Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Using Repeat Microgravity Measurements to Track Reinjection in Liquid-Dominated Fields

Trevor M. Hunt

Institute of Geological & Nuclear Sciences, Private Bag 2000, Taupo, New Zealand

t.hunt@gns.cri.nz; rainbow@reap.org.nz

Keywords: precision gravity, mass changes, reinjection, resaturation, pore fluid, two-phase, single-phase, modelling.

ABSTRACT

The gravitational effect of reinjection will generally depend on the mass of water reinjected and on the conditions of the reservoir near where the water is introduced.

If the reinjected water is introduced directly into a steam zone, and the temperature in the zone is not sufficient to cause significant amounts of boiling to occur, the reinjected water will start to resaturate the zone. Reinjection directly into a two-phase zone (overlying a single-phase deep liquid zone) will produce gravity effects similar to those for reinjection directly into a steam zone except that, with the presence of more liquid already in the pores, less mass will be required to saturate the pores and hence there will be smaller density changes.

If the water is reinjected into a single-phase liquid zone at a relatively shallow depth beneath the two-phase zone then the water displaces some (or all) of the water in the pores near the well upwards, causing the lower part of the two-phase zone near the reinjection well to be resaturated, and thus the deep liquid level to be raised.

1. INTRODUCTION

Reinjection of waste separated water and steam condensate is a common practice in the operation of most liquid-dominated fields. Management of such fields requires information about where the reinjectate goes and how fast it goes there, however, only limited amounts of information are generally available about these important factors. Tracer tests and downhole measurements of pressure, temperature, enthalpy and fluid chemistry are generally confined to a few existing wells which are often not widely distributed spatially.

Experience shows that continued production from a liquid-dominated field often results in hydrological changes and pressure drawdown in the reservoir, and in particular the formation and expansion (vertical and horizontal) of 2-phase conditions near the top of the reservoir. As production and pressure drawdown continues this may result in dryout in the upper parts of this 2-phase zone, leading to formation of a steam zone in which the pores contain steam and a small amount of immobile liquid. It is believed that the liquid saturation in a steam zone will be near-constant at the residual saturation (S_0). In the 2-phase zone the liquid saturation (S) increases with depth until the pores are completely saturated at the deep liquid level, below which the pores are completely saturated (Fig.1). The upper part of the 2-phase zone may be vapor-dominated and the lower part liquid-dominated.

In some fields, water is reinjected into the principal reservoir formation, and in others it is reinjected into a different formation or aquifer that will accept the water. In the latter case, 2-phase conditions may be naturally present in the aquifer.

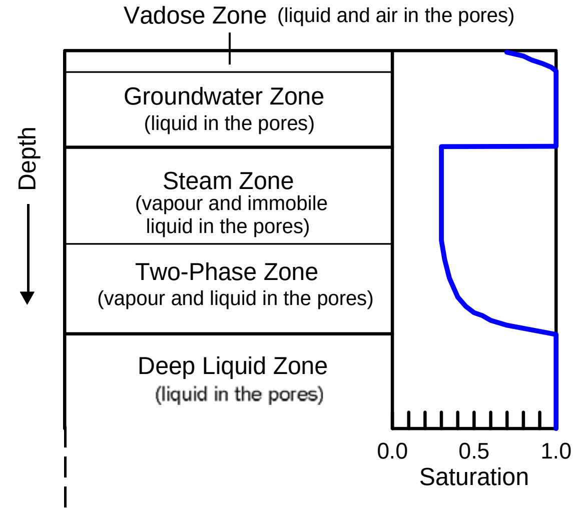

Fig. 1 Sketch of hydrological zones and liquid saturation in the reservoir of an exploited liquid-dominated field in New Zealand. Not to vertical scale. S_0 represents the residual liquid saturation of 0.3 in the steam zone.

