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HISTORY OF GEOPHYSICAL STUDIES AT WAIRAKEI

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SUMMARY - Geophysical studies at Wairakei started shortly after investigations began and have made a major contribution to defining the geothermal system and to understanding the changes which occurred in the reservoir as a result of production. The most successful tools have been the electrical resistivity technique for delimiting the field, and microgravity, heat flow, and groundwater monitoring for helping to understand the production-induced changes. Seismic, gravity and magnetic anomaly techniques have had only limited success.

1 INTRODUCTION

Unlike other developed or prospective geothermal fields in New Zealand, Wairakei was not located and delineated by geophysical methods before drilling began. At that time (1950), geophysics in New Zealand was in its infancy and was used mainly to try and understand the nature of the geothermal resource, rather than its lateral extent. Exploration of the field during the 1950's and early 1960's was instrumental in the formation of the Geophysics Division in 1951, and had a major *impact* on the development of geophysics within the Department of Scientific and Industrial Research (DSIR) during that time. "Special Economic Requirements", including investigation of geothermal resources and hydro-electric *systems*, were one of three main factors in the geophysical programme of DSIR during the period 1951-76 (Hatherton, 1980).

Most early (1950's and 1960's) geophysical results were not formally published, but conveyed orally by DSIR to Ministry of Works and Electricity Dept staff at meetings, or in "Geothermal Circulars" having very limited distribution. Later results have generally been published in national and international scientific journals, and presented in Resource Consent Applications (ECNZ 1990, 1992).

The role of geophysics at Wairakei can be divided into two aspects: defining the system, and understanding the changes to the geothermal system in response to development.

2. DEFINING THE SYSTEM

Although the presence of high-temperature geothermal fluid at shallow depth and some indication of its wide lateral extent had been determined from exploratory drilling, it was considered desirable to ascertain the limits or boundaries of the Wairakei *system* and its internal *structure* by geophysical means.

2.1 Electrical Methods

The potential for using electrical resistivity surveying for mapping thermal regions was recognised at the beginning of the Wairakei investigations. The high temperatures and salinities of *geothermal* fluids were known to have much lower resistivities than cold water in non-thermal ground. Early tests at Wairakei used Wenner electrode arrays which were expanded to an electrode spacing of 200 ft (60 m) but the results were disappointing (Studt, 1951; Dawson, 1989). The available instruments (Gish-Rooney) were unable to accurately measure the small signals generated in the high-resistance potential circuit, and thus resistivities of less than about 50 Ωm could not be resolved. In the early 1960s, Geophysics Division staff overcame this problem with development of measuring equipment of home-grown design. The receiver circuit was based on a laboratory-type DC vacuum-tube voltmeter having a very high input impedance and was capable of measuring voltages as small as a few microvolts. Wairakei became the proving ground for this equipment and for the development of resistivity surveying to define geothermal fields. Use of the Wenner electrode array, with four collinear electrodes *spaced* 1800 ft (549 m) apart, proved suitable for measuring average resistivity to a few hundred metres depth. Maps of the results (Fig 1) showed for the first time that resistivities of thermal ground at Wairakei were very low (c. 5 Ωm) and contrasted sharply with much higher values (>100 Ωm) in the cold ground away fiom the field (Banwell and Macdonald, 1965; Hatherton et *al.*, 1966). Many ingenious mechanical devices for laying and picking up cables fiom 4WD vehicles to speed up the measurement process were also developed.

The resistivity mapping at Wairakei was an important milestone in establishing resistivity surveying as a means of defining geothermal fields, but it came too late to have significant impact on the first phase of drilling and development at Wairakei. For most of the 1960s and 1970s the efforts of DSIR in resistivity prospecting were put into other fields and improving measurement techniques.

During 1978-82, resistivity surveys at Wairakei were made using Schlumberger electrode arrays (AB/2=500 m and AB/2=1,000 m), which had superseded the Wenner array (Fig. 2). In 1982 the first survey at Wairakei was made with the deeper penetrating multiple-source bipole-dipole array. Several Schlumberger resistivity soundings were also made. These new surveys gave a better delineation of the field than the earlier ones (Risk, 1984; Risk *et al.*, 1984).

