RESULTS OF INJECTION TESTING AT WAIRAKEI GEOTHERMAL FIELD, NEW ZEALAND

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ABSTRACT

Well WK301 was drilled to 1440 m depth near Wairakei Power Station as part of reinjection feasibility investigations. The well bottomed in unexpectedly thick, lower Waiora pumice breccias and ignimbrites, suggesting a basin of downfaulted structure in this part of the field. Although the maximum temperature was only 138° C at well bottom, a temperature gradient of 15° C/100 m over the lower 300 m suggests a temperature of close to 230° C at 2 km depth. Static pressure in the well is the same as in the eastern production borefield. Three separate pump tests, which injected cold water at wellhead pressures up to 35 b.g. and flows up to 668 t/h, caused a permanent improvement in the injection capacity of the well. The injectivity increased in sudden jumps, presumed to be hydrofracturing events, and stabilized at 22 t/h/b/. Both inflation of the ground surface (maximum of 4 mm) and induced seismicity (>70 events) accompanied the pump tests.

INTRODUCTION

Wairakei Power Station, which is presently generating at its plant capacity of 157 MW, discharges close to 5300 t/h of waste water (1 tonne/hour = 0.28 l/s). About 4000 t/h of this water is separated in the borefield and flows down drains into the Wairakei Stream, and thence into the Waikato River. The remainder is steam condensate from the power station, which is discharged directly into the Waikato River. Because of the pollutants such as silica, arsenic, boron and lithium in the separated water, Electricity Division - Ministry of Energy is investigating the feasibility of reducing this pollution by either reinjection of the waste water into the ground, or chemical treatment prior to disposal into the Waikato River.

The main short-term advantage of reinjection is expected to be pressure recovery, and therefore increased productivity from the borefield. However, long-term disadvantages could be the breakthrough of cooler injection water into production wells, or decreased upflow of hot recharge water due to the pressure recovery. A critical factor is the time scale for flow back to the borefield, and therefore the location and depth of reinjection wells.

A preferred area of reinjection has been identified on the eastern side of Wairakei field (Figure 1). This area is far from the hottest part of the field, which is west of the

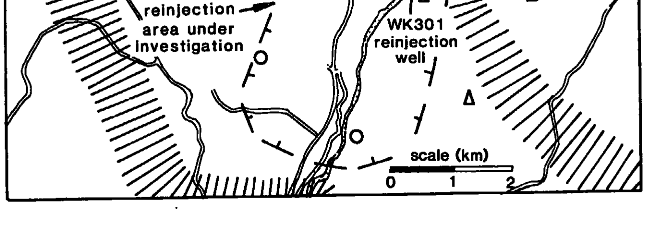

Figure 1. Location of WK301, and the reinjection area under investigation. The resistivity boundary of the field is from Risk and others (1984). Triangles denote microearthquake stations; closed circles are epicentres of earthquakes located during the first injection test; open circles are epicentres located during the second injection test; crossed circles are epicentres of a 17-minute swarm of earthquakes during the second injection test (refer to text).

production borefield, and which is thought to supply most of the recharge water. The site of the first reinjection investigation well, WK301, was chosen close to the power station and the Waikato River for several reasons. This area is 1 km from the nearest production wells, and about 4 km from the inferred hot water recharge region. It is the lowest part of the field, being 30 to 40 m below the production borefield, which would assist eventual pumping of reinjection water to the site. In addition, a large supply of cold water for drilling and injection testing was nearby.

In 1954, a 600 m deep, nonproductive well (WK36) was drilled 100 m from the site of WK301. This well passed through two temperature maxima of 140° C at around 100 m depth, and 145° C at 400 m depth. Cooler temperatures at all other depths and a bottom hole temperature of 100°C suggested at that time that this well was on the periphery of the field. In 1954 this well had an artesian head of 3 b (1 bar = 0.1 MPa = 14.5 p.s.i.), but by 1984 the water level had fallen to 130 m depth, equivalent to a pressure decline of 16 b. This is about 0.6 of the deep liquid pressure decline of Wairakei field, and appeared to confirm that this well was on the margin of the field.

In contrast to the measurements in WK36, both Schlumberger traversing and roving dipole resistivity surveys during the early 1980s showed this area of Wairakei field to have an apparent resistivity low anomaly (Risk and others, 1984). This suggests either hot, conductive water at depth, or extensive hydrothermal alteration of the rock. With the possibility of hot conditions being encountered at depth, sufficient funds were set aside to enable WK301 to be drilled to 1500 m depth. However, it was hoped that good permeability would be encountered at much shallower depth, and such a deep well would not be necessary.

