

SEISMIC ACTIVITY, GRAVITY AND MAGNETIC MEASUREMENTS

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ABSTRACT

Microseismic activity, gravity and magnetic exploration methods are used to provide geoscientists an indirect way to witness beneath the Earth's surface the physical properties of rocks (fractures, density and magnetization, respectively). Microseismic activity can help define the reservoir extension, how active it is and the main trend of faults, which hosts a reservoir. Gravity and magnetic exploration can help locate minerals, faults, geothermal or petroleum resources, and ground-water reservoirs. Potential field surveys are relatively inexpensive and can quickly cover large areas of the ground. The primary goal of studying potential field surveys is to provide a better understanding of the subsurface geology. The methods are relatively cheap, non-invasive and non-destructive, environmentally speaking. They are also passive – that is, no energy needs to be put into the ground in order to acquire data. The small portable instruments (gravimeter and magnetometer) also permit walking traverses.

1. INTRODUCTION

For a detailed conceptual model of a geothermal prospect, besides geological and geochemical studies, a variety of geophysical techniques may be used including seismic activity, gravity and magnetic data analysis. This leads to the interpretation of the integrated studies, which provides the next step to create a deep exploration drilling programme.

Seismicity analysis gives information about fractured zones, active faults and some indications of the heat source of the system. The spatial distribution of the seismicity could also indicate the extension of the geothermal reservoir.

Gravity measurements give structural information and can also give indications on massive intrusions, which may act as heat sources. A Bouguer map should be produced to study density anomalies, and selected profiles might be measured with dense station spacing for more detailed structural studies such as buried faults.

Aero-magnetic and/or ground magnetic surveys should also be performed. Aero-magnetic survey can map demagnetized rocks due to thermal alteration, while magnetic surveys give complementary structural information which helps in the interpretation of other data.

2. SEISMIC ACTIVITY

2.1 Introduction

If a prospect geothermal area is considered to be tectonically and/or volcanically active, a temporary deployment of a few seismic stations might be considered. A preliminary seismic survey needs a seismologist and at least four to six portable seismic stations. Specialized software is needed for locating the hypocentres of the earthquakes. A passive seismic survey should also be performed. Active faults can be located by recording and locating earthquakes. The cooling of heat sources can also produce micro-seismicity (Árnason, et al, 2009).

Figure 1 shows most hydrothermal manifestations in El Salvador, which are found within the Quaternary volcanic chain located in the southern margin of the Central American graben (Rivas, 2000). The Ahuachapán geothermal field (AGF) for example is located at the northern flank of the Ataco – Apaneca volcanic chain, at the western part of the country, and Berlin geothermal field (BGF) located on the northern flank of the Berlin - Tecapa volcanic complex.

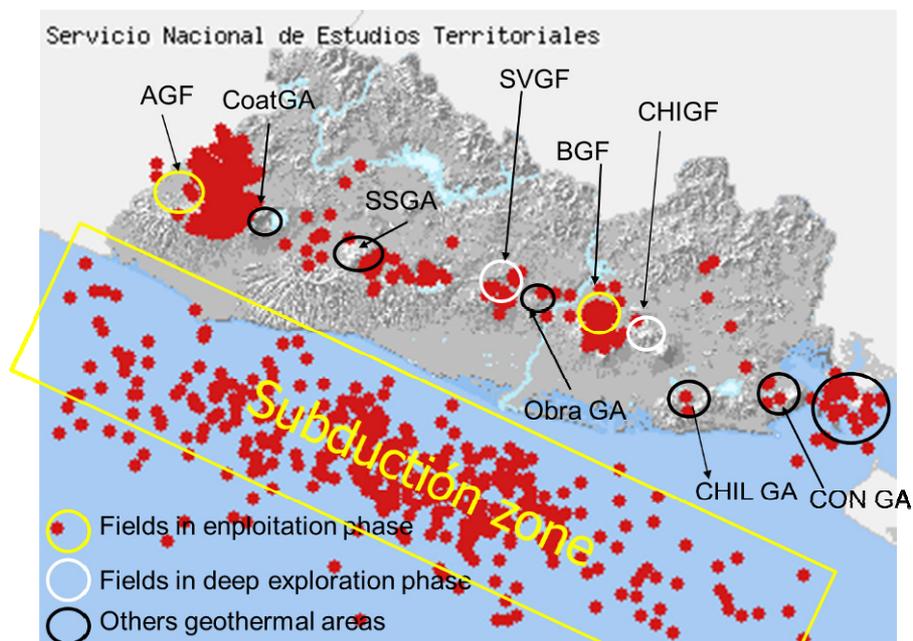


FIGURE 1: Seismicity felt by population during 2002-2010 in El Salvador. Red dots are epicentres.

From left to right: AGF: Ahuachapán Geothermal Field; CoatGA: Coatepeque geothermal Area; SSGA: San Salvador Geothermal Area; SVGF: San Vicente Geothermal Field; Obra GA: Obrajuelo Geothermal Area; BGF: Berlin geothermal Field; CHIGF: Chinameca Geothermal Field; CHIL GA: Chilanguera Geothermal Area; CON GA: Conchagua Geothermal Area. (Modified from www.snet.gob.sv)

Results from volcano-seismic studies of many geothermal fields show that they are possible resource-mapping tools for geothermal exploration and reservoir monitoring. They have been able to map the size and depth of possible shallow geothermal heat sources by analysing data for seismic gaps, S-wave attenuation, reflected arrivals and converted waves. Analysis of shear wave split data for fracture density shows high permeability areas that are potential targets for drilling high-producer wells. Variation of V_p/V_s ratios is related to reservoir fluid phases where low values are related to a decrease in P-wave velocity in the area with low pore pressure, high heat flow, fracturing and steam/gas saturation in the reservoir. High velocity ratios were found in the relatively liquid-saturated high-pressure fields that these ratios are useful tools for monitoring reservoirs under exploitation. The volcano-seismic approach can be useful as a stand-alone tool for analysing geothermal resource both at the exploration and exploitation stage that is cost effective in the long term (Simiyu, 2009).

