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RECHARGE AT BROADLANDS (OHAAKI) GEOTHERMAL FIELD 1967-1983

DETERMINED FROM REPEAT GRAVITY MEASUREMENTS

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ABSTRACT

A revision of previous repeat gravity measurements, made in 1967 and 1974, shows that for the period 1967-1974 (during which time drawdown tests were made) negative gravity differences of about -0.8 to -1.2 µN/kg amplitude occurred over all of the field. Simple modelling suggests that these differences were the result of a net mass loss of about 24-35 x 10^9 kg, and hence there was little or no mass recharge.

Data from a recent survey made in 1983, show that for the period 1974-1983 (during which time there was a reduced amount of mass withdrawal) positive gravity differences of about 0.4 µN/kg amplitude occurred in most parts of the field. Modelling suggests these differences resulted from a net mass gain of about 11 x 10^9 kg, and hence total natural recharge was about 25 x 10^9 kg.

During both periods there was mass loss from a large area west of the field, the cause of which is unknown. Elsewhere, outside the field, there have been no significant mass changes.

INTRODUCTION

Precise gravity measurements were made in and around Broadlands Geothermal Field (Fig. 1) in 1967 and 1974 to determine net mass changes and the amount of recharge into the field following test discharges in the late 1960's and early 1970's. The results of these measurements were equivocal, but suggested that at least 50% of the 35 x 10^9 kg of water (both liquid and gas) withdrawn was replaced (Hunt and Hicks, 1975; Hunt, 1977). Between 1974 and 1983 only a further 14 x 10^9 kg of water was withdrawn (Fig. 2) and another gravity survey was made in April-May 1983 to determine the resulting mass changes.

This paper gives revised results for the gravity measurements for 1967-1974, together with some preliminary results for 1974-1984; a full account of the methods used and interpretation of the results will be published elsewhere.

GRAVITY MEASUREMENTS

The gravity measurements were made on permanent, concrete benchmarks with a La Coste and Romberg G-type gravity meter. In the 1974 and 1983 surveys most benchmarks were occupied three times, and a looping technique used to minimise instrument drift errors and to identify tares and blunders. Gravity values were computed using the method described by Woodward (1982a, b) which is a distinct improvement over that used previously because all the observations in a survey are treated as a set, not just each days measurements. All values were computed relative to benchmark H346, situated on the south-west boundary of the field (Fig. 1).

GRAVITY DIFFERENCES

Differences in the value of gravity at a benchmark, between surveys, may be caused by changes in elevation of the benchmark and in near-surface groundwater level in addition to net mass changes in and near the geothermal reservoir. Since the aim of the gravity measurement is to determine mass changes in the reservoir, the affect. of other changes must be determined and allowed for if possible.

Some ground subsidence has occurred within the field, mainly in the Ohaaki area [Hunt and Hicks, 1975; S. Currie, pers. comm.), and mostly between 1968 and 1972 when the rate of mass withdrawal was greatest. Elevation changes, relative to that of the gravity base (H346), were computed for the periods 1967-1974 and 1974-1983 using data provided by Ministry of Works and Development, and the corresponding gravity effect calculated using the normal 'free-air' gradient of 3.086 µN/kg per metre of subsidence. The largest change at a gravity benchmark was a subsidence of 0.160 m at 8336 in the Ohaaki area (Fig. 1) for the period 1967-1974; this corresponds to an increase in gravity of about *0.5* µN/kg. The gravity effects of most elevation changes however are less than 0.2 µN/kg. Gravity differences corrected for the effect of subsidence are referred to as corrected gravity differences.