More recent resistivity surveys have been aimed at addressing particular resource issues, such as locating the path of reinjected thermal water.

2.2 Gravity and Magnetic Methods

Gravity and magnetic measurements were made in an attempt to map geological structures which might channel the upflow of g e o t h d fluid.

About 1000 gravity measurements were made in the Wairakei-Taupo area during the early 1950's using a North American gravity meter (AG-196) and a Bouguer Anomaly map was compiled (Robertson, 1951; Beck and Robertson, 1955). A residual anomaly map, constructed fiom the data, showed a gravity "high" (amplitude 5 mgal) extended through the Wairakei field. Initially, a simple 2-D interpretation was made, based on the assumption that this "high" was *caused* by a horst in the underlying greywacke basement rocks (Robertson, 1951). However, later interpretations were more cautious; Beck and Robertson (1955) considered the "high" could also have been caused by "dense basic intrusions". Modriniak and Studt (1959) also made a 2-D interpretation of the residual anomalies and interpreted the high as a basement ridge extending to within 1.6 km of the surface - this was later disproved by drilling which failed to encounter greywacke at 2.2 km. Stem (1982) showed that the "high" could be explained entirely by lateral variations in density within the volcanic rocks (andesite, ignimbrite). No detailed 3-D interpretation of these gravity data has been made.

The first magnetic measurements at Wairakei were made in the 1930's, long before the geothermal developments began. Vertical force intensity measurements were made in the Waiora and Wairakei Valleys and it was found that the intensities were up to 200 nT below normal near vigorously active thermal features (Watson-Munro, 1938). The reduction in *intensity* was attributed to either demagnetisation of magnetite as a result of propylisation or temnerature were above the Curie Point at shallow depth.

In September 1950, an airborne magnetic survey was made at a flight height of 2500 ft (760 m asl) over a 13 x 13 mile area including the field using a flux-gate magnetometer (Baird, 1951). A residual Total Force Anomaly *map*, derived fiom the data, showed a magnetic "high" of about 800 nT centred in the southern part of the field (Beck and Robertson, 1955). This *"high"*, called the 'Target Anomaly', was matched by Modriniak and Studt (1959) to that *caused* by a vertical cylinder with a radius of 12,000 ft (3.65 km) and height of 6,500 ft (1.98 km) with a polarisation (intensity of magnetisation) of 2 x 10^{-3} c.g.s. units (2 A/m, sirnilar to values then measured for rhyolites).

A more extensive and detailed Vertical Force magnetic survey at ground level was made in the 1950's which confirmed that magnetic intensity values were low in the Waiora and Geyser Valleys and higher in the south-western part of the field near the centre of the "Target Anomaly" (Studt, 1959). Laboratory measurements on core samples fiom drillholes indicated that most of the magnetisation resided in magnetite within the ignimbrites, and that for ignimbrites with weak magnetisation, most of the magnetite had been converted to pyrite by h y d r o t h d alteration (Studt, 1959).

A further low-level (760 m asl) Total Force aeromagnetic survey was made in 1984. A 3-D interpretation of the residual anomalies (Soengkono and Hochstein, 1992) aided by additional rock magnetisation data fkom drill cores (Lampoonsub, 1987), indicated that most of the rocks within the field had been demagnetised by hydrothermal alteration; however, parts of the Karapiti Rhyolite and rocks beneath the Eastern Borefield had not been demagnetised. The *"Target* Anomaly" was modelled as a large, buried, andesite strato-volcano (Nukuhau Volcano) outside and s.w. of the field.

