



## THE MAGNETIC METHOD

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### ABSTRACT

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 causative lithology of any anomaly from magnetic information alone.

The magnetic method involves the measurement of the earth's magnetic field intensity. Typically the total magnetic field and/or vertical magnetic gradient is measured. Measurements of the horizontal or vertical component or horizontal gradient of the magnetic field may also be made. Magnetism is, just like gravity, a potential field. Anomalies in the earth's magnetic field are caused by induced or remanent magnetism. Induced magnetic anomalies are the result of secondary magnetization induced in a ferrous body by the earth's magnetic field. The shape, dimensions, and amplitude of an induced magnetic anomaly is a function of the orientation, geometry, size, depth, and magnetic susceptibility of the body as well as the intensity and inclination of the earth's magnetic field in the survey area.

The magnetic method is typically used to:

- Locate abandoned steel well casings, buried tanks, pipes and metallic debris
- Map old waste sites and landfill boundaries
- Map basement faults and basic igneous intrusives
- Investigate archaeological sites

For the exploration of geothermal energy, both ground and aero-magnetic data have been used to investigate the presence of a geothermal resource in combination with gravity. From the aero-magnetic maps several of the anomalies can often be 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.

## 1. INTRODUCTION

Geophysicists have been able to develop a mathematical model for the earth's magnetic field, i.e., its shape and intensity across the surface of the earth, Magnetometer surveys indicate that there are many unexpected variations in this model, called "magnetic anomalies". A magnetic high anomaly is where the measured field strength is higher than the value predicted by the global model, and a magnetic low is where the measured field strength is lower than the value predicted by the global model.

Anomalies in the earth's magnetic field are caused by induced or remanent magnetism. Induced magnetic anomalies are the result of secondary magnetization induced in a ferrous body by the earth's magnetic field. Possible causes for magnetic highs include the presence of magnetically charged rocks in the subsurface. Magnetic prospecting looks for variations in the magnetic field of the earth that are caused by changes in the subsurface geologic structure or by differences in the magnetic properties of near-surface rocks. The inherent magnetism of rocks is called the magnetic susceptibility.

Sedimentary rocks generally have a very small magnetic susceptibility compared with igneous or metamorphic rocks, which tend to have a much higher magnetite (a common magnetic mineral) content. Most magnetic surveys are designed to map the geologic structure on or inside the basement rocks (the crystalline rocks that lie beneath the sedimentary layers) or to detect magnetic minerals directly.

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. Where the rocks have high magnetic susceptibility, the local magnetic field will be strong; where they have low magnetic susceptibility, it will be weaker. Rock units with higher susceptibility will show up as areas of high magnetic field strength. In a geothermal environment, due to high temperatures, the susceptibility decreases. Used with gravity, this method can be used to infer heat sources as seen from geothermal exploration at Olkaria. Ground magnetic measurements do provide more detailed information on sub-surface structures that could act as heat sources in comparison to aeromagnetic data. Magnetic gradient anomalies generally give a better definition of shallow buried features such as buried tanks and drums, but are less useful for investigating large geological features. Unlike EM surveys, the depth penetration of magnetic surveys is not impeded by high electrical ground conductivities associated with saline groundwater or high levels of contamination.

## 2. INSTRUMENTATION

A magnetometer is a more complex instrument which measures both the orientation and strength of a magnetic field. When the magnetic field of a rock sample is measured, the result is actually a measure of the field as it is being effected by the earth's magnetic field, as well as any other large bodies of magnetic rock which are near by. Magnetometer surveys measure small, localised variations in the Earth's magnetic field. Magnetometers are highly accurate instruments, allowing the local magnetic field to be measured to accuracies of 0.002%. There are several types of instruments on the market. The common ones used for commercial applications are the proton precession, fluxgate, caesium vapour and gradiometer magnetometer systems. The systems operate on broadly similar principles utilising proton rich fluids surrounded by an electric coil. A momentary current is applied through the coil, which produces a corresponding magnetic field that temporarily polarises the protons. When the current is removed, the protons realign or precess into the orientation of the Earth's magnetic field. The precession generates a small electrical current in the surrounding coil, at a frequency directly proportional to the local magnetic field intensity. Gradiometers measure the magnetic field gradient

rather than total field strength, which allows the removal of background noise. Gradiometers measure the magnetic field gradient rather than total field strength, which allows the removal of background noise.

