GRAVITY CHANGES IN THE WAIRAKEI-TAUHARA GEOTHERMAL FIELD: 1983-1991

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SUMMARY - During the period 1983 - 1991 about 375 Mt (375 x 10^9 kg) of fluid was extracted from the Wairakei borefield and it is estimated a further 40 Mt was discharged naturally. In 1991, precise gravity measurements were made at 88 benchmarks in and around the field to enable the gravity changes since 1983 to be determined. The data show that, for the period 1983 - 1991, gravity increased by 0 - 100 microgals over most of the Wairakei part of the field, and increased by 100 - 400 microgals in the eastern part of the borefield. Only in a small area, northwest of Karapiti Thermal Area, has gravity decreased, and here most of the changes have been less than 50 microgal. The gravity increases probably reflect a decrease of up to 30 m in the thickness of the steam zone, or an increase in liquid saturation of up to 0.05 in the steam zone, over most of the Wairakei part of the field. In the Tauhara part of the field there were gravity increases of 0 - 50 microgal in the northern and western areas, but elsewhere there were no significant changes. Calculations, using Gauss's Theorum, indicate a field-wide net mass gain of about 45 Mt.

1. INTRODUCTION

Exploitation of the geothermal resources of the Wairakei-Tauhara Field (Fig. 1) for electrical power generation began in 1958. Since that date nearly 1700 Mt of geothermal fluid (both liquid and vapour phases) has been withdrawn from the reservoir in the Wairakei part of the field. Less than 10 Mt of this fluid has been returned to the reservoir by way of reinjection tests (Hunt et al 1990). Assuming an average temperature of 200°C, the amount removed represents a volume of nearly 2 km^3. Natural surface mass flow from the Wairakei part of the field prior to exploitation was about 400 kg/s, and has decreased steadily since then to about 200 kg/s in the early 1980's (Allis, 1981). Precise gravity (microgravity) measurements at benchmarks in and around the field have enabled the changes in mass associated with exploitation of the field to be monitored.

Gravity surveys in 1961, 1967, 1974, and 1983 (Hunt, 1977, 1983; Allis and Hunt, 1986) have shown that withdrawal of such a large mass of fluid has caused major hydrological changes and the field has behaved as a dynamic system. Before production began the reservoir contained a thin, liquid-dominated, two-phase zone overlying a deeper liquid zone (Grant and Horne, 1980). Initial production soon caused the two-phase zone to expand, both laterally and vertically, and steam formed at and above the level at which fluid was withdrawn (Allis and Hunt, 1986). This two-phase zone now has two parts: an upper "steam zone" in which steam (vapour) is the continuous pressure-controlling phase, and a lower "liquid-dominated zone" in which liquid is the continuous pressure-controlling phase (although some stem may be present).

