THE WESTERN BOUNDARY OF THE WAIRAKEI GEOTHERMAL FIELD

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SUMMARY – The Wairakei field has reached a mature stage of reservoir response, but new development has provided new data. We concentrate on data from new wells and one year of production from the western low pressure steam zone. The steam zone there is linked to the low pressure steam zone elsewhere, but the composition of the steam there prior to production reflected condensation and fluid-rock interaction. The composition has now converged on that of the Western Borefield. The rate of change and the gas geothermometry show that steam is being provided by boiling from depth or from the east, rather than any substantial boiling of in-situ residual liquid. There is no evidence for a physical hydrological barrier on the western side of the field, nor is there evidence of cool water incursion due to pressure drawdown. The economic limit of the resource is smaller than the resistivity boundary.

1. INTRODUCTION

The Wairakei geothermal field, Taupo, New Zealand has the longest history of exploitation, and had the largest net mass withdrawal, of any liquid-dominated geothermal system in the world. From the mid 1960's until the mid 1980's, there was little change in the way the reservoir was operated. Production peaked at 192 MW and then stabilised at 154 MW. In the subsequent decade some wells' were abandoned in the Eastern Borefield and new production wells drilled in Te Mihi (Figure 1). Since 1996 there have been greater changes, with partial reinjection in the east for the existing Wairakei station, and the commissioning of the new 55 MW McLachlan power station in the west.

This paper describes a conceptual model of the western boundary of the Wairakei geothermal field, based on the results of recent drilling and the first year's operation of the McLachlan power station. It complements Bogie et al. (1995) which described the geological findings from drilling on the McLachlan property and Wood et *al.* (1997) describing the geology and hydrology derived from drilling new reinjection wells in the east. Giggenbach and Reyes (*in* prep. 1999, based on a 1996 unpublished report) reviewed some of the petrology and geochemistry from the McLachlan wells. The principal questions which our paper addresses are:

(1) Is there evidence for a western physical hydrological boundary at Wairakei?

(2) Does the economic and thermal boundary of the field match the resistivity boundary ?

(3) Is there evidence for incursion of cool water from the margins of the field towards the large pressure sink which now exists within the reservoir due to exploitation,?

(4) What are the trends in gas concentration and composition of the steam zone, and can these be used to determine how close new wells are to the margin of the productive reservoir ?

2. GEOLOGY AND HYDROLOGY

The Wairakei reservoir has a layered structure (Figure 2). Young, near-surface volcaniclastics constitute a permeable aquifer containing cool groundwater except where there is local steam heating. The underlying Huka Falls Formation consists largely of low permeability volcaniclastic-lacustrine sediments. Below that, silicic volcaniclastics of the Waiora Formation constitutes the geothermal reservoir. It includes coeval volcanics, of which the most hydrologically significant is the Karapiti IIa Rhyolite. The Waiora Formation and included rhyolites are generally sufficiently permeable to permit widespread pressure equalisation, but not uniformly so, as results from the McLachlan area demonstrate. Superimposed on the layered lithostratigraphy, fault zones provide locally enhanced permeability.

Since Bogie et al. (1995) three more production wells were drilled (WK605, 606 and 613) in the McLachlan area but these were closest to previous wells and did not yield much additional geological data, A reinjection well, WK680, was drilled outside the reservoir about 1.5 km NW of

