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Mantle source provinces beneath the Northwestern USA delimited by helium isotopes in young basalts

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ABSTRACT

We report new He, Nd and Sr isotope results for basalts from the northwestern United States. The new $^3\text{He}/^4\text{He}$ results for olivine phenocrysts in basalts from the eastern Snake River Plain (SRP), the Owyhee Plateau (OP) and the Oregon High Lava Plains (HLP), together with published He isotope data for Yellowstone and the Cascades volcanic arc, delineate distinct mantle sources for each of these sub-provinces. All basalts from the eastern SRP (8 Quaternary localities plus 1 Miocene locality) have $^3\text{He}/^4\text{He}$ ratios higher than observed in normal mid-ocean ridge basalts, but overlapping with ranges observed in hotspot-related oceanic islands. For a lateral distance of some 400 km along the SRP, $^3\text{He}/^4\text{He}$ ranges from $\sim 11 R_A$ in the west to $> 19 R_A$ adjacent to Yellowstone. Such high ratios have not been observed elsewhere in the western U.S., and are consistent with the presence of a mantle plume. The lateral gradient in $^3\text{He}/^4\text{He}$ suggests that the proportion of plume-derived He decreases westward, but this interpretation is complicated by possible addition of crustal helium during open-system crystal fractionation in some SRP basaltic magmas. Although crustal contamination may modulate $^3\text{He}/^4\text{He}$ in basalts along the SRP, the effect is not strong and it does not obscure the elevated $^3\text{He}/^4\text{He}$ mantle source signature. In contrast, young basalts from the HLP and the OP have $^3\text{He}/^4\text{He}$ values of 8.8–9.3 R_A , within the range for mid-ocean ridge basalts; these data reflect a shallow asthenospheric source with no discernible influence from the Yellowstone hotspot. Basalts from Newberry volcano have slightly lower $^3\text{He}/^4\text{He}$ (7.6–8.3 R_A), within the range for other Cascades arc lavas (7.0–8.4 R_A).

Three alternative explanations are possible for the origin of the high $^3\text{He}/^4\text{He}$ signature along the SRP: (1) multi-component mixing of (a) magmas and/or CO_2 -rich fluids derived from plume mantle having high $^3\text{He}/^4\text{He}$, (b) continental lithosphere having low $^3\text{He}/^4\text{He}$, and (c) shallow asthenospheric mantle (MORB source); (2) a mantle plume beneath Yellowstone that has an unusual combination of He, Nd and Sr isotope characteristics; or (3) a continental lithospheric mantle that experienced ancient enrichment of ^3He relative to (U+Th). The isotope relations between He–Nd and He–Sr, along with other considerations, generally favor the first explanation, but the other possibilities cannot be ruled out at the present time.

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1. Introduction

Magmatism in the western United States is associated with several distinct tectonic domains. The Cascades volcanic arc has been magmatically active since ~ 40 Ma, and is best known for its Quaternary expression which comprises more than 2300 mafic monogenetic volcanoes broadly distributed along an arc defined by some 30 large composite stratovolcanoes (Hildreth, 2007). To the east, the Oregon High Lava Plains (HLP) stretch across south-central

Oregon as far as the Owyhee Plateau (OP) in southeastern Oregon and southwestern Idaho. The Snake River Plain (SRP) extends northeast from there across southern and eastern Idaho to the Yellowstone Plateau in northwestern Wyoming. The SRP dominantly comprises bimodal basalt and rhyolite volcanoes, the earliest rhyolitic phases of which become progressively younger approaching Yellowstone (Armstrong et al., 1975; Pierce and Morgan, 1992). Because of this age progression the SRP has been interpreted as the volcanic track of a mantle plume currently located beneath Yellowstone. The Oregon High Lava Plains is also a bimodal (basalt–rhyolite) volcanic province, distinguished by a pattern of westward-migrating silicic volcanism that mirrors the age pattern of calderas stretching along the Snake River Plain (Jordan et al., 2004; Jordan, 2005). This enigmatic mirror pattern for HLP silicic volcanism is sometimes taken as evidence

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against the SRP being the trace of the Yellowstone plume (e.g., Christiansen et al., 2002). The greater predominance of silicic over basaltic volcanism in the SRP is thought to reflect the influence of cratonic crust as a density filter that hinders the ascent of basaltic magmas and enhances the melting of crustal rocks (Bonnichsen et al., 2008). Because these areas are situated within the greater Basin and Range extensional province, the effects of lithospheric deformation on magma genesis must also be considered. Thus, a fundamental question concerns the relative contributions of lithospheric vs. sub-lithospheric processes on generation of the mantle-derived basaltic magmas across this region. Helium isotope variations in basaltic rocks potentially can constrain the nature of the respective magma sources and help to resolve this question.

$^3\text{He}/^4\text{He}$ ratios of 7 to 9 R_A (where R_A is the atmospheric ratio of 1.38×10^{-6}) are typical of mid-ocean ridge basalts (MORBs) and are considered representative of sources within the convecting asthenospheric upper mantle (e.g., Graham, 2002). Lower (more radiogenic) $^3\text{He}/^4\text{He}$ reflects additional contributions from lithospheric mantle or crust (Dunai and Porcelli, 2002; Gautheron and Moreira, 2002; Day et al., 2005). Elevated $^3\text{He}/^4\text{He}$, above 10 R_A , indicates derivation from a region with higher time-integrated $^3\text{He}/(\text{U} + \text{Th})$, usually taken to be from the deep mantle via a thermochemical plume (e.g., Kurz et al., 1982; Allègre et al., 1983; O'Nions, 1987). In continental regions, helium isotopes are especially diagnostic for elucidating the role of mantle plumes in tectonic processes, and in unraveling geochemical variability produced by plume/lithosphere interaction. For example, in East Africa, elevated $^3\text{He}/^4\text{He}$ in lavas and geothermal fluids track the influence of the large Afar plume near the Red Sea and indicate that this material can be traced for more than 500 km along the Ethiopian Rift (Marty et al., 1993; Darling et al., 1995; Marty et al., 1996; Scarsi and Craig 1996; Moreira et al., 1996; Hopp et al., 2004; Pik et al., 2006). In contrast to East Africa, widespread Cenozoic basaltic volcanism across China is characterized by $^3\text{He}/^4\text{He}$ ratios between 5.5 and 9.5 R_A ; because high- $^3\text{He}/^4\text{He}$ mantle plume contributions cannot be discerned, it appears that this volcanism is driven by lithospheric extension and magmatic sources confined to the lithosphere or shallow mantle (e.g., Barry et al., 2007; Chen et al., 2007).

Previous helium isotope studies in the western U.S. have focused on basalts from the southwestern U.S., Basin and Range (Reid and Graham, 1996; Dodson et al., 1998), Columbia Plateau (Dodson et al., 1997) and the Cascades volcanic arc (Poreda and Craig, 1989; Cerling and Craig, 1994; Licciardi et al., 1999; Dodson and Brandon, 1999; Evans et al., 2004). In addition, a large number of geothermal fluid and volcanic gas samples have been analyzed (e.g., Welhan et al., 1988; Kennedy and van Soest, 2007), including many from the Yellowstone region (Craig et al., 1978; Kennedy et al., 1985, 1987; Hearn et al., 1990; Saar et al., 2005). These studies have revealed a uniquely elevated $^3\text{He}/^4\text{He}$ signature for the Yellowstone samples, which supports the notion that there is a significant deep mantle flux of He beneath this area (Craig, 1993, 1997). We note that some investigators disagree with this interpretation and argue that high $^3\text{He}/^4\text{He}$ is an intrinsic characteristic of the shallow mantle (e.g., Christiansen et al., 2002). To better characterize and understand the regional He isotope variations, we have undertaken a study of volcanic rocks from the northwestern U.S. New helium isotope results for young basalts from the eastern Snake River Plain, the Owyhee Plateau and the Oregon High Lava Plains, along with published data for Yellowstone and the Cascades volcanic arc, provide insight to the relationship between the enigmatic High Lava Plains and Yellowstone–Snake River Plain magmatic systems.

2. Regional background

The seismic velocity structure of the upper mantle beneath the western U.S. clearly delineates several provinces (Grand, 1987; Humphreys and Dueker, 1994; Warren et al., 2008; Roth et al., 2008). The Cascades volcanic arc is underlain by the downgoing Juan

de Fuca Plate, marked by seismically fast (cold) mantle material at ~100 km depth. Although situated partly on Archean cratonic lithosphere, the Snake River Plain is underlain by seismically slow (warm) upper mantle to depths of 100–300 km (Schutt and Humphreys, 2004). Recent seismic tomography indicates the presence of an inclined, cylindrical, low-velocity mantle anomaly beneath Yellowstone that plunges to the northwest and extends downward at least 500 km into the mantle (Yuan and Dueker, 2005; Waite et al., 2006). The excess mantle temperature required to produce these velocity anomalies has been estimated to be 150–200 °C (Lowry et al., 2000; Yuan and Dueker, 2005; Waite et al., 2006), although Leeman et al. (2009–this volume) suggest that it is unlikely to exceed 150 °C and may be significantly less. If a mantle plume currently lies beneath Yellowstone, then areas in the wake of the hotspot track have likely evolved considerably over time and with distance from the plume axis. Alternatively, because the SRP low-velocity anomaly is relatively shallow (<300 km) and extends across northern Nevada past McDermitt caldera, and appears to be contiguous with a band of anomalies that extend to the Mendocino triple junction, the SRP might be a trace of mantle flow around the southern edge of the descending Juan de Fuca Plate (Roth et al., 2008). Beneath the HLP, low velocity anomalies are relatively muted except beneath Newberry volcano (Xue and Allen, 2006; Warren et al., 2008; Roth et al., 2008), perhaps due to locally enhanced melting associated with fluid release from the downgoing Juan de Fuca slab (Roth et al., 2008).

