

Microgravity measurements at Wairakei Geothermal Field, New Zealand; a review of 30 years data (1961 - 1991)

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Key Words: Wairakei, gravity changes, recharge, reinjection

ABSTRACT

Twelve repeat, precise gravity (microgravity) surveys have been made at Wairakei Field between 1961 and 1991, spanning most of the production period. Gravity changes determined from these surveys, and corrected for the effects of ground subsidence and groundwater level changes, have proved to be a powerful tool for monitoring changes which occur in the reservoir during exploitation. The results have proved helpful for economic and environmentally responsible management of the field.

Gravity data show that during the initial period of production there was little recharge; fluid was mined from beneath the main production borefield and an area to the northwest. After about 5 years production, natural recharge rose to about 100% and has since remained near that value. In the early 1970s positive gravity changes, indicating net mass gain, were measured in the borefield, and are interpreted as being caused by a rise in the deep liquid level in that area. By the late 1980s these gravity increases had extended to an area south of the borefield.

Gravity data, taken before and after a reinjection test in the Eastern Borefield show the reinjected fluid had mainly flowed westwards towards the Western Borefield and northeastwards towards the centre of ground subsidence. The reinjection caused the deep liquid level to rise in a cone of impression about 50 m high, which slowly subsided after the test. Analysis of the gravity and pressure data obtained during the test indicates values of about 10 d-m for k_h and 9×10^{-6} m/Pa¹ for ρ_{ch} , for the upper part of the reservoir.

INTRODUCTION

Wairakei Geothermal Field (Fig. 1) was the first liquid-dominated field to be exploited, and the second in the world to be developed for generating electric power. Scientific investigation of the field began in 1949 and shallow exploratory drilling commenced in 1950; since then about 150 exploration and production holes have been drilled. Later, electrical resistivity measurements showed the field to extend over an area of about 15 km², and to consist of two main parts: Wairakei, and Tauhara (Fig. 1). Most production is from 200-700 m depth, and from the Wairakei part of the field. In 1958 the Wairakei Power Station began generating base load, electric power. The installed capacity of the station was gradually increased from 69 MWe until it reached 192.6 MWe in 1963; in 1983 four generators were removed because of a decrease in the amount of HP steam available and the installed capacity was reduced to 157.2 MWe (ECNZ, 1992). Electrical production rose to a peak of about 1300 GWh/yr in 1967 and has remained at more than 1100 GWh/yr since then.

Mass withdrawal started in 1952, but remained less than 20 Mt/yr (1 Mt = 10⁹ kg) until commissioning began in 1958. After 1958, withdrawal increased to a maximum of 73 Mt/yr in 1963, and then declined to about 44 Mt/yr in 1991 (Fig. 2). Nearly all the production fluid has been removed from the system; the only

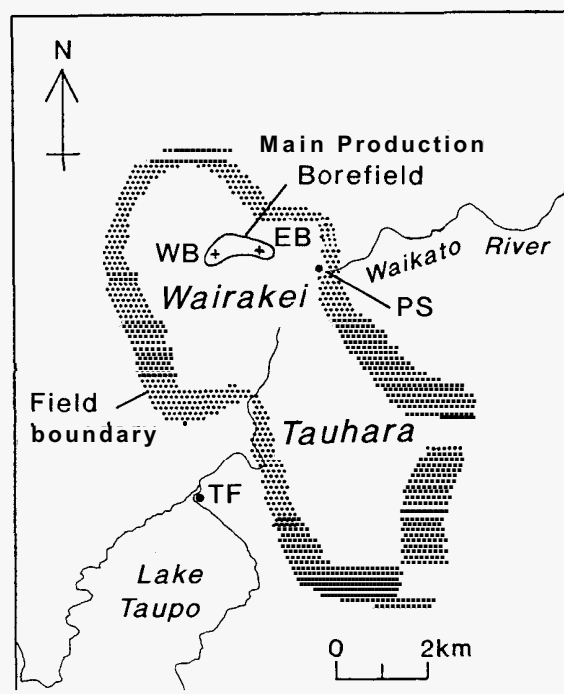


Fig. 1: Wairakei Geothermal Field. Field boundary is as defined by electrical resistivity measurements. WB and EB mark location of Western and Eastern borefields; PS the Power Station; TF the gravity base station.

