Proc. 11th New Zealand Geothermal Workshop 1989

# GEOPHYSICAL EXPLORATION OF THE BROADLANDS (OHAAKI) GEOTHERMAL FIELD: REVIEW

**Trevor M. Hunt**

Geophysics Division, DSIR, Wairakei, Private Bag, Taupo

**ABSTRACT**

Broadlands Geothermal Field was largely discovered and delimited by geophysical methods in the mid 1960's, and is now one of the most thoroughly investigated fields in the world. It has been used to test many geophysical methods of geothermal exploration and development in New Zealand: several different electrical resistivity techniques were tried, in which more than 260 traversing stations, 700 dipole stations, and 21 km of EM survey line were measured. More than 50 km of seismic refraction line, and nearly 30 km of seismic reflection line, have been recorded. Over 600 gravity stations have been made, and 325 km of airborne magnetic survey line flown.

Electrical resistivity traversing was found to be the best reconnaissance tool to locate the field, and roving dipole surveys the best to delimit the boundaries. Seismic refraction measurements combined with gravity anomaly data, gave the most information about geological structures within the field, but were unable to locate normal faults. Near-surface ground temperature, groundnoise, and magnetic measurements mntributed little.

Lessons learnt during the tests at Broadlands have helped to develop a geophysical exploration strategy that has been successfully used in New Zealand and overseas.

## INTRODUCTION

Studt (1968) wrote "The Broadlands Geothermal Field has very little natural heat flow compared with many other fields. Attention was given to it only after the low resistivity area was found to be just as extensive as that at Wairakei or Waiotapu". The foundations for these electrical measurements were laid in the early 1950's when members of Geophysics Division, DSIR, found that there was a large contrast in d.c. electrical resistivity between the rocks inside and those outside the Wairakei Geothermal Field. The first electrical measurements at Broadlands were made in September 1952 by W.I. Reilly, in the vicinity of the Ohaaki Pool; in June 1953, T. Hatherton made measurements in the small area of thermal ground near the Broadlands Road. The measurements confirmed that low resistivities (about 10 Om) were associated with areas of surface thermal activity. However, at that time the low sensitivity of the equipment limited the penetration depth of the method to about 70 m, and no further work was done at Broadlands. By the early 1960's, at the behest of W.J.P. Macdonald, more sensitive equipment had been developed and the worst of the technical problems largely overcome (Banwell and Macdonald, 1965). Routine electrical traversing measurements then began in the Taupo area using the Wenner type of electrode configuration with an electrode spacing of 1800 ft (550 m), which had a much greater penetration depth. Early in 1965, G.B. Dawson and H.H. Rayner made such measurements in the Broadlands area and encountered low resistivities similar to those previously found, but over a much wider area. This suggested that there may be a large, continuous area of low resistivity ground beneath the Broadlands-Ohaaki area, and led to a more detailed survey to delimit the boundaries of the low resistivity area. By June 1965, about 85 measurements had been made, from which the first comprehensive resistivity map of the Broadlands Field was produced. This map showed that apparent resistivities of less than 5 Om were present in an area of about 6.5 $km^2$ (Macdonald, 1967). A number of electrical resistivity soundings (VES) were then made which confirmed that low resistivities extended to depth and it was clear that a significant geothermal resource had been located. A deep drillhole (BR1) was sited using the resistivity data, and completed towards the end of 1965. It confirmed the high temperatures predicted by the resistivity data, but it encountered low permeabilities, and had a limited output.

The early resistivity measurements and the results from BR1 ignited an explosion of detailed geophysical work (Fig. 1) to better delimit the extent of the resource and to aid in siting wells within the field. It was recognised that there was likely to be many more large geothermal fields in the Central Volcanic Region which had few surface manifestations. M.P. Hochstein, especially, championed the idea that there was the opportunity at Broadlands to test and perfect the many existing geophysical exploration techniques so that in future investigations of other fields the few geophysical resources available could be put to best use. Broadlands thus became the testing ground for geophysical exploration of geothermal fields in New Zealand, and the lessons learnt were later put to good use in Chile, Indonesia, and the Philippines. Many new and existing geophysical techniques were tried out (Table 1) with the aims of:

(a) Locating and delimiting the boundaries of the resource, both at the surface and at depth.
(b) Locating faults or paths of high vertical permeability from which the resource may be tapped.
(c) Locating any structures that might enhance or restrict permeability.
(d) Providing information that can assist in management of the field during exploitation.

