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A Systematic Regional Trend in Helium Isotopes Across The Northern Basin and Range Province, Western North America

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Key Words: Helium isotopes, Basin and Range, fault hosted permeability, exploration, Dixie Valley

Abstract

An extensive study of helium isotopes in fluids collected from surface springs, fumaroles and wells across the northern Basin and Range Province reveals a systematic trend of decreasing $^3He/^4He$ ratios from west to east. The western margin of the Basin and Range is characterized by mantle-like ratios (6-8 Ra) associated with active or recently active crustal magma systems (e.g. Coso, Long Valley, Steamboat, and the Cascade volcanic complex). Moving towards the east, the ratios decline systematically to a background value of ~0.1 Ra. The regional trend is consistent with extensive mantle melting concentrated along the western margin and is coincident with an east-to-west increase in the magnitude of northwest strain. The increase in shear strain enhances crustal permeability resulting in high vertical fluid flow rates that preserve the high helium isotope ratios at the surface. Superimposed on the regional trend are “helium spikes”, local anomalies in the helium isotope composition. These “spikes” reflect either local zones of mantle melting or locally enhanced crustal permeability. In the case of the Dixie Valley hydrothermal system, it appears to be a combination of both.

Introduction

The Basin and Range Province and adjacent Snake River Plain in western North America 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. These features have created a vast region of exceptionally high potential for geothermal energy development.

Over the past ~8 million years, magmatism has migrated to the margins of the Basin and Range while NW-SE extension, characterized by high angle block faulting, presently dominates the tectonic processes 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 amagmatic 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 are concentrated along the margins of the province. The extensional amagmatic geothermal systems, which are found throughout the province, are common to the Basin and Range. Very little is known about their origin and development and the connection between their spatial distribution and the tectonic history of the region. It is generally accepted that the heat for these systems is not related to shallow crustal magmatism, but is derived from deep fluid circulation through the high thermal gradient.

Exploration for extensional geothermal systems poses unique problems. As 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 overprints the chemical and isotopic compositions that could provide evidence for the existence of deeper higher temperature reservoirs. This paper synthesizes a regional scale helium isotope study of surface fluids across the northern Basin and Range and surrounding areas, including the Snake River Plain, the Idaho Batholith, and the Cascade back-arc volcanic complex. Although surface emanations and fluids in shallow wells are strongly affected by cold recharge and chemical re-equilibration at cooler temperatures, other studies (Kennedy et al., 1997) and preliminary work within the Basin and Range (Kennedy and van Soest, 2005; Kennedy and van Soest, 2006) suggest that helium isotopes may provide the best, and perhaps only, indication of deep permeability and the possibility that higher temperature fluids exist beneath shallow, cooler reservoirs.

Approach and Background

Helium isotopes provide unequivocal evidence for the presence of mantle derived volatiles in geothermal systems. Helium associated with crustal fluids that have experienced no mantle influence is dominated by ^{4}He produced from the natural radioactivity of U, Th and their daughter products decaying to Pb. Crustal helium, therefore, is characterized by the very low ^{3}He/^{4}He ratio of ~0.02 Ra (where Ra = 1.4×10^{-6}, the ratio in air). Whereas helium associated with mantle fluids is strongly enriched in ^{3}He 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., 1988a,b; Kennedy and Truesdell, 1996) or by the invasion of geo-pressured mantle fluids, presumably degassed from deep mantle melts (Kennedy et al., 1997). Once injected into the crust, the original mantle-like isotopic composition will become diluted with radiogenic ^{4}He from the crust, lowering the ^{3}He/^{4}He ratio. By the time the fluid is sampled at the surface, the ratio will depend on the flux of mantle helium into the crust, the production rate of radiogenic ^{4}He in the crust which is proportional to the concentrations of U and Th along the path of fluid flow, the admixture of other ^{4}He-enriched crustal fluids, and the fluid flow rate through the crust. Therefore, helium isotopes can provide a relative measure of permeability as it governs the fluid flow rate through the crust.

Regional Trends

To evaluate the hypothesis that helium isotopes map zones of deep mantle melting and/or deep crustal permeability, we conducted a regional study of helium isotopes in surface fluids throughout the northern Basin and Range, Cascade volcanic chain, the Snake River Plain and the Idaho Batholith. The goals were to (1) investigate regional trends in helium isotopic values, (2) determine what processes establish the regional trend, and (3) look for local anomalies with respect to the regional trend that may identify zones of deep fluid flow.

