# GEOTHERMAL RESERVOIR INTERPRETATION FROM CHANGE IN GRAVITY

William Isherwood
U.S. Geological Survey
Menlo Park, California 94025

Precision gravity methods provide new information regarding geothermal reservoir mechanisms and depletion. This paper discusses the principles of present interpretations and early conclusions from two producing geothermal fields, Wairakei, in New Zealand, and The Geysers, California.

The acceleration of gravity at any point on the earth's surface is a function of numerous factors including the mass distribution beneath the point and its absolute elevation. A change in the observed gravity at a fixed location in a geothermal field therefore can be interpreted in terms of change in elevation and fluid movement in nearby reservoir rocks, other factors being either corrected for or held constant. Modern gravity meters have sensitivities sufficient to reliably measure differences in gravitational acceleration of between 5 and 10 μgal ($10^{-8}$ m/sec/sec), although changes in gravity measured to date, because they are dependent on baselines established with older equipment, are probably accurate to only about 30 μgal. A 5-10 μgal change can be caused either by several centimeters of elevation change or by the draining of liquid water from a layer about 1 meter thick from an infinite aquifer with 20 percent porosity. Careful repeat measurements of gravity provide the potential for detecting mass loss (depletion) from geothermal reservoirs, which can be used for determining the percentage recharge occurring, for detecting areas of drainage, and to test various reservoir models, provided that elevation change is measured independently and corrected for and production data are available. In practice this requires coordination with a first-order leveling program.

Despite theoretical expectations, it must be demonstrated that changes in gravity observed are in fact related to removal of geothermal fluid--especially when so many other effects could contribute to any one measurement. Trevor Hunt of New Zealand established the first practical test of precision gravimetry in geothermal studies at the Wairakei field (Hunt, 1970, 1977). After correcting for elevation changes and showing that other effects such as changes in local topography and differential changes in ground-water level could be neglected, Hunt's demonstration of the method came largely from the observations of gravity decreases correlating spatially with the limits of the exploited field. The resultant pattern was one of maximum gravity decrease centered on the main production borefield and tapering smoothly toward zero changes at several kilometers distance. This same part of the field showed moderate subsidence, a further suggestion of net loss of fluid from the system.

A program patterned on the New Zealand study was set up at The Geysers, California (Isherwood, 1977). But the situation is, for various reasons, much more complicated. Landsliding and active tectonics could be producing vertical ground motions unrelated to fluid withdrawal. As an underpressured, "vapor-dominated" system, The Geysers may have only slight subsidence potential because internal pore pressure is apparently not contributing much support to the rock matrix. Also, if the reservoir contained only vapor in the pore space (including, of course, fractures), then the mass loss conceivably is distributed over a large volume or is occurring at some distance from the well bores. Finally, California's present severe drought could change local ground-water levels. Despite these complications, areas of gravity decreases (with respect to a reference station outside the field) closely match areas of production (fig. 1). Thirty-six of the gravity stations coincide with remeasured elevation points. Figure 2 shows the correlation between subsidence and gravity decrease. The resultant correlation of +0.72 is particularly significant, inasmuch as changes of gravity caused by landslides or block tectonic elevation changes would produce a correlation coefficient of -1.

Both Wairakei and The Geysers clearly show a net mass loss in the reservoir region. Determining the actual mechanism of loss is prerequisite to understanding the reservoir dynamics. For both reservoirs, the most likely mechanism is the replacement of hot liquid water ($\rho$ water @240$^{\circ}$C=0.8 g/cm$^3$) in the pore space by water vapor ($\rho$ steam @240$^{\circ}$C=0.02 g/cm$^3$) and removal of excess fluid. Where this flashing takes place can be further constrained (as will be explained later). Alternate mechanisms of mass loss seem unlikely or inadequate to explain observed changes. For example, evacuating steam of density 0.02 g/cm$^3$ from the pores of a vapor-dominated system could cause only about 0.001 g/cm$^3$ bulk density change (using the 5 percent porosity suggested for vapor-dominated systems); to change gravity by the amounts observed at The Geysers in just 2 1/2 years would require depletion to a depth of at least 9 km for a 40 km$^2$ field. Changes in density of the liquid or rock, though possible, would presumably be toward greater density, due to reservoir cooling. Similarly, any change in porosity (presumably due to subsidence) would tend to increase bulk density and consequently not contribute to a gravity decrease.

