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OHAAKI RESERVOIR CHEMISTRY: INSIGHTS INTO THE NATURE AND LOCATION OF THE HEAT SOURCE(S)

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ABSTRACT

A recent chemical survey of the Ohaaki geothermal system (New Zealand) has highlighted compositional differences between the East and West Bank production fluids. The highest reservoir Cl concentrations are found on the West Bank, in apparent conflict with maximum reservoir pressures found on the east bank. B/Cl, N_2/Ar and CO_2/He maxima all occur on the East Bank. The current model holds that there are two heat sources for the present-day system, with that on the East Bank comprising of an actively degassing and relatively shallow-seated magmatic intrusion.

1. INTRODUCTION

Questions concerning the source and evolution of thermal fluids in the Ohaaki geothermal field, and the location of the heat source(s) therein, have taken on greater practical significance with the present need for more sustainable steam production from the field. It has been recognised previously (eg. Giggenbach, 1989; Hedenquist, 1990) that considerable differences exist in the fluid compositions of the East Bank from those of the West Bank production bore fields.

This paper reports interim findings of a comprehensive chemical study designed to address the significance of the different fluid compositions between the two fields, and to develop a working model which explains their respective origins.

2. SCOPE OF STUDY

A wide range of discharges were sampled from each of the production fields, and as many geo-indicator techniques were applied to this set of samples as practicable. These techniques focussed on major, trace and isotopic analyses on both waters and gases to develop an internally consistent picture of reservoir heat source inputs. Six production wells (8, 15, 22, 25, 42 and 43) were sampled in 1997, seven production wells (22, 24, 31, 36, 44, 48 and 49) were sampled in 1998, and a further 8 non-production wells (1, 5, 9, 10, 14, 17, 26 and 33) were sampled for gases in 1999. The emphasis was to sample fluids with greatest spatial and depth distribution across the field, including, where possible, the deep exploration wells drilled in 1995.

Waters were analysed for the normal major chemical constituents, and separate samples were collected for trace/ultra-trace element and isotope analysis (including ^{18}O, ^{2}H and ^{36}Cl). Steam samples were collected and analysed for major/minor gas constituents and isotopes (including ^{18}O, ^{2}H, ^{13}C, ^{3}He, ^{4}He, ^{40}Ar, ^{38}Ar, ^{36}Ar, ^{22}Ne, ^{84}Kr and ^{132}Xe). Data were processed to aquifer concentrations with the speciation code ENTHALP (Truesdell and Singers, 1974), using measured enthalpy data provided by Contact Energy Ltd.

Although this work is still in progress, we report the analytical results to hand which have a direct bearing on the question of the nature and position of the heat source(s) for the field.

3. RESULTS

Reservoir Cl values are plotted against reservoir liquid enthalpies, as constrained by quartz solubility, in Fig. 1. A system mixing line is prescribed by the high enthalpy discharge from East Bank well 43, and by steam heated groundwater (cf. Hedenquist, 1990). West Bank well 22 has the highest reservoir Cl concentration in the system, which when corrected for vapor loss back to the system mixing line, prescribes a base fluid Cl composition of about 1100 mg/l at 315 °C.

Discharge from the relatively shallow well 8 shows the greatest thermal and compositional effects of mixing of upwelling base fluid and cooler, meteoric and/or steam heated waters. Vapor-corrected East Bank discharges are some 20% more dilute, with maximum reservoir Cl concentrations reaching ca. 900 mg/l. Fluids from wells 42, 24 and 22 show the greatest amount of isenthalpic cooling.