Withdrawal of geothermal fluid and reinjection of the waste water involves transfer of mass from one part of the reservoir to another, and hence may result in changes in gravity. From repeat measurements, on benchmarks at the ground surface, of these small but measurable gravity changes it is possible to determine the amount and distribution of the mass changes (Hunt, 1995).

This paper examines the gravity effects of reinjection into the different zones of the reservoir of liquid-dominated fields, and gives some examples of what has been observed in New Zealand.

2. GRAVITY EFFECTS OF REINJECTION

Reinjection is generally in the form of liquid-phase water, with a density depending on the temperature of the water. The gravitational effect of reinjection will depend on the conditions of the reservoir near where the water is introduced. The following discussion considers the effects of reinjection into the reservoir of a liquid-dominated field that has been exploited sufficiently for single-phase steam and 2-phase zones to have formed. The gravity effects of reinjection into deep single-phase liquid reservoirs such as Dixie Valley, or into vapour-dominated reservoirs such as The Geysers, may be different (Allis et al., 2000). The discussion also assumes that the reinjected water causes changes mainly to the fluid in the pores, as opposed to the fractures.

The location of where the reinjectate flows out from the reinjection well will depend initially on the casing pattern of the well. If the well is completely solid cased then the water can only exit from the bottom. If the lower part of the well is cased with slotted liner then the location of where the water exits the well will depend on the horizontal permeability of the rocks in the zone of slotted liner. If there is a region of high horizontal permeability it will flow out of the well in this region.

2.1 Reinjection into a steam zone

The reinjected water will principally displace steam in the pores and resaturated the zone. This resaturation will start at the wellbore and, assuming isotropic permeability, gradually move downwards and outwards from the well. There will be a small amount of steam condensation around the reinjection front. The change with time in liquid saturation in the pores will depend on the rate of reinjection, the permeability of the rock and the pressure head driving the reinjection.

The pores contain some immobile liquid: the residual liquid saturation, which may be as high as about 0.5 (Allis & Hunt, 1986). For the purposes of interpreting gravity changes, such immobile water can be considered to be part of the rock matrix.

The density change $\Delta\rho$ in the steam zone due to complete resaturation is given (Allis & Hunt, 1986) by the equation:

$$\Delta\rho = \varphi(\rho_w - \rho_s)(1-S_0) \qquad (1)$$

where φ is the connected porosity, ρ_s is the steam density, ρ_w is the density of the liquid water that has been reinjected, and S_0 is the residual liquid saturation.

For example, if water at 130 ^oC is reinjected into a steam zone at 220 ^oC, having a residual saturation of 0.3 and porosity of 0.2, then the density change (when the pores are completely saturated) will be about 129 kg/m^3 (Table 1). The controlling factors are the values for the residual saturation and the porosity; and the temperature of the reinjectate. The temperature of the steam zone has less influence because the density of steam does not vary as rapidly with temperature as does that of liquid water. For example, if in the above situation the temperature of the steam zone was 260 ^oC (c.f. 220 ^oC) the density change would be about 128 kg/m^3 ; a difference of only 1 kg/m^3 for a 40 ^oC change in steam zone temperature. After the water has been reinjected it becomes heated by the steam and by the rock matrix which will decrease its density. However, this has a larger, but still minor effect, on the density change. If in the above initial example the reinjected water is heated, on average, by 20 ^oC above the initial temperature of reinjection then the value of ρ_w will decrease by about 18 kg/m^3 and the density change will be about 127 kg/m^3.

Unless the vertical permeability is very low then the reinjectate will probably sink down through the steam zone to the 2-phase zone, where it will resaturate the pores in that zone.

2.2 Reinjection into a two-phase zone

Reinjection directly into a two-phase zone (overlying a single-phase deep liquid zone) will produce similar gravity effects (for the same mass of reinjectate) to those for reinjection directly into a steam zone except that, with the presence of more liquid already in the pores, less mass will be required to saturate the pores. Hence there will be smaller density changes, and the thickness of the region being resaturated will be greater.

