FLUID FLOW IN THE WAIOtapu GEOTHERMAL SYSTEM, NEW ZEALAND: IMPLICATIONS FOR ITS POTENTIAL

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ABSTRACT

The Waiotapu geothermal system lies within the Taupo Volcanic Zone of New Zealand; it has the greatest heat flow and largest area of any system in the country.

The system was explored in the late 1950's; maximum measured temperature was 295°C in the south, with temperature inversions measured in the north.

A mixing model incorporating well and surface spring chemistry indicates that the focus of deep (> 1 km) fluid upflow is in the north, below drilled depths. This upflow is deflected southwards by a near surface, laterally flowing fluid.

INTRODUCTION AND SETTING

The purpose of this paper is to describe the geochemical characteristics of the Waiotapu geothermal system, its fluid flow and discuss its potential.

The field is located near the eastern margin of the Taupo Volcanic Zone, New Zealand, 40 km north-east of Wairakei (Figure 1). The area of hot ground (> 15°C) covers ~17 km² and is elongate in a north-northeast direction; the natural heat flow is ~600 mW (Banwell 1965).

The twin dacite volcanoes Maungakakaramea and Maungangaonga (K/A date of 159,000 years) form the northern boundary of the field and an older rhyolite dome (Trig 8566) lies to the west (Figure 1).

The northeast-striking Ngapouri Fault (a splay from the major Paeroa Fault) extends between the dacite domes. Several north-northeast trending lineations, visible in aerial photographs, are present in the southern area of the field (near Champagne Pool) and are intersected by a few east-west lineations; these are probably faults which localised several hydrothermal eruptions ~900 years ago (Figure 1) (Lloyd 1959). Hydrothermal eruptions of similar age also occurred along the Ngapouri Fault.

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Surface activity is located along a 4 km portion of the Ngapouri Fault and within a 2 km wide area extending 5 km southward from Maungakakaramea. In the northern third of the field this activity comprises mainly steaming ground, acid sulfate mud pools, and fumaroles. The abundance of mixed acid sulfate-chloride and neutral chloride hot springs increases southwards, with the highest chloride feature being Champagne Pool.

Many of the thermal features have a linear distribution suggesting a near surface fault control. This is supported by several elongate patterns in the 1 and 30 m depth temperature contours (DSIR Bulletin 155, 1963).

PREVIOUS STUDIES

An assessment of the energy potential of the Waiotapu system was made during the 1950’s (DSIR Bulletin 155, 1963); various geological, geochemical and geophysical studies led to seven wells being drilled to 500 m (Wt - 1, 2, 3 and 5), 1000 m (Wt - 6 and 7) and 1100 m (Wt - 4) (Figure 1).

These encountered surficial tuffs and lacustrine sediments to depths of 50 to 100 m. Below this, the Rangitaiki Ignimbrite, Waiora Formation (air fall) and Waiotapu Ignimbrite were penetrated by all wells: the three deep wells encountered the Paeroa Ignimbrite, comprising three flow units and interbedded breccia deposits. Wt - 4 bottomed in rhyolite similar to nearby Trig 8566 and Wt - 6 and 7 encountered the Ngakoro Andesite between the lower two Paeroa flow units (cross section B-B’, Figure 1).

Cross section B-B’ shows the Ngakoro Fault extending between Wt - 4 and 6. The 165 m downward displacement of the Paeroa Ignimbrite to the north occurred prior to emplacement of the Waiotapu Ignimbrite; its strike is uncertain.

Wt - 1 and 2 intersected the Ngapouri fault but neither discharged appreciably; Wt - 5, on the western margin of the field, did not discharge either. Wt - 3, 4, 6 and 7 were sited to intersect inferred faults, though no major production zones were encountered and evidence for faults was not detected. Wells were cased into the upper part of the Waiotapu Ignimbrite; injection testing showed there to be zones of permeability within the Waiotapu Ignimbrite and deeper breccia units. Wt - 3, 4, 6 and 7 had discharges ranging from 40 to 400 tonnes/hour with enthalpies from 770 to 1280 kJ/kg. These values, compared with chemical geothermometer temperatures (Table 1), indicate that a variable amount of steam contributed to the discharge.