Reservoir $\delta^{18}O$ and $\delta^{2}H$ values for these discharges are plotted in Fig. 2, where they are compared to the meteoric water line, local groundwater, and Waikato River water (cf Fig. 3). With the exception of the discharges from well 48, the data distribution is similar to that described above, with West Bank wells producing both the isotopically heaviest and lightest water, and East Bank discharges showing lesser impact of groundwater incursion. Interestingly, discharges from well 48, which are amongst the highest Cl bearing fluids in the system, are isotopically light with respect to $\delta^{18}O$ and $\delta^{2}H$. The mixing line extending from local groundwater through the data points projects outward to the andesitic water composition described by Giggenbach (1992) at $\delta^{2}H = -20$, and $\delta^{18}O = +10$. Using this as a reference point, the maximum magmatic water component of the reservoir fluid is around 20%.

Initial discharge Cl/B data for the field are plotted in Fig. 3A, including data from the recent deep wells 48 and 49. The topology is similar to that described by Hedenquist (1990), with low Cl/B ratios on the East Bank giving way to progressively higher values on the West Bank. The steep isopleth distribution between wells 42 and 25 (5.8 to 8.4 respectively) and wells 49 and 28(4.7 to 8.3) coincides with a fault structure proposed on geological evidence by Wood (1996). The higher Cl-bearing fluids in the West Bank have considerably lower B contents, suggesting that the notion of a single base fluid composition may not be applicable for this geothermal field (cf. Hedenquist, 1990).

N_2/Ar ratios for the discharges are plotted in Fig 3B. Given that the primary source of Ar in geothermal fluids is that dissolved in convecting meteoric water, the N_2/Ar ratio is useful in identifying the most deeply derived (ie. source) fluid components, especially in magmatic-hydrothermal systems (eg. Giggenbach, 1995). The topology of N_2/Ar isopleths across the system suggests two main upwellings of thermal fluids, one beneath each production borefield. The highest N_2/Ar values are from wells 42 and 49, and coincide with the area of lowest Cl/B ratios previously described.

Application of equilibrium thermodynamics to gas compositions of the Ohaaki discharges is made difficult by the high enthalpy nature of most of the discharges, particularly those on the East Bank. This is evident in Fig. 4, where analytical concentration quotients for the reaction

$$CH_4 + 2H_2O = CO_2 + 2H_2$$

are plotted against quartz equilibrium temperatures for the respective discharges (adapted from Giggenbach, 1980). Most discharges plot above the full equilibrium line in the vapor gain field, with East Bank discharges containing the largest equilibrium vapor fractions (10-40 %). The West Bank discharges contain smaller quantities of added vapor, with wells 15 and 20 producing a vapor depleted fluid. With the exception of the discharge from well 8, there is broad agreement between calculated excess enthalpy contents of the discharges and the “added vapor fractions” evident in Fig.4. Well 8, on the other hand, which produces a relatively cool and dilute but gas-enriched fluid, likely carries an entrained non-condensable gas signature from a higher temperature (deeper) portion of the reservoir.

Relative He, CO_2 and Cl total discharge compositions are shown in Fig. 5. Most of the East Bank fluids are enriched in CO_2 relative to their West Bank counterparts, with typical CO_2/He ratios falling between 4-7x10^5 in the east compared to 2-3x10^5 in the west. As demonstrated by the isenthalpic cooling path for the discharge from well 48, and the preceding relationships (Figs. 1-3), it is clear that these differences cannot be accounted for by physical reservoir processes (mixing or boiling). Rather, the compositional differences between these discharges reflect either differences in the source fluids or, less likely, different reaction-pathways for the East and West Bank fluids.

Preliminary results for $\delta^{13}C$ fractionation between CO_2 and CH_4 reveal fairly uniform equilibrium temperatures of ca. 445 °C for the East Bank wells, and 420 °C for West Bank discharges. Noting that these signatures are little affected by excess enthalpy effects, it is likely that they reflect real reservoir environmental conditions at greater depth.

Previous rare gas isotopic studies at Ohaaki (Hulston and Lupton, 1996) demonstrated a surprisingly large variation in R_C/R_A across the field, with the highest R_C/R_A values (> 6.0) found on the West Bank. These authors also identified elevated $^{40}Ar/^{36}Ar$ ratios in East Bank discharges, and noted a crude inverse correlation between R_C/R_A and Cl/B across the system.

