THE ROLE OF BORON-CHLORIDE AND NOBLE GAS ISOTOPE RATIOS IN TVZ GEOTHERMAL SYSTEMS

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SUMMARY - The model of the geothermal system in which deep circulating groundwater containing noble gases, at air saturated water concentrations, mixes with hot fluids of mantle origin at depth, is extended to include the effect of interaction of the ascending fluid with both solid and gaseous phases of basement (or other) rocks *en* route to the surface. It is demonstrated that this interaction is responsible for most of the CO_2 in the Taupo Volcanic Zone (TVZ) geothermal systems. It is proposed that the modelling of this interaction might be accomplished by techniques similar to those used for the understanding of the oxygen isotope shift found in geothermal systems. The water rock interaction experiments of Ellis and Mahon (1964, 1967) provides some data on the kinetic rates for B and Cl dissolution from rocks likely to be encountered in the geothermal system, but further information on the behaviour of B may be needed. If these problems can be overcome this modelling technique has promise for the estimation of the recharge of geothermal systems and hence the sustainability of these systems.

1. INTRODUCTION

Hulston (1994) proposed the model of geothermal systems shown in Figure 1 in order to interpret the noble gas isotopic results obtained in the Wairakei and Mokai geothermal fields but was non-specific about the source of the "crustal" contribution. In their study of $^3He/^4He$ isotope ratios of the Ohaaki-Broadlands geothermal field, Hulston *et al.* (1986) found a variation of a factor of two in the helium isotope ratio across the field. The only significant correlation found at that time was with the Cl/B ratio. Since that time, Hulston and Lupton (1995) have found a trend line of decreasing $^3He/^4He$ with increasing B/Cl across the whole of the Taupo Volcanic Zone (TVZ). Figure 2 shows the results of Hulston *et al.* (1986) re-plotted in this manner with the TVZ trend line superimposed. Hulston and Lupton (1995) argued that since volcanic gases and rocks are relatively high in Cl and ^3He content and low in radiogenic ^4He, while the Mesozoic greywacke basement is relatively high in B and radiogenic ^4He, the relationship shown in Figure 2 is the result of an interaction of the mantle fluids with greywacke or similar basement rocks. The purpose of this paper is to consider this interaction to see how it might be used to increase our understanding of geothermal systems particularly in relation to the noble gas techniques described by Hulston (1994). The long term aim of this work is to develop a method of assessing the sustainability of the geothermal resource in individual fields. This study has used data from the Ohaaki-Broadlands field because of its central position on the TVZ trend line in Figure 2 and because the extent of the fluid-rock interaction appears to vary across the field.

2. THE STRUCTURE OF SUBDUCTION GEOTHERMAL SYSTEMS

Bibby *et al.* (1995) summarised the results of crustal-scale seismic reflection experiments in the TVZ and concluded from the seismic velocity results that the crust beneath the TVZ extends to a depth of approximately 15km. They were not able to distinguish between greywacke and andesite below 2km depth. Outside the TVZ the crust appears to extend to greater than 25km depth. To date greywacke has not been encountered during drilling in the fields in the centre of the TVZ such as Wairakei and Mokai but has been found in the Ohaaki, Rotokawa and Kawerau fields on the SE edge of the TVZ. The B/Cl and He isotope ratios would imply that fields near the NW edge of TVZ contain greywacke or similar crustal rocks at depth.

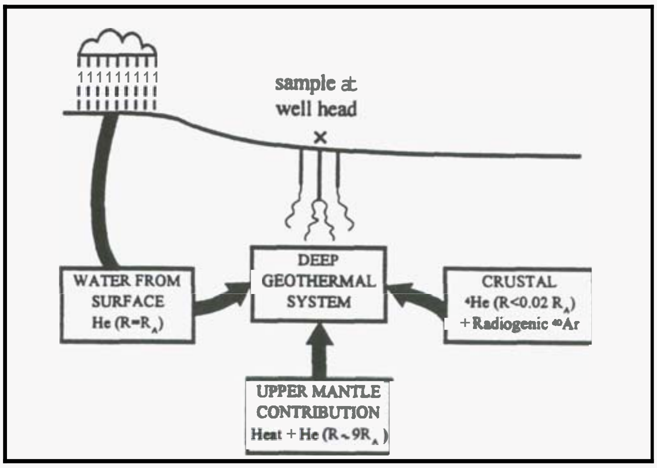

Figure 1 - Light noble gas components in a geothermal model.