Eocene–Miocene age-progressive volcanism (Duncan, 1982), and $^3\text{He}/^4\text{He}$ ratios between 9.4 and 13.7 R_A in accreted terranes of the Oregon Coast Range (Pyle et al., 1995) suggest the possibility of pre-Columbia River Basalt (CRB) volcanism associated with an ancestral mantle plume. Although there is evidence for such earlier manifestations of a hotspot track preserved in the Oregon Coast Range, eruptions of the voluminous Columbia River Basalt Group between 16.8 and 15.0 Ma are usually considered to mark the onset of Yellowstone plume-related magmatism in the northwestern U.S. (e.g., Geist and Richards, 1993). The earliest phase of CRB magmatism is almost exclusively restricted to areas outboard of cratonic North America (e.g., Carlson and Hart, 1987); most feeder dikes occur within Mesozoic oceanic terranes that had been accreted to the continental margin by 80 Ma (Camp and Ross, 2004). However, by 15 Ma this volcanic activity shifted eastward across the craton margin.

Rocks of the HLP are mainly basalts and rhyolites of late Miocene age and younger. These lavas are locally intercalated with volcanoclastic sediments. Silicic volcanism along the HLP forms a rough mirror image to the age pattern for silicic eruptive centers along the SRP. In contrast, HLP basalts do not appear to follow any systematic age progression (Jordan et al., 2004; Jordan, 2005) and they are distinct from the CRB lavas in being true basalts with relatively primitive compositions. Although other variants have been identified, typical HLP basalts are classified as “high-alumina olivine tholeiite” (HAOT). Such lavas are widely distributed across the northwestern U.S. Previous workers have noted that HAOTs compositionally resemble mid-ocean ridge and back-arc basin basalts, except for notable enrichments in Ba, Sr, and Pb and depletions in Nb, Ta, and other high-field-strength elements (Hart, 1985; Draper, 1991; Conrey et al., 1997). A review of 171 chemical analyses of HLP basalts by Jordan (2001) revealed that many are primitive (50% have $\text{Mg}\# > 60$), high-alumina (80% have $\text{Al}_2\text{O}_3 > 16\%$), olivine-tholeiites (70% are hypersthene- and olivine-normative). HLP bimodal (basalt–rhyolite) volcanism occurred during the last 10–12 Ma. The silicic components consist of several large volume rhyolite ignimbrites and numerous small rhyolite domes and lavas. The focus of silicic volcanism migrated westward over time from eastern Oregon to the area of Newberry volcano (strictly speaking, a part of the Cascades backarc).

Volcanic rocks along the SRP consist of caldera- and dome-related rhyolite as well as basalt erupted from cinder cones and small central volcanoes. SRP volcanism is distinctive in that it begins with a

Table 1
Isotope results for Northwestern U.S. basalts.

Location	Sample	Latitude (°N)	Longitude (°W)	Elev (m)	Wt (mg)	³ He/ ⁴ He (R/R _A)	σ	[⁴ He] 10 ^{−9} ccSTP/g	[³ He] 10 ^{−15} ccSTP/g	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd
<i>Newberry Volcano</i>											
S flank	29WHL98	43.591	121.151	1630	324.9	7.96	0.20	2.92	32.3	0.703681	0.512667
E flank	43WHL98	43.724	120.999	1500	426.0	7.59	0.16	6.03	63.6	0.703753	0.512858
<i>High Lava Plains</i>											
Pot Holes Lava	21WHL97	43.769	120.968	1460	347.3	8.96	0.22	3.55	44.2	0.703342	0.512908
Green Butte	30WHL98	43.553	121.293	1710	317.9	8.76	0.14	10.9	133	0.703651	0.512904
Four Craters Lava	85WHL98	43.646	120.683	1380	228.4	8.83	0.11	10.9	134	0.703290	0.512936
Diamond Crater	HLP-98-38a	43.080	118.736	1290	140.9	9.00	0.96	1.26	15.8	0.704218	0.512788
	HLP-98-38b (a + b wtd mean)				368.0	9.42 9.31	0.58 0.50	0.638	8.35		
N of Jackass Butte	HLP-98-33a	43.057	118.958	1460	333.6	22.4	1.03	0.753	23.5	0.704120	0.512807
	HLP-98-33b(1)				310.9	30.1	1.60	0.652	27.2		
	HLP-98-33b(2)				310.9	68.7	3.14	0.404	38.6		
	HLP-98-33b(m)				190.1	204	2.18	22.7	6430		
Older HLP lavas	8WHL97	43.928	121.007	1270	218.7	–	–	0.121	bd	–	–
	17WHL98	43.091	120.837	1460	188.2	–	–	0.130	bd	–	–
	10WHL98	43.646	120.849	1580	219.5	–	–	0.129	bd	–	–
	76WHL98	43.743	120.755	1460	325.9	–	–	0.206	bd	–	–
	89WHL98	43.457	120.823	1410	278.2	–	–	0.287	bd	–	–
	128WHL98	43.817	120.482	1460	422.8	–	–	0.114	bd	–	–
	3WHL99b	43.925	121.075	1430	326.6	–	–	0.202	bd	–	–
	HLP-98-47	43.235	118.746	1320	349.7	–	–	0.240	bd	–	–
	HLP-98-58	43.140	118.444	1360	296.4	–	–	0.160	bd	–	–
	HLP-98-42	43.193	118.819	1280	220.5	–	–	0.249	bd	–	–
	148CHLP98	43.247	119.531	1330	294.4	–	–	0.479	bd	–	–
<i>Owyhee Plateau</i>											
Jordan Craters	R92-OR-01	43.133	117.433	1380	299.3	9.21	0.10	215	2750	0.7040	0.512865
<i>Snake River Plain</i>											
Spencer-Kilgore	R95-SRP-02	44.333	112.033	1870	236.4	19.43	1.17	1.69	45.6	0.706174	0.512380
Gem Valley	R95-SRP-07	42.420	111.728	1540	126.4	14.05	0.91	5.62	110	0.7065	0.512379
Near Idaho Falls	R97-SRP-10	43.511	112.191	1380	166.8	11.42	2.24	1.10	17.5	0.705598	0.512457
Quaking Aspen Butte	R97-SRP-13	43.388	113.224	1680	162.7	15.54	2.95	1.03	22.3	0.706298	0.512387
N Robbers Lava Field	R97-SRP-16	43.379	112.983	1570	108.6	16.20	0.88	6.88	155	0.705552	0.512524
Antelope Butte	R97-SRP-17	43.905	112.598	1460	279.7	17.08	0.70	2.35	55.8	0.708027	0.512344
Spencer-Kilgore	R97-SRP-19	44.283	112.150	1740	92.1	16.40	1.22	5.24	120	0.705698	0.512444
Sonnars Butte	L05-P	43.115	114.077	1350	513.0	10.97	0.53	0.75	11.4	–	–
Sonnars Butte	L88-11 Qb	43.115	114.077	1350	–	13.87*	–	–	–	–	–
W Mt. Bennett Hills	L00-35	43.139	115.301	1470	311.8	13.44	1.38	0.24	4.48	–	–
W Mt. Bennett Hills	L88-5 Tb	43.139	115.301	1470	–	13.04*	–	–	–	–	–
Mesa Falls	L88-13	44.188	111.330	1710	–	14.38*	–	–	–	–	–

Sample locations are in WGS84 datum. Sr and Nd isotope data are for whole rock powders.

Sr isotope data in italics are unpublished data of W.P. Leeman or M.R. Reid for similar samples from the same localities.

Helium isotope results were obtained by crushing of olivine phenocrysts in vacuum to release gas trapped in melt and fluid inclusions, except for HLP-98-33b(m). HLP-98-33b(m) is the melting analysis of this sample powder retrieved after crushing. HLP-98-33b(1) and (2) are individual crushing steps of the same mineral separate. This sample was crushed for the same number of strokes (~150) in each step as other samples. Analytical uncertainties in ³He/⁴He (σ) are the quadrature sum of the uncertainties associated with sample analysis, air standards and blanks.

bd — 11 older HLP samples were also analyzed, but ³He/⁴He are not reported due to very low ⁴He contents (0.11–0.48 nccSTP/g) and ³He at or below detection (~1 × 10^{−15} ccSTP).

* — Denotes ³He/⁴He results obtained in Harmon Craig's lab (SIO) that were provided by D. R. Hilton.

voluminous rhyolitic phase having a duration of 2–4 million years at individual eruptive centers. Basaltic eruptions are rare during this early phase but dominate thereafter. Onset of the silicic phase defines a crude age progression, originating in the Owyhee Plateau and becoming younger northeastward across the SRP to Yellowstone. In contrast, basaltic activity shows no clear age progression. However, because massive injections of basalt into the crust are thought to be essential to production of the initial silicic eruptive phase (Bonnichsen et al., 2008; Leeman et al., 2008), implicitly the pattern of basaltic magmatism must mimic that of the silicic centers, and likely began slightly earlier to allow formation of the voluminous silicic magmas.

The ratio of basalt:rhyolite erupted along the SRP is lower than along the HLP. Total volume productivity (overall magma flux) along the SRP is larger than along the HLP by about a factor of ten, consistent with different causes for volcanism in these regions (e.g., a mantle plume influence beneath the YSRP; Pierce and Morgan, 1992). Along

the SRP large volumes of silicic material mostly occur in caldera-forming eruptions that are >1000 km³ in volume, whereas along the HLP most are volcanic domes with the largest tuffs being ~300 km³. While the actual basalt:rhyolite ratio for both the SRP and HLP is probably of order 10:1, a larger proportion of basalt along the SRP never erupts (Leeman et al., 2008), leading to an erupted ratio ≤0.2 along the SRP compared to a ratio of ~1 along the HLP (these estimates are based on a comparison of map distribution and thickness of map units). This likely reflects differences in underlying crustal architecture and the operation of a crustal density filter. More mafic and denser crust beneath the HLP favors more efficient ascent of basaltic magmas, whereas thicker, more silicic and less dense crust beneath the SRP favors stagnation of ascending basalt and promotes crustal melting. Basalts erupted along the SRP might therefore be expected to have their primary He isotope compositions shifted toward crustal values compared to basalts along the HLP. While there is a hint of such

a shift when $^3\text{He}/^4\text{He}$ is considered with the major elements, the effect is limited and it does not obscure the presence of elevated $^3\text{He}/^4\text{He}$ in all SRP basalts we have studied (see discussion in Section 5.1, $^3\text{He}/^4\text{He}$ and major element variations). Overall the SRP magma volumes probably reflect a greater lithospheric extension, a mantle plume influence, or both.

