GRAVITY CHANGES AT TAUHARA GEOTHERMAL FIELD

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SUMMARY: Microgravity measurements in the northern part of the Tauhara field (Wairakei-Tauhara geothermal system) 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 +175 pgal,, corresponding to a mass increase of about 20 Mt, centred near deep well TH4. It is suggested these gravity changes result fiom 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 resaturation of steam and/or 2-phase conditions in the upper part of the geothermal reservoir. Gravity changes in the central part of the field since 1985 have been less than -70 pgal indicating little net mass loss (<2 Mt), and hence little effect in this area of production from Wairakei.

1. INTRODUCTION

Tauhara Geothermal Field 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 fiom these wells has occurred. However, pressure data fiom these exploration wells show that there has been pressure drawdown, indicating a hydrological connection with Wairakei (Fig. 1). The deep pressure drawdown also appears to have induced ground-subsidence at Tauhara of up to 100 mm/yr, localised in subsidence bowls near Rakaunui Road and Spa Hotel (Allis et al, 2001).

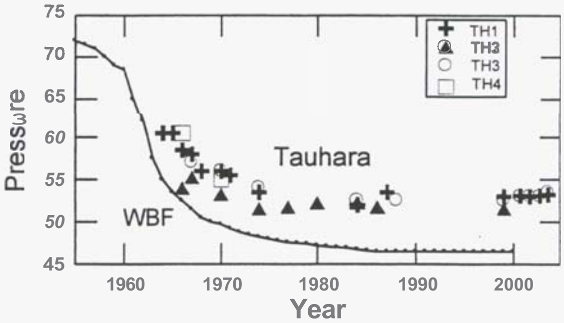


Fig. 1. Pressure changes in **wells** TH1-4 at Tauhara and Wairakei (western borefield, WBF) taken from Contact Energy (1999).

Allis *et al* (1989) noted that despite the deep pressure drawdown there had been no significant chemical or thermal changes to surface features in the southern part of the Tauhara field. They noted that this **was** in contrast to the changes that had occurred to thermal features in the northern part of the field since the early 1960's. This led them to suggest that there had been no pressure drawdown in the southern part, and that a separate geothermal system existed in the southern part of Tauhara field. Since no deep wells exist in the southern part it has not been possible to verify this conclusion.

Measurements of pressure change in the deep wells at Tauhara indicate that by the early 1980s a steam zone, about 50 m thick, had formed in the northern **part** of the field (Allis, 1983). By the late 1990s, three steam zones had been identified in this area:

a) **A** shallow steam zone at about 280-350 m(RL) which feeds surface features such **as** the craters at Taupo Pony Club.

b) ***An*** intermediate steam zone lying at about 50–150 m(RL), in the middle (Huka-2) unit of the **Huka** Falls Formation.

c) **A** deep steam zone in the upper part of the Waiora Formation that lies beneath the lowest (Huka-1) unit of the Huka Falls Formation. This zone has been estimated to be about 150 m thick with the top lying at about -100 m(RL) (Contact Energy, 1999; Menzies & Lawless, 2000).

2. PREVIOUS GRAVITY DATA

Repeat gravity measurements have been made at benchmark BM53 in the northern part of Tauhara field since the early 1970s, and at several other benchmarks since the early 1980s, **as** part of surveys of the Wairakei field. The measurements at **BM53** suggest that fiom the 1970s until the mid 1980s there were negative gravity changes of more than 100 pgal associated with the pressure drawdown (Fig. 2).

If there has been pressure drawdown in the southern part,, then there must have been mass withdrawal fiom that part of the field. If such mass withdrawal was similar to that in the northern part of the field then repeat gravity measurements would show that there had been negative gravity changes there. Such changes might be expected to be of a similar magnitude to those measured at BM53.

