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UCRL-52421

POTENTIAL USES FOR A HIGH-TEMPERATURE BOREHOLE GRAVIMETER

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MS date: March 8, 1978

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ABSTRACT

It is possible to design a canister to cool a borehole gravimeter for use in geothermal and high-temperature (up to 350°C) gas wells. Repeat surveys with such a gravimeter could (1) help estimate the extent of reservoir plugging in geothermal injection well after one year of operation and (2) detect compaction of a geothermal aquifer if the change in thickness of the aquifer exceeds 1 m. The instrument could be used together with conventional logging tools to evaluate radial dependence of density around a well, or to estimate gas-filled porosity around wells drilled with mud. A high-temperature borehole gravimeter could also be used to evaluate structure and stratigraphy around geothermal and high-temperature gas wells.

INTRODUCTION

It has long been recognized that measurements of gravity at different depths in a borehole can be used to calculate an average value of bulk density of the medium over a large volume surrounding the hole.[1-3] In recent years, a high-quality borehole gravimeter has become commercially available[4] so that such measurements have become somewhat routine.[5-7]

From the beginning, it was recognized that stratigraphy and subsurface structure as well as density could affect borehole gravity data. With more experience in the use of the meter, the effects of such phenomona as dipping beds,[8,9] scarps,[10] buried reefs,[11] and structures of regular shape were studied in detail.[12] A computer program is now available for calculating the effects of arbitrarily shaped two-dimensional structures on density measurements with a borehole gravimeter.[10]

APPLICATIONS FOR A HIGH-TEMPERATURE BOREHOLE GRAVIMETER

We discuss four applications for which a high-temperature gravimeter could provide less expensive or more accurate data than other available methods. The first three applications are useful during geothermal energy production, while the last two have many uses.

Deposition Around Geothermal Injection Wells

Introduction

Dissolved solids in brine may precipitate and clog the pores in the formation around a geothermal injection well; the resulting loss of permeability may render the well useless. We are examining methods for measuring or estimating this porosity loss. Well testing based on variable-permeability models may provide some information [13] but such tests should be calibrated with measurements of actual porosity loss. Cased-hole logging is one possible solution (with neutron logs[14] or Thermal Decay-Time Logs[15]), but standard logs do not penetrate far enough into the formation. However, borehole gravimetry is sensitive to masses far from the wellbore. By comparing gravity surveys before and after long periods of injection, a zone of deposition can be mapped.

Density Change and Radius of Deposition

The quantities in Table 1 were used to estimate the volume of the density anomaly from solids deposition around a well. The bulk density change during deposition is $\Delta\rho$, the rate at which solids are

Table 1. Variables used to estimate volume of density anomaly.

Variable	Symbol	Value
Porosity loss	ϕ	0.20
Fluid flow rate	q	0.04 m^3/s
Precipitant concentration	S	500 ppm (weight)
Precipitant density	ρ_s	2.2 g/cm^3
Fluid density	ρ_f	1 g/cm^3
Well radius	r_w	0.2 m

