

TRACKING THE MOVEMENT OF EXTERNALLY REINJECTED GEOTHERMAL FLUID (OUT-FIELD) USING REPEAT RESISTIVITY

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ABSTRACT

External ("out-tiel#) reinjection of hot saline water into cool groundwater aquifers accomplishes the environmental objective of avoiding surface disposal effects, while minimising the detrimental effects of premature reinjection returns to production wells, and enhancing sustainable resource use. Tracking the fate of this fluid can be difficult without an extensive and expensive network of monitor bores. Resistivity monitoring can be used to track the flow direction and lateral extent of the injected water, because of its contrasting conductivity. An example from Qhaaki, New Zealand, illustrates the use of the repeat resistivity method for this purpose. Changes of up to 56% were detected over 5 years of injection into a non-thermal aquifer at about 300m depth. The slow rate of change implies that thermal and alteration effects are probably significant causes. The pattern of change implies quasi-radial flow to about 250m radius, but with a preferred direction parallel to the boundary of the field rather than towards the centre of production. This result supports the inference that the injection and production aquifers are poorly connected, as deduced from the absence of tracer returns. External reinjection, in this setting, appears to be a successful strategy.

1.0 INTRODUCTION

Reinjection is a preferred alternative to the discharge of separated geothermal water into surface waterways because there is less environmental impact. However, if relatively low-temperature geothermal liquids are injected directly into the high temperature reservoir, they can have a detrimental effect by cooling the hot rock, which may reduce the long-term sustainability of the geothermal resource. Another detrimental effect of direct reinjection is

the resulting rise in reservoir pressure, which may suppress the natural recharge of hot water from deep in the geothermal reservoir. Increased deep recharge is stimulated by reservoir pressure drawdown, particularly during the early years of production. Discharge enthalpy changes may also occur when there is insufficient recharge to match the extraction rate. Management of reinjection is concerned with balancing these effects to optimise the sustainable use of the geothermal resource.

One way of managing the detrimental thermal and recharge effects is to inject outside the geothermal reservoir. Outfield injection areas contain liquid at lower temperature, and the pressure connection to the geothermal reservoir is much weaker, usually because of hydrological or low permeability barriers at the geothermal field boundary. However, external injection needs to be environmentally and economically sustainable. There should be no detrimental effect on overlying groundwater used for irrigation or drinking water supplies. Cooling of the injected fluid should not cause unacceptable rates of silica deposition within the receiving aquifer, and reinjection capacity should not be compromised by excessive pressure increases in the receiving aquifer.

2.0 REINJECTION AT OHAAKI

A 110 MW power plant was commissioned at Ohaaki in 1989. From 1993, a change was made to the reinjection strategy at Ohaaki. The original deep reinjection wells, within the southern part of the field, showed evidence of premature fluid returns to production wells. These were permanently closed and replaced by shallower wells to the west and north-west located outside the resistivity boundary of the field. Most of the separated water at Ohaaki (about 11 Mt/yr) is now injected outside the field into permeable rhyolite formations at about 300

to 400m depth. These contain low temperature aquifers that are not well connected to the high temperature reservoir, nor to the overlying shallow groundwater.

BR41 is an example of a good external reinjection well (Figure 1). Since 1994, it has been accepting approximately 308 (\pm 50) tonnes/hour of 150°C separated water into a rhyolite aquifer at 300 to 400m depth, where pre-injection temperatures were less than 50°C. This aquifer is capped by aquicludes of low permeability (Huka Falls Formation mudstones) preventing any pressure or fluid connection to the overlying (perched) groundwater, as demonstrated by monitoring in a nearby, 40m deep, groundwater bore (BR37/0). Tracer tests **also** showed no detectable returns from BR41 injection in any of the production wells sampled, implying that the receiving aquifer is poorly connected to the production aquifers. There has been no evidence of any reduction of injectivity by near well-bore silica deposition (in the formation) as silica-saturated fluids are cooled and diluted.

Since 1994, four sets of DC electrical resistivity measurements have been made in the vicinity of 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 the targeted groundwater aquifer.