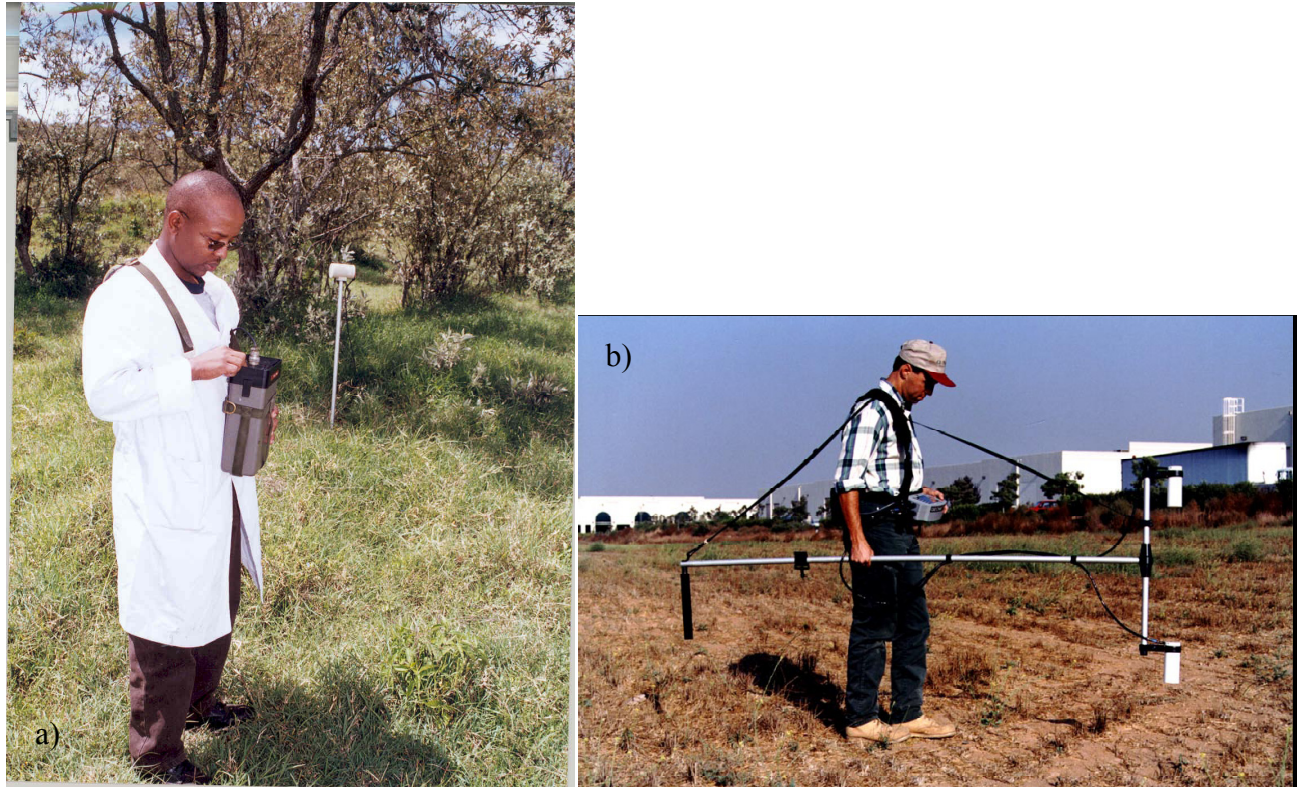


FIGURE 1: Proton Precession magnetometers. (a) Geometrics G-856 (b) Geometrics G-858

### 3. 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 locations (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 another technician. If two magnetometers are available production is usually doubled as the ordinary operation of the instrument itself is straightforward.