DRILLING RESULTS

Drilling of WK301 commenced on 15 April 1984. Minimal drilling fluid losses and apparently poor permeability eventually ended in the well being completed at 1440 m depth. A 24.5 cm (9⅝ inch) production shoe was set at 781 m, and 19.4 cm (7⅝ inch) slotted liner extended from 757 to 1440 m depth. Below 781 m the well was drilled with water. The maximum vertical deviation was 3 degrees at bottomhole.

Lithology

The simplified stratigraphic sequence is shown in Figure 2. Over the uppermost 600 m, the expected sequences of surficial pumice deposits, lacustrine Huka mudstone members and upper Waiora Formation pumice breccia deposits were encountered. However the contact with the underlying Wairakei Ignimbrite is present at about 700 m beneath the production borefield 1 km to the west, and is 900 m deep in WK227, 1.8 km to the east of WK301. Instead, unexpected thick, lower Waiora pumice breccia and ignimbrite members were found (Wood, 1984), suggesting either a basin or graben structure beneath this part of the field.

Density and porosity measurements on core from the well gave values similar to elsewhere in the Wairakei field. The wet density and porosity of the Huka Formation and upper Waiora Formation were typically 1600 to 1800 kg/m^3 and 40 to 50 percent respectively. Core from below 500 m generally gave wet densities in the range 1800 to 2200 kg/m^3 and the porosities of 30 to 40 percent (H.H. Rayner, pers. comm.). Resistivity measurements were also made on core that had been sealed in plastic wrap to prevent drying out (G.B. Dawson, pers. comm.). These measurements suggested in situ resistivity values of around 5 Ω m for the two Huka mudstone members, the top of the Waiora Formation, and a siltstone layer within the Waiora Formation. The four other cores from the Huka pumice breccia member and the Waiora Formation suggested in situ resistivities between 20 and 60 Ωm. The resistivity surveying near WK301 indicated increasing resistivity with depth and an average in situ resistivity of around 10 Ω m.

Static Temperature and Pressure

The well was shut-in and left to equilibrate with the country rock following a 14 hour pump test immediately after drilling was completed. The temperature and pressure profiles after 6 weeks are shown in Figure 2. A local temperature maximum of close to 100° C is present at the top of the Waiora Formation suggesting horizontal flow at this depth. Below 1100 m depth there is a near-constant temperature gradient of 15°C/100 m. The maximum temperature of 138° C occurs at the bottom of the well.

The static pressure profile shows pressures are 11 b lower than in nearby WK36 (which is 600 m deep). The water level in WK301 stands at 240 m depth, and the pressure at the standard Wairakei datum of 150 m below sea level is 23 b. This is identical to the pressure in the eastern production borefield. Subsequent pump tests in WK301 showed the main permeability to be at 1310 m depth. Assuming this to be the pressure control point for the well, the 11 b vertical pressure difference occurs between 400 m depth (probable pressure control point in WK36) and 1310 m depth. This is indicative of the poor

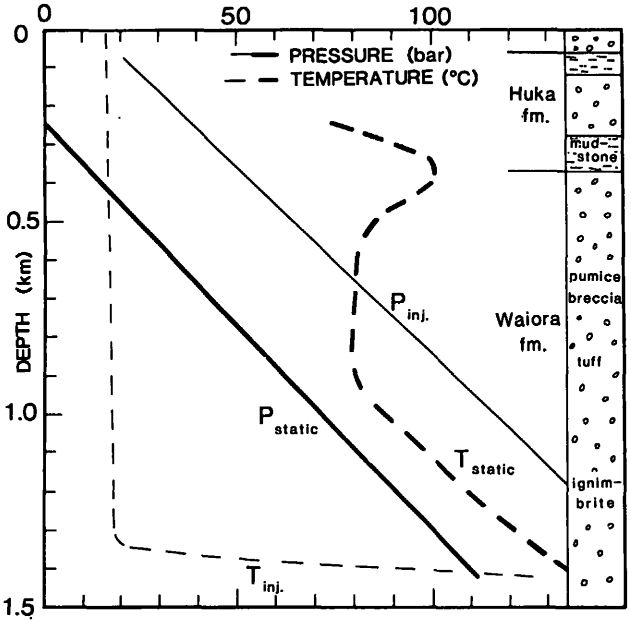

Figure 2. Temperature and pressure profiles in WK301 after the well had been shut-in for 6 weeks (T, P_{static}), and during cold-water injection (T, $P_{inj.}$). A simple lithologic log is shown on the right.

