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**Regional and Local Trends in Helium Isotopes,
Basin and Range Province, Western North America:
Evidence for Deep Permeable Pathways**

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Abstract

Fluids from the western margin of the Basin and Range have helium isotope ratios as high as ~6-7 Ra, indicating a strong mantle melt influence and consistent with recent and current volcanic activity. Moving away from these areas, helium isotope ratios decrease rapidly to 'background' values of around 0.6 Ra, and then gradually decrease toward the east to low values of ~0.1 Ra at the eastern margin of the Basin and Range. Superimposed on this general regional trend are isolated features with elevated helium isotope ratios (0.8-2.1 Ra) compared to the local background. Spring geochemistry and local geology indicate that these "He-spikes" are not related to current or recent magmatic activity, suggesting that the spikes may reflect either localized zones deep mantle melting or deep permeable pathways (faults) with high vertical fluid flow rates. A detailed study of one of the He-spikes (Dixie Valley and the Stillwater Range Front Fault system), indicates that features with high $^3\text{He}/^4\text{He}$ ratios are confined to the range front normal faults characteristic of the extensional regime in the Basin and Range, suggesting that these faults are deep permeable pathways. However, not all range front fault systems transmit fluids with a mantle signature, implying that not all have deep permeable pathways.

Introduction

The Basin and Range Province in western North America and adjacent Snake River Plain are characterized by an anomalous thermal gradient, large heat flux, high regional elevation, volcanism and extensional tectonics that have varied in time and space over the past ~30 million years. This confluence of geology has created a vast region of exceptionally high potential for geothermal energy development.

Beginning ~8 million years ago and continuing to the present, magmatism has migrated to the margins of the Basin and Range while NW-SE extension, characterized by high angle block faulting, dominates in the northwestern and central Basin and Range (e.g. Parsons, 1995). This has given rise to two basic types of geothermal resource in the region: magma hosted and extensional. The magma hosted systems (e.g. Steamboat, Long Valley, Coso, and Roosevelt) are similar to the numerous magma hosted systems throughout the world and, like the presently active volcanic centers, are concentrated along the margins of the province. However, the extensional geothermal systems, which are found throughout the province, are nearly unique to the Basin and Range and very little is known about their origin, development, and what drives their spatial distribution

with respect to the tectonic history of the region. It is generally accepted that the heat for these systems is not related to shallow magmatism but is derived from deep fluid circulation through the high thermal gradient.

Exploration for extensional geothermal systems poses unique problems. For example, first order approaches, such as mapping surface manifestations of young silicic volcanic systems, is not applicable. Furthermore, by the time deep fluids emerge at the surface more often than not, they have either mixed with cooler shallow fluids or re-equilibrated in shallow cooler reservoirs. Either process can overprint the chemical and isotopic compositions that might otherwise provide evidence for the existence of deeper higher temperature reservoirs with economic potential. In essence the deep geothermal reservoirs are “hidden”. In order to see through the shallow processes to the deeper hidden fluid systems, existing and new geochemical and isotopic techniques must be re-evaluated and developed. This paper synthesizes a regional and local scale helium isotope study of the Basin and Range and surrounding areas, including the Snake River Plain. The focus of the investigation is the relationship between the location of known geothermal resources and the presence of fault-hosted, deep, permeable fluid-flow pathways, as identified by anomalous helium isotopic compositions in surface fluids. Although surface emanations and fluids in shallow wells are strongly affected by cold recharge and chemical re-equilibration at cooler temperatures, concealing deep higher temperature reservoirs, other studies (Kennedy et al., 1997) and preliminary work within the Basin and Range (Kennedy et al., 1996; Kennedy and van Soest, 2005) suggest that helium isotopes may provide the best, and perhaps only, indication of deep permeability and the possibility that higher temperature fluids exist beneath the shallow cooler reservoirs.

