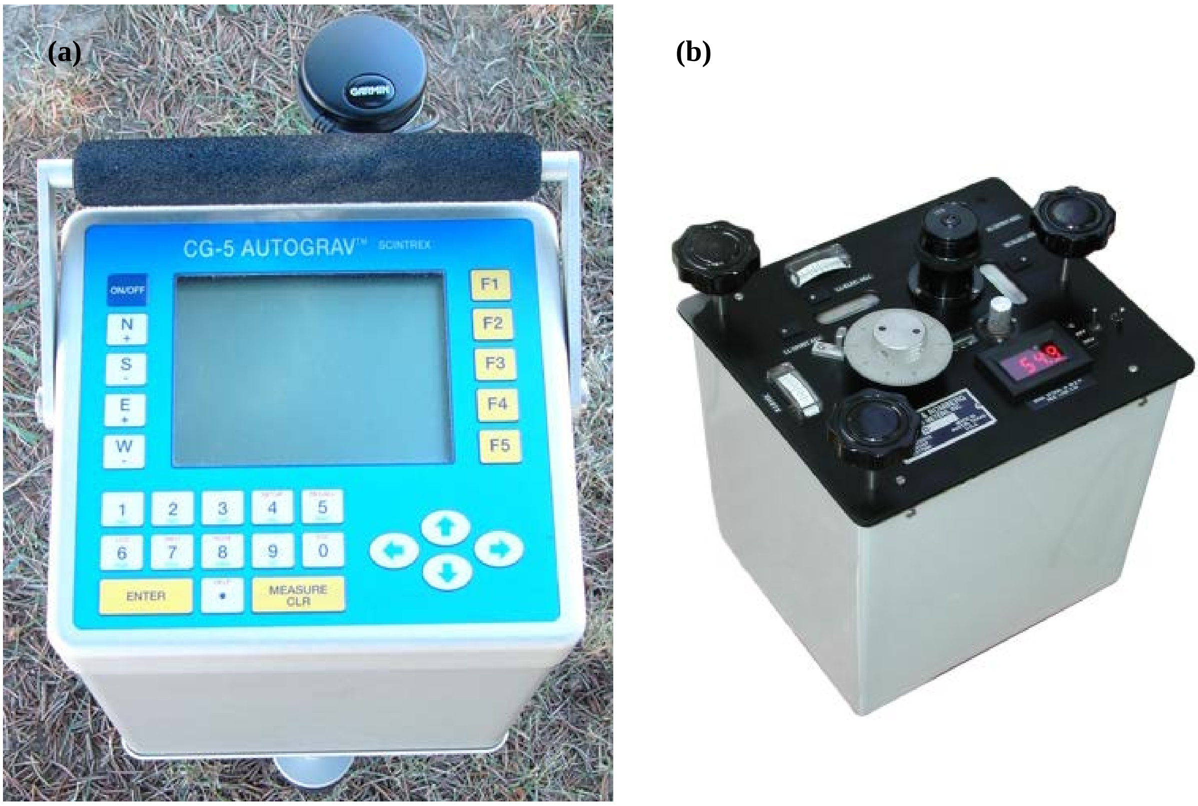

FIGURE 2: Some commonly used gravity meters (a) Scintrex CG-5 Autograv
(b) Lacoste & Rhomberg gravity meter

The survey design is based on the anticipated depth of investigation, density contrast and structure of the geological feature. Additional parameters to take into account for the survey design are the accuracy of the gravimeter, accuracy of the measurement station in location and elevation, the accuracy of the topography in the vicinity of the station, and the frequency of the re-occupation of the base station.

In a gravity survey, measurements must be taken in a closed loop or series of closed loops throughout the measurement period. There is a primary base station to be visited and measured at the beginning and end of each field acquisition day, as well as intermediate base station loops established in the field area. This is because the instrument can experience drift or experience tares due to rough handling. Tidal effects due to the position of the sun and moon and Earth's revolution can be accounted for by repeat occupation of base stations at periods of 2 to 3 hours. High resolution gravity surveys are best conducted in conjunction with differential GPS measurements although conventional survey methods can be used. GPS is fast and can be done simultaneously by the gravimeter operator or by one field assistant.

Field notes should include the station name, gravimeter reading, time of measurement, station location (latitude, longitude, elevation). Terrain data for corrections can be acquired from digital terrain models from the web site. There are corrections to the data which are intrinsic to the gravitational method and involve the removal of the regional field to obtain the residual Bouguer anomaly map. Corrections included in the calculations of the Bouguer anomaly are as follows:

1.7 Corrections necessary for data reduction

1. ***Latitude correction;*** Here we correct for a calculated normal field. The correction takes into account the Earth's rotation, as well as the fact that the distance to the centre of the Earth's mass varies with latitude. Typically, we just calculate the reference gravity and subtract it from our readings, but this relation can be convenient. Remember that gravity increases as you go towards the poles, so we add this correction to our readings as we move to the equator.