TABLE 1: List of geophysical methods, references, and an assessment of their usefulness in exploration of the Broadlands (Ohaaki) Geothermal Field.

| | References | Usefulness |
|---|---|---|
| A. Electrical Surveys | | |
| a. Resistivity traversing | 9, 13, 35, 36, 38, 45, 47 | Very useful |
| b. Resistivity soundings | 42 | Useful |
| c. Roving dipole surveys | 8,41,44,45,46,47, | Very useful |
| d. Resistivity anisotropy survey | 41 | Useful |
| e. Electromagnetic survey | 29, 30, 31, 32 | Little use |
| f. Audio-magnetotelluric survey | 54, 55, 56 | Useful |
| g. Induced Polarisation measurement | 41, 42, 44 | Little use |
| B. Temwrature Surveys | | |
| a. 1 metre temperature survey | 2, 3, 5, 6, 50 | Useful |
| b. Temperatures in shallow holes | 5, 6, 11, 17, 37, 51 | Useful |
| C. Seismic Surveys | | |
| a. Refraction surveys | 14, 15, 19, 20, 21, 38 | Useful |
| b. Reflection surveys | 15 | Useful |
| c. Attenuation studies | 15, 19 | Little use |
| D. Microearthquake Survevs | 12 | Little use |
| E. Ground Noise Surveys | 9 | Little use |
| F. Gravity Survevs | | |
| a. Bouguer anomaly surveys | 15, 19, 22, 38, 39 | Useful |
| b. Repeat gravity surveys | 24, 25, 26, 27 | Very useful |
| G.. Magnetic Survevs | | |
| a. Vertical force ground survey | 38,49 | Little use |
| b. Total force ground survey | 119, 22, 23 | Useful |
| c. Total force airborne survey | 16 | Useful |
| H. Rock Properties | 15, 33, 34 | Useful |

## EIEcrRI~ SURVEYS

**As** described above, the Wenner-type traversing measurements played a critical role in locating and delimiting the field. The results of this survey led in 1966-67 to further electrical resistivity traversing surveys. The original **1800** ft measurements showed a large, high resistivity embayment in the south-western part of the field (Macdonald, 1967) which was initially attributed to a tongue of inflowing cold water. The embayment was investigated, and proved spurious, by a traversing survey with 600 ft (180 m) electrode spacing (Dawson and Rayner, **1968).** It was also not clear how sharp the boundaries of the field were, and whether they were vertical or otherwise. Detailed traversing measurements, with centres at **600** ft **(180** m) intervals, were made across the boundary and showed that the boundary zone in some places was less or equal in width to the centre spacing, and was vertical within &lo° (Macdonald, **1968).** The **600** ft Wenner-type measurements gave only a shallow penetration; then estimated as **300** to 600 **ft (90-180 m)** depth (Gonzales et al. **1968).** In an attempt to map the geothermal fluid at greater depth, a survey with **3600** ft **(1100** m) electrode spacing was made, but logistical and technical difficulties (e.g. current leakage) proved too great, and only 17 sites were occupied (Hatherton and Macdonald, **1968).** To investigate the thickness of the resistivity low within the field, several resistivitv soundinm were made but the data obtained were poor because of technical problems, and there were difficulties in correcting for the influence of the field boundaries.

To overcome limitations of the traversing and sounding measurements, dipole methods were used. Roving dipole suweys were begun in February **1968,** using six current electrode sites (three north, three south of the field), with the current electrodes 1.2 to 2 km apart, and about **200** field stations with the potential electrodes 90 m apart (Risk et at. **1968).** The six apparent resistivity maps obtained did not agree with one another very well, but the reasons for most of the differences became apparent and maps showing the location of the field boundaries at depths of 1.5 and 3 km were produced (Risk et al, **1970;** Risk, **1981).** The maps showed that the field is approximately circular in shape, covers an area of **10-15 km²,** and the boundary between hot and cold ground is vertical to a depth of at least 3 km (Risk et al, **1970).** During the dipole surveys it was found that it was important for the current electrwes to be situated well outside the field, a point not recognised by other overseas investigators at the time. It was also learned that the boundary of a geothermal field is not defined by a single resistivity contour, but is best represented by the zone of steepest (lateral), apparent resistivity gradient. The dipole surveys also led, in the early **1970's,** to the development of theoretical hemispherical and hemispheroidal resistivity models with which to better interpret the measured data (Bibby and Risk, **1973),** and **this** resulted in the value for thickness of the resistivity low within the field being revised to 2 km. Later theoretical modelling, using the finite element method, suggested that the horizontal cross-sectional area of the reservoir increases with depth (Bibby, 1978). However, 2-D modelling of the dipole data suggested that the