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 3 m 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.

Data recording methods will vary with the purpose of the survey and the amount of noise present. Methods include: taking three readings and averaging the results, taking three readings within a meter of the station and either recording each or recording the average. Some magnetometers can apply either of these methods and even do the averaging internally.

Items to be recorded in the field book for magnetics:

- (a) Station location, including locations of lines with respect to permanent landmarks or surveyed points.
- (b) Nearby sources of potential interference

For modern magnetometers, the time of the reading and the actual magnetic field readings are stored internally by the meter.

The experienced magnetics operator will be alert for the possible occurrence of the following conditions:

- (a) Excessive gradients may be beyond the magnetometer's ability to make a stable measurement. Modern magnetometers give a quality factor for the reading. Multiple measurements at a station, minor adjustments of the station location and other adjustments of technique may be necessary to produce repeatable, representative data.
- (b) Nearby metal objects may cause interference. Some items, such as automobiles, are obvious, but some subtle interference will be recognized only by the imaginative and observant magnetics operator. Old buried curbs and foundations, buried cans and bottles, power lines, fences, and other hidden factors can greatly affect magnetic readings.

Airborne surveys are now routinely flown at a ground clearance and grid interval that allows the recording, in great detail, over a wide area of a greater range of frequencies of the magnetic field responses from top to bottom of the subsurface. Aeromagnetic surveys are usually made with magnetometers borne by aircraft flying in parallel lines spaced two to four kilometres apart at an elevation of about 500 metres when exploring for petroleum deposits or geothermal prospects and in lines 0.5 to one kilometre apart roughly 200 metres above the ground when searching for mineral concentrations. Most of the data now being acquired from the air has the capacity to allow the interpreter to also resolve anomalies related to structures, the very features that are hoped to be focused on when beginning a ground exploration program.

#### **4. 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 (Figure 2) or as contour maps (Figure 3). Identification of anomalies caused by cultural features, such as railroads, pipelines, and bridges is commonly made using field observations and maps showing such features.

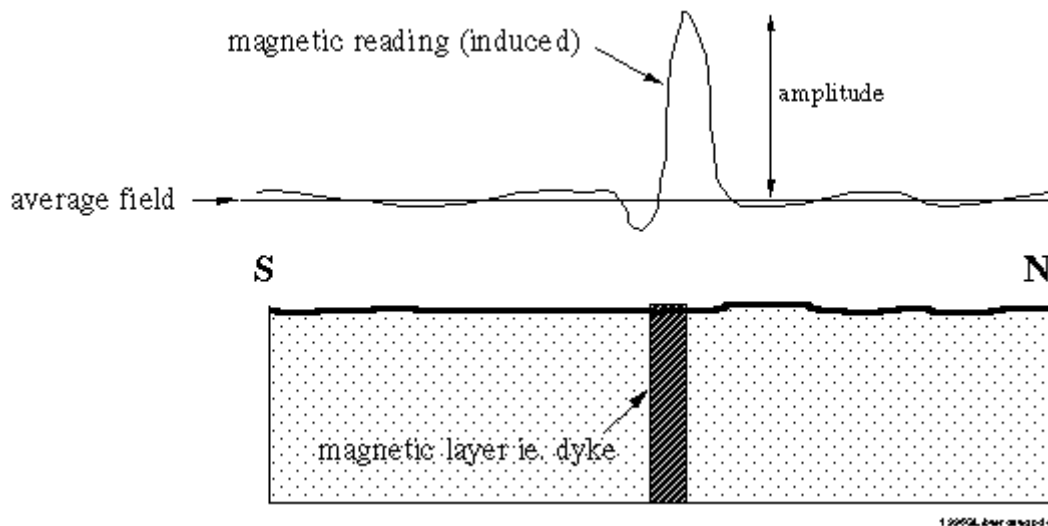


FIGURE 2: A magnetic reading profile across a dyke

## 5. DATA INTERPRETATION

Total magnetic disturbances or anomalies are highly variable in shape and amplitude; they are almost always asymmetrical, sometimes appear complex even from simple sources, and usually portray the combined effects of several sources. An infinite number of possible sources can produce a given anomaly, giving rise to the term ambiguity.