A number of changes in the recent past have modified the capacity to use micro earthquakes for geothermal studies. Recent studies have focused on the use of natural earthquake activity as a tool for geothermal evaluation of the heat source, fluid flow channels-permeability and reservoir properties. These are normally carried out following the objectives below (Simiyu, S.M. 2009):

- a) Map the location of heat sources by using spatial seismic intensity, hypocentre distribution, shear wave attenuation and P wave reflection.
- b) Map high crack density zones as an aide to siting high producer wells by inverting for three dimensional crack direction and crack density in the target volume using the polarization angle.
- c) Determine the fluid phase, reservoir size and characteristics by determining the variation in seismic velocity within the fields.

2.2 The case of Berlin geothermal field

The spatial distribution of seismicity recorded in the period 1996 - 2005 at the Berlin Geothermal Field covering an area of 80 km² is shown on the left in Figure 2. The recorded seismicity reflected the geothermal anomaly and described the limits of the reservoir. The higher concentration of seismic events is where fumaroles, hydrothermal manifestations and hot soils are found. Therefore, the wells (producers and injectors) and power station are located in this area. The high epicentres concentration reveals the main area, the most fractured zone and faults and the limits of the system.

Figure 2 (right) shows a N-S cross section along the central part of the geothermal area. It shows how deep the hypocentres are located, and also a very close spatial correlation with depth and location of the wells and with reservoir. The hypocentre elevation range is between 0 and 3000 m b.s.l at the well zone (where the reservoir has been located) and from 5000 to 6000 m b.s.l., under the volcanic chain. It is believed that the heat source of the system is underlying this seismic zone. The hypocentres below the volcanic chain are deeper, and describes the upflow zone and the influence of the heat source of the system (right side of Figure 2 with blue line). Since the operation of the network, besides the big earthquakes occurred early 2001, at least 30 local events had recorded magnitude M_c of about 3. Because the very shallow depth, lower than 5 km, these events were felt by local communities. Outside the main area, to the south, there is a seismicity related with the upflow zone and influence of the heat source, possible a magmatic chamber underlying the Tecapa volcanic complex, as shown in Figure 2.

Deeper events are located below the Berlín-Tecapa volcanic complex, which is thought to be responsible of the heat source of the geothermal system. Some events suggest a continuation of other faults, at the northern part, which have been buried by alluvium at the lowest topography.

With the database collected during the period 1996-2005, a 3D seismic tomography study was performed. The results showed the velocity fields of P and S waves and the V_p/V_s ratio. These parameters were determined in order to identify zones of low pore pressure, high heat flow, fracturing and steam/gas saturation in the reservoir. Higher values of V_p/V_s ratios (> 1.68) were found in the surrounding areas of the production zone and lower values (< 1.68) where the area is hot, permeable and fractured, that is, where the producing wells are located. Figure 3 shows a map of V_p/V_s (contour lines) superimposed onto P-velocity distribution. The red contour encloses the production zone.

The P-velocity distribution was compared to V_p/V_s ratio in the area of the programmed directional well TR-14A (Figure 4) in 2005. The distribution of the two parameters were generally consistent and cross-correlated (Geosystem, 2005). In particular, well TR-14A seemed to be positioned on the northern flank of an uprising high velocity/high density feature that could be interpreted as a vertical intrusion of denser material (e.g. a dyke structure, which was found later with the drilled TR-19B well). P-velocity, density and V_p/V_s ratio were all suggesting a zone of rapid variations of the

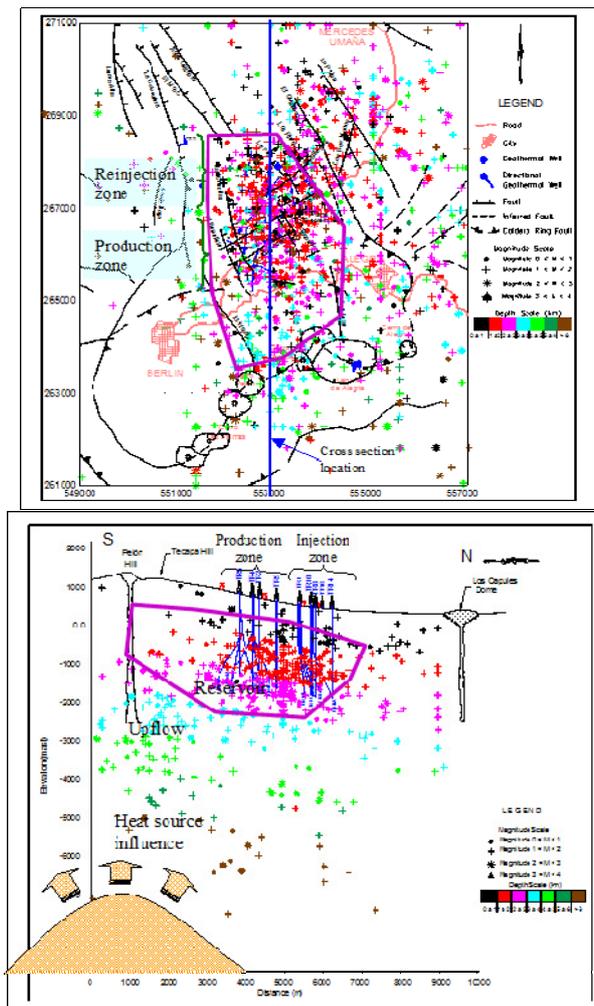


FIGURE 2: Left: Spatial distribution of seismicity at the Berlin geothermal field and surrounding areas defined by pink contour. Period 1996 – 2003: Black lines represents faults. Right: South-North Cross section showing the hypocenters. (See location of cross section, blue line, on left map). Hypocentres located one km far from the profile have been projected (Rivas, 2005)

