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MODELLING THE GRAVITY CHANGES AT WAIRAKEI GEOTHERMAL FIELD

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ABSTRACT

The principal cause of gravity change at Wairakei has Seen the drawdown of liquid and the formation of a steam zone in the upper part of the reservoir. Small but significant gravity changes have also been caused by subsequent saturation changes in the steam zone, groundwater level decline and changing pore water density due to temperature changes. Pore compaction* pore water decompression and mineral precipitation ate unlikely to have caused significant gravity changes (<30 μgal). *An* example of modelling the gravity changes In the eastern production borefield indicates a residual saturation in the steam zone, immediately after liquid drawdown, of 0.6. Dry out of the steam zone during the 1960's caused the saturation to decrease to less than 0.5. During the 1970's there appears to have been negligible saturation change. Continuing pressure and temperature declines in the steam zone are apparently now caused mainly by groundwater invasion.

INTRODUCTION

More than 1×10^{12} kg (1 km^3) of water has been withdrawn from Wairakei field since gravity monitoring began in 1961. However the gravity station network, covering a 50 km^2 area containing Wairakei field, has detected surprisingly small gravity changes. Most of the gravity changes occurred between 1961 and 1967 during the period of rapid liquid drawdown in the reservoir. During this time a maximum decrease of *500* vgal was measured in the eastern part of the production borefield (Hunt, 1977). Subsequently a gravity increase of over 200 μgal has occurred in the eastern production borefield, and a similarly sized decrease has occurred west of the production borefield (Hunt, 1983; 19841. Previous interpretations of these gravity changes have shown that a relatively small fraction (~10%) of the total mass has been derived from shallow drawdown in the reservoir, with the remainder being supplied by recharge (Hunt, 1977; Allis, 1901).

In this paper, all the factors which may have caused significant gravity changes during exploitation are quantitatively assessed and it will be shown that most of them can be calculated from observed pressure and temperature changes in the reservoir. The principal unknown parameter which can only be determined from the gravity change is the deqree of saturation in the steam zone. One example of how the qravity changes can be used to model saturation chdngea with time will be given. A more detailed discussion of the gravity changes that have occurred in various parts of Wairakei field will be given in a review paper presently in preparation. The unit of gravity used here is the ugal; 1 μgal = 0.01 μN/kg. The unit of pressure used is the bar; 1 bar = 01 MPa.

CAUSES OF GRAVITY CHANGES

Once the observed gravity diffetences have been corrected for elevation changes at each station, the residual gravity changes should be predominantly due to mass changes beneath the gravimeter. When considering possible causes of gravity change it must be remembered that the standard error of a gravity observation, for recent surveys at Wairakei field, has been around 10 ugal, and the uncertainty for most of the gravity differences is probably around 30 μgal. The various causes of gravity change at Wairakei field are discussed below in approximate order of importance. In each case one dimensional expressions for the gravity effect are given. Generally this is a good approximation, because the depth to the mass changes is small compared to their horizontal extent.

Liquid drawdown in steam zone

The primary effect of fluid withdrawal from WaFrakei field has been the formation of a steam zone between about 100 and 400 m depth. If S_o is the fraction of pore volume with immobile liquid (i.e. residual saturation) after drawdown; ϕ is the connected porosity; ρ_s is the steam density; ρ_w Is the liquid water density; and G is the gravitational constant (6.67 x 10^{-11} N m^2 kg^{-2}), then the gravity change, (Δg) due to drawdown, is:

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

where h is the thickness, or increase in thickness, of the steam zone. Appropriate values for the steam zone at Wairakei are $\phi = 0.3$ and $\rho_w - \rho_s = 850$ kg/m^3. Equation 1 reduces to:

$$\Delta g\ (\mu gal) = -11\,(1 - S_o)\, h \qquad (2)$$

where h is in m. If, for example, the steam zone increases in thickness by 100 m, and $S_o = 0.5$, than the gravity change is *-550* ugal.

