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Gravity Changes at Wairakei Geothermal Field, New Zealand

ABSTRACT

Measurements of the value of gravity at 50 bench marks at Wairakei Geothermal Field, New Zealand, show that differences of up to 0.5 mgal have occurred between 1961 and 1967 and up to 1 mgal between 1967 and 1968. These differences, corrected for known changes in elevation, are interpreted as reflecting the net mass of water lost from the aquifer. The net loss between 1961 and 1967 is determined to be about 2.9×10^{14}g and hence only about 20 percent of the water drawn off was replaced, but between 1967 and 1968 there was little or no net loss.

INTRODUCTION

The Wairakei Geothermal Field is one of the larger hydrothermal areas in the active volcanic belt of New Zealand (Fig. 1). The geothermal field is underlain by a near-flat, Quaternary, acid volcanic rock sequence (Grindley, 1965) and the bulk of the steam production is obtained from a thick aquifer of pumice breccias (Waiora Formation) that is capped by lacustrine shales (Huka Falls Formation).

Since the opening of the Wairakei Geothermal Power Scheme in 1950 more than 5.6×10^{14}g of water (both liquid and gas phases) have been drawn from the ground for generating electricity, neglecting the small amount discharged into the atmosphere from natural geysers and fumaroles nearby. Extensive ground subsidence in the area was revealed by repeated releveling of bench marks and drew attention to the consequences of this substantial mass loss. Precise gravity measurements were made in August 1961, followed by remeasurements in April 1967 and May 1968 to see whether or not this mass loss could be detected and, if so, from what areas it was being drawn and to what extent it was being replaced. No previous measurements of gravity changes resulting from the exploitation of a geothermal field appear to have been made, although gravity changes resulting from volcanic eruptions (Iida and others, 1952) and earthquakes (Barnes, 1966) have been studied.

GRAVITY MEASUREMENTS

Gravity measurements were made on concrete bench marks in and about the Wairakei Geothermal Field using North American gravimeter AG1-96 (1961 survey) and La Coste Romberg gravimeter G-106 (1967 and 1968 surveys). The measurements were made under optimum ground-noise conditions, and a looping technique (Nettleton, 1940) was used to minimise instrumental drift errors. The gravimeter readings were corrected for instrument drift and for changes in the gravitational attraction of the sun and moon. The instrument drift correction was obtained from the quadratic curve of best fit (least-squares method) through the differences in gravity measured at repeated stations. The correction for changes in the gravitational attraction of the sun and moon was that of Longman (1959) multiplied by 1.2 (to account for deformation of the Earth). All computations were made by a digital computer and the measurements were reduced in terms of a base station on Taupo Fundamental bench mark, 7.2 km from Wairakei, considered to be outside the area affected by mass changes associated with the Wairakei Geothermal Field. Gravity measurements could not be made at bench marks in the vicinity of the uncontrolled "rogue" bore number 204 because of continuous strong microseisms.

GRAVITY CHANGES

In many cases there are differences in the value of gravity at the same point between 1961, 1967, and 1968 that are much greater than the standard error of the measurements. These differences can result from topographic changes adjacent to the points of measurement,