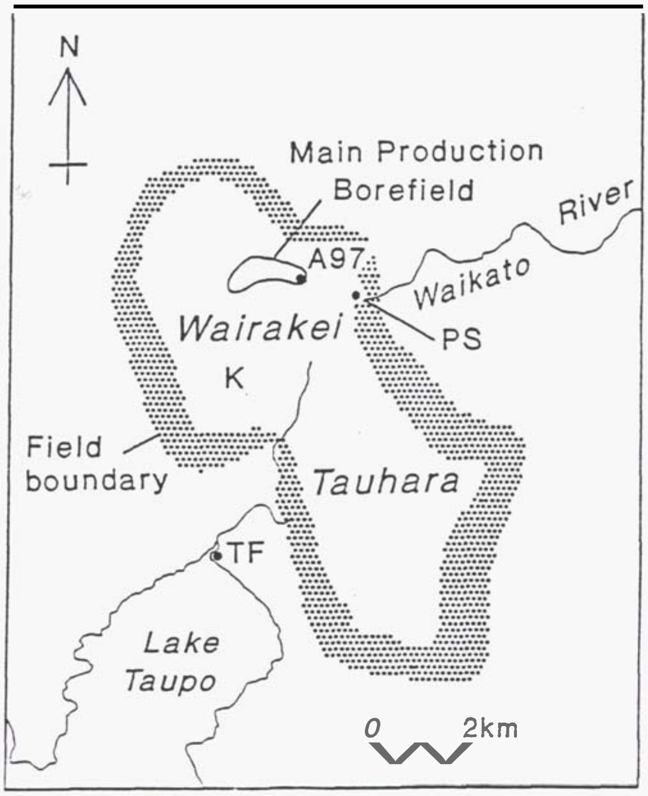

Fig.1: Location and extent of Wairakei-Tauhara Geothermal Field. The dotted area indicates the field boundary as delimited by electrical resistivity measurements. PS marks location of Power Station: TF Taupo Fundamental benchmark: K, Karapiti Thermal Area.

