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THE GRAVITY METHOD

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ABSTRACT

Gravity is a potential field, i.e., it is a force that acts at a distance. The gravity method is a non-destructive geophysical technique that measures differences in the earth's gravitational field at specific locations. It has found numerous applications in engineering, environmental and geothermal studies including locating voids, faults, buried stream valleys, water table levels and geothermal heat sources. 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. For better definition of the bodies causing the perturbations in the gravity field, the gravity data should be collected with small stations spacing, such as 1 km. For engineering investigations this may be as low as 5 meters or less. In addition, gravity station elevations must be determined to within 0.2 meters. Using the highly precise locations and elevations plus all other quantifiable disturbing effects, the data are processed to remove all these predictable effects. The most commonly used processed data are known as Bouguer gravity anomalies, measured in mGal. The interpretation of Bouguer gravity anomalies ranges from just manually inspecting the grid or profiles for variations in the gravitational field to more complex methods that involves separating the gravity anomaly due to an object of interest from some sort of regional gravity field. From this, bodies and structures can be inferred which may be of geothermal interest.

Volcanic centres, where geothermal activity is found, are indicators of cooling magma or hot rock beneath these areas as shown by the recent volcanic flows, ashes, volcanic domes and abundant hydrothermal activities in the form 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 recent volcanism, intensive faulting and geothermal activity. For example, in the Kenya rift, Olkaria, Domes and Suswa geothermal centres are located on the crest of a gravity high.

1. INTRODUCTION

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. It is also passive – that is, no energy need be put into the ground in order to acquire data; thus, the method is well suited to a populated setting. The small portable instrument used also permits walking traverses. 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. 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 3.

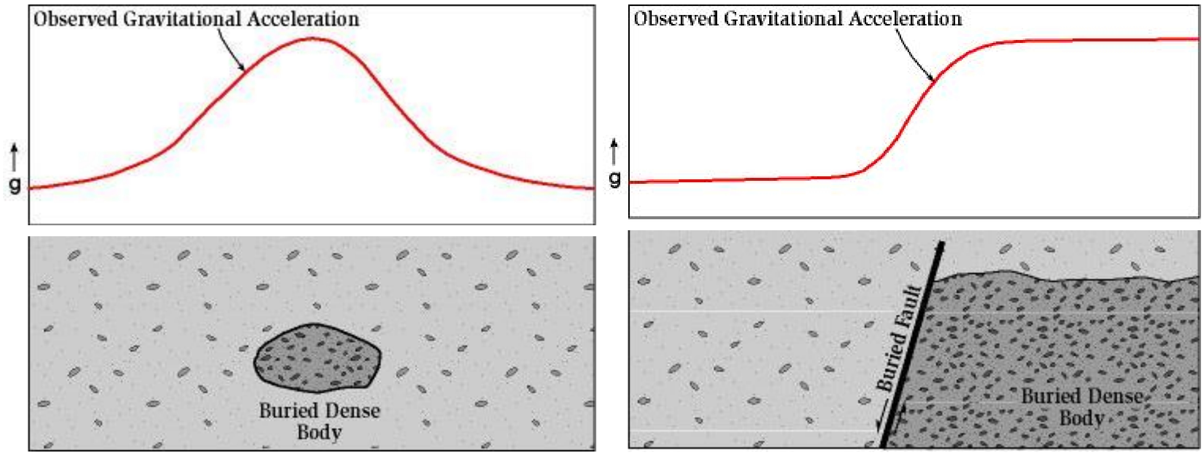


FIGURE 1: Illustrations showing the relative surface variation of Earth's gravitational acceleration over geologic structures

For reliable interpretation of gravity anomaly it is advisable to consult other geophysics data such as magnetics and seismics. The general problem in geophysical surveying is the ambiguity in data interpretation of the subsurface geology. This arises because many different geologic configurations could reproduce similar observed measurements. This basic limitation is brought about from the unavoidable fact that geophysical surveying attempts to solve a difficult inverse problem.