significant reinjection was during a test (1988-89) when about 5 Mt was returned to the reservoir (Hunt et al, 1990b). Since 1958, about 1700 Mt of fluid has been taken from the reservoir (Fig. 2); assuming an average temperature of 200°C, this represents a volume of nearly 2 km³. Natural surface mass flow from the Wairakei part of the field prior to exploitation was about 400 kg/s (12.6 Mt/yr), and has decreased steadily since then to about 200 kg/s (6.3 Mt/yr) in the early 1980s (Allis, 1981). Natural discharges are therefore only a small fraction (<15%) of the amount of fluid removed by exploitation.

In its natural (unexploited) state, the Wairakei Geothermal System is believed to have contained a liquid-dominated two-phase zone overlying a single-phase deep liquid zone (Grant and Home 1980; Donaldson et al, 1983). The nomenclature used here is that of Allis and Hunt (1986).

When exploitation began, production was mainly from the deep liquid zone beneath a small area (1 km²) known as the Main Production Borefield (Fig. 1), hereafter referred to as the "borefield". Removal of fluid resulted in a pressure drop which caused boiling to occur in the upper part of the reservoir. The two-phase zone expanded both laterally and vertically, and by the early 1970's was about 500 m thick. The two-phase zone also divided into two parts: an upper zone called the "steam zone" or "vapour-dominated zone" in which steam is the main pressure-controlling phase; and a lower zone called the "liquid-dominated zone" in which liquid water is the continuous phase but boiling conditions exist and some steam is present (Allis and Hunt, 1986). The boundary between these zones is believed to be gradational, but there is little information available about the vertical distance over which the changes occur. The steam and liquid-dominated zones may not be homogeneous; liquid saturation in the steam zone may be smaller at the top of the zone than at the bottom (Hunt, 1988). Pressures in the deep liquid zone beneath the two-phase zone fell by up to 2.5 MPa (25 bar), but have been relatively stable in most parts of the field since the early 1970s (Fig. 2). However, gravity and pressure data suggest that in the eastern part of the borefield (Fig. 1), the deep liquid level has risen by nearly 100 m since the early 1980s (Hunt, 1988). Deep liquid pressure measurements indicate that this two-phase zone now extends to the boundary of the field north and west of the borefield, but its lateral extent in other directions is not clear.

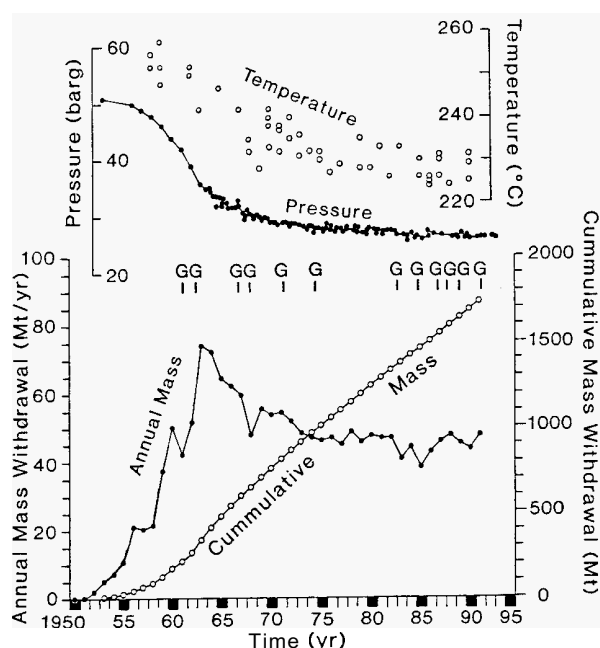


Fig. 2: Mass withdrawal, pressure, and temperature changes with time at Wairakei. Pressures are averages for the borefield at 152 mbsl (approx. 450 m depth). Temperatures are for liquid-fed production wells in Western Borefield. G indicates times of microgravity surveys. Data from ECNZ (1992).