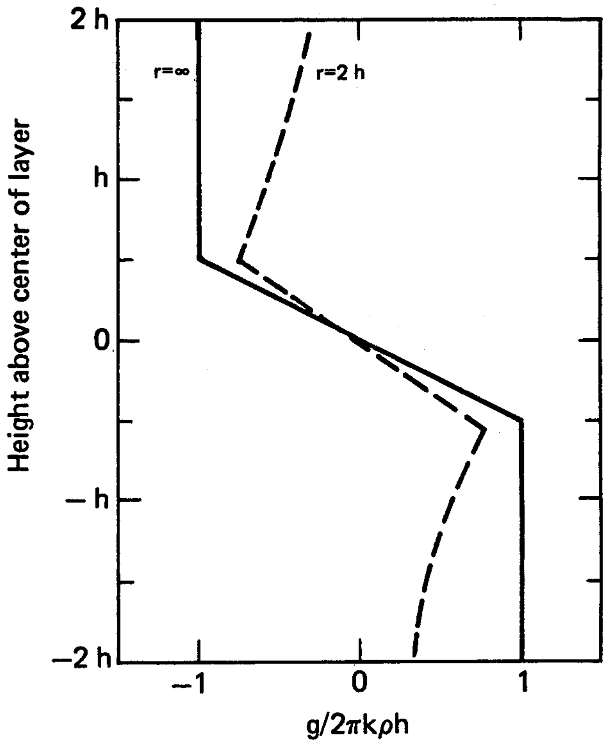

Fig. 1. Vertical gravity component caused by an infinite slab of thickness h (solid line) and a finite cylinder of radius 2h and thickness h (dashed line).

injected in the well is $\Delta m/\Delta t$, and the rate at which the volume of rock with filled pores increases is $\Delta V/\Delta t$, as defined by:

$$\Delta\rho = (\rho_s - \rho_f)\phi \ ,$$

$$\frac{\Delta m}{\Delta t} = \rho_f S q \ ,$$

and

$$\frac{\Delta V}{\Delta t} = \frac{\Delta m}{\Delta t}\,\frac{1}{\rho_s \phi} \ .$$

Assuming the volume to be a right circular cylindrical annulus about the well with height h and outer radius r, then

$$V = (\Delta V/\Delta t)\ \Delta t = \pi h \left(r^2 - r_w^2\right)$$

and

$$r = \sqrt{(\Delta V/\Delta t)\ \Delta t/\pi h + r_w^2}$$

$$= \sqrt{1.45 \times 10^{-5}\ \Delta t/h + r_w^2}\ . \qquad (1)$$

Vertical Gravity Anomaly from Deposition in an Annulus

A borehole gravimeter measures only the "vertical" gravity field. An infinitely wide slab of density ρ and thickness h produces a gravitational attraction $g = 2\pi k\rho h$, where k is the gravitational constant. If the slab is infinitely wide, the magnitude of g does not depend on the distance from the slab; however, g has different signs on opposite sides of the slab. Within the slab, g varies linearly with depth, as indicated in Fig. 1. For a density anomaly extending a finite distance from the borehole, g is more complex. The gravitational attraction falls off with distance above and below the center of the anomaly.

We have calculated the observed vertical gravity g for different cylinders with heights corresponding to different aquifer thicknesses and radii at different injection times Δt (Figs. 2-4). Because the curves are symmetrical, only the half above the center of the layer is shown.

The gravimeter is normally used by taking the difference in gravity readings at two depths. The difference (Δg) can be measured with a limit of resolution of about 0.01 mgal (10^{-7} m/s ^{2}). Measurements of g should be made before and after reinjection so that variations in rock density with depth are cancelled. The density anomaly will be apparent if (1), the vertical gravity anomaly is greater than 0.01 mgal and, (2), gravity measurements are taken at intervals small enough to observe the changes in vertical gravity. The times and observation spacings for which the anomaly is detectable can be read from Figs. 2-4. From results shown in Table 2, we conclude that it is possible to detect the gravity anomaly resulting from the deposition of solids around a geothermal well. The visibility of the anomaly depends strongly on the thickness of the aquifer where deposition occurs. The anomalies will be

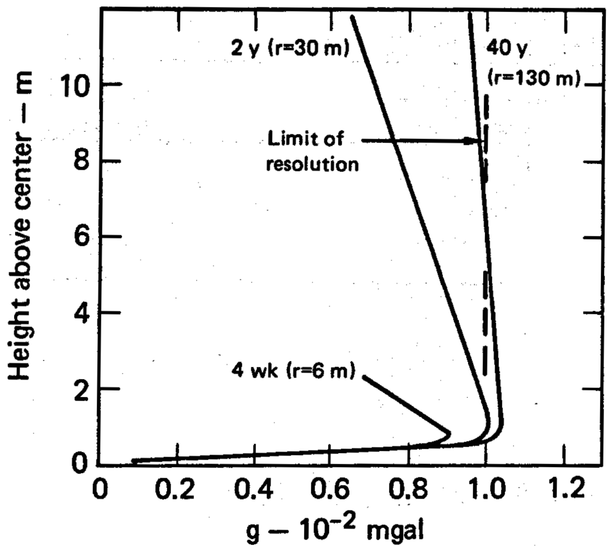

Fig. 2. Vertical gravity above a 1-m-thick layer of deposited solids of density change 0.25 g/cm^3. Different deposition times corresponding to different radii of deposition are shown.