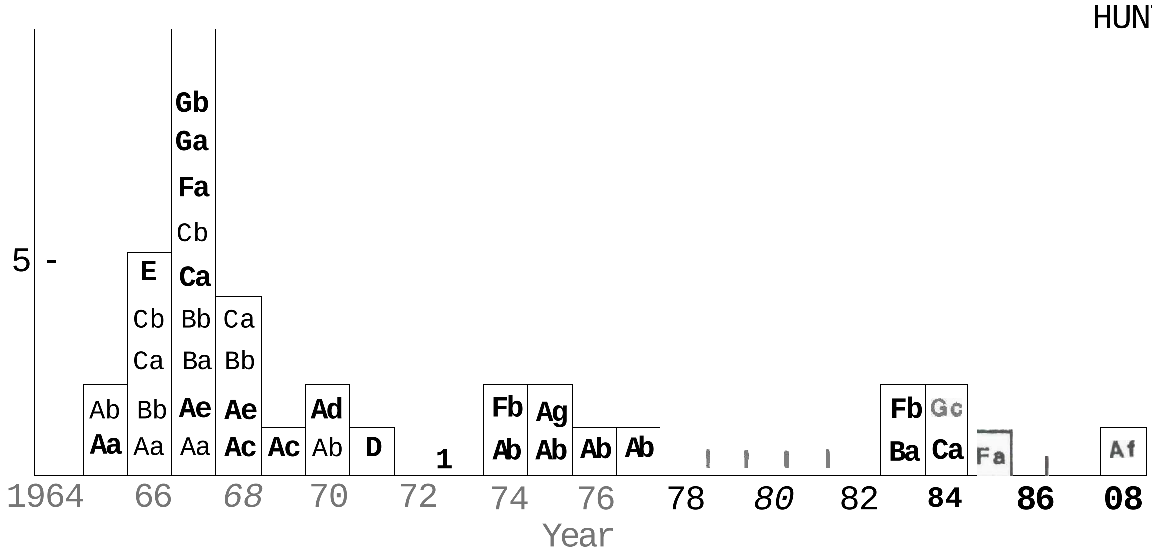


Figure 1: Histogram showing the chronology of geophysical field work at Broadlands Geothermal Field, since **1965.** The letters refer to Table 1.

resistivity boundary structure varied from place to place (Mulyadi and Caldwell, **1979).** In the north-western part of the field the boundary dipped **outwards** at about 70°, in the southeastern part it was vertical, in the eastern part it dipped inwardsat about 70". It was also found that for each current electrode dipole there will be certain portions of the field boundary for which the contrast in resistivity between inside and outside will not be detectable **(Risk, 1981),** and it is therefore necessary to use several dipole sources at different locations around the field. In **1976,** a specially modified form of dipole survey was made to accurately determine the position of the boundary at specific places so that from repeat measurements any lateral changes in its position or nature during exploitation, associated with an inflow of cold water, could be monitored (Risk, **1976a;** Risk a **1977;** Risk, **1981).** For this survey, one current electrode was placed at the centre of the field, the other about 3 km outside. The potential electrodes were 50 m apart, and more than 500 measurements were taken at 50 m intervals along **18** profiles across, and normal to, the boundary. Follow-up surveys have yet to be done.

In an attempt to locate fractures and enhanced permeability at depth, resistivity anisotropy measurements were made in November **1970,** in the Ohaaki area (Risk, **1976b).** Current **was** passed through the area in six directions using four current electrodes located outside the area, and the effects measured at ***58*** sites within the area using arrays of potential electrodes consisting of two perpendicular dipoles, each 30 m in length. It was found that anisotropy was greatest over the flanks of the Ohaaki Rhyolite Dome and coincided with the zone of most productive wells. Resistivity soundings had a similar pattern and suggested that the anisotropic rocks occurred beneath the rhyolite. It was thought that eruption of the rhyolite had caused radial fracturing in the rocks around the eruptive vent, and this had led to the observed resistivity anisotropy.

In the **1960's** resistivity traversing, sounding, and dipole techniques were slow and expensive. A quicker and less expensive resistivity technique was the electromagnetic EM) method, and such a technique (Slingram) was tested in December **1967** and May **1968.** **An ABEM** "ElectromagneticGun", generating a primary field of **440** or **1760 Hz** was used (Lumb **1968a, 1968b),** and measurements were made at 200 ft **(60** m) intervals along 21 km of line in the remarkably short time of **11** days (Lumb and Macdonald, **1970).** ***An*** apparent resistivity map with a penetration depth of about 30 m **was** obtained, and a good correlation between resistivity and ground temperature at **15** m depth **was** observed (Lumb and Macdonald, **1970).** The method proved to be a rapid and inexpensive tool, but the measurements were affected by topography and by metal pipes, drillhole casings, and similar conducting bodies (Lumb, **1968a),** and **so** its uses for reconnaissance and monitoring are limited.

The audio-frequency magnetotelluric fAMT) method, another technique for the rapid measurement of ground resistivity, was also tested. Three surveys were made, mainly using uncontrolled natural sources (distant thunderstorms). In the first **(1974),** AMT measurements were made at frequencies of 8, 20, 85, and 270 Hz at 30 sites, inside and outside the western part of the field (Whiteford, **1976).** The contour maps of apparent resistivity obtained were in reasonable agreement (in shape) with the **1800** ft Wenner traversing data, but the values of AMT resistivity were much smaller (0.3-0.6 times) than those of the Wenner method. In the second survey **(1977)** measurements were made at 50 and 85 Hz, at 20 sites, along three profiles across the field boundary (Whiteford, **1981a, b),** with similar results. The earlier measurements suffered badly from poor signavnoise ratios, poor repeatability, and changes in signal phase during recording (Whiteford, **1976; 1981a).** The best, and satisfactory, results were obtained using 50 Hz signals from mains powerlines, because they come from a virtually constant source and have little change in polarisation. The apparent resistivities obtained using the 50 Hz signals agreed well with the d.c. (dipole) resistivity values; most differences could be explained by differing probing depths (Whiteford, 1981b). In December **1988,** AMT/MT soundings were made at **11** sites along a N-S traverse line through the central part of the field, using frequencies between 1 **kHz** and **0.01** Hz (Ingham, **1989).** Pseudosections of apparent resistivity and phase curves, along the traverse line, were constructed from the data using standard spectral analysis techniques. *An* interpretation (Ingham, **1989)** suggested the reservoir extends, at about 1 km depth, well beyond the southern boundary of the field a defined by the traversing data. This conflicts with t!Ie traversing data and needs to be checked The success of the AMT method therefore came too late to be of importance in locating and delimiting the Broadlands field, but may be of use in future investigations of other fields.