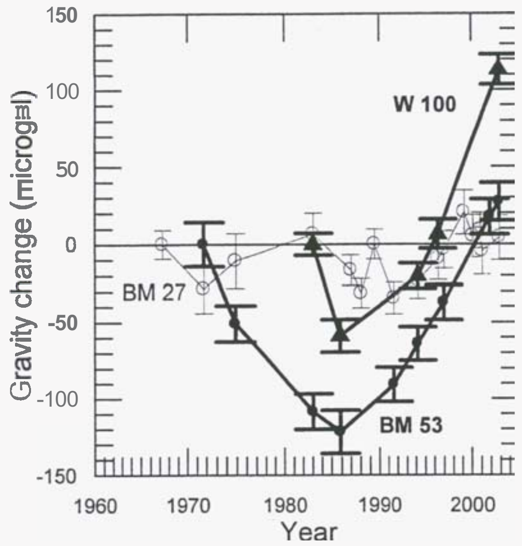


Fig.2. Gravity changes at benchmarks WIOO and BM53 in the northern part of Tauhara field. Note the decreases until 1985, followed by increases. Also shown, for comparison, are changes at BM27 outside the field which show no significant variation.

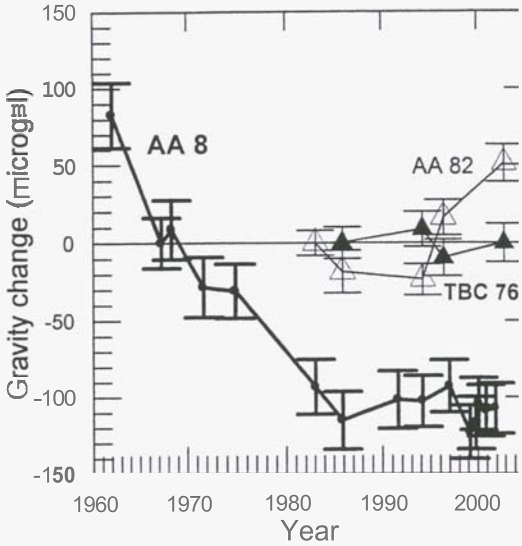


Fig.3. Gravity changes at benchmark AA8 in the northern part of Tauhara field. Note the decreases until 1985, followed by no change. Also shown are changes at AA82 and TBC76 in the centre of the field.

The first survey aimed at measuring gravity in other parts of the Tauhara field **was** made in 1985.9, but the first attempt to cover the whole of the field was not made until 1996.4. We report here the results of a further survey, made in 2002.9, and compare the data with those fiom previous surveys in an attempt to verify the suggestion of Allis *et al* (1989).

3. GRAVITY MEASUREMENTS

All gravity measurements were made using LaCoste & Romberg meter G-106, calibrated on the Wellington Calibration Range. Standard microgravity field techniques were used, and the measurements reduced in the manner described by Hunt (1984), relative to a base station at Taupo Fundamental benchmark.

Corrections were made for ground level changes (subsidence) using repeat levelling data and a value of -300 µgal/m for the vertical gravity gradient (Hunt & Sugihara, 2000).

To correct for any significant gravity changes that had occurred at the base station, measurements were made at several benchmarks located well outside the Wairakei and Tauhara fields. For the period 1996-2002 the mean change at 9 benchmarks located well outside these fields is -16 ($\pm$11) µgal. This suggests a change in the value of gravity had occurred at the base, probably due to groundwater level changes, and so a base correction of 16 µgal was made to the gravity changes for this period. There are insufficient data to allow determination of a base correction for the period 1985-1996.

No corrections have been made for the gravity effects of changes with time in groundwater level (shallow, unconfined aquifer) or changes in soil moisture saturation in the vadose zone. However, we estimate such effects to be less than 20 pgal.

4. GRAVITY CHANGES 1961-1985

Gravity data for this period are confined to only a few benchmarks situated in the area between the Wairakei and Tauhara fields. These data show large decreases in gravity associated with production-induced pressure drawdown at Wairakei (Allis & Hunt, 1986; Hunt & Ikeda, 1994). For example, at benchmark AA8, situated near well TH2, there was a gravity decrease of about 200 pgal between 1961 and 1985 (Fig. 3).