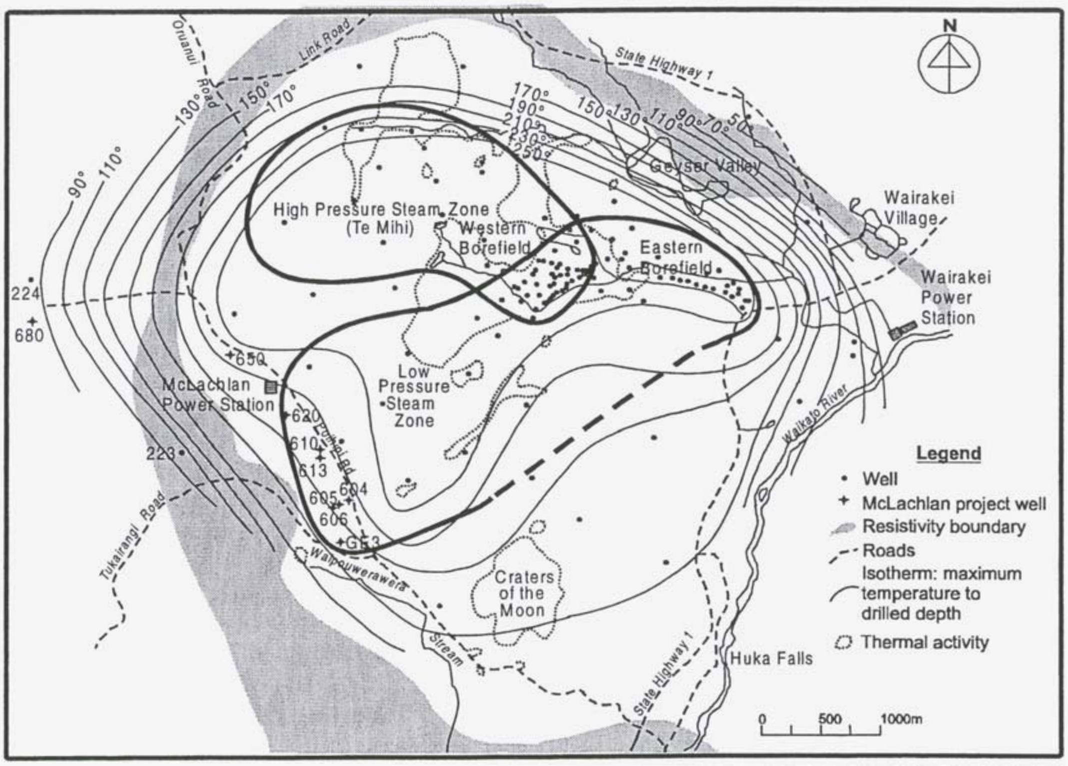


Figure 1 Wairakei Geothermal Field

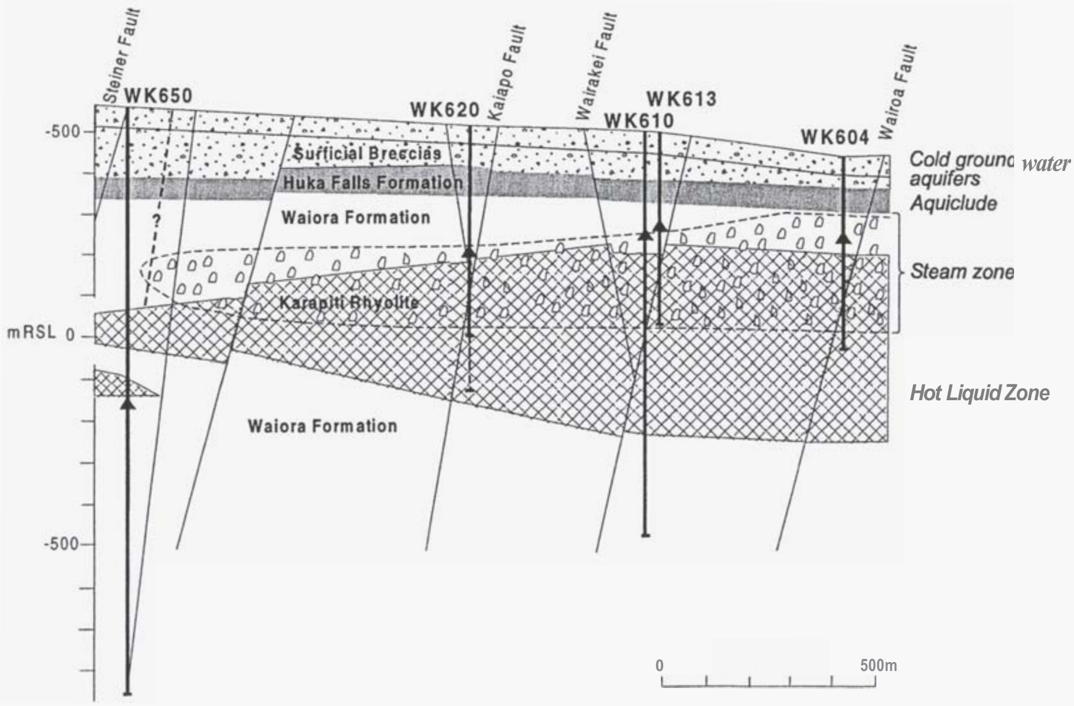


Figure 2 Geological Structure of the Wairakei Reservoir

WK650, near WK224. It encountered a lithological sequence similar to that in the other 600 series wells, but was not deep enough to reach the KIIa Rhyolite. The Rautehuia Breccia was present from 210 to 230 m. Alteration in WK680 was weak, but inconsistent with the maximum measured temperature (14°C at 368 m), consisting of argillic assemblages indicating temperatures up to 150°C. There was also one occurrence of potassic alteration, indicating temperature >300°C. Other rare occurrences of relict high temperature alteration in western Wairakei have been noted (*e.g.* WK650, Gringinger 1996). Permeability in well WK680 was correlated with a recent **NE** trending fault mapped by Grindley (1965).

3. RESERVOIR PROPERTIES IN THE MCLACHLAN AREA

Six of the new wells in the McLachlan area have encountered, within the Waiora Formation or KIIa Rhyolite, steam which in 1995 was at similar pressures to those measured in Contact Energy wells located in the southern part of the low pressure steam zone (Carey *et al.* 1998). For the next two years pressures in the McLachlan wells declined at the same rate as nearby Contact Energy wells. Four of the McLachlan wells are now connected to the McLachlan power station and have been on production since May 1997. Underlying the steam zone in the McLachlan area is liquid water at similar pressure to water underlying the rest of the Wairakei area. Temperature in the liquid water immediately under the steam zone in the McLachlan area corresponds to that of the steam zone, about 180°C. At greater depths temperatures increase but fall below the local boiling point, as in well WK650. The only well that discharged much liquid from below the steam zone, WK620, produced a water with a high bicarbonate content and low chloride (100-200 ppm) indicating that it contained only about 10% of primary chloride brine. However, a downhole sample from WK610 had a composition similar to typical Western Borefield reservoir water (Table 1), confirming that the primary chloride reservoir extends beneath at least part of the McLachlan steamfield and is therefore a potential source of recharge to the overlying steam zone. The relatively diluted water in WK620 is a mixture of chloride brine, steam condensate and unmineralised groundwater that has become bicarbonate-saturated through contact with the steam zone.