Interim rare gas isotope results from this study are largely consistent with those of Hulston and Lupton (1996). A plot of R_C/R_A vs $^{40*}Ar/^4He$ (Fig. 6) shows reasonable inverse linear correlation between these parameters, with R_C/R_A ranging from 5.6 down to 3.5, and $^{40*}Ar/^4He$ (ie. the ratio of purely radiogenic ^{40}Ar to total ^4He) ranging from .09 to .45. The lowest R_C/R_A and highest $^{40*}Ar/^4He$ values are found on the East Bank wells. The discharge from well 25 having a large error bar is compared to data from Hulston & Lupton (1996), which plots more closely to the inverse trend. Interestingly, a single datum point for a super-heated fumarolic discharge from Ruapehu volcano (NZ) falls along the visually fitted line through the data, plotting at relatively low R_C/R_A but high $^{40*}Ar/^4He$ values.

The inverse correlation observed here is similar that found in the Geysers field (Kennedy and Truesdell, 1996), and suggests that there are at least two component sources in the system. A possible model for their origin is discussed below.

4. DISCUSSION

As pointed out by Hulston and Lupton (1996), there are few differences in liquid phase compositions between East and West Bank fluids. Indeed, water stable O and H isotope signatures show little difference between the two fields, and along with $^{84}Kr/^{132}Xe$ ratios, indicate that the fluids from both bore fields are comprised predominantly of meteoric water. The extent and nature of fluid-rock interaction on both banks are very similar (Hedenquist, 1990).

That the highest Cl concentrations are found on the West Bank might suggest that this is the main thermal upwelling for the field. The simplest reservoir model would then entail the more dilute East Bank fluids as representing outflow from the west. This interpretation, however, conflicts with a number of physical and chemical observations for the field. Perhaps most emphatic is the fact that reservoir pressures are some 15 bars higher in the deep East Bank reservoir than in the west (unpubl. data, Contact Energy Ltd.). This provides compelling evidence for the opposite case, ie., that outflow is from east to west. This is, however, precluded by the Cl contents.

The stark differences in Cl/B ratios across the field (Fig. 3A) have been explained by Mahon & Finlayson (1972) and Hedenquist (1990) as representing variations in the depths to basement between the East and West Banks. However, if this were the case, one should expect to see vertical variations in Cl/B ratios within each bore field, which is not observed. Also, other fields with large vertical displacements of basement greywacke should show similar trends, but they typically do not (eg. Kawerau; Christenson, 1997).

In his treatment of TVZ-wide variations in Cl/B ratios, Giggenbach (1995) pointed out that there is little reason to expect the greywacke basement rocks to effect the Cl/B ratio, given that the greywackes have about the same B concentration as the volcanic rocks overlying them (Ellis and Sewell, 1963). He also noted that there is a strong spatial correlation between B and the presence of so-called andesitic fluids within the TVZ. As demonstrated by Quisefit, et al., (1989), B is readily transported in high temperature magmatic gas streams as H_3BO_3, but at lower temperatures (< 400°C), B partitions strongly into the liquid phase (eg. Glover, 1988). In the case of the East Bank fluids, the relatively high B contents can be readily accounted for by localised release of H_3BO_3 gas from cooling magma at depth, and dissolution of this gas into overlying convecting meteoric fluid.

That the East Bank may have a larger magmatic volatile budget than the West Bank is supported by the elevated N_2/Ar and CO_2/He ratios found there. What has been perplexing for some time, however, is the fact that the $^3He/^4He$ ratios are higher on West Bank than on the East, suggesting that in fact the reverse could be true. The high $^{40}Ar/^{36}Ar$ ratios in the east (Hulston and Lupton 1996), combined with the $^{40*}Ar/^4He$-enriched source fluid component found there (Fig. 6) might be explained by enhanced rock dissolution beneath the East Bank. Condensation of magmatic volatiles into meteoric water adjacent to cooling plutons leads to the formation of aggressive, acidic solutions (eg. Christenson and Wood, 1993), and the dissolution of primary rock-forming minerals (eg. White and Christenson, this volume). In as much as this would lead to the ready release of radiogenic gases (such as ^{40}Ar and ^4He) trapped in the matrices of the host minerals, it is plausible that these could make a significant contribution to the overall isotope budget of the system.