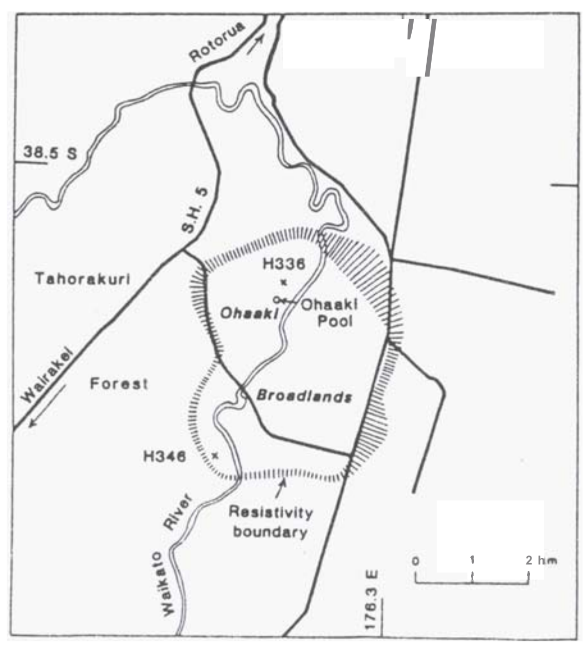

Fig. 1: Map showing the location and extant of the Broadlands (Ohaaki) Geothermal Field, and the Ohaaki and Broadlands parts of the Field. The hatched zone indicates the resistivity boundary of the field (from Risk, et al.)

Measurements of shallow groundwater levels in the Broadlands area have been made infrequently since 1967 by M.W.D. Most measurements are in the Ohaaki area and few were made prior to 1979. The data available indicate that there have been no significant (> 2 m) changes of groundwater level, except in the central part of the Ohaaki area during the period 1967-1974; the effect of such changes in this area will be considered later.

Other changes which might cause gravity differences include changes in topography, changes in temperature of the groundwater (Allis and Webber, 1984), and uncertainties in the calibration of the gravity meter; the effects of these have been investigated and found to be negligible (<0.2 μN/kg).

Since the benchmark used as the gravity base lies on the boundary of the field the question arises as to whether gravity values at this point (and hence the gravity differences) have ken influenced by mass changes within the field. Assuming that no large or extensive mass changes occur outside the field a rough check on this can be made by examining the mean value of corrected gravity differences at benchmarks 'outside the field. For the period 1967-1974 the mean value is -0.06 (± 0.43) μN/kg, and for 1974-1903 it is -0.09 (± 0.36) μN/kg (a negative difference indicates a decrease in observed gravity with time). These values are small, suggesting that the gravity base has not been influenced significantly by mass changes in the field. However, as will later be shown, some areas of negative gravity difference do occur outside the field, but if these are discounted the mean values lie close to zero.

CORRECTED GRAVITY DIFFERENCES

corrected gravity differences for the period 1967-1974 are not as reliable as those for 1974-1983 because, in many instances, only one gravity observation was made during the 1967 survey, rather than three during the 1974 and 1983 surveys. The mean standard error of the differences is 0.25 μN/kg for the period 1967-1974 and 0.18 μN/kg for 1974-1983, but a comparison of the differences at adjacent benchmarks suggests that the accuracy of the differences is probably about ±0.4 μN/kg. Because the differences are generally small (<1 μN/kg), and variable, it is impossible to contour them with confidence, however, the differences for both periods show simple and consistent patterns (Fig. 3).

1967-1974

1. Negative differences occur over the whole of the field with a maximum amplitude of about -1 μN/kg.
2. Gravity differences in the Ohaaki area are similar to those in the Broadlands area (mean of 12 Ohaaki values is -0.7, that of 10 Broadlands values is -0.6 μN/kg).
3. Negative differences, of smaller amplitude, extend at least 2 km west of the field in the Tahorakurf Forest area.

1974-1983

1. Positive differences occur in most parts of the field and extend about 1 km beyond the field boundary to the north and south. The amplitude of the positive differences is about +0.4 μN/kg.
2. Gravity differences in the Ohaaki area are again similar to those in the Broadlands area (mean of 18 Ohaaki values is +0.3; that of 13 Broadlands values is +0.3 μN/kg).
3. Negative differences occur in a north-south trending belt west of the field in the Tahorakuri Forest area.
4. Negative differences of up to -0.5 μN/kg amplitude also occur in the north-east part of the field near BR1.