Table 1. Density change (kg/m^3) (when the pores are fully saturated) associated with reinjection of 130 ^oC water into a steam zone with temperature of 220 ^oC for different saturation and porosity values (assuming no reheating of reinjectate). Values calculated from data in Raznjevic (1976).

Saturation (S)	Porosity (φ) 0.1	0.2	0.3	0.4
0.3	**65**	**129**	**194**	**259**
0.4	**55**	**111**	**166**	**222**
0.5	**46**	**92**	**138**	**185**
0.6	**37**	**74**	**111**	**148**
0.7	**28**	**55**	**83**	**111**
0.8	**18**	**37**	**55**	**74**
0.9	**9**	**18**	**28**	**37**

The density change $\Delta\rho$ due to complete resaturation of the pores is given by the equation:

$$\Delta\rho = \varphi(\rho_w - \rho_s)(1-S) \qquad (2)$$

where S is the saturation prior to reinjection

For example, if water at 130 ^oC is reinjected into a 2-phase zone at 220 ^oC, having a saturation of 0.7 and porosity of 0.3, then the density change (when the pores are fully saturated with liquid) will be about 83 kg/m^3 (Table 1). The controlling factors are again the temperature of reinjectate, and values for the saturation and the porosity.

Experience suggests that reinjection into a 2-phase zone can result in a “bulls eye” gravity change anomaly of several hundred microgal amplitude, extending radially for several kilometers from the reinjection well(s). Such an anomaly indicates that the horizontal permeability in the zone is isotropic. However, the shape of the anomaly may be distorted by anisotropic horizontal permeability or by lateral movement of the reinjectate towards a region of low pressure such as the production zone. Numerical modelling of such anomalies suggests that the region of resaturation has the shape of a cone; in effect the raising of the deep liquid level in a cone of impression (Lo, 1992; syn.: cone of recharge).

Unfortunately, “commercial considerations” prevent the presentation here of some good examples of such reinjection in New Zealand.

2.3 Reinjection into a single-phase liquid zone

In this case the reinjected water is being introduced into rocks in which the pores are already saturated with hot liquid water. Experience and theory suggest there are two general situations:

2.3.1 Reinjection into a deep liquid zone beneath a 2-phase zone.

Experience at Wairakei, described below, suggests that if the water is reinjected into a single-phase liquid zone at a relatively shallow depth beneath the two-phase zone then the water displaces some (or all) of the water in the pores near the well upwards, causing the lower part of the two-phase zone near the reinjection well to be resaturated, and thus the deep liquid level to be raised.

In the late 1980's, a thirteen-month reinjection trial was held at Wairakei in which about 5.2 Mt of waste separated water (130 °C) was injected (under gravity) into the deep single-phase liquid zone beneath the Eastern Borefield using well Wk 62. This 637 m deep, vertical well was drilled in 1958, and had a major feed zone at 450 m depth. Originally it was a high-pressure production well, but subsequently pressures and temperatures fell and it was progressively derated to low-pressure by 1975 and was shut down in 1984. Microgravity measurements were made at about 100 benchmarks in the vicinity of the well, immediately before and after this trial. The measurements, corrected for known elevation changes, showed that a crescent-shaped gravity anomaly with an amplitude of nearly 100 µgal (Fig. 2) was associated with the reinjected fluid (Hunt et al, 1990; Hunt & Kissling 1994).

Analysis of the microgravity and pressure data suggested that the reinjection had resulted in the formation of a crescent-shaped, cone of impression in the deep-liquid level, with a height of about 50 m (Figs. 3). The shape and lateral extent of the cone suggested that the reinjected fluid had flowed westwards towards the Western Borefield (at that time the main production area), and north-eastwards towards the centre of the main ground subsidence bowl (Allis, 2000). Reservoir simulation modelling suggested (Hunt & Kissling, 1994) that the reinjection resulted in two regions of increased density: one at about 450 m depth close to the injection point (Deep Liquid Zone Temp. = 200 °C) and the other at about 300 m depth where the deep liquid level had been displaced upwards into the 2-phase Zone (Fig. 3). The latter region had much larger density changes (up to 90 kg/m^3) and was closer to the surface, hence it dominated the gravity signal.