Basaltic and rhyolitic rocks from the two areas also differ isotopically (Leeman et al., 1992). Those from the SRP show distinctly higher $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{207}\text{Pb}/^{206}\text{Pb}$, and lower $^{143}\text{Nd}/^{144}\text{Nd}$, with much stronger signature in the rhyolites from cratonic crust and lithospheric mantle influences. In contrast, basalts and rhyolites from the HLP are isotopically similar to one another and overlap expected asthenospheric mantle compositions; there is little influence of old, evolved crustal rocks on HLP isotope compositions. They generally have Sr–Nd–Pb isotopic compositions in the range of common oceanic island basalts, suggesting derivation from asthenospheric mantle sources (Hart, 1985; Leeman et al., 1992).

Clear evidence is found in the Sr, Nd and Pb isotopes of crustal xenoliths in Quaternary–Recent volcanic rocks for the presence of ancient crust beneath the eastern SRP (Leeman et al., 1985). Seismic evidence (Peng and Humphreys, 1998) reveals a mafic sill complex approximately 10 km thick within the mid-crust of the eastern SRP. The emplacement of this sill is responsible for flexural subsidence of the SRP and provides a heat source for rhyolite formation (Shervais et al., 2006). Based on the major, trace element and Sr–Nd–Pb–O isotope variability, there appears to have been only limited interaction between the crust and the basalts erupted along the SRP (Leeman, 1982; Menzies et al., 1983; Hart, 1985; Nash et al., 2006; Shervais et al., 2006). Notably, Pb isotope signatures in lavas from the central and eastern SRP are similar to those for the ancient cratonic lithosphere that underlies the SRP, suggesting that the continental lithospheric mantle is a dominant source of Pb in these lavas (Doe et al., 1982; Reid, 1995; Hanan et al., 2008).

In summary, there are marked differences in lithospheric and crustal architecture beneath the HLP, SRP and Cascades arc regions, and these differences modulate many aspects of magmatism and petrologic evolution in these sub-provinces. Seismic tomography captures the current mantle structure, and suggests the presence of warm upper mantle beneath the SRP and a column of hot mantle beneath Yellowstone.

3. Methods

Whole rock samples were collected from fresh road cuts or cliff faces whenever possible, to minimize the potential effects of cosmogenic ^3He production. Samples were progressively crushed to

obtain olivine phenocrysts for helium isotope analysis. Large olivine crystals, typically about 0.25–1 mm in size, were hand-picked under a binocular microscope from the magnetically filtered, crushed fractions of whole rock samples. The range of sample weights analyzed was between 0.1 and 0.5 g (Table 1). To avoid possible contamination from adhering groundmass of the host basalt or from dust, olivine grains were cleaned ultrasonically for 15 to 30 min in deionized water, then in acetone, and then rinsed in acetone and air-dried. The final, cleaned phenocrysts were re-examined under the microscope to ensure the absence of any foreign material before loading for helium isotope analysis.

The helium isotope analyses were performed at NOAA/PMEL in Newport, OR, following procedures described previously (Graham et al., 1998). All gas extractions were performed by crushing in vacuum to liberate helium trapped in melt and fluid inclusions, and to minimize any potential contribution from cosmogenic ^3He (see later discussion). After loading the sample into a stainless steel chamber together with a magnetic piston, the piston was lifted and dropped about 150 times under vacuum using a system of external solenoids, crushing the sample to a powder. Non-condensable, reactive gases were gettered over hot Ti, and the heavy rare gases Ar, Kr and Xe were trapped on activated charcoal using liquid nitrogen. Neon was separated onto a cryogenically-controlled charcoal trap at 38 K. The helium was admitted directly to the mass spectrometer for isotope ratio and peak height (concentration) determination. The vacuum line blank for crushing was $<1 \times 10^{-10}$ ccSTP for ^4He , and line blanks were run before and after all samples. Simultaneous measurement of ^3He and ^4He was performed on a double collector mass spectrometer especially designed for precise and accurate helium isotope analysis by J. E. Lupton.

Sr and Nd isotope compositions for HLP whole rocks were analyzed at the University of Washington and reported in Jordan (2001); representative data are presented here for samples analyzed for He isotope composition. Analytical methods for those samples are described in Nelson (1995). SRP whole rocks were analyzed at UCLA for Sr and Nd isotopes following methods described in Reid and Ramos (1996). Major element analyses were performed by XRF on whole rock powders at Washington State University.

4. Results

Isotopic data for He, Sr and Nd are reported in Table 1. Major element results are reported in Table 2.

$^3\text{He}/^4\text{He}$ is shown vs. [He] in Fig. 1. This diagram is useful for screening analyses that may be compromised by the presence of

Table 2
Representative major element compositions.

Locality	Newberry volcano		High Lava Plains					Owyhee plateau	Snake River Plain						
Sample	29WHL98	43WHL98	21WHL97	30WHL98	85WHL98	HLP-98-38	HLP-98-33	R92OR01	R95SRP02	R95SRP07	R97SRP13 ^a	R97SRP16 ^b	R97SRP17 ^c	L05-P ^d	L88-13 ^e
SiO ₂	52.10	49.98	49.16	53.49	51.02	47.62	48.27	48.14	47.80	47.11	47.54	46.45	47.35	46.77	47.77
TiO ₂	0.91	0.91	1.26	1.09	1.62	1.13	2.17	2.27	1.72	3.20	1.65	2.10	2.36	3.38	1.14
Al ₂ O ₃	16.98	18.32	17.25	17.59	17.22	17.81	16.50	16.60	15.99	15.28	16.46	15.42	15.23	14.40	16.98
FeO*	7.67	7.09	9.41	7.61	8.78	9.96	12.27	9.84	10.89	13.50	10.75	12.29	12.68	14.70	10.57
MnO	0.13	0.13	0.17	0.14	0.16	0.17	0.22	0.16	0.18	0.21	0.17	0.20	0.19	0.22	0.18
MgO	9.61	8.18	8.74	6.02	6.82	8.80	6.45	8.80	9.32	6.57	8.80	9.28	8.11	6.67	9.14
CaO	8.57	11.31	10.10	9.26	9.38	11.34	9.54	9.86	10.93	9.66	11.56	10.81	10.15	9.90	11.47
Na ₂ O	3.23	2.93	3.05	3.68	3.69	2.76	3.46	3.33	2.44	2.71	2.41	2.48	2.67	2.52	2.35
K ₂ O	0.62	0.83	0.52	0.89	0.95	0.27	0.63	0.71	0.43	1.05	0.32	0.40	0.67	0.61	0.24
P ₂ O ₅	0.17	0.31	0.34	0.24	0.38	0.14	0.50	0.29	0.30	0.71	0.33	0.56	0.58	0.83	0.16

Major elements are normalized to 100% volatile-free. FeO* = total iron as FeO.

XRF data are from Washington State University, Pullman, WA except where noted below.

^a Composition for sample 76K50 from Quaking Aspen Butte reported by Kuntz et al. (1992).

^b Composition for sample 84KS2 from N Robbers Lava Field reported by Kuntz et al. (1992).

^c Composition for sample 76K119 from Antelope Butte reported by Kuntz et al. (1992).

^d Composition reported here is for a different sample (L80-54) from the same lava flow, analyzed by Dr. Godfrey Fitton, University of Edinburgh.

^e Composition reported here is for sample 6YC-142 from Island Park reported by Leeman et al. (2008, 2009-this volume).

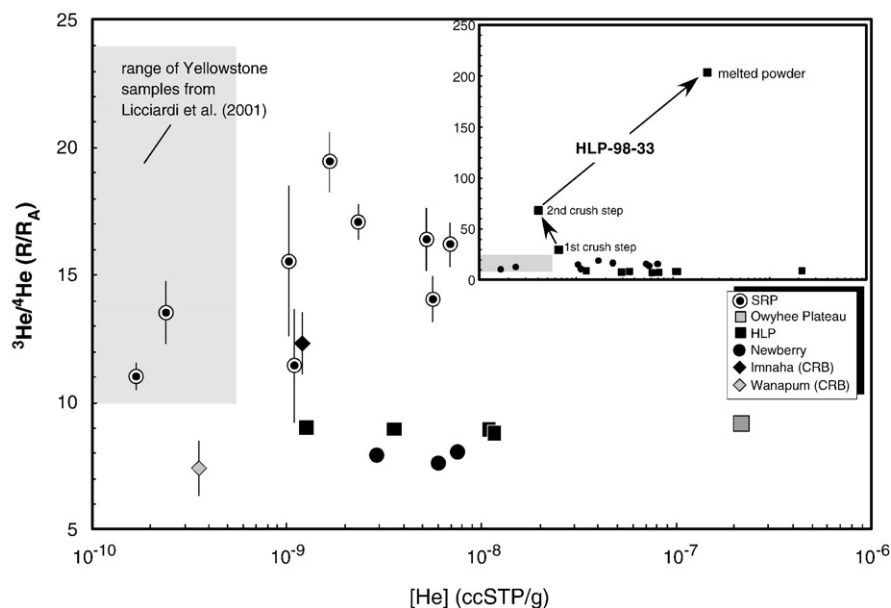


Fig. 1. $^3\text{He}/^4\text{He}$ vs. $[\text{He}]$ in olivine phenocrysts from northwestern U.S. basalts. Evidence for the presence of cosmogenic ^3He , released during stepwise crushing of sample HLP-98-33 and subsequent melting of the crushed powder, is shown in the inset. The range for Yellowstone basalts is from Licciardi et al. (2001), and data from the Columbia River Basalt Group (Imnaha and Wanapum) are from Dodson et al. (1997).