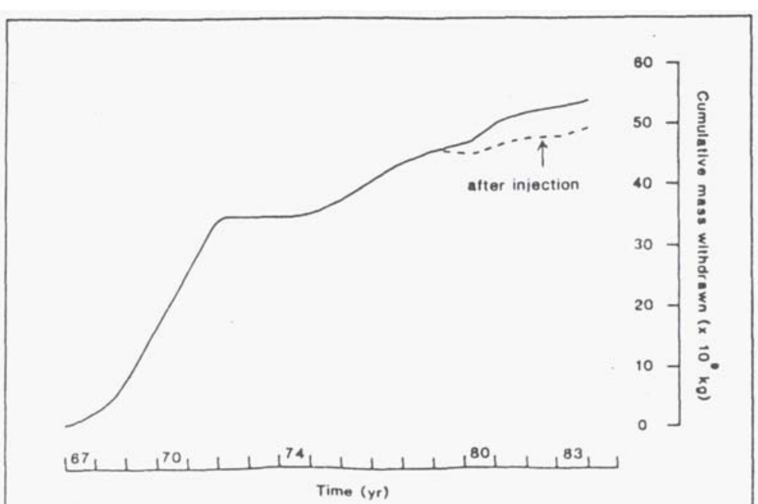

Fig. 2: Cumulative mass withdrawn from Broadlands Geothermal Field. Note the high rate of withdrawal between 1968 and 1971, compared with that subsequently.