The main uncertainty in equation 1 which influences the value of S_o *is* the value of h. The top and bottom of any steam zone is usually poorly identified, even when there are numerous high enthalpy production wells producing from a range of depths. An isobaric part of the reservoir at saturation temperature *is* often assumed to be steam-dominated. However, if it happens to be water dominated, then the value assumed for h is too large, and the resulting value determined for S_o is also too large. The conclusion resulting from an unexpectedly high value of S_o would still be corract: there would be more water in tho steam zone than previously thouyht. The error would be in the assumed vertical distribution of the steam volume, not in the steam volume itself.

Liquid drawdown in groundwater

Equation 1 can also be used to calculate the effect of shallow groundwater level changes. In this case, the fluid is generally cold water, with air filling the unsaturated pore volume. Assuming S_o to be 0.5, and using $\phi = 0.5$, which is a reasonable value for shallow depth at Wairakei, then

$$\Delta g\ (\mu gal) = -10\ h \qquad (3)$$

where h is the fall in water level (m).

Groundwater levels around Wairakei are known to vary by up to ± 1 m due to climatic factors. Such variations are unlikely to be descernible in the gravity differences and can be ignored. However, there is an area on the northern side of the production borefield where groundwater levels have fallen by over 10 m (Allis, 1982). This will have a significant effect on the measured gravity diffetence.

If groundwater level changes in excess of several metres go undetected, then an error in the gravity interpretation may occur.

Steam zone saturation change

Pressure and temperature in the steam zone at Wairakei field have steadily decreased since formation of the zone in the late 1950s and early 1960s. Between 1962 and 1982 the pressure decreased by around 10 bar and the temperature decreased by 20-30°C depending on location within the field. These decreases could be due to steam loss causing 'dry-out' of the steam zone, or they could be due to cooling and condensation from invading groundwater. With the former, the saturation gradually decreases as immobile water boils due to the pressure decrease; with the latter, the saturation may increase with time.

Equation 1 gives the gravity change for a saturation change, ΔS, if $(1 - S_o)$ is replaced by ΔS. If dry-out is occurring, then the fractional volume of fluid lost, $\phi \Delta S$, can be calculated from the observed temperature or pressure drop in the steam zone. Heat balance considerations yield:

$$\phi \Delta S = \langle \rho c \rangle \Delta T / (H_{sw} \rho_w) \qquad (4)$$

where H_{sw} is the latent heat of water, ΔT is the temperature change during dry-out, and $\langle \rho c \rangle$ is the volumetric heat capacity of the saturated rock. That is,

$$\langle \rho c \rangle = \phi S_w \rho_w C_w + (1 - \phi) \rho_r C_r \qquad (5)$$

(C = specific heat; r = rock; w = water; S = saturation). Typical values for these parameters in the steam zone at Wairakei are: $\langle \rho c \rangle$ = 2700 kJ/kg°C, H_{sw} = 1900 kJ/kg, and ρ_w = 850 kg/m^3. Therefore on substitution in equations 4 and 5:

$$\phi \Delta S = 0.0017\ \Delta T \qquad (6)$$

where ΔT is in °C. The gravity change due to dry-out is therefore (from Equation 1):

$$\Delta g (\mu gal) = 0.061\ h \Delta T \qquad (7)$$

where h is the average thickness of the steam zone (m). A 100 m thick steam zone which declines in temperature by 10°C due to dry-out will therefore cause a gravity decrease of around 60 ugal (ϕ = 0.3). The pore saturation will have decreased by 0.06. The gravity change is therefore relatively small, but still significant.

The accuracy of the above calculation depends firstly on whether dry-out is the sole cause of the temperature and pressure declines in the steam zone, and secondly on the actual thickness of the steam zone. If equation 7 is used then the assumed value for the parameters should result in a combined uncertainty of less than 10% if the steam zone temperature is between 150 and 230°C.