A reinjection well outside the field (WK680) encountered cold water under the Huka Falls Formation at pressures 25 bar greater than those measured at similar elevation inside the reservoir, but similar to pressures in local groundwater and in the nearby well WK224, indicating high lateral pressure gradients across the reservoir boundary.

Two of the new production wells encountered anomalous hydrological conditions below the **Huka** Falls Formation. WK620 encountered a strong downflow of cold (25 °C) water from below the Huka Falls Formation. The well was worked over by casing deeper to prevent this downflow, after which it stabilised with steam overlying liquid water at temperatures and pressures typical of the low pressure steam zone. After work over, the well initially discharged steam with a very high gas content. We consider that this well intersected the margin of the steam zone that had become gas-enriched due to natural condensation, though drilling water also raised the gas content by condensing steam. It was remarkable that cold water at high pressure (similar to pressures found outside the reservoir and to 70 "C fluid reported by Wood *et al.* (1997) in WK305) was encountered beneath the **Huka** Falls Formation at an elevation where the low pressure steam zone is normally found. At shallow depths WK620 had tapped the cold water geohydrological system typically present outside the reservoir boundaries and below this it had intersected the low pressure steam zone and underlying liquid that are typical of the geohydrology inside the reservoir. We conclude that this (vertical) well was drilled through a low permeability boundary of the steam zone, and that the boundary is not vertical. WK613 encountered at depth temperatures and pressures characteristic of the low pressure steam zone, but as with WK620, it also intersected a shallow liquid feed zone below the Huka Falls Formation. In WK613 pressures in the shallow feed are similar to or lower than the low pressure steam zone and so it only contributes to well discharge at lower wellhead pressures. This well is poorly permeable and it is not used for production.