Individual magnetic anomalies - magnetic signatures different from the background- consist of a high and a low (dipole) compared to the average field. In the Southern Hemisphere the high is located to the north and the low to the south of the magnetic body. The position and size of the anomaly depend on the position and size of the magnetic body. A change in latitude will also affect the positioning of anomalies over the magnetic body. This allows the geoscientists to interpret the position of the body which has caused the anomalous reading. Often however the reading is complicated because of the position of the body in relation to other rocks, its size, and what happens to the body at depth.

Data are usually displayed in the form of a contour map of the magnetic field, but interpretation is often made on profiles. From these maps and profiles geoscientists can locate magnetic bodies (even if they are not outcropping at the surface), interpret the nature of geological boundaries at depth, find faults etc. Like all contoured maps, when the lines are close together they represent a steep gradient or change in values. When lines are widely spaced they represent shallow gradient or slow change in value. A modern technique is to plot the magnetic data as a colour image (red=high, blue=low and all the shades in between representing the values in between). This gives an image which is easy to read such as that shown in Figure 3.

When interpreting the aeromagnetic image it is useful to know that magnetite is found in greater concentrations in igneous and metamorphic rocks. Magnetite can also be weathered or leached from

rocks and re-deposited in other locations, such as faults. In a geothermal environment, this is a very useful feature as it may indicate the presence of faults, target for drilling.