The gravity method has found wide applications in geothermal energy investigations as well as the monitoring of geothermal reservoirs under exploitation. This is because it is fairly cheap, fast in data collection with minimum logistics preparation. The method can infer location of faults, permeable areas for hydrothermal movement. It is however, more commonly used in determining the location and geometry of heat sources.

2. INSTRUMENTATION

A gravity meter or gravimeter measures the variations in the earth's gravitational field. The variations in gravity are due to lateral changes in the density of the subsurface rocks in the vicinity of the measuring point. Because the density variations are very small and uniform, the gravimeters have to be very sensitive so as to measure one part in 100 million of the earth's gravity field (980 gals or 980,000 mgals) in units of mgals or microgals.

The most commonly used meters do not measure an absolute gravitational acceleration but differences in relative acceleration. There are several gravity meter manufacturers where the accuracies of these meters can vary greatly. The common gravimeters on the market are the Worden gravimeter, the Scintrex and the La Coste Romberg gravimeter. Since these meters are temperature controlled and contain small pen lights to read the meters, they are connected to rechargeable batteries. The meter usually has two batteries, which allows for over 16 hours of readings. The Worden gravimeter is an entirely mechanical and optical relying only on an AA battery for illuminating the crosshairs. It uses a fixed length spring and mass attached to a calibration spring and veneer scale to measure gravitational acceleration. The Scintrex Autograv is semi-automated, but although a bit more expensive, it has been shown to have a higher stability and experience less tares (a sudden jump in a gravity reading) over long periods of time. The Lacoste and Romberg model gravity meter has an advertised repeatability of 3 microgals (980,000,000 microgals is the Earth's gravitational field) and is one of the preferred instruments for conducting gravity surveys in industry.

FIGURE 2: The Worden and La Coste Romberg gravity meters

3. DATA ACQUISITION

Gravity data acquisition is a relatively simple task that can be performed by one person. However, two people are usually necessary to determine the location (latitude, longitude and elevation) of the gravity stations. In order to detect a target (e.g., a dense body or fault), gravity readings must be taken along traverses that cross the location of the target. Its expected size will determine the distance between readings (station spacing), with larger station separations for large target and small separations for small ones. It is usually advisable to model the expected anomaly mathematically before conducting fieldwork. From this, along with the expected instrument accuracy, an estimate can be made of the anomaly size and the required station spacing.

Surveys are conducted by taking gravity readings at regular intervals along a traverse that crosses the expected location of the target. However, in order to take into account the expected drift of the instrument, one station (a local base station) must be located and has to be reoccupied every half to 1 hour or so (depending on the instrument drift characteristics) to obtain the natural drift of the instrument. These repeated readings are performed because even the most stable gravity meter will have their readings drift with time due to elastic creep within the meter’s springs and also to help remove the gravitational effects of the earth tides readings have to be taken at a base station. The instrument drift is usually linear and less than 0.01 mGal/hour under normal operating conditions (Figure 3 shows a typical drift curve). Since gravity decreases as elevation increases, the elevation of each station has to be measured with an error of no more than about 3 cm. Readings are taken by placing the instrument on the ground and levelling it. This may be automatic with some instruments, as it is with the Scintrex.