Liquid density change - thermal effects

If the density of water in an aquifer changes due to a temperature change, and no saturation change results (i.e. the aquifer is confined) then the resulting gravity change will be:

$$\Delta g = 2\pi G\ \phi \Delta \rho\ h \qquad (8)$$

where $\Delta \rho$ is the average density change and h is the average aquifer thickness with changed temperature ΔT. At about 200°C, the volumetric coefficient of expansion for water is almost 2 orders of magnitude, greater than that of rock, so the effects of rock volume changes can be ignored. For temperatures between 180 and 230°C, and ϕ = 0.3, the gravity effect is:

$$\Delta g (\mu gal) = 0.015\ \Delta T\ h \qquad (9)$$

where h is in m, and ΔT is in °C. If the temperature of a 500 m thick aquifer decreases by an average of 10°C in the above temperature range, gravity will increase by about 75 ugal.

The uncertainty with this calculation is whether the aquifer is confined or not, and whether saturation changes could have occurred because of the change in the vertical pressure gradient over some portion of the liquid column. For example, if the increase in density due to a temperature decrease causes the water level (or a steam-water interface within the aquifer) to fall, then the gravity increase will be partially compensated. The amount of compensation is proportional to the value of $(1 - S_o)$ in the unsaturated zone above the changing water level.

One of the most important areas where this effect may be occurring is in the two-phase liquid zone beneath the steam zone. At about 500 m depth at Wairakei, the temperature has fallen from more than 250°C to as low as 210°C in some places. Gravity modelling at Wairakei indicates that S_o in the steam zone is in the range 0.6-0.8, so the effect of these temperature changes may be largely uncompensated if changes in height of the water-steam interface do occur.

An additional uncertainty is whether significant changes in water level occur at all as a result of water density changes. The size of any change will depend on the permeability in the upper portion of the liquid zone. If there is a zone of relatively high horizontal permeability near the water surface then the pressure within this zone will control the height of the water surface. Pressure changes due to deeper temperature changes will be restricted to greater depth. Similarly, if there is very low permeability around the water surface, then the underlying liquid column tends to be confined, and water level changes may also not occur. The only circumstance favouring water level changes is when good vertical permeability exists over the liquid volume, and pressure in the column is controlled by good horizontal permeability beneath the zone of decraaeed temperature.

It has been assumed here that water density changes due to temperature changes do not in general cause compensating changes in water level. At worst, compensation may occur, and the gravity effect could be overestimated by up to 402. For most of Wairakei field, this error would be a very small fraction of the total gravity change.

Liquid density changes - pressure effects

The depressuring of pore water causes a decrease in fluid density which will cause a gravity decrease. This is given by:

$$\Delta g = 2\pi G c_w \phi \rho_w h \Delta P \qquad (10)$$

where c_w is the average compressibility of the water, h is the thickness of the aquifer, and ΔP is the pressure decrease. The compressibility of water ranges between 5 x 10^{-5} bar^{-1} for cold water and 1 x 10^{-4} bar^{-1} for 200°C water. In the hot part of the reservoir at Wairakei, the gravity effect, Δg, of depressuring the pore water is:

$$\Delta g(\mu gal) = -0.001\ h\ \Delta P \qquad (11)$$

where h is in m and ΔP is in bar ($\phi = 0.3$). A 10 bar pressure decrease over a 1 km thick aquifer will cause a gravity decrease of only 10 μgal. This effect can generally be neglected, except where phase separation (steam or gas) occurs as a result of depressuring. As already discussed, the resulting saturation changes would cause a very large gravity change.