extraneous (non-magmatic) helium, due to interaction of lavas with the crust or to long exposure at the Earth's surface. Lavas that have lost a large fraction of their volatile inventory during ascent through the lithosphere and crust are potentially quite susceptible to lowering of their initial (mantle-derived) $^3\text{He}/^4\text{He}$ ratio by additions of radiogenic helium from the crust. Such an effect would produce lower $^3\text{He}/^4\text{He}$ at lower $[\text{He}]$ levels. (The addition of any post-eruptive helium in olivine should be negligible for the young samples analyzed here.) In contrast, lavas that have been exposed at the Earth's surface for extended time periods are susceptible to addition of cosmogenic ^3He . For example, Yokochi et al. (2005) showed that up to 25% of matrix-sited ^3He could

be extracted during prolonged crushing of olivine, probably because cosmic ray spallation also leads to crystal lattice damage and reduced ^3He retention. Not accounting for such effects could lead to erroneous conclusions about the helium isotope character of the mantle source. Cosmogenic ^3He production will be more pronounced in samples from higher elevations, other factors being equal. Our samples come from a restricted range of elevations (see Table 1) and the elevation effect is unlikely to be significant. Cosmogenic ^3He is also potentially significant in samples collected from hot, dry environments (such as eastern Oregon in the summer) where erosion rates are low and diffusive loss of inherited ^3He is enhanced. We attempted to minimize

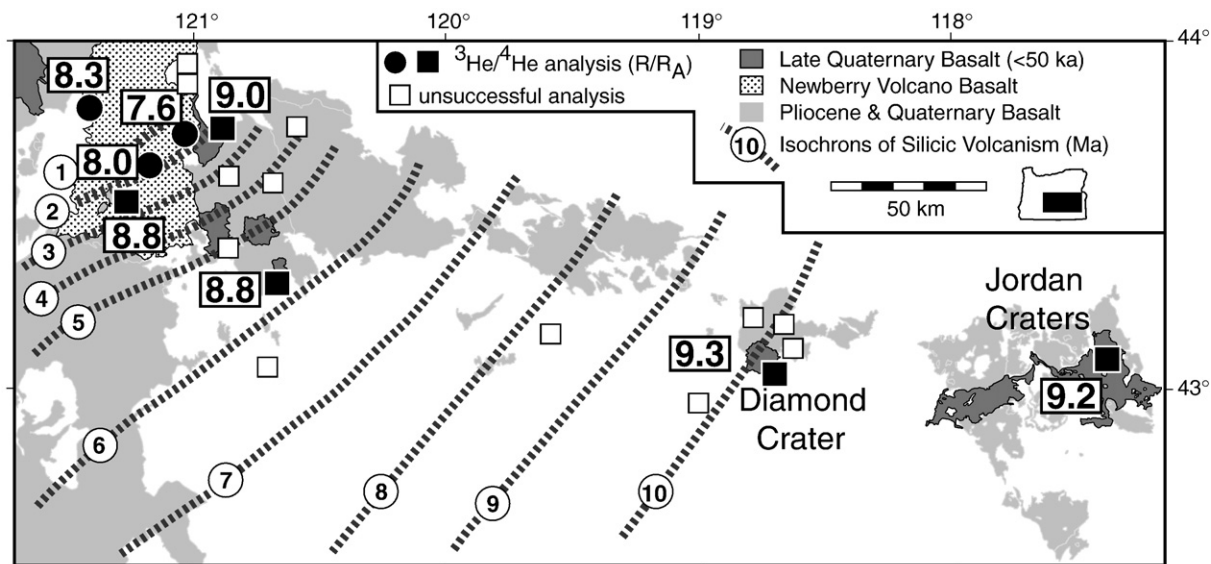


Fig. 2. Map of $^3\text{He}/^4\text{He}$ variations for olivine phenocrysts in basalts from Newberry volcano (filled circles), the Owyhee Plateau and the Oregon High Lava Plains (filled squares). All results are for crushing in vacuum. All samples with reported $^3\text{He}/^4\text{He}$ are Quaternary in age ($n=8$). Older HLP samples ($n=11$; open squares) had insufficient helium contents to obtain a meaningful $^3\text{He}/^4\text{He}$ measurement. Dashed contours are the age of inception of silicic volcanism in millions of years before present. The Owyhee Plateau encompasses Pliocene and Quaternary basalt fields around Jordan Craters. Data shown are from this study except for a single sample from Lava Butte ($^3\text{He}/^4\text{He}=8.3 R_A$ from Licciardi et al., 1999), one of a series of vents that align along a radial fissure of Newberry volcano.

this latter effect by collecting samples from beneath exposed surfaces, or from fresh road cuts and cliff faces whenever possible. If present, cosmogenic ^3He should produce higher $^3\text{He}/^4\text{He}$ with decreasing amounts of helium released by crushing (such as during a stepwise crushing analysis). Because cosmogenic ^3He is dominantly produced and held within the crystalline lattice of minerals, its presence can be further corroborated by analysis of gas released by fusion of the residual powders from the crushing analysis (cf. Kurz, 1986).

Although He concentrations overlap, the helium isotopic compositions of our samples fall into distinct groupings according to tectonic setting. Five young (Quaternary) basalts from the High Lava Plains and Owyhee Plateau have $^3\text{He}/^4\text{He}$ ratios between 8.8 and 9.3 R_A ; essentially, these data are uniform within the analytical uncertainty

(Table 1). One sample from Diamond Craters (HLP-98-38) was analyzed in duplicate and the results agree within analytical uncertainty (its weighted mean $^3\text{He}/^4\text{He} = 9.3 \pm 0.5 R_A$). A basalt from Green Butte (30WHL98), a kipuka of pre-Newberry lava flows (Fig. 2), has $^3\text{He}/^4\text{He} = 8.8 R_A$ similar to other HLP lavas. Basalts from Newberry volcano (2 analyses from this study plus one from Licciardi et al., 1999) show slightly lower $^3\text{He}/^4\text{He}$ (7.6–8.3 R_A), and overlap the range for the Cascades volcanic arc (7.0–8.4 R_A ; Poreda and Craig, 1989; Cerling and Craig, 1994; Licciardi et al., 1999; Dodson and Brandon, 1999). Eleven additional samples of hand-picked olivine from mostly older HLP basalts were also analyzed (sample locations are shown in Fig. 2). Unfortunately, all of these older samples had ^3He contents near the

