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 km^2 and is elongate in a north-northeast direction; the natural heat flow is ~600 MW (Banwell 1965).

The twin dacite volcanoes Maungakakaramea and Maungaongaonga (K/Ar 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 on aeriel photographs, are present in the sourthern 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.

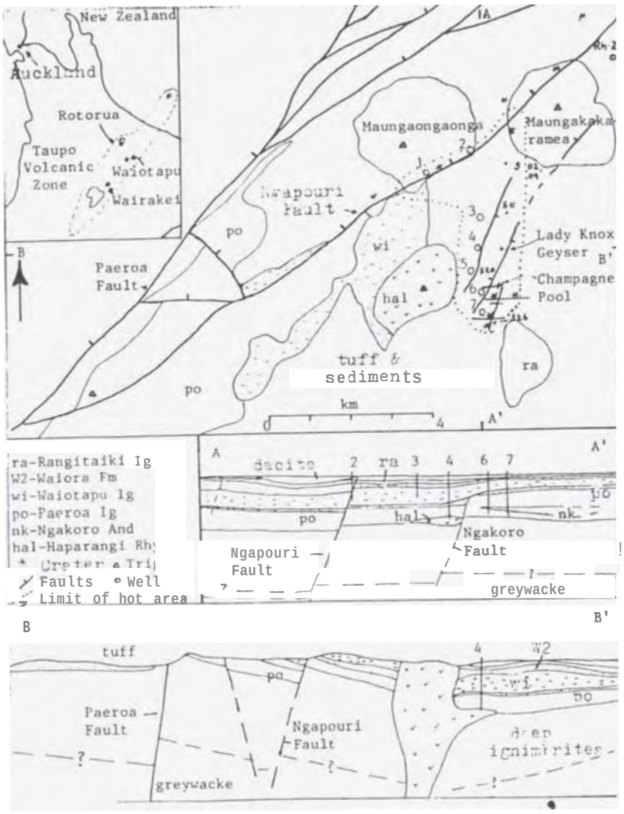

FIGURE 1: Geologic sketch map and cross-sections of the Waiotapu area, showing locations of hot ground, springs and wells. Also shown are the locations of hydrothermal eruption craters, all formed ~ 900 years ago. After Nairn 1973 and Hedenquist 1982.

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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 kms. 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^1, Figure 1).

Cross section B-B^1 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 Waiorapu 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 geothemometer 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 maximums of 180° to 220°C at ∿ 300 m depth.

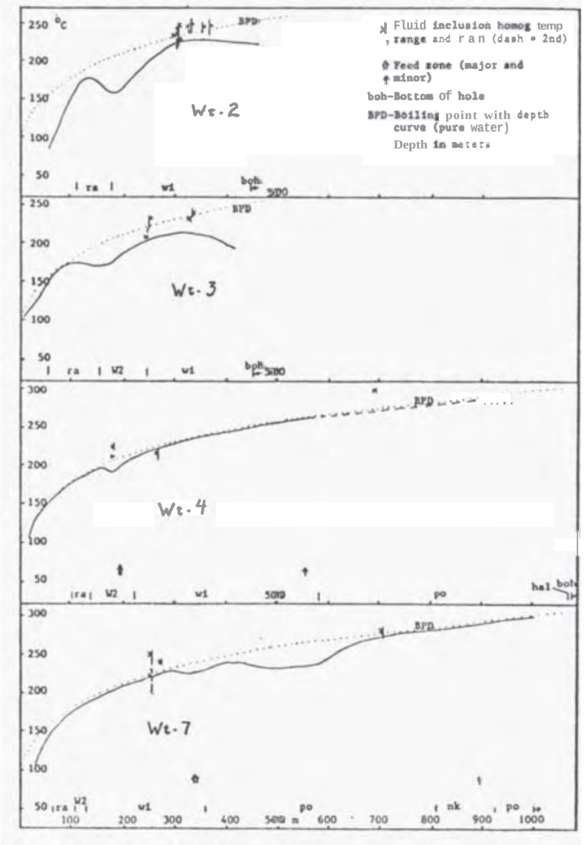


FIGURE 2: Measured temperature profiles for Wt-2. 3, 4 and 7, showing flow zones inferred from injection tests. Also plotted are fluid inclusion homogenization temperatures (all falling closely on the boiling point with depth curve) and the stratigraphic sequence (see Figure 1). After Hedenquist 1982.