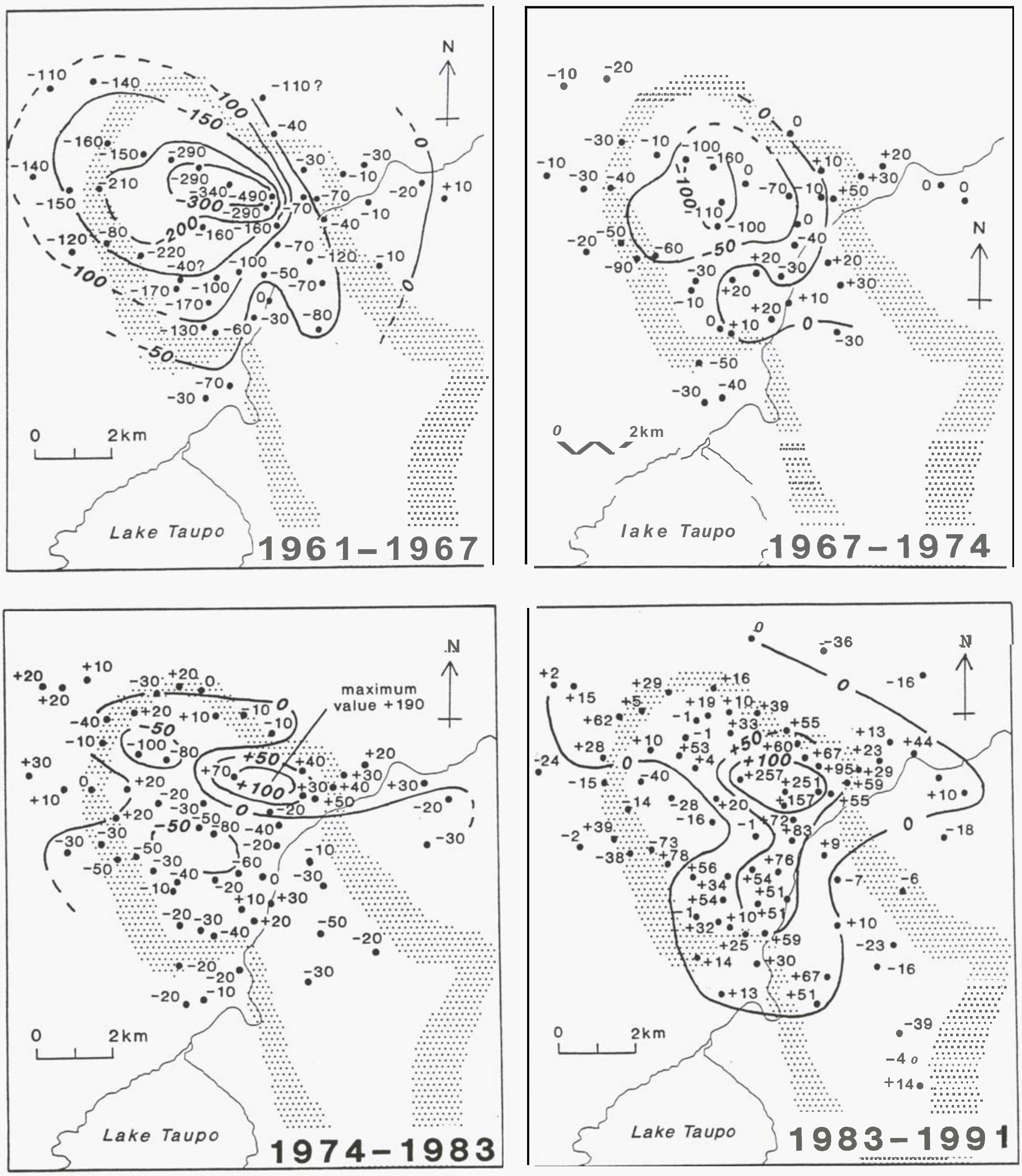

Fig. 2: Gravity changes (microgal) at Wairakei - Tauhara Geothermal Field. Data for periods prior to 1983 - 1991 are from Allis and Hunt (1986). The values have been contoured at an interval of 50 microgal, which is about twice the significance level of the data. For clarity some contours have been omitted.

Precise gravity measurements showed that for the period 1961 - 1967 there were large (up to **490** microgal = 0.49 mgal) gravity decreases (corrected for elevation changes - dominantly subsidence) in the **Main** Production Borefield (hereafter called the "borefield") (Fig. 1); these decreases were mainly associated with the formation and lateral expansion of the two-phase zone and in particular the **steam** zone (Allis and Hunt, 1986). The data showed that in the early 1960's only a small proportion of the **mass** extracted was replaced; in other words the field was "mined" (Hunt, 1977). Later gravity surveys showed that for the periods 1967 - 1974 and 1974 - 1983, the gravity changes were much smaller (Fig.2) and the net gravity change over the whole field was near zero. The largest changes during these periods were decreases of about 100 microgal in an area 1 - 2 km west of the borefield (Allis and Hunt, 1986). These data showed that after about 1966, nearly as much fluid was flowing into the reservoir, as was being removed by the wells. A new and important feature of the 1974 - 1983 period was an area of gravity increases in the eastern part of the borefield (Fig. 2). This and later measurements in the borefield area (Allis and Hunt, 1986: Hunt et al 1990) showed that the increases were associated mainly with a local rise in the bottom of the steam zone (i.e. a thinning of the steam zone) as a result of vapour pressure decline in the steam zone.

This paper reports the results of a further field-wide survey, made in middle of 1991, and compares the gravity changes for the period 1983 - 1991 with those for previous periods.

The continuation of these microgravity studies is important because Wairakei is the only field where there is a long, accurate, and welldocumented record of gravity changes, and hence **mass** changes, which will enable the behaviour of liquid-dominated geothermal fields during exploitation **to** be determined and the hydrological dynamics to be understood. What happens at Wairakei will help predict the behaviour of other, more recently developed fields.

2. MEASUREMENT TECHNIQUES

The techniques of microgravity surveys are **now** well established and documented (Hunt, **1984).** The only difference between the 1991 and previous surveys is that the gravity meter was transported, between the 88 benchmarks used in this survey, in a sprung cage designed **to** reduce the effects of sudden **shocks** and so minimise the number and magnitude of tares.

3. REDUCTION OF DATA

The gravity data were reduced in the standard manner described by Hunt (1984). Differences in gravity, between surveys, have been corrected for the gravity effects **of** changes in elevation (ground subsidence) and shallow groundwater level, and are called gravity changes. Gravity increases are referred to as being positive; decreases as negative.