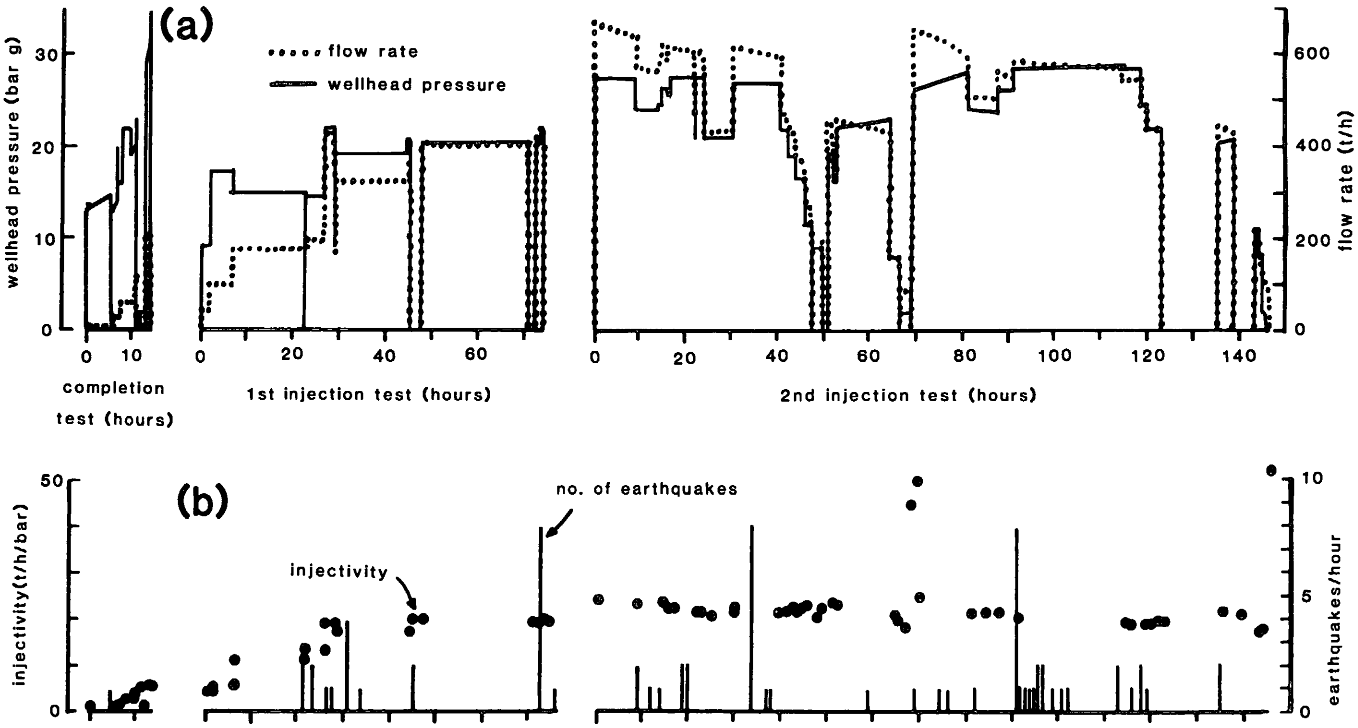

Figure 3(a). WHP and flow rate into WK301 during the three pump tests

(b). Variation in apparent injectivity (flow rate/WHP). Note the increase in injectivity during the first two tests. The frequency (hour^{-1}) of nearby earthquakes is also shown.

permeability in much of the Waiora Formation in this part of the field.

PUMP TESTS

Three pump tests were made on WK301: a completion test on 16 May 1984 while the drilling rig was still over the well; an initial injection test between 26-29 June 1984; and a second injection test between 18-24 July 1984 in the hope of achieving higher flow rates. All three tests used cold water. Details of the tests are contained in Leaver (1984). The wellhead pressure (WHP) and flowrate variations during the three tests are shown in Figure 3. Downhole temperature, pressure and spinner flowmeter measurements during the completion test indicated all the water was flowing out at 1310 m depth (Figure 2). Unfortunately similar measurements were not made near the end of tests to check whether any changes had occurred.