Subsequent gravity measurements suggest that after the reinjection had stopped the cone of impression decayed with time (collapsed) due to lateral flow (Fig. 4).

Another example is that of a possible natural downflow in a disused well in Tauhara Geothermal Field. Tauhara is contiguous with Wairakei Geothermal Field, which has been exploited since the early 1950's. Several deep exploration wells (TH1-4) were drilled in the northern part of the Tauhara field during the 1970's, but no significant production from these wells has occurred. However, pressure data from these exploration wells show that there has been pressure drawdown of about 2 MPa, indicating a good hydrological connection with Wairakei.

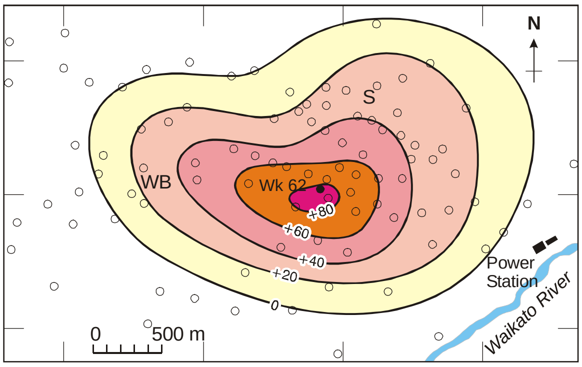

Fig.2. Gravity changes (µgal) associated with the reinjection trial using well Wk 62 at Wairakei. Open circles indicate measurement points. WB indicates Western Borefield, S is the centre of the area of ground subsidence. Taken from Hunt et al. (1990).

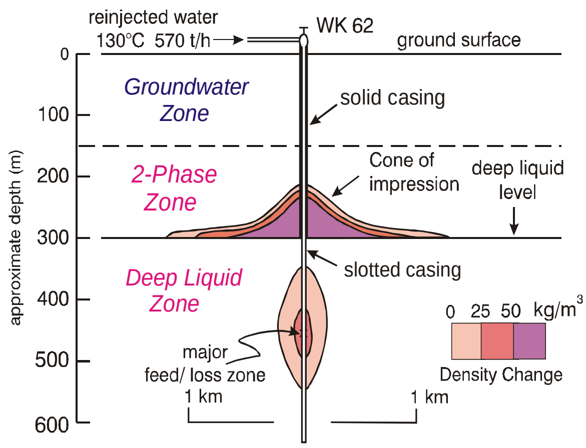

Fig. 3. Sketch showing density changes associated with reinjection trial using well Wk 62 at Wairakei, derived from a numerical reservoir simulation model. Adapted from Hunt & Kissling (1994).

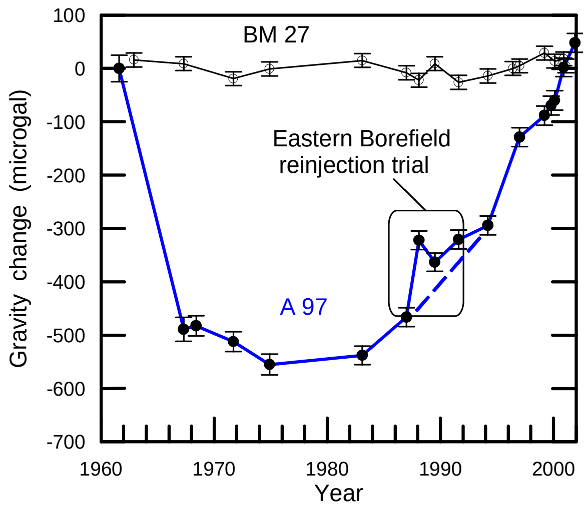

Fig. 4. Gravity changes (µgal) with time at benchmark A97, near Wk 62, showing effect of the reinjection trial. Values are also shown, for comparison, for BM27 which lies outside the field. Locations of these benchmarks are shown in Fig. 8.