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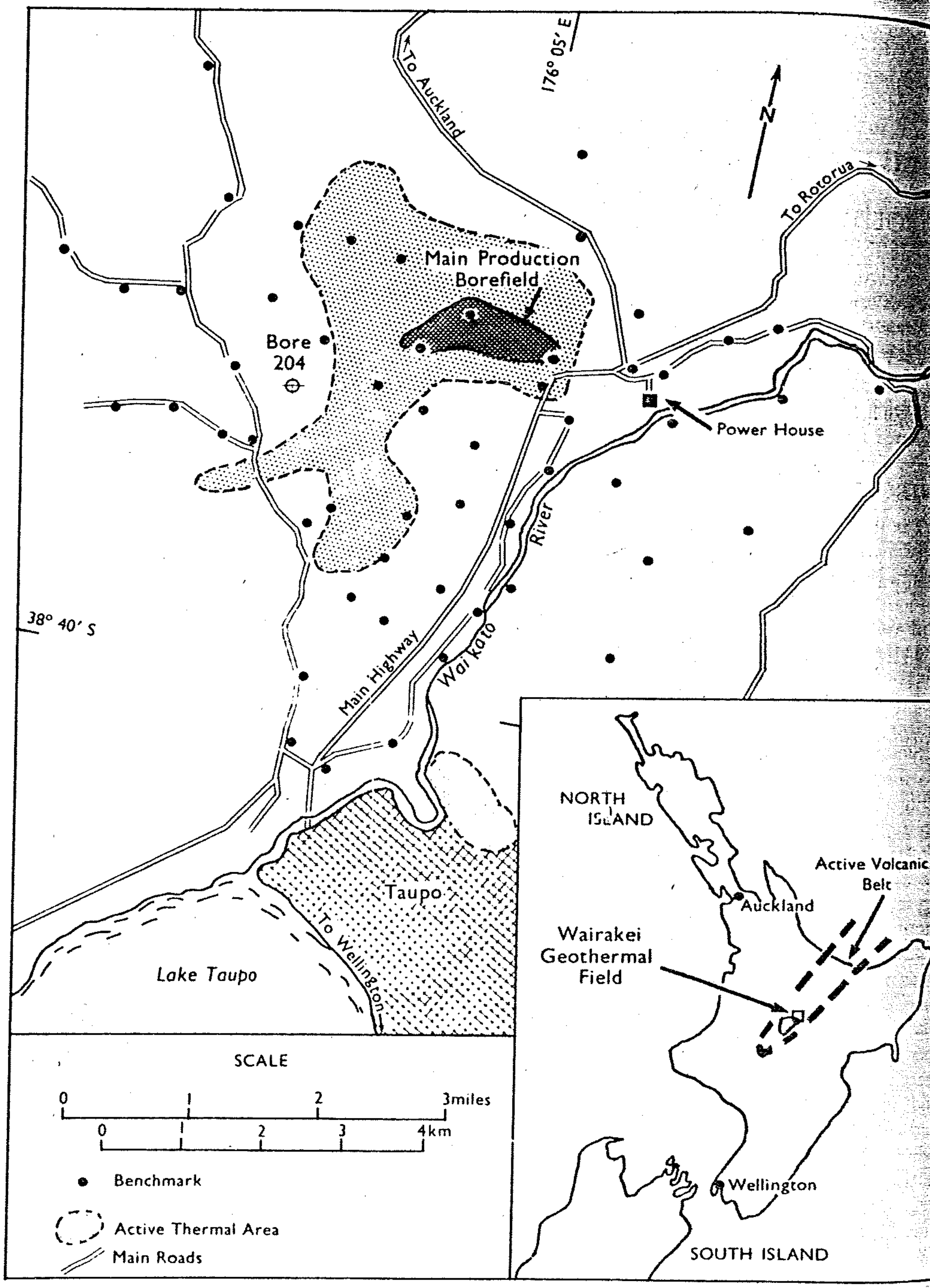

Figure 1. Location of Wairakei Geothermal Field, New Zealand, and bench marks used in the surveys.

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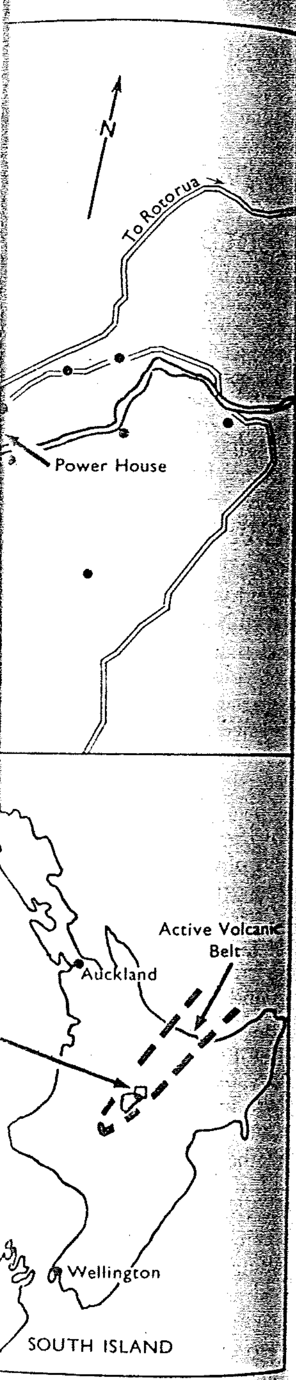

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...al changes in the ground-water level, changes ... the elevation of the points of measurement ...ative to one another or to the base station, ...d a net loss of water from the aquifer.