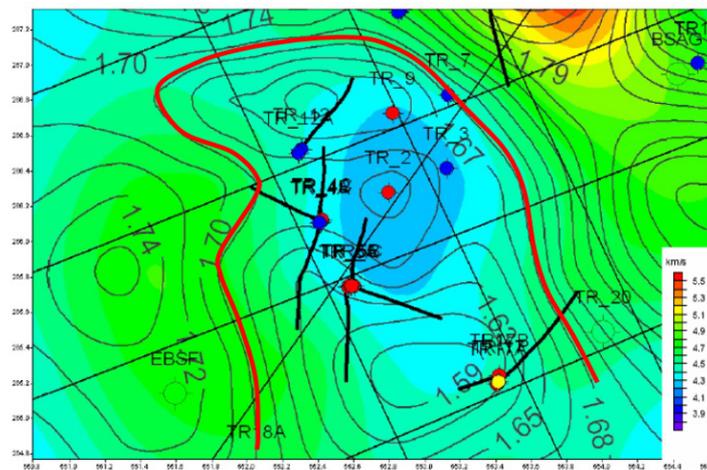


FIGURE 3: V_p/V_s ratio (countour lines) superimposed onto the P-velocity distribution at an elevation of 1500 m.b.s.l. Red and yellow circles are producing wells, blue circles are injector wells. Red contour encloses the production zone (Modified from Geosystem, 2005)

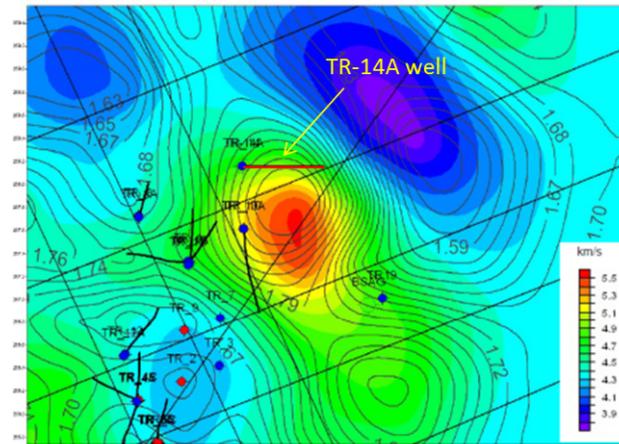


FIGURE 4: V_p/V_s ratio (contour lines) superimposed onto the P-velocity distribution at an elevation of 1500 m b.s.l. in the area around the planned directional well TR-14A (modified from Geosystem, 2005)

parameters from large to smaller values going E-W. This seemed to be especially true at the eastern termination of the well. The TR-14A was the best injector well with almost 150 kg/s absorption capacity.

Based on the cross-section shown in Figure 5 (profile WSW-ENE, left), a relative low V_p/V_s ratio (1.59, blue zone) and (profile NNW-SSE, right) low density (2.3 g/cc) were found (blue zone); where the wells are producing. In addition, an uprising high velocity/high density feature is seen in Figure 5, left, (red colour) that could be interpreted as a vertical intrusion of denser material (e.g. a dyke structure). This intrusive body was intercepted when the well TR-19B was drilled.

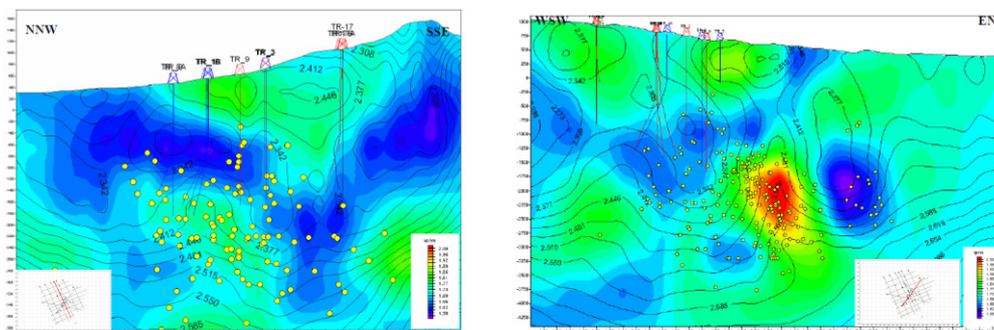


FIGURE 5: V_p/V_s -ratio (colour) cross-section. Left: Along profile SSW-NNE from seismic dataset inversion with superimposed the contour lines of the density model obtained after the inversion. Right: The same but in different direction, profile NNW-SSE (Modified from Geosystem, 2005)

3. GRAVITY METHOD

3.1 Introduction

Gravity survey measures variations in the Earth's gravitational field caused by differences in the density of sub-surface rocks. Gravity methods have been used most extensively in the search for oil and gas, particularly in the twentieth century. While such methods are still employed very widely in hydrocarbon exploration, many other applications have been found, some examples of which are (Reynolds, 1997):

- Hydrocarbon exploration
- Regional geological studies
- Isostatic compensation determination
- Exploration for, and mass estimation of, mineral deposits
- Detection of sub-surface cavities (microgravity)
- Location of buried rock-valleys
- Determination of glacier thickness
- Tidal oscillations
- Archeogeophysics (micro-gravity); e.g. location of tombs
- Shape of the earths (geodesy)
- Military (especially for missile trajectories)
- Monitoring volcanoes

Perhaps the most dramatic change in gravity exploration in the 1980's has been the development of instrumentation which now permits airborne gravity surveys to be undertaken routinely and with a high degree of accuracy. This has allowed aircraft-borne gravimeters to be used over otherwise inaccessible terrain and has led to the discovery of several small but significant areas with economic hydrocarbon potentials.

In geothermal application, the primary goal of studying detailed gravity data is to provide a better understanding of the subsurface geology. The gravity method is a relatively cheap, non-invasive, non-destructive remote sensing method that has already been tested on the lunar surface. It is also passive – that is, no energy needs to be put into the ground in order to acquire data; thus, the method is well suited to a populated setting. The small portable instrument also permits walking traverses, especially in view of the congested tourist traffic in some places.

Measurements of gravity provide information about densities of rocks underground. There is a wide range in density among rock types, and therefore geologists can make inferences about the distribution of strata.