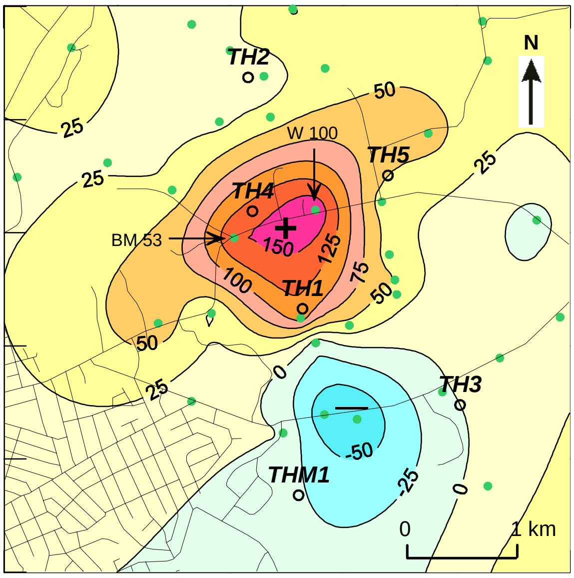

Fig. 5. Gravity changes (µgal) in the northern part of Tauhara Geothermal Field for the period 1985-2002. Solid dots are measurement points, open circles are deep wells.

Microgravity measurements in the northern part of the Tauhara field began in 1972, and repeat surveys over the whole of the Tauhara field were made in 1985, 1996 and 2002. In the northern part of the field there were large gravity decreases prior to 1985, associated with pressure drawdown from production at Wairakei. Since then, there have been gravity increases here of up to about +175 µgal, corresponding to a mass increase of about 20 Mt, centred near deep well TH4 (Hunt et al., 2003).

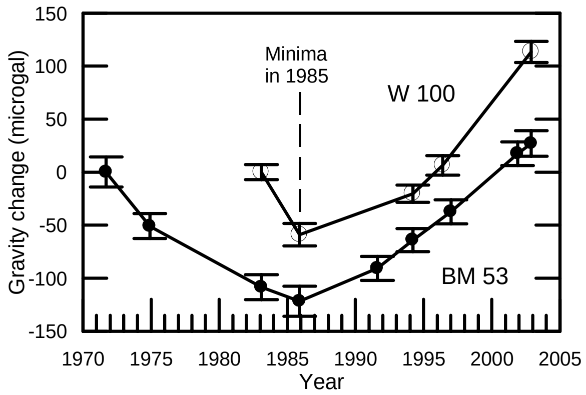

Fig. 6. Gravity changes at two benchmarks near the centre of the gravity high near well TH4, Tauhara field. Note the change in the trend of gravity changes about 1985. Adapted from Hunt et al. (2003).

Hunt et al (2003) suggest that these gravity changes result from a downflow of water in the well (via a known casing break at 24 mRL, 393 m depth) from a confined groundwater aquifer, which has resulted in localised resaturation of steam and/or 2-phase conditions in the upper part of the geothermal reservoir.

Simple 2.5-d modelling of the gravity changes along an east-west profile through the gravity increases suggests the region of resaturation is consistent with a cone of impression about 150 m high and extending for 1-2 km laterally from the well (Fig. 5).