The withdrawal of mass and the formation of a two-phase zone led to large density changes in the reservoir. Conversion of liquid water at 200°C to vapour at the same temperature involves a density change of about 860 kg/m³, and assuming a porosity of 0.3 and residual saturation of 0.5, the density change is about 130 kg/m³. Formation of a 100 m thick steam zone will cause a gravity decrease of about 500 microgal (1 microgal = 0.01 µN/kg = 10⁻⁸ m/s²) which is easily measurable (Hunt and Allis, 1986).

GRAVITY MEASUREMENTS

Detailed gravity surveys were made at Wairakei in 1950 to assist in interpreting the geology of the area. The measurements were made at survey pegs, 1200 ft (365 m) apart, along 8 profile lines through the field. Despite several diligent searches of the archives, the original field observations have not been found; the only data available are computed Bouguer anomalies from which it is not possible to recover the values of gravity.

In the early 1960s it was recognised that large masses of fluid were being lost from the system which might give rise to gravity changes. Accordingly, precise gravity (microgravity) measurements were made by W I Reilly in Aug. 1961 at about 60 permanent concrete benchmarks in and around the field, and a repeat survey was made by C J Banwell and others in Nov. 1962. The differences between the 1961 and 1962 gravity values, however, revealed numerous large (up to 1 mgal) and irregularly distributed differences and the technique was discarded. In 1966, I found the survey data in the archives, and having made some theoretical calculations from the mass production values available, decided there should have been coherent, measurable gravity changes. Examination of the survey data suggested that many of the 1962 observations were erroneous; probably as a result of tares or observer error. A further microgravity survey was therefore made in April 1967, which showed consistent gravity decreases of up to 510 microgal had occurred since 1961 (Hunt, 1970), and demonstrated that the technique was viable. This has led to 9 further microgravity surveys, over all or parts of the field, in: April 1968, Sept. 1971, Dec. 1974, Jan. 1983, Feb. 1985, Jan. 1987, Jan. 1988, May 1989 and July 1991 (Fig. 2).

GRAVITY DIFFERENCES

Allis and Hunt (1986) showed that the main causes of differences in gravity at Wairakei, between surveys, are:

- net mass loss from the geothermal reservoir;
- vertical ground movement;
- changes in shallow groundwater level.

To determine the gravity effects of net mass loss the differences must be corrected for vertical ground movements and changes in groundwater level; the corrected differences are referred to as **gravity changes**.

The gravitational effects of changes in topography, horizontal ground movements, uncertainties in gravity meter calibration, and regional gravity changes due to deep mass movements, are small (<30 microgal) and can be neglected (Allis and Hunt, 1986).

Vertical ground movement

Most vertical ground movements in response to exploitation have been subsidence; in one part of the field it has reached a maximum of 11 m. The amount of subsidence has been determined from 2nd order levelling surveys at about 500 benchmarks and survey marks on pipe support structures in and around the field. Since the first survey in 1950, 18 levelling surveys have been made but not all have extended beyond the field as far as the gravity surveys. The elevation changes at the gravity benchmarks, between the times of the gravity surveys, have been determined by interpolation of the elevation change data or from maps of subsidence rate (Fig. 3).