3.0 WELL BR41 DATA

BR41 is located near the north-western resistivity boundary of the Ohaaki geothermal field, adjacent to BR37 (Figure 2). It was drilled to a depth of 428m in November 1993, specifically for the reinjection of separated brine outside the field. The receiving aquifer is Broadlands Rhyolite, a formation that traverses the field boundary on the western side of the field. Production casing is cemented to 179m and the major permeable zone is at 308m depth, with minor loss zones at 340m and 386m. Before injection started in June 1994 the well stood with a water level at 15m depth. Temperatures were less than 50°C (Figure 1).

A good hydraulic connection exists between permeable zones at similar depth in BR41 and

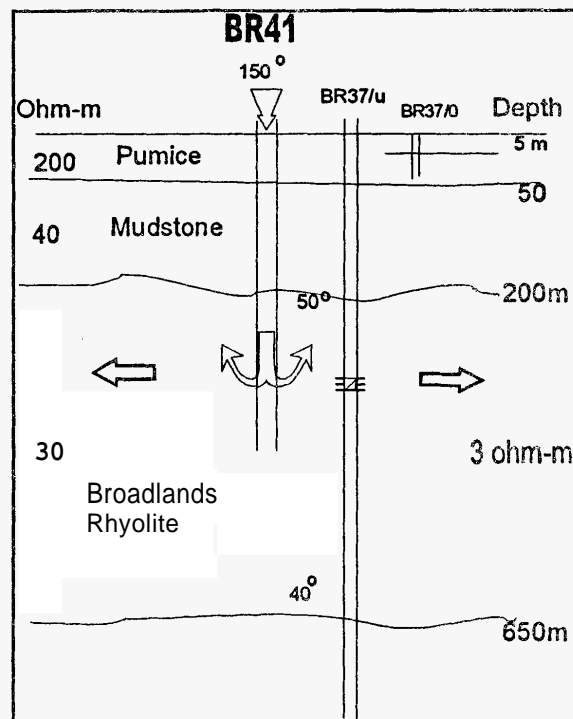


Figure 1. Cross-section showing resistivity layers and geology at BR41. Reinjection of 150°C geothermal fluid displaces cool groundwater (<50°C). BR37/U (upper perforation) and BR37/0 are monitor bores. The shallow pumice layer hosts a separate, perched, groundwater aquifer.

the neighbouring bore BR37, which is used for pressure monitoring at two levels (37U, 37L). There is **also** a 40m deep groundwater monitoring bore (BR37/0) nearby. It has a water level at 5.7m (\pm 0.7) depth, which varies with rainfall recharge, but not with BR41 injection pressure. The 9m 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. The two aquifers are not connected. Aquicludes help protect the shallow groundwater environment from any effects that may be caused by rising pressures or temperatures in the 300m deep confined aquifer used for injection.

In the north-western sector of the Ohaaki 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