The question as to the depth of an intrusive heat source beneath the East Bank field, apart from it being shallower than the west, is more difficult to ascertain. Measured temperatures on the East Bank are little different from those on the west. However, the higher $\delta^{13}C$ CH_4-CO_2 equilibrium fractionation temperatures in the east, and the fact that re-equilibration rates for this reaction are strongly temperature dependent (Giggenbach, 1982), are consistent with a shallower heat source in the eastern bore field.

With regard to reservoir pressure on the East Bank, the equilibrium temperatures in excess of 400 °C suggest that the equilibrium environment was close to the brittle-plastic transition zone, marking the effective barrier to convective circulation (eg. Fournier, 1991). Apart from the likely contribution that higher gas contents would make to pressure-depth relations in the eastern part of the field, this rheological effect may also make a contribution to the measured pressures, as found during deep drilling in the high temperature region of the Geysers field in California (Fournier, 1991).

5. CONCLUSIONS

This study has highlighted the differences in reservoir fluid composition between the two production fields at Ohaaki. The simplest explanation is that there are two separate heat sources for the field, both are of magmatic origin. The heat source beneath the eastern borefield is younger, and probably seated at a shallower depth to that in the west.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Christenson BW and Wood CP 1993 Evolution of a vent-hosted hydrothermal system under Ruapehu Crater Lake, New Zealand. *Bull. Volc. 55: 547-565.*

Christenson BW 1997 Kawerau Geothermal Field: Geochemical structure of the reservoir and its response to exploitation *Geoth. Res. Council Trans., 21:17-24.*

Ellis AJ and Sewell JR 1963 Boron in waters and rocks of New Zealand's hydrothermal areas. *NZ J Sci. 6:589-606.*

Fournier RO 1991 The transition from hydrostatic to greater than hydrostatic fluid pressure in presently active continental hydrothermal systems in crystalline rock. *Geophys. Res. Letters 18:955-958.*

Giggenbach WF 1980 Geothermal gas equilibria. *Geochim. Cosmochim. Acta 44:2021-2032.*

Giggenbach WF 1982 Carbon-13 exchange between CO_2 and CH_4 under geothermal conditions. *Geochim. Cosmochim. Acta 46:159-165.*

Giggenbach WF 1989 The chemical and isotopic position of the Ohaaki Field within the Taupo Volcanic Zone. *Procs. 11th NZ Geoth. Workshop, p 81-88.*

Giggenbach WF 1992 Isotopic shift in waters from geothermal and volcanic systems along convergent plate boundaries and their origin. *Earth Planet Sci Lett 113:495-510.*

Giggenbach WF 1995 Variations in the chemical and isotopic compositions of fluids discharged from the Taupo Volcanic Zone, New Zealand. *J Volc. Geoth. Res. 68:89-116.*

Glover RB 1988 Boron distribution between liquid and vapour in geothermal fluids. *Proc. 10th NZ Geoth. Workshop, p 223-227.*

Hedenquist JW 1990 The thermal and geochemical structure of the Broadlands-Ohaaki geothermal system, New Zealand. *Geothermics 19:151-185.*

Hulston JR, Lupton JE and Lovelock BG 1996 Recent isotopic measurements at Ohaaki. Procs. 18th NZ Geoth. Workshop, p183-187.