During the **1973** dipole boundary survey, interference attributed to Induced Polarisation (IP) effects was noticed on records from places along the southern boundary of the field (Risk, **1976).** The area ww examined in detail in **1980;** IP, further resistivity, and ground magnetic measurements were made, and a **156** m deep hole was drilled (Risk, **1981b).** The hole was cased to 57 m, and it was found that the source of the IP signal was at shallower depth. Cores from 25-38 m depth had strong IP effects in the laboratory, but petrological examination showed they contained no sulphides and detrital magnetite was less than 1%. The origin of the IP effects here is still a mystery but IP effects in **BR16** are clearly associated with sulphide mineralisation (Allis, **1989).**

## TEMpEaATuRE SURWYS

In the early **1960's** it was **known** that surface thermal features were associated with faults or paths of good vertical permeability. However, at that time it was not clear what the relationships were between the extent of such features and the size of a geothermal field, or between the temperatures of springs (and hot ground) and deep fluids. *At* Broadlands there was the opportunity to examine these relationships before the effects of exploitation occurred.

Detailed 1 m depth temperature surveys made in **1967** showed that ground temperatures greater than ***5°C*** above ambient occurred mainly in a 1 $km^2$ area in the north-western part of the field and in a smaller area near **BR7** (Thompson, **196Sb).** Measurements were also made in seismic shot holes, and these showed that temperatures greater than 1°C above ambient, at a depth of 15 m, occurred over most of the field (Hochstein, **1968).** A survey was also made to locate and measure the temperature and heat output of all hot springs, seeps, and thermal ground (Dickinson, **1968).** Calculations from these data showed that the natural heat output of the field was only about **75** MW (c.f. **400** MW at Wairakei before exploitation), although there was a large uncertainty in this value because the amount of seepage into the Waikato River was poorly known. Thus, by the late 1960's a comparison could be made between the temperature (and heat flow) data, the results of the electrical resistivity surveys, and temperatures measured in many deep drillholes. This comparison showed that the surface heat output was not a good indication of the power potential of the field (Macdonald and Hatherton, **1968),** nor was it very good at indicating structures within the field. This is because the heat flow is by convection (hot water) rather than by conduction (Allis and Webber, **1984).**

It was, however, realised that surface heat flows are good indicators of changes in the shallow groundwater system associated with exploitation of the deeper geothermal reservoir. A baseline 1 m temperature survey were therefore made in **1983** (Ais and Webber, **1984).**

## SEISMIC SURVEYS

**In** the **1950's,** seismic refraction and reflection surveys were made in an attempt to map geological structures in the Wairakei and Waiotapu fields, but with little success. The main problems were: high ground noise, lateral velocity changes, poor and discontinuous reflectors, velocity inversions, and rapid absorption of seismic energy (strong attenuation).

Both refraction and reflection methods were tried at Broadlands in **1966-68** because new equipment had become available, techniques had improved, and there was a better knowledge of the field (Hochstein et al. **1967;** Hochstein and Innes, **1968;** Hochstein and Hunt, **1970).** The main aim of the work was to map the rhyolite bodies because it had been found that the early productive wells were situated over these bodies (Macdonald and Hatherton, **1968).** A further objective was to try and map faults by locating vertical offsets in sub-horizontal refractors or reflectors. Studies of attenuation and changes in compressional wave velocity were also planned. Refraction surveyswere made along 10 profiles (total length 52 km) but the quality of data obtained was poor (at least by today's standards). Four seismic layers were identified, all from within the volcanic rock sequence; no refracted arrivals from the greywacke basement were observed except at places outside the field, emphasizing the strong attenuation of seismic waves in the field. The data allowed construction of contour maps of the depth of the upper surface of the Ohaaki Rhyolite Dome and the Broadlands Rhyolite Dome (later renamed Dacite). No faults with a throw of more than 50 m could be identified, and towards the end of the surveys it became clear that features initially believed (Hochstein et a1 1967) to be major faults were more likely to be steep scarps on the edges of these domes.

Most of the **1966-68** data was reinterpreted in **1987** (Henrys, **1987)** using modern computer-aided, iterative, ray-tracing techniques, and constrained by geological information from 42 deep drillholes (c.f. about nine holes available in **1966-68).** The new seismic velocity modeis obtained confirwed the basic features reported earlier, but improved significantly on the details. For the first time, rock units other than the igneous bodies could be identified and mapped.