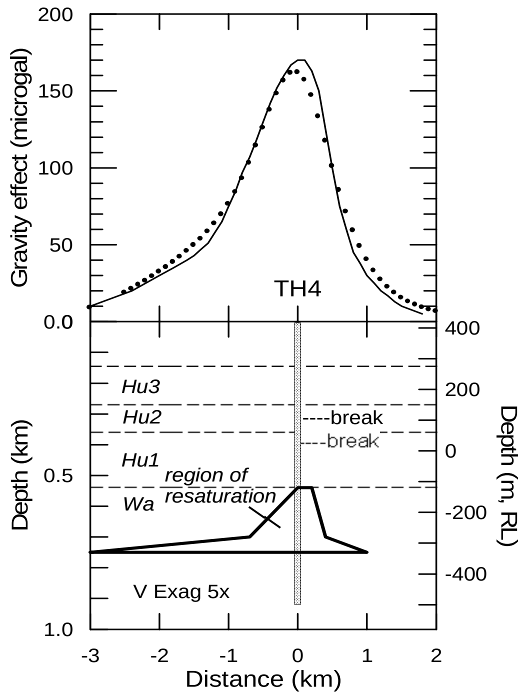

Fig. 7. A simple interpretation of gravity increases (1985-2002) in part of Tauhara field. Profile (E-W) is centred on TH4. Solid line is measured changes, taken from Fig. 5; solid dots are computed values for the region of resaturation (assumed to extend ±225 m normal to the profile line).

2.3.2 Reinjection distant from the two-phase zone.

Because liquid water has very low compressibility (approx. 5.10^{-10} Pa^{-1}), reinjection may cause lateral displacement of fluid resident in pores near the reinjection well, and the consequent introduction of the same volume of water into a steam- or 2-phase zone, or into a partially saturated formation, some distance from the reinjection well. In these cases the reinjected water is replacing water, not steam, and so the mass (and density) change in the pores near the well will be much smaller and the associated gravity change will be small. Even if the water is reinjected into a cold groundwater aquifer, the density change at the point of reinjection is small. For example, if reinjectate at a temperature of 130 ^{o}C replaces water at 10 ^{o}C the density change is a decrease of only 65 kg/m^3, compared to replacing steam at 220 ^{o}C in which case the density change is an increase of 923 kg/m^3 (Raznjevic, 1976). The largest gravity change associated with reinjection in this case is likely to be where it causes liquid to replace steam.

If the reinjected water displaces a slug of water some distance away from the reinjection point, the gravity value at a measurement point above the reinjection point would be expected to first increase due to the extra mass associated with the temperature decrease, but subsequently decrease with time because, as reinjection (at the same temperature) continues, then the region of mass change moves away from the reinjection point. Thus for small increments of time, the region of maximum gravity change between the start and end of that time period, would progressively move away from the reinjection point. However, if the gravity values at the reinjection point before reinjection starts are compared with those at some later date there should always be a gravity increase.

Early in the 1990's several wells were drilled near the Wairakei Power Station for the purposes of reinjection. Some of these are strongly deviated in a vertical plane to enable the bottom sections of the wells to target potential host formations up to 2 km distant from the well heads. Reinjection into these wells started in late 1994, but significant amounts of water were not reinjected until late 1997. Tests showed that the best injection wells were Wk 308 and Wk 310 (Fig. 8). By the end of 2001 about 58 Mt had been injected of the 378 Mt withdrawn from the field. Circulation losses during drilling of these wells suggest that the reinjected water leaves Wk 308 at about 450 m depth in the Karapiti Rhyolite Formation, and in Wk 310 at about 800 m depth in the Waiora Formation. Here, both these formations are believed to have been fully saturated before reinjection started. The reinjected water has a temperature of about 130 ^oC, and the data from other (exploration) wells in the area (Wk 34, 226) indicate at 450 m depth in the Karapiti Rhyolite the temperature is about 200 ^oC, and at 800 m in the Waiora Formation the temperature is about 250 ^oC. The reinjected water is thus about 70-120 ^oC cooler than the resident water it replaces.

Repeat gravity measurements were made at benchmarks in the eastern part of the field in 1991.6 and 1994.2, before reinjection commenced. After reinjection began, measurements were made at 55 benchmarks in 1997.0, 1999.2, 2000.1, 2000.9 and 2001.9; in addition a limited survey was made in 1999.8.