Kennedy BM and Truesdell AH 1996 The northwest Geysers high temperature reservoir: Evidence for active magmatic degassing and implications for the origin of the Geysers Geothermal Field. *Geothermics 25:365-387.*

Mahon AW and Finlayson JB 1972 The chemistry of the Broadlands geothermal area, New Zealand. *Am. J. Sci., 272:48-68.*

Quisefit JP, Toutain JP, Bergametti G, Javoy M, Cheynet B and Person A 1989 Evolution versus cooling of gaseous volcanic emissions from Momotombo Volcano, Nicaragua: Thermochemical model and observations. *Geochim. Cosmochim Acta, 53:2591-2608.*

Truesdell AH and Singers W 1974 Computer calculation of down-hole chemistry in geothermal areas. *US Geol. Surv. J. Res. 2(3):271-278.*

White S and Christenson BW 2000 Modelling the alteration halo of a diorite intrusion. *This volume.*

Wood CP 1996 Basement geology and structure of TVZ geothermal fields, New Zealand. *18th NZ Geoth. Workshop, p157-162.*

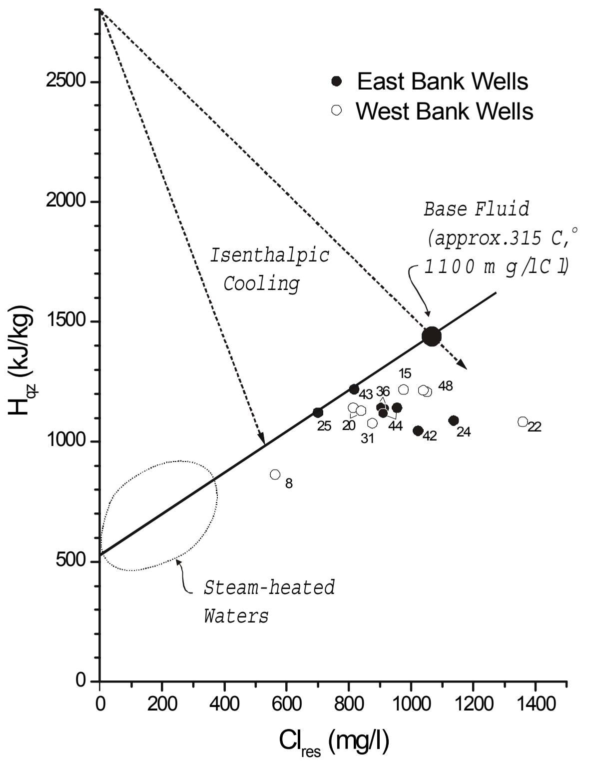

Fig. 1. Cl-enthalpy relations for Ohaaki production fluids.

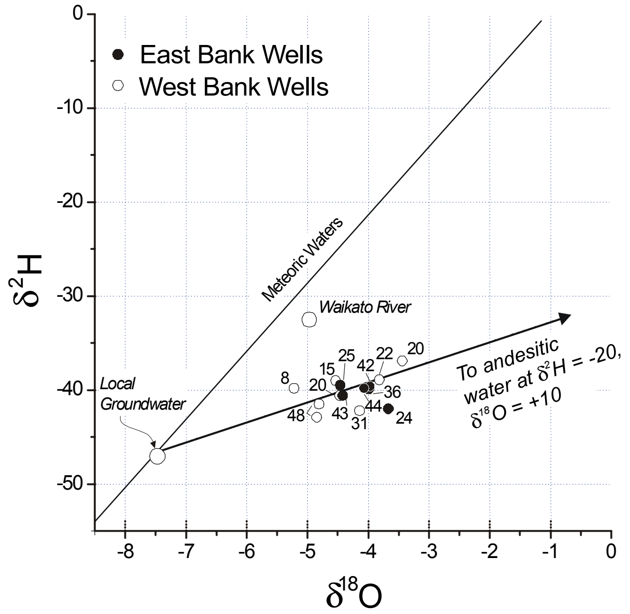

Fig. 2. $\delta^{18}O$ vs δ^2H plot for Ohaaki production fluids.

