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GEOPHYSICAL MONITORING THE EXPLOITATION OF THE BROADLANDS (OHAAKI) GEOTHERMAL FIELD

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ABSTRACT

Monitoring physical changes which accompany exploitation of a geothermal field can provide useful information about the response of the reservoir to production and injection, and so contribute to rational, economical, field management. Monitoring can also assist management of the field to minimise any adverse environmental effects caused by exploitation.

At Broadlands, repeated microgravity surveys could be used to determine mass recharge, saturation changes in the steam zone; and test numerical reservoir simulation models. Repeated electrical resistivity measurements may allow changes, with time, in the position of the field boundary to be detected. Levelling surveys can provide information about any ground, subsidence. Airborne infrared data, ground temperature measurements, and observations of thermal features would allow changes in natural geothermal activity to be monitored. Measurement of water level changes in shallow wells can provide information about the response of the groundwater system to exploitation of the reservoir. A network of seismometers will detect any exploitation induced earthquakes. In most cases, sufficicnt measurements have already been made for natural changes to be distinguished from exploitation induced changes.

INTRODUCTION

The Ohaaki Power Station, situated on the Broadlands Geothermal Field, was commissioned this year and generates about **110** MW of electricity using fluid drawn from the north-western (Ohaaki) part of the field, at a rate of about **1500** t/hr. The waste fluid is injected, at depth, in the south-eastern part of the field. Tests at Broadlands, and experience in other fields, show that such a rate of withdrawal is significant despite the large size of the thermal resource. It is expected that during exploitation pressures and temperatures in the upper part of the reservoir will decline, and cause other physical changes inside and outside the field, both at the surface and at depth.

Exploitation of a geothermal field should not be an unrestrained mining operation; the resource must be used in an economical manner. Some of the questions that will need to be answered when managing the exploitation are:

What is the extent of the steam zone?
Is it changing in thickness?
What are the saturation changes in the steam zone?
Where is the reinjected fluid going?
Is cold water from outside the field invading the reservoir, and if so where?
How good are numerical reservoir simulation models for exploitation of the field?

It is now recognised that measurement and monitoring of the physical changes accompanying exploitation can provide useful information about the response of the field to fluid withdrawal and either answer some of these questions, or place limits on the answers. Geophysical techniques can therefore be important for rational, economical, field management, and are particularly useful for measuring in places where there are no drillholes.

Exploitation of a geothermal field must also be done in an environmentally responsible manner. It is well known that exploitation can lead to physical changes in natural geothermal features at the surface and to the near surface groundwater (Allis, **1981**). Some of the questions that will need to be answered, in this respect, are:

What is happening to the natural geothermal features such as the Ohaaki Pool?
Are near surface ground temperatures changing, and if so, where?
Has the groundwater been affected?
Is there ground subsidence?
Is the withdrawal of fluid, or reinjection, causing increased earthquake activity?

Geophysical monitoring can also help to recognise physical changes at, or near, the surface and so assist in management of the field to minimise or ameliorate any adverse environmental effects caused by exploitation.

Measuring the physical changes accompanying exploitation is not necessarily straight forward because a geothermal field in its natural state is a dynamic hydrological system, and many of the physical changes are already occurring naturally. It is first necessary to set up baselines and determine the location and magnitude of any natural changes before exploitation begins.

The main geophysical techniques that could be employed at Broadlands are:

GRAVITY CHANGES

Studies, principally at Wairakei Geothermal Field, have shown that repeated precise gravity (microgravity) measurements can provide: field-wide and local values for recharge of fluid within a geothermal system (Hunt, **1977),** information about changes in saturation in different parts of the steam zone (Allis and Hunt, **1986),** and test complex, 3-dimensional, numerical reservoir simulation models for exploitation (Hunt, et **al, 1989).**