In the geothermal fields in El Salvador, mapping of subsurface faults is usually done. Because faults commonly intercept rocks of different densities, the gravity method is an excellent exploration choice. The equipment used for measuring the variation of the earth gravimetric field is the “gravity meter” or gravimeter.

3.2 Basic theory

The basis on which the gravity method depends is based on two laws derived by Newton, namely the universal law of gravitation, and the second law of motion. The first of these two laws states that the force of attraction between two bodies of known mass is directly proportional to the product of the two masses and inversely proportional to the square of the distance between their centres of mass Equation 1). Consequently, the greater the distance separating the centre of the mass, the smaller the force of attraction between them.

Force = gravitational constant \times mass of the earth (M) \times mass (m) / (distance between masses (R))²

Or

$$F = G \times M \times m / R^2 \quad (1)$$

where the gravitational constant, $G = 6.67 \times 10^{-11} \text{ Nm}^2\text{kg}^{-2}$

Newton's law of motion states that a force (F) is equal to mass (m) \times acceleration (Equation 2). If the acceleration is in a vertical direction, then it is mainly due to gravity (g). In theoretical form, Newton's second law of motion states that:

$$\text{Force (F)} = \text{mass (m)} \times \text{acceleration (g)}$$

or

$$F = m \times g \quad (2)$$

Equations 1 and 2 can be combined to obtain another simple relationship:

$$F = G \times M \times m / R^2 = m \times g$$

thus

$$g = G \times M / R^2 \quad (3)$$

This shows that the magnitude of acceleration due to gravity on earth (g) is directly proportional to the mass (M) of the Earth and inversely proportional to the square of the Earth's radius (R). Theoretically, acceleration due to gravity should be constant over the earth. In reality, gravity varies from place to place because the earth has the shape of a flattened sphere, rotates, and has an irregular surface topography and variable mass distribution.

3.3 Gravity units

The normal value of g at the Earth's surface is 980 cm/s^2 . In honour of Galileo, the C.G.S. unit of acceleration due to gravity (1 cm/s^2) is Gal. Modern gravity meters (gravimeters) can measure extremely small variations in acceleration due to gravity, typically one part in 10⁹. The sensitivity of modern instruments is about ten parts per million. Such small numbers have resulted in sub-units being used such as the:

milliGal ($1 \text{ mGal} = 10^{-3} \text{ Gal}$);
 microGal ($1 \mu\text{Gal} = 10^{-6} \text{ Gal}$); and
 1 gravity unit = 1 g.u. = 0.1 mGal [$10 \text{ gu} = 1 \text{ mGal}$]

3.4 Measurements of gravity

There are two kinds of gravity meters. An absolute gravimeter measures the actual value of g by measuring the speed of a falling mass using a laser beam. Although this meter achieves precisions of 0.01 to 0.001 mGal (milliGals, or 1/1000 Gal), they are expensive, heavy, and bulky. A second type of gravity meter measures relative changes in g between two locations, see Figure 6. The Figure 6 shows a local base station and a site measurement using the gravity meter model CG-5 from Scintrex. This instrument uses a mass on the end of a spring that stretches, where g is stronger. This kind of meter can measure g with a precision of 0.01 mGal in about 5 minutes.

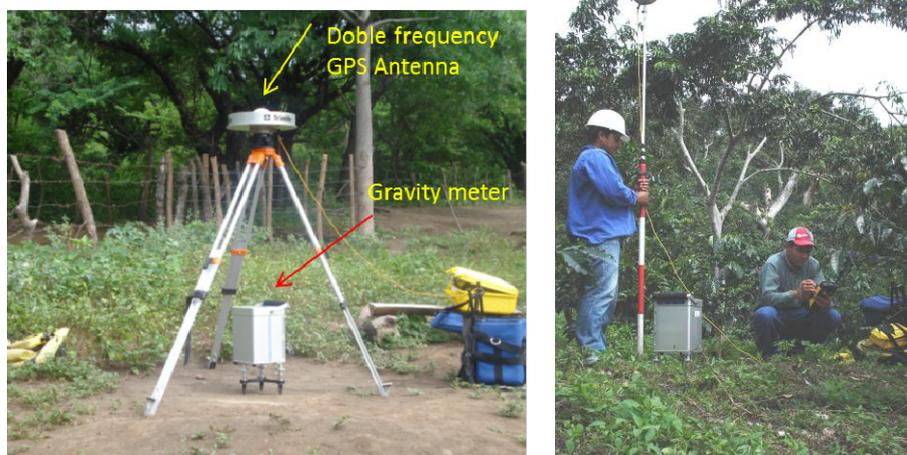


FIGURE 6: Left: Gravity meter at a base station opening loop, together with a remote reference GPS. Right: A site measurement, gravity and position using double frequency GPS

A relative gravity measurement is also made at the nearest absolute gravity station, one of a network of worldwide gravity base stations. The relative gravity measurements are thereby tied to the absolute gravity network (www.usgs.gov) (see Figure 7), which shows the absolute gravity station network of Central America.

Lateral density changes in the subsurface cause a change in the force of gravity at the surface. The intensity of the force of gravity due to a buried mass difference (concentration or void) is superimposed on the larger force of gravity due to the total mass of the earth.



FIGURE 7: Central American absolute gravity station cities; taken from NOAA, 2001.