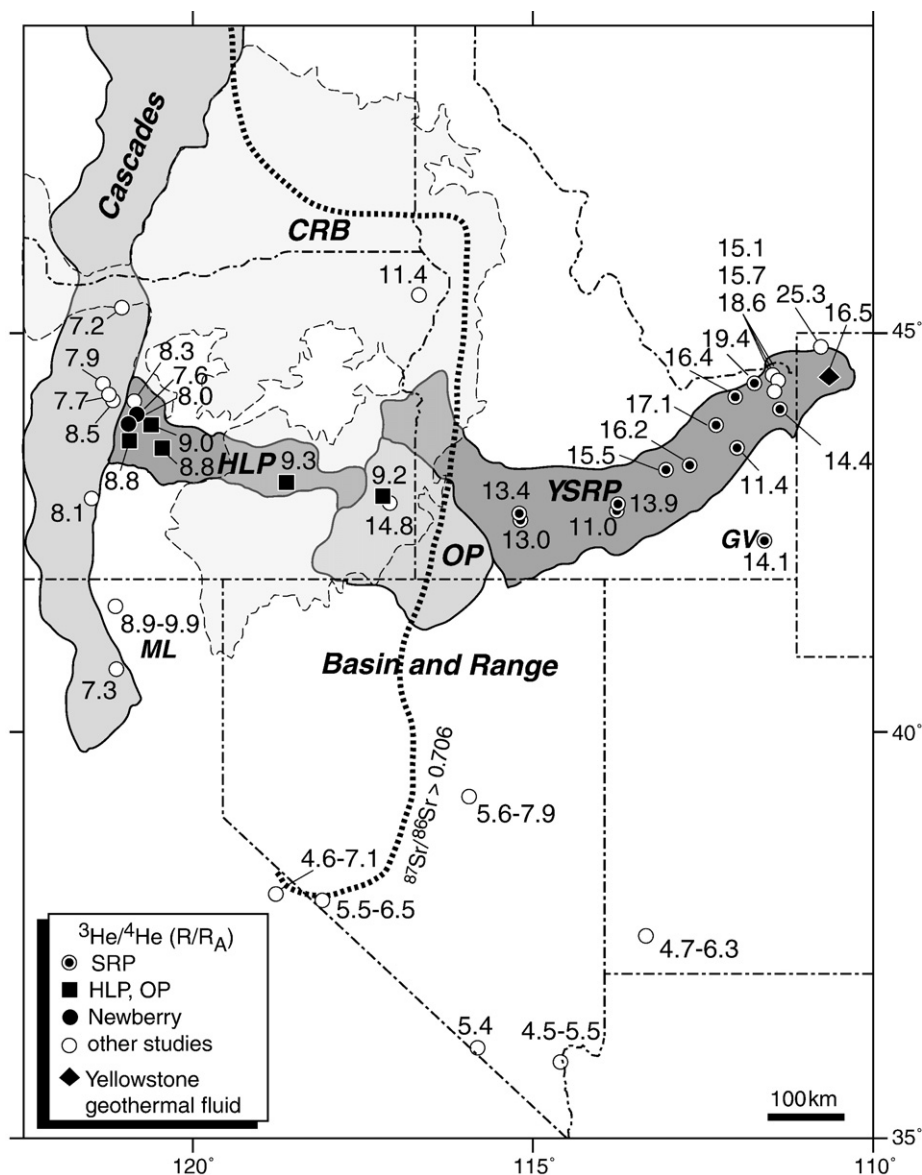


Fig. 3. Map of $^3\text{He}/^4\text{He}$ (R/R_A) variations in the western U.S. Geologic/physiographic provinces are outlined, including the distribution of Columbia River and Steens middle Miocene flood basalts from Camp and Hanan (2008). Locality abbreviations are CRB = Columbia River basalts, HLP = High Lava Plains, YSRP = Yellowstone–Snake River Plain, OP = Owyhee Plateau, GV = Gem Valley, ML = Medicine Lake. The dashed line for $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ is taken to reflect the edge of the North American craton. The extent of the Basin and Range north of the YSRP is not shown. All basalts analyzed for $^3\text{He}/^4\text{He}$ are young (Pleistocene to Recent) with the exception of the Columbia River basalts (Imnaha and Wanapum formations; 16 Ma) and a single Miocene lava from the SRP (westernmost sample of 13.4 R_A). Cascades data are for basalts from Mt. Mazama (Cerling and Craig, 1994), and from Belknap Crater, Clear Lake and Yapoah Crater lava flows (Licciardi et al., 1999), plus fumaroles from Lassen Park and Mt. Hood from Poreda and Craig (1989). Basin and Range basalts are from Reid and Graham (1996) and Dodson et al. (1998). CRB results are from Dodson et al. (1997). Data for three Island Park lavas and one lava north of Yellowstone Caldera (Osprey basalt) are from Abedini et al. (2006). The highest $^3\text{He}/^4\text{He}$ for geothermal fluid in Yellowstone Park is 16.5 R_A (Craig et al., 1978). One lava from the Jordan Craters volcanic field (Owyhee Plateau) has $^3\text{He}/^4\text{He} = 14.8 R_A$, as reported in an abstract (Craig, 1997); the analytical uncertainty, gas extraction method, and He content of that sample are unknown and we therefore excluded it from further discussion.

detection limit of the mass spectrometer and no reliable information could be obtained concerning their He isotopic composition.

One outlier sample (HLP-98-33) from the HLP yielded an elevated $^3\text{He}/^4\text{He}$ ratio of $22 \pm 1 R_A$ the first time it was crushed. A second split of olivine from this sample was analyzed by crushing in two steps, and then by melting the residual powder. All analyses of HLP-98-33 gave elevated $^3\text{He}/^4\text{He}$ compared to other Quaternary basalts from the HLP region. The two stepwise crushing results for this sample yielded increasing $^3\text{He}/^4\text{He}$ with decreasing He content (30 and 69 R_A , respectively; Fig. 1 inset). These data, combined with low He contents (1 to 3×10^{-9} ccSTP/g), strongly suggest that the elevated $^3\text{He}/^4\text{He}$ in this sample is due to the presence of cosmogenic ^3He produced during surface exposure of the lava. This suspicion was confirmed by the melting results for the residual powder, which yielded a $^3\text{He}/^4\text{He}$ ratio of $200 R_A$. Because this melted $^3\text{He}/^4\text{He}$ ratio is too high to represent any reasonable estimate for a present day reservoir within the Earth (e.g., Porcelli and Elliott, 2008), we have excluded this sample from further discussion.

A single analysis of $14.8 R_A$ was reported in an abstract by Craig (1997) for a basaltic lava from the Jordan Crater volcanic field (Owyhee Plateau). We obtained $^3\text{He}/^4\text{He} = 9.2 \pm 0.1 R_A$ for our sample from this locality (Fig. 3). Because no details are available concerning the extraction method or the He content for Craig's sample, we consider only our new datum in the subsequent discussion of this area. Clearly, more work in the HLP-Owyhee Plateau region is warranted.

Olivine phenocrysts separated from Snake River Plain basalts collected in this study have a range of $^3\text{He}/^4\text{He}$ between 11.0 and 19.4 R_A (Fig. 3), with relatively low He contents (0.2 to 7×10^{-9} ccSTP/g;

Fig. 1). These concentrations overlap values measured in olivines from High Lava Plains basalts (this study), and those measured by crushing in a ^3He exposure age study of basalt boulders in Yellowstone glacial moraines (Licciardi et al., 2001). All SRP $^3\text{He}/^4\text{He}$ ratios measured here and previously reported by Craig (1997) are higher than the range observed in MORBs distal from ocean island hotspots (7 – $9 R_A$; Graham, 2002). The highest $^3\text{He}/^4\text{He}$ measured in this study is $19.4 \pm 1.5 R_A$ for a basalt from the Spencer–Kilgore area immediately to the west of Yellowstone. This value is comparable to the highest $^3\text{He}/^4\text{He}$ measured in geothermal samples from Yellowstone ($16.5 R_A$; Craig et al., 1978). Abedini et al. (2006) report an even higher $^3\text{He}/^4\text{He}$ value ($25 \pm 4.4 R_A$, 1σ) for the Osprey basalt from north of the Yellowstone caldera. We also call attention to our datum for the Quaternary basalt from Gem Valley, which is near the southernmost extent of SRP petrologic influence. This basalt may have erupted from a vent within 50 km of the SRP as part of the volcanic fields that are generally considered related to the development of the SRP (Armstrong et al., 1975; Fiesinger et al., 1982). The Gem Valley basalt analyzed here signifies that elevated $^3\text{He}/^4\text{He}$ ratios ($14.1 R_A$) may be characteristic of a very broad region (~ 100 km) away from Yellowstone.

5. Discussion

Plume theory forms a central paradigm in mantle convection, the formation of large igneous provinces, and the origin of ocean island volcanism (e.g., Duncan and Richards, 1991; Davies and Richards, 1992). Whereas age-progressive volcanic tracks are common in oceanic settings, they are rare on the continents – the most notable

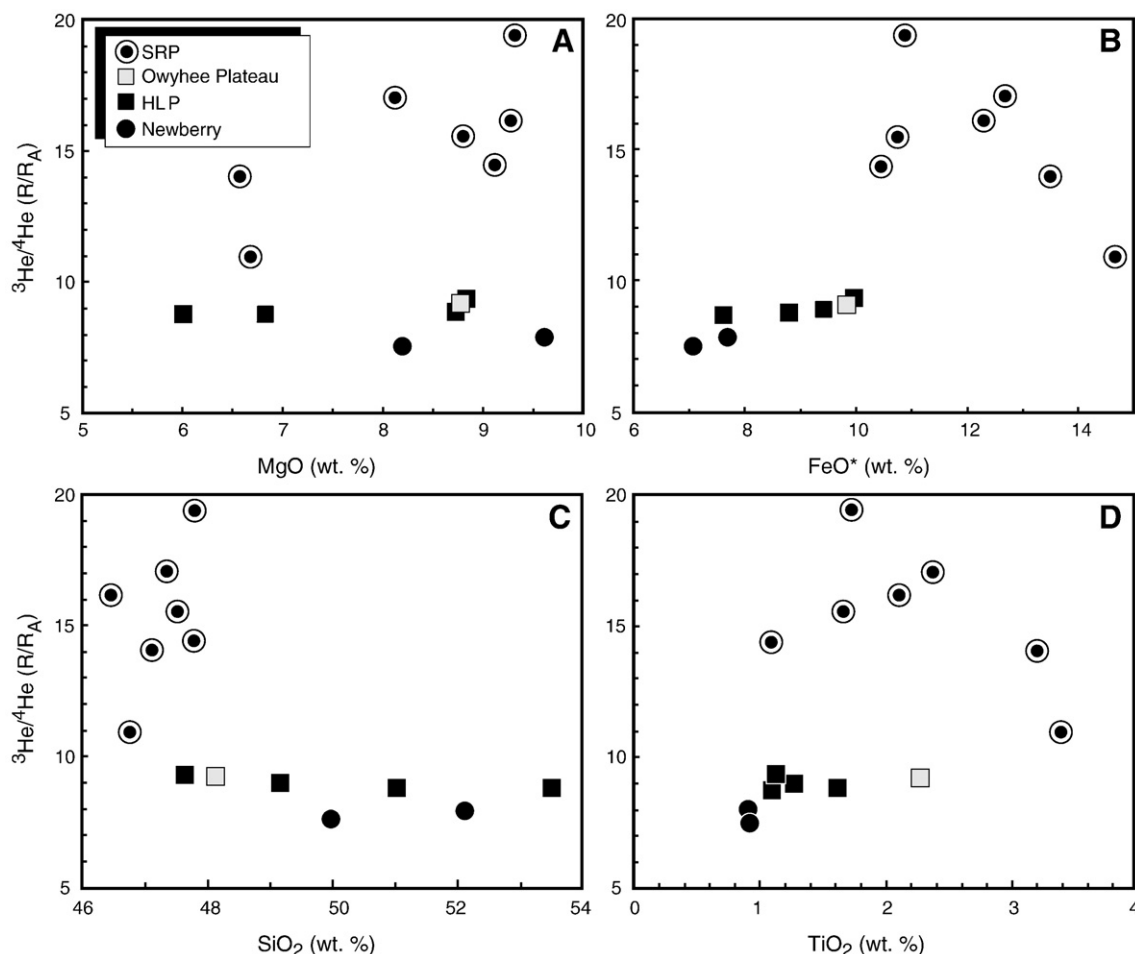


Fig. 4. $^3\text{He}/^4\text{He}$ variation with major elements. (A), MgO, (B), FeO^* , (C), SiO_2 , (D) TiO_2 . All helium analyses are for olivine separates crushed in vacuum; major elements are from Table 2 for whole rock powders.

examples being the Yellowstone–Snake River Plain province in North America and the Cenozoic volcanic province along the eastern margin of Australia (Duncan and Macdougall, 1989). These continental systems offer a rare opportunity to investigate changes in mantle plume–continental lithosphere interaction during tectonic plate migration.

