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Improvements To Microgravity Monitoring— Determination of the Vertical Gravity Gradient

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ABSTRACT

Repeat gravity measurements, made to detect mass changes in the reservoir, generally need to be corrected for ground movements. Such corrections depend on the amount of movement and on the vertical gravity gradient (VGG), but this is not (as often assumed) constant.

Direct measurements of VGG at 8 sites in Yanaizu Geothermal Field show that it varies, between sites, from -244 to -333 microgal/m. However, there is no significant change in VGG with height above the ground surface; a single value can therefore be used at each site to correct for the gravitational effect of ground movement. There is no significant correlation between VGG and elevation (above sea level) or Bouguer Anomaly value.

Introduction

Recently, improvements to numerical simulation modelling have been made by incorporating other independent parameters, such as chemistry changes (Kissling *et al.*, 1996) and gravity changes (Hunt *et al.*, 1990; Ohsato *et al.*, 1998), into the models.

Gravity values at a point, in a producing geothermal field, often differ between surveys. The differences (except for intrinsic instrumental and reading errors) result not only from mass changes in the reservoir, but also from vertical ground movements, changes in groundwater level, changes in soil moisture content, local topographic changes, and changes in gravity at the base station. The gravity effects of mass movements in the geothermal reservoir, called gravity changes, are obtained by correcting the observed gravity differences for the effects of these factors. These corrections are generally small compared to the gravity effects of mass changes in the reservoir, but in some cases may be large and require careful determination, especially for ground movements. For example, at Wairakei Geothermal Field (New Zealand) there has been up to 14 m of ground subsidence in part of the field: the gravity change at a point in the centre of this subsidence due to this movement is more than +4000 microgal (4 milligal). However, this is an extreme case and in most geothermal fields the ground subsidence is much smaller (<1 m), but still sufficient to require a correction.

Ground movement

Vertical ground movements, both upwards (inflation) and downwards (subsidence) have occurred in many geothermal fields as a result of mass withdrawal and reinjection. For example:

- Wairakei Field (New Zealand), subsidence of up to 14m, since 1958 (Allis *et al.*, 1998);
- Ohaaki Field (New Zealand), subsidence of up to 2m, since 1988 (Allis *et al.*, 1997);
- Takigami Field (Japan), subsidence of up to 11mm, between 1993 and 1997 (Ehara *et al.*, 1998);
- Hatchobaru Field (Japan), +35 to -15 mm, between 1990 and 1996. (Ehara *et al.*, 1998);
- Travale Field (Italy), subsidence of up to 0.4m, between 1973 and 1991 (di Filippo *et al.*, 1995);
- The Geysers Field (USA), subsidence of up to 0.9m, between 1977 and 1996 (Mossop and Segall, 1997).

The movements have generally been monitored by making repeat surveys using traditional optical levelling techniques (2-3rd Order Standard) at permanent survey marks (benchmarks).

The causes of the subsidence have been determined at Wairakei and Ohaaki Fields (New Zealand). Here, a rock formation (lake sediments) having large vertical compressibility (>30kb^{-1}) exists above the reservoir in parts of the fields. Mass withdrawal has caused a decline in deep reservoir pressures (up to 25 bar), resulting in the pore fluid within the formation to drain downwards into the reservoir (Allis *et al.*, 1997). Removal of the pore fluid has caused compaction of the formation, and the overlying rocks (poorly-compacted volcanic tephra) have little strength and have collapsed, resulting in subsidence of the ground surface. However, it is difficult to invoke such a mechanism for ground movements in geothermal fields situated in old basement rocks, such as at the Geysers Field (USA). Here, it was initially thought (Lofgren, 1981) that the subsidence was also related to a decline in reservoir steam pressures, however, Denlinger *et al.* (1981) noted that the small reduction in steam pressure ($\Delta P \approx 1$ MPa), combined with the large bulk modulus determined from seismic data ($K_d \approx 3 \times 10^{10}$ Pa), was not consistent with the observed subsidence. They thought the strain was due to a combination of thermoelastic and poroelastic deformations, in which the major component was thermal. The thermoelastic strains occur because most of the reservoir water is stored as a liquid phase within the rock, and when the liquid water flashes into steam, the phase change absorbs large amounts of heat and so lowers the reservoir temperature. The cooling reservoir contracts and this is observed at the surface as subsidence. Recent modelling studies (Mossop and Segall, 1997), however, show that the major part of the subsidence at the Geysers cannot be explained by thermoelastic contraction, but can be explained by poroelastic contraction associated with the reduction in steam pressures

Subsidence is generally associated with production, and inflation with reinjection., but subsidence is generally much greater in magnitude and extent than inflation. The location of subsidence is different in different fields, and may be outside of the production area. Inflation, however, generally appears to be located in the immediate vicinity of reinjection wells. The location and rate of ground movement cannot be predicted until after it begins. The amount of ground movement appears to be independent of the size of the field or the amount of fluid withdrawn and reinjected.

