

Supereruptions of the Snake River Plain: Two-stage derivation of low- $\delta^{18}\text{O}$ rhyolites from normal- $\delta^{18}\text{O}$ crust as constrained by Archean xenoliths

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ABSTRACT

Supereruptive volumes of low- $\delta^{18}\text{O}$ rhyolites define the Snake River Plain–Yellowstone Plateau volcanic province, begging the question of the sources and the processes by which ^{18}O -depleted magmas are generated. New analyses show that Archean crustal xenoliths from the central and eastern Snake River Plain have normal- $\delta^{18}\text{O}$ signatures of 6‰–9‰, precluding them as a low- $\delta^{18}\text{O}$ source in the genesis of >10,000 km³ of low- $\delta^{18}\text{O}$ ($\delta^{18}\text{O} < 6$ ‰) Snake River Plain rhyolites. Synthesis of O–Sr–Nd–Pb isotope data for Archean xenoliths and Snake River Plain magmas defines separate compositional fields of rhyolites and their crustal and mantle sources. Sr–O and Nd–O isotopic mixing models for the most recent volcanic fields in the eastern Snake River Plain, Yellowstone Plateau and Heise, show that normal- $\delta^{18}\text{O}$ rhyolites have variable crust (~30%–50%) and mantle (~50%–70%) proportions that are specific for each eruption. Low- $\delta^{18}\text{O}$ rhyolites can be traced along a genetic array of mixing lines from normal- $\delta^{18}\text{O}$ rhyolite end members to a low- $\delta^{18}\text{O}$ (~–1‰) source. The data support a two-stage magma genesis process, in which normal- $\delta^{18}\text{O}$ rhyolites are generated by partial melting and hybridization of the crust by mantle-derived basalt, and low- $\delta^{18}\text{O}$ rhyolites tap ~20%–80% of hydrothermally altered portions of normal- $\delta^{18}\text{O}$ rhyolitic rocks. This two-stage magma genesis process may be applicable to other caldera systems around the world for which the characteristic O isotope depletions are either less pronounced or undiscovered.

INTRODUCTION

The Snake River Plain–Yellowstone Plateau (SRP-YP) volcanic province in the western United States has produced some of the most voluminous rhyolitic eruptions on Earth. Most rhyolites in the SRP-YP province were generated by partial melting and hybridization of continental crust by massive basaltic intrusions into the North American craton (Leeman et al., 2008). More than 10,000 km³ of low- $\delta^{18}\text{O}$ rhyolite (1‰–6‰ depleted from normal magmatic values) has erupted from four volcanic fields in the SRP-YP volcanic province (Figs. 1A and 1B). Because oxygen is the most abundant element in rhyolitic melts, understanding the cause of these isotopic depletions is essential for resolving the petrogenesis of SRP-YP rhyolites. This remains a topic of great debate. Some workers advocate melting of a pre-Miocene low- $\delta^{18}\text{O}$ crustal source such as hydrothermally altered portions of the Idaho batholith (Borroughs et al., 2005), whereas others prefer a model of wholesale remelting and batch assembly of hydrothermally altered intracaldera rhyolites from Miocene–Pleistocene eruptions (Bindeman et al., 2007). Archean crustal xenoliths brought to the surface by Pliocene–Holocene lavas provide samples of cratonic North American crust underlying the SRP-YP volcanic province, and thus an opportunity to constrain the oxygen isotope composition of the largest crustal reservoir in the SRP. Here, we provide oxygen isotope data for a suite of such xenoliths from the central and eastern SRP (Fig. 1A; Table 1).

