MONITORING OF REINJECTED FLUID USING REPEAT RESISTIVITY AT OHAAKI

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SUMMARY – Repeated resistivity measurements made around BR41 reinjection well at the north-western boundary of the Ohaaki geothennal field indicate large resistivity changes (up to 50% reduction) during five years of injection. These changes have a lateral extent of 200 to 300 m from the well. They are caused by hot (150°C) saline water (1200 mg/kg chloride) replacing cool groundwater in a rhyolite aquifer at about 300 m depth. The pattern of resistivity changes suggests radial flow, but with a preferred flow direction to the northeast., along the boundary of the field, rather than towards the production area of deep pressure drawdown.

1. INTRODUCTION

Over the past five years, four sets of DC electrical resistivity measurements have been made in the vicinity of Ohaaki reinjection bore BR41, to monitor changes in resistivity caused by the injected fluid. The purpose of these measurements was to investigate a possible method for tracking the extent and flow direction of reinjected fluid passing through a groundwater aquifer.

BR41 is located near the north-westem resistivity boundary of the Ohaaki geothermal field, adjacent to BR37 (Fig. 1). It was drilled to a depth of 428 m in November 1993, specifically to reinject separated brine into the Broadlands Rhyolite aquifer outside the field. Production casing is cemented to 179 m and the major permeable zone is at 300 m depth, with minor loss zones at 340 m and 386 m. Before injection started on 8/6/94 the well stood with a water level of 15 m (from the CHF elevation of 309.4 m). Temperatures were reported to be less than 30°C.

A good connection exists between permeable zones at similar depth in BR41 and the neighbouring bore BR37, which is used for pressure monitoring (37U). There is also a 40 m deep groundwater monitoring bore (BR37/0) nearby. It has a water level of 5.7 (± 0.7) m, which varies with rainfall recharge, but not with BR41 injection pressure. The 9 m difference between the undisturbed water level in the shallow groundwater aquifer, and that in BR41, is an indication of sub-hydrostatic pressure gradients in this area, also suggesting that the two aquifers are not connected. Separating aquicludes therefore help protect the shallow groundwater environment from any effects that may be caused by rising pressures or temperatures in the 300 m deep confined aquifer used for injection.

Background geoscientific information on the Ohaaki geothermal field is summarised in Contact Energy (1998), appendix 5. In the north-westem sector of the field, some minor effects on shallow groundwater levels, temperatures and chemistry have been observed as a result of production induced draw-down (Bromley et al, 1993). However, these have been restricted to groundwater bores near thermal features (e.g. BR4/0, BR3/0, BR2/0), where water levels have declined by a few meters as local downflows developed. Bores near areas of temporary surface disposal (by soakage) of separated geothermal brine have shown changes in groundwater chloride concentrations (Contact Energy, 1998). Except for these local effects, shallow groundwater levels in this north-westem sector generally follow a gradient from west to east of about –77 m/km, implying flow towards the Waikato River.

The receiving aquifer, at about 300 m depth in BR41, originally consisted of unmineralised cold water. Tracer tests undertaken in November 1994 showed no detectable returns from BR41 injection in any of the production wells sampled. It is concluded, therefore, that the receiving aquifer at BR41 is poorly connected to the production aquifers. The injectate consists of separated water from Ohaaki flash plants at a temperature of about 150°C and a chloride concentration of 1200 mg/kg. Flowrates into the well have varied, decreasing fiom about 360 tonnes/hr for the first few years to about 250 tonnes/hr in 1999 (May).

Resistivity measurements are an established method of determining the presence of geothermal water in the ground. A large increase in chloride concentration and temperature should, therefore, produce a measurable resistivity decrease around the well. The resistivity changes should also indicate the direction and lateral extent of subsurface injectate flow. In the absence of any tracer test returns, or detectable pressure or temperature effects in monitor wells, there appears to be no other means of tracking this fluid when it is reinjected outside the field boundary.

Several resistivity surveys have been conducted at Ohaaki to delineate the field The only other repeat set of measurements (1975 and 1993) was reported by Risk (1993). These were made at 50m intervals along several traverses across the resistivity boundary. Although most traverses showed no significant changes over this period that could be caused by movement of fluid across the resistivity boundary, it was noted that a decrease in resistivity on several traverses, just inside the southern boundary, may be attributable to deep injection into BR30, about 600 m to the northeast.