The gravity effect of the subsidence is calculated from the elevation change and the vertical gravity gradient. For gravity surveys prior to 1983, a normal "free-air" gradient of -308.6 microgal/m was adopted, but for later measurements a measured gradient of -302 (± 5) microgal has been used (Hunt et al., 1990). Simple calculations, using reasonable models, show that the effect of mass withdrawal has negligible effect (<5 microgal/m) on the

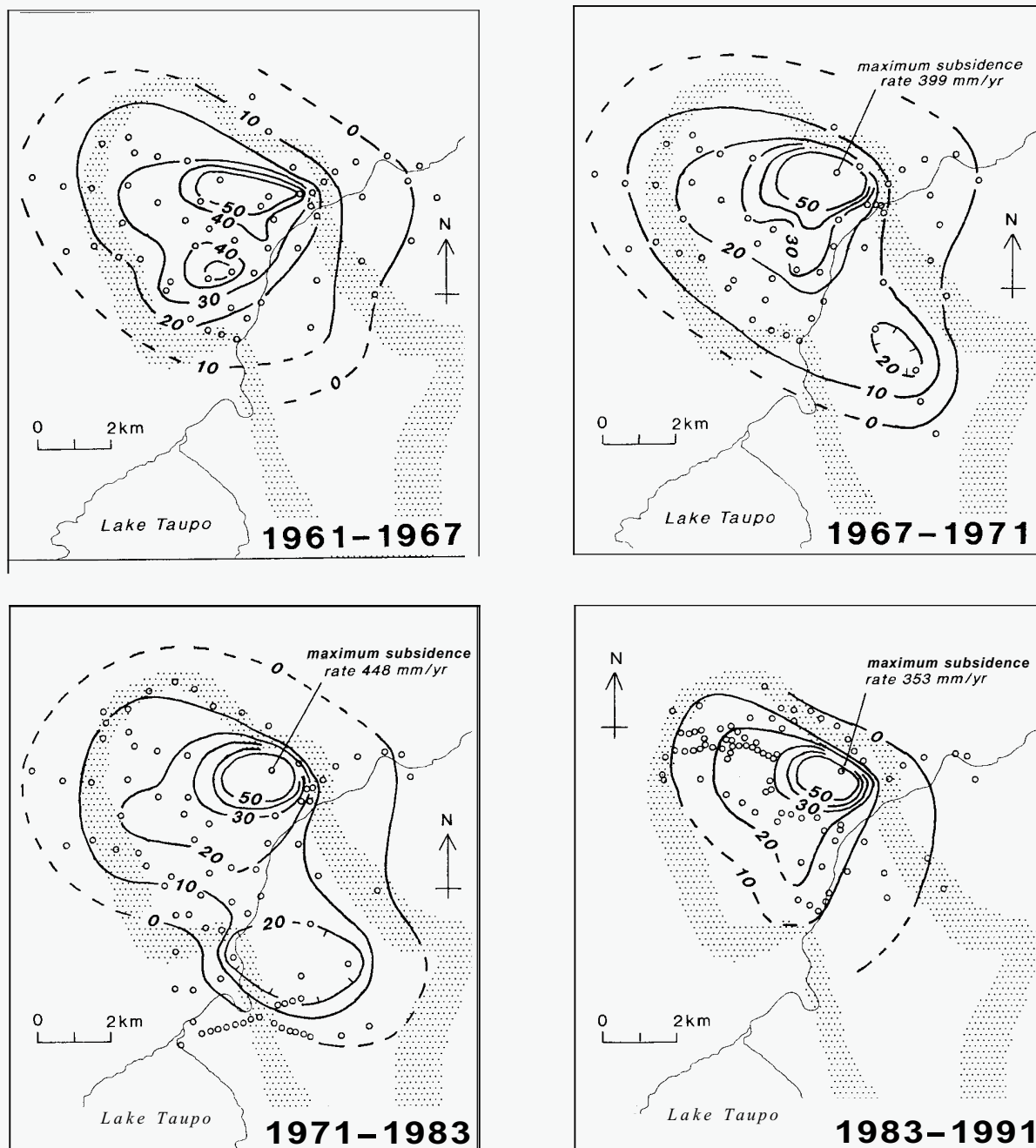


Fig. 3: Subsidence rates (mm/yr) at Wairakei. Numerous data points and contour lines in the borefield area have been omitted for clarity.

gradient (Reilly and Hunt, 1976): the gradient is dominated by the mass of rock and immobile fluid which remains unchanged by the fluid changes. Lateral changes in the gradient, resulting from lateral density changes associated with geological structures, have not been investigated.