5.1. $^3\text{He}/^4\text{He}$ and major element variations

The variation of $^3\text{He}/^4\text{He}$ with selected major elements is shown in Fig. 4. While olivine accumulation can be locally important for basaltic lavas, the magnitude of the TiO_2 and FeO^* variations is too large to be explained solely by olivine accumulation in the samples analyzed here. The crude $^3\text{He}/^4\text{He}$ covariation with MgO , FeO^* and TiO_2 for the SRP basalts hints at the possibility that addition of crustal helium during crystal fractionation in some of these young basalts leads to slightly lower $^3\text{He}/^4\text{He}$. However, the analytical uncertainties in $^3\text{He}/^4\text{He}$ are large and the data set is small in number and broad in spatial coverage. $^3\text{He}/^4\text{He}$ ratios in a cogenetic suite of SRP basalts have yet to be analyzed to test for crustal contamination effects at the scale of an individual volcanic area. In contrast to the SRP, no covariation of $^3\text{He}/^4\text{He}$ with major elements is observed in the HLP–OP basalts of this study (Fig. 4). We conclude that while crustal contamination may modulate basaltic $^3\text{He}/^4\text{He}$ ratios along the SRP, the effect is not strong and it does not obscure the elevated $^3\text{He}/^4\text{He}$ mantle source signature.

5.2. Spatial variability of $^3\text{He}/^4\text{He}$ and mantle source provinces of the Western U.S.

Elevated $^3\text{He}/^4\text{He}$ ratios, typically seen in mantle hotspot regions such as Hawaii and Iceland (e.g., Breddam et al., 2000; Kurz et al., 2004), are absent along the High Lava Plains and Owyhee Plateau (Fig. 2). The range of values across the HLP and OP is relatively narrow,

between 8.8 and 9.3 R_A ($n=5$), and these values are identical within analytical uncertainty. Basalts from Newberry volcano have slightly lower $^3\text{He}/^4\text{He}$ (7.6–8.3 R_A), and overlap the range for basalts from the Cascades volcanic arc (7.0–8.4 R_A). Collectively, these results suggest that helium in the HLP mantle source is dominated by shallow asthenospheric mantle, similar to the reservoir commonly sampled by magmatism along mid-ocean ridges. Although speculative, there appears to be an abrupt decrease in the influence of the downgoing Juan de Fuca Plate just to the east of the Cascades and Newberry volcano where they juxtapose the HLP region, marked by slightly lower $^3\text{He}/^4\text{He}$ in the Cascades region. The observation that Newberry volcano resembles the Cascade arc in its helium isotope characteristics contrasts with suggestions that it is related to a mantle hotspot based on its displacement from the arc axis and on seismic tomography (Xue and Allen, 2006). This “hotspot” appears to have a shallow mantle origin based on its $^3\text{He}/^4\text{He}$ ratio.

For comparison, all He isotope data for western U.S. basalts are shown in map view in Fig. 3. Previous studies have shown that lavas from the Basin & Range province and adjacent areas in the southwestern U.S. extend to low $^3\text{He}/^4\text{He}$ ratios, to $<5 R_A$, reflecting the involvement of Proterozoic continental lithosphere (Reid and Graham, 1996; Dodson et al., 1998). This map accentuates the ^3He anomaly associated with the Yellowstone–Snake River Plain province.

All SRP basalts analyzed to date have $^3\text{He}/^4\text{He}$ significantly higher than expected for the upper mantle. The SRP lavas analyzed here are relatively young (Pleistocene and younger) with the exception of one Miocene (ca. 8 Ma) basalt from the western Mt. Bennett Hills (L00-35) that has $^3\text{He}/^4\text{He} = 13.4 R_A$. The elevated $^3\text{He}/^4\text{He}$ observed in young SRP basalts is therefore also a characteristic of older SRP basalts downstream of the inferred Yellowstone plume location in the past. The young SRP basalts appear to define a crude gradient in $^3\text{He}/^4\text{He}$ over a lateral distance of ~400 km, from 11 R_A in the west to $>19 R_A$ near Yellowstone (Fig. 5). Such high ratios are absent elsewhere in the

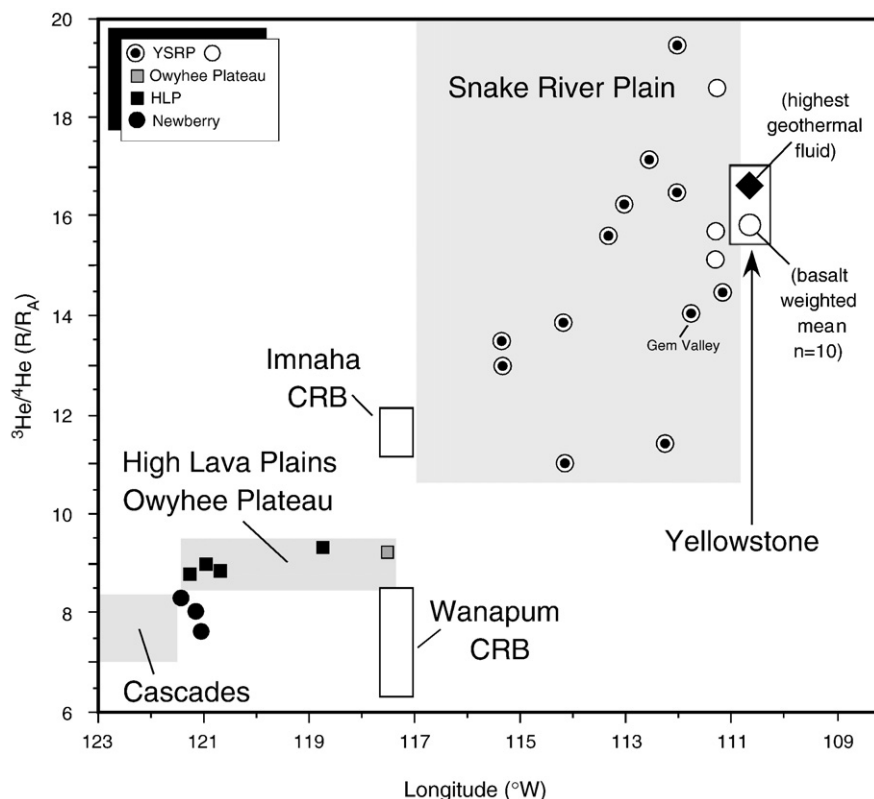


Fig. 5. $^3\text{He}/^4\text{He}$ vs. longitude ($^{\circ}\text{W}$) for basalts from the northwestern U.S. Data sources are the same as for Figs. 1–3. The weighted mean $^3\text{He}/^4\text{He}$ for Yellowstone basalts (15.8 R_A ; weighted inversely to the analytical uncertainty; $n=10$, which excludes 2 samples with very low $^3\text{He}/^4\text{He}$ of 4 R_A and very low He contents, as reported by Licciardi et al., 2001) is similar to the highest $^3\text{He}/^4\text{He}$ measured in geothermal fluid samples (Murdering Mudpots volcano, $^3\text{He}/^4\text{He} = 16.5 R_A$; Craig et al., 1978).

western U.S. (Fig. 3). The high $^3\text{He}/^4\text{He}$ ratios along the SRP are consistent with geophysical evidence (Lowry et al., 2000; Yuan and Dueker, 2005; Waite et al., 2006) suggesting the presence of plume-derived material, either in the shallow asthenosphere or emplaced within the continental lithosphere downstream from Yellowstone. The $^3\text{He}/^4\text{He}$ gradient suggests that the contribution from the plume source to young volcanism along the SRP decreases westward.

5.3. The origin of elevated $^3\text{He}/^4\text{He}$ along the Snake River Plain

The isotope systematics involving He and lithophile tracers such as Sr, Nd and Pb may be explained in three alternative ways, which we discuss below. One possibility is that the high $^3\text{He}/^4\text{He}$, low $^{143}\text{Nd}/^{144}\text{Nd}$ signatures of the SRP and Yellowstone region reflect mixing among different geochemical components, including shallow upper