Our results show three general trends (Figure 1). First, all of the high helium isotope ratios (>3 Ra) occur along the western margin of the Basin and Range and reflect high ^{3}He fluxes related to 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 Newberry Caldera. Second, excluding the volcanic centers, the preponderance of elevated ratios (>0.6 Ra) 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 from regions of little or no recent volcanism. Third, moving east the helium ratios quickly subside to values <0.6 Ra, with values <0.3 Ra dominating the central and eastern Basin and Range.

FIGURE 1

Figure 1: Shaded relief sample location map of the Basin and Range (B&R) and surrounding areas. The symbols give an indication of the magnitude of the 3He/4He at the locality. Labeled features are: CA: Canby geothermal well; FB-SV: Fort Bidwell-Surprise Valley; BRD: Black Rock Desert; AD: Alvord Desert; DV: Dixie Valley; BV: Buffalo Valley hot spring; OW: Owyhee River Canyon; TC: Tuscarora Geothermal Prospect; DIV: Diamond Valley; K & AB: Klobe (K) hot spring and Adobe (AB) hot springs (the lowest ratios, 0.014 and 0.019 Ra, observed to date); MN: Monte Neva hot spring; CF: Cove Fort geothermal energy plant. Additional data sources: Jenkins, unpublished data; used with permission; Welhan et al. 1988a,b; Saar et al., 2005.

The systematic nature of the regional trend is illustrated is most evident in Figure 2, in which the helium isotopic compositions are plotted as a function of longitude for different bands of latitude. The general trend of declining ^{3}He/^{4}He from west-to-east is clearly demonstrated. Several factors contribute to this trend. First, mantle melting increases toward the west as indicated by the active crustal magma systems that occur along the western margin of the Basin and Range. Second, accompanying mantle melting will be a decrease in the thickness of the mantle lithosphere and the formation of shallow crustal magma chambers. Combined, these first two factors contribute to an enhanced flux of mantle ^{3}He across the base of the crust. The third factor is an increase in the magnitude of northwesterly extensional strain detected by GPS velocities (Bennett et al, 2003, Hammond and Thatcher, 2004). The increase in northwesterly-oriented strain begins at 242-243^o East Longitude at the Central Nevada Seismic Belt (CNSB). To the east of 242-243^o East Longitude, extension is nearly east-west with an average northwesterly component of only ~2-3 mm/yr (relative to the North American reference frame). West of the CNSB, the northwest velocity component increases linearly to ~12 mm/yr, equivalent to the average northwest velocity of the Sierra-Great Valley Province. The shift in the magnitude and direction of strain reflects the general impact of the northwest movement of the Pacific Plate on the western margin of the North American Plate (Flesch et al., 2000). The "drag" induced by this movement adds a dextral shear component to the general east-west extension of the Basin and Range. This induced shear component is most evident in the tectonics of the Walker Lane along the eastern Sierra Nevada, but impacts most of the northern Basin and Range. From the GPS data (Bennett et al., 2003; Hammond and Thatcher, 2004), the shift in strain is super-imposed on the regional helium isotope trend in Figure 3. The strong correspondence between the helium isotope trend and the increase in northwest strain velocity suggests that the increasing shear component significantly enhances average regional crustal permeability, allowing for more rapid fluid flow rates through the crust preserving the higher $^3He/^4He$ ratios observed at the surface.

FIGURE 2

Figure 2: The helium isotopic composition of surface fluids in the Basin and Range plotted as a function of longitude across the Province for two bands of latitude: 38.5-41°N and 41-43°N. The shaded curve indicates the trend of the baseline helium isotope ratio decline going from west to east. The anomalous features with elevated helium isotope ratios are immediately apparent and are labeled in Figure 1.

FIGURE 3

Figure 3: Same as Figure 2 with the average change in total strain velocity (heavy black line), calculated from data in Bennett et al. (2003) and Hammond and Thatcher (2004), plotted superimposed on the regional helium trend.