In either case (WK620 or 613) there was no obvious geological reason in terms of lithology, structures nor alteration for the presence of the anomalous shallow liquid zones, yet in both cases these zones must have been hydrologically isolated from the productive steam zone before drilling. Pressures measured in boundary wells in 1995 are shown in Figure 3 in relation to pressures in productive vapour and liquid dominated zones of the reservoir.

4. TRENDS IN STEAM AND GAS CHEMISTRY

There are numerous reviews of the chemistry of the Wairakei geothermal system and the changes in fluid chemistry following production (*eg*: Glover, 1977; Brown *et* al., 1987) although almost all public domain data date from before 1988.

Table 1: Representative Water Chemistry for Wairakei Wells

Well	Date	Type	Enthalpy kJ/kg	WHP b.g.	C.P. b.g.	pH	Na	K	Ca	Cl	SO_4	HCO_3 (total)	B	SiO_2
McLachlan Wells:														
Wk 620	30-Oct-95	Weirbox	1270	2.1	0.0	8.13	-	-	53.0	205	48	278	-	283
Wk 613	19-Sep-97	Sep'd Water	-	-	-	9.00	121	13	0.4	124	18	62	2.6	287
Wk 610	17-Jan-98	DH: 650 m	-	-	-	3.55	1019	134	33.4	1669	122	19	20.9	474
Western Borefield:														
WK 067	19-Sep-91	Weirbox	1070	3.5	0.0	8.5	977	142	16.7	1666	30	<5	22.0	509
WK 107	19-Nov-74	Weirbox	1035	9.8	0.0	7.8	1256	195	29.1	2162	35	60	26.8	557
Te Mihi and Outlying Wells:														
WK 205	Mar-62	Weirbox	1186	9.1	0.0	8.3	1285	216	20.0	2178	36	96	29.3	545
WK 207	06-Mar-89	Weirbox	961	-	0.0	-			-	2330	-		-	581
WK 212	May-62	Weirbox	1140	-	0.0	-	1580	290	16.0	2726			-	665
WK 220	Jan-62	Weirbox	1233	9.5	0.0	-	1200	207	21.0	2092	-	-	-	500

Limited recent data was given by Lovelock (1995). In 1994 about 35 wells were producing from single-phase liquid conditions from below 500 m depth, with 7 wells producing from overlying steam zones of varying pressure and distribution.

Calculated reservoir chloride concentrations range from 1400 to 1800 ppm with highest concentrations seen to the north of the Western Borefield and in the Te Mihi area (Table 1). The deep Te Mihi reservoir water has a chloride concentration of about 1650 ppm: little changed from pre-1960 water, apart from it having undergone boiling and degassing. This, together with the higher steam zone gas concentrations (*e.g.*: 2 Wt% in WK234, ECNZ, 1992) suggest Te Mihi is close to the upflow of the Wairakei system.