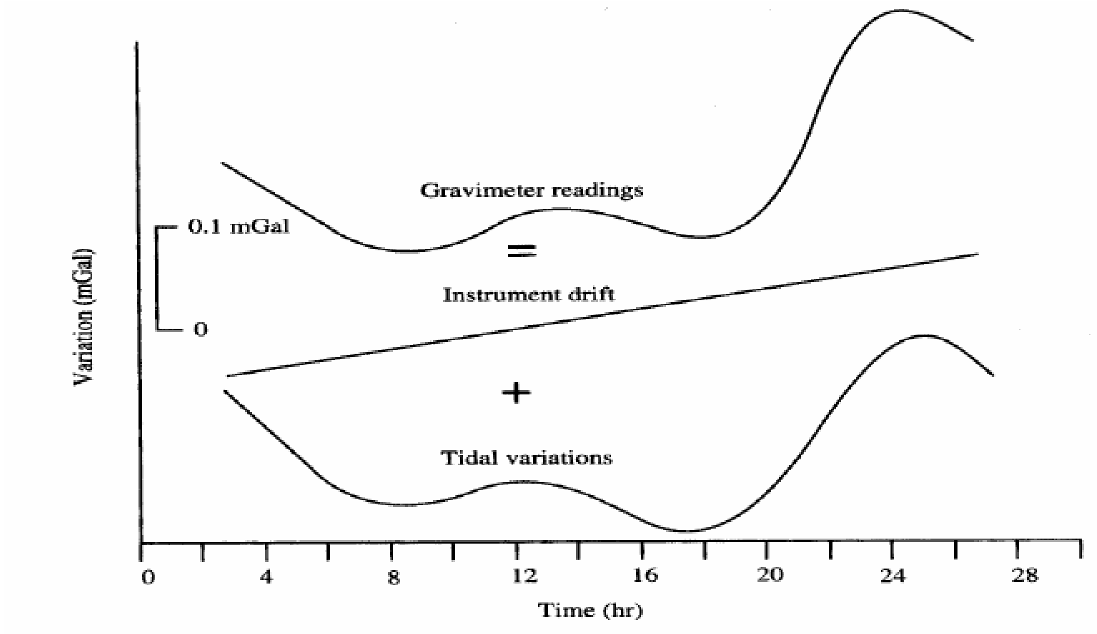


FIGURE 3: Typical linear drift curve (middle curve) which is a combination of instrument drift and earth tidal variations.

An important factor in obtaining useful gravity values in detailed surveys is determining the earth tide effect as their gravitational effects may be greater than the gravity field variations due to the anomalous features being sought. The final aspect of reading a gravity meter concerns seismic activity or cultural movement such as those of vehicles or people. These will disrupt the readings (the meter is actually a low-frequency seismometer) and even though the Scintrex meter has an anti-seismic filter (the La Coste-Romberg meters are also mechanically damped to lessen the effects of earthquakes), readings will still be disrupted. If this occurs, all operations should be stopped. Experience indicates that one should wait at least 1-2 hours after a seismic event before resuming the survey. From the drift curve, a base reading corresponding to the time a particular gravity station was measured is obtained by subtracting the base reading from the station reading. This gravity reading is not in mGal but in gravity meter units. One must multiply the gravity meter reading by the manufacturer supplied meter constants (calibration constants) to obtain mGal.

In addition to obtaining a gravity reading, a horizontal position and the elevation of the gravity station must be obtained. The horizontal position could be either latitude and longitude or the x and y distances (meters or feet) from a predetermined origin. The required elevation accuracy for detailed surveys is between 0.004 and 0.2 m and to obtain such accuracy requires performing either an electronic distance meter (theodolite) survey or a total-field differentially corrected global positioning survey (GPS).

4. DATA PROCESSING

The last task of most fieldwork is to determine the topographic changes and the effects of buildings surrounding a gravity station. Both of these effects will be used later in processing the gravity data. There are a number of techniques to determine the elevation changes and these usually involve a combination of recording elevation changes in the field and computer computations using digital elevation models (DEM). The most common technique is by Hammer where one records an elevation change in quadrants at set distances (commonly from 0 to 1000 meters) from the gravity station. A newly developed technique uses a laser-positioning gun to obtain more accurate elevation changes within 100 meters of a gravity station. The best technique is to use Hammer's method for near (up to 200 meters) station elevation changes and computer methods based on accurate (at least 10 meter 7.5 minute quadrangles) DEM's.

The observed gravity readings obtained from the gravity survey reflect the gravitational field due to all masses in the earth and the effect of the earth's rotation. Several corrections have to be applied to the field gravity readings. To interpret gravity data, one must remove all known gravitational effects not related to the subsurface density changes. Each reading has to be corrected for elevation, the influence of tides, latitude and, if significant local topography exists, a topographic correction. To understand the corrections, a gravity reading is first considered on the surface of a flat ground surface. Corrections are then applied to account for deviations from this condition. As the distance from the centre of the earth increases, the pull of gravity decreases. The correction to account for this is called the elevation correction. If the gravity reading is taken on top of a hill, then there is a deficit of mass on either side of the hill, compared to a horizontal ground surface, as is illustrated in Figure 4. This is corrected with a topographic correction. It is important to realize that mass higher than the reading site will also influence the data and has to be accounted for. This may occur in areas of significant topography or when surveys are conducted near large buildings. In a modern instrument such as the Scintrex, the meter may automatically apply the tidal and drift corrections.