The information is based on gravity changes measured on permanent concrete benchmarks in and around the field (Fig. 1). Details of measurement techniques and data reduction are given by Hunt **(1987).** Generally the gravity values have to be corrected for the effects of ground level changes (usually subsidence), groundwater level changes, and topographic changes. For most surveys the standard error of the gravity measurements is about **7-15** microgal, but values of corrected gravity difference at points well outside the fields suggest only changes greater than **30-50** microgal are significant (Hunt, **1988).**

At Broadlands, several gravity surveys have already been made prior to exploitation so a good baseline exists from which to measure future changes. The first two surveys **(1967, 1974)** spanned the drawdown test period **(1968-1971)** and showed that negative gravity differences of about **80-120** microgal occurred over the whole field, although most of the fluid withdrawn was taken from the north-western part of the field (Hunt, **1987).** Simple modelling suggested that the gravity changes were the result of a net mass loss of **24-35** Mt, and hence there was little mass recharge. After the drawdown test the field appeared to recover. The second and third surveys **(1974-1983)** showed that positive gravity differences of about **40** microgal occurred in most parts of the field, and modelling suggested that there was a net mass gain of about 11 Mt (Hunt, **1987).**

However, these changes are small compared with those expected during exploitation. Simple modelling suggests that gravity changes of several hundred microgal can be expected, and that most of the changes will occur during the first few years of exploitation. It would therefore be prudent to make further surveys, at appropriate times, to monitor the gravity changes and from the data determine changes in the extent of the steam zone, saturation changes, and test and refine reservoir simulation models.

RESISTIVITY CHANGES

One effect of the decrease in pressure in a geothermal reservoir during exploitation might be to suck the cold water surrounding the field into parts of the reservoir, with associated problems for continued exploitation. Information about the location and extent of such an invasion is obviously of importance in managing exploitation of a field. In most water-dominated geothermal fields, such as Broadlands, there

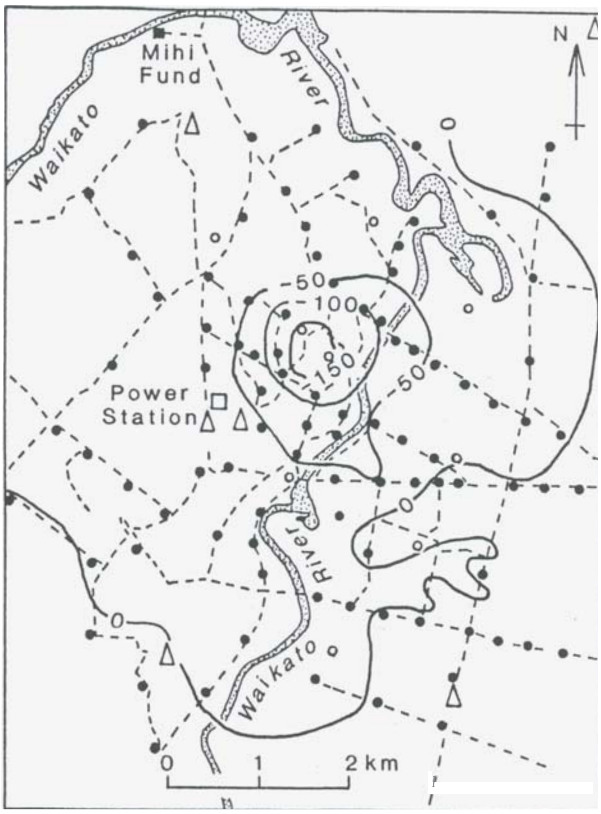

Figure 1: Map showing gravity stations (solid circles), the levelling network (broken lines), and ground subsidence between **1968** and **1974** (solid lines, mm). Also shown are existing trig stations (triangles) and new trig stations (open circles). Not all gravity stations in the Ohaaki area are shown.

is a large electrical resistivity contrast (1-2 orders of magnitude) between the hot, saline fluid-saturated rocks inside the field and the colder surrounding rocks. Cold, invading water, will be non-saline and have high resistivity. ***An*** invasion of such water is likely to result in a shift in position, and a change in the signature, of the resistivity boundary. It may be possible to locate an invasion and map its progress with time, **by** making repeat resistivity surveys across the boundaries of the field.