Western Borefield wells are of two types; they either produce from a liquid reservoir at 220-225°C or an overlying vapour zone. The water is relatively diluted (10-20%) with respect to Te Mihi. It has undergone prolonged boiling and is largely degassed, with a gas content as low as 30 ppm (0.003% by weight) in the early 1990's, and a CO_2/H_2S ratio of 5-10 (Lovelock, 1995). There is no recent chemistry data available for the shallower dry steam wells in the Western Borefield (*e.g.* WK25, 45, 118 and 216), but older data from various sources (*e.g.* ECNZ 1990, Giggenbach and Reyes 1996) suggests the current steam zone gas content is probably around 0.3% and the CO_2/H_2S ratio about 30. Over the past 20 years it appears the steam zone gas contents have been falling as the underlying water has become more degassed.

The origin of the Western Borefield steam zone vapour is not clear, but to produce the difference in CO_2/H_2S ratio between the Western Borefield liquid zone ($CO_2/H_2S \approx$ 5-10) and the overlying vapour zone (25-30) requires boiling of liquid through a temperature range of only 5-10°C(for example boiling of liquid initially at from 235 to a final temperature of 225°C)This indicates that the steam zone is not forming above an upflow located in the Western Borefield but is more likely the last-formed steam produced from a degassing liquid outflow, possibly originating from the higher-gas Te Mihi area.

There is no recent chemistry data available for the outlying "200-series" wells between the Western Borefield and the McLachlan steamfield. However, data from the early 1960's for WK205 and WK220 (Table 1) show that a chloride reservoir did exist close to the McLachlan area and with a composition similar to that of typical Western Borefield fluid

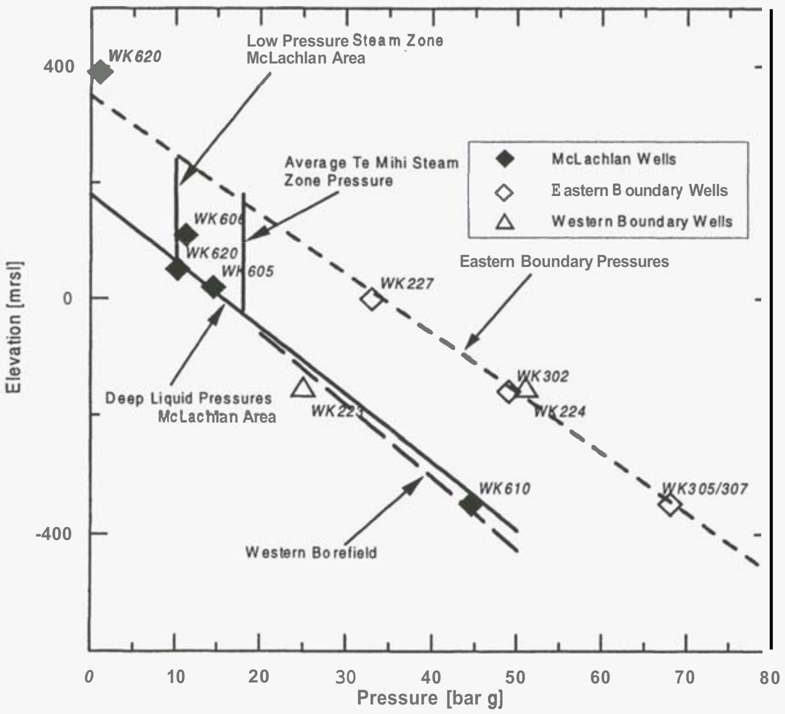
Four McLachlan wells (WK604, 605, 606 and 610) have been producing for almost two years. No reservoir water samples have been collected since commissioning as all production wells produce dry steam. The only well to have discharged significant water was WK620 during its initial testing in 1995.

Gas contents in steam from initial testing of the McLachlan wells were high compared to those from the Western Borefield. Giggenbach and Reyes (1999) concluded from the proportions of N_2, Ar and He in pre-production steam samples that the McLachlan steam is genetically related to steam from the larger Wairakei system, thereby indicating a common source. Gas geothermometer temperatures (T_{H2-Ar} values) of about 250°C and liquid-phase equilibrium conditions were seen as indicating that the steam had migrated from a higher-temperature part of the Wairakei field but had formed "recently" **from** the boiling of the deep chloride reservoir.