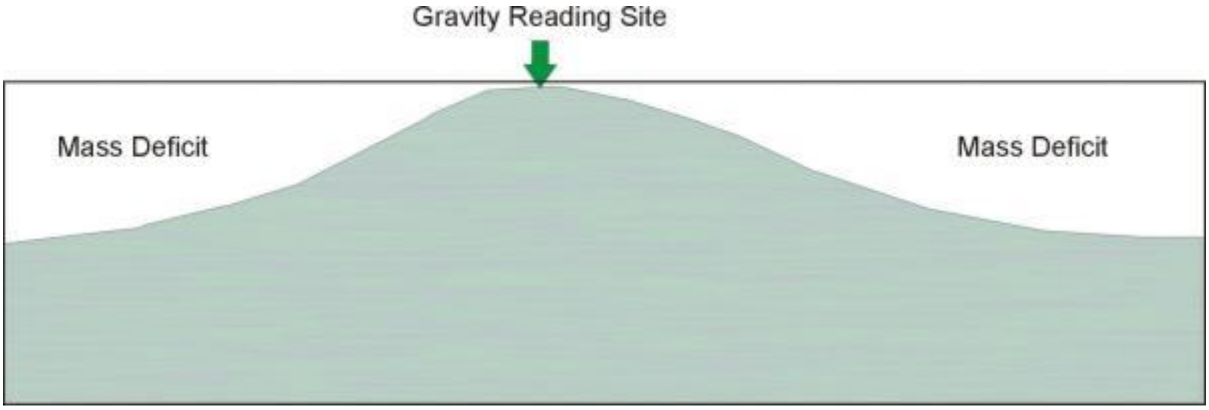


FIGURE 4: Need for correction for topography

The difference between observed gravity (g_{obs}) and theoretical gravity (g_{th}) at any point on the Earth's surface after reducing the gravity readings to the geoidal surface (i.e., making all the required corrections) is known as the Bouguer gravity anomaly or Bouguer gravity and the results are now due to lateral variations in density in the subsurface (assumed to be caused by geologic structure being sought) which can be used for interpretations.

5. DATA ANALYSIS AND INTERPRETATION

The object of the gravity method is to determine information about the earth's subsurface. One can just carry out a qualitative examination of the grid of gravity values, contour maps or the gravity profiles to determine the lateral location of any gravity variations or one can perform a more detailed analysis in order to quantify the nature (depth, geometry, density) of the subsurface feature causing the gravity variations. To determine the later, it is usually necessary to separate the anomaly of interest (residual) from the remaining background anomaly (regional) (see Figure 5). Then the residual gravity anomaly is modelled to determine the depth, density and geometry of the anomaly's source.