Since 1993, the reinjection strategy has changed at Ohaaki. Reinjection wells to the south (including BR7, 29 and 30) that showed evidence of premature returns to production wells, were permanently closed. They were replaced by shallower wells to the west and northwest (BR38, 41 and 46). Currently, most of the separated water is injected outside the field, into low temperature rhyolite aquifers that are not well connected to the high temperature reservoir (Clotworthy, in press).

2. RESISTIVITY FIELDWORK

The first resistivity survey around BR41 was made in Feb/March 1994 prior to commencement of reinjection,. At this time, only a relatively small quantity (about 10 l/s) of separated geothermal water was being disposed of in a soak-pond, 100 m east of BR41. The second survey was made in August 1994. At this time reinjection had been in progress at BR41 for about 8 weeks. Separated water was no longer being disposed of in the soak-pond, but it contained some fresh water from recent heavy rain. The third survey was made in January 1997, after reinjection had been in progress for about 2.5 years at an average rate of about 360 tonnes/hour (100 l/s). The latest survey was completed in May 1999, after five years of injection at a rate declining to about 240 tonnes/hr (67 l/s). On the last two surveys the soak pond was empty of water.

The resistivity measurements were made at 50 m intervals out to 300 m along six lines, radial to the reinjection bore BR41. Difficulties in clearing access through regenerating scrub resulted in some lines not being fully completed in the later repeat surveys. Figure 2 shows the location of measurement sites and line names. The location of this area of investigation is shown as a box in Figure 1. Original locations of the measurement sites were obtained using a tape and compass, and marked with a white peg for precise relocation. However, due to machine re-clearing of the access lines several of the pegs could not be found. In these cases the site locations were re-measured with a tape and are likely to be within 10 m of the original sites. Because of the disposal of separated geothermal water into the soak pond during the January 1994 survey, several extra measurements were made near this pond to help define any area of associated low resistivity. They were not re-occupied during subsequent surveys.

At each measurement site an orthogonal pair of potential electrodes is used to determine the magnitude and direction of the electric field DC electric current is passed into the ground through two fixed current electrodes (A and B of Fig. 1) spaced 1.14 km apart at an azimuth of 143°.

The effective penetration depth of the resistivity measurements using this vector Schlumberger array is about 300 (± 150) m, which is comparable to the injection depth in BR41. Therefore, apparent resistivity changes caused by injection should be readily detectable.

3. RESULTS

Resistivity values fiom the pre-injection survey (Feb 94) show that BR41 is indeed centred in a NE trending boundary zone of steeply increasing apparent resistivity: values over 100 ohm-m, 250 m to the NW, and as low as 6 ohm-m, 300 m to the SE. The average value 50 m fiom the well was 43 ohm-m. Superimposed on this background pattern, there was a small area of very low resistivity (3-10 ohm-m) adjacent to the soak pond east of BR41. The size of the pond was approximately 25 m by 12 m, and the resistivity reducing effect of about 10 l/s of infiltrating brine was observed up to 50 m from the pond edges. Another local anomaly was observed on line B (at 100m). Here, a large reduction in observed resistivity is probably caused by distortion fiom the nearby reinjection pipeline. This data point is therefore discarded.

The first repeat set of measurements (Aug 94) showed little change in the apparent resistivity contours. The average value 50 m fiom BR41 had dropped to 39 ohm-m (-12%), but the resistivity adjacent to the soakage pond increased from 3 to 5 ohm-m in response to the replacement of geothermal water with rainwater.

Although incomplete, the January 1997 survey showed significant decreases in resistivity within about 200 m of BR41, after 2.5 years of injection. The average resistivity within 50 m of the well reduced to 33 ohm-m (-24%). At nine sites the resistivity had decreased by between 25% and 42%. This is well outside the range of measurement error for these data (± 10%) and the expected variation in resistivity from natural causes (± 10%), such as changes in vadose zone saturation caused by rainfall.

