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SEISMIC MONITORING DURING A COLD WATER INJECTION EXPERIMENT, WAIRAKEI GEOTHERMAL FIELD: PRELIMINARY RESULTS

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ABSTRACT

A microearthquake survey showed that induced seismic activity occurred during cold water injection tests at Wairakei Geothermal Field. Over a six week period more than 120 microearthquakes were recorded; 90 of these occurred during the nine days of injection tests. No simple correlation between the occurrence of seismic activity and rate of injection, well head pressure, or step increases in injectivity was observed. Nineteen microearthquakes were located; their epicentres having a roughly elliptical distribution with the major axis in a NE-SW direction. Epicentres were up to 3.3 km from the injection site, the more distant occurring outside the field boundary. The observed 'b' value of 0.6 for the microearthquakes is typical of normal tectonic earthquakes.

INTRODUCTION

As part of an investigation into injection of waste water from the Wairakei Geothermal Field a test injection well, WK301, was drilled. The total depth was 1450 m, with the well cased to 80 m. A standard completion test, carried out on 1984 May 16, indicated rocks encountered by the well had low permeability except for a single major permeable zone at 1311 m. About six weeks later two cold water (<25°C) injection tests were made to investigate longer term injectivity characteristics. Leaver (1984) discusses the completion and injection tests, noting that injection capacity at 20 b.g. WHP (bars gauge well head pressure) improved significantly, stabilising at 400 tonnes/hour of cold water. At 1311 m, the maximum excess pore pressure was about 52 b.g. Precise levelling (Currie, 1984) showed ground inflation of up to 40 mm at the end of the second injection test, with the effect of injection on levels extending at least 500 m from WK301.

The low permeability of the rocks meant high injection pressures would be necessary, and suggested induced seismicity might occur. Although microearthquake activity associated with injection has not been recorded before in New Zealand it has been detected in several areas overseas, in both geothermal: Southern Negros (Bromley and Rigor, 1983), Larderello (Batini, et al., 1980), The Geysers (Bufs and Shearer, 1980) and non-geothernal areas: Denver (Healy, et al., 1968).

Hunt and Latter (1982) conducted a five week microearthquake survey at Wairakei. They concluded seismic activity occurred mainly in swarms at shallow depths (<2 km), in or close to the Taupo Fault Belt. The largest microearthquake located within 6.5 km of the borefield was of magnitude 1.25, and the b-value for the earthquakes in this region was found to be 0.7 ± 0.2. They concluded that production from the Wairakei field had not caused a large increase or decrease in seismic activity within or near the field.

To investigate any seismic activity associated with the injection tests five portable microearthquake recorders were installed around the injection site, in addition to the permanent seismograph at Wairakei Power Station (WNZ). However, WNZ is a low-gain instrument and recorded only the largest microearthquakes, even though it is only 200 m from the injection site. The closest portable recorder was 700 m from the injection site and the furthest about 3 km away. The positions of some recorders were moved between injection tests. Recording began on June 12. The first injection test began on June 26 and continued for three days; the second test began on July 18 and continued for six days. During both tests injection was almost continuous. Recording ceased and the recorders were removed on July 26.

MICROEARTHQUAKE ACTIVITY

A preliminary microearthquake survey using only one instrument, in addition to WNZ, was made during the 14 hour completion test at WK301 on May 16. One microearthquake was recorded which had an S-P interval of 0.8 sec and was felt at Wairakei, but it is not clear if it was related to the completion test.