Gravity effect of movement

Assuming (initially) that there are no mass changes involved, the effect of ground movement at a point, between gravity surveys, is to move the gravity meter through the Earth's gravity field. Subsidence will bring the instrument closer to the centre of mass of the Earth thus increasing the value of gravity, and conversely inflation will decrease the value of gravity. The gravitational effect of such movement therefore needs to be determined and corrected for in order to isolate any gravity changes associated with mass changes in the geothermal reservoir.

The size of any gravity change (Δg_h) associated with ground subsidence or inflation (Δh) is:

$$\Delta g_h = (\partial g/\partial z).\,\Delta h$$

where ($\partial g/\partial z$) is the ***vertical gravity gradient*** (VGG), and Δh is small (i.e. changes in the gradient can be neglected). The unit of gravity gradient is the Eotvös unit (1 E = 10^{-6} mgal/cm = 0.1 microgal/m) but, for simplicity, gradients will be expressed here in terms of microgal/m.

To calculate Δg_h it is therefore necessary to determine $\partial g/\partial z$, in addition to measuring the amount of vertical ground movement (Δh). A first approximation for VGG can be determined from the gravity field of the Reference Ellipsoid derived from world-wide gravity measurements (Garland, 1965):

$$\partial g/\partial z = -0.30855 - 0.000227.\cos 2\phi + 0.000145.h \text{ (mgal/m)}$$

where ϕ is the geocentric latitude (deg) and h is the elevation of the point (km, asl). This yields the value of -308.55 microgal/m (at sea level, lat 45°), which is commonly used for the *free-air correction* in Bouguer Anomaly surveys. However, measurements show that the vertical gradient varies from place to place by up to 10%, depending not only on the latitude and elevation of the point, but also (and more importantly) on the geology and topography near the point (Kumagai *et al.,* 1960; Fajklewicz, 1976; Ager and Liard, 1982).

Measurement of VGG

One method of determining VGG at a point is to make numerous precise gravity measurements at and around the point and mathematically compute the first vertical derivative (vertical gradient) (Morelli & Carrozzo, 1963; Marson & Klingele, 1993). However, this is difficult and time consuming because the value of gravity and the elevation of the gravity meter must be very precisely measured at a large number of points (Kumagai *et al.*, 1960).

A simpler method is to determine the vertical gradient directly by making gravity measurements at several different heights on the various floors of a multi-storey building, or using a portable tower. In the case of making measurements in a building, a correction may be needed for the mass of the floor(s); this can easily be calculated using the Bouguer infinite plate equation and a knowledge of the thickness and density of the floor(s). In the past, the best results have been obtained using a portable tower (Kumagai *et al.*, 1960; Janle *et al.*, 1971); the mass of the tower and observer is too small to significantly affect the gradient. Many such studies were made in the 1950's and 1960's, generally as a means of locating shallow geological features and caves (Thyssen-Bornemisza, 1958; Thyssen-Bornemisza and Stackler, 1956; Fajklewicz, 1976).

The vertical gravity gradient $\partial g/\partial z$ is approximated by $\Delta g/\Delta h$:

$$\frac{\partial g}{\partial z} = \lim_{h \to o} \frac{\Delta g}{\Delta h}$$

For an error in g of 5 microgal, and an error in measurement of Δh of 2mm over a height difference of 1m, then the error in VGG is about 7.7 microgal/m. However, as Δh gets smaller, the error in VGG increases rapidly. For the same errors, over a height difference of 0.3m, the error in VGG will be about 23 microgal/m. This shows that the measurement of gravity needs to have a precision of about 1 microgal to enable measurements of VGG to be made over vertical intervals of less than 0.5m. For the best results, the tower needs to be very stable and unaffected by wind or vibration; such conditions are difficult but not impossible to obtain in the field.

VGG measurements at Yanaizu

Measurements were made at Yanaizu–Nishiyama Geothermal Field (Japan), with the aims of determining the likely range of values of VGG at or near the ground surface, whether the gradient varied depending on lateral position or ground elevation (and if so, by how much), and if the gradient was constant with height above the ground surface.