5. GRAVITY CHANGES 1985-1996

A contour map of the gravity changes for the period 1985-1996 (Fig. **4)** shows gravity increased by about 50 pgal at benchmarks BM 53 and **W** 100 on Centennial Drive, near Fletchers Mill. In the centre of the field, south of these marks there was an area of small decrease with an amplitude of about 35 pgal. In the southern part of the field there were gravity increases of 32, 43 and 65 pgal.

6. GRAVITY CHANGES 1996-2002

A contour map of the gravity changes for the period 1996-2002 (Fig. 4) shows a large, near-circular shaped, area of gravity increase occured in the northern part of the Tauhara field, centred on benchmark W 100. The amplitude of this

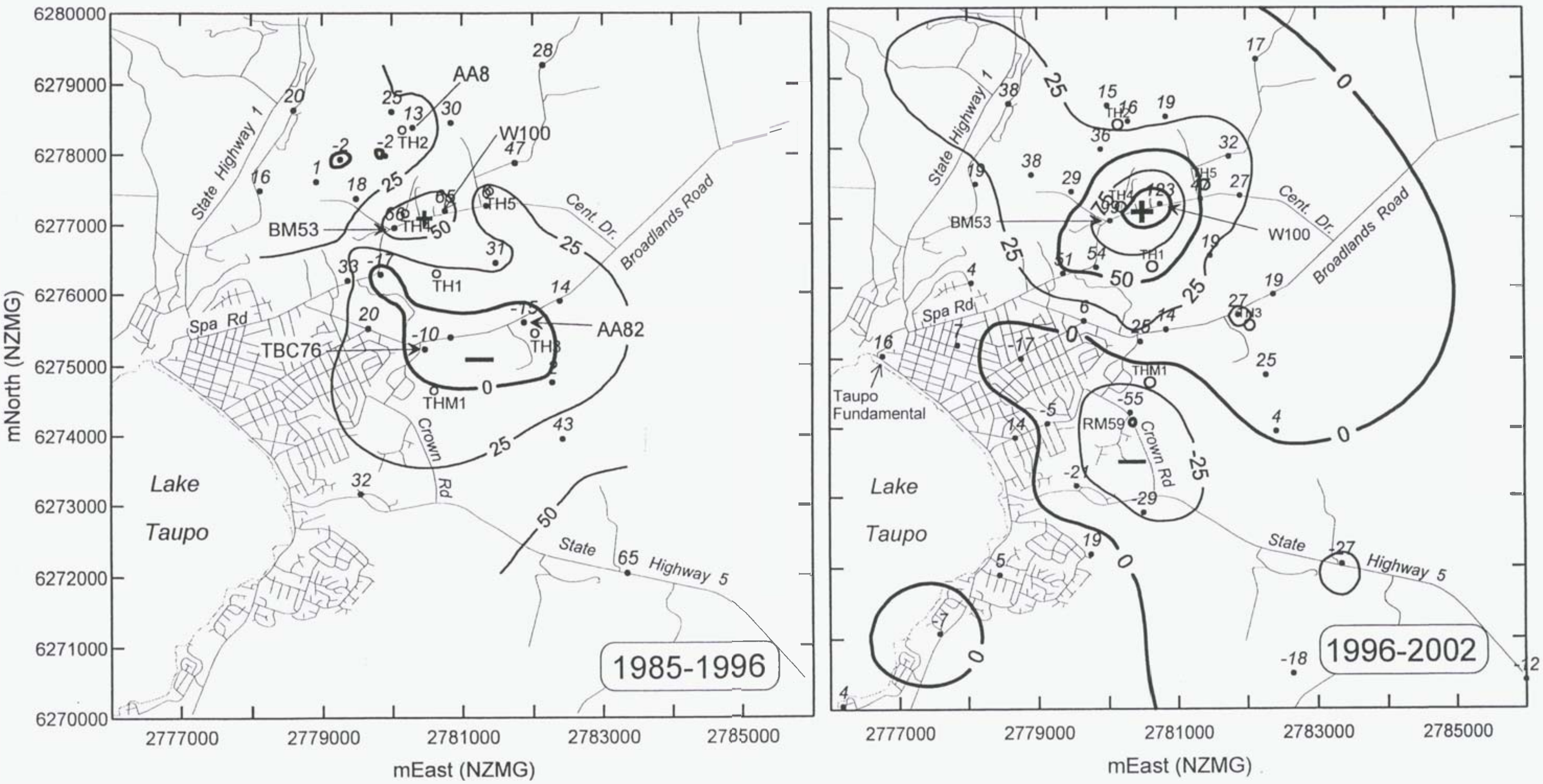


Fig. 4. Gravity changes (μgal) in Tauhara field for the period 1985-1996 and 1996-2002. Solid dots are measurement points, open circles are deep wells. Note the gravity increases (>50 μgal) at benchmarks W 100 and BM53 in the northern part and decreases in the central part of the field.