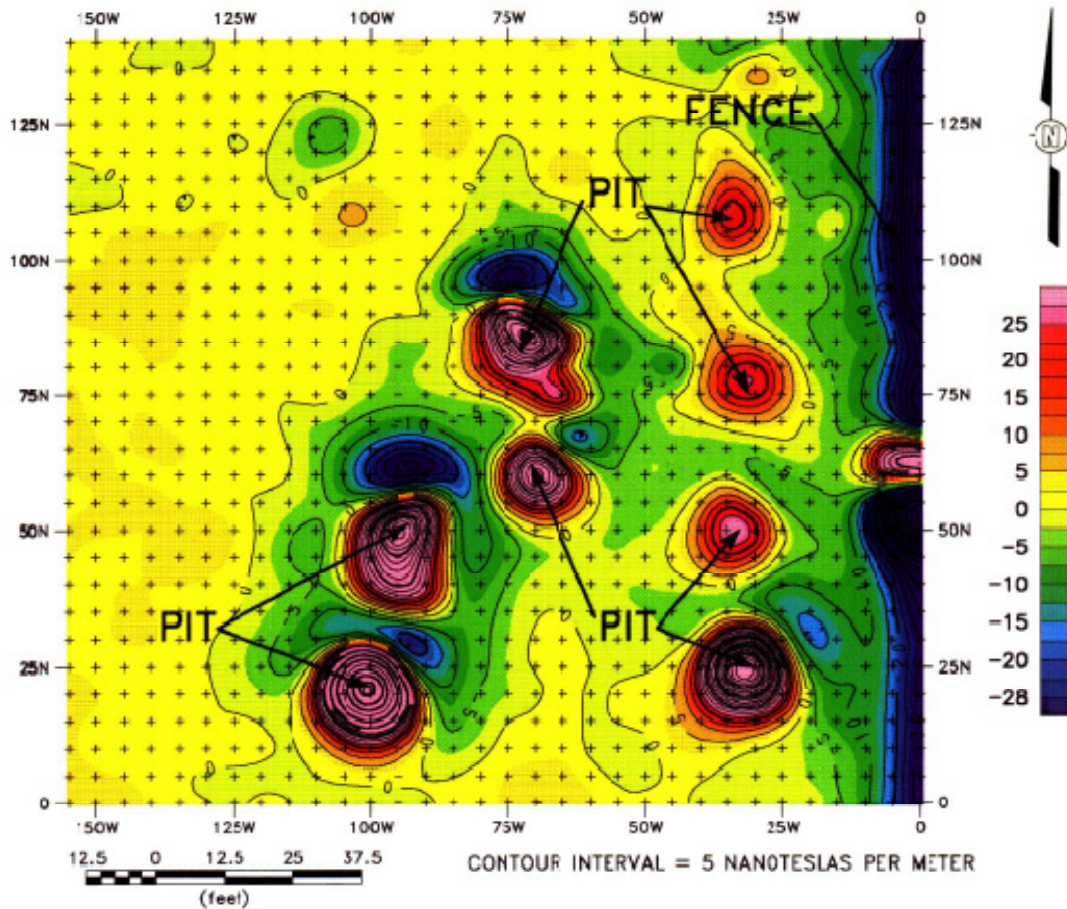


FIGURE 3: Magnetic Survey contour map to locate pits containing buried Metallic Containers

## 6. RESULTS FROM AEROMAGNETIC SURVEYS OF OLKARIA GEOTHERMAL FIELD, KENYA

Residual aeromagnetic data acquired within the Rift Valley 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.