A limited amount of reflection seismic work was done in **1966-67.** No coherent reflections were observed from within the field (Hochstein et , **1967)** and **so** the technique was abandoned. By the mid-1980's, vastly improved equipment (digital) and techniques were available, and another attempt was made to use the reflection method. Tests were conducted in October **1984** at two sites (inside and outside the field) but preliminary analysis of the data showed the quality of reflections at both sites was poor (Henrys, **1987);** shot-generated noise in the form of low frequency ground roll, converted waves, and reverberating refractions were the main problems. It was thought that "state of the art" computer processing techniques could overcome these problems and **six** seismic lines **(26 km** total) were recorded late in **1984** (Henrys, **1987).** However, despite considerable data processing, only incoherent reflectors could be mapped (few horizons could be traced for more than **300** m) and no faults could be identified. Significant progress in mapping the subsurface structure of the field was only achieved by combining the results of the reflection survey with the reinterpreted refraction data, the reinterpreted gravity measurements, and all the deep drillhole information (Henrys, **1987).** By itself the reflection method was not very profitable.

Early seismic work at Wairakei in the **1950's** revealed that in geothermal areas, seismic velocities were lower than normal and there was strong attenuation. It was thought these effects may be due to high steam content of the rocks and one aim of the **1966-68** seismic measurements at Broadlands was to test this idea and also see if the effects could be used as a prospecting tool. It was found that the recorded amplitude of high velocity (V >2.1 **km/s)** refracted arrivals decreased from over **100** pV outside to 20-50 $\mu$V within the field (Hochstein et al, **1967).** However, it was concluded (Hochstein and Hunt, **1970)** that attenuation measurements were of little use in geothermal prospecting because different values were obtained when shot point and geophone positions were interchanged, due to near surface conditions. Furthermore, other causes of attenuation were present. However, much better attenuation data were obtained from the **1984** seismic survey, which show that there is a low-velocity zone **(10-20%** c outside) within the field which coincides with the region of highest signal attenuation (Q c20), the area of productive wells, and the region of highest fluid temperatures (>ZOO at 1 km depth) (Henrys, **1986, 1987).**

## MICROEARTI-IQUAELE SURVEYS

***An*** association between geothermal activity and microearthquakes is found in some parts of the world, and this led in the early **1970's** to suggestions that microearthquake surveys could be used to locate geothermal fluids. In **1971-72,** a survey of the Rotorua-Taupo region was made (Evison et al, **1976).** Five seismographs were operated in and near the Broadlands field for about three weeks, but during this period no crustal earthquakes with magnitudes greater than zero in or within 5 km of the field, were recorded. The lack of seismic activity was found to be typical of that of the Taupo-Reporoa Basin in which the field lies, and was attributed to the crustal rocks here having low strength or being in a zone of low tectonic stress. The method appears to be of little use for locating geothermal fluids in the Central Volcanic Region, but may be of importance in monitoring injection during exploitation of the field.

## GROUND NOISE SURVEYS

During the early seismic surveys it was noted that there appeared to be abnormally high ground noise near geothermal areas. Reconnaissance ground noise amplitude and spectra measurements were made at Broadlands in **1966,** and the data were interpreted (Clacy, **1968)** as showing that the field coincided with places of relatively high noise amplitude *(6 x* background) and low frequency (2 Hz). However, later, more rigorous measurements at Waiotapu Geothermal Field showed that the earlier interpretation was not valid (Whiteford, **1970).**

## GRAVITY SURVEYS

**In** the **1950's** and early 1960's, gravity measurements in the Central Volcanic Region showed that local gravity "highs" of up to **10** mgal amplitude occurred in the vicinity of some thermal areas. It was thought that the gravity "highs" were the result of uplift of the basement surface, believed to be greywacke. At the start of geophysical exploration of the Broadlands field, gravity surveys were planned with the expectation that detailed gravity measurements might reveal basement structure and help in locating faults up which hot fluids might be flowing.

In **1967,** more than **600** gravity measurements (k 0.1 mgal) were made in the Broadlands area, at stations with surveyed heights (±0.05 m) (Hunt, 1968a). The residual gravity anomalies, calculated by manually removing a regional field, showed a series of closely spaced NE-trending contours associated with the c on d i t i o the n s . e n t rocks to the NW, but within the field there was a large bulge in the contours towards the NW. It soon became clear, from calculations, that the bulge could not be caused by uplift of the basement in that area. Cores were available from 16 deep drillholes, and analysis of the density data obtained indicated that there was a significant (up to 400 $kg/m^3$) increase in density with increase in rank of hydrothermal alteration, in rocks oi the same geological rock unit. The residual gravity anomaly pattern was therefore interpreted in terms of an elliptical gravity "high" of about 10 mgal amplitude associated mainly with densification, superimposed on a smooth gravity pattern associated with a uniformly dipping basement surface (Hunt and Hochstein, 1970). The concept of gravity "highs" **being** associated with basement uplift was therefore discarded. The densification was attributed to deposition of minerals from the hot geothermal fluids as they rose and cooled within the field.