Measurement Techniques

The measurements were made using a square-section portable tower constructed from metal framing. The lower part of the tower contained a wooden floor at about 0.17m above ground level, and the upper part another floor which could be repositioned at about 0.86, 1.36 and 1.86 m above ground level. The observer was on an aluminium ladder alongside, but not touching, the tower. Adjustable feet on the bottom of the tower enabled it to be oriented vertically despite small variations in the ground surface; this also improved stability of the structure and minimised levelling of the gravity meter.

Gravity Measurements

Gravity values were measured at ground surface, 0.17, 0.86, 1.36 and 1.86 m height at 8 sites (Figure 1, Table 1) using a SCINTREX CG-3M gravity meter (No 704380), set in automatic recording mode. Readings were obtained at 1 sec. intervals, and averaged for 120-500 readings (excluding rejections, depending on the noise conditions). At most sites, three consecutive sets of readings were made at each floor position, and observations were repeated several times at each floor position to enable the gravity meter drift to be determined and corrected for.

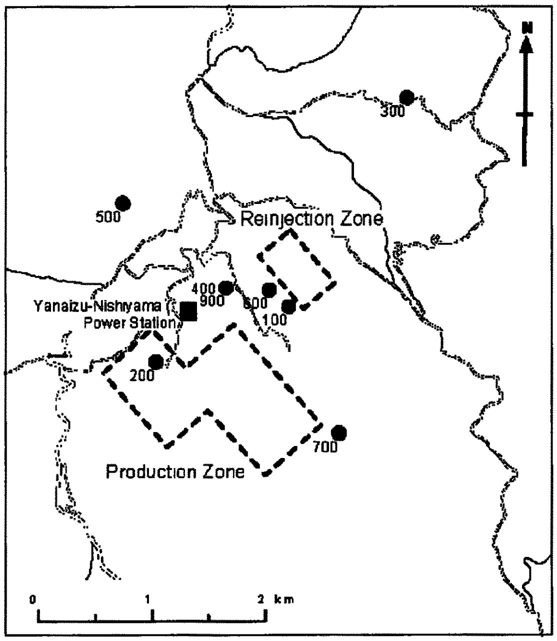

Figure 1. Location of measurement sites at Yanaizu-Nishiyama field.

An inherent characteristic of SCINTREX CG-3 type gravity meters is a high, but relatively uniform, drift rate compensated for by an automatic real-time compensator. However, initial analysis of the data showed the compensation was insufficient, and after "trial and error" it was found the most consistent results were obtained after a linear 2nd order drift correction for each site was applied. This was obtained by plotting the averaged readings at each site against time, and determining the slope of the best-fit line through these points.

Table 1. Measured values (weighted mean) of vertical gravity gradient (VGG) at Yanaizu-Nishiyama field. Sites 400, 600, & 900 were inside garages.

Site	Position wrt field	Elevation (m)	VGG(error) (microgal/m)
100	Inside	437	-310.6 (2.4)
200	Inside	426	-333.2 (11.1)
300	Outside	376	-243.7 (5.7)
400	Inside	372	-306.8 (4.2)
500	Outside	419	-288.9 (8.9)
600	Inside	403	-313.8 (4.1)
700	Inside	508	-293.5 (3.0)
900	Inside	372	-305.5 (1.7)

To further improve the accuracy of the gravity measurements, the gravity values obtained were weighted according to the inverse cube of the "error" indicated by the gravity meter ("SD"), and the weighted values averaged.

The end result of these manipulations is a good estimate of the gravity value (and its error) on each floor of the tower at each site. The term "estimate" is used here because if a different weighting function or 2nd order drift correction had been used, then slightly different values would have been obtained, but within the error. The error in the gravity values was taken as the (population) standard deviation of the gravity values corrected for 2nd order drift.

No corrections were made for the small differences in the (measured) height of the instrument above the floor(s) of the tower, between successive occupations, because these would correspond to an error of only about ± 0.3 microgal.

Vertical Gravity Gradient

The vertical gravity gradients (VGG) at each site were then computed from the gravity values and the height differences assuming the gradient is that at the point midway between the measurement points; if the gradient is not linear over the vertical range between the points then this assumption will be incorrect, however, analysis of the results (given below) suggests this assumption is valid.

Errors in the value for VGG were calculated from the errors in the gravity differences and assuming an error in the height difference of ± 1 mm.