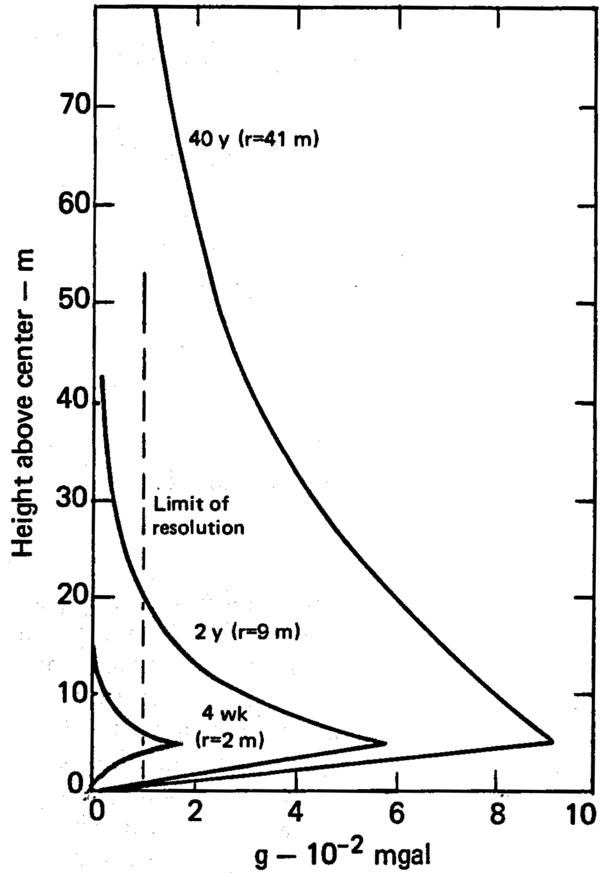

Fig. 3. Vertical gravity above a 10-m-thick layer of deposited solids of density change 0.25 g/cm^3. Different deposition times corresponding to different radii of deposition are shown.