Changes in groundwater level

At most places in the field, the geothermal reservoir is overlain by a cold groundwater zone; only near some discharging thermal features is the groundwater hot. The top of the groundwater zone is generally between 5 and 25 m below the surface. The depths of groundwater level have been regularly measured in 7 (1955) to 35 (1993) shallow monitor holes (< 60 m deep). These data (Fig. 4) show that over most of the field the water level varies by about

2 m due to variations in rainfall. However, in a small part of the borefield the water level has fallen by up to 30 m; this has been attributed to a cold downflow caused by pressure decrease in the two-phase zone resulting from exploitation (Bixley, 1990). It has been estimated that by the late 1970s about 200 kg/s (6.3 Mt/yr) of cold water was being drawn down into the reservoir (Allis, 1982); about half of this being associated with internal flows in shallow-cased wells, and half along natural high-permeability paths. By the mid-1980s most of the internal flows were stopped by modifications to the wells.

To determine the mass changes in the reservoir the gravity differences need to be corrected for the gravity effects of change in groundwater level. For Wairakei, the gravity effect is about -10 microgal/m fall in water level (Allis and Hunt, 1986).

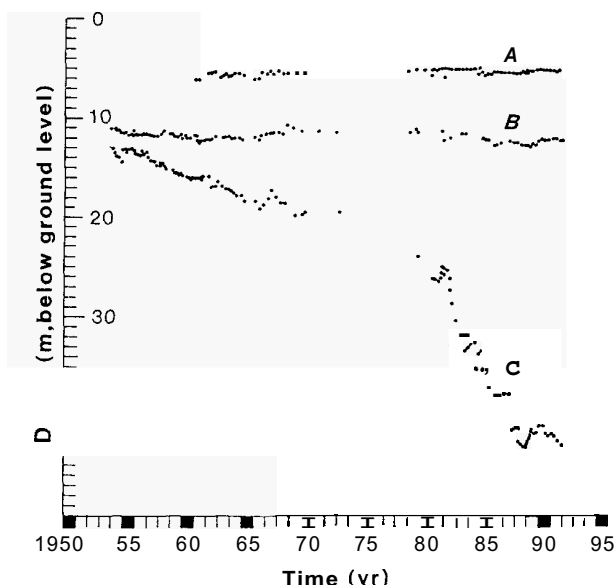


Fig. 4: Changes in groundwater level with time at Wairakei. Plots **A** and **B** are typical of monitor wells in most parts of the field; Plot **C** is for a monitor well close to the area of cold downflow in the borefield. Data have not been corrected for ground subsidence, but the effect of this is small.

GRAVITY CHANGES

For convenience, a decrease in gravity is referred to as a negative change and an increase a positive change. Negative changes imply net mass loss; positive changes imply net mass gain.

Causes of change

Allis and Hunt (1986) have shown that the main causes of gravity change, associated with mass changes in the reservoir are:

- liquid drawdown in the two-phase zone;
- saturation changes in the two-phase zone;
- changes in liquid density due to temperature changes.

The gravity effects of pressure-induced liquid density changes, pore compaction, and mineral precipitation at Wairakei are insignificant (<10 microgal).