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 this 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). These models appear contrary to the observed systematic trend of declining ratios towards the east. Alternative models, such as the simple shear model of (Jones et al., 1992), restrict current mantle melting and under-plating to localized regions offset from the highly extended terrain with suppression of volcanism during periods of rapid extension (Gans and Bohrson, 1998). These models are more consistent with the distribution and age of volcanism in the Basin and Range and suggest that the heat flow anomaly in the central Basin and Range is related to either crustal thinning, older wide spread melting events, or recent local, albeit small-scale mantle melting.

FIGURE 4

Figure 4: Theoretical helium isotope west to east profile across the Basin and Range.

A theoretical helium isotope profile consistent with the simple shear model is shown in Figure 4. Although the observed helium trend and the trend predicted from the simple shear model of Jones et al (1992) are a good match, there is a caveat. Presently, the helium data are restricted to the northern Basin and Range, whereas the Jones et al (1992) model is derived from field, geophysical, and geochemical data from the Death Valley-Lake Mead extended domain which is a region of rapid and extensive amagmatic extension in the central Basin and Range. Perhaps the helium isotope trend and very high ratios in the northwest Basin and Range indicate the onset of rapid extension in this region and northerly migration of the Walker Lane Shear Zone.

Local Anomalies

Superimposed on the regional trend are features with elevated helium isotope ratios (~0.8-2.1 Ra) compared to the local background values [e.g. Black Rock Desert (BRD), Dixie Valley (DV), Diamond Valley (DIV), and Monte Neva (MN); Figure 2]. The Roosevelt Hot Spring anomaly at the eastern margin of the Basin and Range is related to a small crustal magma system (Nielson and Moore, 1979; Welhan et al., 1988a). However, the other anomalies, such as Black Rock Desert, Dixie Valley, Buffalo Valley, etc, appear to be amagmatic, lacking any geologic or geophysical evidence for recent shallow crustal magmatism.

A detailed hydro-chemical study of the Dixie Valley hydrothermal system (Goff et al., 2002; Kennedy and van Soest, 2006) indicated a wide range in fluid chemistry and helium isotopic compositions throughout the valley and bordering ranges. However, the highest helium ratios are restricted to fluids emerging directly from the Stillwater Range Front Fault system, a high-angle normal fault that defines the western margin of the valley which is the primary conduit for vertical flow of the hydrothermal fluids (Blackwell et al., 2000). To account for the anomalously high $^3He/^4He$ ratios, the fault must have high permeability (Kennedy and van Soest, 2006). Deep permeability along the fault is consistent with observations of a high incidence of deep (~12-15 km) seismicity following the 1954 7.1M Dixie Valley earthquake that ruptured a large segment of the Stillwater Fault (Smith et al., 1989). Furthermore, a recent east-west high resolution deep magneto telluric study that crossed through Dixie Valley revealed an extensive zone of low resistance at a depth of ~25 km that appears to be connected to the surface at Dixie Valley (Wannamaker et al., 2005). Although the evidence is somewhat circumstantial, the Dixie Valley helium anomaly appears to reflect a combination of local, deep mantle melting and an enhanced deep crustal permeability, with the range front fault system providing the fluid conduit. It follows that other “local anomalies” may point to similar fault zones characterized by relatively high and deep permeability.

Most of the helium anomalies are located in the northwestern Basin and Range (in, or to the west of, the CNSB) and appear to be related to the high strain rates and a large shear component that characterize this area. However, there are anomalously high helium ratios that fall outside of this area, such as those found at Diamond Valley and Monte Neva. The origin of deep permeability in these cases is not immediately apparent. One possibility is that older deep structural features provide pathways for transport of mantle ^3He. For instance, in Diamond Valley the range front fault along which the high helium ratios occur appears to intersect a deep crustal feature identified from aeromagnetic data as a mid-Miocene rift zone related to the inception of the Columbia River Flood basalts (Glen and Ponce, 2002).

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. A systematic helium isotope trend across the Basin and Range and super imposed local anomalies provide a tool for locating faults with deep and high permeability. Future work should concentrate on more detailed studies of those areas with elevated (anomalous) 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. Helium isotopes combined with other techniques, particularly high-resolution deep magneto telluric data and perhaps InSAR data capable of mapping real-time strain, can provide a very useful tool in the exploration for hidden amagmatic geothermal systems.