Approach and Background

The helium isotopes are of particular interest because they provide unequivocal evidence for the presence of mantle derived volatiles in geothermal systems. Its most important attribute is that helium associated with crustal fluids, that have experienced no mantle influence, is dominated by radiogenic ^4He produced from radioactive decay of U and Th to Pb and is characterized by a $^3\text{He}/^4\text{He}$ ratio of ~ 0.02 Ra (Ra = 1.4×10^{-6} , the ratio in air). Whereas, helium associated with mantle fluids is strongly enriched in ^3He with typical ratios ranging from ~ 6 -35 Ra, depending on the mantle source (e.g. plume volcanism vs. MORB). Studies of helium isotopes in erupted basalts throughout the Basin and Range suggest that the mantle source for the basalts has a helium isotope composition of 6-9 Ra (Reid and Graham 1996; Dodson et al. 1998).

Mantle helium enters the crustal hydrologic system either by direct intrusion and degassing of mantle derived magmas (e.g. Kennedy et al., 1985; Welhan et al., 1988; Sorey et al., 1993; Hilton, 1996; Kennedy and Truesdell, 1996; Christenson et al., 2002) or by the invasion of geo-pressured mantle fluids, presumably degassed from deep mantle melts (Kennedy et al., 1997). After mantle helium is injected into the crust, its original mantle-like isotopic composition will become diluted by the addition of radiogenic ^4He from the crust, lowering the $^3\text{He}/^4\text{He}$ ratio. By the time the fluid reaches the surface and is sampled the degree to which the ratio is lowered (diluted) will depend on the flux of

mantle helium into the crust, the production rate of radiogenic ^4He in the crust which is proportional to the concentrations of U and Th along the path of fluid flow, the admixture of other crustal fluids, and the residence age or fluid flow rate within the crust. For instance, the helium isotopic composition in crustal fluids that mine heat from active near surface magmatic systems, typically, are similar to the composition in the mantle source (e.g. Coso, ~ 7 Ra, Welhan et al, 1988; Long Valley, $\sim 2-7$ Ra, Sorey et al., 1993; The Geysers, $\sim 8-9$ Ra, Kennedy and Truesdell, 1996), consistent with the very large flux of mantle helium associated with near surface degassing of mantle magmas.

Local Helium Isotope Trends: Dixie Valley

The Dixie Valley Geothermal Field (DVGF), which produces ~ 270 °C fluid from the Stillwater Range Front fault system, is considered a classic example of an extensional Basin and Range geothermal system. Helium isotopic compositions were determined in several springs, wells, and fumaroles through out the Dixie Valley area, including samples from the geothermal field production wells. The study was conducted in conjunction with a Dixie Valley regional geochemistry study of surface fluids (Goff et al, 2002). A more detailed discussion can be found in Kennedy and van Soest (2005). The results are summarized in Figure 1, where the helium isotopic compositions are plotted as a function of the “He-enrichment” factor [$F(^4\text{He})$], which is a measure of the amount of excess helium in the fluids (normalized to ^{36}Ar) with respect to air [$F(^4\text{He}) = 1$] or air saturated groundwater [$F(^4\text{He}) \sim 0.2$].

The helium associated with the production fluids from the Dixie Valley geothermal reservoir has an isotopic composition of 0.70 - 0.76 Ra and are among the highest ratios measured within the valley. The ratios are elevated with respect to those expected for a purely crustal source ($R \sim 0.02$ Ra), indicating unequivocally that a mantle helium component is present in the Dixie Valley reservoir fluid. If it is assumed that the mantle source has a helium isotopic composition of 6-9 Ra, then as much as $\sim 8-12\%$ of the total reservoir helium is mantle-derived.

Given the absence of an actively degassing crustal magma system the potential ^3He sources are limited to the following: (1) fluid circulation through either the erupted Miocene basalts or an aged and non-active magma chamber originally charged with mantle helium, i.e. the source chamber for the Miocene basalts; or (2) fluid transport up along the range-front fault from much deeper sources, either a deep melt zone at or near the base of the crust (e.g. Jarchow et al., 1993) or fluids exsolved from deeper melting (~ 100 's km) that have found a pathway into the range front fault system (e.g. Kennedy et al., 1997). As argued in more detail in Kennedy and van Soest (2005), the first source can be ruled out. The Miocene basalts were erupted ~ 8 my ago. Therefore, due to the rapid in-growth of radiogenic ^4He since emplacement and eruption, the basalts are too old to support the high R/Ra values observed today. By default we are left with source two, fluid transport from the mantle up along the range front fault.