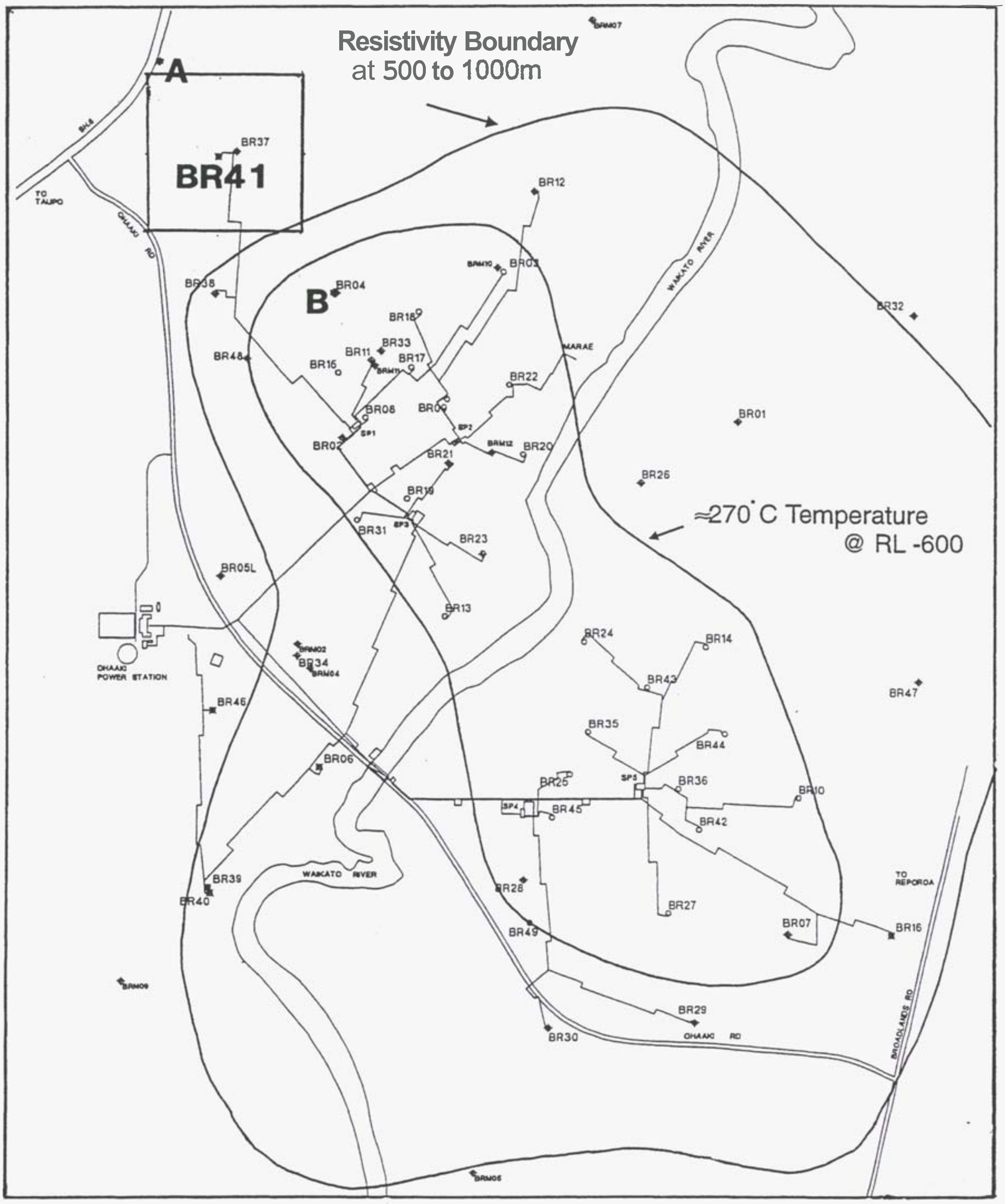

Figure 1. Map of Ohaaki Geothermal Field from Contact-Energy (1998). A box shows the area of repeat resistivity measurements in Figure 2. A and B are current electrode sites.

The latest set of resistivity measurements, in May 1999, after five years of injection, has shown a continuing decline in resistivity at most sites. Notable exceptions are at 300 m radius on lines B, C and D, that is, to the south and west, where resistivities have remained relatively constant since the *start*. The average resistivity within 50 m of BR41 is now 28 ohm-m (-35%). The average resistivity decrease between Feb 1994 and May 1999 for all sites (with the exception of those distorted by the soak pond and the reinjection pipeline, and the ends of lines B to E) is -32%.