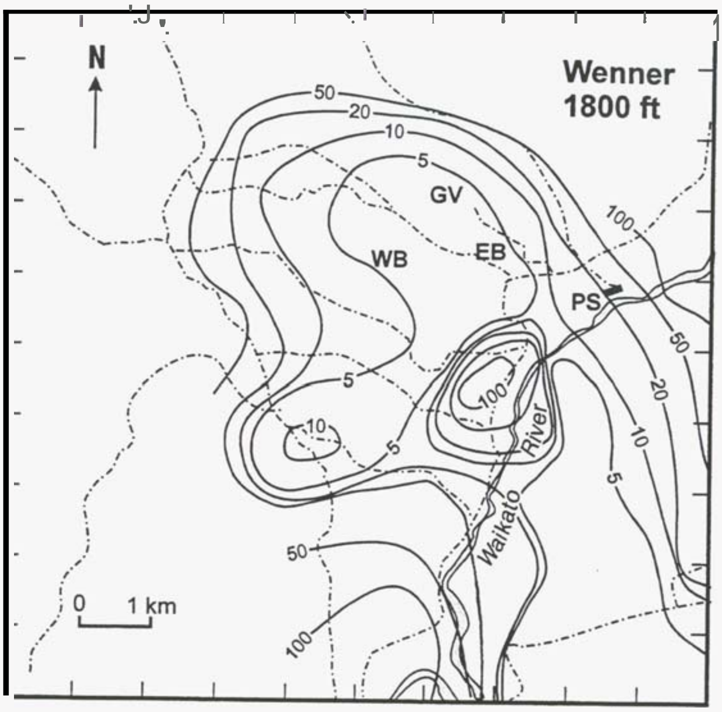

Figure 1 - Map of electrical resistivity (Ωm) made using a Wenner array with electrode spacing of 1800 ft (taken from Banwell & Macdonald, 1965). PS = Power Station, EB = Eastern Borefield, WB = Western Borefield, GV = Geyser Valley.

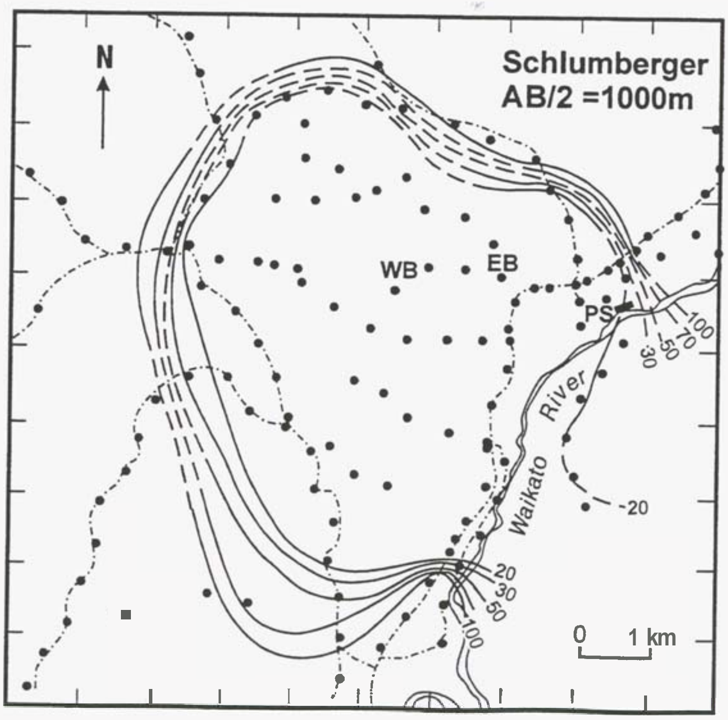

Figure 2 - Map of electrical resistivity (Ωm) made using a Schlumberger array with AB/2 = 1000 m (taken from Risk *et al.* 1984). Solid dots indicate the centres of the electrode arrays.

The magnetic measurements were unable to resolve any *structural* information within the field; the data merely showed regions where the rocks had been demagnetised by hydrothermal alteration. Since the process of demagnetisation is irreversible, the technique was unable to locate present upflow zones but much was learnt about the process of magnetisation and demagnetisation of rocks in geothermal systems.