Pore compaction

Fluid decompression also causes pore compaction, and the resulting fluid loss causes a decrease in gravity. The effect can be calculated from equation 10, with rock compressibility replacing the term ϕc_w. Since rock compressibility and the appropriate thickness of the formations can be extremely variable and uncertain, it is easier to calculate this effect directly from the amount of subsidence. Assuming the amount of subsidence equals the amount of compaction, Z, then

$$\Delta g = 2\pi G \rho_{w,s} Z \qquad (12)$$

where $\rho_{w,s}$ is the density of the fluid phase lost during pore compaction. If the compaction Is occurring in the steam zone and steam is lost, then $\Delta g \approx -0.4$ μgal/m of subsidence. If water is lost, then $\Delta g \approx -40$ μgal/m of subsidence- Allis and Barker (1982) showed that in the eastern production borefield, and probably also in the main subsidence bowl at Wairakei, the compaction is mostly occurring in the steam zone (in the Huka breccia layer)'. Although the rate of subsidence is as high as 0.45 m/year here, the gravity effect is still negligible. Elsewhere away from the production borefield, the total subsidence since the early 1960's has been less than 0.5 m. Even if the compaction is expelling water, the gravity effect in this part of the field can be neglected.

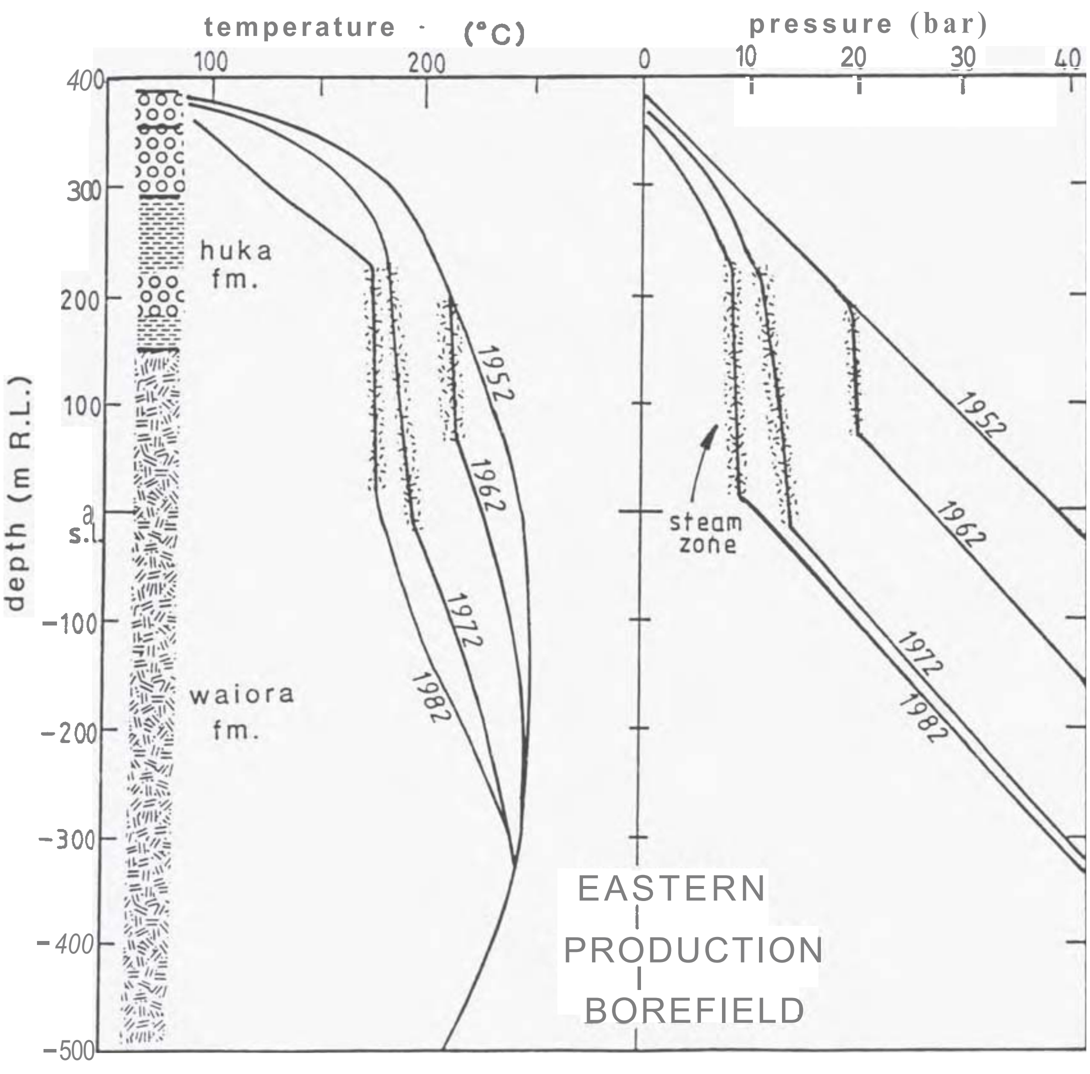

Fig. 1: Temperature and pressure changes in the eastern production borefield, Wairakei. ALL profiles are based on data collected by M.W.D. Wairakei. The 1952 pressure profile is from Grant and Horne, (1980).

Precipitation

As the geothermal fluid is drawn towards the production wells, boiling occurs, causing silica to be precipitated near the production borefield. The average temperature drop due to boiling is about 15°C (Henley, pers. comm.); for temperatures between 255 and 220°C, this causes a drop in silica concentration of around 70 mg/kg. Using a total mass flow figure of 10^{12} kg since 1961, the mass of silica precipitated is therefore 7 x 10^{7} kg. Assuming this to be concentrated within a 1 km^2 area of the production borefield, the maximum gravity increase would be 3 μgal which is insignificant. The gravity effects of calcite precipitation caused by the heating of invading cool water saturated with CO_2 should be even smaller than the effect of silica precipitation.