At Broadlands, a satisfactory monitoring programme could not be achieved by repeating any of the early resistivity surveys used to locate and delimit the field because the measurement sites were at least **400** m apart and many of them had been only approximately located (Risk, **1981;** Risk, et al., **1977).** To overcome these limitations a special dipole resistivity survey was made in **1975,** in which one current electrode was placed at the centre of the field, and the other about 3 km outside the field. The potential electrodes were **50** m apart and more than 500 measurements were made at 50 m intervals along 18 profiles across, and normal to, the field boundary (Figure 2). The measurement points were accurately located with respect to permanent benchmarks so that the survey could be repeated in the future if it is suspected that lateral changes in the position of the boundary have occurred.

The depth to which changes in the boundary can be detected is not certain, but it is estimated (Risk, 1981) to be about 1 km. The minimum distance of migration of the boundary which could be detected will depend on the sharpness of the boundary. In places where the boundary is narrow (100-200 m), such as along the southern perimeter of the field, a lateral migration of about 100 m should be detectable. In places where the boundary is broad (300-500 m), such as in the eastern part of the field, a lateral migration of several hundred metres would be needed for it to be detected (Risk, et al., 1977). However, repeating the dipole survey may not detect all cold-water intrusions into the field. Thin tongues of cold water, up to about 200 m thick may not be detected (Risk et al., 1977). Also, if the migrating boundary left behind thermally altered rocks having low resistivity it may not be possible to distinguish the new boundary (Risk, et al., 1977).

Since the magnitude and extent of any future boundary changes are unknown, it would be advisable if some theoretical modelling was done, before any repeat surveys, to determine the resistivity changes accompanying various kinds of boundary change and to allow better identification of when and how the surveys should be made.

GROUND DEFORMATION

Pressure drops in a geothermal reservoir due to exploitation may cause significant compaction of incompetent (highly compressible) rocks and lead to deformation at the surface. Ground deformation has occurred in most exploited geothermal fields, and in some instances the results have been dramatic. For example at Wairakei, a similar field to Broadlands, the rate of ground subsidence in some places is greater than 450 mm/yr, and the total subsidence since 1960 has been more than 10 m. Also, there have been significant horizontal movements (both compressional and tensional) with strain rates of up to $5 \times 10^{-4}\ yr^{-1}$ (Allis, 1982a). Locating and measuring the amount of surface deformation is obviously of great importance for the construction and maintenance of engineering structures such as buildings, pipelines, and equipment. Measurement of vertical ground movements is also important for the interpretation of gravity changes.

At Broadlands, about 600 permanent, concrete benchmarks are located in and around the field, and survey marks have been installed at about 100 m intervals on support structures along the main pipelines. Numerous levelling surveys, to 3rd order standard or better, have been made since 1968 although few covered the whole field. The surveys showed that during the drawdown test period, ground subsidence of up to 190 mm occurred in the Ohaaki area from where most of the fluid was withdrawn (Figure 1). The lack of any subsequent rebound of the ground (Figure 3), despite a 50% recovery in reservoir pressure, indicates that consolidation is occurring as permanent pore collapse rather than elastic compression (Allis, 1982a). Analysis of the subsidence suggests the collapse is not confined to the upper part of the reservoir but is also occurring in some of the overlying rocks (Allis, 1982a).