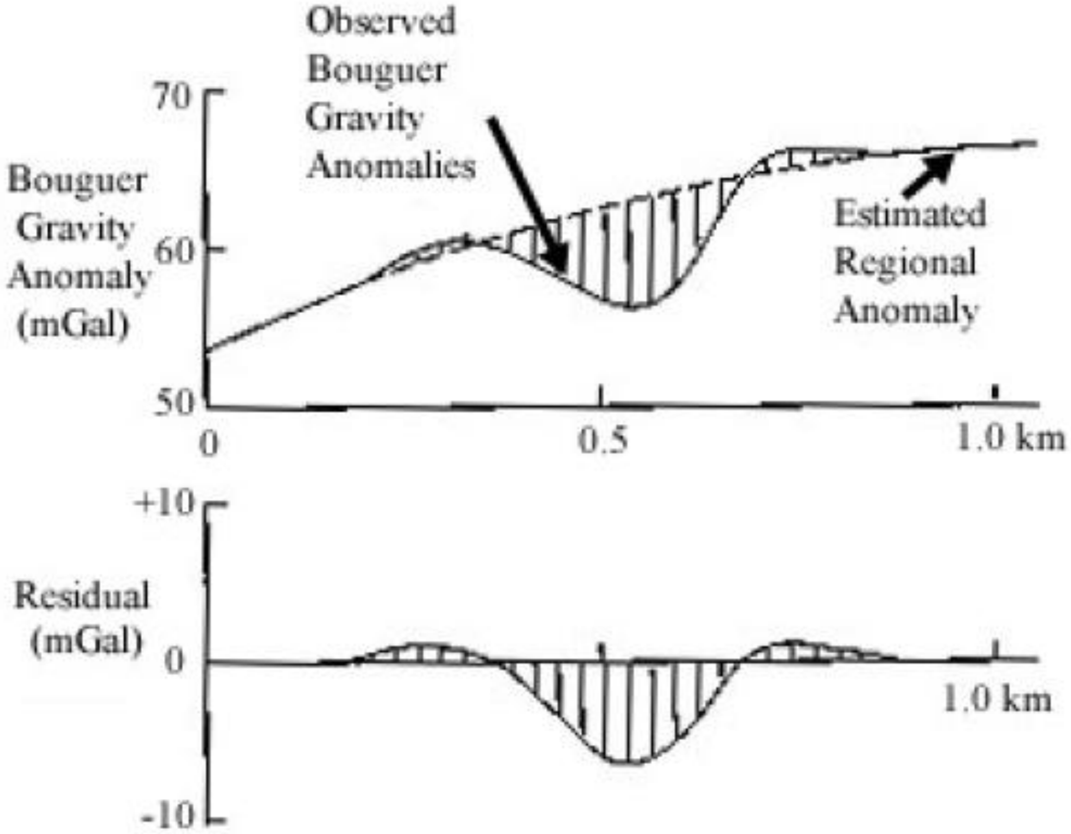


FIGURE 5: Example of a regional-residual gravity anomaly separation using graphical smoothing

Most other regional-residual anomaly separation techniques involve mathematical operations using a computer. One problem with the mathematical techniques is that they do not accurately represent the "true" residual gravity anomaly due to a specific body. Thus, they should not be used for quantitative interpretation of the subsurface but only for qualitative interpretation. The most common mathematical techniques are surface fitting and weighted averaging. Once the residual has been removed from the Bouguer gravity data modelling can be done over the feature of interest.

Gravity modelling is usually the final step in gravity interpretation and involves trying to determine the density, depth and geometry of one or more subsurface bodies. The modelling procedure commonly involves using a residual gravity anomaly. When modelling a residual gravity anomaly, the interpreter must use a density contrast between the body of interest and the surrounding material, while modelling Bouguer gravity anomalies; the density of the body is used. There are many different techniques available to perform the modelling procedure and they can be broken down into three main categories: 1) analytical solutions due to simple geometries, 2) forward modelling using 2-(two-dimensional), 2.5- (two and one-half dimensional) and 3-D (three-dimensional) irregularly shaped bodies, and 3) inverse modelling using 2-, 2.5- and 3-D irregularly shaped bodies. Most of these techniques involve iterative modelling (by the aid of a computer), where the gravitational field due to the model is calculated and compared to the observed or residual gravity anomalies. If the calculated values do not match the observed anomalies, the model is changed and the procedure is performed again until the match between the calculated values and the observed anomalies is deemed close enough. Figure 6 is an example of such a model from really data.