MODEL FOR GRAVITY CHANGES IN THE EASTERN PRODUCTION BOREFIELD

Average pressure and temperature profiles at 10 yearly intervals since exploitation began in the early 1950s are shown in Fig. 1. Each profile is made up from numerous dwnhole measurements in both production and monitor wells in the eastern production borefield. The scatter in observations mostly lies within an envelope about each line of ±2 bar or ±10°C. The important changes in Pig. 1 are as follows. Until the early 1970s, the steam zone increased in size due to both deep liquid pressure decline and steam zone pressure decline. Subsequent stabilization of the deep liquid pressure, but continued steam zone pressure decline, has caused the bottom of the steam zone to move upwards. The position of the top of the steam zone during this time is uncertain, but it is unlikely to have also moved upwards. The temperatura in the two-phase liquid zones above and below the steam zone fell below saturation conditions during the late 1970s. Since shallow wells still produce from the steam zone in this part of the field, the steam zone here is presumably now sustained either by a lateral flow of steaa, or by a localised upflow region not represented by the 1982 temperature profile in Fig. 1.

The various gravity effects of these changes are shown in Fig. 2a. The effects have been computed in three, 10 year steps. Finer time increments are considered to be unjustified in view of the uncertainties in the steam zone thickness. Four options for the gravity effect of liquid drawdown are shwn, with S_o ranging between *0.5* and *0.8*. The best fit to the data shown in Fig. 2b is obtained with S_o = *0.6*. This closely matches the increase in gravity observed at most stations since the early 1970s, if it is also assumed that no dry-out occurred in the steam zone after 1972. If dry-out was the main cause of the decline in pressure and temperature in the steam zone since 1972, then the gravity would have been steadily decreasing. This has not been observed over most of the eastern production borefield. The slight decrease in gravity at A97 suggests some dry-out has continued to occur at the southeast end of the borefield.