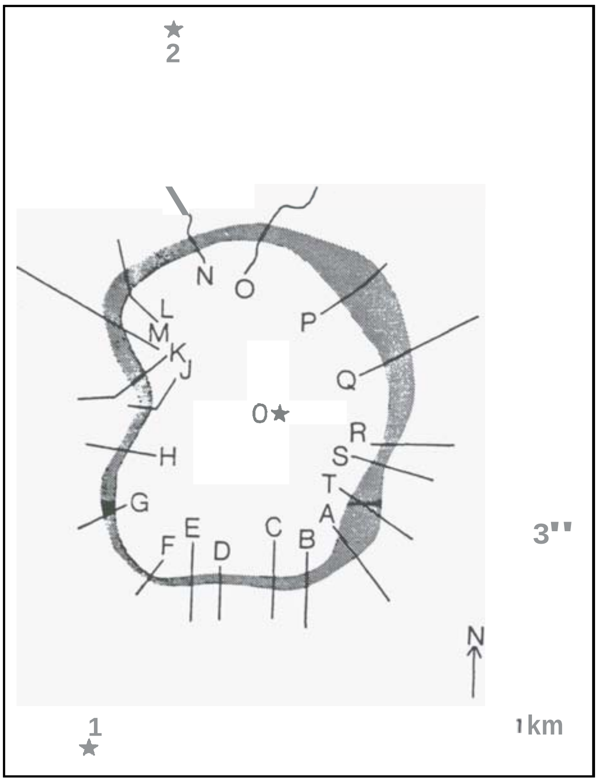

FIGURE 2: Electrode arrays used to locate the resistivity boundary (Risk, 1981). Current was passed in turn through electrode pairs 0-1, 0-2, and 0-3. Solid lines are traverse lines along which the potential electrodes were accurately located. The present position of the field boundary is shown by shading.

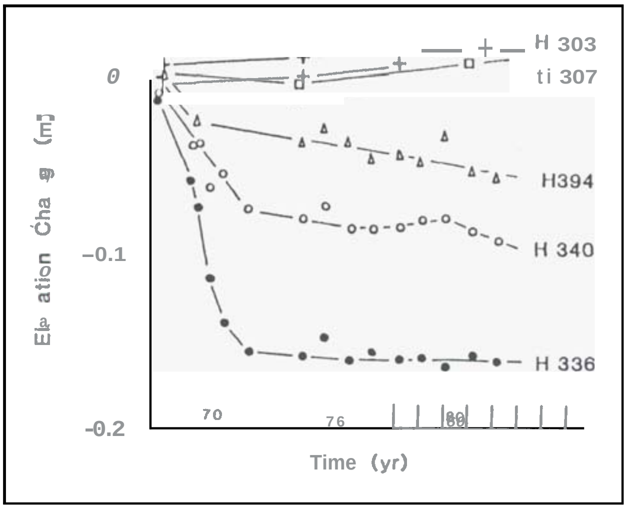

FIGURE 3: Plots of elevation change with time. Benchmarks H336 and H340 are located in the north-western (production) part of the field; H394 is in the eastern part; H307 and H383 are on the edge of the field. Note the rapid subsidence of H336 and H340 during the drawdown test period, and the lack of subsequent recovery.

The levelling data was used to locate the Power Station to the west of the Ohaaki area, in an area of minimal subsidence. The data also helped in siting the new bridge across the Waikato River, and in locating an emergency fluid holding pond. The surveys suggested that future ground subsidence was unlikely to cause serious flooding of land in the Ohaaki area, apart from present areas of lagoon, swamp, and marshland (MWD, 1977). Future levelling surveys will be able to monitor any subsidence and provide information to help manage its environmental effects.

To monitor horizontal deformation 10 new pillar type trig stations were installed to supplement 9 existing trig stations (Figure 1). The relative movements of these points have been measured to 1st order accuracy using theodolites and geodimeters in 1968, 1974, 1978, and 1981. Analysis of the 1968-1974 set of observations suggests that during the drawdown test period the maximum horizontal movement was about 120 mm, but the layout of the stations at that time was not completely satisfactory to obtain the accuracy required (MWD, 1977). Data from the subsequent surveys have not yet been analysed. Future surveys should be made if pipelines indicate significant amounts of horizontal strain are occurring, in which case more trig stations may be needed within the field.

