THE ROLE OF HELIUM AND OTHER NOBLE GASES IN THE MODELLING OF GEOTHERMAL SYSTEMS

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SUMMARY - A 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 described. It is proposed that the ^3He/heat ratio should be similar to that observed in mid-ocean ridge systems, in which case the ^3He to atmospheric argon ratio in geothermal discharges would be an indicator of the likely heat content of a system. As a first test of this hypothesis the noble gas results of Mazor *et al.* (1990) have been presented as the ^3He/heat ratios for Wairakei and early Mokai wells and fumaroles. Their simplified boiling model has been used to correct for the effects of gas-water separation which occurs in underground boiling. At Wairakei, the resultant range of ^3He/heat values is 140-8500 atoms ^3He $mW^{-1}s^{-1}$, similar (except for the lowest values) to the range measured in mid ocean ridges. Further work is needed, but the available data show that the technique has promise for the modelling of deep geothermal systems and providing input to simulation models currently being used in reservoir engineering. The technique has potential to distinguish between stored heat systems and renewing systems.

1. INTRODUCTION

In the development of geothermal systems the key requirements are for maximum energy (viz. quantity of heat) and optimum heat to water ratio (in terms of enthalpy and temperature). As these parameters can only be fully measured after development, various geochemical and geophysical techniques are generally used to predict them. Many geochemical studies have concentrated on the major components particularly water, chloride and carbon dioxide.

In this paper I wish to concentrate on the light noble gases which are the most conservative components within the geothermal system in terms of chemical reaction, although, as will be seen later, gas-water fractionation is significant. In the deep system where the temperature is above the critical temperature of the fluid (375400°C) these noble gases cannot separate from the other constituents of the fluid and serve as an effective tracer of the fluid. However in the upper geothermal system where temperatures are below critical and pressures drop, steam-water separation may occur with the relatively insoluble noble gases mainly following the steam phase. Methods of correcting for this effect and of using these light noble gases in the modelling of geothermal systems are discussed below.

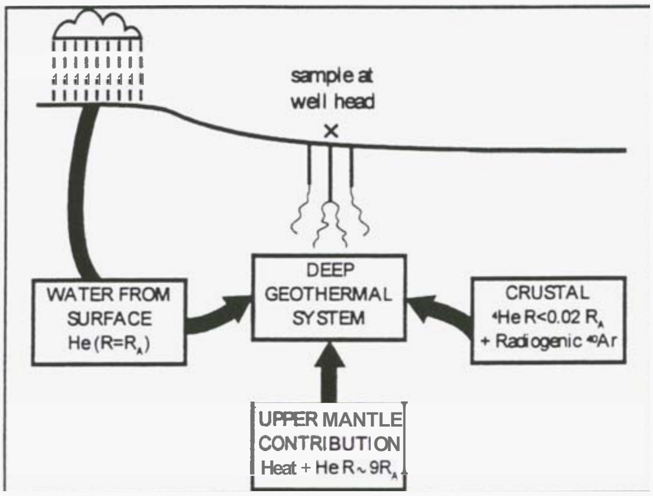

Figure 1 - Light noble gas components in a geothermal model.

2. SOURCES OF NOBLE GASES IN GEOTHERMAL SYSTEMS

The three major sources of light noble gases in geothermal systems (Figure 1) are (1) a mantle component (mainly helium) which is normally associated with the heat source; (2) a radiogenic component from decay of uranium and thorium which release helium, and from potassium which releases argon; and (3) an atmospheric component, with both light and heavy noble gases, which is incorporated when air saturated, groundwater enters the geothermal system either at depth or near the surface. There are other minor sources of noble gases from other naturally occurring nuclear reactions but these will not be discussed further here.