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).

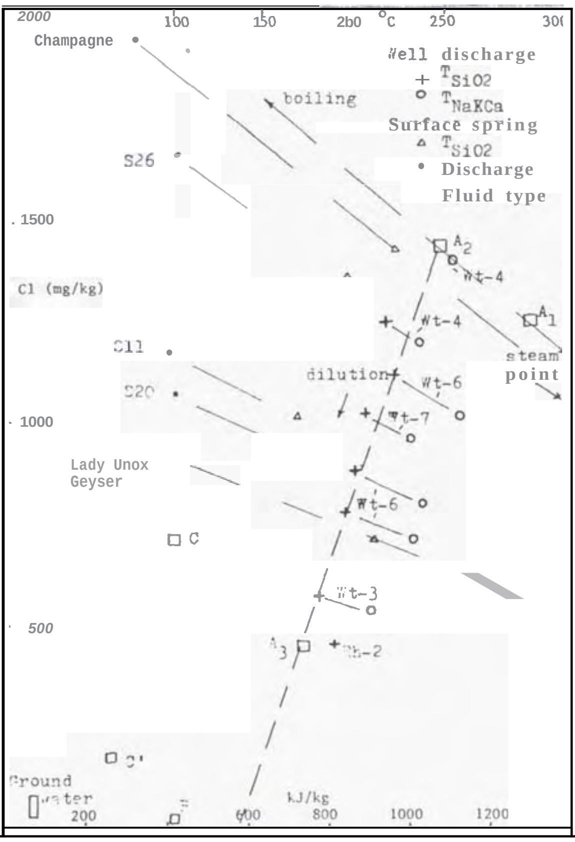
Sheppard and Robinson (1980) sampled surface features, and some of their chemical results are summarized in Table 1.

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_{Sio_2} and T_{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_{Sio_2})[2] indicating a variable mixture of two fluids. This line interests the 'boiling line' of the highest chloride discharge (Wt-4) at ~ 240°C and ~ 1450 mg/kg Cl; this is termed the A_2 endmember (Table 2).

Extrapolation of the mixing line from A_2 in&-sects the zero chloride line at % 140°C. Such a hot but non mineralised fluid would likely be acid, with a high gas and sulfate content (from steam heating; type B). Since Wt-3 fluid is little greater in sulfate than the less diluted discharges. This is not a likely source of diluting fluid. Rather a fluid at ~ 170°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_2 fluid content (increasing dilution by A_3) 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°C) indicates a minimum deep fluid temperature of ~ 300°C; this is similar to temperatures determined from gas compositions of well discharges, assuming a methane breakdown reaction (Hedenquist 1982). If such a fluid (type A_1) boiled as it ascended to A_2 composition, its deep Cl content would be ~ 1250 mg/Fkg (Figure 3)[2].

FIGURE 3: Mixing diagram for Waiotapu well disbharges and representative hot springs (see Tables 1 and 2). T_{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.

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1. T_{NaKCa} is 10° to 30°C greater than T_{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 A $^{13}C_{CO_2-CH_4}$ of 440°C in the north to 360°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

														°C			Gas		
Feature	Description	T°C	pH	Na	K	Ca	Mg	Cl	SiO_2	HBO_2	SO_4	HCO_3	Type	T_{SiO_2}	T_{NaKCa}	H (kJ/kg)	$\frac{mmol}{mol}$ discharge	% CO_2	H_2S
02	Acid pool	99	2.2	32	6.6	4	0.8	6	308	< 2	338	-	B	-		-	-	86.8	9.2
04	Acid pool	53	2.4	97	21	12	2.5	148	353	3	323	-	C	203	220				
11	Hot spring	97	7.2	701	77	22	0.04	1174	203	14	75	17	A	170	212			81.0	1.6
14	Lady Knox Geyser	98	7.0	581	85	4.4	0.5	911	432	12	151	34	A	216	245			-	-
20	Hot spring	100	2.2	622	82	21	0.9	1069	348	15	728	-	C	202	222				
21	Champagne Pool	76	6.0	1118	163	36	0.04	1934	495	33	103	62	A	226	236			73.0	1.7
26	Lake Ngakoro Pool	100	6.2	1009	36	35	0.2	1655	322	28	68	10	A	197	153			92.8	2.3
Well																			
Wt-3		100	8.8	535	38	11.5	-	673	254	10.9	83	37	A	183	211	770	0.23	91.0	4.5
Wt-4		100	7.5	965	135	22.5	-	1600	450	25.3	48	-	A	219	235	1279	0.41	78.0	15.2
Wt-6		100	8.8	587	104	8.8	0.06	1121	363	14.6	73	112	A	205	251	1000	0.33	87.3	10.7
Wt-7		100	8.7	836	106	9.0	-	1285	356	20.4	86.5	53	A	204	235	877	1.00	92.0	5.3

