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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 $^3He/^4He$ 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 $^3He/^4He$ 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, $^3He/^4He$ ranges from ~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 $^3He/^4He$ 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 $^3He/^4He$ in basalts along the SRP, the effect is not strong and it does not obscure the elevated $^3He/^4He$ mantle source signature. In contrast, young basalts from the HLP and the OP have $^3He/^4He$ 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 $^3He/^4He$ (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 $^3He/^4He$ signature along the SRP: (1) multi-component mixing of (a) magmas and/or CO_2-rich fluids derived from plume mantle having high $^3He/^4He$, (b) continental lithosphere having low $^3He/^4He$, 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.

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.

$^3He/^4He$ 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) $^3He/^4He$ reflects additional contributions from lithospheric mantle or crust (Dunai and Porcelli, 2002; Gautheron and Moreira, 2002; Day et al., 2005). Elevated $^3He/^4He$, above 10 R_A, indicates derivation from a region with higher time-integrated $^3He/(U+Th)$, 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 $^3He/^4He$ 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 $^3He/^4He$ ratios between 5.5 and 9.5 R_A; because high-$^3He/^4He$ 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 $^3He/^4He$ 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 $^3He/^4He$ 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 $^3He/^4He$ ratios between 9.4 and 13.7 R_A in accreted terrains 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 volcaniclastic 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 Mg#>60), high-alumina (80% have Al_2O_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