To distinguish between the above sources of noble gases it is necessary to use their differing isotopic compositions; e.g. uranium and thorium decay release pure ^4He, whereas the atmosphere has a low $^3He/^4He$ ratio of 1.386×10^{-6} (Clarke *et al.*, 1976) (commonly referred to as R_A) and mantle derived helium has $^3He/^4He$ greater than $8R_A$. Atmospheric argon has $^{40}Ar/^{36}Ar$ of 295.6 while radiogenic argon (from ^{40}K decay) is essentially pure ^{40}Ar. The overall scheme of noble gases in geothermal systems is summarised in Figure 1 where the $^3He/^4He$ ratio is represented by R.

In the Taupo Volcanic Zone, the proportions of gas components are such that $^3He/^4He$ (R) is generally in the range **5-7.5R_A** (Torgersen *et al.* **1982,** Lupton and Hulston **1989)** and $^{40}Ar/^{36}Ar$ is in a relatively small range between the atmospheric value of **295.6** and 3**15** (Mazor *et al.* **1990,** Hulston *et al.* **1986).** It is thus feasible within'a given field to assume interpolated isotopic ratios in the interpretation of good quality chemical analyses of noble gas data.

3. THE RELATIONSHIP BETWEEN HEAT AND MANTLE HELIUM

In order to make effective use of the noble gas data in a model of the geothermal system, it is necessary to determine the relationship between the heat source and the mantle. We will consider an overview model in which the mechanism of subduction creates a rising plume of magma of upper mantle origin (possibly contaminated by the upper edge of the sinking oceanic plate) which ultimately releases its heat and volatiles by reaction with descending groundwater, probably through hydro-fracturing from magma transport (Watson and Brennan, **1987).** Jenkins *et al.* **(1987)** estimated on the basis of measurements in the Galapagos Rift a ^3He/heat ratio of 3500 ^3He atoms $mW^{-1}s^{-1}$. Torgersen **(1993)** has extended this estimate to a number of other systems and found that the ^3He/heat ratios varied by at least a factor of 2 between systems but chose *to* use the Jenkins value above as a first approximation. The same approach is taken in this paper but it must be recognised that variations will probably occur between fields.

4. THE IDEAL MODEL

This model begins with the assumption that there are no heat loses by conduction or separation of gas and steam from the geothermal fluids from the time the heat and ^3He components from the mantle interact with groundwater until they are discharged from a geothermal well. The only variable in the system is then the heat to groundwater ratio arising from a variable quantity of groundwater being involved both in the original interaction with the magma and in the subsequent dilution at upper levels. The value of the heat to water ratio as calculated at various points in a geothermal field should then be consistent with that calculated by measuring the ^3He/water ratios of the discharge, and could then be used to refine the ^3He/heat value adopted above.

In practice a number of processes are operating, the most important of which is steam-water separation. This process is already familiar to researchers who use enthalpy-chloride plots to distinguish steam loss-gain and local groundwater dilution processes.

5. CORRECTIONS FOR STEAM-WATER SEPARATION - THE SIMPLIFIED BOILING MODEL

The process of steam-water separation which occurs with boiling results in a separation of both heat and helium between the two phases with the majority of the helium going into the steam phase at relatively small separation factors while larger separation factors are required before the majority of the heat is carried in the steam phase. Mazor *et al.* **(1990)** have discussed the effect of this steam-water separation on the noble gas contents of geothermal discharges and have developed a "simplified boiling model" where the ascending geothermal fluid separates into a noble-gas-enriched steam phase, issuing as fumaroles and steam wells, and a noble-gas-depleted residual liquid, discharging in low enthalpy wells. Their measurements of a number of Wairakei geothermal wells and fumaroles showed that steam-water separation has occurred to the extent that the atmospheric noble gases (ANG) are frequently depleted by a factor of **5-10** in the low enthalpy wells and enriched by a factor of **2-5** in the high enthalpy wells (with one well which discharges pure steam showing an enrichment of >20). Measurements of argon isotopic ratios indicated that non-atmospheric (viz. radiogenic+ mantle) argon comprised less than 10% of the total argon thus confirming the major role of groundwater derived from precipitation which has been fully equilibrated with atmospheric gases.