During the main survey one recorder, Wk35 (Fig. 1), was operated for the full 44 days. A histogram of microearthquake activity, recorded at WK35, is shown in Fig. 2. This shows that there was a significant variation in seismicity with time and that injection clearly induced seismic activity. Induced microearthquakes recorded at WK35 typically had S-P intervals of 0.6 to 1.0 sec, consistent with them being located close to the injection site. During the two tests three microearthquakes were felt at the Wairakei Tower Station and Wairakei Village. During the 44 day period, 124 events (of S-P < 3.0 sec) were recorded; an average of 10 per day when injection was taking place and only one per day at other times. During injection the microearthquakes occurred at irregular intervals; events showed clustering in tine (not resolvable in Fig. 2) with up to 5 being recorded within a single minute at one stage. Activity was also clustered in time during periods of no injection with a maximum of 11 events (S-P = 1.7 sec) in any one 24 hour period and no more than three successive days with no events.

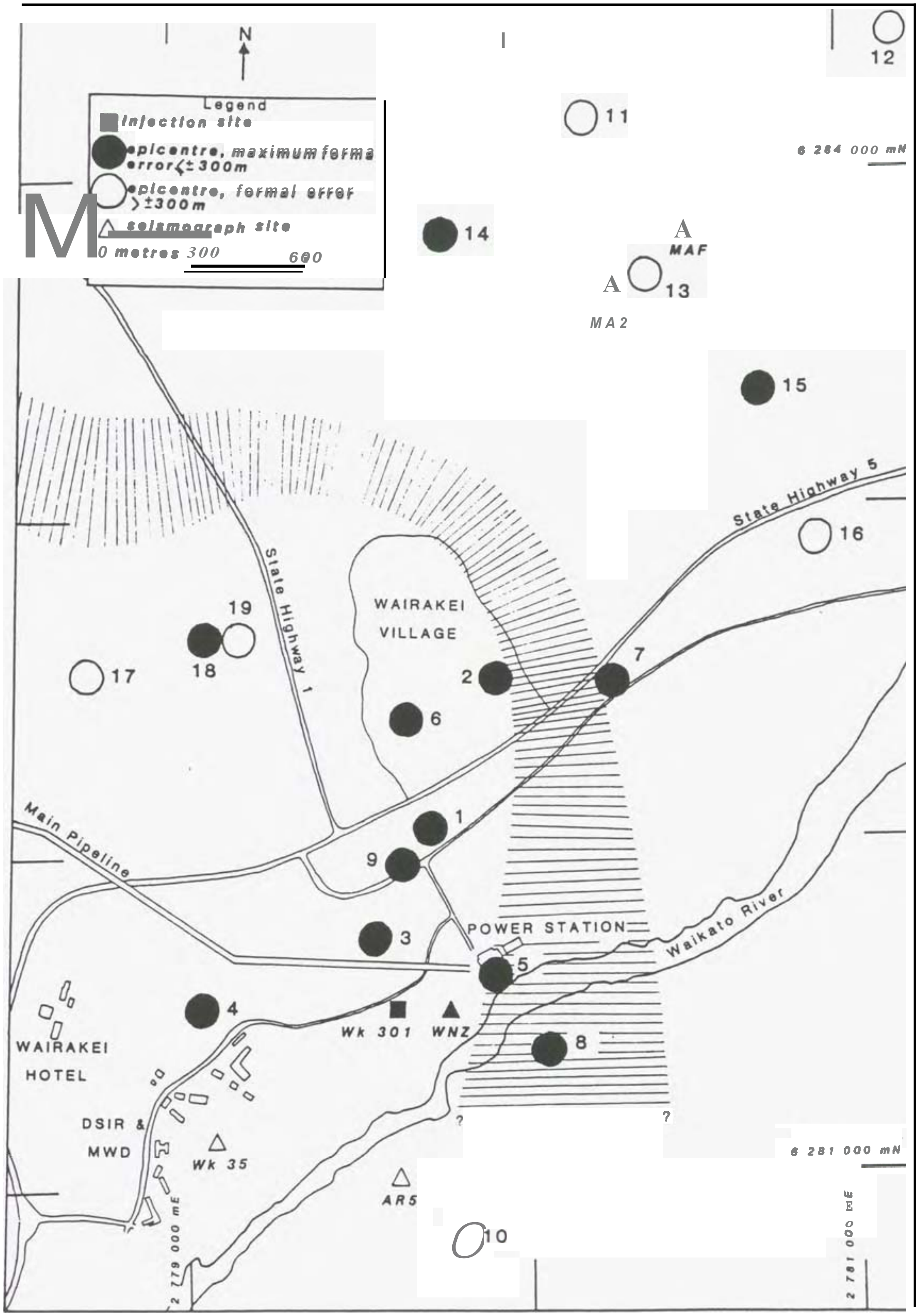


Fig. 1: Epicentres of microearthquakes located during injection. Epicentres 1-5 occurred during the first injection teat, all others during the second; 11-16 between 1034 and 103H on July 20 (U.T.) and 18-19 on July 23. All epicentres are calculated with depths restricted to 0.5 or 1.0 km. Not all portable recorder sites are shown hare. The hatched region is the boundary of the geothermal field, (Risk, et al., 1984).

Seismicity did not increase immediately on commencement of injection, for the first test there was a 23 hour delay and a 9 hour delay for the second test. The delay in the commencement of induced seismicity may be linked to the volume of fluid injected. A certain excess pore pressure may have to be exceeded over a certain surface area of fractures before induced seismicity begins; such an area will be related to the volume of fluid injected. During the first test 3310 m^3 of fluid (average WHP 15 b.g.), and during the second test *6067* m^3 of fluid (average WHP 27 b.g.) was injected before induced seismicity was recorded.

