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HEAT AND HELIUM IN GEOTHERMAL SYSTEMS

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ABSTRACT

The bulk of the Earth's heat budget and all of the ^{4}He is produced by natural uranium and thorium radioactivity, thus uniquely coupling heat and helium in geothermal systems. In the relatively simple geothermal systems associated with mid-ocean ridges, the helium isotopic composition and heat/^{3}He ratios are similar to the theoretically predicted values, confirming the coherence between heat and helium. These systems also reveal that magma degassing and aging can fractionate helium from heat.

In the more complicated continental geothermal systems, heat-helium coherence provides a technique for identifying and calculating the proportion of heat derived from each source (crust vs. mantle). Processes in addition to magma degassing and aging, such as adiabatic cooling, fluid mixing, and conductive heat loss, act on these systems fractionating helium from heat. However, detailed studies of individual fields can uniquely identify the heat-helium fractionation processes, which can then be used to constrain reservoir models.

INTRODUCTION

In continental terranes, high temperature geothermal reservoirs acquire heat either from active or recently active magmatic systems or by deep fluid circulation in regions with elevated thermal gradients. In this paper we investigate the theoretical coherence between helium and heat, present a method by which the heat source can be uniquely identified, and show how in favorable cases the thermal history of a geothermal reservoir can be ascertained.

HEAT – HELIUM COHERENCE

Theory

The Earth's heat budget is derived almost exclusively (~75%) from the natural radioactivity of uranium and thorium. The isotopes of uranium and thorium initiate a decay chain that is terminated with the stable (non-radioactive) isotopes of lead. Through these decay chains the isotopes of U and Th and their intermediate daughter products emit energetic (>1 MeV) α-particles (Table 1). These particles come to rest as ^{4}He atoms depositing their energy as heat in mineral lattices. This suggests that there should be a unique coherence between helium and heat in the Earth. The energy of the U and Th derived α-particles range from ~4-8 MeV (~6.4 – 12.8 x 10^{-13} Joule; Lederer and Shirley, 1978), which when summed over the total number of α-particles, translates to an average Heat (Q)/^{4}He ratio of ~2.5 x 10^7 Joule/ccSTP.

Table 1: Helium and Heat Production from Uranium and Thorium

Parent Isotope	Daughter Isotope	Total # of α-particles	Total Energy (MeV)
^{238}U	^{206}Pb	8	42.6
^{235}U	^{207}Pb	7	41.9
^{232}Th	^{208}Pb	6	37.0

In volcanic terranes, mass and heat are supplied to the crust by partial melting of the mantle which drives magma genesis. The upper mantle of the Earth is characterized by a relatively constant ^{3}He/^{4}He ratio of 8-9 Ra (Ra is the ^{3}He/^{4}He ratio in air, 1.4 x 10^{-6}). Therefore, the mass and heat flux associated with magma genesis should be characterized by a relatively constant Q/^{3}He ratio of ~2 x 10^{12} Joule/ccSTP. (Note that the helium isotopic composition associated with "hotspot" volcanism, such as Hawaii, is ~32 Ra corresponding to a lower Q/^{3}He ratio of ~0.6 x 10^{12} Joule/ccSTP).

In crustal regimes, far removed from volcanic processes, helium in fluids is dominated by radiogenic ^{4}He and characterized by ^{3}He/^{4}He ratios of ~0.02 Ra. This corresponds to a Q/^{3}He ratio of ~1 x 10^{15} Joule/ccSTP, almost three orders of magnitude larger than the expected mantle value. The large difference in the heat/helium ratios between volcanic and non-volcanic terranes suggests that the isotope composition of helium in thermal fluids, when coupled to the ratio of fluid enthalpy to ^{3}He, can readily differentiate the relative proportions of mantle and crustal heat driving continental geothermal systems.