Schematic diagrams in Figure 8 show the result of measurements, indicating the relative surface variation of gravitational acceleration over geologic structures. When the spatial craft passes over a denser body or crosses to another denser block of rocks, the gravitational attraction is increased. At the top of the diagram is a curve, which describes the gravity behaviour

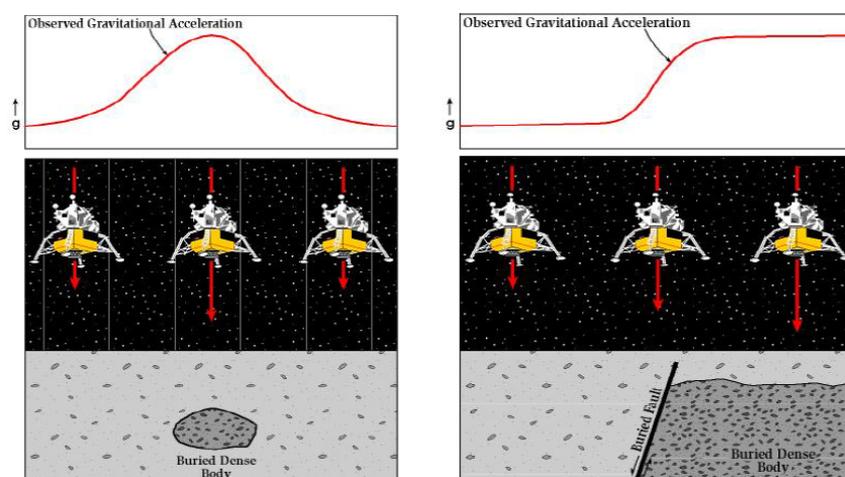


FIGURE 8: Cartoon illustrations showing the relative surface variation of gravitational acceleration over geologic structures
(taken from: [geoinfo.nmt.edu/geoscience/projects/astronauts/gravity method.html](http://geoinfo.nmt.edu/geoscience/projects/astronauts/gravity%20method.html))

3.5 Variation of gravity with latitude

The value of acceleration due to gravity varies over the surface of the earth for a number of reasons, one of which is the earth's shape. As the polar radius (6,357 km) is 21 km shorter than the equatorial radius (6,378 km), the points at the poles are closer to the earth's centre of mass; and therefore, the value of gravity at the poles is greater than that at the equator. Another aspect is that as the earth rotates once per sidereal day around its north-south axis, there is a centrifugal acceleration acting on it, which is greatest where the rotational velocity is largest, mainly at the equator (1,674 km/h; 1,047 miles/h); and decreases to zero at the poles. Gravity surveying is sensitive to variations in rock density, so an appreciation of the factors that affect density will aid the interpretation of gravity data.

3.6 Reduction of data

Gravimeters do not give direct measurements of gravity; rather, a meter reading is taken which is then multiplied by an instrumental calibration factor to produce a value of observed gravity (known as gobs). The correction process is known as **gravity data reduction or reduction to the geoid**. The various corrections that can be applied are the following.

Instrument drift: Gravimeter readings change (drift) with time as a result of elastic creep in the springs, producing an apparent change in gravity at a given stations. The instrumental drift can be determined simply by repeating measurements at the same stations at different times of the day, typically every 1 – 2 hours.

Earth's tides: Just as the water in the oceans responds to gravitational pull of the Moon, and to a lesser extent of the Sun, so too does the solid earth, which gives rise to a change in gravity of up to three g.u. with a minimum period of about 12 hours. Repeated measurements at the same stations permit estimation of the necessary correction for tidal effects over short intervals, in addition to the determination of the instrumental drift for a gravimeter.

Observed gravity (gobs) - Gravity readings observed at each gravity station after corrections have been applied for instrument drift and earth tides.

Latitude correction (gn) - Correction subtracted from gobs that accounts for earth's elliptical shape and rotation. The gravity value that would be observed if the earth were a perfect (no geologic or topographic complexities) rotating ellipsoid is referred to as the normal gravity.

$$g_n = 978031.85 * (1.0 + 0.005278895 \sin^2(\text{lat}) + 0.000023462 \sin^4(\text{lat})) \text{ (mGal)} \quad (4)$$

where lat is latitude

Free-air corrected gravity (gfa) - The free-air correction accounts for gravity variations caused by elevation differences in the observation locations. The form of the free-air gravity anomaly, gfa, is given by:

$$g_{fa} = g_{obs} - g_n + 0.3086h \text{ (mGal)} \quad (5)$$

where h is the elevation (in m) at which the gravity station is above the datum (typically sea level).

Bouguer slab corrected gravity (gb) - The Bouguer correction is a first-order correction to account for the excess mass underlying observation points located at elevations higher than the elevation datum (sea level or the geoid). Conversely, it accounts for a mass deficiency at observation points located below the elevation datum. The form of the Bouguer gravity anomaly, gb, is given by:

$$g_b = g_{obs} - g_n + 0.3086h - 0.04193r h \text{ (mGal)} \quad (6)$$

where r is the average density of the rocks underlying the survey area.

Terrain corrected bouguer gravity (gt) - The terrain correction accounts for variations in the observed gravitational acceleration caused by variations in topography near each observation point. Because of the assumptions made during the Bouguer Slab correction, the terrain correction is positive regardless of whether the local topography consists of a mountain or a valley. The form of the Terrain corrected, Bouguer gravity anomaly, gt , is given by:

$$gt = gobs - gn + 0.3086h - 0.04193r h + TC \text{ (mGal)} \quad (7)$$

where TC is the value of the computed terrain correction.

Assuming these corrections have accurately accounted for the variations in gravitational acceleration, they were intended to account for any remaining variations in the gravitational acceleration associated with the terrain; corrected Bouguer gravity can be assumed to be caused by a geologic structure.

Once the basic latitude, free-air, Bouguer and terrain corrections are made, an important step in the analysis remains. This step, called regional-residual separation, is one of the most critical steps. In most surveys and in particular those engineering applications in which very small anomalies are of greatest interest, there are gravity anomaly trends of many sizes. The larger size anomalies will tend to behave as regional variations, and the desired smaller magnitude local anomalies will be superimposed on them.

3.7 Bouguer anomaly

The main end-product of gravity data reduction is the Bouguer anomaly, which should correlate only with lateral variations in density of the upper crust and which is of most interest to applied geophysicist and geologists. The Bouguer anomaly is the difference between the observed gravity value ($gobs$), adjusted by the algebraic sum of all the necessary corrections, and that of a base station ($gbase$). The variation of the Bouguer anomaly should reflect the lateral variation in density such that a high-density feature in a lower- density medium should give rise to a positive Bouguer anomaly. Conversely, a low-density feature in a higher-density medium should result in a negative Bouguer anomaly. See example in Figure 9 of Bouguer and residual anomaly maps.