During the injection tests there does not appear to have been any simple coincidence in time between the occurrence of microearthquakes and well head pressure, flowrate, and step-like increases in injectivity. A more detailed examination of this data will be made in the future.

On the cessation of both injection tests microearthquake activity with an S-P interval typical of induced events ceased immediately. Between injection tests only one microearthquake with the typical S-P interval was recorded; this was located in the borefield.

MICROEARTHQUAKE LOCATIONS

A six plane layer velocity model (Table 1) derived from local well geology (Grindley, 1965), formation densities, and ultrasonic velocity measurements (Stern, 1982) was used in determining microearthquake locations. In setting up the model a constant P to S velocity ratio of 1.73 was adopted. The model differs slightly from that used by Hunt and Latter (1982) but at this stage is still preliminary.

Of the 124 microearthquakes recorded 19 were located (Fig. 1) and the accuracy of location for most of these earthquakes is ±300 m. Epicentres were calculated assuming focal depths of 0.5 km and 1.0 km and the best solution adopted; the positions for these solutions differed at most by about 400 m. Generally travel-time residuals were less than 0.15 sec.

Epicentres for both injection tests occurred within a roughly elliptical zone, 4 km by 1.5 km, with the major axis aligned in a NE-SW direction (Fig. 1). The major axis of the zone *is* roughly parallel to the major faults in the Taupo Fault Belt (Grindley, 1965).

The injection site was situated in the SW part of the zone. There appeared to have been some migration of epicentres during the total injection time; in general later epicentres occurred further from the injection site. In particular, microearthquakes forming part of a group of at least 15 that occurred between 1034 and 1051 hrs on July 20 (Universal Time) lay almost 1 km NE of any previously located events.