An unexpected feature of the pump tests was the increase in permeability that occurred during the first two tests. During the completion test, a maximum flow of 206 t/h was achieved at 35 b.g. WHP; during the first injection test the maximum flow was 430 t/h at 22 b.g., and during the second injection test the maximum flow was 668 t/h at 27 b.g. These figures become more meaningful if an apparent injectivity is calculated from the ratio of flow rate to WHP. (The true injectivity is more correctly calculated with respect to the static water level: WHP + 24 b.)

Variations in apparent injectivity are plotted in Figure 3b. For the first 6 hours of the completion test the injectivity was around 1 t/h/b. This increased in several discrete jumps during the following 4 hours to 5 t/h/b. The greatest increase in injectivity occurred during the early part of the first injection test. After 3 hours of pumping 100 t/h at 17.4 b.g., the flow rate suddenly increased to 176 t/h and the WHP fell to 15.4 b.g. This corresponds to an injectivity increase from 6 to 12 t/h/b. Another large increase in injectivity occurred when the WHP was raised from 15 to 22 b.g., 27 hours into the first injection test. At this time the flow rate increased from 190 t/h to 430 t/h, corresponding to an injectivity jump from 13 to 19 t/h/b. For the remainder of the first injection test and the second injection test, the apparent injectivity remained around 20 t/h/b.

The sudden increases in injectivity were probably due to hydrofracturing. Close inspection of the timing of induced seismicity, which accompanied the injection tests, shows no obvious correlations (Figure 3b). The hydrofracturing was therefore aseismic, or more likely, had insufficient energy to be detected by the seismograph network.

A stable, linear relationship between flow rate and WHP was attained for WHPs above 7 b.g. (Figure 4). The best-fit line implies a true injectivity of 22 t/h/b ($r^2 = 0.9$). When extrapolated to zero WHP, this line passes through the point of zero flow rate, as if the well had a static water level at the ground surface. However, a larger flow rate of around 100 t/h at 1 to 2 b.g. WHP was actually observed, suggesting an average true injectivity of only 4 t/h/b when the pressures in the well are between 0 and 26 b above static pressure. Such nonlinear behaviour is analogous to the increase in compressibility that occurs when a rock passes from a preconsolidation phase into normal consolidation (e.g. Narasimhan and Goyal, 1979). At Wairakei, the rock has experienced an increase in effective stress of around

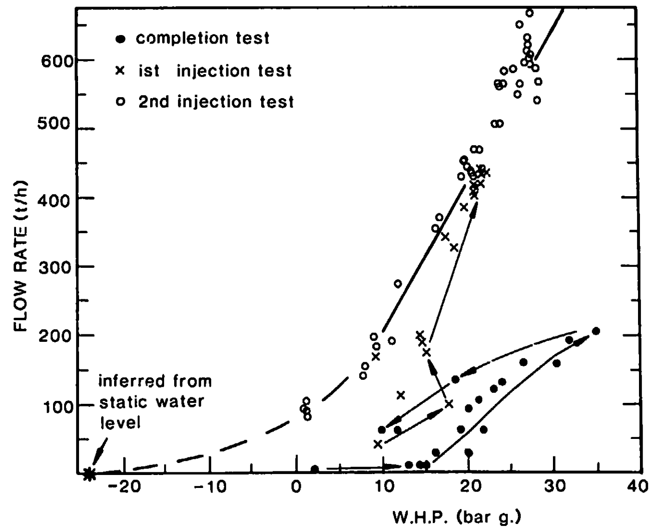

Figure 4. Response of WK301 to varying flow rate and WHP. Arrows indicate the path of increasing injectivity with time.

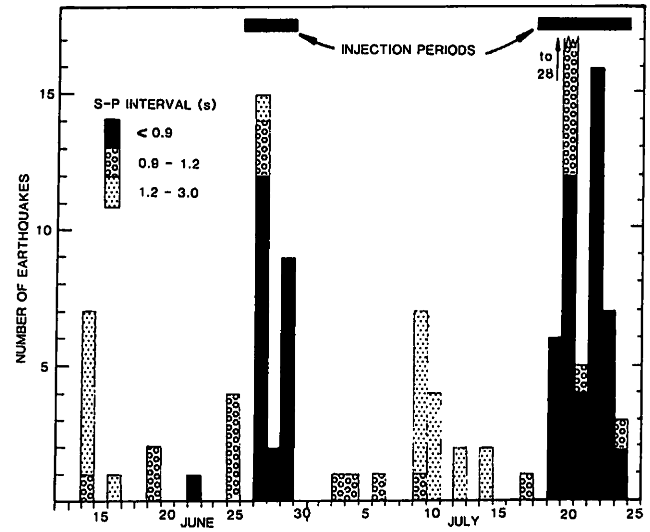

Figure 5. Histogram of the number of earthquakes recorded at the WK35 site during the monitor period. An S-P interval of 0.9 s represents approximately 3 km.