The maximum temperature measured was 295°C at the bottom of Wt - 7. The temperature profile for this well, Wt - 4 and 6 closely approximates the boiling point with depth curve (Figure 2) whereas Wt - 1, 2, 3 and 5 showed temperature inversions with maximum of 180°C to 220°C at ∼ 300 m depth.

All wells clogged with varying amounts of calcite when they were discharged for periods of up to four months.

Exploration at Waiotapu ceased in 1959 due to expanding development at Wairakei and never resumed. The lack of further interest in Waiotapu's potential is largely due to the poor well outputs and problems encountered during exploration; this is despite the high temperatures and heat flow (due to a high fluid flow).
Sheppard and Robinson (1980) sampled surface features, and some of their chemical results are summarized in Table 1.

**PRESENT STUDY**

The present study developed a fluid flow model based on surface and well discharge chemistry; fluid inclusion and hydrothermal mineral alteration also allowed an assessment of the thermal and chemical evolution of the system.

**Well discharge chemistry**

The chemistry of fluids discharged from the wells and their calculated chemical geothermometer temperatures are listed in Table 1. The quartz and Na-K-Ca temperatures ($T_{\text{SiO}_2}$ and $T_{\text{NaKCa}}$ respectively; Fournier 1981) for the discharge fluids are plotted in terms of enthalpies against their chloride concentrations (prior to steam separation) in Figure 3. Mixing and boiling relationships may be expressed on this diagram (Truesdell and Fournier 1976) and allows the composition and temperature of end-member fluids to be identified.

The compositions of the well discharges tend to lie on a straight line (in terms of $T_{\text{SiO}_2}$) indicating a variable mixture of two fluids. This line interests the ‘boiling line’ of the highest chloride discharge (Wt-4) at $\sim 240^\circ C$ and $\sim 1450$ mg/kg Cl; this is termed the $A_2$ endmember (Table 2).

Extrapolation of the mixing line from $A_2$ indicates the zero chloride line at $\sim 1400^\circ C$ with 450 mg/kg Cl (type $A_3$ is preferred as a diluting fluid; this is similar to the dilute fluid discharged from Rh-Z north of Maungakakaramea (Figure 1).

Extrapolation of the mixing line from $A_3$ intersects the zero chloride line at $\sim 1700^\circ C$ with 450 mg/kg Cl (type $A_3$ is preferred as a diluting fluid; this is similar to the dilute fluid discharged from Rh-Z north of Maungakakaramea (Figure 1).

The mixing trend (Figure 3) indicates that the order of decreasing $A_3$ fluid content (increasing dilution by $A_2$) is Wt-4,6,7 and 3; however, the discharge from Wt-6 is variable, probably due to differing input from two sources to the total well discharge.

The maximum measured temperature (295$^\circ C$) indicates a minimum deep fluid temperature of $\sim 300^\circ C$; this is similar to temperatures determined from gas compositions of well discharges, assuming a methane breakdown reaction (Hedenqufst 1982). If such a fluid (type $A_1$) boiled as it ascended to $A_2$ composition, its deep Cl content would be $\sim 1250$ mg/kg Fkg (Figure 3$^2$).

**FIGURE 3:** Mixing diagram for Waiotapu well discharges and representative hot springs (see Tables 1 and 2). $T_{\text{SiO}_2}$ versus Cl for well discharges fall on a mixing line; most hot springs can be accounted for by boiling of the mixed fluid.

1. $T_{\text{NaKCa}}$ is $10^5$ to $30^\circ C$ greater than $T_{\text{SiO}_2}$; this is due to the non-linear nature of the NaKCa geothermometer when two fluids are mixed and is not necessarily caused by a slower reequilibration of the NaKCa geothermometer.