GROUND TEMPERATURE AND HEAT FLOW CHANGES

Surface thermal features such as hot springs, fumaroles, geysers, and areas of thermal ground are associated with most water-dominated geothermal fields in New Zealand. These localised features generally result from steam or hot water from the deep reservoir migrating upwards along faults or fissures, through the overlying cold groundwater system, to the surface. Exploitation of the field usually results in changes in shallow ground temperature, heat flow, and the nature of the surface thermal features (Allis, 1981). The changes occur because pressure drops in the reservoir lead to variations in the amount of steam migrating upwards. A large pressure drop can even result in a reversal of this trend such that the overlying cold groundwater drains down into the reservoir. In this case, thermal features would die and shallow ground temperatures in the vicinity would decrease to ambient groundwater temperature. The main uses of ground temperature measurements are in environmental monitoring and in locating areas of cold downflow. However, Allis and Webber (1984) showed that ground temperature changes appear to be much more sensitive to groundwater depth changes than to groundwater temperature changes. A knowledge of groundwater levels is therefore critical for interpretation of measured ground temperature changes.

A shallow (1 m depth) ground temperature survey was made at Broadlands in 1967 (Thompson, 1968). The results 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 a smaller area in the eastern part near BR7. Another 1 m temperature survey was made in 1983 (Allis and Webber, 1984) but the data could not be compared directly with the 1967 data, because the measurement points had not been accurately located.

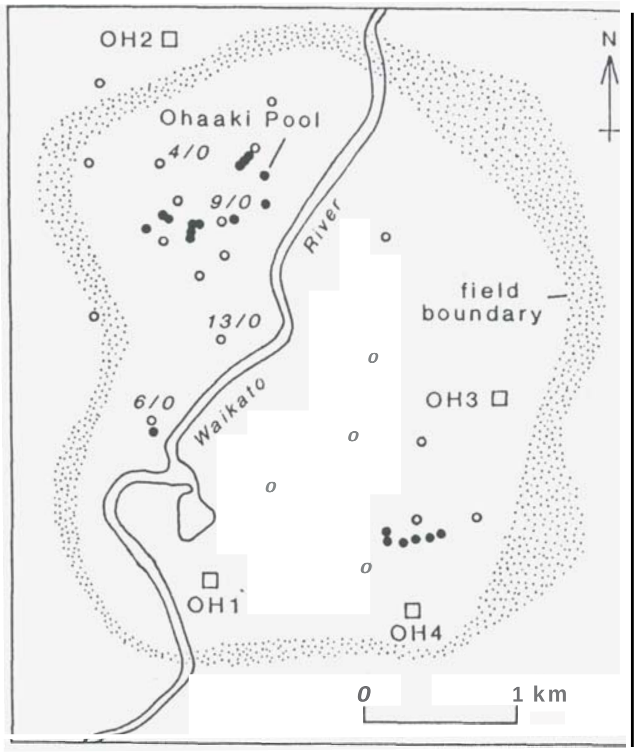

Figure 4 Map showing natural geothermal features worthy of monitoring (solid circles), the location of groundwater level monitor holes (open circles), and seismometers (open squares).

Recently, a new method of measuring ground temperatures has been investigated which uses thermal-infrared imagery (Mongillo, 1988). The detector is mounted beneath a helicopter which flies at about 500 m above ground level along a series of parallel lines approximately 150 m apart. Imagery in the 8-12 μm emissive thermal-infrared band is video taped, and selected images are computer processed using EPIC image processing software. Ground resolution is about 1-2 m, and temperature differences of about 1°C can be detected. This method overcomes the need for numerous, precisely located, measurement points and allows direct comparison of surveys at different times. It could be used, in conjunction with ground temperature measurements and photographs of natural thermal features (Fig. 4), to monitor any environmental changes that may occur at Broadlands due to exploitation. The method could also assist field management by providing a rapid means of locating places where cold groundwater might have started flowing down into the reservoir.