All concentrations in mg/kg. Well discharge composition after flushing to 100°C.
See Figure 1 for feature and well locations.
Data for features from Sheppard and Robinson (1980) and for wells from DSIR, Chemistry Division.

TABLE 2: Characteristics of fluid components

Fluid Types	Source	Depth (m)	T (°C)	pH	Cl (mg/kg)
A_1	Deep upflow	∿ 1000	300° +	5.5	< 1250
A_2	Boiled A_1	250–250	∿ 240°	6	1450
A_3	Lateral flow from North	∿ 200	∿ 170°	6	450
B	Streanihearted groundwater	< 50	< 100-120°	2–3	0
C	Various mixtures of A and B	< 100 (intermittent to 200)	< 100-150°	3-5	200–700

- Surface Fluid Chemistry

The chemistry of representative surface features '(Table 1, Figure 1) is plotted in Figure 3. Champagne Pool fluid is derived from boiling of A_2 whereas fluid of Lady Knox Geyser more likely derives from the boiled mixture of $A_2 + A_2$.

Type B fluids (steam heated acid sulfate features) lie at 100° to 120°C and zero chloride. Type C fluids (containing a mixture of types A and B) may also be diluted by groundwater. Two of the more common fluid compositions for these features are shown in Figure 3 (C and C').

These data suggest that the Champagne Pool area is a discharge focus for least diluted type A_2 fluid; dilution with A_3 fluid increases to the north as does the occurrence of steam heated type B and C features.

- Fluid Inclusion Studies

The homogenization temperatures of fluid inclusions from hydrothermal calcite and quarts are plotted along with present temperatures in Figure 2.

Fluid inclusion temperatures tend to follow the hydrostatic boiling point with depth curve and do not exhibit the measured inversions in Wt-1,2, and 3. This suggests that the inversion, indicating a lateral fluid flow, has occurred since the inclusions formed; thus temperature has declined at the bottom of Wt-1, 2 and 3 by 20° to 40°C.

Freezing point depression measurements of fluid inclusions (Hedenquist 1982) indicate that CO_2 concentration in Wt-7 was $\sim$ 10 x greater ($\sim$ 0.5 mo/al) during their formation than at present. The results for Wt-3 indicate only slightly higher CO_2 ($\sim$ 2 x) at the time of inclusion formation.

- Hydrothermal Alteration

Browne (1978) has suggested a minimum formation temperature of $\sim$ 240°C for egidote. At Waiotapu epidote occurs as low as $\sim$220 C in Wt-1, 2 and 3, supporting the fluid inclusion evidence for a cooling from hotter conditions in the north. The lowest temperature of epidote occurrence in Wt-4 is $\sim$ 250°C; it does not occur in Wt-6 and 7. This may be due to higher (2 to 3 x) CO_2 now present in fluid of Wt-6 and 7 (Hedenquist 1982).

The groundmass of the volcanic rocks is variably recrystallised to quartz, pyrite, sphene and leucoxene; the primary mafic phenocrysts are completely altered to a variable assemblage of white mica, chlorite, pyrite and sphene.

Primary andesine phenocrysts are partially to completely altered to albite and/or adularia with alteration being slightly more extensive in the north. These alkali feldspars are, 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 on $\sim$ 6 (Hedenquist 1982); this pH decrease may be accounted for by an order of magnitude increase in CO_2. Therefore, the present CO_2 concentration is $\sim$ 10 x greater than during albite-adularia formation but is $\sim$ 10 x less than during Wt-7 fluid inclusion formation.