If gravity measurements are made with sufficient coverage and precision to permit accurately contouring the change in gravity over an area, then Gauss' potential theorem can be used to determine the total change of mass (in this case the net fluid loss) without assuming a shape or depth of the source. Hunt used this approach in studying mass loss from the Wairakei field over a 16-year period. Comparison of the mass loss calculated from gravity with the measured mass of produced fluid showed as much as 90 percent net loss during the early years of exploitation but an apparent increase in natural recharge percentage with prolonged production. If a true steady-state situation is eventually attained, the initial unfavorable trends in lowered pressure, flow rate, etc., may be temporary, at least for some hot water systems. Continued monitoring will be required to confirm whether an equilibrium recharge rate has indeed been reached at Wairakei.

Preliminary calculations of the mass balance at The Geysers by Gauss' theorem show the mass loss to be essentially the same as the calculated mass of produced steam during the same time. Because of the limited areal coverage and duration of the study, this estimate of 0 percent recharge could be in error by as much as 20 percent. This uncertainty should be reduced in a few years as instrumentation is upgraded and the net is expanded to more gravity stations and more than 150 km additional first-order leveling lines. Still unresolved are (1) whether lack of recharge is related to the drought, and (2) barring eventual recharge, how large a volume can be tapped by the present wells.

Interpretations regarding the distribution of mass loss are not unique, although the "forward calculations" are. That is, if we know the net mass removed and its distribution (shape and depth) the gravity effect at all surface points can be calculated. Through such calculations more substantial conclusions about The Geysers geothermal reservoir have been made. The work at The Geysers typifies the additional information that can be derived. Certain assumptions are useful in simplifying computations. Recognizing that the distribution of mass loss may be complicated in detail, the first assumption is that we may treat the loss as a body or small number of bodies with some uniform density change. Due to the normally smooth character of the gravity field and distance from source to observation, this bulk characterization is considered reasonable. That the bulk density change is not exactly known scarcely affects the results. Representative parameters are established using reservoir properties considered reasonable on the basis of geologic and reservoir engineering studies.

For convenience of calculation, the shape of the mass loss is assumed to be that of a cylinder with its axis vertical (fig. 3). Using the mass of the net produced fluid (estimated at $7.5 \times 10^{10}$ kg over 2 1/2 years) as a maximum loss, the gravity effect at the surface can be calculated for various combinations of cylinder radius and depth. Figure 4 shows such a matrix for a bulk density change of 0.04 g/cm$^3$. (This density change would result from the flashing of hot water of density 0.82 g/cm$^3$ to steam of density 0.02 g/cm$^3$ if the liquid initially saturated a uniform 5 percent porosity or filled half the pore volume at 10 percent porosity.) For instance, a cylinder of 1 km radius, which would have a thickness of about 600 m (density contrast and mass given), would have a gravity effect directly above it of 129 μgal if the top were 1500 m deep and bottom about 2100 m deep and an effect of only 84 μgal if the top were 2000 m deep and bottom at about 2600 m. Because a change in the radius changes the thickness, an optimum radius produces the maximum effect--in all cases decreasing with depth. The shaded zone on figure 4 represents the observations at The Geysers, where a maximum observed change is about 120+30 μgal. Within this shading, the observed changes could be accounted for by this set of parameters and zero recharge. If the true parameters fall to the left (shallower) side of the shading where the calculated effect is too large, the observed change could have been caused by less mass loss--indicating partial recharge. To the right of the shaded zone the calculated effect is less than observed, showing (1) that there is additional mass loss by some unknown mechanism or (2) that such a shape-depth combination would be impossible. A change in the density contrast by a factor of 2 changes the depth to the center of the cylinder only a few percent at the depth range of interest, although the top and bottom will vary more to accommodate the appropriate change in cylinder thickness. Similarly, the maximum depth to the mass loss can not be increased greatly by considerations of shape (e.g. sphere versus cylinder) and it actually decreases if the regions around individual production sites are considered separately. Consequently, if we assume no additional mass loss beyond what has been produced, we can rule out the possibility of steam boiling solely off a water table deeper than about 2500 m. Some contribution from this depth is not precluded, but the major loss must be shallower, probably near the 1-2 km depth of most well completions. This supports the model of Truesdell and White (1973) which proposes liquid water throughout the reservoir, such water flashing to steam as a direct result of pressure decrease caused by exploitation.