25 b due to the pressure drawdown caused by production, and this additional stress must be removed before fractures can open.

Analysis of one pressure transient from the completion test gave a transmissivity of 3 d.m., a skin of -5, and an incremental injectivity of 3 t/h/b. Unfortunately similar analyses were not possible after the improvements in injectivity of the well because of the use of centrifugal pumps during the two injection tests, and the additional pressure transients associated with flow rate changes.

Induced Seismicity

A microearthquake survey was carried out during the injection tests because of the anticipated high pumping pressures, and the possibility that seismicity would be induced. Although microearthquake activity associated with injection has not been recorded before in New Zealand it has been detected in many geothermal and nongeothermal areas overseas. Five portable microearthquake recorders were installed around the injection site, in addition to a 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 (Figure 1). The positions of some recorders were moved between injection tests.

A preliminary microearthquake survey using only one instrument, in addition to WNZ, was made during the 14 hour completion test. One microearthquake was recorded that 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. Recording for the main survey began on June 12, 14 days before the first injection test. One recorder located at WK35 (Figure 1) was operated continuously until July 26, 2 days after the end of the second injection test. A histogram of microearthquake activity, recorded at WK35, is shown in Figure 5. 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 less than 0.9 s, consistent with them being located <3 km from the injection site. During the two tests three microearthquakes were felt at the Wairakei Power Station and Wairakei Village. There were 124 events (of S-P < 3.0 sec) recorded during the 44 day period; 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 and showed clustering with time (Figure 3b). 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 3 successive days with no events.

Seismicity did not increase immediately on commencement of injection; for the first test there was a 21 hour delay and a 9 hour delay for the second test. The delay in the detection 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 is detected. 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 did not appear to have been any simple coincidence in time between the occurrence of microearthquakes and WHP, flow rate, and steplike increases in injectivity. On the cessation of both injection tests microearthquake activity with an S-P interval typical of induced events *ceased immediately*.

Of the 124 microearthquakes recorded, 19 were located using a six plane-layer, velocity model and assuming focal depths of 0.5 or 1 km (Sherburn, 1985). The epicentres are shown in Figure 1 and have an estimated accuracy of ±300 m. All epicentres plotted in Figure 1 occurred during the two injection tests. Most are located within 2 km of WK301. It is uncertain whether the two events 3 km southwest of WK301, and a swarm of events 3 km northeast of WK301 were induced by the water injection.

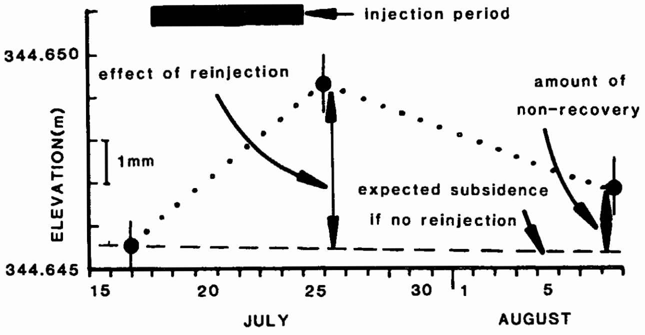

Figure 6. Example of the level changes measured during and after the second injection test. This benchmark (SMB301) is situated 50 m southeast of the wellhead.

It has not yet been possible to determine the absolute magnitudes of the seismic events. Felt reports from the largest events suggest a maximum magnitude of between 1 and 2. A cumulative frequency-magnitude plot using relative magnitudes gives a b- value of 0.8 ± 0.2 over a magnitude range of 1.25 (Sherburn, 1985). 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) in an earlier microearthquake survey of the Wairakei region. A focal mechanism solution of the induced earthquakes is also very similar to the northeast-trending dextral shear solution obtained by Hunt and Latter (1982). This suggests that the induced earthquakes were due to a sudden release of elastic strain stored in the rock prior to injection, and that they were triggered by the additional fluid pressure during injection.