The Dixie Valley samples, which have the highest helium isotopic compositions, are from the production wells. The helium compositions of springs and other wells throughout the valley are a mixture of this deep fluid with a younger less He and ^3He -

enriched groundwater [$R < 0.4 R_a$, $F(^4\text{He}) < 10$], overprinting the composition of the deep reservoir fluid. The exceptions to the simple mixing trend are two fumaroles (SE and Senator Fumaroles) and Dixie Hot Spring (located ~30 km southwest of DVGF). Although these features have low $F(^4\text{He})$ reflecting either air contamination or boiling (Kennedy and van Soest, 2005), they all have high $^3\text{He}/^4\text{He}$ ratios indicating that their fluid compositions have not been affected by shallow groundwater, as is the case for the other springs and wells in the valley. The fact that they also emerge directly from the range front fault system provides further evidence that the Stillwater fault is the primary path for vertical fluid flow, the fluids that flow through are relatively unencumbered by local hydrology unlike the other springs and wells in the valley, and the fault must be in direct communication with the mantle to account for the ^3He . The latter requires deep permeability and is consistent with local thermal gradients indicating that the Range Front Fault system serves as the primary conduit for heat transport to the surface (Blackwell et al., 2000, 2002).

Regional Trends

The Dixie Valley study suggests that helium isotopes may provide a new tool for mapping zones of deep permeability and therefore the potential for high fluid temperatures. The permeable zones are identified by local enrichments in ^3He relative to a regional helium isotope trend. To evaluate this hypothesis we embarked on a Basin and Range regional study of helium isotopes in surface fluids. The goal was to see if indeed there is a regional trend in helium isotopic values to which local anomalies could be compared and identified as zones of potential deep fluid flow.

Early models developed to explain the anomalous high Basin and Range heat flow invoked large scale regional under-plating of mantle derived melts. It is expected that such wide-spread mantle melting and under-plating of the crust would induce a high regional ^3He flux across the crust-mantle boundary, resulting in uniformly high helium isotope ratios in surface features across the Basin and Range (Torgersen, 1993). More recent models restrict current mantle melting and under-plating to localized regions. These models are more consistent with the distribution and age of current and recent volcanism in the Basin and Range, which suggests that major zones of mantle melting currently occur along the western margin of the Basin and Range and that the heat flow anomalies in the central Basin and Range are related to either crustal thinning, older wide-spread melting events, or more recent areas of local small scale mantle melting.

A theoretical helium isotope profile consistent with the more recent models is shown in Figure 2. High, mantle-like, helium isotope ratios would be confined to the regions of current large scale mantle melting where the ^3He flux will be the greatest. This area would coincide with the Walker Lane shear and volcanic zone along the eastern Sierras. Away from this zone to the east, helium isotope ratios would be expected to decrease rapidly as the flux of mantle ^3He declines. Current localized magmatism like that observed at Roosevelt, Utah (RV in Figure 2 and 3) may generate local elevated helium isotope ratios compared to its surroundings.