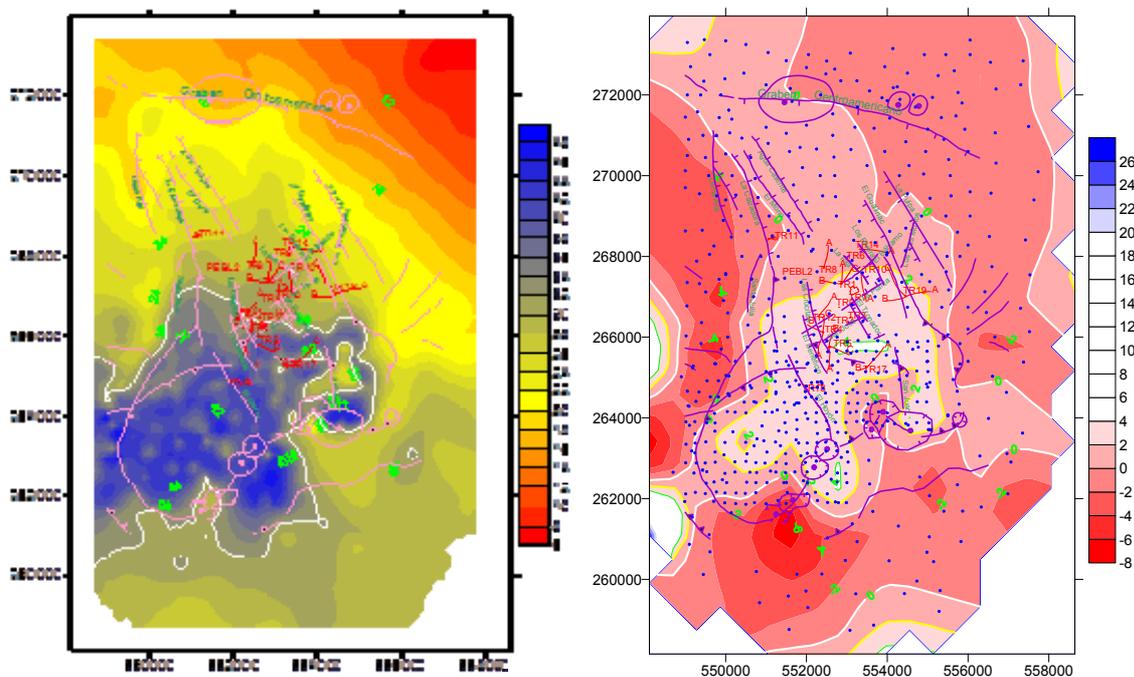


FIGURE 9: Bouguer anomaly map (left) and residual anomaly map (right) of the Berlin geothermal field

4. MAGNETIC METHOD

4.1 Introduction

The magnetic method is a very popular and inexpensive approach for near-surface metal detection. Engineering and environmental site characterization projects often begin with a magnetometer survey as a means of rapidly providing a layer of information on where utilities and other buried concerns are located (www.aogeophysics.com).

The principal operation is quite simple. When a ferrous material is placed within the earth's magnetic field, it develops an induced magnetic field. The induced field is superimposed on the earth's field at that location creating a magnetic anomaly. Detection depends on the amount of magnetic material present and its distance from the sensor. The anomalies are typically presented on colored contour maps. Common uses of magnetometers include:

- Locating buried tanks and drums
- Fault studies
- Mineral exploration
- Geothermal exploration
- Mapping buried utilities, pipelines
- Buried foundations, fire pits for archaeological studies

In geothermal application, the main objective of the magnetic study is to contribute with information about the relationship among the geothermal activity, the tectonic and stratigraphy of the area by means of the anomaly interpretation of the underground rocks' magnetic properties (Escobar, 2005).

Most of the rocks are not magnetic; however, certain types of rocks contain enough minerals to originate significant magnetic anomalies. The data interpretation that reflects differences in local abundance of magnetization is especially useful to locate faults and geologic contacts (Blakely, 1995).

The magnetic anomalies can be originated from a series of changes in lithology, variations in the magnetized bodies thickness, faulting, pleats and topographical relief. A significant quantity of information can leave a qualitative revision of the residual magnetic anomaly map of the total magnetic field. In this sense, the value of the survey does not end with the first interpretation, but rather it enriches as more geology is known.

It is more important, at the beginning, to detect the presence of a fault or intrusive body, than to determine their form or depth. Although, in some magnetic risings, such determination cannot be made in a unique manner, the magnetic data has been useful because the intrusive is more magnetic than the underlying lava flows. Faulting creates open spaces so that the hot fluids can be transported, therefore altering the host rocks. The temperature of the hydrothermal system and the oxygen volatility will determine the quantity of the present load in the fault zone and therefore, giving their magnetic response.

4.2 Basic theory

If two magnetic poles of strength m_1 and m_2 are separated by a distance r , a force, F , exists between them. If the poles are of the same polarity, the force will push the poles apart; and if they are of opposite polarity, the force is attractive and will draw the poles together. The equation for F is the following:

$$F = m_1 m_2 / 4\pi\mu^2 r^2 \quad (8)$$

where μ is the magnetic permeability of the medium separating the poles;
 m_1 and m_2 are pole strengths; and
 r the distance between them.

4.3 Magnetic units

The magnetic flux lines between two poles per unit area is the flux density **B** (measured in weber/m² = Tesla). **B**, also called the **magnetic induction**, is a vector quantity. The unit of Tesla is too large to be practical in geophysics work, so a sub-unit called a nanotesla (1 nT = 10⁻⁹ T) is used instead, where *1 nT* is numerically equivalent to *1 gamma* in C.G.S. units (1 nT = 10⁻⁵ gauss).

4.4 The Earth's magnetic field

The geomagnetic field at or near the surface of the earth originates largely from within and around the earth's core. It can be described in terms of the declination (D), inclination (I), and the total force vector F (Figure 10). The vertical component of the magnetic intensity of the earth's magnetic field varies with latitude, from a minimum of around 30,000 nT at the magnetic equator to 60,000 nT at the magnetic poles.