Plots of VGG against height at each site are shown in Figures 2 and 3. Except for Site 300, the gradients at the sites are within the range -290 to -330 microgal/m which is as expected. The gradients at Site 300 are significantly less (230-260 microgal/m) than those measured at the other sites, but the reasons for this are not known at present. No corrections were made for the effects of local topography because most sites were in areas of relatively flat ground. The site having the greatest local topographic relief is probably Site 700 situated near Well 25P; here there is a steep bank above and approximately 8 m from the location of the measurements. However, the gradient values obtained at this site (-279 to -299 microgal/m) are not greatly different from those measured elsewhere at Yanaizu (except at Site 300).

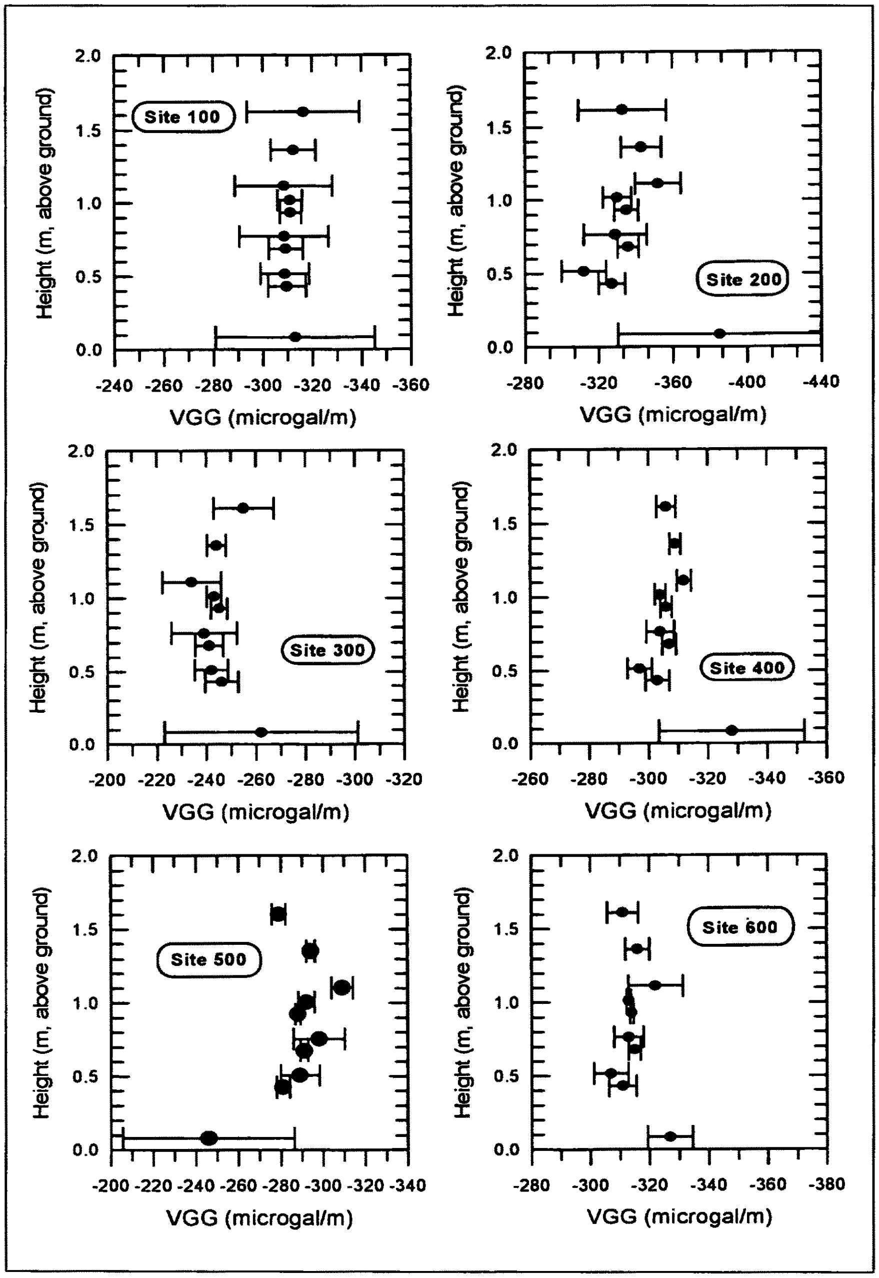

Figure 2. Measured values of VGG at Yanaizu-Nishiyama field. Site numbers are shown in boxes.

A plot of VGG against elevation above sea level (Figure 4) shows no systematic variation of VGG with elevation at Yanaizu. VGG values at Sites 100, 400, 600 and 900 lie close to the theoretical values of -308.67 to -308.69 microgal/m determined from the formula given by Garland (1965). Value at sites 200, 300, 500 and 700, however, differ from the theoretical values.