3. THE ORIGIN OF GEOTHERMAL CARBON DIOXIDE

The reasons for the variations in CO_2 content of the fields of the TVZ gas have been debated for some time. It is therefore useful to consider if the origin of this CO_2 is linked to the near-surface process which produces the B in these systems rather than from the much deeper mantle wedge zone (Giggenbach, 1995). This would seem particularly appropriate since sedimentary rocks such as greywacke are likely to be rich in carbonate. Figure 3 plots the $CO_2/^3He$ ratio against B/Cl, where the $CO_2/^3He$ ratio is used to provide a measure of the CO_2 relative to the mantle component, and shows a strong tendency for CO_2 to be associated with the source of the B over a wide extent of the TVZ. Those systems with mid-range R_C/R_A (and B/Cl) values, such as Ohaaki have the highest absolute concentration of CO_2 in the TVZ. The Ohaaki geothermal system is therefore ideal to study the effects of interaction of ascending geothermal fluids of mantle origin.

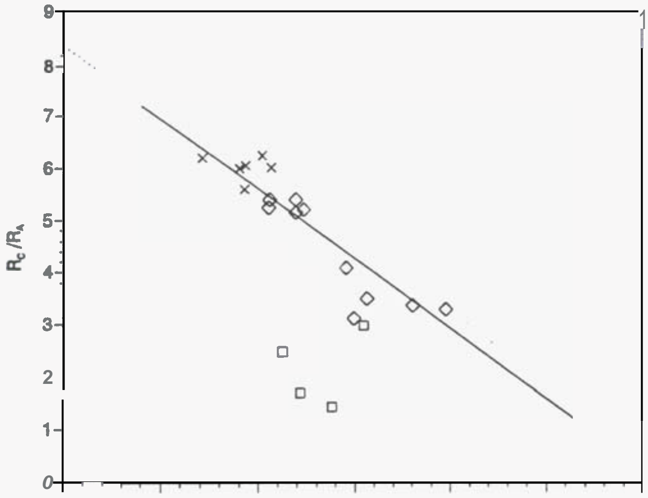

Figure 2 - $^3He/^4He$ ratio (R_C/R_A) vs. B/Cl molar ratio for the Ohaaki-Broadlands field (re-plotted from Hulston *et al.*, 1986). The line shows the TVZ trend.

4. THE INTERACTION PROCESS

The model shown in Figure 1 can be extended to include interaction of the mobile fluid with the stationary basement and other rocks. As fluid of mantle origin flows through a permeable zone, the rock may release B, Cl and gases such as He and Ar. Gases such as CO_2 may also be released or absorbed according to the conditions existing (Giggenbach, 1981). After sufficient fluid has passed through an initial part of the permeable trajectory, an equilibrium state is attained and no further reaction occurs. The actual quantity of fluid required before this state is reached is a function of the quantity of "releasable" material in the rock and the kinetic rate of the interactions. In a high temperature environment, where reactions proceed to equilibrium, the quantity of fluid that has passed through an envisaged part of the aquifer can be calculated exactly by transport equations or serial box models, while the errors incurred by using single-box mixed models can encompass several orders of magnitude. Transport theory also permits the exact calculation of quantity of fluids if temperatures are too low for complete equilibration during flow, provided reaction rates and Damköhler numbers are known for each reaction. A related formalism has been developed for stable isotopes by Lassey and Blattner (1988) using the approach of Goldstein (1953).

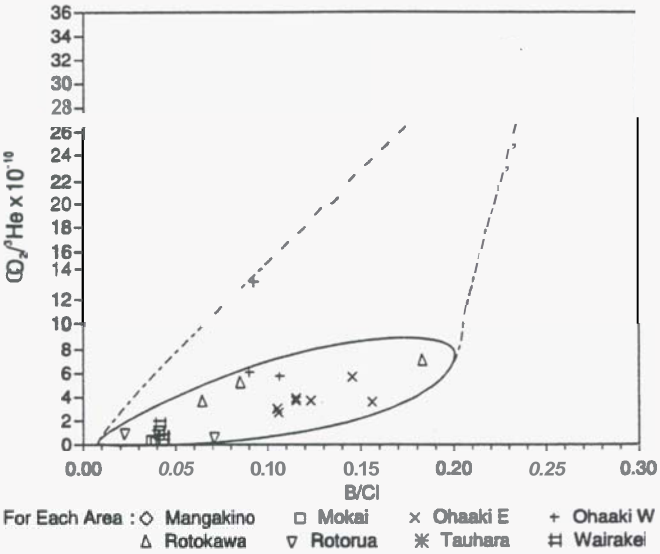

Figure 3 - $CO_2/^3He$ ratio ($\times 10^{-10}$) vs. **B/Cl** molar ratio for some TVZ geothermal **areas** (data from Hulston and Lupton, 1995).