Regions of drainage may be recognized by comparing a map of elevation-corrected changes in gravity to areas of known production. Asymmetry to the pattern of gravity change at Wairakei (Hunt, 1977) suggests greatest depletion to the west of the main production borefield. At The Geysers, some of the critical stations surrounding the present field have not yet been releveled to provide elevation correction. Consequently, although measurements from the stations to the southwest (around power plant 15, fig. 1) are suspect because of their apparent large decreases in gravity, we must await the leveling data for interpretation.

Projections of reservoir longevity at The Geysers and elsewhere will be reliable only when we have a longer period of observation and our interpretation techniques are refined. Gravity changes reflect what has happened between measurements, and, in conjunction with other reservoir data, can eventually allow for projections which will lead to informed management of reservoirs.

## REFERENCES

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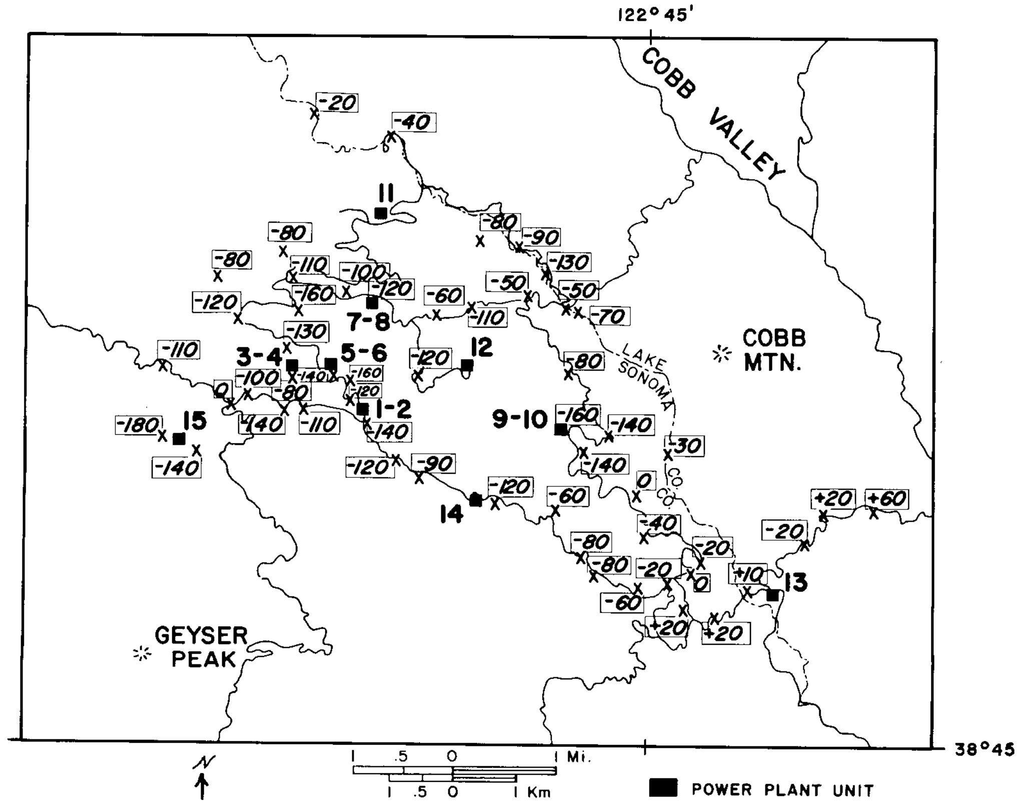