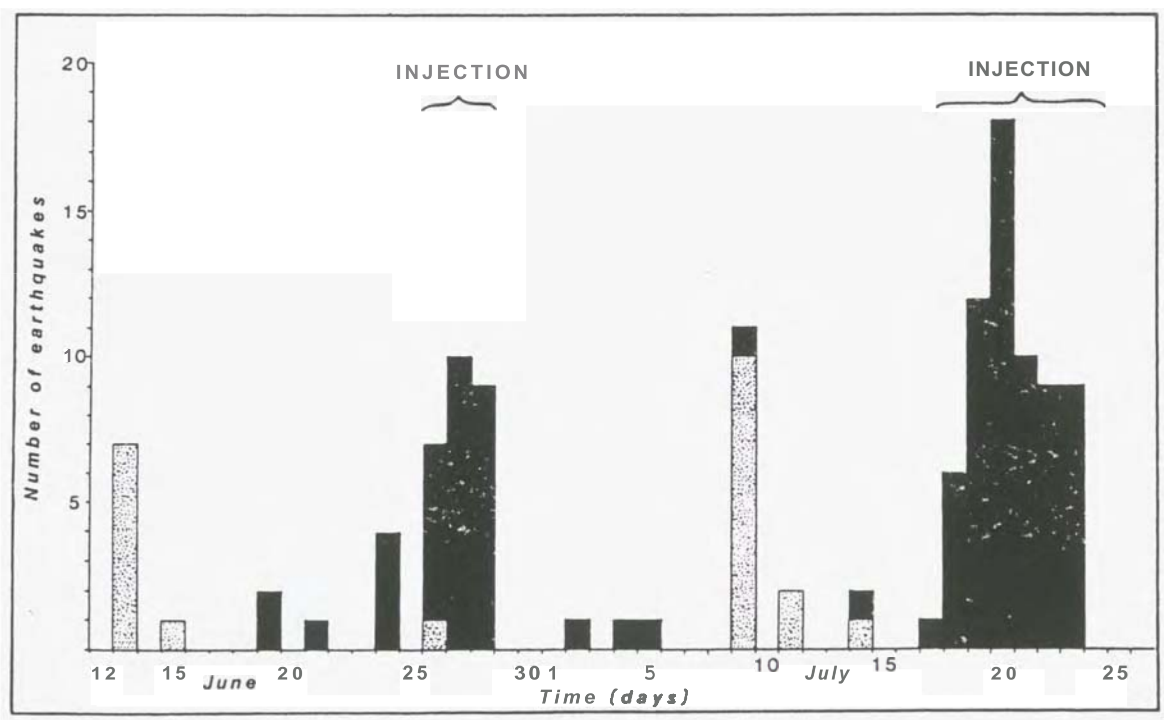


Fig. 2: Histogram of the number of microearthquakes recorded at WK35 during the monitor period. Solid bars indicate events of S-P interval less than 1.5 sec, approximately 5 km distant; dotted bars events of S-P interval between 1.5 and *3.0* sec, approximately 5-13 km distant. Injection periods are shown.

TABLE 1: Velocity model adopted to determine locations of microearthquakes recorded during injection testing. The two velocities for the Waiora Formation are not intended to correspond to individual members of that formation.

Rock Unit	P-wave velocity (km/s)	Model thickness (km)
Superficial ash and pumice	0.85	0.1
Huka Falls Formation	2.2	0.3
Waiora Formation (1)	2.5	0.6
Waiora Formation (2)	2.8	0.7
Wairakei Ignimbrite	3.3	0.8
'basement'	4.5	half-space

MAGNITUDES AND b-VALUE

Determination of absolute magnitudes is not yet possible; the portable recorders must first be calibrated against ragnitudes determined from WNZ. Unfortunately all the induced microearthquakes occurred too close to WNZ to allow magnitudes to be calculated, but it is hoped to calibrate the portable recorders using more distant earthquakes recorded during the six week monitoring period.

For this paper relative magnitudes have been calculated using a duration measurement and the formula $M = 2 \log T$ (T is duration in seconds) which is representative of such formulas already published. An additive constant will need to be applied, possibly about -2 making the absolute magnitude of the largest microearthquake about one. Further work on the magnitudes of events will be discussed elsewhere.

A cumulative frequency-magnitude plot (Fig. 3) for magnitudes between 0.5 and 3.0 (unadjusted) gives a b-value of 0.6 (regression coefficient 0.97). This value is typical of normal tectonic earthquake sequences and is in agreement with the value of 0.7 ± 0.2 obtained by Hunt and Latter (1982). It is, however, smaller than those determined in other geothermal areas where induced seismicity has been observed: Southern Negros 1.27 (Bromley and Rigor, 1983), Larderello 1.19 (Batini, et al., 1980). However, the b-value observed during injection tests at Wairakei was obtained from 80 events occurring over a period of only 9 days. Further monitoring would be necessary to confirm this value.