A plot of VGG against height above ground surface (Figure 5) shows there is no systematic change with height above ground surface (at least to a height of 1.6 m), and therefore any correction for subsidence can be made using a single value for VGG at each site.

A plot of measured VGG against Bouguer Anomaly values (Figure 6), similarly shows no correlation.

The large difference (-64.9 microgal/m) in the value of VGG at Site 300, compared to other sites and to the theoretical value, indicates that the correction for ground movement of about 15cm would be in error by 10 microgal if the theoretical value of VGG was used at this site. However, Site 300 lies *outside* the field and is likely to experience only small amounts of exploitation-induced ground movement. The largest measured difference *within* the field, where movement is likely to occur, is at Site 200. Here, the VGG is 24.6 microgal/m different from the theoretical value, which if used for computing a correction for ground movement would be in error by 10 microgal for a movement of about 40 cm.

Conclusions

1. Ground movements, mainly subsidence, occur in many exploited geothermal fields. The causes of these movements are poorly understood; in some cases it is due to pressure drawdown in the geothermal reservoir, in other cases it may be due to thermal contraction associated with the reinjection of cooler waste fluid.

2. Repeat gravity measurements, made to detect mass changes in the reservoir, generally need to be corrected for ground movements. Such corrections depend on both the amount of movement and the vertical gravity gradient (VGG).

3. Measurements in many parts of the world, and in both geothermal and non-geothermal areas, show that the vertical gravity gradient is not (as often assumed) constant but varies depending mainly on: latitude, elevation (above sea level), geology (lateral density variations), and local topography.

4. Measurements of VGG at 8 sites in Yanaizu Geothermal Field show that:

a) Values of VGG are -244 to -333 microgal/m. However, for most sites the range is -289 to -333 microgal/m; a variation of 6-8% of the normal free air gradient;

b) At all sites, there is no significant change in VGG with height above the ground surface. A single value for VGG can therefore be used at each site to correct for the gravitational effect of any ground movement;

c) There is no significant correlation between VGG and elevation (above sea level) or Bouguer Anomaly value.

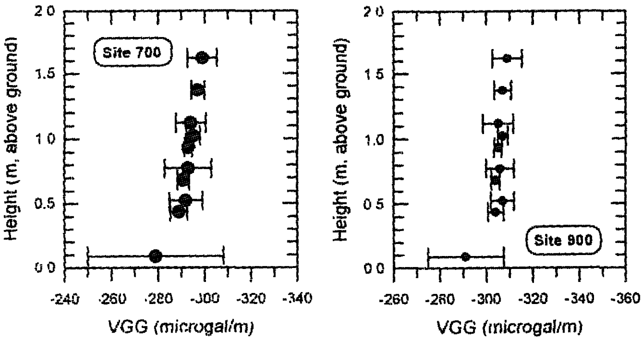

Figure 3. Measured values of VGG at Yanaizu-Nishiyama field. Site numbers are shown in boxes.

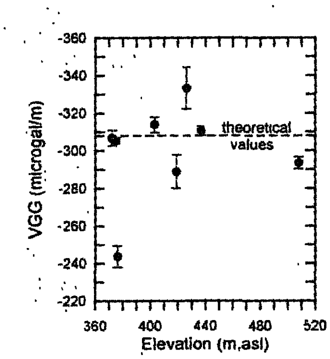

Figure 4. Plot of VGG against elevation, at Yanaizu-Nishiyama field. Data for the smallest height difference (0.85 m) have been omitted.

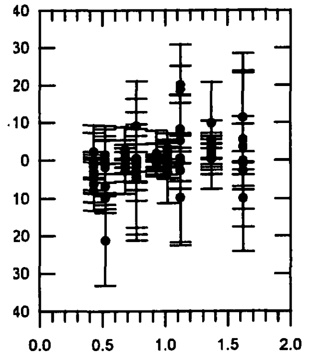

Figure 5. Plot of differences in VGG against height, at Yanaizu-Nishiyama field. Differences are between measured values and the weighted mean for that site.

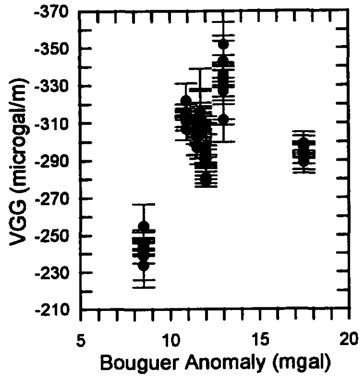

Figure 6. Plot of variation of VGG against Bouguer Anomaly values, at Yanaizu-Nishiyama field.

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