To estimate the helium-3 to heat ratio I have used the noble gas enrichment factors calculated for a number of wells and fumaroles at Wairakei and Mokai by Mazor *et* al., using the above model to estimate the helium-3 in the discharge just prior to boiling. In these circumstances (unless the enrichment factor is close to unity) it is not appropriate to use the enthalpy of the particular well to estimate the heat content and I have therefore taken an arbitrary value of $1200 Jg^{-1}$ as the heat content (enthalpy) of the discharges. The results of this exercise set out in Table 1 give helium-3 to heat ratios varying from **139 to 8561** ^3He atoms $mW^{-1}s^{-1}$ with **10995** for Mokai well MK1. As a comparison helium-3 to heat values calculated using the ideal model are also shown in Table 1. As would be expected these show a very much smaller range of values demonstrating the effectiveness of the simplified boiling model in reducing the range of helium-3 to heat ratios.

By using the differing solubilities of the noble gases, Mazor *et nl.* **(1990)** were able to identify from their measurements, in some wells, the following physical processes: (a) mixing of early separated steam with residual liquid; (b) mixing of a few per cent groundwater with residual liquid; (c) addition of air; (d) addition of excess Ne; and (e) encroachment of recent groundwater due to pressure decrease.

Further consideration of these effects may make it possible to further reduce the range of helium-3 to heat values but this will not be pursued further in this paper and the simplified boiling model will be used in the following section.

6. THE RELEVANCE OF HELIUM-3 TO ATMOSPHERIC ARGON RATIOS

Returning now to the deep circulation model outlined earlier in section **2** and Figure 1, an attempt will be made to use the helium-3 to atmospheric argon content as an indicator of the ratio of heat to deep groundwater entering the deep geothermal system. Application of the simplified boiling model is completely straight-forward because the solubilities

Table 1 - Wairakei and Mokai well, fumarole and pool results from Mazor *et al.* (1990)

Field	Location	PHASE	$^{40}Ar/^{36}Ar$	Fract Enrich	Ideal M At ^{3}He $mW^{-1}s^{-1}$	Boiling M At ^{3}He $mW^{-1}s^{-1}$	$(^3He/^{36}Ar)_{ASW}$	$(He/Ar)_{ASW}$	$(He/Xe)_{ASW}$
Mokai	MKI	MK steam	294	0.15	2265	10995	7582	1089	970
Wairakei	F Pump House	Fumarole	301	11	40234	8461	5909	829	680
Wairakei	F9/2 Waiora	Fumarole	315	8	24139	6980	5319	713	918
Wairakei	WR80	Steam	292	1.6	3426	3589	2863	414	339
Wairakei	F4/2 Tukairangi	Fumarole	298	8.8	13580	3570	2632	373	299
Mokai	MK2	MK steam	285	0.2	508	4029	2234	331	369
Wairakei	POOL 217B	Gas Bubbles	294	0.36	22	139	2089	300	362
Wairakei	Tauhara-nrSpa	Gas Bubbles	294				2012	289	277
Wairakei	Soda Pool	Gas Bubbles	293	0.09	123	480	1755	253	327
Wairakei	WR17	Steam	298	0.033	108	3154	1687	239	360
Wairakei	WR116	Stem	297	0.03	28	986	1442	205	47
Wairakei	WR42	Steam	298	0.23	379	11744	1051	149	190
Wairakei	WR38	Steam	316	0.81	753	1377	950	127	118
Wairakei	WR86	Steam	302	I	784	1148	780	109	109
Wairakei	WR28	Steam	293	0.14	96	756	618	89	55
Wairakei	WR45	Steam	302	2.2	660	694	515	72	68
Wairakei	WR103	Steam	300	0.12	33	643	504	71	54
Wairakei	WR25	Stem	311	29	7587	605	493	67	55
Mokai	Bath -S Mokai	Gas Bubbles	295				398	57	I8
Wairakei	Soda Pool	Water	288				348	51	47
Wairakei	F Karapiti	Fumarole	306	14	4043	668	326	45	132
Wairakei	WR24	Stem	295	0.17	58	458	300	43	39
Wairakei	WR26B	Steam	295	0.026	8	344	293	42	29
Wairakei	T12 Kathleen	Water	301	0.05	59	413	285	40	98
Wairakei	WR47	Steam	301	0.42	134	335	242	34	50
Wairakei	WR18	Stem	301	3.1	662	304	221	31	46
Wairakei	WR66	Steam	297	0.017	4	225	148	21	30
Wairakei	Pool 217B	Water	301		0		107	15	
Wairakei	WR57	Stem	290	0.23	48	217	76	11	57