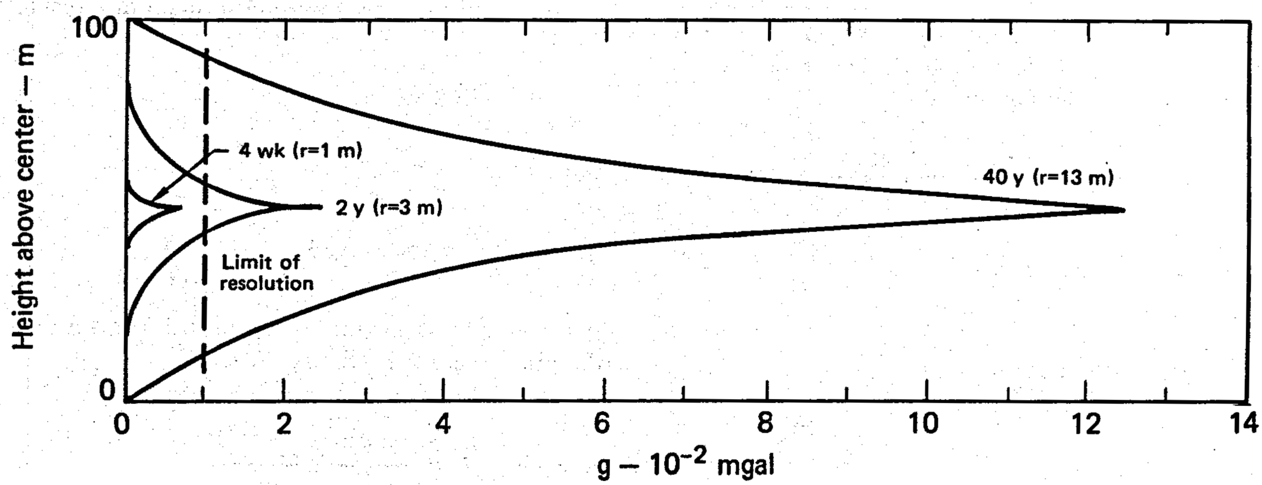

Fig. 4. Vertical gravity above a 100-m-thick layer of deposited solids of density change 0.25 g/cm^3. Different deposition times corresponding to different radii of deposition are shown.

Table 2. Time and observation spacings for detectible anomaly.

Figure No.	Layer thickness, m	Time when anomaly becomes detectible	Observation spacing, m
2	1	Barely detectible	1
3	10	4 wk	2–5
4	100	1 y	5–20

more difficult to see if the density varies smoothly with depth.

Compaction of an Aquifer around a Production Well

Introduction

As water and steam are withdrawn from a geothermal reservoir, the reservoir will likely compact from pore collapse as the pore pressure drops. Compaction may result in eventual subsidence of the ground surface, which can be measured. It is desirable to measure the actual compaction of the reservoir because first, it may take considerable time for the deformation to propagate to the surface, and second, the relationship between reservoir compaction and the surface deformation is not well understood, partly because little data are available on reservoir compaction. Borehole gravimetry may be a way to measure the compaction of an aquifer directly.

Density Change from Compaction of an Aquifer

Consider an aquifer with original bulk density ρ_0 and fluid density ρ_f. We determined the increase in density if an aquifer of thickness h compacts an amount Δh. Assuming that all the volume change is a result of porosity loss, and setting A equal to the areal extent of the aquifer, then

$$h = \frac{V_{rock}}{A} = \frac{V_{matrix} + V_{pores}}{A} ,$$

$$\Delta h = \frac{\Delta V_{pores}}{A} ,$$

and

$$\frac{\Delta h}{h} = \frac{\Delta V_{pores}}{V_{rock}} . \qquad (2)$$

The new density is

$$\rho = \frac{\text{new mass}}{\text{new volume}} = \frac{\rho_0 V_{rock} + \Delta V_{pores}\, \rho_f}{V_{rock} + \Delta V_{pores}}$$

$$= \frac{1}{1 + \frac{\Delta h}{h}} (\rho_0 + \rho_f\, \Delta h/h) . \qquad (3)$$

Therefore, the density change is

$$\Delta\rho = \rho' - \rho_0 = - \frac{(\rho_0 - \rho_f) \frac{\Delta h}{h}}{1 + \frac{\Delta h}{h}} . \qquad (4)$$

For example, the data in Table 3 show the density change needed to produce 1 m of compaction in an aquifer ($\rho_0 - \rho_f = 1.5$ g/cm^3):

Using a Borehole Gravimeter to Measure Compaction

If the measurements are in a horizontally infinite medium of density ρ, the difference in two gravity measurements separated by depth Δz is:

$$\Delta g = 2\pi k \rho \Delta z .$$

If the layer density changes to $\rho' = \rho + \Delta\rho$, then a second gravity survey would result in an difference:

$$\Delta g' = 2\pi k \rho' \Delta z,$$

and

$$\Delta = \Delta g' - \Delta g = 2\pi k \Delta\rho \Delta z.$$

If z is chosen as the initial aquifer thickness h then the gravity gradient change Δ is:

$$\Delta = 2\pi k \Delta\rho h = \frac{2\pi k \Delta h\, (\rho_0 - \rho_f)}{1 + \Delta h/h}$$

$$\cong \frac{6.3 \times 10^{-4}\ \text{mgal}}{\text{cm of compaction}} . \qquad (5)$$

measurement is saturated, then $\phi_A = 0$, and

$$\rho_B - \rho_B' = \phi_A'(\rho_W - \rho_A), \tag{13}$$

and if $\rho_w \approx 1$, then $\rho_A \simeq 0$ (for ordinary gas wells) and

$$\rho_B - \rho_B' = \phi_A', \tag{14}$$

the gas-filled porosity.