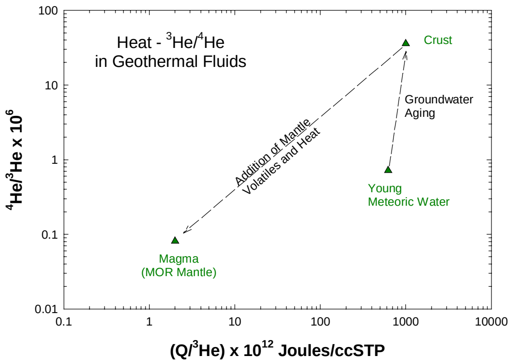

Figure 1: Schematic representation of the coherence between heat and helium in crustal fluids, and how the composition of these fluids evolve in accordance with their environment.

As fresh, or young, meteoric water circulates deep into the crust, it will acquire radiogenic ^{4}He by diffusion from the host rock minerals into the fluid and water-rock interaction; heat is gained by conduction, in accordance with the thermal gradient (Figure 1). The heat/^{3}He ratio and helium isotopic composition of the aging groundwater will be constrained to the meteoric water – crust mixing line in Figure 1. The ultimate temperature and ^{4}He concentration attained by the groundwater will be a function of the thermal gradient, the host rock concentrations of U and Th, and the water residence time. Deep crustal fluids influenced by volcanism will evolve along the crust – mantle mixing line. The relative proportions of heat from the crust and mantle can be calculated from the composition of the evolved fluid along this mixing line.

Mid-Ocean Ridge Hydrothermal Systems

The hydrothermal systems associated with active mid-ocean ridge (MOR) spreading centers provide an excellent opportunity to evaluate the validity of the theoretical coherence between heat and helium. These systems are relatively simple: the initial fluid composition and temperature is well constrained (seawater), there is little or no boiling or phase separation, the composition of the host rocks is uniform (basalt), and in most cases there is no sedimentary overburden. Fluids from these systems are sampled by submersibles from plumes of upwelling water identified by a chemical and thermal anomaly relative to ambient seawater. The heat/helium ratios of the upwelling fluids are calculated by comparing the concentration of ^{3}He in excess of the seawater composition to the excess temperature of the upwelling plume (Lupton et al., 1989, 1999a, 1999b; Baker and Lupton, 1990). As seen in Figure 2, helium isotopic compositions of plume fluids are indistinguishable from the mantle (as defined by mid-ocean ridge basalts) and the Q/^{3}He ratios vary from ~1 – 10 x 10^{12} Joule/ccSTP. The measured heat/helium ratios are remarkably similar to the theoretically predicted value, providing a measure of validity to the theory of heat-helium coherence in geothermal systems.

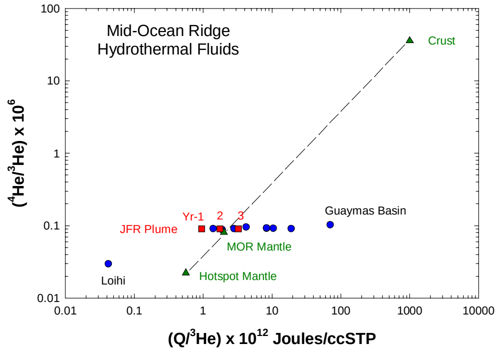

Figure 2: Helium and heat in mid-ocean ridge hydrothermal systems. The data is from Lupton et al. (1989) and Baker and Lupton (1990). JFR: Juan de Fuca Ridge.

HEAT – HELIUM FRACTIONATION

The observed range in Q/^{3}He values for mid-ocean ridge hydrothermal fluids (Figure 2) suggests that processes acting on the system fractionate mass and heat. Insight into these processes has been gained by studying the evolution of a plume over a period of three years associated with the Juan de Fuca Ridge (JFR; Baker and Lupton, 1990). Initially (Yr-1), the plume was characterized by a deficiency in the heat/helium ratio relative to the theoretical value, defined by the dashed line. Baker and Lupton proposed that the initial low Q/^{3}He ratio records a period of accelerated ^{3}He degassing from a magma body that may have been induced by an intrusive event. With time the Q/^{3}He ratio steadily increased. By the third year (Yr-3), the ratio evolved to a more constant value that is characteristic of other established MOR plumes and vent fields. This seems to imply that the system evolves to a steady state with heat and helium released in constant proportion from the cooling magma at, or slightly greater, than the theoretical value.