In order to utilise this extended model, one has to know or estimate the concentrations and availability of the relevant components of the rocks, in order to arrive at a limiting calculation for equilibrium, or some approximation of partial equilibrium. Although we are still far **from** complete knowledge of the above mentioned kinetic rate data, much information on the kinetics of release, as well as obtainable quantities of components can be **gained** from the experiments of Ellis and Mahon (1964, 1967). They reported the results of a number of experiments conducted to determine the quantity of Cl, B and a number of other chemical species which could be extracted **from** rocks likely to be found in geothermal systems. These showed (Ellis and Mahon, 1967) that at 600°C at least 45% of **the** Cl and B could be extracted within two weeks from pumice, dacite, andesite and greywacke by geothermal-like fluids in a 1:1 water-rock ratio at 1500 bars pressure (for obsidian, rhyolite. ignimbrite and basalt the yields were above 15%). While these data show that Cl is extracted in a consistent manner, the B results show some unusual features in that Ellis and Mahon (1964) found the B content after 300 hrs was consistently lower than that after **2** hrs in the 200°C to 350°C experiments (by a factor of 4.5 in the case of the 350°C experiment). Furthermore in Ellis and Mahon (1967), where all the experiments were conducted for two weeks, the B extraction rises consistently from 4.9% to 48% as the temperature of the experiment was raised **from** 400°C to

600°C, whereas the Cl extraction remained above **60%** throughout this temperature range.

It was felt advisable to delay intensive application of the above formalism until further information on the kinetics of B release can be established. In particular the extent of loss of B into the lattice structure of alteration clay minerals (Harder, 1961) needs to be assessed. Information on the kinetics of the release of ^{4}He and CO$_2$ from rocks by geothermal-like fluids also needs to be established in order to undertake further modelling of the interaction process.

5. VARIATIONS OF NOBLE GASES AND CO$_2$ WITH EXPLOITATION AT OHAAKI

Clotworthy ***et al.*** (1995) have reported on changes which have occurred at Ohaaki since production began in 1988, showing an enthalpy decline in the West Bank reservoir caused by the ingress of relatively shallow groundwater. In the East Bank sector, two-phase reservoir conditions developed with enthalpy and gas contents peaking after three years and then gradually declining. Four wells have also shown major returns of re-injected separated water. In order to search for evidence of flush-out of B as a result of fluid extraction it would be necessary to carry out a detailed analysis of B/Cl ratios in order to avoid wells showing the effects of re-injection and this has not been attempted in this study. The behaviour of the noble gases in the East Bank Ohaaki wells in relationship to the rise in CO$_2$ which Clotworthy ***et al.*** (1995) illustrate, has however been investigated. In general both He and Ar show similar rises and it is therefore more useful to plot the ratio of He to CO$_2$ shown in Figure **4** where a significant rise in He occurred at the time of the CO$_2$ peak. Unfortunately no He or Ar isotope sample collections were made at that time. If they had, it would have been possible to determine if the He peak originated from radiogenic He extracted from greywacke close to the surface or a deeper source which was preferentially extracted from the geothermal fluid by the boiling process which also released the CO$_2$. In any case a re-measurement of the noble gases in Ohaaki would seem appropriate in the near future.

6. CONCLUSIONS

1 The relationship between ^{3}He/^{4}He and B/Cl ratios previously found at Ohaaki-Broadlands appears to be due to the interaction of mantle derived fluids with the greywacke or similar basement rocks *en route* to the surface. Other results from Hulston and Lupton (1995) indicate that this appears to apply to most of the TVZ but that the relationship does not extend to the Ngawha geothermal area (North Auckland).

2 A thorough study of the behaviour of this interaction as a field is developed can provide an opportunity to increase our understanding of TVZ geothermal systems. In particular this interaction seems to be responsible for the major part of the CO$_2$ found in the TVZ geothermal systems.

3 The higher B/Cl ratios in the East Bank area together with the changes which have occurred in the Ohaaki Geothermal field make it one of the most suitable for study (provided the effects of re-injection can be determined).

4 If the processes occurring within the geothermal system can be more fully understood it should in principle be possible to contribute to the development of better methods of estimating the heat recharge into a geothermal system and hence its sustainability under development.