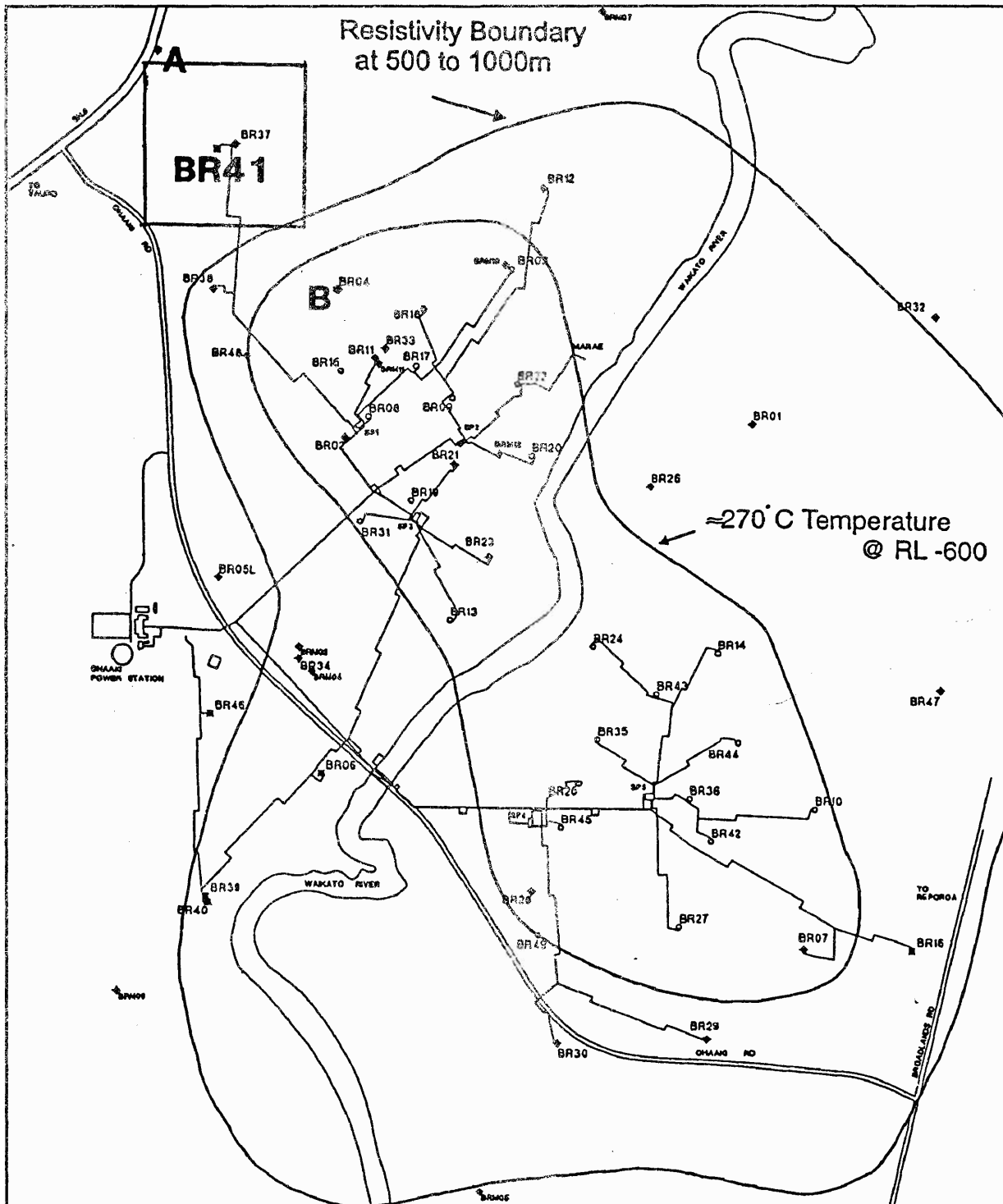


Figure 2. Map of Ohaaki Geothermal Field . Inset box shows the area of repeat resistivity measurements in Figure 3. A and B are current electrode sites.

(e.g. BR4/0, BR3/0, and BR2/0), where water levels have declined by a few meters as local down-flows developed. Bores near areas of temporary surface disposal (by soakage) of separated geothermal brine have shown changes in groundwater chloride concentrations (Contact Energy, 1998). With the exception of these local effects, shallow groundwater levels in this north-western sector are generally undisturbed, and follow the topography with a west-east gradient of about -77 m/km, towards the Waikato River.

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

4.0 RESISTIVITY MONITORING

An established method of determining the presence of geothermal water in the ground is electrical resistivity. At BR41, low resistivity injectate progressively displaces unmineralised (high-resistivity) water away from the injection well. A large increase in chloride concentration and temperature around an injection well should produce a measurable resistivity decrease. The spatial distribution of the resistivity changes may 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 practical means of tracking this fluid when it is reinjected outside the field boundary.

The Ohaaki field has been delineated by several resistivity surveys in the past. A repeat set of measurements (1975 and 1993), reported by Risk (1993), were made at 50m intervals along several traverse lines across the resistivity boundary. For most traverses there were no significant resistivity changes over this period that could be attributed to movement of fluid

across the resistivity boundary. However, it was noted that a measured decrease in resistivity just inside the southern boundary, could have been caused by deep injection, between 1989 and 1993, into nearby well BR30.