The gravity changes for the period 1994-2001 (Fig. 8) show that the largest changes (> 300 μgal) occurred in the now-disused Eastern Borefield (benchmarks A97, H1215), and the pattern extends in a northwest direction. In the Western Borefield area the changes were about +100-200 μgal. Application of Gauss's Theorem to the data for 1994-2001 gives a value for the net mass gain in the field of about 40 Mt.

There were no significant gravity changes in the vicinity of the injection (loss) points in the reinjection wells Wk308 and 310, into which most of the waste water had been reinjected (Fig. 9). This is surprising, considering the mass of water injected and that the reinjected water has a density of about 70 - 135 kg/m^3 greater than the water originally in the vicinity of the reinjection wells at the depths of the injection points. The lack any significant gravity changes here could be due to either the reinjected water quickly exiting the area (along high permeability paths) or to it being rapidly reheated.

The closest region of steam and/or 2-phase conditions into which water might be displaced is beneath the Western Borefield. For the period 1997.0-2001.9, the measured gravity changes in the Western Borefield (+100-200 μgal) are only about half of those calculated for a mass of 40 Mt (400 μgal), but are closer to those measured in the Eastern Borefield (300 μgal). This suggests that a significant portion of the reinjected water, or an equivalent mass that had been displaced, did not remain beneath the Western Borefield but was drawn off again (recycled) or entered the steam zone (now mainly 2-phase conditions) beneath the Eastern Borefield.

The asymmetrical shape of the profile of measured gravity changes (Fig. 9) suggests resaturation has occurred mainly in the south-eastern part of the zone. The measured changes can be approximately matched by the gravity effects of a triangular model representing a density increase of about 80 kg/m^3 (Fig. 9); this corresponds to a mass increase of about 18 Mt. Assuming reasonable values of 0.3 for φ, 865 kg/m^3 for ρ_w (200 ^oC), and 8 kg/m^3 for ρ_s, and substituting ΔS for (1-S_0) in Equation (1), we obtain a value of about 0.3 for the increase in liquid saturation in the region being resaturated.

However, interpretation of the gravity changes is best done by using a reservoir simulator equipped with a gravity processor.

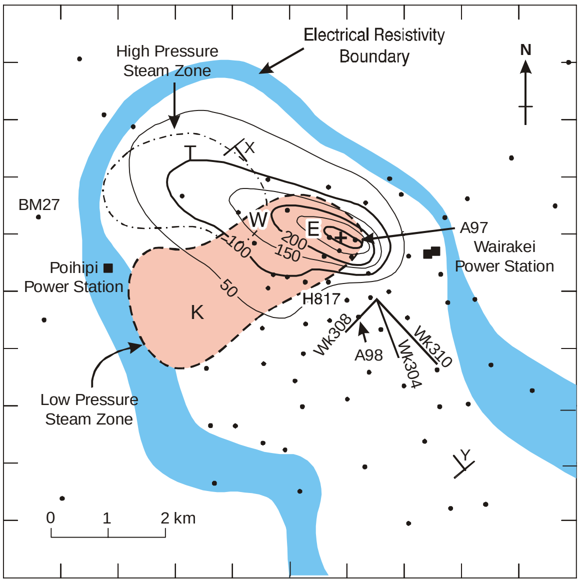

Fig. 8. Map showing the gravity changes for the period 1994-2001, location and paths of the reinjection wells, and location of benchmarks used in the microgravity surveys. Crosses indicate location of injection points on the reinjection wells. Letters W, E, and T mark the approximate positions of the Western, Eastern and Te Mihi borefields respectively. K marks Karapiti Thermal Area. X and Y show the location of the profile given in Fig. 9.