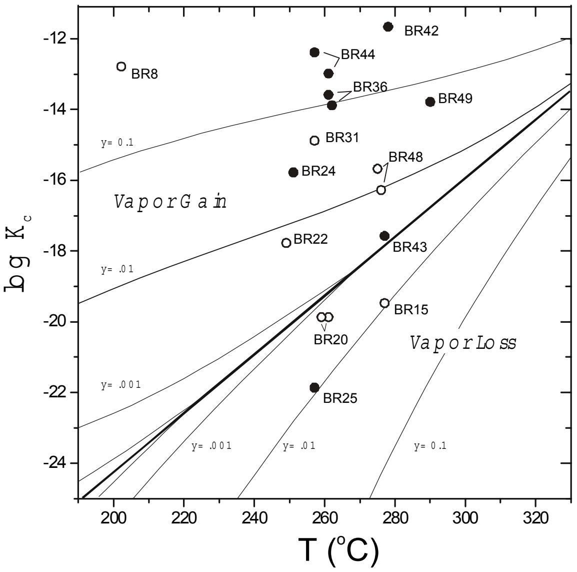

Fig. 4. Log K plot for CH_4-CO_2 in total discharge as a function of quartz equilibrium temperature.

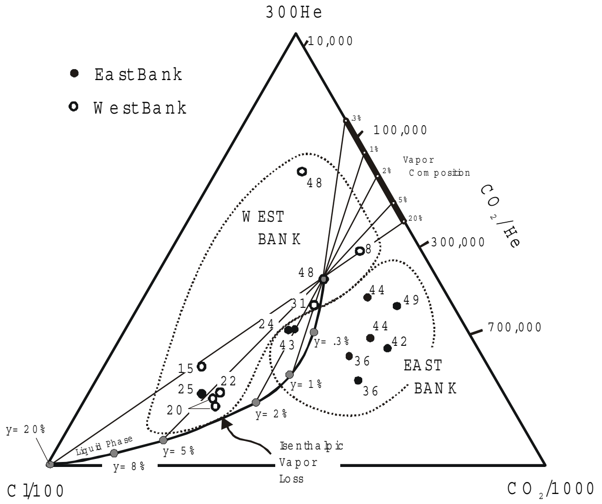

Fig. 5. Relative compositions of Cl-He-CO_2 for Ohaaki production fluids.