2. Lyon and Cox (in Sheppard and Robinson 1980) have determined $11^C$ of 440$^\circ C$ in the north to 360$^\circ C$ in the south from surface discharge analyses; this also suggests a north to south flow of deep fluid.
### TABLE 1: Representative surface spring and well discharge chemistry

| Feature Description | Temperature (°C) | pH | Na | K | Ca | Mg | Cl | SO₄²⁻ | HCO₃⁻ | Type | CO₂ (k/kg) | H₂S (k/kg) | % | Gas % |
|---------------------|------------------|----|----|---|----|----|----|-------|-------|-------|---------|-----------|-----------|---|-------|
| Acid pool 02        | 99               | 2.2| 32 | 6.6| 4   | 0.8| 6  | 308   | <2    | 338   | B       |           |           |   |       |
| Acid pool 04        | 53               | 2.4| 97 | 21 | 12  | 2.5| 148| 353   | 3     | 323   |         |           |           |   |       |
| Hot spring 11       | 97               | 7.2| 701| 77 | 22  | 0.04| 1174| 203   | 14    | 75    | 17      | A         | 170       | 212| 81.0  |
| Hot spring 14       | 98               | 7.0| 581| 85 | 4.4 | 0.5| 911 | 432   | 12    | 151   | 34      | A         | 216       | 245|       |
| Lady Knox Geyser 20 | 100              | 2.2| 622| 82 | 21  | 0.9| 1069| 348   | 15    | 728   |         |           |           |   |       |
| Champagne Pool 21   | 76               | 6.0| 1118|163| 36  | 0.04| 1994| 495   | 33    | 103   | 62      | A         | 226       | 236| 73.0  |
| Lake Ngakoro Pool 26| 100              | 6.2| 1009|36 | 35  | 0.2 | 1655| 322   | 28    | 68    | 10      | A         | 197       | 153| 92.0  |
| Hot spring          | 86.8             | 9.2|     |    | 2.3 |     |     |       |       |       |         |           |           |   |       |

All concentrations in mg/kg. Well discharge composition after flushing to 100°C.

Data for features from Sheppard and Robinson (1980) and for wells from DSIR, Chemistry Division.

### TABLE 2: Characteristics of fluid components

<table>
<thead>
<tr>
<th>Fluid Types</th>
<th>Source</th>
<th>Depth (m)</th>
<th>T (°C)</th>
<th>pH</th>
<th>Cl (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₁</td>
<td>Deep upflow</td>
<td>≈ 1000</td>
<td>300°²</td>
<td>5.5</td>
<td>&lt; 125</td>
</tr>
<tr>
<td>A₂</td>
<td>Boiled A₁</td>
<td>250-250</td>
<td>240°²</td>
<td>6</td>
<td>1450</td>
</tr>
<tr>
<td>A₃</td>
<td>Lateral flow from North</td>
<td>≈ 200</td>
<td>170°²</td>
<td>6</td>
<td>450</td>
</tr>
<tr>
<td>B</td>
<td>Streamheated groundwater</td>
<td>&lt; 50</td>
<td>&lt; 100-120°²</td>
<td>2-3</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>Various mixtures of A and B</td>
<td>&lt; 100 (intermittent to 200)</td>
<td>&lt; 100-150°²</td>
<td>3-5</td>
<td>200-700</td>
</tr>
</tbody>
</table>
Primary andesine phenocrysts are partially altered to albite and/or adularia with alteration being slightly more extensive in the north. These alkali feldspars, in turn, being altered by white mica, analogous to muscovite.

This shift in hydrothermal mineral assemblage implies that there was a decrease in pH of at least one unit to the present deep pH of 6 (Hedenquist 1982); this pH decrease may be accounted for by an order of magnitude increase in CO₂. Therefore, the present CO₂ concentration is 10 x greater than during albite-adularia formation but is 10 x less than during Wt-7 fluid inclusion formation.