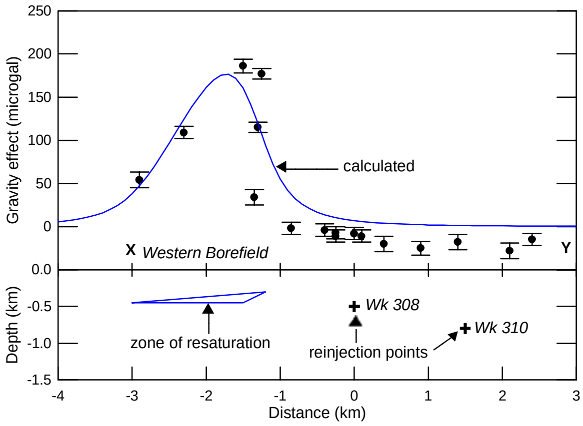

Fig. 9. Calculated gravity effects for a model representing direct resaturation of the steam zone beneath the Western Borefield by the water reinjected into Wk 308 (mainly) and Wk 310. Crosses mark the reinjection points in these wells. Locations of points X and Y are shown in Fig. 5. Solid dots show measured gravity changes for the period 1997.0-2001.9. Note the lack of any significant gravity changes (increases) near the reinjection points. The zone of resaturation represents a net mass increase of about 18 Mt.

4. CONCLUSIONS

- Repeat gravity measurements can be used to track reinjection of amounts of water as small as 5 Mt into steam or 2-phase zones of an exploited liquid-dominated reservoir.

- The gravity signature of reinjected liquid water depends on the conditions in the region into which the water is reinjected: steam zone, 2-phase zone, single-phase liquid zone beneath 2-phase zone, or single-phase liquid zone distant from unsaturated conditions. The largest gravity signature is likely to occur where liquid water resaturates a steam or 2-phase zone, and this may occur some distance from the reinjection point. Secondary effects include: replacement of hot liquid water by cooler reinjectate, heating of reinjectate by the rock matrix and existing pore fluid, condensation of existing steam by reinjectate, and changes in liquid density as a result of pressure changes associated with reinjection.

- Interpretation of the measurements may be complicated by recycling of reinjected water.

ACKNOWLEDGEMENTS

Some of the work reported here was carried out with funding from the NZ Foundation for Science, Research & Technology. C.J. Bromley and W.M. Kissling are thanked for providing useful discussions and comments on the manuscript.

REFERENCES

Allis, R.G., 2000. Review of subsidence at Wairakei field, New Zealand. *Geothermics* 29, 455-478

Allis, R.G., Gettings, P., Chapman, D.S., 2000. Precise gravimetry and geothermal reservoir management. *Proceedings 25 th Workshop on Geothermal Reservoir Engineering*, Stanford University, 179-186.

Allis, R.G., Hunt, T.M., 1986. Analysis of exploitation-induced gravity changes at Wairakei geothermal field. *Geophysics* 51, 1647-1660.

Clotworthy, A., 2000. Response of the Wairakei geothermal reservoir to 40 years production. *Proceedings World Geothermal Congress 2000*, 2057-2062.

Hunt, T.M., 1995. Microgravity measurements at Wairakei Geothermal Field, New Zealand; a review of 30 years data (1961-1991). *Proceedings World Geothermal Congress 1995*, 863-868.

Hunt, T.M., Bixley, P.F., Carey, B.S., McCabe, W.M., Young, R.M., 1990. Results of a 13-month reinjection test at Wairakei geothermal field, New Zealand. *Geothermal Resources Council Transactions* 14, 1193-1200.

Hunt, T.M., Kissling, W.M., 1994. Determination of reservoir properties at Wairakei geothermal field using gravity change measurements. *Journal of Volcanology & Geothermal Research* 63, 129-143.

Hunt, T.M., Graham, D.J., Kuroda, T. 2003. Gravity changes at Tauhara Geothermal Field. *Proceedings 23rd NZ Geothermal Workshop*, 121-126.

Lo, S., 1992. *Glossary of Hydrology*. Water Resources Publications, Littleton, Co. USA. ISBN 0918334748.

Raznjevic, K. 1976. *Handbook of thermodynamic tables and charts*. McGraw-Hill. 392p. ISBN 0070512701.