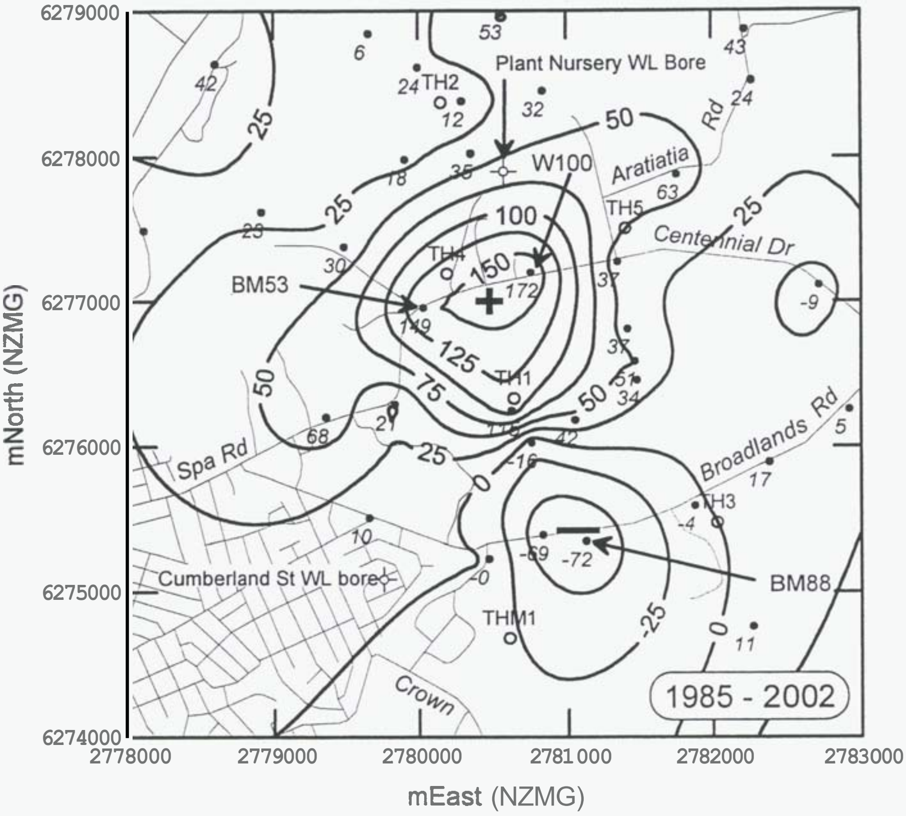


Fig. 5. Gravity changes (pgal) in northern and central parts of Tauhara field for the period 1985-2002. Compiled directly from data for 1985 and 2002. Symbols as for Fig. **4**.

increase was greater than 100 pgal. It is clear **from** the record of gravity changes at W 100 and BM 53 (Fig. 2) that they have been occurring since 1985, and the total increases in gravity at these benchmarks since this date are about 175 and 150 pgal respectively (Fig. *5*). In the centre of the field, south of these marks, there is an area of small decrease with an amplitude of about 25 pgal. There is some uncertainty about the value of -55 pgal change at RM 59 (Fig. **4)** because the same point may not have been occupied in each survey.