Our results, to date, of the regional helium isotope study are summarized in Figure 3. Three general trends are evident. First, all of the high helium isotope ratios (>3 Ra, black crosses and dotted circles) occur along the western margin of the Basin and Range. The ratios reflect high ^3He fluxes related to presently or recently active crustal magma systems of the Walker Lane shear zone and the Cascade volcanic chain. From south to north these systems are: Coso, Long Valley, Mono Lake, Steamboat, Lassen, Shasta, Medicine Lake, Crater Lake, and Newbury Caldera. Second, excluding the volcanic centers, the preponderance of elevated ratios (>0.6 Ra, black diamonds, squares, and open circles) occur in the northwest Basin and Range, the Snake River Plain, and parts of the Idaho Batholith. In some cases these elevated ratios may be related to the Cascade volcanics, but for the most part they are associated with regions of little or no recent volcanism and occur along range front faults. Third, moving east away from the western margin and elevated ratios of the northwest, the helium ratios quickly subside to values <0.6 Ra (black circles), with values <0.3 Ra (black triangles) dominating the central and eastern Basin and Range. Superimposed on this latter regional trend are features which have elevated helium isotope ratios (0.8-2.1 Ra) compared to the local background [e.g. Black Rock Desert (BRD), Dixie Valley (DV), Diamond Valley (DIV), and Monte Neva (MN)]. As is the case for Dixie Valley discussed above, the features are located along range front faults and the local geology indicates that they are not related to current or recent magmatic activity, suggesting that the “He-spikes” reflect local zones of deep permeability. However, most of the features with low $^3\text{He}/^4\text{He}$ ratios (<0.3 Ra, black triangles) are also associated with range front fault systems. Therefore, not all range front fault systems transmit fluids with a strong mantle signature, implying that not all have comparable deep permeability.

The northwest and central Basin and Range are characterized by high angle normal faults striking northeast- southwest. Seismic activity along these faults is related to the present day extension rates. The central seismic zone, a NE-SW trending zone of high seismicity, passes through Dixie Valley and marks a boundary between decelerating extension and relatively low seismic activity to the east and accelerating extension and high seismicity to the west (Parsons, 1995). The majority of elevated helium ratios occur west of this zone where extension is accelerating with concurrent high seismicity, indicating a cause and effect relationship between deep permeability and high extension rates, as logically expected. The extensional fabric of the northwest Basin and Range appears to extend into the Idaho Batholith, which is characterized by both NE-SW striking normal faults in the northwest sector of the batholith and NW-SE striking faults in the southeast sector. All of the springs associated with NE-SW faults have elevated helium ratios consistent with extension and deep permeability. Whereas, those along NW-SE faults tend to have ratios ≤ 0.3 Ra, suggesting a lack of deep permeability along faults that strike perpendicular to the extensional fabric.

It is likely that deep permeable pathways are a necessity in the development of a viable geothermal resource in the Basin and Range. The deep pathways provide access to high temperature and can host fluid convection cells. Obviously more work needs to be done, but it appears that helium isotopes may provide the best and perhaps only tool for locating faults with deep and high enough permeability to host an economic geothermal

system. Future work will concentrate on more detailed studies of those areas with elevated ratios, the transition zone between the Basin and Range and the Cascade volcanic arc, and establishing a link between zones of high permeability and known geothermal resources. Furthermore, mapping of isotopic and geochemical information into a tectonic and geophysical context will facilitate a better understanding of these systems and their spatial distribution across the Basin and Range.

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Figure Captions

Figure 1: Helium isotopic compositions of a variety of Dixie Valley fluids plotted as a function of the helium enrichment factor [$F(^4\text{He})$]. Filled black circles are hot springs and fumaroles, filled grey circles are wells outside of the geothermal field. The ellipse labeled DVGF represent the range in compositions found in the production fluids from the Dixie Valley Geothermal field (squares, triangles, and diamonds; symbol delineate

year of sampling). The dashed line depicts mixing between the DVG fluid and a younger, cooler shallow groundwater. The dotted line depicts either boiling and or air contamination (see text).

Figure 2: Theoretical helium isotope west to east profile across the Basin and Range.