2.3 Seismic Methods

Seismic reflection and refraction surveys were first made in New Zealand during the 1930s and 1940s, and proved useful for identifying underground *structures* in oilfields and dam foundations. Thus, shortly ater the commencement of the Wairakei project, seismic surveys were made in an attempt to determine underground *structure*. Measurements were made along several lines crossing the Wairakei field. However, compared with the earlier surveys, the conditions were less favourable. High levels of natural ground noise in the thermal areas and strong attenuation of the seismic waves often masked the seismic signals (Modriniak 1950,1951; Modriniak and Studt, 1959). Reflections could not be traced continuously, but the velocities of near-surface layers could be found from refraction data. The origins of groundnoise were subsequently investigated (Clacy, 1968; Whiteford, 1970) in the hope that this might help delineate the *system* and provide indications of high permeability at depth. However, detailed studies later showed the source region to be shallow and the vibrations to be predominantly surface waves (Whiteford, 1975).

Recently (1989-1991), more successful seismic reflection profiling has been done at Wairakei using the much improved modem seismic equipment. The seismic shots were set off in holes drilled to beneath the water table ensuring better coupling of the energy with the ground and higher signal levels. Modem signal processing techniques enable enhancement of the coherent reflections fiom the interfaces between layers. Good reflections, which could be traced continuously, were obtained from horizons in the Huka Falls Formation down to about 300 m depth.

2.4 Heatflow

Natural geothennal heatflow measurement techniques were extensively tested and developed over 30 years by early researchers at Wairakei (Benseman, 1959; Dawson, 1964; Robertson and Damn, 1964; Damn & Dickinson, 1970) because of a perceived link between natural surface heatflow and the long term sustainable energy yield of the resource. Heat losses from discharging hot *springs* were calculated from temperatures and flowrates, assuming an appropriate ambient temperature. Fumaroles were assessed using average vent velocity, cross-sectional area, and temperature, or relative *steam* plume sizes. Uncertainties arise when there are difficult vent geometries, unstable flows, and differing weather conditions. Evaporative heat loss from large pools and boiling mudpools *can* be calculated, but is dependent *on* wind, ambient temperature, isolation, and ebullition height, as well as area and temperature. Allis (1979) again modified the techniques, and some assessment methods (particularly for steaming ground) are still under review today (Walsh *et al.*, 1998). Dawson (1964) found a convenient means of classifying thermal ground for heatflow purposes using a thermal vegetation index, but this is also subject to large uncertainties due to residual soil acidity, micro-climatic and seasonal effects. The overall accuracy of the above techniques was assessed by *Allis* (1981) as ±25%.

Early assessments of total natural heat output from Wairakei thermal features (springs and steaming ground) varied between 600 MWt (Grange, 1955), based on physical measurements, and 340 MWt (Ellis and Wilson, 1955), based on natural chloride inflows to the Waikato River (including Spa Sights, Tauhara). The higher estimate was later revised downwards to 430 MWt (relative to 12°C) when amended heat flow factors for steaming ground were used (Fisher, 1964). Hochstein (1988) speculated that this revised value was still too high. Allis (1979) considered that Fisher's heat output weighting factors for low grade thed ground were appropriate, but an over-estimate was possible in areas of steaming ground. Both methods of estimating the natural heat output prior to development are subject to considerable uncertainty, and ignored any subsurface outflows of hot water from the field. However, a figure of approximately 400 MWt (± 25%) has been chosen (ECNZ, 1992) to allow comparison with later *estimates* of natural heat output changes.

3.0 UNDERSTANDING THE CHANGES CAUSED BY DEVELOPMENT

During the early stages of development it became clear that production caused changes to the hydrothermal *system* within the reservoir, and emphasis moved away fiom defining the system to monitoring and understanding the changes. Wairakei was the first developed field in which such changes were noticed, and several methods of geophysical monitoring were pioneered here.