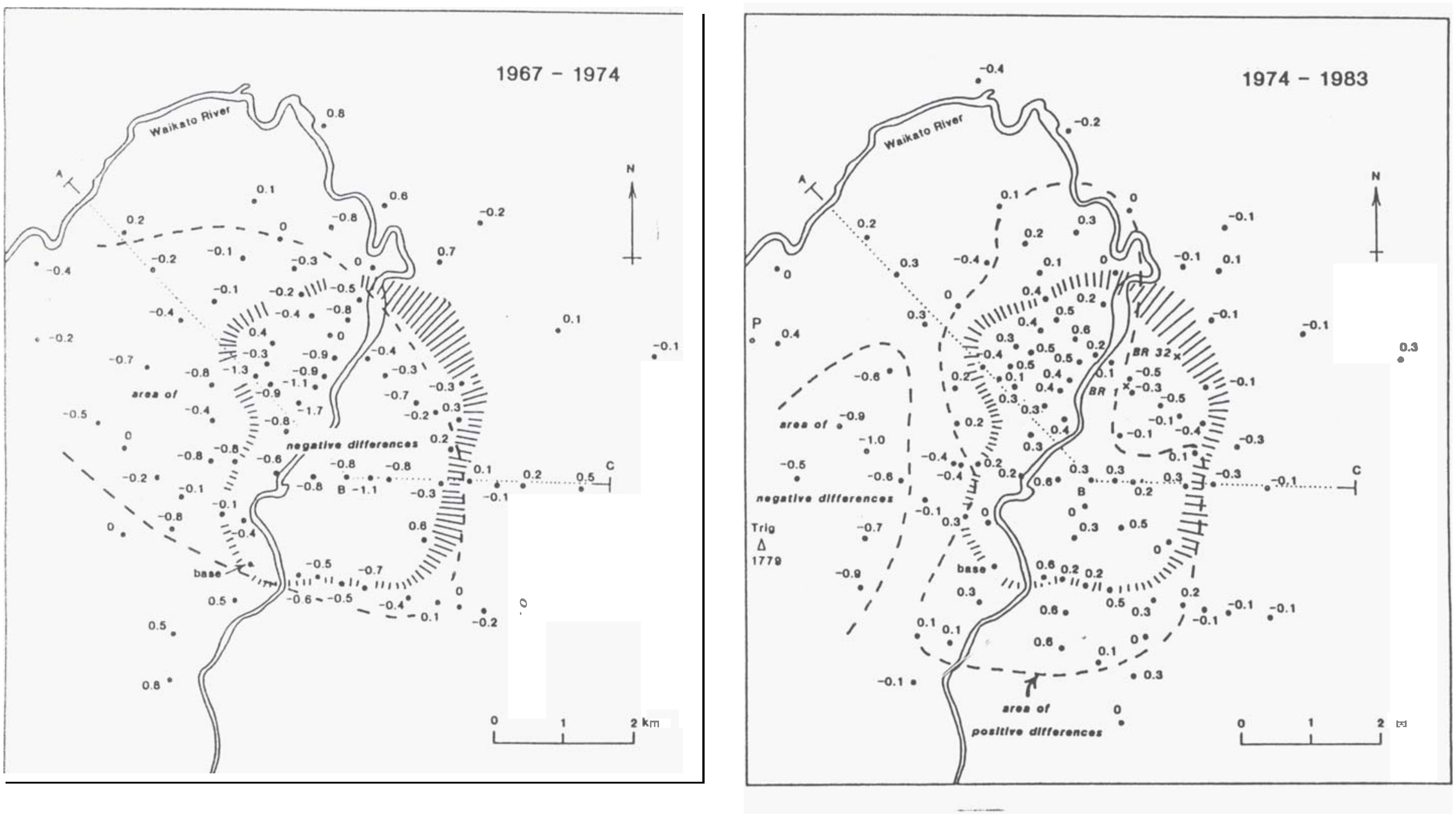

Fig. 3: Corrected gravity differences (µN/kg) at Broadlands for the periods 1967-1974 and 1974-1983 (1 µN/kg = 0.1 mgal = 100 µgal). Negative values indicate a decrease in gravity. The dotted line indicates the position of the profile A-B-C given in Fig. 5. The hatched zone indicates the resistivity boundary. Crosses indicate the positions of drillholes BR1 and BR32.

MASS CHANGES 1967-1974

During this period, which includes that of greatest mass withdrawal (Fig. 2), the corrected gravity differences are mainly negative indicating a net mass loss. The negative differences occur not only over the whole area of the field, but also extend a considerable distance (2 km) west of the field (although here they are of much smaller magnitude).

Because the corrected differences are small (compared to, say, those measured at Wairakei), and difficult to contour, it is impossible to determine accurately the net mass loss using Gauss's Theorum (Hunt, 1970). However, a rough estimate of the net mass loss can be made by examining the differences along a profile through the field (Line A-B-C, Fig. 5). Differences along this profile have a broad minimum with an amplitude of between -0.8 and -1.2 µN/kg (Fig. 5). Assuming that the net mass loss from the field can be modelled by cylinders of various sizes and density contrast, the gravity effects of cylinders representing likely models for withdrawal were computed (Reilly, 1969) on a trial and error basis. Constraints placed on the models were that mass withdrawal occurred over an area of radius at least 15 km (i.e. over most of the field) but not from depths less than 500 m (top of the production zone). Good fits between the measured differences and the computed effects were obtained for models with radius 15 km, 200 m thick, with upper surface at a depth of 500 m, and having density contrasts of between -16 and -25 kg/m^3 (Fig. 5). These values of density contrast correspond to net mass losses of 24-35 x 10^9 kg. Other models having smaller density contrast (i.e. less net mass loss), or greater horizontal extent, did not have sufficient gravity effect to match the observed gravity differences.