The first resistivity survey around BR41 was made in February 1994, prior to commencement of reinjection into the north-western outfield injection sector. At this time, some separated geothermal water was being disposed of in a soak-pond, 100m east of BR41, but this only affected measurements close to the pond (Figure 3). 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 2.5 years at an average rate of 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.

Vector resistivity measurements were made at 50m intervals, out to 300m, along six lines, arranged radially around the reinjection bore BR41 (Figures 3 and 4). The location of this area of investigation is shown as a box in Figure 2. 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 was used to determine the magnitude and direction of the electric field. DC electric current was passed into the ground through two fixed current electrodes (A and B, Figure 2) spaced 1.14 km apart at an azimuth of 143° . The effective penetration depth of the resistivity measurements using the vector Schlumberger array is about $300 (\pm 150)$ m, which is similar to the injection depth in BR41. This array was chosen so that apparent resistivity changes caused by injection would be readily detectable. Other resistivity methods (CSAMT, TEM) are less applicable for monitoring in this setting because of locally high levels of electrical noise.

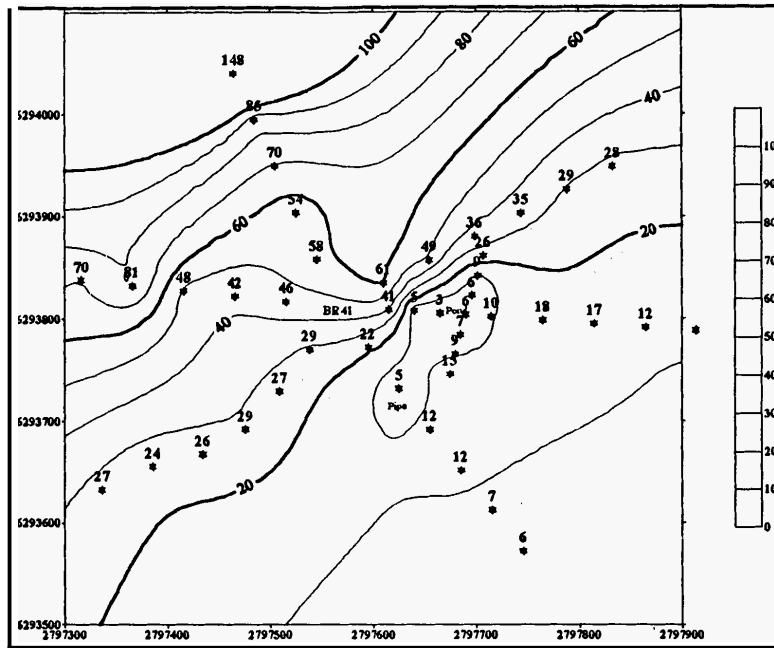


Figure 3. Apparent resistivity contour map (AB/2=500m), prior to reinjection (February 1994), in the vicinity of BR41, on the NW boundary of Ohaaki (see figure 2 for location).