At worst, if ϕ_A is unknown, we would calculate a minimum value for ϕ_A'. Also if we measure the water content near the hole, (ϕ_W) with a properly calibrated neutron log, Eq. (11) gives us the true water content.

In the absence of the effects of structure and stratigraphy (for which corrections may be required[10]) gravimetric density is accurate to ~0.02 g/cm^3. A gamma-gamma density log is accurate to ~2% under good conditions (smooth hole, good corrections for mudcake, etc.), which often will be ~0.05 g/cm^3. Averaging over the interval used for borehole gravimetry at a logging speed of ~7 m/min is equivalent to taking the mean of 25 samples, which should make the error of the mean ~0.01 g/cm^3, neglecting systematic errors. The error in the difference will be ~0.025 g/cm^3.

Thus, assuming 10% porosity, we can likely distinguish between 25% and 50% saturation, or in general, observe 2.5 vol% water.

Stratigraphy and Structure

From Refs. 1-12, we can conclude that with the aid of a gravimeter, it is often possible to infer the existence of dipping beds or subsurface structures that cannot be detected from a single borehole by other means. Use of the gravimeter, therefore, can often lead the geologist to new interpretations of old data or help him recognize that data from seismic surveys or boreholes are needed to fully understand the geologic situation.

PROBLEMS IN DESIGNING A GRAVIMETER FOR HIGH-TEMPERATURE WELLS

Most conventional logging tools are limited to operation in wells below those temperatures at which critical components fail. For a gravimeter, the temperature limit is limited by the necessity to maintain a constant temperature in the sensing element for precise results. The newest instruments are heated to 126°C. For geothermal and deep gas wells, the temperature-regulating system of the gravimeter cannot work because the outside temperature is higher than that of the gravimeter. Therefore, it is necessary to insulate the gravimeter and use a heat sink to absorb the heat that enters the insulating canister and that is generated by the gravimeter.

It is possible to cool a gravimeter for its use in a high-temperature well. The LLL Geothermal Energy Program commissioned EG&G [18] to study the feasibility of adapting insulation canisters and temperature control systems successfully used in the LLL Rio Blanco Program [19] to the gravimeter. Unwanted heat is made to vaporize water, and the resultant temperature- and pressure-controlled water vapor is collected in a calcium oxide chamber.[20] EG&G concluded that a suitable instrument canister can extend the temperature limits of existing gravimeters from 125 to 350°C. The complete package could be designed for use in wells with inner diameters of 18 cm or more. A simpler package with a heat sink that works on heat of fusion might also be satisfactory.

Another problem in designing a high-temperature gravimeter is that logging cables cannot withstand temperatures in the hotter geothermal wells, nor can they resist the corrosive brine found in most geothermal wells. Recent developments suggest that a temperature- and corrosion-resistant cable can be obtained. A cable made with seven conductors, each surrounded by ceramic insulation and an Inconel 600 sheath, is commercially available. The Bureau of Mines [21] recently found that some Inconel alloys are sufficiently corrosion-resistant for use as cable armor. Other corrosion-resistant materials (such as Hastalloy C-276) are available that may be suitable for logging cables, but the cost of such a prototype cable made from this alloy would be an order of magnitude higher than cables made from Inconel.

Table 3. Density change $\Delta\rho$ vs thickness h needed to produce 1 m compaction.

h	10 m	30 m	100 m	300 m	1 km
$\Delta\rho$	0.17	0.05	0.015	0.005	0.0015

Measurement Uncertainty

Measurement uncertainty in Δ comes from the resolution of the gravimeter and uncertainty in depth location. The gravity difference can be measured to approximately 0.01 mgal, and the second difference Δ would have an uncertainty of approximately $\pm$ 0.014 mgal. The uncertainty in the depth interval would strongly depend on the measuring method. For this example, we used an uncertainty of 0.01 Δz or 1 m, whichever is less. The uncertainty in Δ is shown in Table 4. The data in this table indicate that compaction of about one meter can be observed if it occurs over an infinitely wide aquifer. Measurement resolution can probably be improved by taking many measurements within the aquifer.