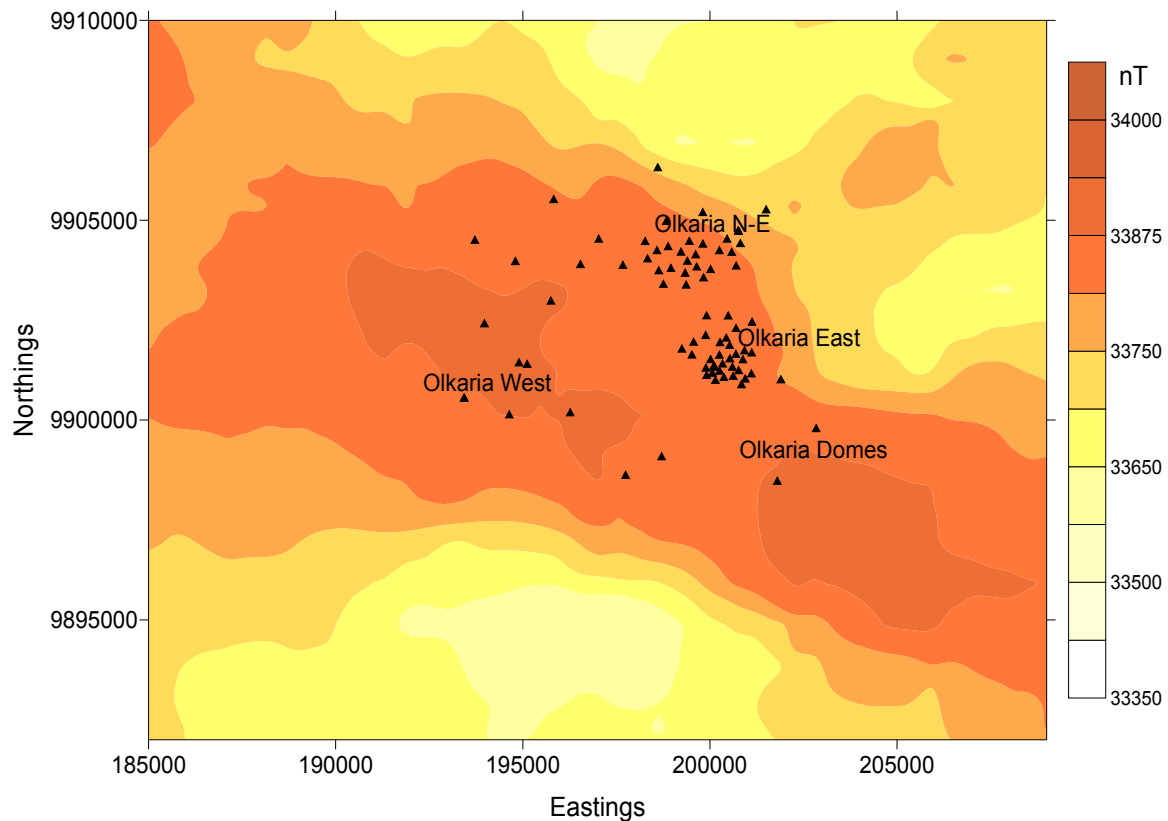


FIGURE 4: Total magnetic intensity over the Greater Olkaria area

## 7. COSTS OF MAGNETIC SURVEYS

Magnetic surveying is ideal for both reconnaissance and focused surveys. It is expedient and cost effective, covers more ground in less time, and requires a minimum of field support. The portability of the instruments makes magnetic surveying well suited to sites with topographic variations. The costs are much lower if the equipment belongs to the client.

Estimate of the cost of a ground magnetic survey is derived from the parameters designed for the survey such as the size of the area, topography and station spacing. These can be modified to reduce cost without causing significant degradation of data quality. Economic factors governing a ground survey include:

- It takes 30 seconds to take a reading
- Mobilization and demobilization will require 1/2 day each
- Total person-hours required for processing, interpretation and report preparation is the same as total person-hours in the field
- Estimate the diurnal component of the field by continuously monitoring the field at a base station. Thus, one will need to rent two instruments and supply field crews for both.
- Field hands make \$10/hour, and two are required at all times in the field with the survey instrument. One is required at all times to monitor the base station instrument.
- Field hands will only work 8 hours per day.
- Data processing, interpretation and report writing make \$20/hour

- Subsistence and travel expenses are \$100/person/8-hour day while doing the field work
- The magnetometers depreciated at the rate of 1%/day (original cost = \$7,500)
- Vehicle depreciation is \$50/day
- Fringe benefits for employees are 25% of salary
- Overhead is 100% of total direct cost excluding equipment depreciation
- Consulting fee is \$200/hour

Aeromagnetic surveys are more expensive than ground investigations but they cover a wide area over a short time. Further, they are less affected by cultural noise.

## 8. CONCLUSIONS

The Earth's magnetic field is a composite of anomalies of varying frequencies. The highest frequency events of interest are those created by geological conditions in the shallow subsurface and the lowest frequency events are caused by magnetic property contrasts at or beneath the basement surface. Intermediate frequency events are created within a sedimentary section.

There are a number of geological causes for local distortions in the Earth's magnetic field. Causes especially important to an explorer are those that put near-surface formations with contrasting magnetic properties in contact with one another. The result is minor but measurable anomalies. Important lateral variations and contrasts in magnetic properties of the shallow formations are brought about singularly or by some combination of faulting, deposition and mineralization associated with structural displacement.

Airborne surveys are now routinely flown at a ground clearance and grid interval that allows the recording, in great detail, of a greater range of frequencies of the magnetic field, responses created throughout the near surface structures, top to bottom. These types of surveys are expensive, as compared to ground investigations but they do cover a wide area in a comparatively short time.

Structuring the near-surface formations gives rise to a characteristic high wave-number magnetic expression. The symmetry of the various elements of such an anomaly, important to their accurate interpretation and definition, is best observed in residual profile form.

With the proper processing and analysis of an area's total spectrum of magnetic responses an interpreter can produce not only a picture of basement structure and topography but also an overlay of the areal distribution of formation magnetic anomalies - linear anomalies thought to be the expression of fracture zones and non-linear anomalies attributable to local structural relief.

Modern magnetic surveys have the capacity to let us view the distribution and trending of shallow structure relative to deep structure for an expanded perception of the structural setting. It's still a reconnaissance method, but now, one with a greater focusing power and information potential than conventional magnetic surveys of years past. In a geothermal environment, due to high temperatures, used along with gravity, this method can be used to infer heat sources and faults as seen from geothermal exploration at Olkaria. Ground magnetic measurements do provide more detailed information on sub-surface structures that could act as heat sources in comparison to aeromagnetic data.