In 1985, the gravity measurements were revisited (Henrys, 1987). By this time data was available from 44 wells, and the results of a new seismic survey were available. By combining all the now considerable amount of seismic, rock property, and gravity data available, it was possible to construct a detailed three-dimensional model for the field, incorporating both lateral and vertical changes in rock properties. The original interpretation of the gravity data (Hochstein and Hunt, 1970)was proved to be basically correct, but more importantly the combination of seismic and gravity methods was able to provide detailed geological structure, especially information about the lateral variations in thickness of the rhyolite and dacite flows. This information will be important for the constructing better numerical reservoir simulation models to monitor and predict the behaviour of the field during exploitation.

In addition to the gravity anomaly data, precise gravity measurements were made in 1974 and 1983, at about 120 benchmarks, to determine recharge and to test numerical reservoir simulation models for exploitation of the field (Hunt and Hicks, 1975; Hunt, 1984, 1987; Hunt et al. 1989).

## MAGNETIC SURWYS

Prior to the early 1960's, extensive ground and airborne magnetic surveys in the Central Volcanic Region had shown that in and around **known** geothermal areas the hydrothermal fluids had often destroyed the magnetisation in the rocks, resulting in local magnetic "lows". It was also known that there were alternative explanations for such magnetic "lows", and therefore magnetic measurements were probably of limited use in locating geothermal fields, except perhaps on a regional scale. However, magnetic measurements were made at Broadlands partly to confirm these ideas, and partly in the hope that the presence of any magnetic "high" within part of the field would indicate a poor prospect for finding significant amounts of geothermal fluid (Le. poor permeability) in that area.

Detailed, ground magnetic surveys were made in 1967 (Hunt, 1968b; Macdonald and Hatherton, 1968; Thompson, 1968a; Hochstein and Hunt, 1970), which showed that the field lay in a broad, smooth, magnetic "low" superimposed on which were many local, short-wavelength anomalies. This "low" was consistent with data obtained on cores from the deep drillholes which showed nearly all the rocks in the field were non-magnetic (Leopard 1968a, b). The only feature of interest was a local magnetic "high" (~200 nT amplitude), centred about 1 km outside the eastern boundary of the field. This "high" was interpreted (Hochstein and Hunt, 1970) as being associated with that part of the Broadlands Rhyolite (Dacite) Dome situated outside the field and unaffected by geothermal fluids which had destroyed the magnetisation of the other part which lay within the field.

A low-level (≈150 m above ground), airborne magnetic survey covering an 180 $km^2$ area was made in 1984, with flight lines 750 m apart. The data were interpreted in conjunction with the new seismic and reinterpreted gravity measurements (Henrys and van Dick, 1987), and largely confirmed the earlier interpretation. It **was** found that about two-thirds of the Broadlands Dacite had been demagnetised, and the boundary between the unaltered and demagnetised parts of the body was near vertical. However, both the Broadlands and Ohaaki rhyolites also extend across the boundaries of the field but do not appear to vary significantly in their magnetic properties. For the Broadlands Rhyolite, this was explained (Henrys and van **Dijck,** 1987) by the unaltered rocks having a low (0-0.5 A/m) magnetisation. Recently, it was suggested (Allis, 1989) that the magnetisation in these rhyolites has been destroyed by low temperature, mildly-acidic (pH 549, C0,-bearing fluids which are widespread at shallow depths (400 m) in the vicinity of the field.

It is clear that the magnetic measurements have given little specific information about the location of the hot areas in general or of productive areas in particular. Thus, the magnetic studies have not contributed much to our understanding of the Broadlands field.

## CONCLUSIONS

Geophysical methods were very successful in lwting and delimiting the boundaries of the Broadlands Field to a depth of several kilometres. Electrical resistivity traversing and roving dipole measurements were the most successful. However, no method was found that could directly locate faults or paths of high vertical permeability. A combination of gravity anomaly and seismic refraction data was able to provide information about the distribution of geological rock units, especially the rhyolites and dacites, but the interpretation relied heavily on constraints imposed by deep drillhole data. Precise gravity, resistivity dipole, airborne thermal IR, and shallow ground temperature measurements will assist in future management of the resource. The reader is invited to compare the results obtained at Broadlands with those obtained by Ward (1983) in the western part of the United States.

Geophysical exploration and development strategies based on the tests conducted at Broadlands, and modified for local conditions, have been successfully applied in Chile, Indonesia, and the Philippines, as well as in New Zealand.

## ACKNOWLEDGEMEITIS

I am grateful to G. Dawn, T. Hatherton, and W.I. Reilly for finding traces of the early work. R.G. Allis, WJ.P. Macdonald, and G.F. Risk made valuable suggestions about the manuscript, and reminded me about work that I had forgotten about.