2. ***Free-air correction;*** This correction is made for the reduction in the gravity field from sea level to the altitude of the measuring site. Often we make observations at different elevations, and we know that gravity will decrease as we get farther from the center of mass of the Earth. Therefore, we choose a reference elevation (typically sea level) and adjust our readings to be what they would be at that elevation. Most land surveys are done above sea level, so the free air correction will generally increase the gravity reading.

3. ***Bouguer correction***; Here we subtract the effect of the rock mass between the measuring site and sea level. Of course, now that you have taken your reading down to sea level, you have to account for all the mass between your original elevation and sea level. This correction is called the “Bouguer Correction” and is calculated by assuming an infinite slab of material of thickness Δh lying between the station and sea level. Again, because land surveys are usually above sea level, the Bouguer correction usually decreases the gravity reading.

4. ***Terrain correction;*** This correction accounts for the topography in the vicinity of the measuring station. In this regard it is necessary to have a good map (preferably digital) of the area around the observation site. Terrain corrections traditionally are made by estimating the differences between the elevation of the station and that of the topography surrounding the station. Remember that terrain always reduces the gravity reading: mass excess above the station (mountains) pull up on the station, while mass deficiencies below (valleys) “push” (the correction is for a negative mass). Thus, a terrain corrected reading will always be greater than it originally was.

1.8 Density determinations

In order to remove the effects of topography, Bouguer and terrain corrections made routinely as part of gravity data reduction require knowledge of the average density of the rocks that constitute the topographic relief of the surveyed area. The success of these corrections depends on determining the best average density possible for these rocks. No one density value is completely satisfactory for a large area, but there are a number of techniques available to estimate the density of rocks in situ (Nettleton, 1939). The underlying goal in these techniques is to minimize the correlation between Bouguer gravity anomalies and elevation. Table 1 shows the density variations of different materials.

The density of a rock is dependent on both its composition and porosity

TABLE 1: Densities of materials

Material	**Density (g cm^{-3})**
Air	~0
Water	1
Sediments	1.7-2.3
Sandstone	2.0-2.6
Shale	2.0-2.7
Limestone	2.5-2.8
Granite	2.5-2.8
Basalts	2.7-3.1
Metamorphic rocks	2.6-3.0

1.9 Micro-gravity monitoring

Surface subsidence of uplift is monitored by repeated micro-gravity measurements 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. 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. MAGNETIC METHOD

The magnetic method is the study of the distribution of magnetic minerals in the upper sub-surface of the earth's crust. The magnetic method may also be used to estimate the thickness of the crust or to constrain temperatures in the crust using the Curie isotherm (the temperatures at which minerals lose their strong magnetic properties), whichever is shallower (Nabighian 2005).

The Curie point method has the potential for providing confirmation of the existence of a hot rock mass in the crust. When rocks are heated above temperatures of a few hundred degrees Centigrade, they lose their ferromagnetism. Under favourable circumstances, the depth to this demagnetisation level can be determined with reasonable accuracy. Magnetic measurements in geophysical exploration record variations in the magnetic field due to lateral variability in the magnetization of the crust. The lateral variation may produce anomalous regions which are indicative of structural or lithological contrasts in the subsurface. These data can be collected at the earth's surface, from the air, the sea or in a borehole environment.

2.1 Data acquisition

Ground magnetic measurements are usually made with portable instruments at regular intervals along more or less straight and parallel lines which cover the survey area. Often the interval between measurement stations along the lines is less than the spacing between lines. The magnetometer is operated by a single person. However, grid layout, surveying, or the buddy system may require the use of an extra person. Intense fields from man-made electromagnetic sources can be a problem in magnetic surveys. Steel and other ferrous metals in the vicinity of a magnetometer can distort the data. Large belt buckles, etc., must be removed when operating the unit. A compass should be more than 3m away from the magnetometer when measuring the field. A final test is to immobilize the magnetometer and take readings while the operator moves around the sensor. If the readings do not change by more than 1 or 2 nT,. On very precise surveys, the operator effect must be held under 1 nT. Most magnetometers are designed to operate in fairly intense 60-Hz and radio frequency fields. However extremely low frequency fields caused by equipment using direct current or the switching of large alternating currents can be a problem. To obtain a representative reading, the sensor should be operated well above the ground. This procedure is done because of the probability of collections of soil magnetite disturbing the reading near the ground. In rocky terrain where the rocks have some percentage of magnetite, sensor heights of up to 4 m have been used to remove near-surface effects.