However, the overall range in mid-ocean ridge Q/^{3}He ratios suggests that more extensive fractionation can occur. For a steady state Q/^{3}He ratio to be attained requires that conductive mining of heat from a cooling magma body occur at the same rate as diffusive loss of ^{3}He. In a detailed study of Icelandic hydrothermal systems, it was proposed that high Q/^{3}He ratios were generated by "magma aging", defined as the preferential loss of ^{3}He from a magma chamber relative to heat (Poreda and Arnorsson, 1992). Heat – helium fractionation was modeled as a Rayleigh process as follows:

$$\left[{}^3\mathrm{He}\right]=\left[{}^3\mathrm{He}\right]_o F^{(\alpha-1)}$$

$$Q=Q_o F \qquad (1)$$

$$\alpha=\left[\left({}^3\mathrm{He}/Q\right)_{\mathrm{fluid}}\right]\Big/\left[\left({}^3\mathrm{He}/Q\right)_{\mathrm{magma}}\right]$$

Where F defines the fracxtion of heat remaining in the magma body, α is the heliu-heat fractionation factor that defines the preferential loss of ^{3}He relative to heat, and the subscrpt (o) represents the original conditions or composition. Fluids associated with the spreading ridge in the Guaymas Basin have the highest heat/helium ratio and slightly elevated ^{4}He/^{3}He. The Guaymas system is different from the other mid-ocean ridge systems in that the ridge is buried beneath a thick blanket of sediments. It is not clear whether the Guaymas magma chamber is highly evolved (fractionated) or if the sediments play a role in separating heat from helium.

Geothermal systems in continental regions are inherently more complex than deep oceanic systems. In addition to magma degassing and "magma aging", the coherence between heat and helium can be modified by several other processes, such as mixing geothermal fluids with cooler (meteoric or injectate) waters, adiabatic cooling (boiling), or conductive cooling without loss of ^{3}He. As demonstrated in Figure 3, each process affects the heat and helium content of a geothermal reservoir in an unique manner. Therefore, in favorable cases, the dominant process(es) responsible for the heat and volatile inventory of fluids produced from a geothermal reservoir can be identified.

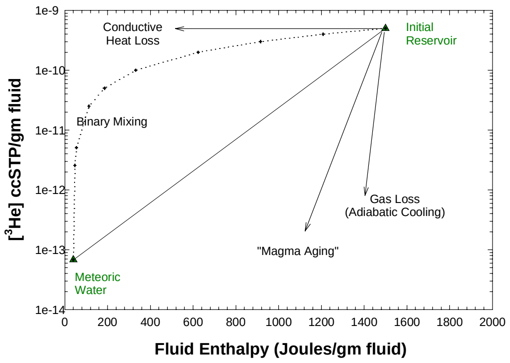

Figure 3: Fractionation of heat and ^{3}He in geothermal reservoirs. The trajectory for "magma aging" is constructed from the Rayleigh fractionation equations (Eq. 1) assuming $\alpha = 20$ (Poreda and Arnorsson, 1992). The adiabatic cooling trajectory assumes boiling and gas loss at 250 °C, and the binary mixing trajectory is constructed using meteoric water in equilibrium with air at 10 °C.

CONTINENTAL HYDROTHERMAL SYSTEMS

Continental geothermal systems, for which the appropriate helium and heat data exists, show a wide range of Q/^{3}He ratios (Figure 4). Most of the systems, such as the Northwest Geysers, Wairaki, etc., derive most of their heat from magmatic sources but have experienced significant Q/^{3}He fractionation. The exceptions are Dixie Valley and Beowave. Both of these geothermal fields are located in the Basin and Range Province of the United States. Although neither system is associated with recent (5 Myr) volcanism, both produce fluids with significant ^{3}He. Applying mass balance to the Crust-Mantle mixing line (Figure 4), ~90% of the ^{3}He in Dixie Valley and Beowave fluids is from the mantle but only ~5-10% of the heat is mantle derived. For these two systems, therefore, the bulk of the heat is derived from fluid circulation along an elevated geothermal gradient (e.g. Sass, 1995).