Distribution of changes

For convenience, the gravity changes have been divided into four periods: 1961-1967, 1967-1974, 1974-1983, and 1983-1991 (Fig. 5). The data clearly show that:

- During the early 1960s, there were large, negative gravity changes in and west of the borefield, which even extended beyond the field boundary.
- During the 1970s and early 1980s there were no large, widespread gravity changes, although there were significant negative changes in a small area west of the borefield, and positive changes in the Eastern Borefield.
- During the late 1980s there were large positive gravity increases in the Eastern Borefield, and smaller positive changes in an area extending about 4 km south of the borefield.

INTERPRETATION OF GRAVITY CHANGES

The long and detailed history of gravity changes at Wairakei, covering most of the exploitation period of the field, has allowed techniques for interpretation to be developed and refined. The principal uses (although not necessarily independent) of microgravity data, discovered at Wairakei, are:

Determination of areas of mass loss or gain

From contour maps of gravity change (Fig. 5), localised areas of net mass loss or gain over a specific period can be identified. The data (Fig. 5) show that in the initial production period there was a net mass loss from most of the Wairakei part of the field; this loss being associated with development of the two-phase zone (Allis and Hunt, 1986). In the late 1960s and 1970s the net mass loss was confined to areas west of the borefield. In the late 1970s and 1980s there was a net mass gain in the borefield area, particularly in the Eastern Borefield; this gain was associated with a rise in the deep liquid level (Hunt, 1988).

Determination of mass changes

By integrating the gravity changes and substituting in Gauss's Potential Theorem (Hammer, 1945) the net mass changes can be calculated for specific periods and field-wide values for recharge determined (Hunt, 1970). Such calculations show (Table 1) that recharge was low (<50%) during the early 1960s (initial development period), but in the late 1960s and 1970s had increased to about 100%. By the late 1980s more fluid was flowing into the reservoir than was being withdrawn; most of this excess being in the Eastern Borefield where the lower part of the two-phase zone was being resaturated and the deep liquid level was rising. Total mass loss at Wairakei, up to 1991, is estimated to be nearly 2000 Mt and recharge to be about 1670 Mt (Table 1). These values are independent of any assumptions about porosity, permeability, or density. Uncertainties in these values, apart from those associated with intrinsic measurement errors, are caused mainly by errors in numerical integration (La Fehr, 1965) and the estimate of natural mass loss from surface thermal features. For Wairakei, the values of recharge are estimated to have an uncertainty of about 15%.

TABLE 1: Mass discharge and recharge values for Wairakei

Period	MB	MN	MT	IS	MC	MR
1950-61	145	125	270	na	-100?	170
1961-67	360	55	415	-71	-235	180
1967-74	400	60	460	-13	-35	425
1974-83	390	45	435	0	0	435
1983-91	375	40	415	+19	+45	460

MB	=	Mass withdrawn from borefield (Mt)
MN	=	Natural mass discharged (Mt)
MT	=	Total mass loss from surface (Mt)
IS	=	Integrated sum of gravity changes ($\text{N m}^2/\text{kg}$)
MC	=	Net mass change (Mt)
MR	=	Mass recharge (Mt)

Determination of saturation changes

Pressures and temperatures in the two-phase zone at Wairakei have decreased by up to 2.5 MPa (25 bar) and 50°C respectively (Fig. 2) due to loss of steam, or cooling and condensation as a result of cold downflows. With the former, liquid saturation decreases as immobile water boils off due to pressure decrease: cooling and condensation cause the saturation to increase with time.