Acknowledgements

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FIGURE CAPTIONS

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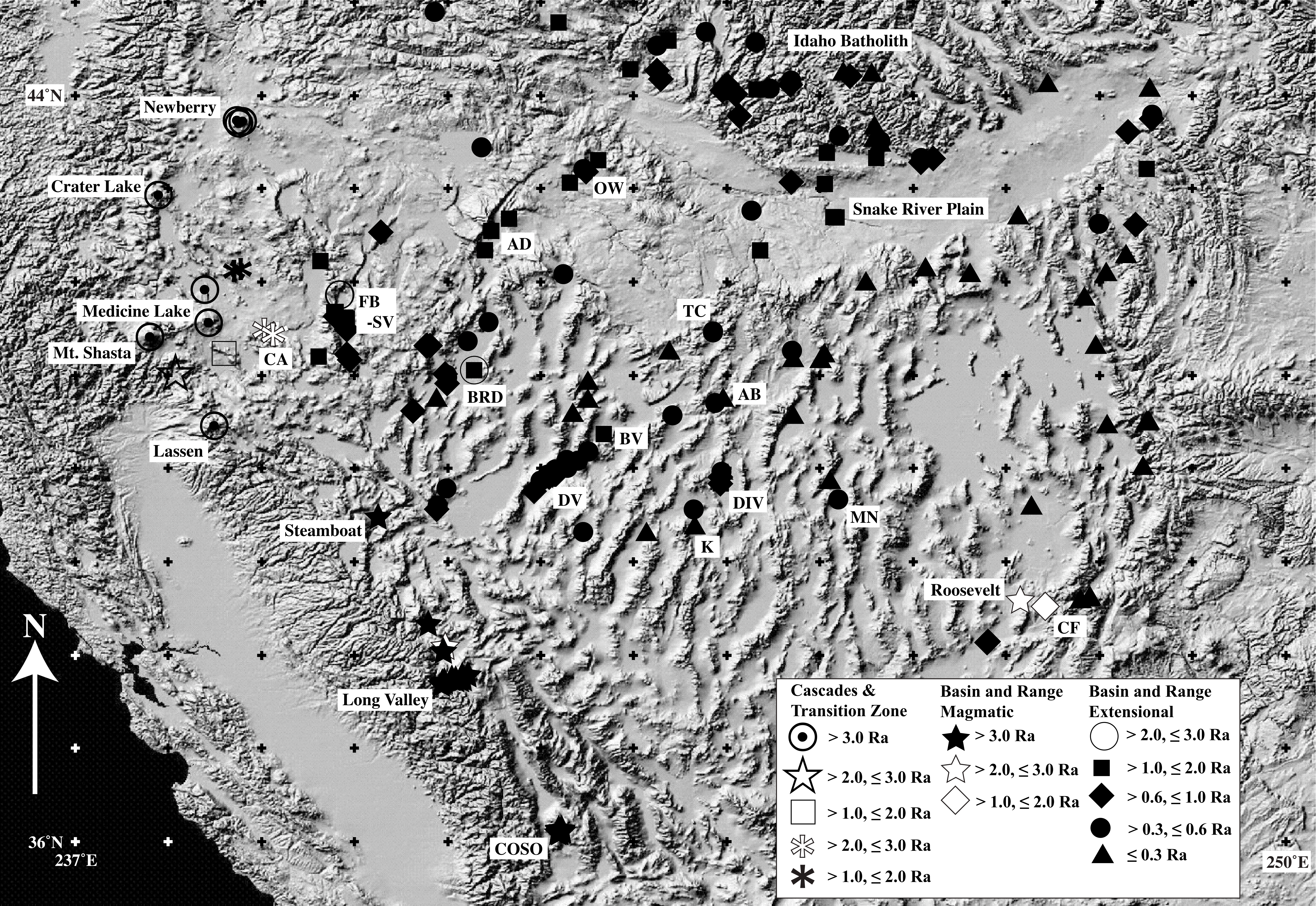
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Crater Lake
Medicine Lake
Mt. Shasta
Lassen
CA
FB
-SV
AD
OW
Idaho Batholith
Snake River Plain
TC
AB
BRD
BV
DV
DIV
MN
K
Steamboat
Roosevelt
CF