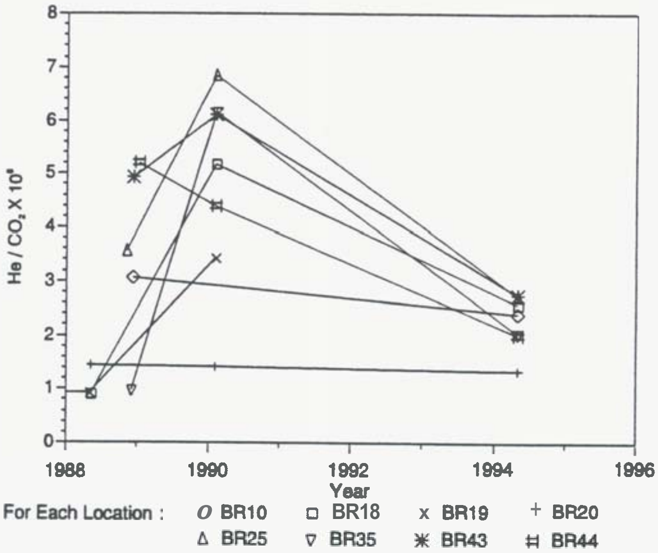

Figure 4 - He/CO$_2$ (x10^6) vs. date of collection for some Ohaaki wells.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Bibby, H.M., Caldwell, T.G., Davey F.J. and Webb T.H. (1995). Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. ***J. Volcan. Geoth. Res.*** (in press Sept 1995 issue).

Clotworthy, A., Lovelock, B. and Carey, B. (1995). Operational history of the Ohaaki Geothermal Field, New Zealand. In ***Proc World Geothermal Congress, Florence, Italy 1995*** Vol. 3, 1797-1802.

Ellis, A.J. and Mahon, W.A.J. (1964). Natural hydrothermal systems and experimental hot-water/rock interactions. ***Geochim. Cosmochim. Acta,*** Vol. ***28,*** 1323-1357.

Ellis, A.J. and Mahon, W.A.J. (1967). Natural hydrothermal systems and experimental hot-waterhock interactions (Part II). *Geochim. Cosmochim. Acta,* Vol. 31, 519-538.

Giggenbach, W.F. (1 981). Geothermal mineral equilibria. *Geochim. Cosmochim. Acta.* Vol. 45, 393-410.

Giggenbach, W.F. (1 995). Variations in the chemical and isotopic composition of fluids discharged from the Taupo Volcanic Zone, New Zealand. *J. Volcan. Geoth. Res.* (in press Sept 1995 issue).

Goldstein, S. (1953). On the mathematics of exchange processes in fixed columns, I. Mathematical solutions and asymptotic expansions. *Proc.* R. *Soc. (London) Ser. A.* Vol. 252, 334-347.

Grant, M.A. (1977). Broadlands - A gas-dominated geothermal field. *Geothermics* Vol. 6, 9-26.

Harder, H. (1961). Einbau von Bor in detritishe Tonminerale. *Geochim. Cosmochim. Acta.* Vol. 21, 284-294.

Hulston, J.R., Lupton, J.L., Rosenberg, N. (1 986). Variations of $^3He/^4He$ isotopic ratios within the Broadlands Geothermal Field, New Zealand. *Proc 8th Geothermal Workshop, Univ of Auckland, Nov 1986,* 13-16.

Hulston, J.R., Lupton, J.L. (1989). Helium isotope studies in the Taupo Volcanic Zone, New Zealand. In: Miles (editor) "Water-Rock Interactions", 317-320. Balkema, Rotterdam.

Hulston, J.R., 1994. The role of helium and other noble gases in the modelling of geothermal systems. *Proceedings of the 16th NZ Geothermal workshop, University of Auckland, November 1994,* 17-20.

Hulston, J.R. and Lupton, J.E. 1995. Helium isotope studies in the Taupo Volcanic Zone, New Zealand. (in prep).

Lassey, K.R. and Blattner, P.B. (1988). Kinetically controlled oxygen isotope exchange between fluid-rock in one-dimensional advective flow. *Geochem. Cosmochim. Acta.* Vol. 52, 2169-2175.

Mazor, M., Bosch, A., Stewart, M.K. and Hulston, J.R. (1990). The geothermal system of Wairakei, New Zealand: physical processes and age estimates inferred fiom noble gases. *Appl. Geochem.,* Vol. 5, 605-624.

Torgersen, T. (1993). Defining the role of magmatism in extensional tectonics: Helium-3 fluxes in extensional basins. *J. Geoph. Res.* Vol. 98 (B9) 16,257-16269.

Torgersen, T., Lupton, J.L., Sheppard, D.S. and Giggenbach, W.F. (1982). Helium isotope variations in the thermal areas of New Zealand. *J. Volcan. Geotherm. Res.* Vol. 12, 284-294.