The saturation changes in the portion of the steam zone which formed first is shown in Fig. 2c. This is situated between about 100 and 150 m RL, and is immediately beneath the lower Huka mudstone layer. By the early 1960s the saturation had fallen to around 0.6 as mobile water drained from the upper part of the reservoir, Steam drawoff by

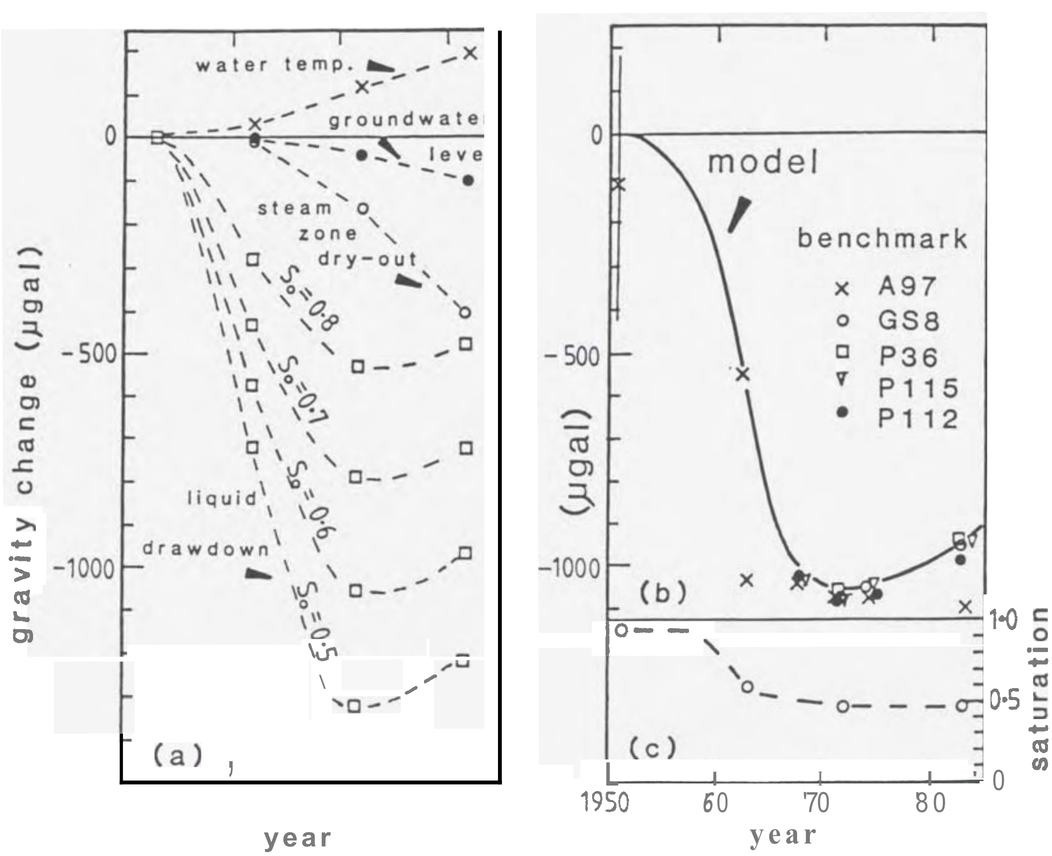

Fig. 2a: Gravity effects of changing conditions in the eastern production borefield, Wairakei (excluding the effects of elevation changes of the ground surface with time).
b: Theoretical model for the gravity changes in the eastern production borefield compared with the observed changes at 5 benchmarks. The model assumes S_o = 0.6, and that dry-out of the steam zona does not occur after 1972.
c: Saturation changes in the steam-zone predicted by the gravity model in Fig. 2b.

shallow production wells then became the main factor causing the saturation to decline to less than 0.5 by the early 1970s. However subsequently there appears to have been little change in saturation, with the continued pressure and temperature decline in the steam zone being predominantly caused by invading groundwater.

CONCLUSIONS

Interpretation of the gravity changes in the eastern production borefield has yeilded estimates of the saturation changes in the underlying steam zone. The changes provide insight into the causes of rundown in this part of the field and this, in turn, provides a physical basis for predicting the future response of the borefield. A more detailed discussion of these results, and the results of modelling the gravity changes elsewhere at WaFrakei field will appear in a review paper currently in preparation.

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