Long Valley
COSO
N
36°N
237°E
250°E
Cascades &
Transition Zone
⊙ > 3.0 Ra
☆ > 2.0, ≤ 3.0 Ra
□ > 1.0, ≤ 2.0 Ra
> 2.0, ≤ 3.0 Ra
✱ > 1.0, ≤ 2.0 Ra
Basin and Range
Magmatic
★ > 3.0 Ra
☆ > 2.0, ≤ 3.0 Ra
◇ > 1.0, ≤ 2.0 Ra
Basin and Range
Extensional
○ > 2.0, ≤ 3.0 Ra
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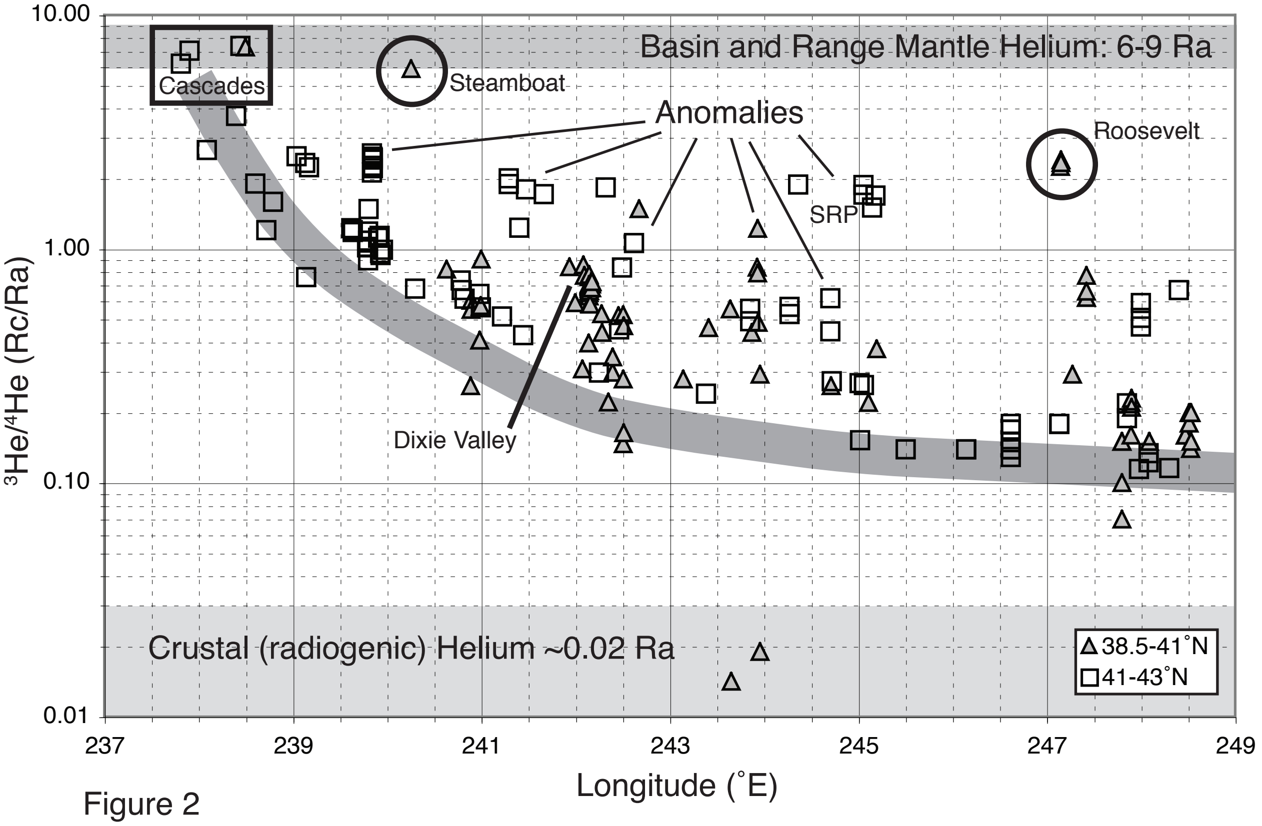
● > 0.3, ≤ 0.6 Ra