4.5 Magnetics instruments

The equipment used for magnetic measurements are called **magnetometer**, which is used specifically in geophysical exploration. There are two main types of resonance magnetometer: the proton free-precession magnetometer, which is the best known, and the alkali vapour magnetometer. Both types monitor the precession of atomic particles in an ambient magnetic field to provide an absolute measure of the total magnetic field, F.

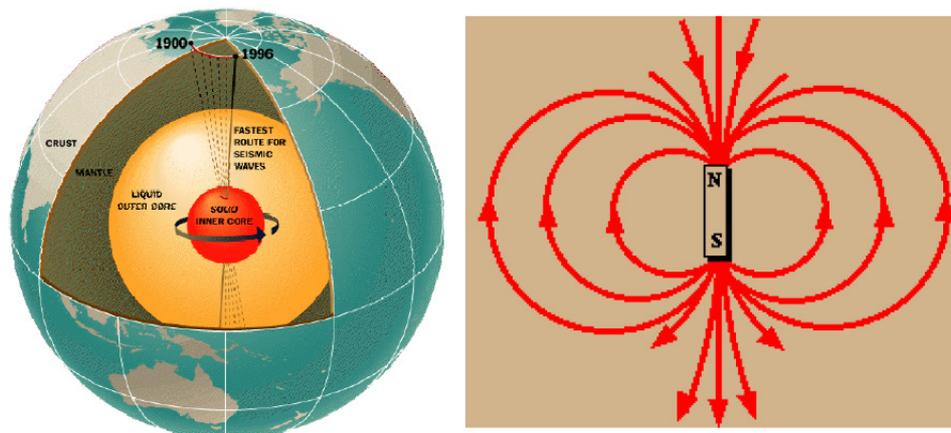


FIGURE 10: Left: Origin of the Earth's magnetic field. Right: Displacement of the force lines of the Earth's magnetic field, equivalent to the ones of the magnet

The proton magnetometer has a sensor which consists of a bottle containing a proton-rich liquid, usually water or kerosene, around which a coil is wrapped, connected to the measuring apparatus. Each proton has a magnetic moment (M) and, as it is always in motion, it also possesses an angular momentum (G), like a spinning top. Figure 11 shows examples of field measurements with a magnetometer model GEM-19T from GEM System, owned by LaGeo in a survey around the San Vicente volcano area.

4.6 Magnetic surveying

Local variations or anomalies in the earth's magnetic field are the result of disturbances caused mostly by variations in concentrations of ferromagnetic material in the vicinity of the magnetometer's sensor. Magnetic data can be acquired in two configurations:

1) A rectangular grid pattern

2) Along a traverse

Grid data consists of readings taken at the nodes of a rectangular grid; and traverse data is acquired at fixed intervals along a line. Each configuration has its advantages and disadvantages, which are dependent upon variables such as the site conditions, size and orientation of the target, and financial resources. An example of a grid along lines is shown in Figure 12. This took place in the San Vicente geothermal area in El Salvador.



FIGURE 11: Examples of a field measurement with a magnetometer model GEM-19T from GEM System, owned by LaGeo; a magnetic survey in the San Vicente volcano area

In both traverse and grid configurations, the station spacing or distance between magnetic readings is important. Single point or erroneous anomalies are more easily recognized on surveys that utilize small station spacing.

Ground magnetic measurements are usually made with portable instruments at regular intervals along more or less straight and parallel lines that cover the survey area. Often the interval between measurement locations (stations) along the lines is less than the spacing between lines. It is important to establish a local base station in an area away from suspected magnetic targets or magnetic noise, and where the local field gradient is relatively flat. Ideally, the base station is placed at least 100 m from any large metal objects or travelled roads and at least 500 m from any power lines when feasible.

The base station location must be very well described in the field book, as others may have to locate it later, based on the written description.

There are certain limitations in the magnetic method. One limitation is the problem of “cultural noise” in certain areas. Man-made structures that are constructed using ferrous material, such as steel, have a detrimental effect on the quality of the data. Other features to be avoided include steel structures, power lines, metal fences, steel reinforced concrete, surface metal, pipelines and underground utilities. When these features cannot be avoided, their locations should be noted in a field notebook and on the site map.

To make accurate 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 magnetic surveys should not be made. The correction for diurnal drift can be made by repeating 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 repeated base station readings.

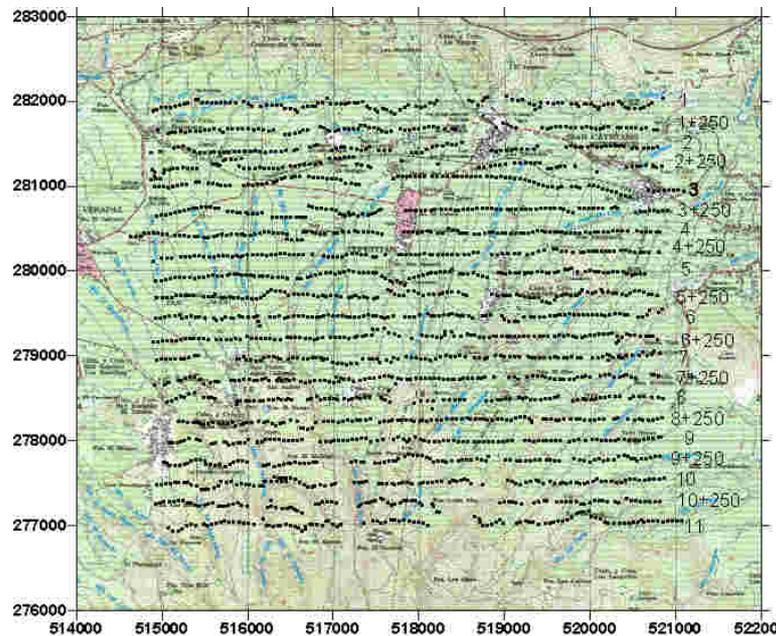


FIGURE 12: Land magnetic survey at San Vicente geothermal area; lines are six km long and measure sites every 100 m. Spacing lines are 250 m

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, data acquisition is usually doubled as the ordinary operation of the instrument itself is straightforward.