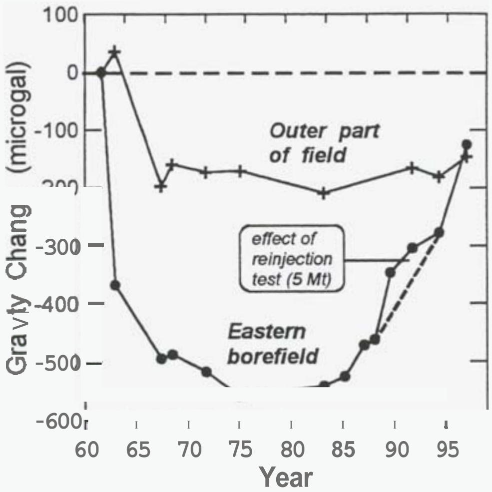

Figure 3 - Gravity changes at two benchmarks in Wairakei Field.

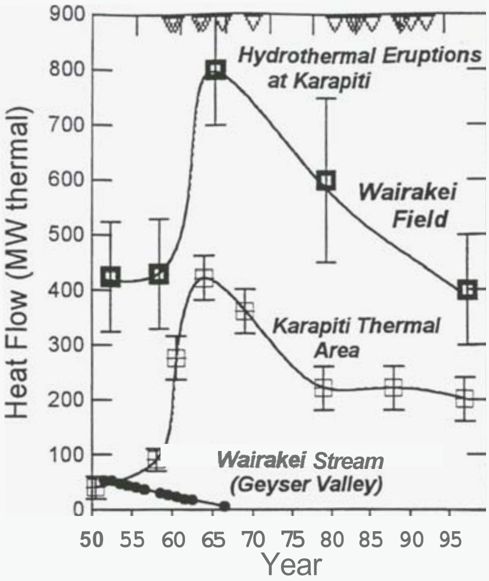

Figure 4 - Changes in heat flow, and times of hydrothermal eruptions at Karapiti Thermal Area.

3.1 Microgravity Changes

It was recognised that withdrawal of large volumes of geothermal fluid (without reinjection) could result in large mass changes in the upper part of the reservoir, and thus small gravity changes. Repeat precision gravity (microgravity) surveys were made in the 1960's which clearly demonstrated that detectable changes were occurring (Hunt, 1970). This led to development of the methodology required (Hunt, 1984), and an understanding of the causes (Allis and Hunt, 1986). Since the first microgravity survey in 1961, about 14 repeat surveys have been made (Hunt, 1995). The data showed 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 five years of 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 Eastern Borefield (Fig. 3), and interpreted as being caused by a rise in the deep liquid level in that area.

Gravity data taken before and after the 1987-88 reinjection test in the Eastern Borefield showed that the reinjected fluid had mainly flowed westwards towards the Western Borefield and north-eastward towards the centre of ground subsidence. Analysis of the data showed the reinjection caused the deep liquid level to rise in a cone of impression about 50 m high, which slowly subsided after the test (Hunt et *al.*, 1990). The gravity and pressure data obtained during the test was also used to determine reservoir properties such as permeability-thickness (10 d-m) and storativity (9×10^{-6} m/Pa) (Hunt and Kissling, 1994). The microgravity data has also been used to constrain numerical simulation models for the field (Blakely and O'Sullivan, 1985).

3.2 Heatflow Changes

After production at Wairakei began, changes in the natural thermal activity and associated heat flow were observed. Banwell (1954) noted patches of dead trees and hydrothermal eruptions at Karapiti Thermal Area, suggesting an increase in heat output. Chloride springs and geysers in Geyser Valley began to reduce in flow, as deep reservoir pressures declined (Thompson, 1957; Glover and Hunt, 1996). The resulting heat inflow into the Wairakei Stream at Geyser Valley decreased over 14 years from about 52 MWt to 6 MWt (Fig 4) (Glover, 1977). However, heat output at Karapiti increased ten-fold from 40 (±20) MWt to a peak of about 400 MWt in 1964 (Dawson and Dickinson, 1970). After this peak, the heatflow at Karapiti declined to about 220 MWt and the total Wairakei heatflow declined from a peak of about 750 MWt (in 1964) to 600 (±150) MWt in 1979 (Allis, 1981). For comparison, the maximum heat discharge from all Wairakei wells (in 1963), amounted to 2900 MWt (producing 180 MWe), i.e. four times the natural heat output at the time.