▲ ≤ 0.3 Ra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1.00
0.10
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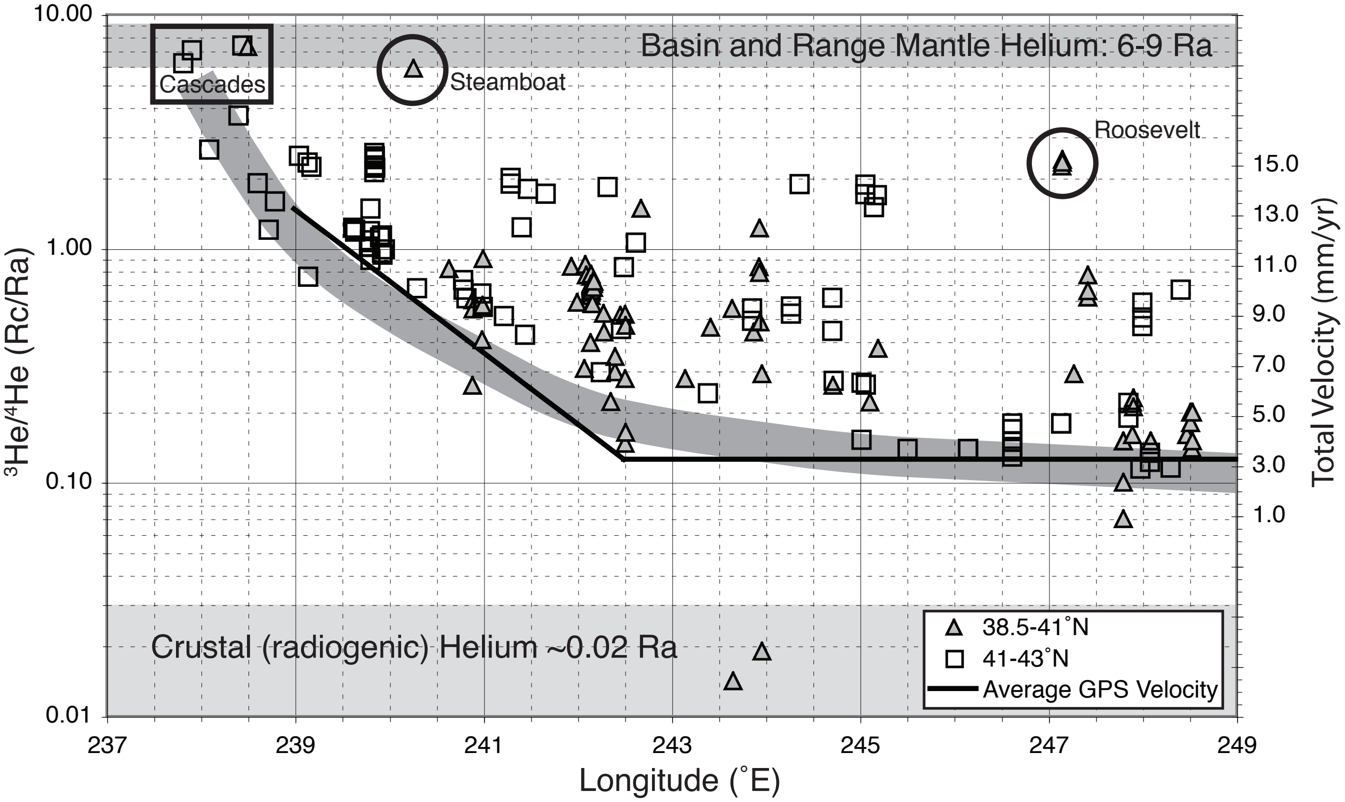
^{3}He/^{4}He (Rc/Ra)
237
239
241
243
245
247
249
Longitude (˚E)
Basin and Range Mantle Helium: 6-9 Ra
Cascades
Steamboat
Anomalies
Roosevelt
SRP
Dixie Valley
Crustal (radiogenic) Helium ~0.02 Ra
△ 38.5-41˚N
□ 41-43˚N