Small topographic changes associated with ...velopment of the geothermal power scheme ...ve occurred adjacent to a few points, but in ...l cases the resulting gravitational change is ...timated as being less than or equal to 0.01 mgal.

Measurements of water levels in 14 shallow ...ill holes in the Wairakei area between 1961 ...d 1966 showed that there was no continuous ...se or fall of ground-water level, but local ...ariations having an average fluctuation of 2 m ...ccurred, which might cause variations of about ...03 mgal. The bench marks were levelled in 1956, 1961, 1962, and 1966, and graphs of change of level with time for each bench mark have been drawn from which differences in elevation between 1961, 1967, and 1968 were determined (Figs. 2a, 3a). Bench-mark levels for April 1967 and May 1968 had to be obtained by extrapolation of the level-change graphs, but individual values are unlikely to be in error by more than 0.03 m. The bench marks were levelled in terms of bench mark A93, which was not a suitable gravity base station, and unfortunately Taupo Fundamental bench mark was not included in these levellings. Bench marks close to the Taupo Fundamental gravity base show little or no change in elevation relative to A93, however, and it has been assumed that elevation changes relative to Taupo Fundamental are equal to those relative to BM A93.

Assuming that no horizontal mass change took place in the subsidence, the gravity change would be approximately 0.31 mgal/m, the normal "free-air" gradient. Gravity differences for the periods 1961 to 1967 and 1967 to 1968 corrected for the elevation changes using a factor of 0.31 mgal/m are shown in Figures 2b and 3b. The mean standard error of the corrected gravity differences between August 1961 and April 1967 is 0.04 mgal and 0.03 mgal between April 1967 and May 1968. Contouring the gravity differences involved adjusting individual values by up to 0.1 mgal to obtain smooth contours. These corrected gravity differences are likely to represent the net mass differences in the aquifer of the Wairakei hydrothermal field for the periods 1961 to 1967 and 1967 to 1968.

The removal of a known mass of water from an aquifer of uniform thickness can be approximated by a change in density σ of a cylindrical disc for which the corresponding gravitational change can be computed. The change is given by:

$$\sigma = m/r^2h,$$

where m = mass of water withdrawn, r = radius to which withdrawal occurs, and h = thickness of aquifer. This assumes a uniform high permeability within a radius r about a central point and low permeability beyond.

At Wairakei the Waiora Formation has an average thickness of 0.5 km and over most of the geothermal field is at a depth of about 0.2 km. Using the cylindrical disc model and taking the measured mass loss of 3.6×10^{14}g for the period August 1961 to April 1967, I computed the change in gravity at the surface for various values of r (Fig. 4). If the water drawn off came solely from that portion of the aquifer below the main production bore field and was not replaced, a maximum gravity change of about −2.7 mgal would be expected. If the water was completely replaced there should be no gravity change, and if there was partial replacement or the water was extracted from a greater volume there would be corresponding gravity changes smaller than −2.7 mgal.

The gravity differences between August 1961 and April 1967 corrected for changes in elevation (Fig. 2b) show that:

(1) in all but one case there was a decrease in the value of gravity with a maximum change of −0.51 mgal;
(2) the greatest decrease in gravity measured occurred within the main production bore field and the gravity differences become smaller farther away from the bore field;
(3) the decrease in the value of gravity is not symmetrical about the main production bore field but extends in a westerly direction, roughly coincident with the level changes.