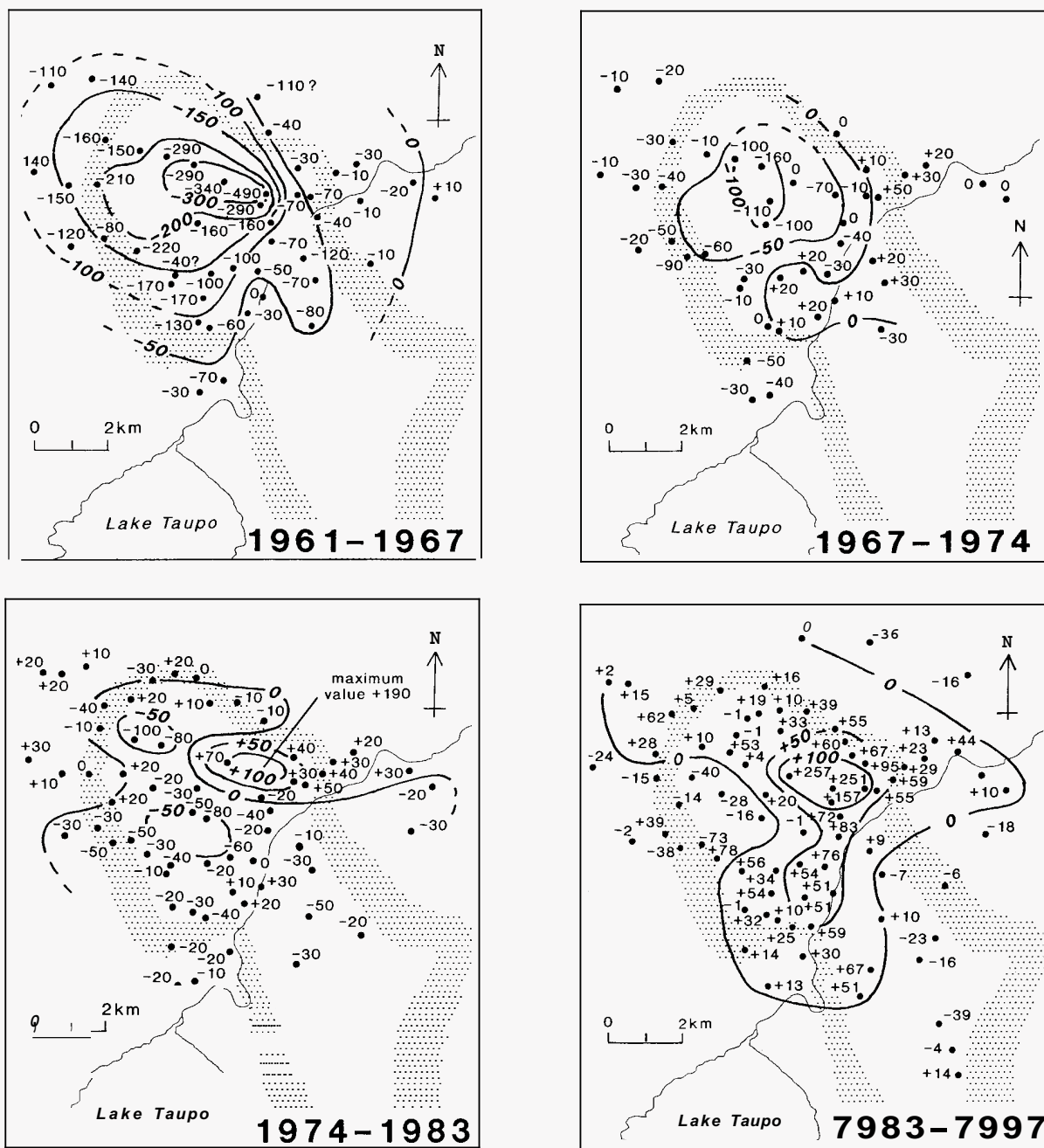


Fig. 5: Gravity changes (microgal) at Wairakei

Allis and Hunt (1986) derived equations relating gravity changes to saturation changes, and by simple (1D) modelling showed that in the Eastern Borefield the average liquid saturation in the 2-phase zone fell to about 0.7 by 1962, and 0.6 by 1972. Subsequent analysis (Hunt, 1988) suggested that saturation, and saturation changes, are unlikely to be uniform with depth in the two-phase zone. The best way to determine saturation changes with time is by numerical reservoir simulation modelling; the saturation in each block is adjusted until a match is achieved with measured enthalpy, pressure, temperature, chemistry, and gravity changes.