of helium and argon are almost identical at 200°C and thus the relative enrichment or depletion factors for helium and argon due to boiling are virtually identical. Thus, provided a gas sample free of direct air contamination can be analysed, the helium-3 to groundwater ratio of the original ascending fluid can be determined. In conjunction with the He and Ar isotopic analyses it is then possible to determine the mantle ^{3}He to groundwater ratio. Then the 3500mW value above can be used to obtain a simple estimate of the heat flow in the ascending geothermal fluid.

The most convenient units to use in the helium-3 to atmospheric argon are to normalise these ratios to air saturated water (ASW) at 10°C. This has the advantage that the numerical values are the same irrespective of whether the ratio is relative to atmospheric argon or to ^{36}Ar (which is present only in atmospheric argon). For reasons of brevity the $^3He/^{36}Ar$ ratio has been used in Table 1 and in Figure 2. The $^{40}Ar/^{36}Ar$ ratio is an indicator of the proportion of argon of radiogenic origin and a measure of the integrated product of the potassium content of the rocks along the fluid pathway, and the effective contact time with the geothermal fluids during ascent to the surface. When knowledge of potassium content is available, this provides a potential to estimate storage times in geothermal systems and hence to distinguish between stored heat systems and renewing systems.

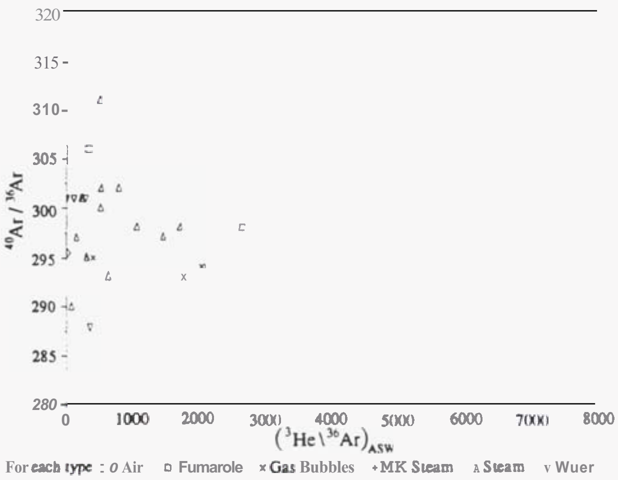

Figure 2 - Argon isotope ratio v $(^3He \backslash ^{36}Ar)_{ASW}$

7. CONCLUSIONS

1 The use of the simplified boiling model of Mazor *et al.* *(1990)* reduces the range of 'He to heat **flux** in Wairakei geothermal fluid samples from **4-40000** (uncorrected) to 140-8500 atoms 'He mW^{-1}s^{-1}.

2 The above range of 'He to heat ratios, except for the lowest values, covers that found by Torgersen (1993) for mid-ocean ridge systems, thus indicating a similarity in the processes of heat and ^{3}He release in these systems.

3 If the processes occurring within the geothermal system can be more fully understood it should in principle be possible to contribute to the modelling of the geothermal field.

4 When these mechanisms are more fully understood, the mantle helium to atmospheric argon ratio would appear to provide an excellent measure of deep groundwater dilution of the ascending geothermal fluids and thus provide a tool to assist in determining the wells which are most likely to maintain high heat flows over time.

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