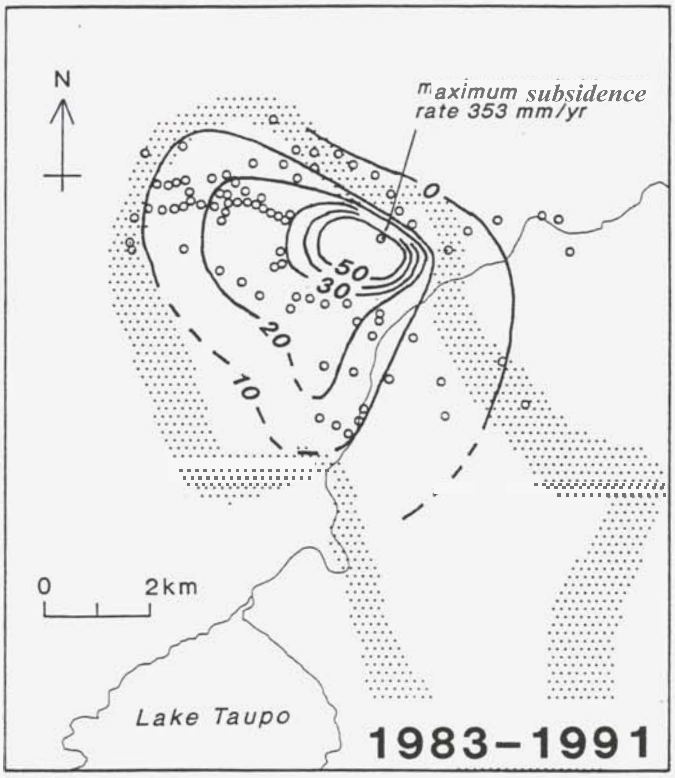

Fig.3: Subsidence rates (mm/yr) at Wairakei-Tauhara for the period 1983-1991. Map compiled from data at about 290 benchmarks. For clarity, benchmarks with subsidence >30 mm/yr and contours >50 mm/yr have been omitted.

Small improvements are periodically made to the computer programme for reduction of the gravity data and to ensure that the results from the 1991 and 1983 survey were reduced in the same manner, the data from the 1983 survey were recomputed.

A minor difference between the computation of gravity changes for the **period** 1983 - 1991 and previous periods is that for the period 1983 - 1991, a value of 302 (±5) microgal/m of subsidence was used for the vertical gravity gradient when correcting for the gravity effects of ground subsidence. **This** value was obtained from measurements at 3 places in the borefield (Hunt et al, 1990). For previous periods the value had been assumed to be 308 microgal/m, but the difference between the two values **is** minor and will not cause **an** error of more than about 18 microgal, and less than 5 microgal at all but 3 benchmarks used here. The amount of ground subsidence in the northern part of the field **was** determined from repeat levelling surveys; the last levelling data available **was** for 1989.4, necessitating an extrapolation of the data for 2.1 years from then until 1991.5. However, plots of elevation against time at many benchmarks show that subsidence **is** uniform with time over periods of 3 - 5 years (Allis, 1990; ECNZ, 1990) and errors associated with the extrapolation are estimated to be less than 10 microgal. At benchmarks around the edges of the field and outside the field, where little or no elevation change data were available, the amount of ground subsidence was calculated from average subsidence rates over a longer period (Fig. 3). Comparison of the subsidence calculated from this map with actual subsidence measured at a few points suggests that the errors involved are less than 0.05 m (equivalent to 15 microgal).

During the period 1983-1991, regular measurements of groundwater level were made in about 30 shallow (<60 m depth) monitor wells in the Wairakei part of the field. These data show that there were no significant (>2 m) water level changes, except in a small area in the centre of the borefield.

A good test of whether the value of gravity at the base station has changed, which would result in a spurious, consistent bias to all the gravity changes, is to examine the mean of the gravity changes at benchmarks well outside the field. The value of this mean should be zero, or close to zero. For the period 1983-1991, the mean value of the gravity changes at 11 such benchmarks is -23 (± 22) microgal; this suggests that the value of gravity at the base station (Taupo Fundamental Benchmark; TF, Fig.1) had decreased by 23 microgal, possibly due to a local change in the shallow groundwater level. The gravity changes at all benchmarks for the period 1983 - 1991 were therefore adjusted by +23 microgal.