The *cause* of the large increase in heatflow from areas of steaming ground, together with a decrease in output from the chloride *springs*, was pressure drawdown (caused by extraction of fluids at production depths), which resulted in the formation and expansion of a *steam* zone at about 200 - 500 m depth. This allowed stronger upflows and lateral flows of *steam* into the overlying groundwaters, passing through fractures that had previously been filled with water (Allis, 1981). For the past 20 years, the total natural heatflow at Wairakei has declined gradually as shallow *steam* zone pressures have declined. Several thermal areas have cooled off completely, while others have remained relatively stable.

Recent attempts (1997,1998) at reassessing the heatflow from thermal features have used airborne thermal infra-red surveys to improve determination of the changes in lateral extent of t h e d ground (Mongillo *et a?*, 1993). Interim results *suggest* that heatflow from Karapiti is currently about 200 (±40) MWt, and total Wairakei heatflow has returned to the pre-development value of about 400 MWt. (Fig. 4).

3 3 Induced Seismicity

Wairakei Field lies on the *eastern* edge of the Taupo Fault Belt, a zone of active normal faulting. Regional microearthquake *surveys* in the early 1970's showed that much of the seismic activity in the Belt occurred as swarms with the earthquakes having shallow (<6 km) focal depths (Evison *et al.*, 1976). A five-week *survey* of the Wairakei Field in 1978 confirmed the earlier data, and established that there was no seismic activity associated with the production borefield or the area of ground subsidence (Hunt and Latter, 1982). *At* that time, seismic activity within the field was similar to that outside the field, and production did not appear to have influenced seismic activity in adjacent parts of the Belt. During the 1984 reinjection test in a well near the Power Station (WK301), induced seismicity was detected: the seismicity began <1 day after reinjection *started* and *ceased* immediately it stopped (Allis et a?., 1985). However, during the 1987-88 reinjection test in the Eastern Borefield, no induced seismicity was detected (Sherbum *et al.*, 1990). The difference in behaviour was attributed to the differences in wellhead pressures: in 1984 this was 20-30 bar, but in 1988-89 there was no pumping during reinjection.

3.4 Groundwater Changes

Measurements by MWD and Contact Energy in shallow (<60 m depth) monitor holes have shown there has been production-induced lowering of groundwater level (up to 30 m) in a small area of the production borefield and adjacent *Geyser* Valley (*Allis*,1982; Hunt, 1995). These changes are attributed to localised cold downflows of groundwater into the upper part of the reservoir through conduits that once fed natural surface features in Geyser Valley. The decline appears to have accelerated in the 1980's, but stabilised in the 1990's, which has been attributed to the water level reaching that of the Wairakei Stream (ECNZ, 1990). Groundwater temperatures (at or near w.l.) have increased, particularly in the area of water level decline, as a result of upflow of *steam* (*Allis*,1982). *An* important aspect of these *studies* has been the integration of ground subsidence, water level, temperature, and reservoir pressure data to provide a good understanding of the processes occurring in rocks above the reservoir, and a recognition that these are not always isolated from production-induced changes in the reservoir.

4. CONCLUSIONS

The application of geophysical techniques at Wairakei has had a profound influence on the geophysics of geothermal areas in New Zealand.

At Wairakei, the most successful geophysial technique for defining the location and extent of the reservoir has clearly been electrical resistivity measurements; seismic, gravity, and magnetic studies have been less successful. The greatest successes in helping to understand the processes occurring in the g e o t h d *system* when it was developed have probably been the use of heat flow, micro gravity, and groundwater changes.

The results of many of the geophysical studies at Wairakei have been used in other geothermal fields, both in New Zealand and overseas.

5. ACKNOWLEDGEMENTS

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