The presence of calcite in wells indicates that the fluids have been saturated at times, probably during the low CO₂ period; the present fluid has slightly undersaturated with respect to calcite, but small amounts of boiling (5 to 10°C) and gas loss will cause calcite to precipitate (Hedenquist 1982). This suggests that fluids in Wt-4 have boiled the least, since there is relatively little calcite present in cores from this well, compared with its abundance in all other wells.

DISCUSSION

Figure 4 is a model of present fluid flow in the Waiotapu system based on surface and well discharge chemistry.

A₁ fluid likely rises north of Wt-4, with separated steam contributing to the steam-heated features. Gas isotope temperatures from surface springs also support this area being above the deep upflow. This upflow may be controlled by the northward extension of the Ngakoro Fault.

Boiling of A₁ to ~350 m depth results in generation of A₂ fluid, with the upward flow path deflected southwards by the southerly flowing, cooler A₁ fluid (largely confined to the Waiohotu Formation). Boiling of A₂, possibly steam heated by A₁, also results in the acid sulfate type B features in the north. Mixing of type B and A fluids produces type C fluids.

A₂ fluid is the dominant contributor to Wt-4 discharge, and also is little diluted before flowing into Champagne Pool.

- System Evaluation

It is likely that at one time A₁ fluid rose vertically towards the surface, as evidenced by higher mineralogic and fluid inclusion temperatures than are presently measured. Mineral alteration and deposition occurred from a fluid with a lower P_CO₂,
A large increase in $P_{CO_2}$, possibly associated with volcanic activity at nearby Taupo, resulted in increased boiling. If the system was locally sealed, the total fluid pressure would have increased greatly due to the $P_{CO_2}$ increase, resulting in hydrothermal eruptions. This sudden depressuring would serve to draw adjacent, near-surface fluids into the system.

The incursion of $A_3$ fluid from the north is likely related to such a depressuring, and its southerly flow caused a pressure front that has deflected $A_3$ upflow southwards; this has cooled the northern area and left it dominated by steam-heated features.

CONCLUSIONS

Deep neutral chloride fluid rises in the northern portion of the Waiotapu system at temperatures above 300°C. This upflow has been deflected southwards by the influence of relatively cool ($\sim 170°C$) fluid; the least diluted fluid enters Wt-4 and is discharged at the surface in Champagne Pool a further 1 km south. This incursion of surface fluid may be the result of a sudden depressuring caused by boiling following hydrothermal eruptions (themselves caused by an increase in $P_{CO_2}$).

This has resulted in surficial and near-surface ($<500 m$) activity shifting southwards, possibly as recently as 900 years ago. The near-surface ($<500 m$) of the northern portion of the system has cooled due to the lateral influx of fluid from the north; however, the temperature may increase again at depths of $>1 km$ beneath Wt-3.

This interpretation suggests that the area near Wt-3 would be most favourable for deep drilling ($>1 km$) to encounter hot fluids ($\sim 300°C$). At these depths, vertical flow is likely controlled by a few major fractures, possibly extensions of the Ngakoro Fault. Lateral permeability should also be good in some of the deep, intra-Paeroa Ignimbrite breccias.

3. Hedenquist (1982) has shown isotopic evidence for the increased $CO_2$ to have a deep-seated source.
Development Potential

The potential for development at Waiotapu appears very good. Its natural heat flow is the highest of any single system in New Zealand, indicating a fluid flow of \( \sim 450 \ T^2/\text{sec} \). Apparently drilling did not intersect the major fluids channels carrying this flow.

Calcite scaling, a problem during well discharge to the atmosphere, should be no greater than at Broadlands under proper discharge conditions.

Identification of the trend of the Ngakoro Fault north of WR-4 would be desirable to locating a deep permeable channel.

However, further exploration and development will destroy the delicate natural balance of this geothermal system; this fact must be considered in any future decisions concerning the system.

ACKNOWLEDGEMENTS

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REFERENCES


4. The minimum fluid flow, based on the measured surface flux, is 250 \( T^2/\text{sec} \) (Sheppard and Robinson 1980).