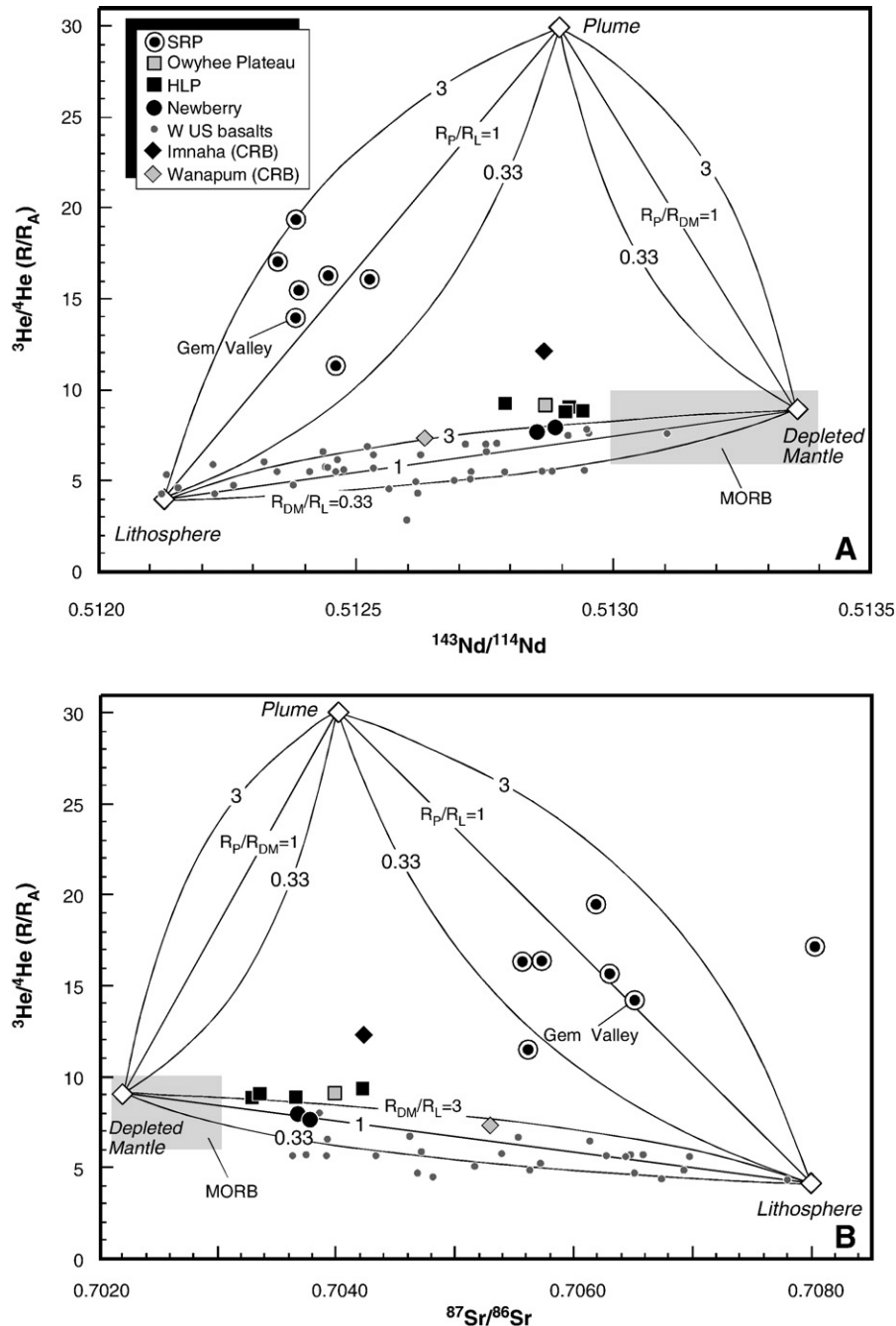


Fig. 6. A) $^3\text{He}/^4\text{He}$ (R/R_A) vs. $^{143}\text{Nd}/^{144}\text{Nd}$ and B) $^3\text{He}/^4\text{He}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for western U.S. basalts. Data from Table 2 are plotted with those for western U.S. basalts (Reid and Graham, 1996; Dodson et al., 1998), and Columbia River Basalts (Imnaha and Wanapum volcanic groups) from Dodson et al. (1997). Two data points in (b) (Gem Valley and Jordan Craters–Owyhee Plateau) are paired results using unpublished Sr isotope data for lavas from the same area as the He isotope analyses (see Table 1). The range for mid-ocean ridge basalts (MORB) distal from ocean island hotspots is from the literature. Curves show representative binary mixing hyperbolae between: (1) putative plume mantle with $^3\text{He}/^4\text{He} = 30 R_A$, $\epsilon_{\text{Nd}} = +5$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.7040$, similar to the “C” or common composition observed in ocean island hotspot basalts and MORB (Hanan and Graham, 1996); (2) depleted MORB-source mantle having $^3\text{He}/^4\text{He} = 9 R_A$, $\epsilon_{\text{Nd}} = +14$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.7022$, and (3) lithospheric mantle having $^3\text{He}/^4\text{He} = 4 R_A$, $\epsilon_{\text{Nd}} = -10$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.7080$. Hypothetical end-members and curves are for illustration purposes only; other end-members are possible, particularly for continental lithosphere which varies across the western U.S. (Dodson et al., 1998). R = He/Nd concentration ratio in (A), and He/Sr in (B), where subscripts P, L and DM denote plume, lithosphere and depleted mantle, respectively.

mantle (MORB source with $^3\text{He}/^4\text{He} \sim 8 R_A$ and high $^{143}\text{Nd}/^{144}\text{Nd}$), lithospheric mantle and (or) crust (having low $^3\text{He}/^4\text{He}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$), and plume mantle (having high $^3\text{He}/^4\text{He}$ and intermediate $^{143}\text{Nd}/^{144}\text{Nd}$; see Fig. 6). A second possibility is that Yellowstone has an unusual mantle plume source with high $^3\text{He}/^4\text{He}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ (e.g., if one takes the He and Nd isotope compositions for SRP basalts at face value as indicating a discrete mantle composition). Collectively, the He–Pb–Nd–Sr isotope characteristics of the SRP basalts are atypical of mantle sources deduced from studies of oceanic basalts, with the exceptional case of Samoa (Farley et al., 1992; Jackson et al., 2007). A third possibility is that lithospheric mantle is the dominant magma source, and the elevated $^3\text{He}/^4\text{He}$ reflects enrichment of $^3\text{He}/(\text{U} + \text{Th})$ in the continental lithospheric mantle. An added complication that we discuss is the possibility that He may be decoupled from other lithophile elements owing to its selective transport in a fluid phase – in which case it would behave somewhat independently of elements like Sr, Nd, or Pb that have a strong affinity for silicate melts (e.g., Stone et al., 1990; Valbracht et al., 1996). We consider this complication and the three different alternatives below.

We argue that the spatial pattern of $^3\text{He}/^4\text{He}$ in the western U.S. is consistent with the influence of a thermochemical mantle plume rising beneath Yellowstone. This suggests that either the upper mantle (asthenosphere) or the mantle portion of the continental lithosphere downstream from Yellowstone contains plume-derived helium. According to this scenario, the elevated $^3\text{He}/^4\text{He}$ along the SRP and in the Yellowstone region ultimately originates from the deep mantle. In contrast, the magmatic Sr, Nd and Pb isotopic signatures appear to be dominated by material from the continental lithosphere (Doe et al., 1982; Leeman et al., 1985; Hildreth et al., 1991; Hanan et al., 2008).

Warm sub-lithospheric mantle beneath the SRP appears to be broadly consistent with geophysical observations and the numerical model of Lowry et al. (2000). In that model, swell elevation (produced by thermal buoyancy from a hypothetical Yellowstone plume having a buoyancy flux similar to that for Hawaii) is estimated from a synthesis of topography, gravity measurements, crustal-scale seismic refraction velocity, and surface heat flow. The model swell elevation represents topography produced by buoyancy beneath the lithosphere. The numerical model also incorporates a variable thickness lithosphere (computed from lateral viscosity variations), lithospheric strain and the buoyancy of a melt depleted residue, as well as an imposed uniaxial NE–SW lithospheric extension downstream of Yellowstone (~ 1 cm/y opening across the Basin & Range). The model predicts a downstream thermal anomaly of ~ 150 °C in the sub-lithospheric upper mantle for several hundred kilometers, comparable to the length scale of $^3\text{He}/^4\text{He}$ variation in young SRP basalts, and similar to the seismic tomographic anomaly observed in the upper mantle below this region (Humphreys et al., 2000; Schutt and Humphreys, 2004; Roth et al., 2008). Alternatively, Leeman et al. (2009–this volume) show that SRP basalts can be derived from a mantle source having a potential temperature ≤ 1450 °C, significantly lower than estimates for typical hotspots like Hawaii or Iceland, but broadly similar to ambient mantle sampled by mid-ocean ridges and the Basin and Range province. From a petrologic perspective, SRP magmatism might therefore be a consequence of the extensional deformation that characterizes much of the western U.S., and be dominantly linked to partial melting of continental lithospheric mantle, with additional heat and fluid contributions from sublithospheric (asthenospheric or plume) mantle (Manea et al., 2009–this volume).

Several additional points pertaining to the above (multi-source) scenario should be considered.

(1) Plume-derived melts may ascend and acquire a lithospheric signature via interaction with lithospheric mantle (and possibly lower crust). The high $^3\text{He}/^4\text{He}$ of SRP basalts indeed appears to indicate a plume derivation, but it may suffer dilution by lithospheric and asthenospheric melts derived from sources that have lower $^3\text{He}/^4\text{He}$. One possible, but *ad hoc*, explanation is that

magma derived from the plume mantle has higher elemental ratios of He/(Sr, Nd, Pb) than the lithosphere though which it passes (Fig. 6). This is analogous to the mixing model proposed by Hanan et al. (2008) to explain the Pb isotope observations in drilled SRP basalts. According to that model, the elevated Pb concentration of the lithospheric mantle compared to the plume source, typically by a factor of 100, is responsible for the dominant ancient cratonic Pb signature observed in SRP basalts, which are formed by mixing of magmas derived by melting of these two distinct sources (plume mantle vs. lithospheric mantle). The “preferential” sampling of elevated $^3\text{He}/^4\text{He}$ could simply reflect the mass balance associated with mixing partial melts from the plume and lithospheric mantle if they have dramatically different He/Nd and He/Sr ratios.

(2) Another possibility is that kinetic effects associated with wallrock exchange are important. While young SRP basalts are often interpreted to involve a continental lithospheric source, they do show some chemical similarities to oceanic basalts derived from enriched mantle attributed to mantle plumes (Reid, 1995). The Th isotope signature of basalts from the Great Rift of southern Idaho resembles that of the depleted mantle source for MORB (Reid, 1995), in stark contrast to the Pb isotope systematics just discussed. Helium and thorium in this case appear to be similar in their ability to transfer a sub-lithospheric signature to SRP basalts with only minor modification. This may suggest that these two elements have a similar chemical Peclet number (the product of a system's characteristic scale length, or grain size a , and fluid velocity v divided by the diffusion coefficient D ; $Pe = v \cdot a/D$). When $Pe \gg 1$, dispersion of a chemical species by advection will dominate and large gradients can exist in a system; when $Pe \ll 1$ diffusion dominates mass transport. If deep (> 10 km) trans-lithospheric magma transport is by percolative flow rather than by hydrofracture, then trace element concentrations may be altered locally and at different rates by exchange with the surrounding wallrock. This may lead to a retardation in transport of elements that are more compatible in the surrounding solid compared to the average magma ascent velocity. Navon and Stolper (1987) showed that when percolation distance is large relative to grain size, flowing melts that are not in equilibrium with the surrounding matrix show chromatographic effects whereby incompatible elements migrate faster through the column than more compatible ones. Therefore, unique information carried by the He and Th isotope compositions of SRP basalts may also be rationalized as due to Th and He having faster percolation rates into and through the continental lithosphere compared to other incompatible elements such as Sr, Nd and Pb.