We consider that the higher gas concentrations in the McLachlan production wells are principally due to condensation of steam by contact with cooler groundwater on the margins of the steam zone. This is supported by the discharge of dilute Na-Cl-HCO_3 water from well WK620. Gas contents in WK620 were very much higher (>50 Wt%), as was the CO_2/H_2S ratio, than in the other wells when the well was first tested on discharge. This can be attributed in part to the condensation of steam both by drilling fluids and by a 25°C downflow that developed soon after the well was completed, but gas contents were still high (5-15 Wt% depending on WHP) at the end of the test. Stable isotope data (δ^2H, $\delta^{18}O$) from WK620 shows that the steam was affected by local groundwater. The presence of air introduced during drilling could be partly responsible for the generally higher CO_2/H_2S ratios observed during initial testing in this and the other wells, with H_2S being oxidised to sulphate. Giggenbach and Reyes (1996) showed that the variation in CO_2/H_2S could not be caused just by condensation of steam or vapour-liquid separation processes, and concluded that the higher ratios were caused by removal of H_2S by the formation of sulphide minerals.

Since commissioning of the McLachlan power plant and steamfield there has been a decline in total discharge gas concentrations for all the wells. The gas contents for WK604, 605 and 606 have levelled off at about **0.4%** and a CO_2/H_2S ratio of around 30 (Figure **4**), compared to an assumed gas content of ~0.3% and CO_2/H_2S of ~30 in the Western Borefield.

This suggests that the steam zone in the region of the McLachlan Borefield is being recharged by "fresher" steam from somewhere in the north east. The steam from WK610 still has a higher gas concentration of about 0.6% and a higher CO_2/H_2S ratio of about **50.** Condensation of WK604-type vapour could produce the higher gas content but not the higher CO_2/H_2S ratio. It therefore appears that the WK610 vapour still has a proportion of the original higher-gas fluid seen with the early testing. However, the gas chemistry is still changing and it is probable the chemistry will eventually converge on that of the other McLachlan production wells.



Notes: All pressures refer to 1995
Eastern boundary pressures after Wood et. al. 1997
The line showing eastern boundary pressures is hydrostatic at 25°C
Pressures in WK223, WK224, Western Borefield and Te Mihi after Carey et. al. 1998
The line showing Western Borfield Pressures is hydrostatic at 225°C
The line for deep liquid pressures in the McLachlan area is hydrostatic at 180°C
The elevation ranges of lines showing steam zone pressures are indicative only.

Figure 3 Wairakei Geothermal Reservoir Pressures

The latest gas sample from WK620 (October **1997)** has a much lower gas content **(0.75** Wt%) compared with earlier data **(5-10** Wt%) and suggests steam in this part of the borefield is being replaced by steam less affected by the condensation and/or rock reaction seen earlier. This also means that cold water incursion is not occurring in this vicinity despite declining reservoir pressures.

Accompanying the fall in gas contents and CO_2/H_2S, ratios has been a fall in nitrogen proportions and N_2/Ar ratios. The N_2/Ar ratios were initially closer to atmospheric values of about **84** indicating the presence of free air in the reservoir steam, presumably introduced during drilling. Since commissioning these ratios have moved towards air-saturated water values of about **40,** which would be expected if the N_2 and Ar were introduced with groundwater.

The sustainability of the McLachlan steam zone will rely upon recharge of vapour from boiling of in-situ liquid and migration of steam from outside the McLachlan borefield. The source of recharge can be modelled **from** projection of gas trends. Using assumed values of steam zone volume, porosity and liquid saturation, modelling shows that with recharge solely from boiling of liquid in-situ within the steam zone, gas levels would have declined rapidly over a period of 6 months. The fact that **gas** levels have stabilised indicate that recharge is being derived from outside sources, either from boiling of chloride brine beneath the steam zone or migration of steam from the (north?)east.