Figure 2


Basin and Range Mantle Helium: 6-9 Ra
Cascades
Steamboat
Roosevelt
Crustal (radiogenic) Helium ~0.02 Ra
38.5-41˚N
41-43˚N
Average GPS Velocity
^{3}He/^{4}He (Rc/Ra)
10.00
1.00
0.10
0.01
Total Velocity (mm/yr)
15.0
13.0
11.0
9.0
7.0
5.0
3.0
1.0
237
239
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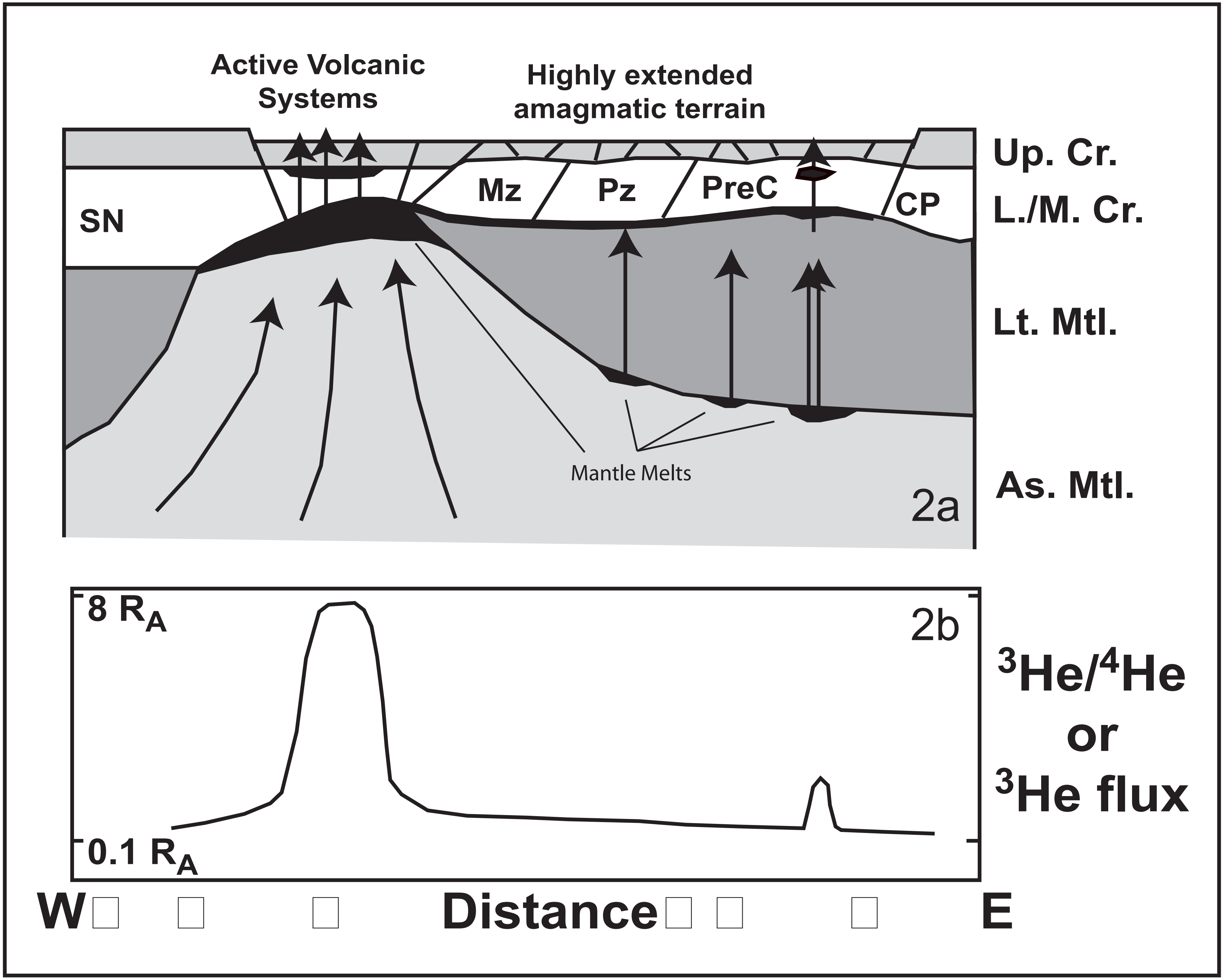
Longitude (˚E)

Figure 3


Active Volcanic Systems
Highly extended amagmatic terrain
SN
Mz
Pz
PreC
CP
Up. Cr.
L./M. Cr.
Lt. Mtl.
As. Mtl.
Mantle Melts
2a
8 R_A
0.1 R_A
2b
$^3He/^4He$ or ^3He flux
W
Distance
E