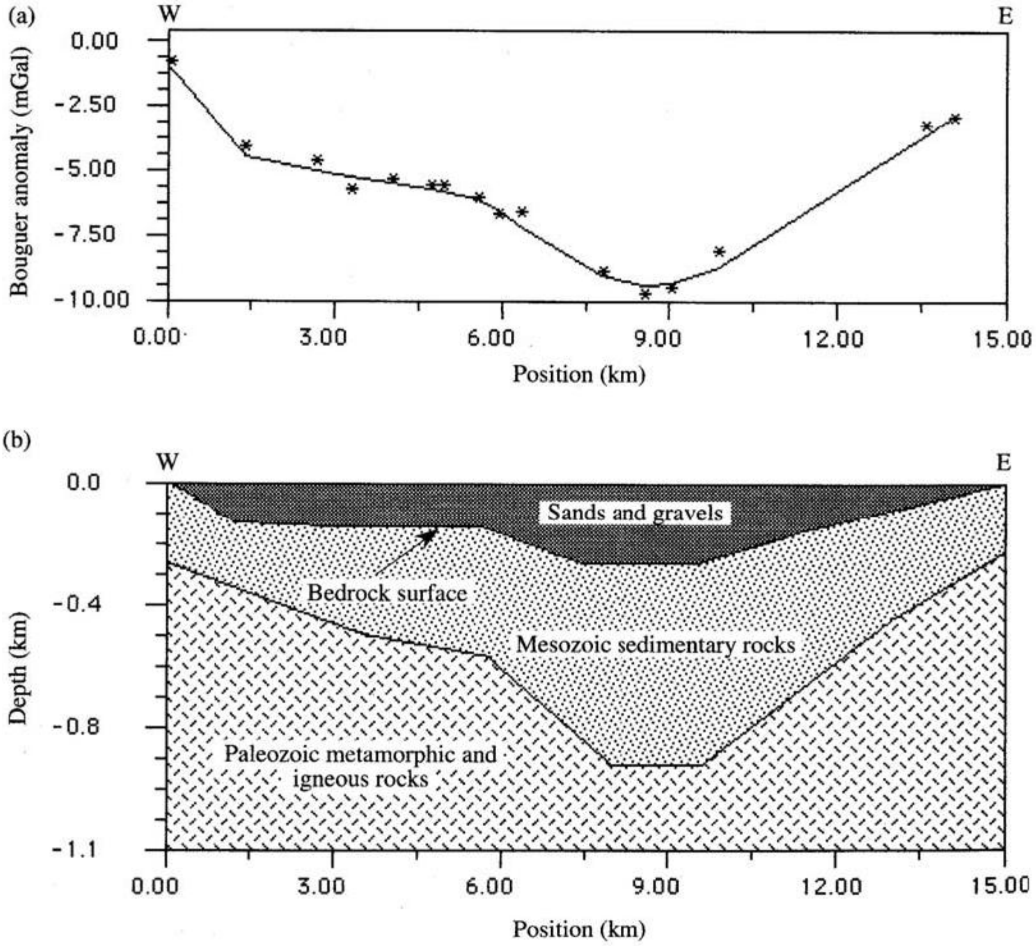


FIGURE 6: Two-dimensional gravity model. The solid line is the calculated gravity values due to the model (b) and the stars are the observed data.

6. MICRO-GRAVITY MONITORING

Reservoir engineering calculations of mass and energy balance on producing geothermal reservoirs require information about in- and out-flows from the reservoir. Such information is usually available for surface flows, such as production, injection, and natural discharge. Values for subsurface in- or out-flows are difficult to get. One method used is a history matching process whereby reservoir performance is computed for various strengths of influx and the matched against observed performance.

A more direct and independent method is through repeat micro-gravity 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.

7. RESULTS FROM GRAVITY SURVEYS OF OLKARIA GEOTHERMAL FIELD, KENYA

Gravity investigation was one of the initial geophysical surface methods used during exploration for geothermal energy resources over Olkaria Geothermal Field in the early 1970's. Its data, along with resistivity and micro-seismology indicated the best drill sites for geothermal wells. Figure 7 is a contour map for gravity data over Olkaria. Interpretation of gravity data within the Greater Olkaria Area shows gravity highs corresponding to dense bodies below areas in the present production fields.