Fig. 3: Frequency magnitude relationship for 80 induced microearthquakes recorded during monitoring. Magnitudes were determined using the signal duration at WK35 and the formula $M = 2 \log T$. Magnitudes have not been adjusted to agree with WNZ. The line shown is a least squares fit to the points representing magnitudes >0.5 (regression coefficient 0.97). Log N is calculated at each 0.25 interval of magnitude, N is the cumulative number of events of magnitude >M. Horizontal bars represent the effect of the uncertainty in duration measurement on the magnitude.

SUMMARY

1. Injection of cold water induced seismic activity.

2. The induced seismicity did not begin immediately on the commencement of injection, suggesting both pore pressure and volume of rock affected by injection nay have had to reach some critical value before slippage could occur.

3. During injection, the occurrence of microearthquakes clustered in time and exhibited a similar manner to that observed at other times.

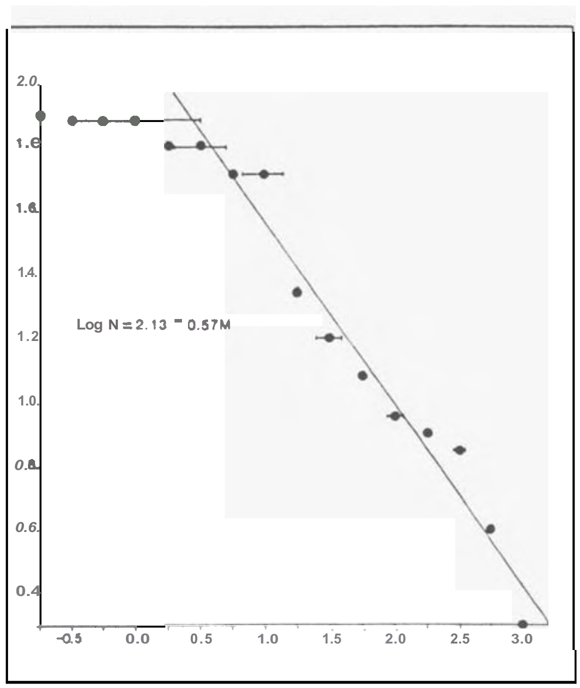
4. When injection stopped the induced seismic activity stopped immediately.

5. The induced seismicity did not appear to be affected by changes in the rate of injection, well head pressure, or increases in injectivity.

6. Many of the induced earthquakes that were located occurred outside the boundary of the field. The epicentral region was oriented parallel to the Taupo Fault Belt suggesting earthquakes resulted from slippage along existing fractures.

7. The distance of epicentres from the injection site generally increased with time during the injection tests.

8. The b-value is similar to that of normal tectonic earthquake sequences in the Wairakei area.



DISCUSSION

The author suggests that the induced seismicity at Wairakei was the result of the release of elastic strain caused by a reduction of the effective normal stress across fractures due to excess pore pressure. The immediate cessation of seismicity following that of injection does not follow the model of a propagating front of increased pore pressure (Healy, et al., 1968). When injection stopped this front would continue to over pressure pore spaces at greater distances from the injection site thereby continuing to induce seismicity, while pore pressures in the immediate vicinity of the injection site would drop below the critical level causing a return to the normal level of seismicity near the well. However, this discrepancy maybe a result of the short time over which injection took place, the relatively small quantity of injected water (85 k tonnes), and the relatively high permeability of the rocks in the Wairakei area.

RECOMMENDATIONS

If permanent injection at Wairakei takes place further over pressuring of pore spaces would be likely, and induced seismicity very possible. Seismic monitoring would be advisable, particularly during the initial period of injection.

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