5. RESISTIVITY AND TEMPERATURES

A summary of the resistivity surveying to that date was provided by Risk et *al.* **(1984).** More recently, two resistivity surveys were carried out over a portion of the western boundary of the Wairakei field for the McLachlan project. A resistivity boundary based on all of those surveys is shown in Figure 1. In contrast to deeply-penetrating resistivity surveys on the eastern boundary of the Wairakei field that Risk and Bibby **(1997)** interpreted as an inclined boundary, the boundary at least in the northern part of the McLachlan property is vertical.

Also shown on Figure **1** are well temperatures, and the known extent of the steam zones. Because the resistivity surveys used a variety of techniques with different (and not precisely known) depths of penetration, and to avoid the complicating effects of the (isothermal) steam zones, maximum measured temperatures regardless of depth are presented in Figure **1** rather than temperatures at a single elevation (as were presented in a similar figure by Risk et *al.*, **1984).** Temperatures measured in shallow wells, those that only encounter steam and those with cool downflows are shown as minimum values. Although the data are insufficient to draw well-constrained isotherms, it is apparent that the resistivity boundary does not closely correspond to the extent of the steam zone. Whether it corresponds to the boundary of the economically exploitable liquid resource depends on what is considered economic, but given the current electricity price in

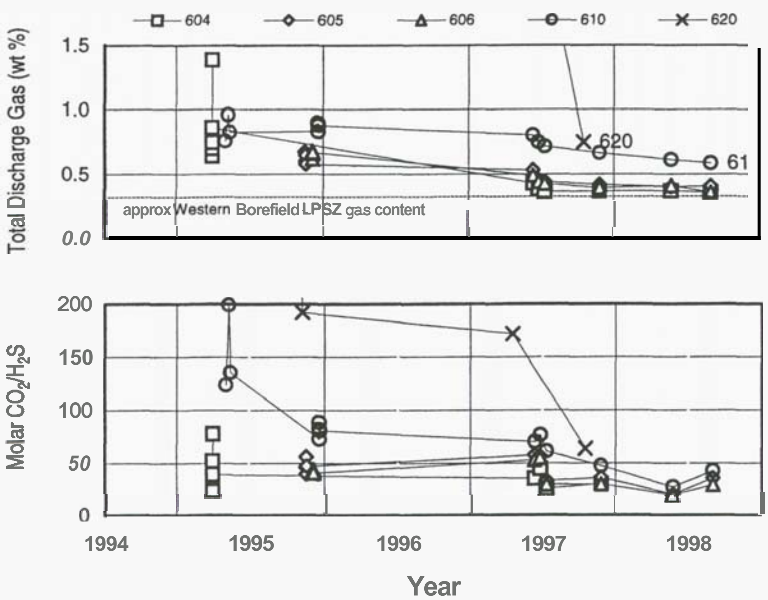


Figure **4** Trends in total NCG content and CO_2/H_2S ratio with time

New Zealand this is no less than 230 °C, which must lie some hundreds of metres within the resistivity boundary.

6. DISCUSSION

The Huka Falls Formation provides an upper boundary to the steam zone which is breached in places to allow both leakage of steam out of the reservoir (e.g. Craters of the Moon) and incursion of cool water into the reservoir (e.g. Geyser Valley). On the western side of the Wairakei field, other than the distribution of the autobrecciated zone at the top of the KIIa Rhyolite, there is no obvious geological control on the lateral extent of the steam zone; nor is there any obvious geological difference between formations at the depth of the productive reservoir inside and outside the field, apart from the nature of the alteration. It is possible there is a zone of mineral deposition acting to isolate the reservoir laterally, but there is no direct evidence for this. This is in contrast to the eastern boundary of the Wairakei field, where Wood *et al.* **(1997)** concluded that a listric caldera margin fault exerts control on the location of the resistivity boundary and the hydrological boundary of the field. The "resistivity boundary" of the field in the west does not correspond closely either to the lateral boundary of the steam zone or to the economic boundary of the resource (given current technology). As suggested by Risk *et* al. *(1984)*, it probably corresponds approximately to the **150 °C** isotherm at around *500* m depth. It may correspond to the hydrological boundary of the field, but there is insufficient data on which to determine this, and the anomalously low pressures in WK223 are not consistent with this interpretation. (Bolton **1970).** Although Contact Energy **(1998)** stated that there has been 20 °C cooling in well WK208 (further to the south east) which they attributed to cool water incursion, there is as yet no evidence for the incursion of cold water laterally into the steam zone within the McLachlan area, despite the fact that well WK620 was clearly very close to the edge of the steam zone at the time it was drilled. On the contrary, the chemical changes in well WK620 are consistent with an expansion of the steam zone. Studt's **(1958)** suggestion that the principal control on lateral cool water incursion is the viscosity of cold water remains perceptive and pertinent.