The processes driving Q/^{3}He fractionation in these systems are not uniquely resolved in Figure 4. All of the systems appear to have experienced either significant "magma aging" or adiabatic cooling. To resolve these processes would require a detailed study of each system and some knowledge of the initial reservoir heat and helium content (e.g., Figure

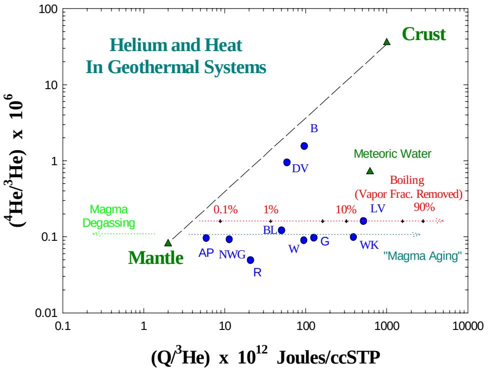

Figure 4: Heat and helium in continental hosted geothermal systems: AP, Alto Peak; B, Beowave; BL, Broadlands; DV, Dixie Valley; G, Guanacaste; LV, Long Valley; NWG, Northwest Geysers; R, Reykjanes; W, Waiotapu; and WK, Wairakei. Data from: Nathenson and Muffler, 1975; Welhan et al. (1988); Giggenbach and Corrales (1992); Poreda and Arnorsson (1992); Giggenbach et al. (1993); Giggenbach and Poreda (1993); Kennedy and Truesdell (1996); unpublished data LBNL noble gas laboratory.

3). However, without information regarding the initial reservoir, useful information about reservoir processes can be learned by studying the heat and helium content of individual wells within a production field. For example, a closer look at the Mahanagdong and Tongonan fields in the Philippines (Figure 5) reveals that the distribution of fluid enthalpy and ^{3}He content is consistent with admixture of cooler waters to the respective geothermal reservoirs. The mixing trajectories depict addition of either cold (10 °C) or warm (100 °C) air saturated water.

CONCLUSIONS

Theory predicts that there should be an unique coherence between heat and helium in geothermal systems. This is because ~75% of the Earth's heat budget and all of the ^{4}He is produced by natural uranium and thorium radioactivity. The helium isotopic composition and heat/^{3}He ratios determined for simple systems, such as mid-ocean ridge hydrothermal fields, are similar to the theoretically predicted values. This confirms the unique coherence between heat and helium. However, these systems also reveal that magma degassing and aging can decouple or fractionate heat from helium.

In more complicated systems, such as geothermal fields in continental regions, additional processes may fractionate heat from helium, such as adiabatic cooling, fluid mixing, and conductive heat loss. In this case, a detailed study of individual fields is required to decipher the heat-helium fractionation processes. Despite these complications, the unique coherence between helium and heat provides a technique for identifying the heat source (crust vs. mantle) for a continental-hosted system and calculating the proportion of heat derived from each source.

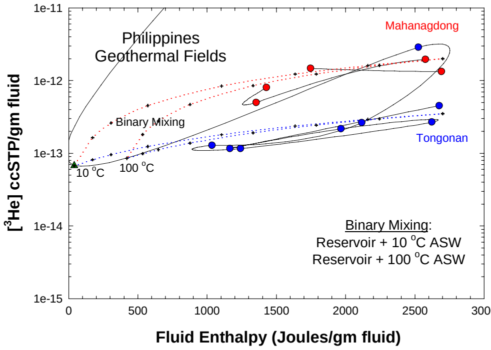

Figure 5: Heat and ^{3}He contents for individual wells in the Mahanagdong and Tongonan geothermal fields, Leyte, Philippines. The dashed lines represent mixing of reservoir fluid with cooler (10 and 100 °C) air saturated water (ASW).

The heat-helium coherence can provide a unique tool for geothermal exploration. For instance, in the early exploratory phase, regions can be mapped in terms of the relative proportion of heat derived from magmatic systems. The present state of a geothermal reservoir with regard to conductive and/or adiabatic heat loss and fluid mixing can also be evaluated and used to constrain reservoir models.

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