It follows from Gauss's potential theorem that the total anomalous mass m (in this case the net loss of water) can be determined by integrating the gravity anomaly (in this case the gravity differences) over the plane of measurement without assuming or calculating the shape and depth of the source (Hammer, 1945; Parasnis, 1962). The integration can be approximated by a summation

$$m = \frac{1}{2\pi G} \Sigma \Delta g \Delta s$$

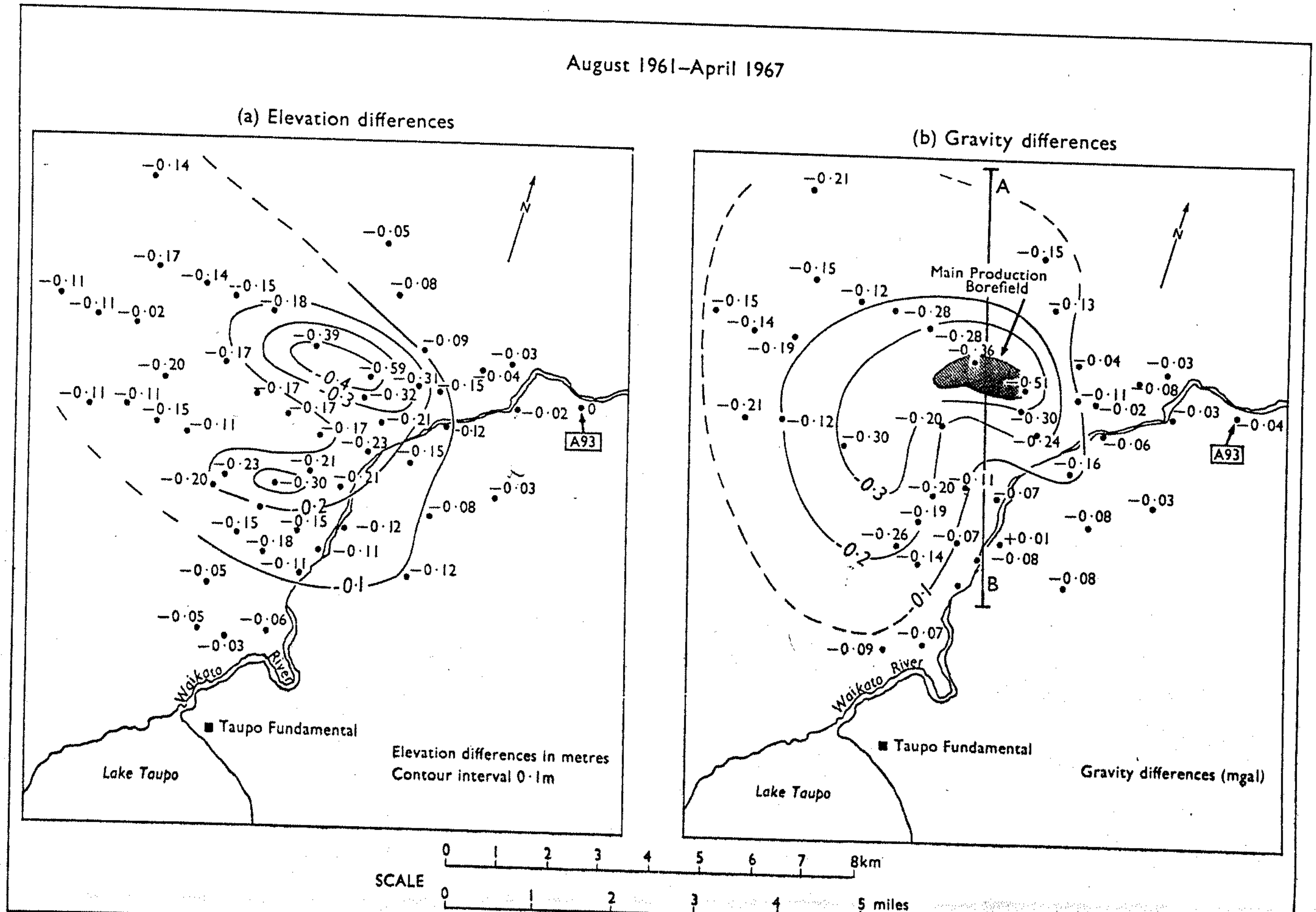
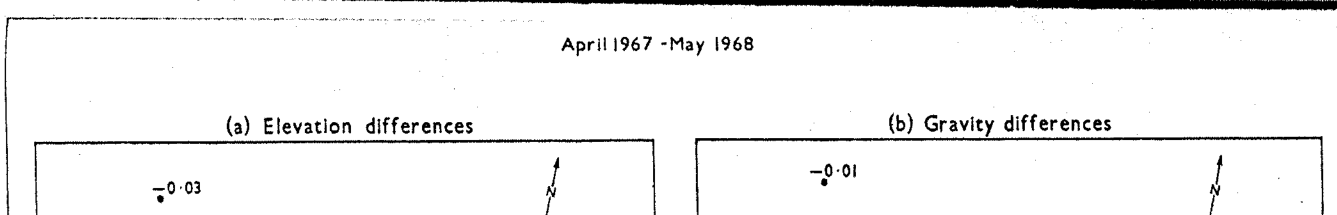
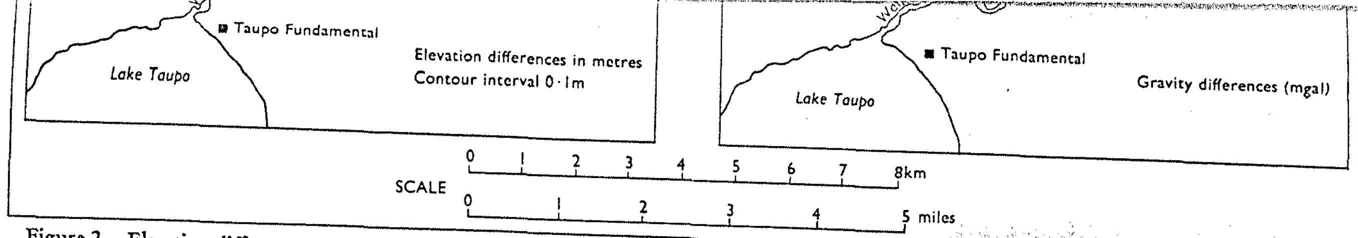