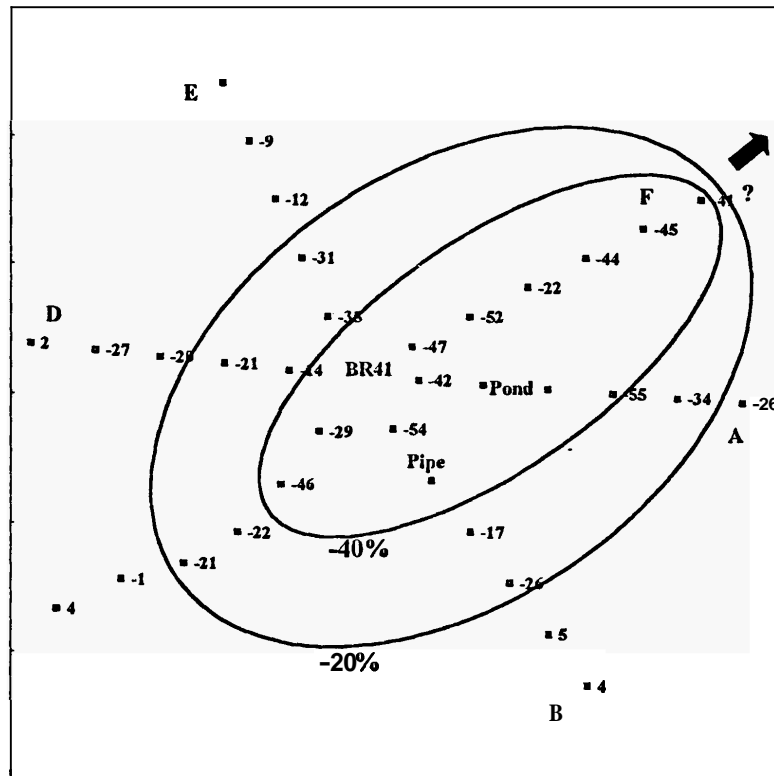


Figure 4. Map of repeat resistivity sites on lines A to F around BR41. Values show percentage changes in resistivity between Feb 94 and May 99. Elliptical contours show preferred flow direction to the north-east, parallel to the resistivity boundary. Disturbed values are discarded.

5.0 RESISTIVITY RESULTS

Resistivity values from the baseline (pre-injection) survey of February 94 confirm that BR41 is centred in a 600m-wide, NE trending, boundary zone of laterally increasing apparent resistivity values, ranging from 6 to over 100 ohm-m (Figure 3). Superimposed on this background pattern, there was a small area of very low resistivity (3-10 ohm-m) adjacent to a soak pond, east of BR41. The size of the pond was approximately 25x12m, and the resistivity reducing effect of about 10 l/s of infiltrating brine was observed up to 50m from the pond edges. The repeat sets of measurements (after 8 weeks, 2.5 years and 5 years of injection) generally showed decreasing apparent resistivity values. The average value 50-m from BR41 dropped from 43 ohm-m to 39, 33 and then 28 ohm-m (-35%). An exception was the resistivity adjacent to the soakage pond, which initially increased from about 3 to 5 ohm-m in response to the replacement of geothermal water with rainwater.

By May 1999, most resistivity monitoring sites within 250m of BR41 had reduced in value by 25% to 50%. This is well outside the range of maximum measurement error for these data ($\pm 10\%$), or the expected variation in resistivity from natural causes ($\pm 10\%$), such as changes in soil saturation caused by rainfall. At 300m radius on lines B, C and D (i.e. to the south and west), resistivities have remained relatively constant since the start of measurements. The distribution of percentage changes in resistivity over five years shows (Figure 4) that there is a preferred direction of flow to the north-east, where the resistivity reduction effects are observed to at least 300m distance from BR41 compared to 200m distance to the south and west.

Figure 5 is an illustration of the resistivity changes against time at nine selected sites labelled by station number (line A to F), and distance from BR41. Note that the two closest sites (E50, F50) decreased more rapidly in resistivity during the first 8 weeks of injection, while sites further away showed little change in the first two months but decreased thereafter. This is consistent with a conceptual model of the injected fluid causing a chemical and temperature front which gradually moves laterally away from the bore.

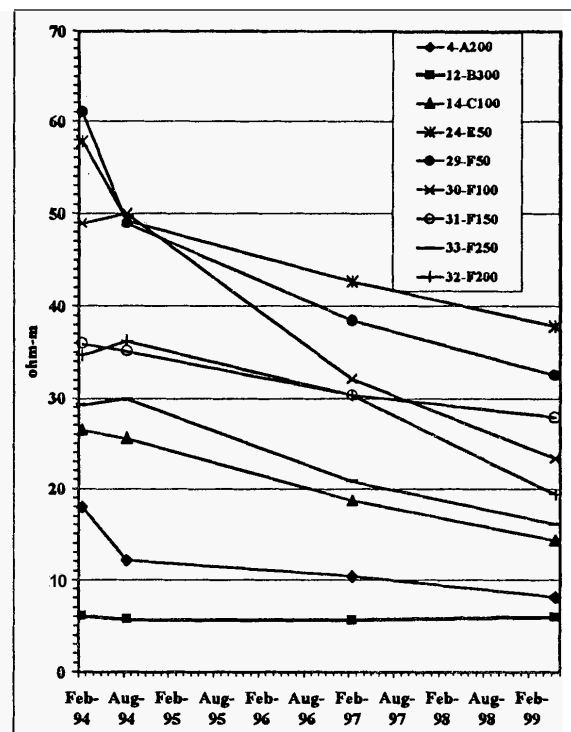


Figure 5. Changes in measured resistivity over years, at selected sites labelled by station number, line letter and distance from BR41.