Finite-Size Reservoir

We can calculate the reduction of the gravity effect for a cylinder of finite radius. For measurements separated by the aquifer height (h), the gravity effect is not decreased significantly if the radius is 5h. For any distribution of compaction within a reservoir, the resulting gravity effect can be easily calculated.

Gas-Filled Porosity

In many situations, we would like to know the amount of gas-filled porosity. A reasonable method of doing this, practiced in the gas industry,[17] is to compare the density measured by near-hole logs, such as gamma-gamma density, to that measured with a gravimeter. In some geothermal wells, removal of water can reduce the pressure enough to cause some of the remaining water to flash to steam. For these wells, one can estimate steam-filled porosity by comparing pre- and post-production gravimeter data as follows. When a hole is drilled with mud, water is injected into the medium. The value of ρ_B, the bulk density measured by the gamma-gamma density log (even when corrected for the anomalous electron density of water), is not representative of the formation because the range is only ~20 cm.

Table 4. Uncertainty in Δ and Δh for compaction measurements.

	10 m	30 m	100 m or larger
Uncertainty in Δ, mgal	0.015	0.023	0.064
Uncertainty in Δh, cm	24	37	45

Let the average density over an interval of 10 to 20 m, measured by a gamma-gamma density log or the first gravity run be ρ_B:

$$\rho_B = \rho_G(1 - \phi_w - \phi_A) + \phi_w\rho_w + \phi_A\rho_A, \qquad (6)$$

where ϕ_w and ϕ_A represent the volume percent of water and gas in the invaded zone or the preproduction medium and ρ_G, ρ_W and ρ_A are the grain, fluid, and gas densities. We then measure the same interval with a borehole gravimeter whose range is many tens of meters which should give a true value of bulk density, ρ_B':

$$\rho_B' = \rho_G(1 - \phi_W' - \phi_A') + \phi_w'\rho_W + \phi_A'\rho_A, \qquad (7)$$

where the symbols with primes are the values far from the well or at later times.

If we assume that the medium is homogeneous, the total porosity is the same either near or far from the hole, or before and after production so that:

$$\phi_w + \phi_A = \phi_w' + \phi_A'. \qquad (8)$$

Subtracting Eq. (7) from Eq. (6),

$$\rho_B - \rho_B' = \rho_G(-\phi_w - \phi_A + \phi_w' + {}_A') + (\phi_w - \phi_w')\rho_W + (\phi_A - \phi_A')\rho_A, \qquad (9)$$

$$\rho_B - \rho_B' = (\phi_w - \phi_w')\rho_W + (\phi_A - \phi_A')\rho_A, \qquad (10)$$

and from Eq. (8),

$$\phi_w - \phi_w' = \phi_A' - \phi_A, \qquad (11)$$

so that

$$\rho_B - \rho_B'(\phi_A' - \phi_A)(\rho_W - \rho_A). \qquad (12)$$

If the medium near the hole or during the initial

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SUMMARY AND CONCLUSIONS

Borehole gravimetry is a unique well-logging method because it is sensitive to material far from the well. By comparing densities measured with conventional logging tools and with a gravimeter, we can often estimate variations in density away from the wellbore. Because gravimetry is effective in cased wells, and because repeated measurements can detect small changes in density with time, gravimetry is an effective way to study changes in density caused by production or injection in wells. Geothermal energy production requires high flow rates of water, so that the potential for plugging or compacting the reservoir is great. Furthermore, geothermal wells usually have relatively large diameters, allowing the use of a relatively large logging tool. For these reasons, borehole gravimetry is particularly applicable to the study of geothermal production problems. To be useful in geothermal wells, gravimeters must be adapted to operate at high temperatures in corrosive environments. It appears that this adaptation is feasible and would be worthwhile.