Ground Deformation

Three precise leveling surveys were carried out to see whether measurable ground deformation occurred as a result of the second injection test (Currie, 1984). The initial survey was made 1 to 2 days before injection began; a second survey was made 1 to 2 days after the injection ceased; and a third survey was made another 2 weeks later. The origin for the surveys was a benchmark 900 m northeast of WK301. Almost all benchmarks had established subsidence histories, so all level changes were compared with the expected subsidence (relative to the origin) if there had been no injection (Figure 6). The measurement uncertainty for the level changes was estimated to be ±0.7 mm.

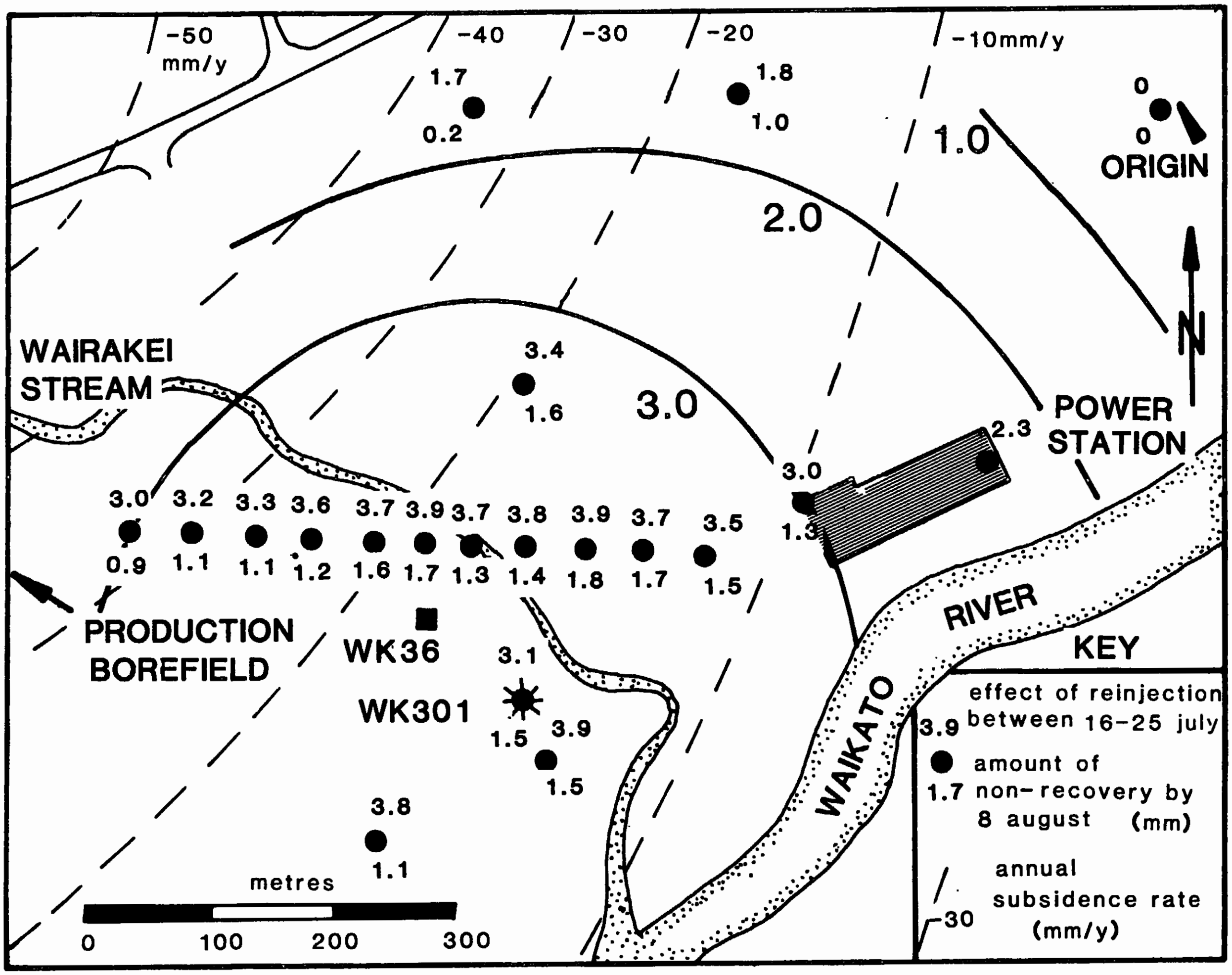

Figure 7. Compilation of the level changes (mm) measured immediately before and after the second injection test (upper number) and in the 2-week period after the test (lower number). Heavy contours are drawn from the upper numbers; dashed contours are the long-term subsidence rates relative to a benchmark distant from the field. Refer to Figure 6 for an example of the changes in level.