Tracking the path of reinjected fluid

During a reinjection test in 1988-89, about 5.2 Mt of separated water (130°C) was injected at a near-constant rate (570 t/h) into the centre of the Eastern Borefield for 13 months. Gravity changes of up to +80 microgal associated with the reinjection were measured.

A contour map of the gravity changes is roughly crescent-shaped, centred near the reinjection well, with one arm extending towards the Western Borefield and the other towards the centre of ground subsidence (Hunt et al, 1990b). Interpretation of the data suggest the reinjected fluid flowed out of the well into the deep liquid zone and displaced the deep liquid level upwards in a cone of impression about 50 m high, and extending in two, near-perpendicular directions for about 1.5 km.

Determination of reservoir properties

Analysis of the pressure and gravity change data collected during the reinjection test showed that the cone of impression in the deep liquid level was a transient phenomena. During reinjection the cone rose, and after reinjection ceased it collapsed as the liquid within it flowed away laterally. This led to the realisation that the rate of formation and collapse of such a cone was related to

reservoir properties; mainly to permeability (k) or permeability-thickness (kh). Furthermore, by monitoring gravity changes during and after such reinjection the size of the cone, and its rate of change, could be determined and from this values for the reservoir properties in the vicinity of the reinjection well. Analysis of the gravity change data using analytical reservoir models provided values of: 9.9 d-m for kh, and 9.2×10^{-6} m/Pa for storativity, assuming isotropic permeability: 18.2 and 5.4 d-m for maximum and minimum kh, and 8.7×10^{-6} m/Pa for storativity, assuming anisotropic permeability (Kissling and Hunt, 1992).

MULKOM model calculations show that the gravity changes associated with permeabilities of 50 and 100 md would be clearly distinguishable (>50 microgal) within two years of the start of exploitation at Wairakei (Hunt and Kissling, 1994). A measured gravity change of -415 microgal at a benchmark in the Eastern Borefield, for the period 1950-1961, suggests a permeability of 100 md for rocks in the upper part of the two-phase zone; this value is consistent with those obtained from well tests (50 - 500 md) and from reservoir simulation models (10 - 300 md). An important result of the theoretical calculations, however, is that the gravity changes during formation and expansion of a two-phase zone, such as at Wairakei, are strongly dependent on the permeability; analysis of gravity change data during this time can lead to estimates of permeability.

Validation of numerical simulation models

Hunt et al (1990a) showed that gravity change data could be used to test the validity of numerical reservoir simulation models constructed using other data. This is in effect the converse of using gravity change data to determine saturation changes and reservoir properties, where the model is presumed to be valid. Gravity change data have not yet been used in conjunction with detailed models for Wairakei; such models are still confidential.

LESSONS LEARNT

The use of microgravity data to help with management of geothermal systems under exploitation is now a standard procedure in New Zealand, and is generally required as a condition of a developer obtaining a Resource Consent. They are also standard practice in the Philippines at Tiwi and Bulalo fields. Development of the technique was done mainly at Wairakei field, and in the process we learnt:

1. It is important that a good baseline data set is obtained before exploitation begins.
2. The gravity surveys need to be accompanied by surveys to monitor ground subsidence and groundwater level changes.
3. The measurement points need to extend well beyond the field boundaries to locate areas where reinjected fluid may be going, and to determine the significance level of the measurements.
4. The largest changes occur in the early stages of exploitation and are associated with development of a two-phase zone: surveys at this time need to be frequent.
5. The greatest benefits are achieved when the gravity change data are used in conjunction with numerical reservoir simulation models.

ACKNOWLEDGEMENTS

I thank my colleagues R G Allis, H M Bibby, W M Kissling, and W I Reilly, who over the years have provided valuable constructive criticism. ECNZ have generously provided data without which this work could not have been published. Publication has been funded by NZ Foundation for Science Research and Technology.

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