Figure 2. Elevation differences and gravity differences corrected for elevation differences, between August 1961 and April 1967, Wairakei Geothermal Field, New Zealand.





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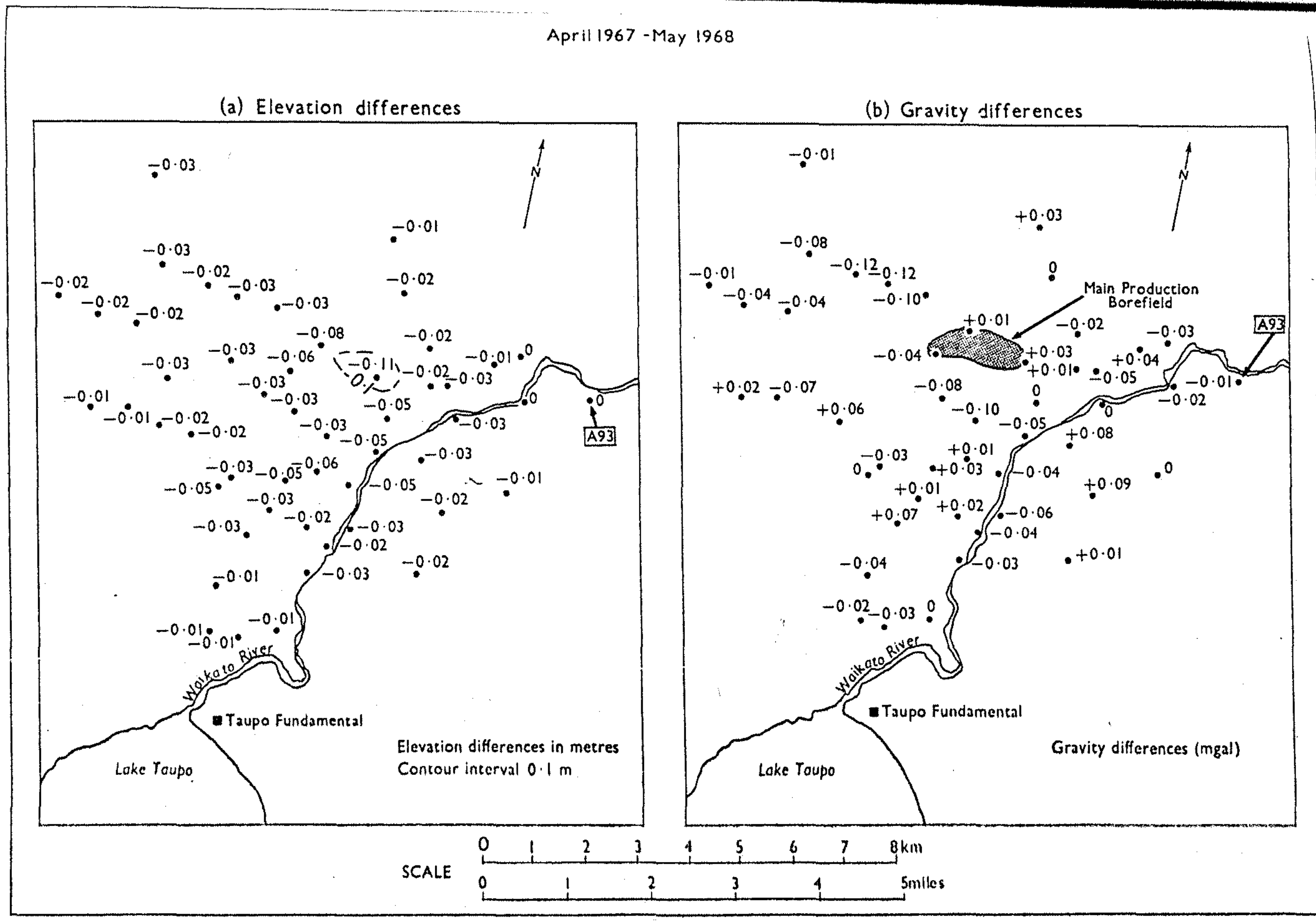