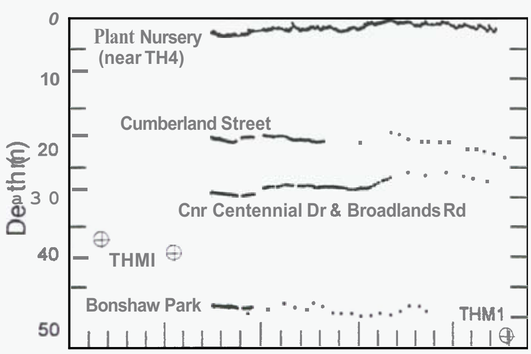
7. INTERPRETATION

7.1 Gravity increases in the northern part of Tauhara field.

The most likely explanation for the large gravity increases centred near Centennial Drive, which began in 1985 (Fig. 5), is that they result from liquid resaturation of two-phase or steam zone conditions resulting **from** pressure drawdown associated with production from Wairakei.

Measurements in shallow monitor wells show that there have been no significant changes in the level of the shallow unconfined groundwater level in the area (Plant Nursery bore, Fig. *6*). It is therefore probable the water comes from a deeper, confined groundwater aquifer overlying the deep geothermal reservoir at Tauhara.

The centre of the area of gravity increase lies close to the disused deep well TH4 (1038 m total depth; cased to 914 m) that was drilled in 1967. Data from this well shows that since about the mid 1970s there are casing breaks at 105 m RL (3 12 m depth, Huka-2) and 24 m RL (393 m depth, Huka-1). No measurements have been made in this well below the breaks since the mid 1970s. On 11 September 2003 the well was temporarily put on bleed and discharged steam **(A.** Maxwell, pers. comm.). We suggest that the lower break is allowing liquid from a groundwater aquifer in the Huka-1 unit to enter the reservoir, and that the steam is **from** the intermediate steam zone (Huka-2) and is entering the well at the upper break.



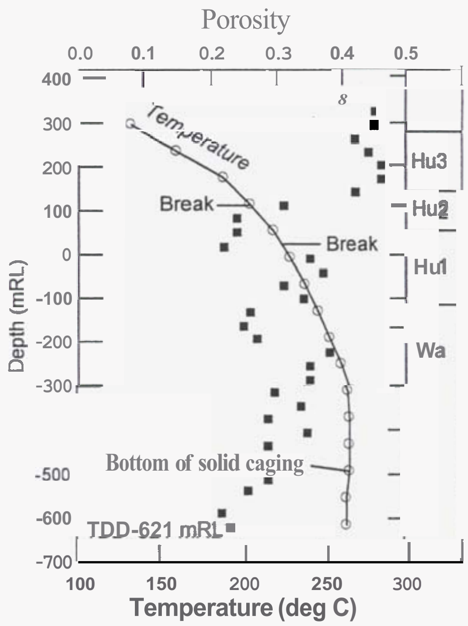


Fig. 7. Variation of temperature (May 1972) and porosity with depth in well TH4. Geological column on right hand side: Hu is **Huka** Fm., Wa is Waiora Fm.

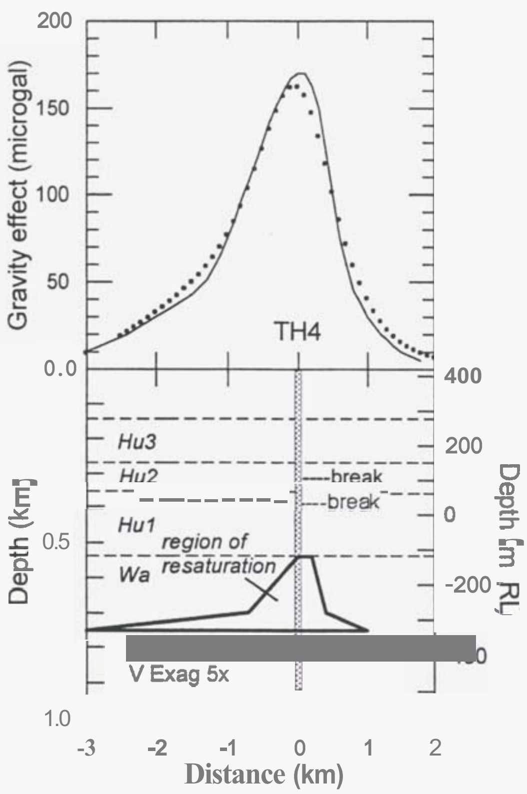


Fig.8. A simple interpretation of gravity increases (1985-2002) in northern part of Tauhara field. Profile (E-W) is centred on TH4. Solid line is measured changes, taken from Fig. 5; solid dots are computed values for the region of resaturation (assumed to extend ±225 m normal to profile line).