The distribution of percentage changes in resistivity over five years is illustrated in Figure 2. Ignoring data distorted by local effects, it appears that the resistivity values have generally decreased as a result of radial flow of injected fluid. Furthermore, these data also suggest that there is a preferred direction of flow to the northeast, where the effects are observed to at least 300 m distance fkom BR41. To the south and west, the effects are observed only out to about 200 m distance.

Figure 3 is an illustration of the resistivity changes against time at nine selected sites. They are labelled by station number, line A to F (clockwise from east), and distance from BR41 (50 m to 300 m). Note that the two closest sites (E50, F50) decreased more rapidly in resistivity during the first two months of injection, while sites further away generally showed little change in the first two months but decreased thereafter. This is consistent with the conceptual model of injection causing a chemical and temperature front which gradually moves laterally away from the bore.

4. DISCUSSION

Interpretation and modelling of the observed resistivity changes with time, caused by injection at BR41, are at a preliminary stage. A 2D model of the Ohaaki resistivity boundary in the vicinity of BR41 is under consideration. It will need to be better constrained by additional resistivity soundings in this area. Some shallow soundings to the south-east (near BR4) reported in Bromley et al(1993) suggest that a 20 m thick Surface layer of about 200 ohm-m overlies lower resistivity formations. Using the 1975 bipole dipole resistivity traverse measurements, Mulyadi *et al* (1979) modelled an outward sloping boundary to the NW, near BR41. Risk (1993) used a simple vertical boundary within the depth range of 50 to 500 m. Resistivities inside the field are about 1.5 to 5 ohm-m, and outside they are about 40 to 30 ohm-m. However, some interfingering at the boundary probably occurs because of cross flows of hot or cold fluid at different depths.

The injected water at BR41 has a calculated resistivity of 1.2 ohm-m (using standard formulae for resistivity of Na-Cl electrolyte solutions as a function of temperature). The effective water resistivity in the cool receiving environment outside the boundary is about 10 ohm-m, taking into account the effect of free sorbed ions on the walls of pores and joints. Therefore, the fluid resistivity reduces by a factor of 8 if all the cool groundwater is replaced by hot injected water. The effect that this has on measured apparent resistivities at the Surface depends on the effective porosity, the thickness of the receiving formation, and the lateral extent of the injected water. The average porosity of nine cores of Broadlands Rhyolite, at depths of 220 to 570 m, in BR37 and BR6, is 20%. The thickness of the rhyolite is 435m in BR37. If we assume that the entire injected volume over five years of about 14 million m^3 has completely replaced the previous cold fluid in a cylinder of average radius 250 m, then the affected aquifer thickness is about 350 m.

If, as a first approximation, this cylinder is treated as a layer at 220 m to 570 m depth, then the theoretical effect on measured apparent resistivities at the centre of the cylinder (BR41) can be calculated. At an AB/2 spacing of 500 m, an observed apparent resistivity decrease from 43 ohm-m to 28 ohm-m (-35%) can be accounted for by a 70% reduction in layer resistivity, for example from 40 ohm-m to 12 ohm-m A value of 12 ohm-m for a layer that is saturated with 1.2 ohm-m saline fluid, would imply an apparent formation factor ($\rho/\rho w$) of about 10. A theoretical formation factor for clean rock, using Archie's Law ($\rho = a\, \rho w\, Ø^{-n}$), with $a = 1$, $n = 2$, $Ø = 0.2$, is 25. The lower apparent formation factor of 10 could be caused by the contributing effect of matrix conduction (from clays). Matrix resistivity, in this case, would be about 20 ohm-m.

To summarise, it is possible to explain the observed changes in resistivity with time at BR41 in terms of a conceptual model of hot saline injectate displacing cool groundwater. We plan to refine this model, and thereby improve this method of tracking injected geothermal fluids.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial, logistic and technical support of Contact Energy in undertaking this work. Funding was also provided through the NZ Foundation for Research and Technology, Contract CO5807.