GROUNDWATER LEVEL CHANGES

At Broadlands, a shallow, cold groundwater system overlies the deep, hot reservoir of the field. The groundwater level is generally about 5-15 m below ground surface (Hunt, 1987). Groundwater levels have been monitored since the late 1960's in 14 shallow holes in the field (Figure 4); in addition the level in the Ohaaki Pool has been measured. The data (Hunt, 1987) shows that seasonal variations in level are less than 3 m in most parts of the field. During the drawdown test period, pressures in the deep reservoir decreased by about 1.5 MPa, but subsequently rose by about 0.7 MPa (Grant, et al., 1982; Figure 5). During and shortly after the drawdown test period, groundwater levels in some of the shallow monitor holes in the north-western part of the field dropped by up to 7 m (BR4/0), and subsequently rose by up to 5 m (BR9/0). However, in other holes in this part and elsewhere in the field the change in water level was much smaller (BR6/0, BR13/0; Figure 5). The data indicate that in some places in the north-western part of the field the shallow groundwater system is affected by changes in deep reservoir pressure.

During exploitation, reservoir pressures are expected to decrease by more than that which happened during the drawdown test, hence significant changes in groundwater level are likely to occur in places. Changes in groundwater level are important in interpreting repeat gravity and temperature changes (Allis and Webber, 1984; Hunt, 1987). Measurements should therefore be made at regular intervals to monitor the changes in groundwater level.

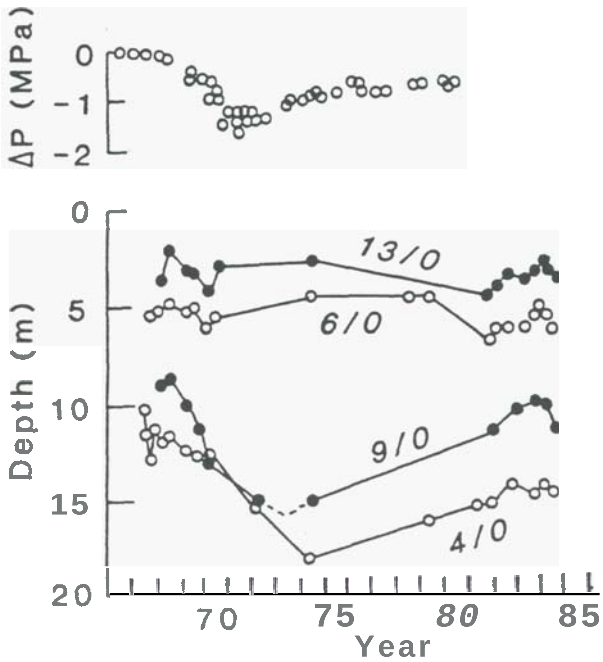

FIGURE 5: Plots of change with time in reservoir pressure (Grant et al, 1982) and groundwater level (Hunt, 1987).

CHANGES IN SEISMIC ACTIVITY

Many geothermal fields are located in seismically active areas and exploitation sometimes leads to changes in the location, magnitude, and number of shallow earthquakes within the field. A notable example is The Geysers field (California) where increased production led to increased seismic activity (Eberhart-Phillips and Oppenheimer, 1984). At Wairakei field an increase in local seismicity was clearly associated with fluid injection (Allis et al., 1985). However, in some other fields there has been no evidence for changes in seismicity associated with either production or injection (Bromley and Rigor, 1983). Increases in seismicity associated with production may be caused by thermal contraction (Denlinger and Bufe, 1982), ground subsidence (Yerkes and Castle, 1976), or conversion of aseismic creep to stick-slip deformation through drying out or silica deposition (Allis, 1982b). Increases in seismicity associated with injection of waste fluids are generally believed to result from an increase in pore pressure which allows a release of stress on preexisting faults (Majer and McEvilly, 1979). Exploitation induced seismicity is characterised by numerous, local, shallow earthquakes, which may occur as swarms or as a continuous sequence. This seismic activity may provide the opportunity to locate faults up which fluid could be flowing, or into which fluid is being injected. Locating the earthquakes is therefore of use both for environmental monitoring and reservoir management purposes.