Data from shallow drillholes adjacent to bores BR2, 4, 9 and 11 (Fig. 4), together with water level measurements in the Ohaaki Pool (Fig. 1), have shown that the shallow groundwater level in the central part of the Ohaaki area has dropped by up to 7 m but no gravity measurements were made in this part of the area. The greatest difference (-1.7 µN/kg) occurs at BM H340 near BR19, in the south-west part of the Ohaaki area, and several differences at nearby benchmarks are more than -0.8 µN/kg which suggests that part of these measured differences may be due to the drop in groundwater level. However, the scarcity of gravity and water level data makes it difficult to determine quantitatively what proportion of the measured differences is due to ground water level changes, and how much is due to net mass loss from the reservoir; for the purposes of this paper the effects of groundwater level changes in the Ohaaki area have therefore been ignored.

The simple modelling described above suggests that between 1967 and 1974 about one third or less of the 35 x 10^9 kg of fluid removed from the Broadlands field was replaced. This result differs from those previously given (Hunt and Hicks, 1975; Hunt, 1977), however, it must be realised that the total mass withdrawn during this period is small relative to that taken during a similar period from Wairakei or Kawerau, and the associated gravity differences are barely recognisable. Furthermore, the revised differences given here suggest that withdrawal occurred over a much larger area than previously considered. The new result suggests the behaviour of the Broadlands field during 1967-1974 was similar to that at Wairakei during 1961-1967 (Hunt, 1977): during initial exploitation any recharge is small.