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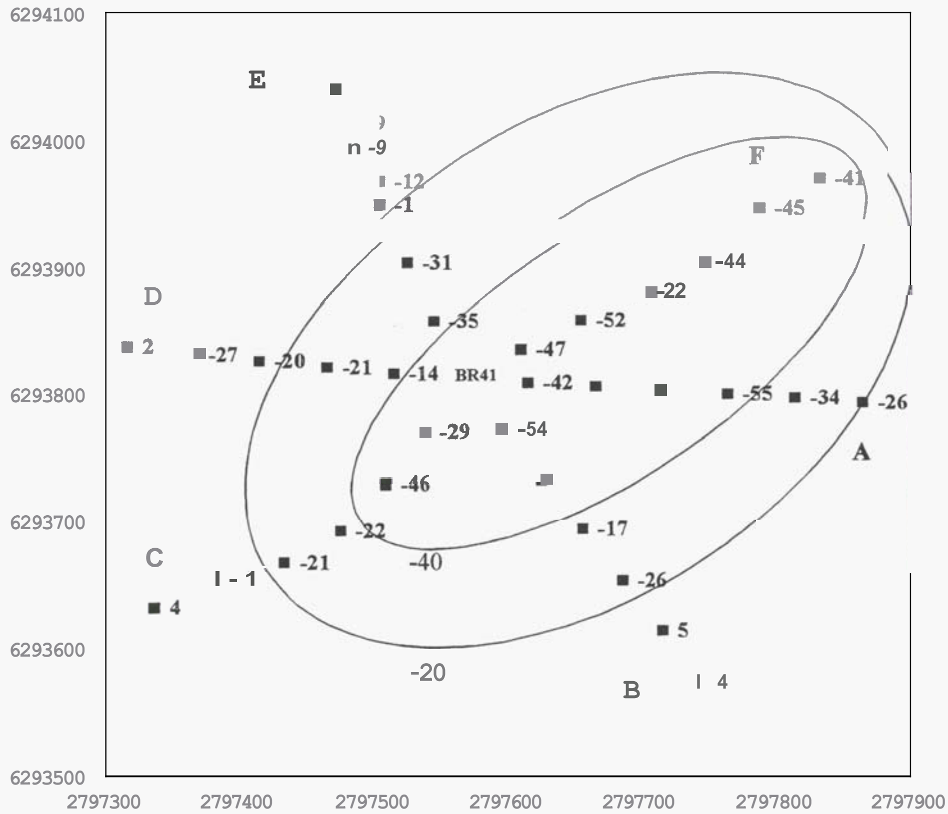

Figure 2. **Map of** repeat resistivity sites around BR41, lines A to F, showing percentage changes in resistivity between May99 and Feb94. Locally disturbed values are deleted.

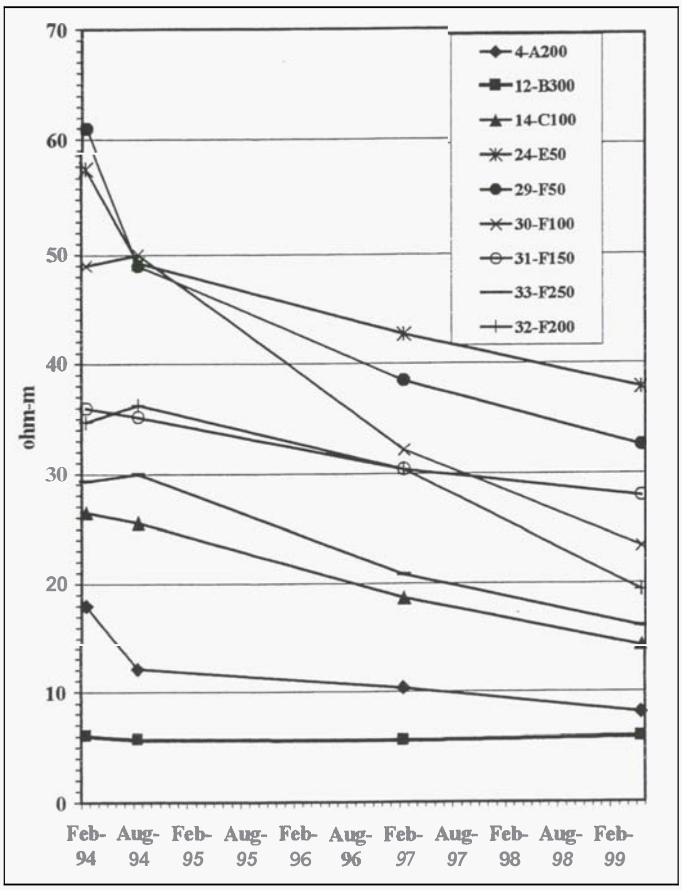

Figure 3. Changes in measured resistivities with time at selected sites, labelled by Stn #, line letter and distance fiom BR41.

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