The presence of calcite in wells indicates that the fluids has been saturated at times, probably during the low CO_2 period; the present fluid has slightly undersaturated with respect to calcite, but small amounts of boiling ($\sim$ 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.

A_1 fluid likely rises north of Wt-4, with separated steam contributing to the northern, steam-heated features. Gas isotope temperatures from surface springs also support this area as being above the deep upflow. This upflow may be controlled by the northward extension of the Ngakoro Fault.

Boiling of A_1 to $\sim$ 350 m depth results in generation of A_2 fluid, with the upward flow path deflected southwards by the southerly flowing, cooler A_3 fluid (largely confined to the Waioro Formation). Boiling of A_3 , possibly steam heated by A_1 , also results in the acid sulfate type B features in the north. Mixing of type B and A fluids produces type C fluids.

A_2 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 A_1 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_{CO_3} and the system became locally sealed.

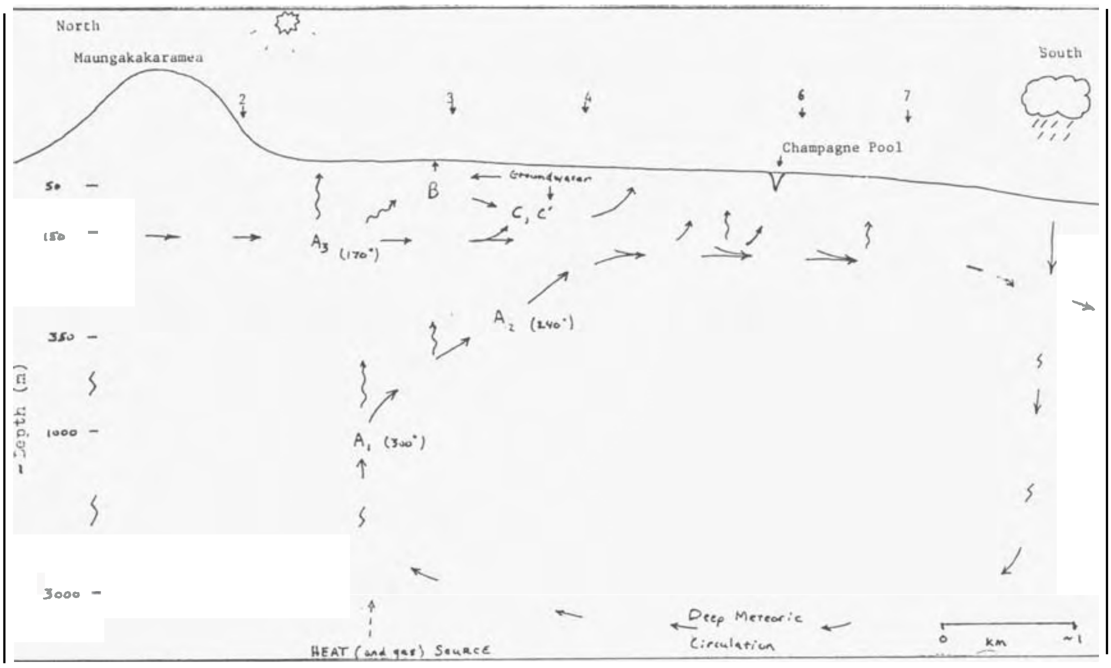

FIGURE 4: Schematic north-south cross-section of fluid flow and mixing in the Waiotapu system. Deep meteoric circulation (with a magmatic heat and gas source) rises and boils beneath the northern half of the field and is deflected southwards by a shallow, southerly flow; Champagne Pool has the highest chloride fluid of surface features. Steam from A_1 and A_3 heats groundwater to form type B fluids which mix with type A fluids to form type C.

A large increase in P_{CO_2}[3], possibly associated with volcanic activity at nearby Tarawera, 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_1 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 (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 (∼ 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.

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[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 ∼ 450 ℓ/sec.[4] 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 Wt-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.

ACKHOWLEDGEMENTS

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[4] The minimum fluid flow, based on the measured surface flux, is 250 ℓ/sec (Sheppard and Robinson 1980).