During the period of injection, the benchmarks were expected to subside by up to 0.8 mm, depending on their location. In fact, all benchmarks were elevated by up to 3.7 mm, which is equivalent to an anomalous rise of 3.9 mm (Figure 7). The origin may also have been affected by the induced ground movement so this figure may have been underestimated. The data suggest a circular doming that was centred near WK301 and had a half-peak radius of about 500 m. The level change of the benchmark on the cellar of WK301 during the injection test is not considered reliable.

In the interval between the two surveys following the injection test, all benchmarks subsided at rates exceeding their expected rates (Figure 6). However 14 days after the test, the benchmarks were still up to 1.8 mm above their expected elevations if there had been no injection test. Either the excess pore pressure caused by the injection test was still present in the country rock around the well, or some of the deformation was anelastic and permanent.

DISCUSSION AND CONCLUSIONS

Measurements made in WK301 have shown that the area of the field around Wairakei Power Station is not in a boundary zone as previously thought. The pressure below 780 m depth is the same as in the eastern production borefield at depth, and a constant temperature gradient of 15°C/100 m in the lower part of the well implies a temperature close to 230°C at 2 km depth. This confirms the recent resistivity surveying, which puts the boundary of the field further east than earlier surveys had indicated. The lithology of the well indicates either a basin or a downfaulted structure at depth with at least 500 m of relief.

Pumping at WHPs of 15 to 35 b.g. (overpressures of 39 to 59 b) permanently increased the injectivity in several jumps from an initial value of 1 to 3 t/h/b to 22 t/h/b due to hydrofracturing. However the average incremental injectivity for overpressures up to about 26 b (2 b.g. WHP) is still only 4 t/h/b. This nonlinear behaviour is attributed to the approximately 25 b of additional effective stress that is now acting on the rock at depth due to drawdown from the production borefield.

Both inflation of the ground surface (4 mm) and induced seismicity (>70 recorded events) were caused by the injection tests. The viability of long-term injection or reinjection into this part of the field therefore requires a careful assessment of these effects because it is close to the power station. There are several mitigating factors however. Firstly, economic considerations will necessitate injection pressures considerably less than the WHPs typical of these injection tests. Secondly, inflation of the ground surface would reverse the tilt and subsidence of the power station, which has been occurring since its construction. Power Station A has experienced 340 mm of subsidence since 1958, and the present rate is 9 mm/y. The average rate of tilt since 1968 has been 19 μrad/y, equivalent to a maximum differential of 1.1 mm/y across the northwest axis of the station. During the second injection experiment the tilt at the power station was 7 μrad to the southeast. The third mitigating factor is that relatively high rates of ground inflation and induced seismicity may be temporary. Both phenomena are caused by increasing pore pressure at depth, and after an initial transient period, the pressure should stabilize in the vicinity of the well. Nevertheless, the injection tests indicate that a gradual increase in fluid pressure across Wairakei field due to large-scale reinjection may cause an increase in the level of microseismicity over all the field.

The success and economic viability of a reinjection scheme for Wairakei field will require many reinjection wells, even if they all have good permeability. For example, the 4000 t/h of separated water would require at least eight wells, each accepting a flow of 500 t/h. The moderate permeability found in WK301 at 1310 m depth is an initial indication that finding good permeability in a suitable location of Wairakei field will be neither a simple exercise nor a cheap one. Economic considerations dictate that the finding of good permeability at shallow (<500 m) depth (towards the boundary of the field) should be a priority. The two most attractive zones for future reinjection tests are the Karapiti rhyolite 2 to 3 km south of the production borefield, and coarse pumice breccia layers within the Huka Formation and upper Waiora Formation between WK301 and the eastern production borefield. In view of the financial investment already committed to WK301, and the hot conditions at depth inferred from both the resistivity surveys and the temperature gradient in the bottom of WK301, deepening this well by another 500 to 800 m may also be warranted.

ACKNOWLEDGEMENTS

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