4.7 Distortion

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, the operator is "magnetically clean". Zippers, watches, eyeglass frames, boot grommets, room keys, and mechanical pencils can all contain steel or iron. On very precise surveys, the operator effect must be held at under 1 nT.

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. An experienced field geophysicist will specify which technique is required for a given survey. In any case, the time of the reading is also recorded unless the magnetometer stores the readings and periods internally.

Sheet-metal barns, power lines, and other potentially magnetic objects will occasionally be encountered during a magnetic survey. When taking a magnetic reading in the vicinity of such items, it should describe the interfering object and note the distance from it to the magnetic station in the field book. Items to be recorded in the field book for magnetic include:

- a) Station location, including locations of lines with respect to permanent landmarks or surveyed points;

- b) Magnetic field and/or gradient reading;
- c) Time;
- d) Nearby sources of potential interference.

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

1. 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.
2. 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 magnetic operator. Old buried curbs and foundations, buried cans and bottles, power lines, fences, and other hidden factors can greatly affect magnetic readings.

4.8 Data reduction and interpretation

The data should be corrected for diurnal variations, if necessary. If the diurnal data does not vary more than approximately 15 to 20 gammas over a one-hour period, correction may not be necessary. However, this variation must be approximately linear over time and should not show any extreme fluctuations. The global magnetic field is calculated through a previous established model (IGRF-International Geomagnetic Reference) in Figure 9, and obtained analytically with the help of field observations. Due to the fact that the global magnetic field is variable, these maps are generated every 5 years. There are filters used for highlighting the contrast of anomalies, which are:

- Derivatives of different order or gradients
- Upward or downward continuation regarding the anomaly
- Band pass or high pass filters
- Pole reduction

After all corrections have been made, magnetic survey data are usually displayed as individual profiles or as contour maps. Identification of anomalies caused by cultural features, such as railroads, pipelines, and bridges is commonly made using field observations and maps showing such features.

4.9 Presentation of results

The final results are presented in profile and contour map form (see Figure 13). Profiles are usually presented in a north-south orientation, although this is not mandatory. The orientation of the traverses must be indicated on the plots. A listing of the magnetic data, including the diurnal monitor or looping data should be included in the report. The report must also contain information pertinent to the instrumentation, field operations, and data reduction and interpretation techniques used in the investigation.

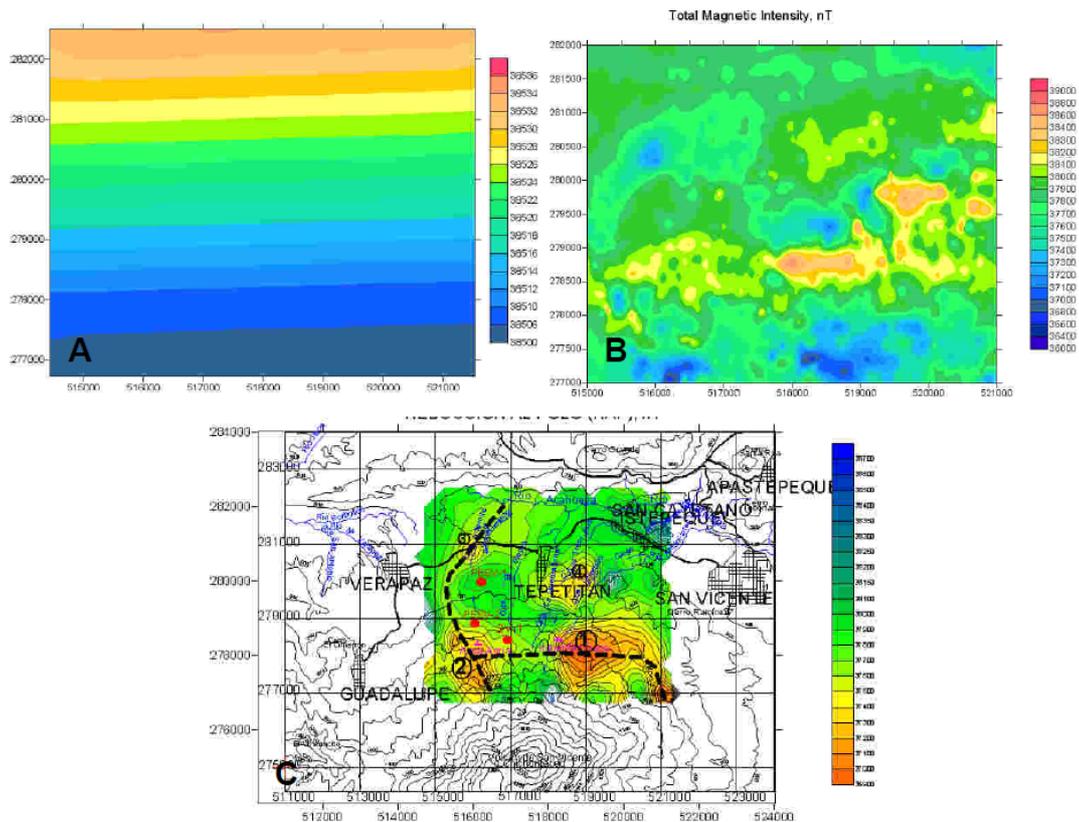


FIGURE 13: Examples of magnetic maps. A) Regional magnetic field in the San Vicente geothermal area (IGRF); B) Total magnetic field intensity, C) Pole reduction in the San Vicente magnetic survey

5. CONCLUSION

Microseismic analysis, gravity and magnetic methods have been performed in El Salvador to contribute to the surface exploration programme, and construction or updating the conceptual models of different geothermal areas such as Berlin Geothermal Field (seismic and gravity), Ahuachapán Geothermal Field (gravity), Chinameca Geothermal Area under deep exploration activities (gravity and magnetic) and San Vicente Geothermal Area under deep exploration (seismic, gravity and magnetic).

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