At Broadlands, a seismic network was set up in 1987. Three of the four seismometers were specially located in the south-eastern part of the field (Figure 4), to be close to the area of injection. Signals from the seismometers are telemetered to Wairakei for analysis (Hurst, et al., 1989). Since operation of the network began there have not been any locatable earthquakes within the field (Sherburn, pers. comm.). This result is similar to that of a three week survey, made in 1971-72, during which time no crustal earthquakes with magnitude greater than 0 were recorded (Evison, et al., 1976). It is surprising, however, that no earthquakes were recorded during a recent pumping test in which wellhead pressures of about 3 MPa were maintained for several days.

Operation of the seismic network at Broadlands for two years has therefore enabled a good baseline, of no seismic activity, to be established before production. Continued operation during the next few years would enable any induced seismicity to be clearly recognised.

SUMMARY

Rational, economical field management could be assisted by repeat gravity, electrical resistivity, ground temperature, and microearthquake surveys. Management of any environmental effects associated with exploitation could be assisted by ground deformation, ground temperature, groundwater level, and microearthquake surveys at appropriate times. In most cases, sufficient data have already been collected for natural changes to be distinguished from exploitation induced changes.

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REFERENCES

Allis, R.G. **1981:** Changes in heat flow associated with exploitation of Wairakei Geothermal Field, New Zealand, N.Z. Journal of Geology and Geophysics **24: 1-19.**

Allis, R.G. **1982a:** Comparison of subsidence at Wairakei, Broadlands, Kawerau fields, New Zealand. Proceedings of the 8th Stanford Geothermal Reservoir Engineering Workshop, Stanford Univ.: **183-188.**

Allis, R.G. **1982b:** Mechanism of induced seismicity at The Geysers geothermal reservoir, California. Geophysical Research Letters, **9 629-632.**

Allis, R.G., Currie, S.A., Leaver, J.D. and Sherburn, S. **1985:** Results of injection testing at Wairakei Geothermal Field, New Zealand. Transactions 1985 International Symposium on Geothermal Energy. (Geothermal Resources Council): **289-294.**

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

Allis, R.G. and Webber, S. 1984 Shallow temperature measurements at Wairakei and Broadlands fields. Report 197, Geophysics Division, D.S.I.R., Wellington, New Zealand.

Bromley, C.J. and Rigor, D.M. Jr **1983:** Microseismic Studies in Tongonan and Southern Negros. Proceedings 5th N.Z. Geothermal Workshop: **91-96.**

Denlinger, R.P. and Bufe, C.G. **1982:** Reservoir conditions relating to induced seismicity at The Geysers steam reservoir, northern California. Bulletin Seismological Society of America, 72 **1317-1327.**

Eberhart-Phillips, D. and Oppenheimer, D.H. **1984:** Induced seismicity in The Geysers geothermal area, California. Journal of Geophysical Research 89 **1191-1207.**

Evison, F.F., Robinson, R. and Arabaz, W.J. **1976** Microearthquakes, geothermal activity, and structure, Central North Island, New Zealand. N.Z. Journal of Geology and Geophysics. 19 **625-637.**

Grant, M.A., Donaldson, I.A. and Bixley, P.F. **1982:** "Geothermal Reservoir Engineering": Academic Press, **369** p.

Hunt, T.M. **1977:** Recharge of water in Wairakei Geothermal Field determined from repeat gravity measurements. N.Z. Journal of Geology and Geophysics 20 **303-317.**

Hunt, T.M. **1987:** Recharge at Broadlands Geothermal Field **1967-1983** determined from repeat gravity measurements. Report 216. Geophysics Division, Department of Scientific and Industrial Research, Wellington, New Zealand.

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 11th N.Z. Geothermal Workshop: this volume.

Hunt, A.W., Sherburn, S. and Stagpoole, V.M. **1989:** The Taupo Seismic System in "Volcanic Hazards" (J.H. Latter, Ed.), Springer-Verlag, Berlin.