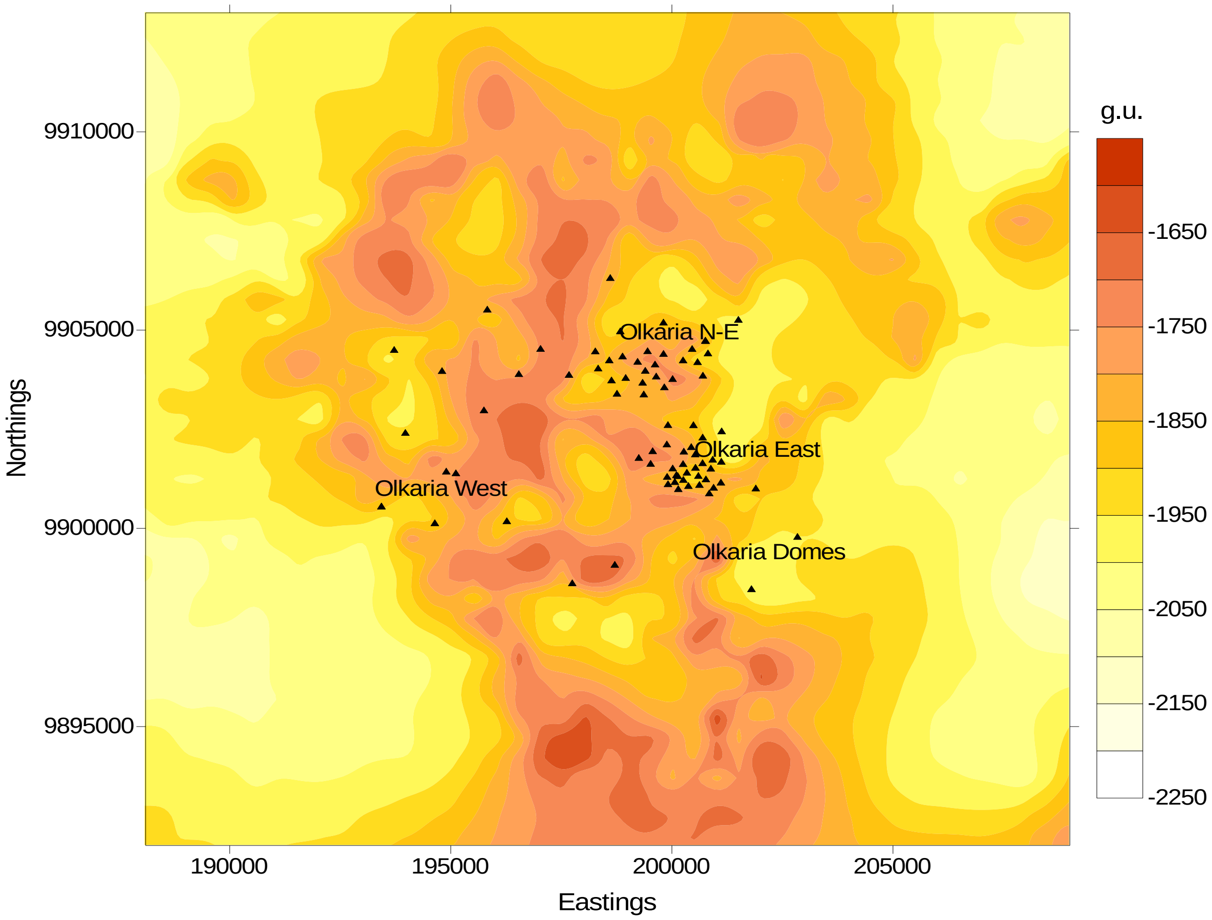


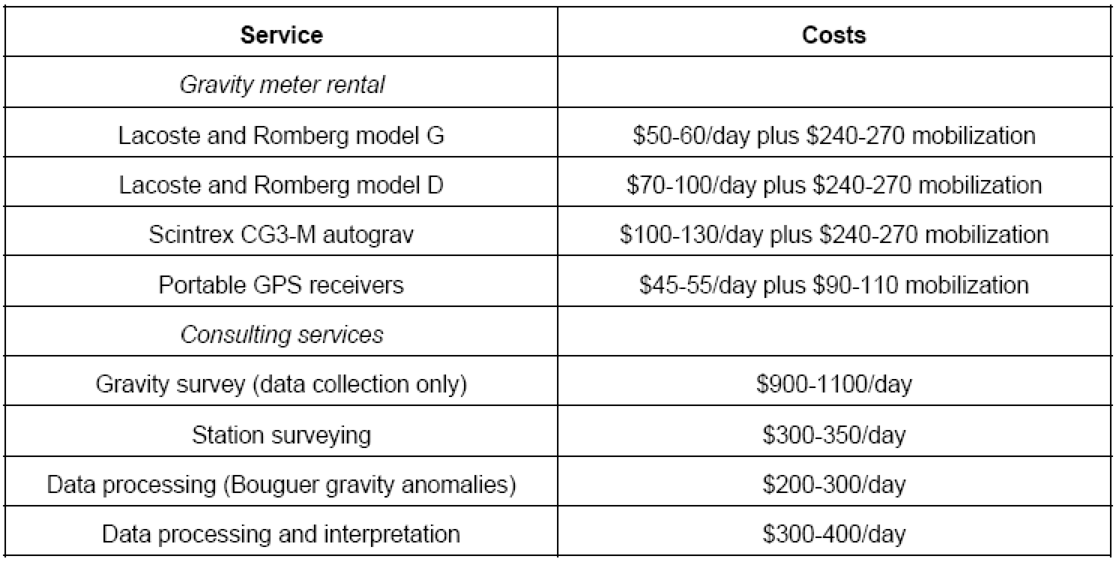
Figure 7: Gravity distribution at Olkaria area. Note that the geothermal wells are located at gravity 'highs' which infer heat sources.

8. COSTS FOR A GRAVITY SURVEY

The typical costs for a gravity survey depends on if the clients wants to perform the survey themselves, contract out the survey to a consulting company, the amount of interpretation and data processing, the number of stations, and the object of interest. A gravity survey is not as complicated as a seismic refraction/reflection survey but not as easy as a magnetic survey. If the client has experience collecting and processing gravity data, they may just want to rent a gravity meter. Typical international rental costs are shown in Table 1 for the most commonly used gravity meters. If the client wishes to contract out the survey to a consulting firm, of course, the costs jumped dramatically. The per day costs include equipment rental and one person performing the survey. Surveying the station locations will add additional costs, which costs more than magnetic surveys because of the accuracy needed in the elevations.

The amount of data processing and interpretation (map making and estimates of the depth to density contrasts) depends on the source target. If only gravity anomaly maps are required, costs are less but still more time consuming than for the magnetic method because time-consuming terrain corrections are usually required. If geologic mapping is the objective, more detailed modelling and data enhancement techniques are required which is more time consuming to perform.

TABLE 1: Typical international costs for gravity surveys



Service	**Costs**
Gravity meter rental	
Lacoste and Romberg model G	$50-60/day plus $240-270 mobilization
Lacoste and Romberg model D	$70-100/day plus $240-270 mobilization