2.2 Data processing

To make accurate magnetic anomaly maps, temporal changes in the earth's field during the period of the survey must be considered. Normal changes during a day, sometimes called diurnal drift, are a few tens of nT but changes of hundreds or thousands of nT may occur over a few hours during magnetic storms. During severe magnetic storms, which occur infrequently, magnetic surveys should not be made. The correction for diurnal drift can be made by repeat measurements of a base station at frequent intervals. The measurements at field stations are then corrected for temporal variations by assuming a linear change of the field between repeat base station readings. Continuously recording magnetometers can also be used at fixed base sites to monitor the temporal changes. If time is accurately recorded at both base site and field location, the field data can be corrected by subtraction of the variations at the base site. After all corrections have been made, magnetic survey data are usually displayed as individual profiles or as contour maps.

2.3 Data interpretation

Interpretation of magnetic data can be more complex than gravimetric data. This is because magnetic anomalies are controlled by more parameters, such as susceptibility, remanent magnetization and its orientation. Again finding a unique model is difficult as the same anomaly can be explained with different constellations of bodies and magnetic parameters.

2.4 Use of magnetics in geothermal exploration

Magnetic surveys are an effective method to locate a prospective geothermal reservoir. For example, igneous and metamorphic rocks generally have a higher magnetic susceptibility than sedimentary rocks. An igneous intrusion or pluton is detectable in a magnetic survey due to the contrast in magnetic susceptibility with the surrounding rock. Where the rocks have high magnetic susceptibility, the local magnetic field will be strong and where they have low magnetic susceptibility, it will be weaker. Alteration minerals may be present in zones of circulation of hydrothermal fluids. This alteration is the transition from magnetic minerals (such as magnetite) to hydrous oxide or clay minerals with low magnetic susceptibility. This alteration mineralogy lowers the magnetic susceptibility in the vicinity of hydrothermal activity and indicates the presence of the geothermal reservoir and conduit structures such as faults or dikes. In addition, it is possible using magnetics to map the Curie point at depth. This enables an inference of the temperature gradient and this has been applied to geothermal fields around the world.

2.5 Information derived from magnetics method

Lithology: Presence of magnetic minerals such as magnetite.

Stratigraphic/Structural: Mapping of basement structures, horst blocks, fault systems, fracture zones, dykes and intrusions.

Hydrological: The circulation of hydrothermal fluid may impact the magnetic susceptibility of rocks.

Thermal: Rocks lose their magnetic properties at the Curie temperature (580° C for magnetite) and, upon cooling, remagnetize in the present magnetic field orientation. The Curie point depth in the subsurface may be determined in a magnetic survey to provide information about hydrothermal activity in a region.

2.6 Physical properties

The primary component of the earth's magnetic field originates from convection of liquid iron in the outer core of the earth and the field strength is on the order of ~50,000 nT. Additionally, the earth's magnetosphere is influenced by diurnal variations and solar winds. The remaining component of the earth's magnetic field is due to magnetized materials in the upper earth's crust.

$$1\text{Tesla} = 10^9 \text{ nT} = 10^4 \text{ gauss} = 10^9 \text{ gamma}$$

The magnetic susceptibility is the physical property which defines the magnetic characteristics of a rock, i.e. how easily the material can be magnetized. Magnetic susceptibility relies on the volume percent content of ferromagnetic minerals such as magnetite. Table 2 outlines typical magnetic susceptibilities for various rock types.

TABLE 2: Typical magnetic susceptibilities of rocks

Rock type	Susceptibility (k)
Altered ultra basics	10^{-4} to 10^{-2}
Basalt	10^{-4}
Gabbro	10^{-4} to 10^{-3}
Granite	10^{-5} to 10^{-3}
Andesite	10^{-4}
Rhyolite	10^{-5} to 10^{-4}
Metamorphic rocks	10^{-4} to 10^{-6}
Most sedimentary rocks	10^{-6} to 10^{-5}
Limestone and chert	10^{-6}
Shale	10^{-5} to 10^{-4}

3. CONCLUSION

Both gravity and magnetics methods are structural methods and therefore their accuracy are strongly dependent on how efficiently the regional trends and very local (terrain) effects are removed from the anomalies processed. For gravity many different mass distributions can generate identical potential fields, so there is an inherent non-uniqueness to gravity work. As with gravity data, magnetic results are rarely unique and other data are needed to fully interpret and understand them. Joint inversion of magnetic data with gravity or other geophysical data types, however, makes it more useful.

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