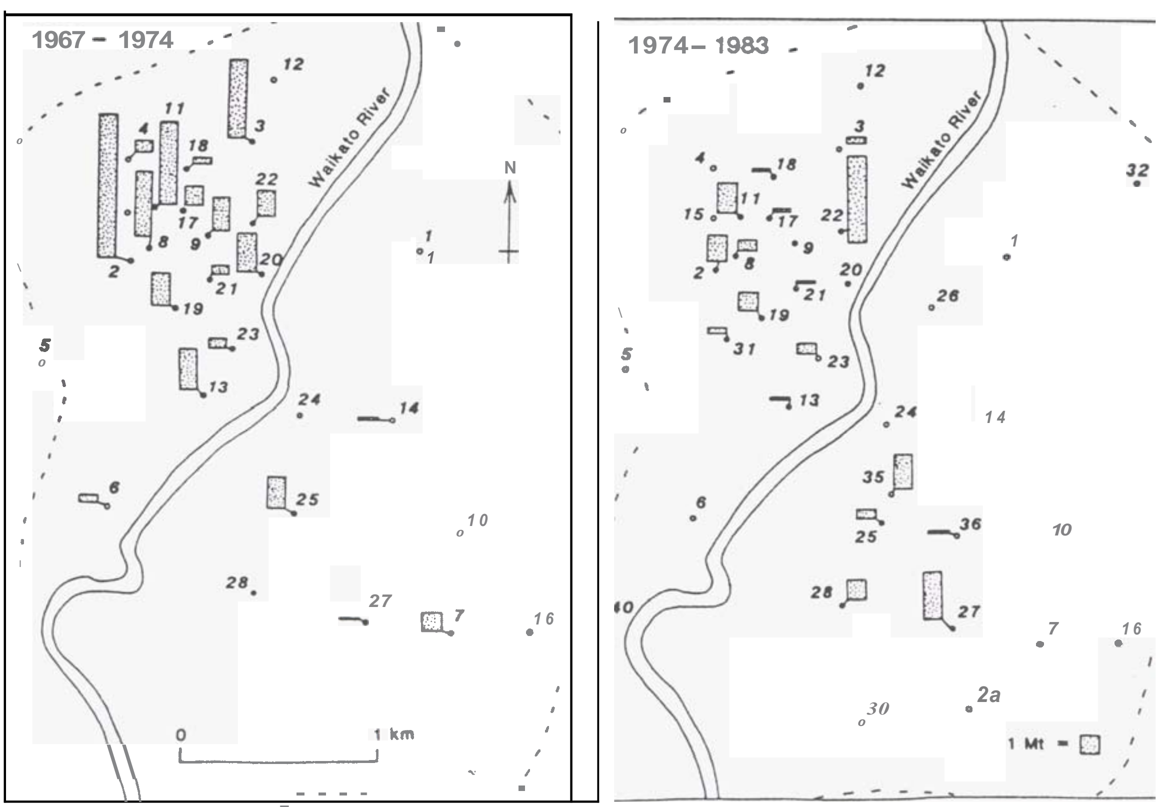

Fig. 4: Maps showing the amounts (Mt) of geothermal fluid withdrawn from deep drillholes in the Broadlands field during the periods 1967-1974 and 1974-1983. Solid circles indicate production wells, open circles non-production wells; numbers indicate the drillhole number. The broken Line indicates the approximate boundary of the field. Note that during the period 1967-1974 most of the mass withdrawn was taken from the Ohaaki part of the field, but during 1974-1983 roughly equal amounts were taken from the Ohaaki and Broadlands areas.

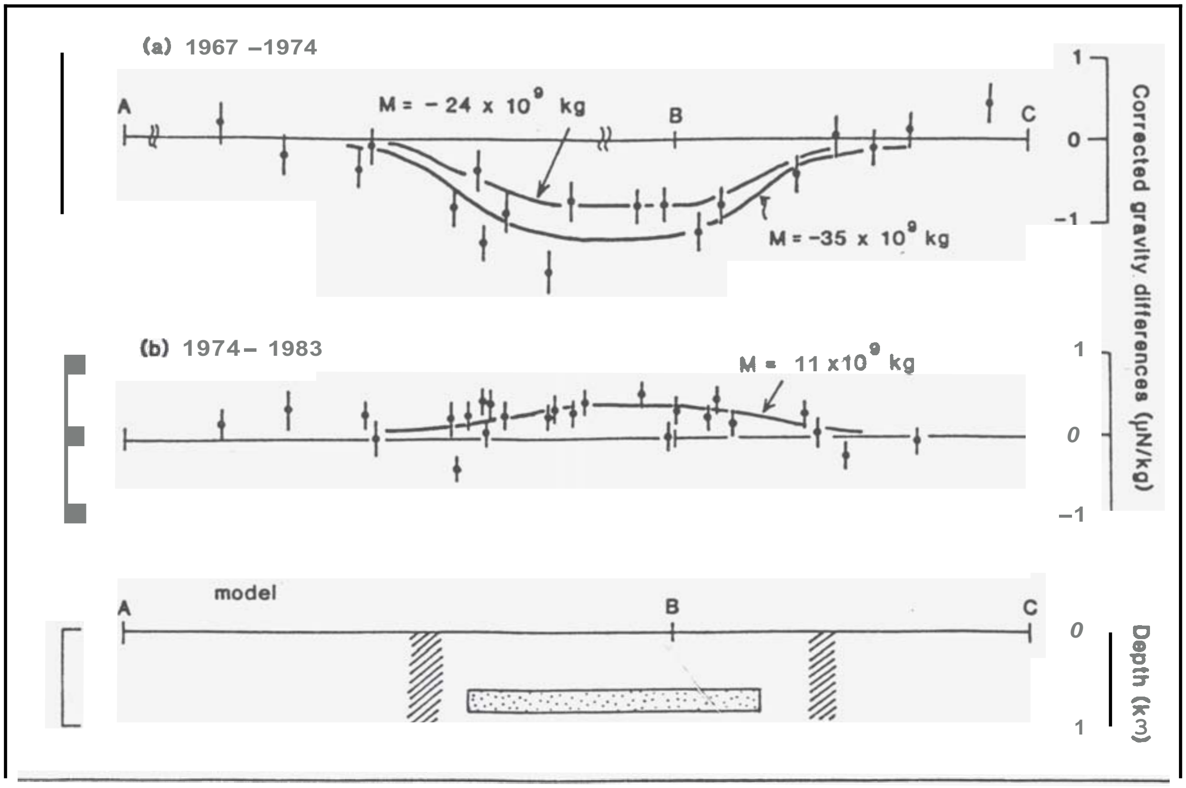

Fig. 5: Corrected gravity differences (μN/kg) along profile A–B–C (see Fig. 2). Solid dots indicate the values of difference; the bars on these dots the calculated standard errors of the differences. The solid lines indicate the computed gravity effects of withdrawing various amounts of mass (M) from the cylinder model shown. The hatched area shows the position of the boundary of the field relative to the model.