Figure 3. Elevation differences and gravity differences corrected for elevation differences, between April 1967 and May 1968, Wairakei Geothermal Field, New Zealand.

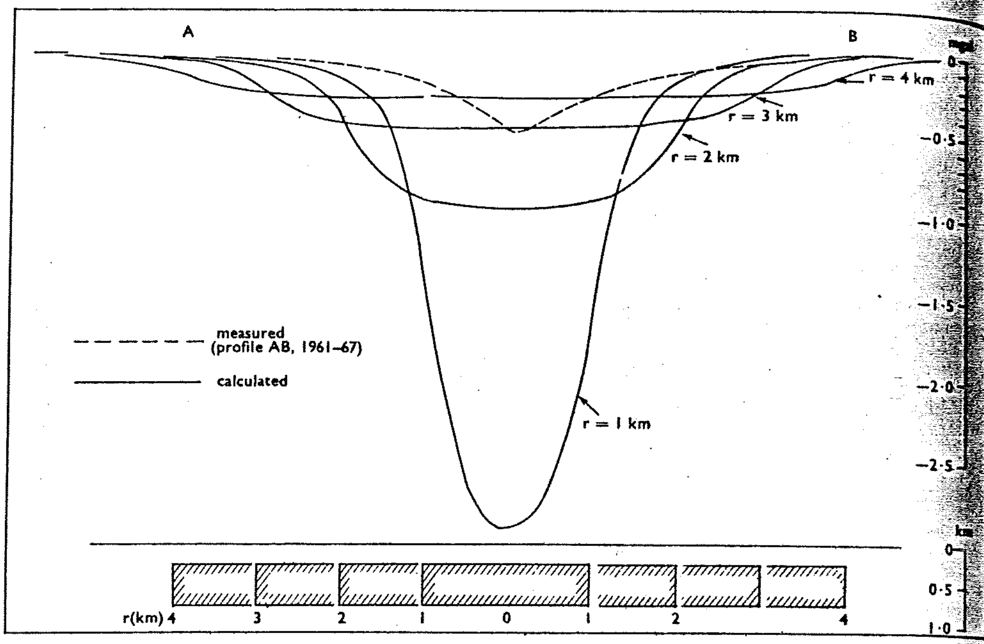

Figure 4. Gravity profiles over cylinders of different radius representing the mass loss between August 1961 and April 1967 (3.6 × 10^{14}g).

where G = universal gravitational constant and Δg = local gravity anomaly associated with an areal element Δs of the plane P.