## REFERENCES

1. Allis, R.G. 1989 Geophysical anomalies over epithermal systems., Journal of Geochemical Exploration (in press.).

2. Allis, R.G. and Webber, S. **1983:** Interpretation of repeat shallow temperature surveys at Wairakei and Broadlands fields. Proceedings 5th N.Z. Geothermal Workshop: **55-60.**

**3.** Allis, R.G. and Webber, S. **1984:** Shallow temperature measurements at Wairakei and Broadlands fields. Geophvsics Division Re-port **197.**

4. Banwell, CJ. and Macdonald, WJ.P. **1965:** Resistivity Surveying in New Zealand thermal areas. Proceedings 8th Commonwealth Mining and Metallurgical Congress **213.1-8.**

**5.** Banwell, CJ. **1967:** Surface and subsurface temperatures pressures and power potential of the Broadlands Geothermal Area, Geophvsics Division Report **48: 15-24.**

**6.** Banwell, CJ. **1968:** Drillhole temperatures to December 1967. Geophvsics Division Report **4 9** **18-22.**

7. Bibby, H.M. **1978.** Direct current resistivity modelling for axially symmetric bodies using the finite element method. Geophvsics **43: 550-562.**

**8.** Bibby, H.M. and Risk, G.F. **1973:** Interpretation of dipole-dipole resistivity survey using a hemispheroidal model. Geophysics **38: 719-736.**

**9.** Clacy, G.R.T. **1968:** Geothermal ground noise amplitude and frequency spectra in the New Zealand Volcanic Region. Journal of Geophvsical Research **73:** 537743233.

**10.** Dawson, G.B. and Rayner, H.H. **1968** Discussion of the final 600 ft Wenner resistivity map of the Broadlands Field. Geophvsics Division Report **53: 16-19.**

11. Dickinson, D.J. **1968:** The natural heat output of the Broadlands Geothermal Field. Geophysics Division Report **49: 23-27.**

**12.** Evison, F.F.; Robinson, R.; Arabasz, WJ. **1976** Microearthquakes, geothermal activity, and structure, rentral North Island, New Zealand. N.Z. Journal of Geology and Geophysics **19: 625-637.**

**13** Gonzales, J.A.; Dawson, G.B.; Rayner, H.H. **1968:** Resistivity mapping with 600 ft Wenner Configuration. Geophvsics Division Report 4 9 2-4.

**14** Henrys, S. **1986:** Shallow structure of the Broadlands-Ohaaki Geothermal Field (NZ): analysis of seismic refracted arrivals by iterative ray tracing. Proceedings 8th NZ Geothermal Workshop: 85-90.

**15.** Henrys, S. **1987:** Structure of the Broadlands-Ohaaki Geothermal Field based on interpretation of seismic and gravity data. Ph.D. Thesis, Geolop~ Department, University of Auckland.

**16.** Henrys, S. and van Dijck, M.F. **1987:** Structure of concealed rhyolites and dacites in the Broadlands-Ohaaki Geothermal Field. Proceedings 9th N.Z. Geothermal Workshop: **43-48.**

**17.** Hochstein, M.P. **1968a:** Temperature survey at a depth of 50 ft. GeoDhvsics Division Report **49:** 14-**17.**

**18.** Hochstein, M.P. **1968b:** Introduction. Geophvsics Division Report **53:** 1-4.

**19.** Hochstein, M.P. and Hunt, T.M. **1970:** Seismic gravity and magnetic studies, Broadlands geothermal field, New Zealand. Geothermics Special Issue 2 **333-346.**

**20.** Hochstein, M.P.; Innes, D.G.; Carrington, L. **1967:** Seismic studies in the Broadlands Geothermal Area. Geophvsics Division Report 4 8 7-14.

21. Hochstein, M.P., and Innes, D.G. **1968** Additional seismic measurements. Geophysics Division Report *A3* 8-9.

**22.** Hunt, T.M. **1968a:** Gravity and magnetic measurements. GeophvsicsDivision Report 4 9 **10-11.**

23. Hunt, T.M. 1968b: Total force magnetic anomalies, Broadlands Field. Geophvsics Division Remrt **53: 34-37.**

24. Hunt, T.M. **1984:** Recharge at Broadlands (Ohaaki) Geothermal Field **1967-1983.** Proceedings 6th N.Z. Geothermal Workshop: **195-200.**

25. Hunt, T.M. **1987:** Recharge at Broadlands Geothermal Field **1967-1983** determined from repeat gravity measurements. Geophvsics Division Report **216.**

26. Hunt, T.M. and Hicks, S.R. **1975:** Repeat gravity measurements at Broadlands Geothermal Field, **1967-1974.** Geophysics Division Report 113.

27. Hunt, T.M.; Allis, R.G.; Blakely, M.R. and O'Sullivan, M.J. **1989** Test of a reservoir simulation model for the Broadlands Geothermal Field using repeat gravity measurements. Proceedings 1lth N.Z. Geothermal Workshop: (this volume).