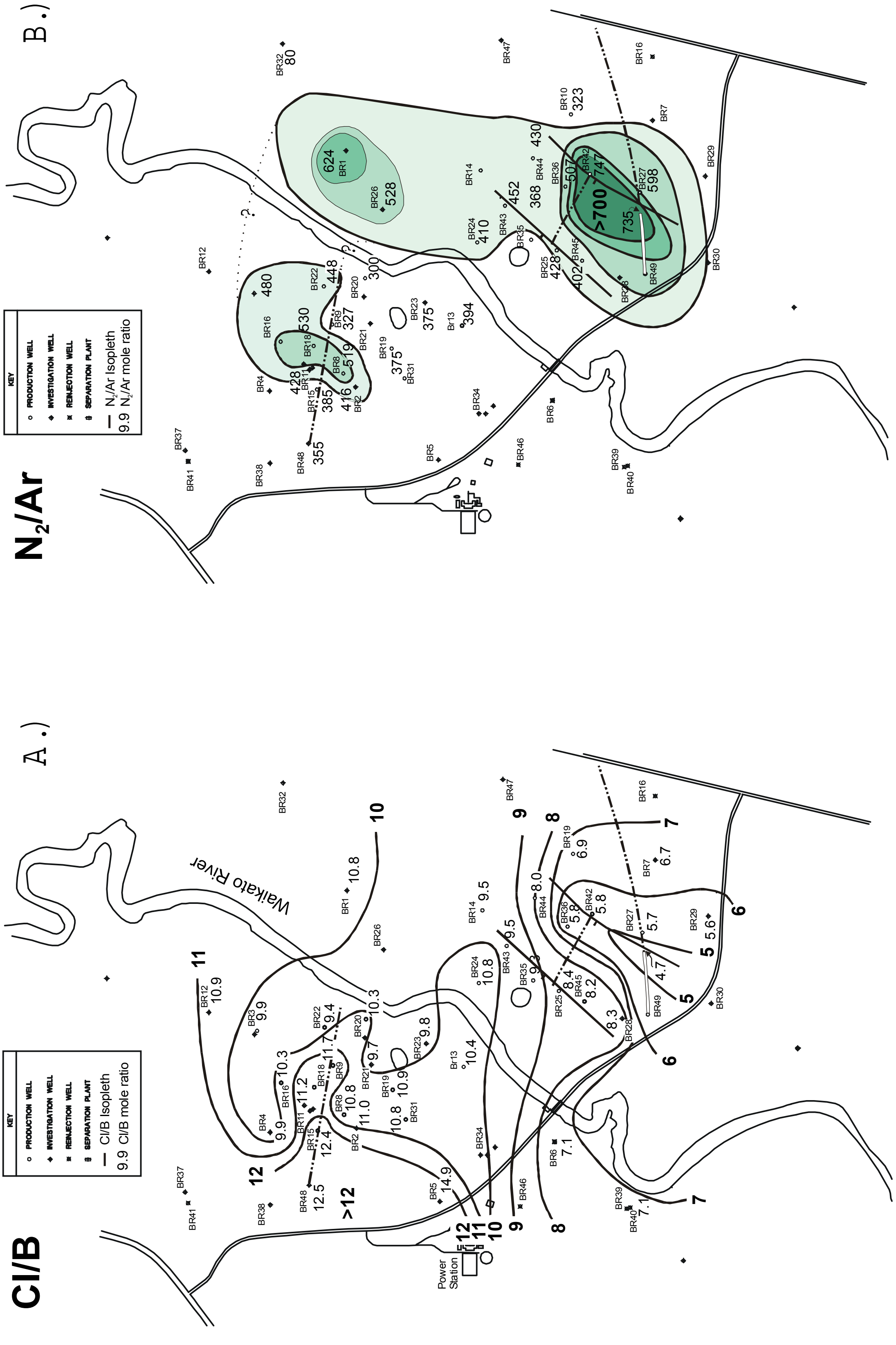

Fig 3. A. Cl/B ratios from production discharges across the Ohaaki system. B. N_2/Ar ratios.

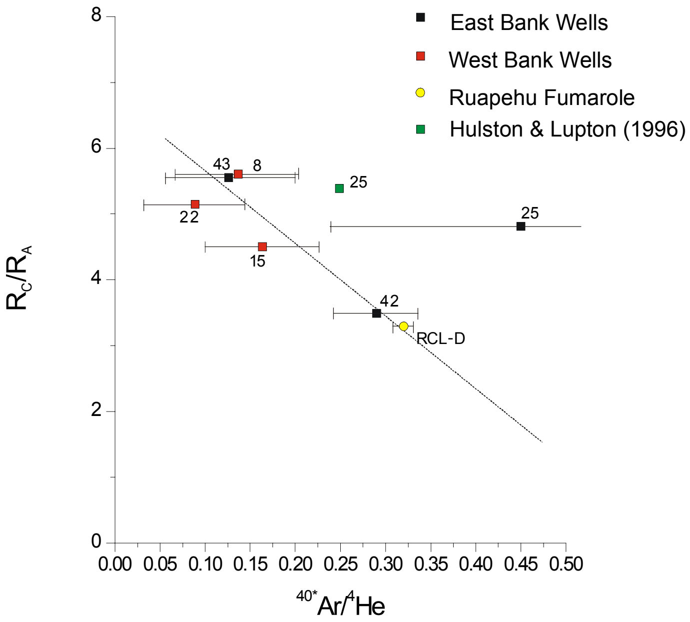

Fig. 6 R_C/R_A vs $^{40*}Ar/^{4}He$ for 3 East Bank and 3 West Bank discharges, compared to a fumarolic discharge from Mt Ruapehu volcano.