From numerical integration of the gravity increases near TH4 for the period 1985-2002 (Fig.5) and application of Gauss's Theorum (Hunt, 1970) it is determined there was a net mass increase in this area of about 20 (±5) Mt. This determination is independent of any assumptions of depth or porosity of the host rocks, and suggests that between 1985 and 2002 at least 20 (±5) Mt of water entered the deep reservoir via this downflow – more if some of the water in the supply aquifer was not completely replaced

Temperature measurements in TH4, before any significant effects of a downflow might have occurred, indicate the temperature at about the depth of the lower casing break (24 mRL) was 220 °C (Fig. **7;** Contact Energy, 1996). The density of liquid water at 220 "C is about **840** kg/m^3, therefore the volume of water in such a downflow, between 1985 and 2002, would have been about 24 (±5) x **10**^{6} m^3. The average rate of downflow would be about 130 t/hr (0.7 l/sec).

If the gravity increases are associated with a downflow in TH4, it is likely that the downflowing water exited from the well in the region of slotted casing at a depth range of about -500 to -600 mRL. The outflow of water then displaced single-phase liquid into the overlying steam zone, upwards in the form of a cone of impression, in a similar manner to that which occurred during gravity-fed reinjection at Wk62 in the Eastern Borefield at Wairakei (Hunt et al, 1990). In the latter case, most of the measured gravity increases were associated with the resaturation of part of the steam zone, rather than the influx of cooler water at the injection depth.

Assuming the steam zone temperature is 250 °C, its porosity is 0.3 (Fig. 7), and residual saturation is 0.3, then resaturation would cause a density increase of about 165 kg/m^3. However, the influx of downflowing water in the region **of** slotted casing (temperature 265 °C, porosity 0.2, residual saturation 0.3) would result in a density increase of only about 10 kg/m^3. Similarly, if the downflowing water was replaced in the groundwater aquifer (porosity 0.4, residual saturation **0.3)** by cooler water having a temperature of (say) 100 "C, then the density increase in the aquifer would be about **33** kg/m^3. The gravity increases thus reflect mainly the resaturation of the steam zone.

Simple 2.5-d modelling (Webring, 1985) **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. 8).

7.2 Gravity changes in other parts of the Tauhara field

In the northern part of the field, prior to 1985, there were gravity decreases of about 10 µgal/yr as a result of the pressure drawdown (Fig.2). However, there have been no similar rates of gravity decrease in the other parts of the field since then. The largest decreases between 1985 and 2002 have been at benchmarks BM 88 and H 1193A, situated on Broadlands Road, near the Pony Club, where the changes have been only about -70 pgal (about -4 µgal/yr). The data suggest that significant mass changes have not extended much further south than the Crown Road area. This is consistent with the absence of changes to thermal features in the southern part of the field (Allis et al. 1989; Bromley & Glover, 1996). However the gravity changes could also be the result, in part at least, of deep groundwater level changes. In monitor well THMl the water level fell by about 15 m between 1985-2002 (Fig. 6), which would be expected to result in a gravity decrease of about 15 pgal.

Numerical integration of the gravity changes (Fig. 5) and application of Gauss's Theorum (Hunt, 1970) provides a value of about 2 (±1) Mt for the net mass loss in this area between 1985 and 2002.

8. IMPLICATIONS

The presence of this previously unsuspected mass increase has not been taken into account in any numerical simulation modelling published so far (Contact Energy, 1999; Menzies & Lawless, 2000). The resaturation of the deep steam zone will need to be included in any future modelling.

9. ACKNOWLEDGEMENTS

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