A good estimate of the significance level of the gravity changes is the standard deviation of the mean of the changes at benchmarks well outside the field (Hunt, 1987). The standard deviation for the period 1983 - 1991 is 22 microgal, suggesting that the significance level of the gravity differences is about 25 microgal.

4. RESULTS

The gravity data for 1983 - 1991 (Fig.2) show that the largest changes are in the eastern part of the borefield where they are more than +100 microgal, and exceed +400 microgal at one benchmark. Over most of the remaining areas of the Wairakei part of the field, the gravity changes are positive (net mass increase) and 0-100 microgal in amplitude; the shape of the contours (Fig.2) suggests that tongues of positive changes extend southwards and eastwards from the borefield. The only place with negative changes (net mass loss) is a small area near Poihipi Road, northwest of Karapiti Thermal Area (K, Fig.1). In the Tauhara part of the field, the gravity changes are positive and 0-50 microgals in the northern and western parts, and are near zero in the central and eastern parts.

The main difference in the gravity change patterns between the 1974- 1983 and 1983 - 1991 periods is that whereas the gravity changes over most of the field for the former period were negative (indicating net mass loss), for the latter period they are positive (indicating net mass gain). In the borefield the changes were dominantly negative up until the

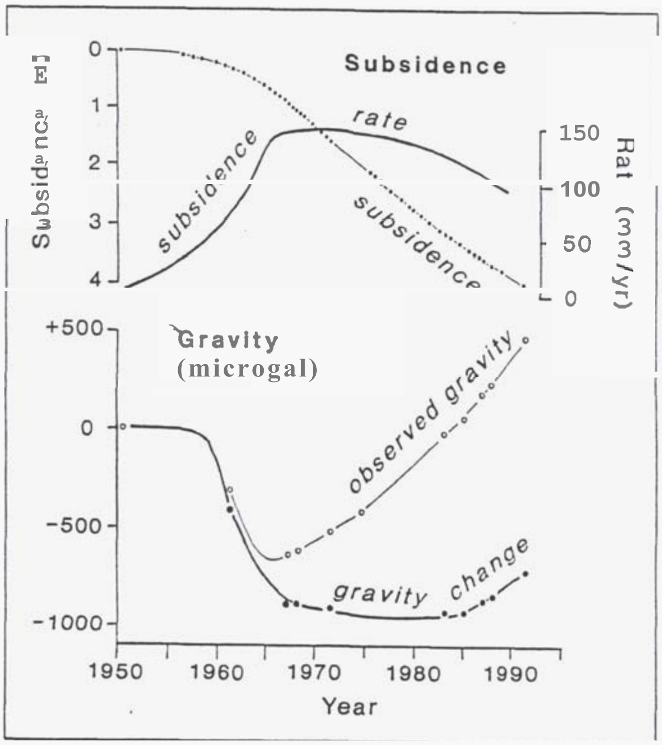

Fig. 4: Gravity and ground subsidence data at benchmark A97 in the borefield (Fig.1). Subsidence data is from Allis (1990); gravity data is mainly from Allis and Hunt (1986) and Hunt (1988). Note the increase in gravity change began in the mid 1980's.

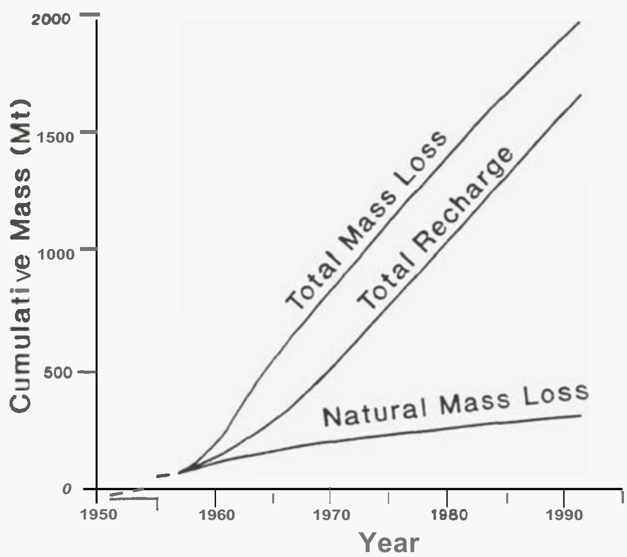

Fig. 5: Cumulative mass changes, With time, at Wairakei-Tauhara field.