6.0 DISCUSSION

Interpretation and modelling of the observed resistivity changes with time, caused by injection at BR41, is based on simple 2D models of the Ohaaki resistivity structure in this vicinity. To the south-east (near BR4) a 20m thick surface layer of about 200 ohm-m overlies much lower resistivity formations (Bromley et al, 1993). Within the depth range of 50 to 500m, resistivities inside the field are about 1.5 to 5 ohm-m, and outside they are about 30 to 40 ohm-m (Figure 1). Although Risk (1993) used a simple vertical boundary structure, some interfingering of hot or cold fluids at the boundary probably occurs because of cross flows at different depths. (The pre-injection temperature inversion from 50 to 40°C in BR41 is evidence of this- see Figure 1).

The injected hot water at BR41 has a resistivity of 1.2 ohm-m, calculated from its salinity and temperature. The effective water resistivity in the cooler 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 effective fluid resistivity reduces by a factor of 8 if all the cool groundwater is replaced by hot injected water. The influence 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 570m from nearby wells, is 20%. The thickness of the rhyolite is 435m in BR37. Assuming that the entire injected volume over five years of about 14 million m³ 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 apparent resistivity decrease of about 35% near the centre can be accounted for by a reduction of about 70% in average layer resistivity, from 30 ohm-m (as modelled in Figure 1) to 9 ohm-m. A value of about 9 ohm-m for a layer that is saturated with 1.2 ohm-m saline fluid, would imply an apparent formation factor (ρ/ρ_w) of about 7.5. Using Archie's Law ($\rho = a \rho_w \phi^n$), a theoretical formation factor for clean rock is 25, with $a = 1$, $n = 2$, $O = 0.2$. The low apparent formation factor of 7.5 is probably caused by the contributing effect of matrix conduction (from clays).

In reality, the injected fluid is mixing with in-situ groundwater, and diluting along various flow-paths away from the injection well. The north-east orientation of the resistivity change contours implies a preferential flow in this direction, which is parallel to the resistivity boundary in this area and to the predominant regional fault trend. The chemical "front" of the injectate probably travelled quite rapidly; previous tracer tests suggest rates of movement for a chemical "front" of up to 100m/day through some of the more permeable Ohaaki aquifers (Clotworthy, 1989). The thermal "front" is much slower because of the conductive cooling effect of the rock matrix through which the fluid is passing. Diffusion of injectate into areas of lower permeability will also occur more slowly. The slow rate of change of the resistivity over 5

years (see figure 5), with initial changes occurring at less than 50 m/month, suggests that the dominant resistivity change effect is related to thermal changes and diffusion effects rather than rapid salinity changes along permeable channels. A gradual increase in temperature from about 50°C to about 150°C in the rock matrix will cause a decrease in the resistivity of the existing clays embedded within the matrix. There will also be an increased contribution to matrix conduction from additional clays as hydrothermal alteration intensifies at higher temperature. The dominant clay types that form from hydrothermal alteration of rhyolite at these temperatures are smectites and zeolites. Both of these clay groups are highly conductive because of their high ion-exchange capacities.

To summarise, a reasonable explanation for the observed reduction in resistivity with time around BR41 at Ohaaki can be given in terms of a conceptual model of hot saline injectate displacing cool groundwater, then heating and hydrothermally altering the surrounding rock matrix. The extent and preferred direction of injectate flow is mapped from the resistivity change contours. This method of tracking injected geothermal fluids using surface-based resistivity measurements could have widespread application to other geothermal field developments where external reinjection at shallow depth is contemplated.

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