Figure 3: Shaded relief sample location map of the Basin and Range (B&R) and surrounding areas. The different symbols give an indication of the magnitude of the $^3\text{He}/^4\text{He}$ at the locality. Coding is as follows: Black triangles ≤ 0.3 Ra; 0.3 Ra $>$ Black circles ≤ 0.6 Ra; 0.6 Ra $>$ Black diamonds ≤ 1.0 Ra; 1.0 Ra $>$ Black Squares ≤ 2.0 Ra; 2.0 $>$ Open circles ≤ 3.0 Ra; 3.0 Ra $>$ Black cross ≤ 4.0 Ra; Dotted circle > 4.0 Ra. Certain features are labeled: SV: Surprise Valley; BRD: Black Rock Desert; AD: Alvord Desert; DV: Dixie Valley; OW: Owyhee River Canyon; DIV: Diamond Valley; K: Klobe hot spring: so far the lowest observed $^3\text{He}/^4\text{He}$ ratio in the B&R at 0.014 Ra; MN: Monte Neva hot spring; RV: Roosevelt hot spring and geothermal energy plant; CF: Cove Fort geothermal energy plant. Additional datasources: Jenkins, unpublished data; used with permission; Welhan et al. 1988a,b; Hilton, 1996; Saar et al., 2005.