TABLE 1: Mass discharge and recharge values for the Wairakei part of the field. Data for periods prior to 1983 - 1991 taken from Allis (1981), Allis and Hunt (1986), and Hunt (1977).

Period	Time (years)	Mass Withdrawn from borefield (Mt)	Natural Mass Discharged (Mt)	Total Mass Loss from the surface (Mt)	Integrated Sum of Gravity Differences ($N.kg^{-1}.m^2$)	Net Mass Change (Mt)	Mass Recharge (Mt)
1950-1961	~ 11	145	125	270	na	-100?	170
1961-1967	5.6	360	55	415	-71	-235	180
1967-1974	7.5	400	60	460	-13	- 35	425
1974-1983	8.3	390	45	435	0	0	435
1983-1991	8.4	375	40	415	+19	+45	460

mid 1980's, and subsequently have been positive (Fig.4). This trend now appears to have extended over most of the Wairakei part of the field.

5. MASS CHANGES

The net mass change associated with the measured gravity changes can be determined using Gauss's Potential Theorem (Hammer, 1945; Hunt, 1977). The sum of the gravity changes ($\Sigma\Delta g\Delta a$) obtained from Fig. 2 is about +19 $N.kg^{-1}.m^2$, and substitution of this value in Gauss's Formula provides a value of +45 Mt for the net mass change. In other words, for the period 1983 - 1991 there was a net mass increase of about 45 Mt. Corresponding values of net mass change for other periods are given in Table 1. Cumulative mass changes since 1950, derived from this data, are given in Fig.5.

6. DISCUSSION

Allis and Hunt (1986) and Hunt (1988) showed that the increases in gravity in the eastern part of the borefield were due mainly to a decrease in the thickness of the steam zone as a result of a rise in the bottom of the steam zone. It is likely that gravity increases in other parts of the field, during 1983-1991, are also due to a decrease in the thickness of the steam zone, although of a much smaller amplitude than in the borefield. Allis and Hunt (1986) showed that, for the steam zone at Wairakei, a gravity change Ag (microgal) is related to a change in thickness Δh(m) by the formula:

$$\Delta g = -2\pi G\phi (\rho_w - \rho_s)(1 - S_o)\Delta h \qquad ....(1)$$

where G is the Universal Gravitational Constant ($6.67 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$), ϕ is the connected porosity of the rock, ρ_s is the steam density, ρ_w is the liquid water density, and S_o is the residual liquid saturation.

Taking values of $\phi = 0.3$ and $\rho_w - \rho_s = 850\ kg.m^{-3}$, which are appropriate for the steam zone at Wairakei, and substituting in equation (1) then:

$$\Delta h = \Delta g/11(1 - S_o) \qquad ....(2)$$

where Ag is in microgal, and Δh is in m.

Assuming that the residual liquid saturation in the lower part of the steam zone is 0.7 (Hunt, 1988), substitution in equation (2) suggests that a gravity increase of 100 microgal would result from a decrease in thickness of the steam zone of about 30 m.

An alternative explanation for the gravity increases is that liquid saturation has increased in the steam zone. The change in saturation AS associated with a gravity change Ag can be determined by replacing ($1 - S_o$) by AS, and Ah by h, in Equation (1) (Allis and Hunt, 1986). Assuming that the thickness of the steam zone (h) is 200 m, and the values for ϕ and ($\rho_w - \rho_s$) are the Same as given above, substitution in this formula suggests that a gravity increase of 100 microgal would result from an increase in saturation of about 0.05. However, this value is strongly dependent on the values assumed for thickness and connected porosity of rocks in the steam zone.

7. ACKNOWLEDGEMENTS

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