28. Ingham, M. **1989:** Audiomagnetotelluric-Magnetotelluric soundings of the Broadlands-Ohaaki Geothermal Field. Proceedings 1lth N.Z. Geothermal Workshop: (this volume)

29. Keller, G.V. **1969** Electro-magnetic surveys in the Central Volcanic Region, Preliminary Report. GeoDhvsics Division Report **55.**

30. Lumb, J.T. **1968a:** Electromagnetic studies, a preliminary report. Geophvsics Division Report **49:** 7.

31. Lumb. J.T. 1968b: *An* electromagnetic survey of the Broadlands Field. GeoDhysics Division Report 53:- 8-15.

32. Lumb, J.T. and Macdonald, WJ.P. 1970 Near-surface resistivity surveys of geothermal areas using the electromagnetic method. Geothermics Swcial Issue 2 311-317.

33. Leopard, AE. 1968a: Measurement of rock properties. GeoDhvsics Division Report 4 9 28-39.

34. Leopard, AE. 1968b: Further measurements of rock properties of cores from the Broadlands Field. Geophvsics Division Reuort 53: 41-46.

35. Macdonald, W.J.P. 1967: Resistivity measurements in the Broadlands Geothermal Area. Geophysics Division Report 48: 3-6.

36. Macdonald, W.J.P. 1968: Resistivity traverses across the boundaries of the Broadlands Geothermal Area. Geophysics Division Report 49: 5-6.

37. Macdonald, W.J.P. 1975: The useful heat contained in the Broadlands Geothermal Field. Proceedings 2nd U.N. Svmwsium on the DeveloDment and Use of Geothermal Resources: 1113-1119.

38. Macdonald, W.J.P. and Hatherton, T. 1968: Broadlands Geothermal Field - Geophysical Investigations In "Report on Geothermal Survey at Broadlands 1968", N.Z. Dept. Scientific Research, Wellington (also known as DSIR Geothermal Report *5).*

39. Macdonald, W.J.P. and Hunt, T.M. 1968: A preliminary interpretation of gravity anomalies - Broadlands Geothermal Field. Geophvsics Division ReDort 53: 29-33.

40. Mulyadi, A and Caldwell, G. 1979: Analysis of the resistivity boundary structure of the Broadlands Geothermal Field. Proceedings 1st N.Z. Geothermal Workshop: 298-306.

41. Risk, G.F. 1976a: Monitoring the boundary of the Broadlands Geothermal Field, New Zealand. Proceedings 2nd U.N. Symposium on Development and Utilisation of Geothermal Resources: 1185-1189.

42. Risk, G.F. 1976b Detection of buried zones of fissured rock in geothermal fields using resistivity anisotropy measurements. Proceedings of 2nd U.N. Symposium on Development and Utilisation of Geothermal Resources: 1191-1198.

43. Risk, G.F. 1981a: Induced polarisation (IP) anomaly in the Broadlands Geothermal Field. Proceedings 3rd N.Z. Geothermal WorkshoD: 43-48.

44. Risk, G.F. 1981b: Defining boundaries and structures of Broadlands Geothermal Field, New Zealand, by geophysical methods - **case** history. Proceedings 2nd Circum-PacificEnerm and Mineral Resources Conference: 325-332.

45. Risk, G.F.; Brown, D.B.; Dawson, G.B.; Rayner, H.H. 1968: Preliminary results of the dipole resistivity survey of the Broadlands Field. Geophvsics Division Remrt 53: 20-28.

*46.* Risk, G.F. a 1977: The resistivity boundary of the Broadlands Geothermal Field. Geophvsics Division Report 123.

47. Risk, G.F.; Macdonald, W.J.P.; Dawson, G.B. 1970 D.C. resistivity' surveys of the Broadlands Geothermal Region, New Zealand. Geothermics Stxcial **Issue** 2: 287-294.

48. Studt, F.E. 1968: Summary and Conclusions. "Report on Geothermal Survey at Broadlands 1968". N.Z. Department of Scientific and Industrial Research, 132 p.

49. Thompson, G.E.K. 196th: Vertical force magnetic map. GeoDhvsics Division Rewrt 4 9 12.

50. Thompson, G.E.K. 1968b: Ground temperatures at a depth of one metre. Geophysics Division Report 49: 13.

51. Thompson, G.E.K 1968~: Measurements of temperature, chloride, and water level in shallow monitor bores at Broadlands. Geophysics Division Report 5 3 5-7.

*52.* Ward, S.H. 1983: Geophysical studies of active geothermal systems in the northern Basin and Range. Geothermal Resources Council Special Remrt 13: 121-157.

53. Whiteford, P.C. 1970 Ground movement in the Waiotapu Geothermal Region, New Zealand. Geothermics Special Issue 2: 478-486.

54. Whiteford, P.C. 1976 Assessment of the audio-magnetotelluric method for geothermal resistivity surveying. Proceedings 2nd U.N. Svmmsium on DeveloDment and Utilisation of Geothermal Resources: 1255-1261.

55. Whiteford, P.C. 1981a: Investigation of the audio-frequency magnetotelluric method of determining an apparent resistivity tensor. Geophysics Division Report 156.

56. Whiteford, P.C. 1981b Audio-frequency magnetotelluric measurements in the Broadlands Geothermal Field using 50 I& mains power **as** the signal source. Proceedings 3rd N.Z. Geothermal Workshop: 63-68.