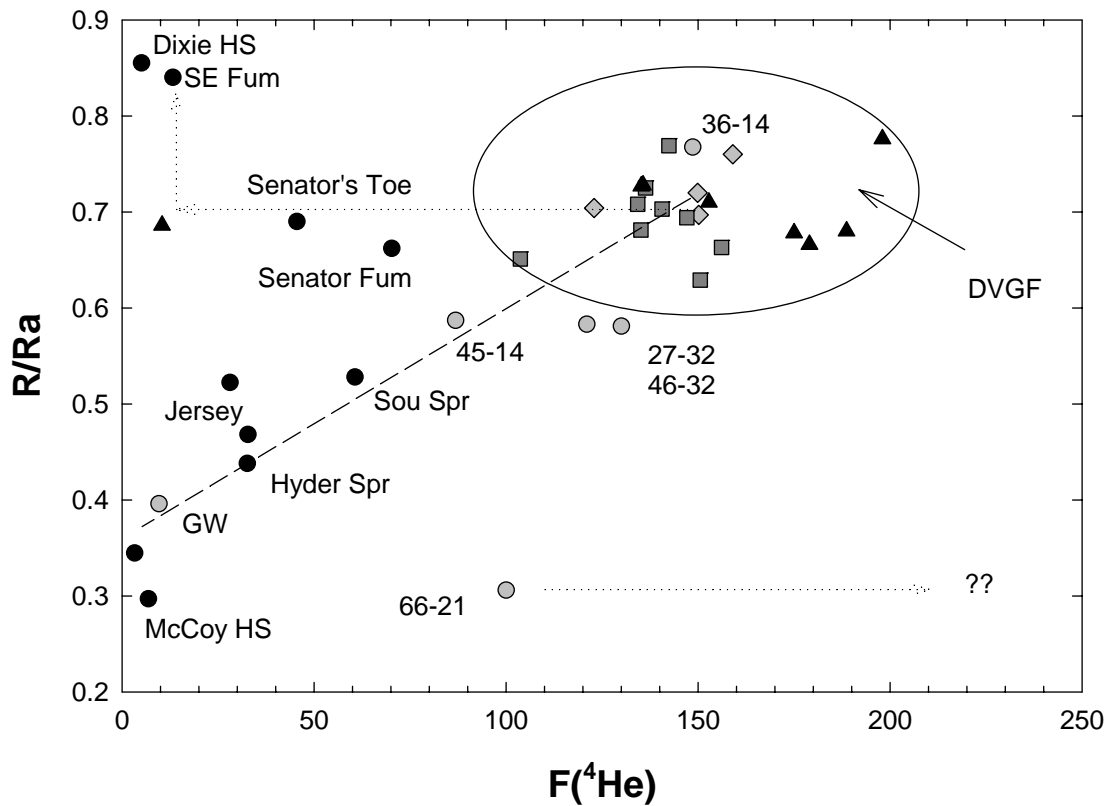


Figure 1

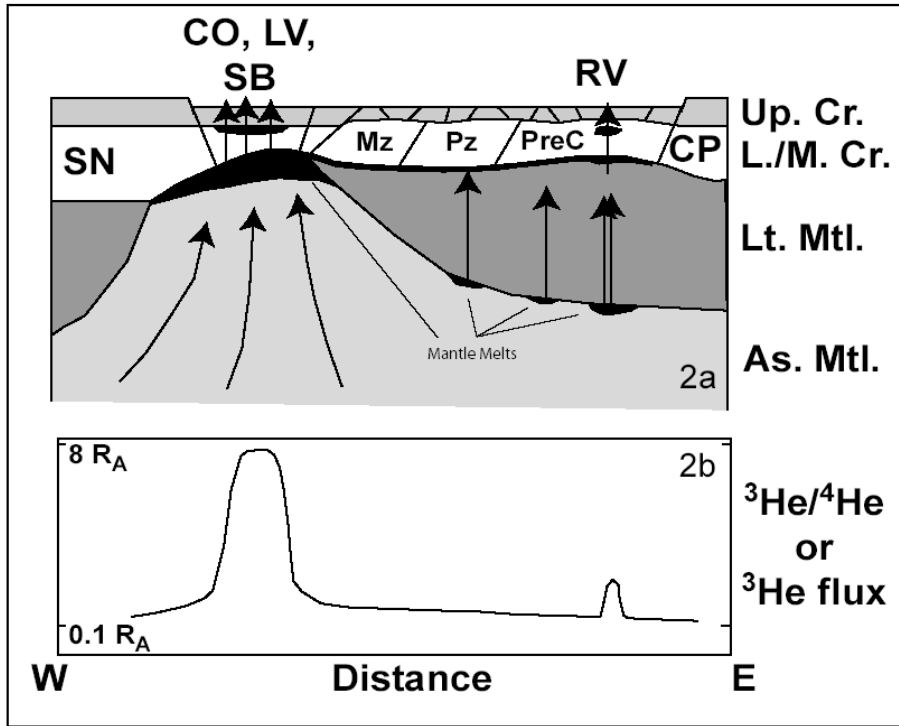


Figure 2

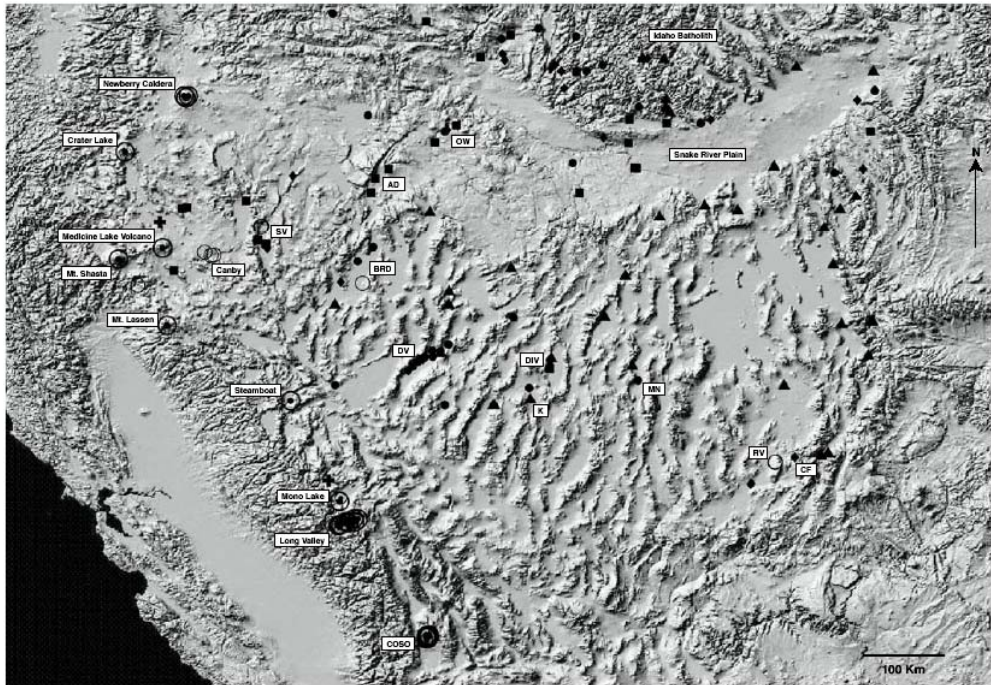


Figure 3