Scintrex CG3-M autograv	$100-130/day plus $240-270 mobilization
Portable GPS receivers	$45-55/day plus $90-110 mobilization
Consulting services	
Gravity survey (data collection only)	$900-1100/day
Station surveying	$300-350/day
Data processing (Bouguer gravity anomalies)	$200-300/day
Data processing and interpretation	$300-400/day

9. CONCLUSIONS

The gravity method responds directly to a mass excess or deficit. The method requires a relatively small amount of instrumentation and is an unobtrusive method able to be conducted in environmentally sensitive areas. It is a straightforward geophysical technique that can be applied to a variety of engineering and environmental problems as well as exploration for geothermal energy including the location of heat sources and faults. The costs are much lower than other geophysical methods especially if performed by the client himself.

However, the technique has some limitations. Gravity surveying is a labour-intensive procedure requiring significant care by the instrument observer. Gravity instruments require careful levelling before a reading is taken. This may have to be done manually or it may be performed by the instrument itself. Once the reading has been taken, the gravity sensing mechanism must be clamped to stop excessive vibration that would influence the sensing mechanism and cause excessive drift, thereby affecting future readings. The instrument must be placed on solid ground (or a specially designed plate) so that it does not move (sink into the ground). All of the stations have to be accurately surveyed for elevation. Because the anomaly from targets rapidly becomes smaller with target depth, detectability rapidly decreases with depth. Because of this, pre-survey modelling using as much geologic information as possible is important to establish the expected anomaly size, and to determine if a gravity survey is feasible.