The sum of the gravity differences between 1961 and 1967, obtained from the contours in Figure 2b, is about −12 mgal km², which corresponds to an anomalous mass of −2.9 × 10^{14}g or 80 percent of the mass of water actually withdrawn. This means that between August 1961 and April 1967 about 20 percent of the water removed from the aquifer was replaced. However, this value is only approximate because of the errors involved in obtaining the summation, as discussed by Hammer (1945), and the uncertainty of the 0.1-mgal change contour west of the main production bore field.

Despite a mass draw-off of 0.5 × 10^{14}g between April 1967 and May 1968, the corrected gravity differences (Fig. 3b) are generally small, and no consistent pattern can be seen except for a small area of decrease in gravity west of the main production bore field. This suggests that either the water is being drawn from a much greater area than was surveyed or, what is more likely, the mass inflow equalled the mass draw-off. Between December 1967 and April 1968 about 60 percent of the main

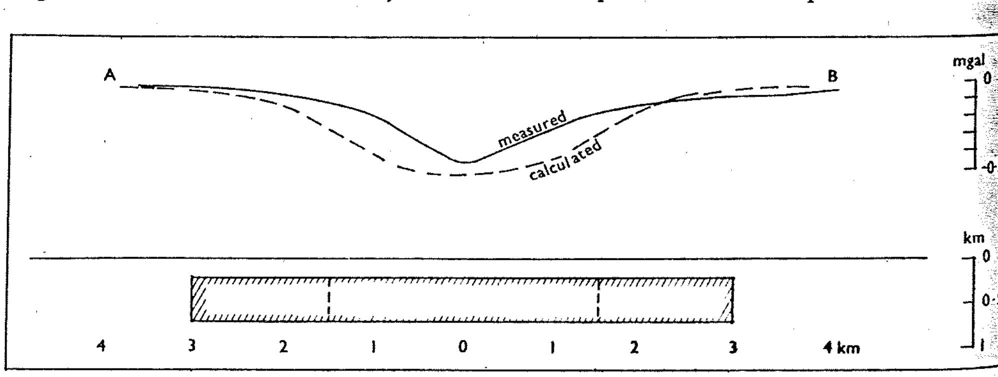

Figure 5. Comparison of gravity differences (August 1961 to April 1967) along profile AB with the gravity profile over a double cylinder model.

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duction bore field was shut down, and this ould have assisted recharging.

The asymmetry of the gravity differences etween August 1961 and April 1967 suggests at the aquifer is not of uniform effective orosity and that either:

(1) water is being drawn from areas west of the main bore field in preference to the east; or
(2) the aquifer has high effective porosity in areas east of the main bore field, allowing rapid replacement of water drawn from those areas.

Measurements made in drill holes have shown that east of the main bore field the aquifer pressures do not respond to pressure changes originating in the main bore field as do those to the west, indicating low effective porosity to the east. This would suggest that water has been drawn from western areas at a greater rate than it has been replaced. There does not appear to be any geological explanation for this.

A comparison of a section AB (Fig. 2b) through the measured gravity differences for the period 1961 to 1967 with the theoretical curves is given in Figure 4. The measured anomaly profile is difficult to reconcile with those of the various theoretical models, but a closer fit is obtained if a double cylinder model (Fig. 5) is taken, in which half the mass loss comes from an inner cylinder of radius 1.5 km and half from an annulus of inner radius 1.5 km and outer radius 3 km. This suggests that in any one direction the net amount of water lost is an inverse function of the distance from the centre of the bore field.

The mean temperature between 0.3 km and 0.6 km beneath the geothermal field has been averaged for all drill holes at two-monthly intervals since 1953, and in the period 1955 to 1962 the temperature in that zone has remained within the range 240° to 250° C (Grindley, 1965) in which water has a density of about 0.8 g/cm^3 (Forsythe, 1954). Taking this value for density, the water lost (net) from the geothermal system in the period August 1961 to April 1967 would have a volume of about 4×10^{14} cm^3. The volume of surface subsidence between August 1961 and April 1967, obtained by integrating the elevation differences shown in Figure 2a over the area, is about 1×10^{13} cm^3, which is only about 3 percent of the volume of water lost from the geothermal system.

CONCLUSIONS

The gravity method can be used to monitor the net mass loss from a geothermal field under exploitation and can also give an indication of the area from which the water has been drawn.

ACKNOWLEDGMENTS

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