Figure I. **GRAVITY CHANGES, IN μGAL, BETWEEN JULY 1974 AND FEB. 1977, THE GEYSERS GEOTHERMAL AREA, CALIFORNIA.**

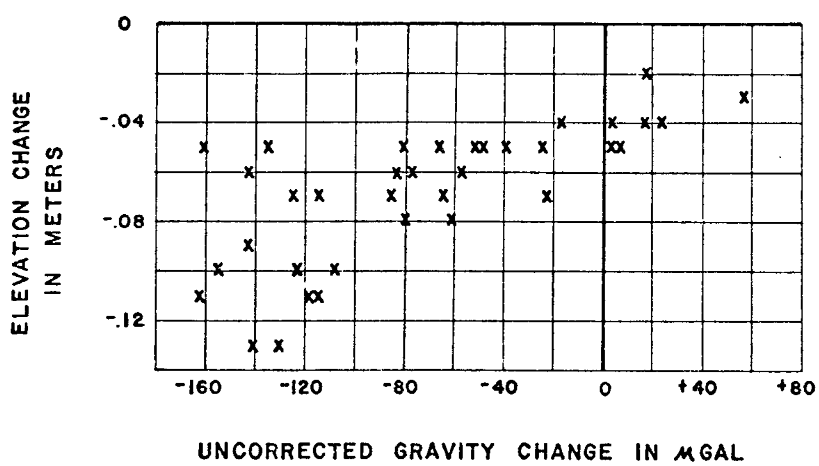


**Figure 2.** Relation between gravity change (July 1974 to Feb. 1977) and elevation change (late 1973 to late 1975), at The Geysers, California.

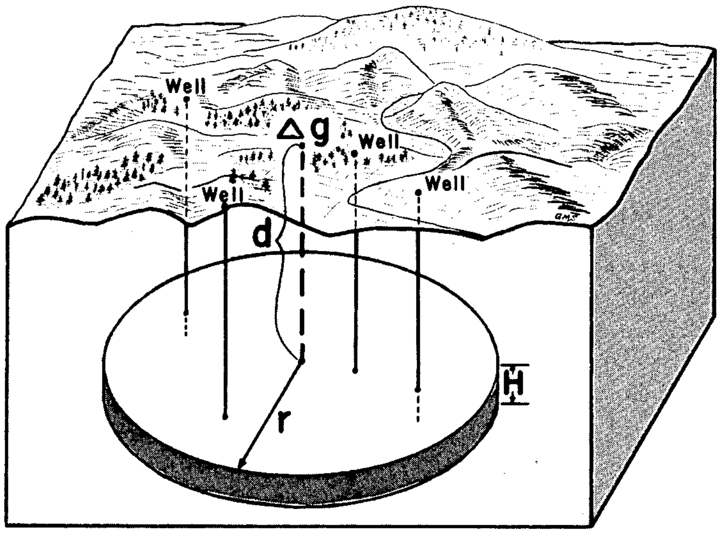


Figure 3. **CYLINDRICAL APPROXIMATION TO MASS LOSS**

$$\Delta g \text{ (in } \mu\text{gal)} = 41.85 \quad \rho \left[ H - \left( \sqrt{(d+H)^2 + r^2} - \sqrt{d^2 + r^2} \right) \right]$$

(in meters)

| Radius (km) | Depth to top (meters): 0 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 |
|---|---|---|---|---|---|---|---|
| .1--- | 167 | 16 | 8 | 5 | 4 | 3 | 3 |
| .5--- | 750 | 275 | 136 | 82 | 55 | 40 | 31 |
| 1.0--- | 726 | 387 | 213 | 129 | 84 | 59 | 43 |
| 1.5--- | 405 | 272 | 177 | 117 | 81 | 58 | 44 |
| 2.0--- | 242 | 182 | 132 | 96 | 70 | 53 | 41 |
| 2.5--- | 156 | 125 | 98 | 75 | 58 | 46 | 36 |
| 3.0--- | 110 | 91 | 75 | 60 | 49 | 39 | 32 |
| 3.5--- | 81 | 69 | 59 | 49 | 41 | 34 | 28 |
| 4.0--- | 62 | 55 | 47 | 40 | 34 | 29 | 25 |

Figure 4. GRAVITY EFFECT OF CYLINDER WITH $\Delta\rho = 0.04 \text{ g/cm}^3$ (in μgal) FOR MASS OF TOTAL PRODUCING FIELD