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

J.R. HULSTON
Nuclear Sciences Group, IGNS, Lower Hutt, NZ

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 CO₂ 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 Mokaigehot fields but was non-specific about the source of the "crustal" contribution. In their study of ³²He/³²He 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 ³²He/³²He 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 ³²He content and low in radiogenic ³⁵He, while the Mesozoic greywacke basement is relatively high in B and radiogenic ³²He, 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 15 km. They were not able to distinguish between greywacke and andesite below 2 km depth. Outside the TVZ, the crust appears to extend to greater than 25 km 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$_2$/He ratio against B/Cl, where the CO$_2$/He 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](image)

Figure 2 - $^{3}$He/$^{4}$He 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 INTERACTIONS 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](image)

Figure 3 - CO$_2$/He ratio (x10$^{-10}$) 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 3He and CO₂ 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 CO₂ 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 CO₂ 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 CO₂ shown in Figure 4 where a significant rise in He occurred at the time of the CO₂ 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 CO₂. 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 3He/4He 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 CO₂ 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.

7. ACKNOWLEDGEMENTS

I would like to thank Brian Carey, ECNZ for making available the Ohaaki monitoring data discussed in this paper. My colleagues at the Institute of Geological & Nuclear Sciences assisted with useful discussions. Brian Lovelock provided valuable background information.

8. REFERENCES