One Fmportant result of the data.*is* that not only did mass changes occur throughout the field, but also in a large area outside the field boundary. If the changes outside were not due to shallow groundwater level changes, then it appears that the effects of mass withdrawal from the Ohaaki area extend over a much larger area than the field itself. This is consistent with the results of a recent interference test in which the response of BR5 (feed depth 420 m) to a discharge from BR40 showed no observable boundary effect within a radius of 2.5 km of either bore (McGuinness, 1984).

MASS CHANGES 1974-1983

Changes within the field

During this period mass withdrawal from the field continued, though a reduced amount (14 x 10^9 kg) was taken. However, the gravity differences over most of the field are positive, indicating a net mass gain; hence recharge exceeded mass withdrawn, presumably in response to the field-wide depletion which occured during the period 1967-1974.

The gravity differences are again small and difficult to contour. Values along profile A-B-C (Fig. 5) have a broad maximum with an amplitude of about +0.4 μN/kg. Calculations using the modelling technique and cylinder model described above (Fig. 5) suggest that the net mass gain in the field was about 11 x 10^9 kg, hence the total natural mass recharge was about 25 x 10^9 kg. However, these values could easily be in error by as much *as 50%.*

Only in the north-east corner of the field, near BR1, are the gravity differences negative, indicating a continued net mass loss from this area. The reason for *this* loss is not clear. There was no significant discharge from either of the two bores in the area (BR1, 32) and unfortunately there are no groundwater level data for the area. Groundwater levels in the shallow monitor hole BR14/0, on the edge of the area, fell by about 1.5 m but such a drop is not sufficent to account for the observed differences of up to *-0.5* μN/kg.

Changes outside the field

Significant negative gravity differences (up to -1 μN/kg in magnitude) appear to have occurred in an area west of the field, indicating water continued to be lost from this area. Unfortunately the extent of these negative differences is not known, particularly in a south-west direction. It is possible that these differences reflect a drop in the shallow groundwater level in the area (a drop of about 5-10 m would be required to explain the observed gravity differences) but no water level measurements are available in the immediate area. However, groundwater levels in two, nearby, shallow (<75 m) holes, situated about 1 km west of point P and 1 km south-west of Trig 1779 (Fig. 3), during the period 1975-1978 and in 1983, showed no changes greater than ±1 m (seasonal variations). These data suggest that groundwater level changes are unlikely to be the Cause of the neqative differences in the area, and that the source of the differences must lie much deeper. The magnitudes and extent of the negative differences are similar to those of the positive differences observed within the field and it is tempting to speculate that the two mass changes are associated; hopefully, future surveys will clarify the situation.

Elsewhere, outside the field, the gravity differences are small and variable and little can be deduced from them. It should be noted, however, that positive gravity differences associated with most of the field appear to extend up to 1 km beyond the field boundary to the north and south; this nay suggest that the reservoir extends, at depth (>1 km), in these directions.

CONCLUSIONS

1. During the period of drawdown testing (1967-1974) geothermal fluid was mined from all of the field and there was little recharge. In addition some water was lost from an area outside and west of the field.

2. Subsequently, during the period of reduced withdrawal (1974-1983), natural recharge exceeded the amount of mass withdrawal over most of the field. However, water continued to be lost from the north-eastern part of the field and from outside and west of the field.

3. The data clearly show the need for gravity, levelling, and shallow groundwater level measurements to be made at regular intervals, at places outside the field as well as within.

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