With time, the gas content in steam from the McLachlan wells has dropped, and the gas ratios have changed in a manner consistent with fresher steam coming into the area as a result of production. This applies both to the wells used for production and well WK620 which has not been used for production and is **400** m from the nearest production well. The process is continuing and is not yet complete but it can be anticipated that with time the gas content and composition of the steam in the McLachlan area will be very similar to that in the Western Borefield.

These changes demonstrate the dynamic nature of the steam zone. The gas composition of the steam in the McLachlan area prior to production cannot be explained by a simple condensation process from the steam in the Western Borefield. There must have been interaction with rocks and mineral deposition also. A schematic model of the boundary of the steam zone is shown in Figure **5**.

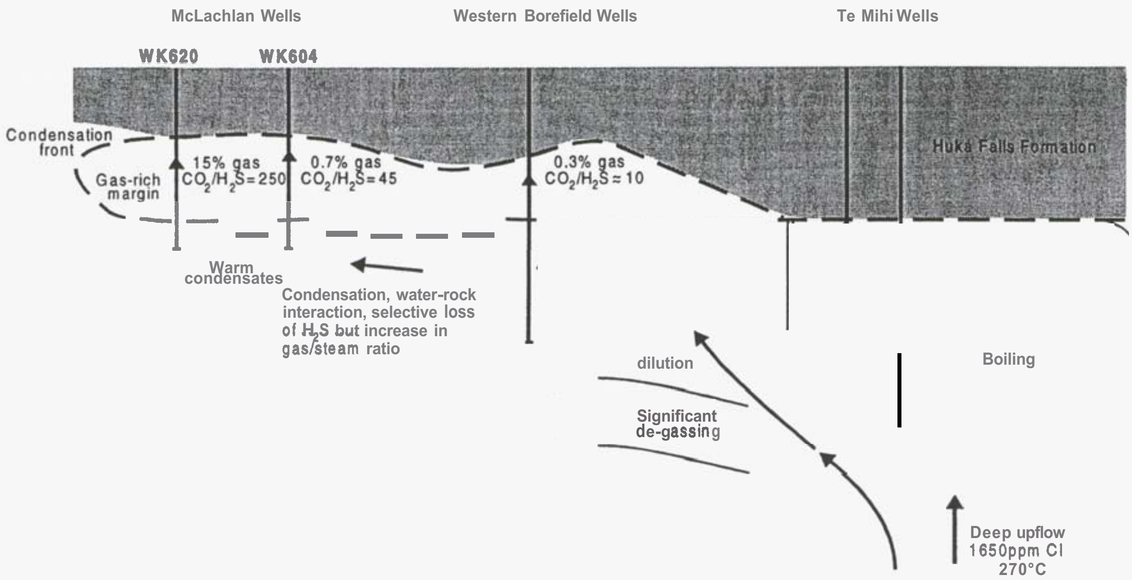


Figure **5** Schematic of chemical processes in Wairakei reservoir – not to scale and simplified (gas concentrations and ratios in McLachlan area are early values, both have subsequently dropped).

7. ACKNOWLEDGEMENTS

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