Mongillo, M.A. **1988:** Thermal infrared video imagery of the Rotorua Geothermal Field. Proceedings 10th N.Z. Geothermal Workshop; **333-338.**

Majer, E.L. and McEvilly, T.V., **1979** Seismological investigations at The Geysers geothermal field. Geophysics. **44: 246-269.**

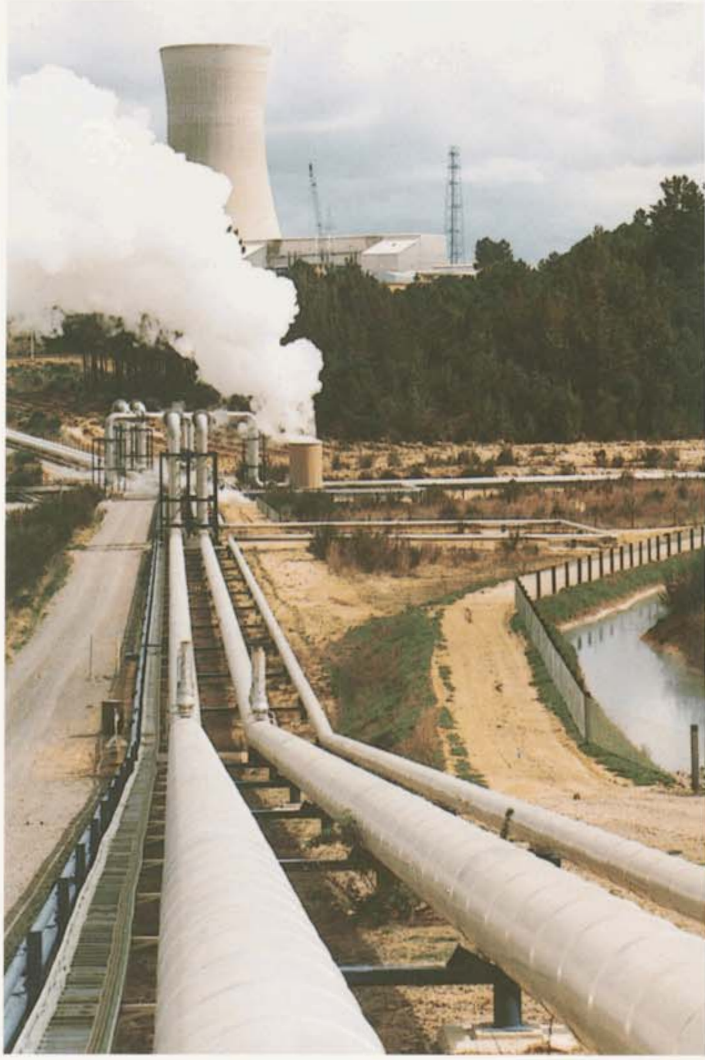
Ministry of Works and Development **1977** Broadlands Geothermal Investigation Report. Unpublished report, compiled in the office of the Chief Power Engineer, Ministry of Works and Development, Wellington, New Zealand, **236 p.**

Risk, G.F. **1981:** Defining boundaries and structures of Broadlands Geothermal Field, New Zealand, by geophysical methods - case history. In "Energy Resources in the Pacific Region", (M.T. Halbouty, Ed.) American Association of Petroleum Geologists, Tulsa. **578** p.

Risk, G.F., Groth, M.J., Rayner, H.H., Dawson, G.B., Bibby, H.M., Macdonald, W.J.P. and Hewson, C.A.Y. **1977** The resistivity boundary of the Broadlands Geothermal Field. Report 123, Geophysics Division, D.S.I.R., Wellington, New Zealand.

Thompson, G.E.K. **1968:** Ground temperatures at a depth of one metre. Report 49 Geophysics Division, DSIR, Wellington.

Yerkes, R.F. and Castle, R.O. **1976:** Seismicity and faulting attributable to fluid extraction. Engineering Geology. 10: **151-167.**



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