(3) A third possibility is that the basaltic melts along the SRP are dominantly lithosphere-derived, e.g., via melting of the ancient mantle keel associated with cratonic North America. In this case, both low He contents and low $^3\text{He}/^4\text{He}$ ratios would be expected, so the observed high $^3\text{He}/^4\text{He}$ may indicate the addition of plume-derived helium from ascending, ^3He -rich deep mantle (e.g., either as a carbonate-rich magma, or as a CO_2 gas phase released from an ascending plume). Metasomatic enrichment of the lithosphere in the wake of a mantle plume was also suggested to account for the MORB-like Th isotope signatures of SRP basalts (Reid, 1995). This alternative is also a multiple source model, but in this case it is a binary model wherein different magmatic components originate in separate mantle domains (e.g., Valbracht et al., 1996). This type of model has a long history. For example, Bailey (1970, 1980, 1983) and Wyllie (1988) reasoned that volatiles are focused from the underlying mantle into zones of weakness in the lithosphere, such as extensional rifts or areas downstream of mantle plumes. This flux may lead to melting of the lower crust and lithospheric mantle, and the localization along rift zones of continental magmas (especially alkali-rich ones). Evidence for such volatile focusing is the emission of CO_2 during volcanically quiescent periods, such as that observed at several East African Rift localities. This model is rather speculative for the SRP, but the association of helium with

carbon dioxide in mantle-derived magmas is well established (e.g., Marty and Jambon, 1987).

- (4) Based on their narrow range of $^3\text{He}/^4\text{He}$, the HLP basalts may represent melting of asthenospheric mantle that has a negligible plume contribution. Alternatively, melting of an “oceanic” lithospheric mantle domain attached to the accreted terranes in this region might be responsible for the observed $^3\text{He}/^4\text{He}$, as well as Sr–Nd–Pb isotopic characteristics. The HLP mantle source is similar to that for depleted mid-ocean ridge basalts in its $^3\text{He}/^4\text{He}$ characteristics, but it is slightly enriched in key trace elements, such as Sr, Pb and Ba, and more akin to some ocean island basalts in its Sr and Nd isotope compositions (Fig. 6). In the HLP region, temporal variation in $^3\text{He}/^4\text{He}$ is an important constraint but we currently have only a single reference. The Imnaha basalts, the most primitive lavas of the Columbia River Basalt Group (Dodson et al., 1997), resemble the HLP basalts in Sr and Nd isotope characteristics but have elevated $^3\text{He}/^4\text{He}$ (Fig. 6). The elevated $^3\text{He}/^4\text{He}$ of the Imnaha basalt suggests a plume-related input around 16 Ma, possibly with the He–Sr–Nd characteristics of the plume end-member shown in Fig. 6 (i.e., the ‘C’ composition commonly observed in OIBs and MORBs; Hanan and Graham, 1996). The absence of an elevated $^3\text{He}/^4\text{He}$ in young HLP basalts requires that any plume helium contribution has since dissipated, either because plume residual mantle is no longer present beneath the HLP region, or because the depth of melting has migrated to where it only intersects normal asthenospheric mantle.

A potential complication is the extent to which the spatial pattern of $^3\text{He}/^4\text{He}$ variation reflects metasomatism of lithospheric mantle by fluids derived from small degree, plume-derived melts that crystallize near the lithosphere–asthenosphere boundary (point 3 above). Such melts would subsequently freeze at shallow levels in the lithospheric mantle during magma “heat death” (e.g., Spera, 1984). If vapor dominated, these fluids might not carry a strong signature of plume lithophile elements yet they could locally dominate the noble gas signature. Melting associated with subsequent tectonic extension could remobilize such crystallized phases because they would melt preferentially during the earliest periods of thermal perturbation (cf. Harry and Leeman, 1995). On the other hand, such ^3He -enrichment of lithospheric mantle seems unlikely based on observations at ocean island hotspots. For example, although late stage (“post-erosional”) volcanism in the Hawaiian islands shows a transition to lithosphere-dominated melts over time, these lavas show no elevation in $^3\text{He}/^4\text{He}$ indicative of earlier plume metasomatic effects (e.g., Kurz et al., 1983, 1996). Furthermore, decreasing $^3\text{He}/^4\text{He}$ away from the site of plume impingement is consistent with observations of ocean island hotspots that exhibit coeval volcanism stretched over several hundreds of kilometers (analogous to the young volcanism along the SRP). For example, in Iceland (Breddam et al., 2000) and in the Galápagos (Graham et al., 1993; Kurz and Geist, 1999), the highest $^3\text{He}/^4\text{He}$ ratios occur in areas of active magmatism above the purported location of plume impingement (central Iceland and western Galápagos, respectively), and $^3\text{He}/^4\text{He}$ decreases in coeval lavas away from those areas.

In our opinion, the spatial pattern of $^3\text{He}/^4\text{He}$ variations in young basalts along the SRP is most plausibly explained by a mixing scenario that involves magma derived from plume, asthenospheric and lithospheric sources, with dilution of the plume component in the upper mantle downstream from Yellowstone. We also note that increasing $^3\text{He}/^4\text{He}$ ratios in the SRP lavas appear to be accompanied by Sr and Nd isotopic values that become more lithospheric-like (Fig. 6). This could be accounted for by a change in R values ($R = \text{He}/\text{Nd}$ or He/Sr) for the differing source materials, perhaps associated with eastward migration of volcanic activity. This might occur if lithospheric mantle downstream of the hotspot becomes preferentially “mined” of its He relative to Sr and Nd (which leads to an increase in $R_{\text{plume}}/R_{\text{lithosphere}}$). Given the present data set and the scatter observed in Fig. 6 we can only speculate that such a process might be occurring.

A second possibility we consider is that Yellowstone has an unusual mantle plume source, having high $^3\text{He}/^4\text{He}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ (e.g., if one takes the He and Nd isotope compositions for SRP basalts at face value as indicating a discrete mantle composition). The elevated $^3\text{He}/^4\text{He}$ signal is best preserved in our sample suite where the lithophile isotopes suggest a strong involvement of continental lithosphere (Fig. 6). As noted by Reid (1995), both the isotopic and chemical characteristics of lithophile elements in SRP basalts are remarkably similar to enriched mantle sources deduced from oceanic basalts, so the question of whether this character reflects a recycled continental signature in the Yellowstone plume is intriguing. The combination of elevated $^{87}\text{Sr}/^{86}\text{Sr}$, low $^{143}\text{Nd}/^{144}\text{Nd}$, and high $^3\text{He}/^4\text{He}$ observed in SRP basalts is rare in the ocean basins, although Samoa represents a possible counterpart (Farley et al., 1992; Jackson et al., 2007). Nevertheless, given the potential for assimilation of continental crust and/or lithosphere by SRP basalts, use of the observed Sr and Nd isotope signatures along the SRP as plume source indicators is tenuous given the present data set.

A third possibility we consider is that the elevated $^3\text{He}/^4\text{He}$ reflects an ancient enrichment of $^3\text{He}/(\text{U} + \text{Th})$ in the continental lithospheric mantle. Some investigators have suggested that high $^3\text{He}/^4\text{He}$ ratios could be an intrinsic feature of the shallow mantle rather than the deep mantle (Anderson, 1998; Christiansen et al., 2002). These arguments are based on the reasoning that incompatible elements (such as He) will be concentrated in the upper mantle and lithosphere. However, continental intraplate volcanic rocks generated at or near the lithosphere–asthenosphere boundary layer, such as intraplate alkaline volcanics (Day et al., 2005) and lavas from the Basin and Range Province (Reid and Graham, 1996; Dodson et al., 1998) have $^3\text{He}/^4\text{He}$ ratios that resemble MORB values or are lower. This is partly due to upward concentrations of U and Th which subsequently decay to produce radiogenic ^4He , and hence, lower $^3\text{He}/^4\text{He}$ ratios. In addition, $^3\text{He}/^4\text{He}$ ratios in lithospheric mantle xenoliths from continental regions show a narrow range at individual localities that often overlaps with the MORB range (Dunai and Porcelli, 2002), evidence for the periodic influx of magma and fluids from the upper mantle. Thus, lithospheric or asthenospheric mantle sources with high $^3\text{He}/^4\text{He}$, reflecting high time-integrated $^3\text{He}/(\text{U} + \text{Th})$, are unlikely to be a general feature of the Earth. The higher $^3\text{He}/^4\text{He}$ lavas, from the SRP basalts, cluster together (Fig. 6) and may represent mixtures dominated by plume-derived and lithosphere-derived magmas, with only minor involvement of depleted upper mantle. In contrast, basalts from the southwestern U.S. stretch along mixing trajectories between depleted mantle and continental lithosphere (Fig. 6). These overall He–Sr–Nd relations further support the notion that ancient source reservoirs within the continental lithosphere do not house high $^3\text{He}/^4\text{He}$ ratios.

Given the evidence, we consider the first alternative (multi-source mixing of magmatic components derived from a mantle plume, the asthenosphere and the lithosphere) as the most likely explanation for the origin of the He–Nd–Sr isotope signatures observed in basalts from the northwestern U.S. The second alternative (a unique mantle plume composition) appears to be less likely given the presence of old continental mantle in this region. Nevertheless, this explanation is possible, because in rare instances such as Samoa, similar He–Nd–Sr isotope systematics are observed in the ocean basins. The third alternative, an ancient $^3\text{He}/(\text{U} + \text{Th})$ enrichment within the continental lithospheric mantle, appears to be the least likely explanation.

6. Conclusions

Collectively, $^3\text{He}/^4\text{He}$ variations in the northwestern U.S. reveal three distinct tectono-magmatic provinces: (1) the Cascades volcanic arc including Newberry volcano; (2) the High Lava Plains and Owyhee Plateau; and (3) the Yellowstone–Snake River Plain system. The high $^3\text{He}/^4\text{He}$ ratios and their spatial variation reveal the unique character of the Yellowstone–Snake River Plain system. The Snake River Plain is a prime location for future study of the potential interactions between a deeply

sourced mantle plume and continental lithosphere, through temporal studies of lavas obtained via deep continental drilling.

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