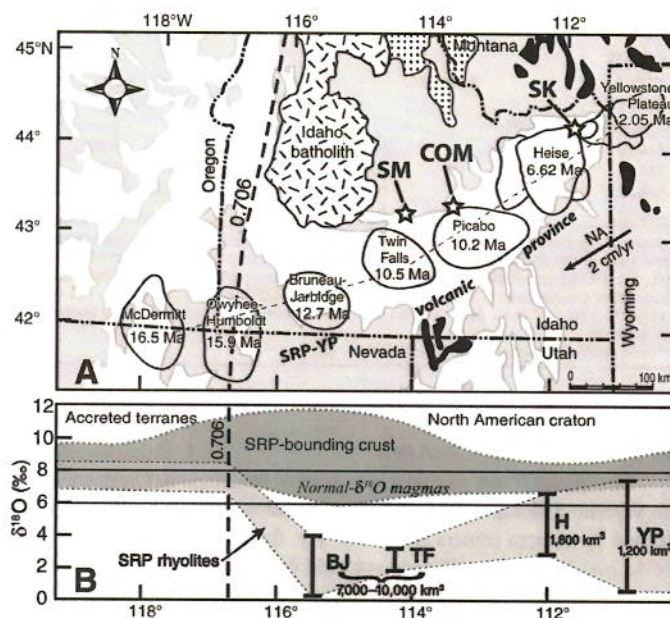


Figure 1. A: Map of the Snake River Plain–Yellowstone Plateau (SRP-YP) volcanic province with the locations and ages of major volcanic fields and crustal features. Crustal features include outcrops of Archean (black) and Proterozoic (stippled) basement, and the Jurassic–Eocene Idaho batholith (hatched). The $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ line defines a west to east transition from Mesozoic–Paleozoic accreted oceanic terranes ($^{87}\text{Sr}/^{86}\text{Sr} < 0.706$) to the Precambrian craton of North America ($^{87}\text{Sr}/^{86}\text{Sr} > 0.706$). Velocity and direction of movement of the North America (NA) plate is shown by the black arrow. Stars mark the crustal xenolith localities of this study: Square Mountain–Magic Reservoir (SM), Craters of the Moon (COM), and Spencer–Kilgore (SK). B: Oxygen isotope composition versus longitude for SRP-bounding crust and SRP rhyolites. Oxygen isotope ranges are shown for Bruneau–Jarbridge (BJ), Twin Falls (TF), Heise (H), and Yellowstone Plateau (YP) rhyolites. The number beneath the label is the volume of low- $\delta^{18}\text{O}$ rhyolite erupted in each volcanic field. Note: See the GSA Data Repository¹ for compilation of references for $\delta^{18}\text{O}$ values of SRP-bounding crust and SRP rhyolites and volumes of low- $\delta^{18}\text{O}$ rhyolites.

¹GSA Data Repository item 2010147, Oxygen isotope data and references for Snake River Plain (SRP) basement rocks, volumes and references for low- $\delta^{18}\text{O}$ SRP rhyolites, oxygen isotope analyses of SRP crustal xenoliths, compilation and references for O, Sr, Nd, and Pb isotope data for SRP magmas, plots of Pb versus O isotopes for SRP xenoliths and magmas, and calculations and additional figures for Sr–O and Nd–O binary mixing models, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. ISOTOPIC DATA FOR SRP XENOLITHS

Sample	Longitude	U-Pb zircon age (Ga)*	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	Average $\delta^{18}\text{O}$ (‰)
SK locality 111.7°W								
B1			0.70579	0.511467	16.73	15.45	37.25	6.42
B2			0.70235	0.510918	—	—	—	7.26
B3			0.70382	0.510883	14.18	14.98	34.71	7.26
B10			0.70246	0.510809	14.80	14.81	33.73	6.77
R4			0.70274	0.511154	—	—	—	6.75
73-68X			0.72550	0.510895	14.95	15.18	43.18	6.95
SK-3		3.10, 2.90, 2.76	—	—	—	—	—	6.26
COM locality 113.5°W								
CKI-1			0.73359	0.510499	13.56	14.72	35.01	9.35
70-40			0.71525	0.510454	14.11	14.82	35.73	7.76
SI-1			0.71795	0.510590	16.09	15.64	59.07	6.98
COM-1			0.81728	0.510228	—	—	—	7.43
COM-9A		2.60–2.50	—	—	—	—	—	9.20
COM-9B			—	—	—	—	—	7.91
COM-14			—	—	—	—	—	6.43
COM-22		3.20, 2.75	—	—	—	—	—	6.85
COM-25			—	—	—	—	—	6.67
SM locality 114.5°W								
SM-2A			0.73138	0.511484	16.36	15.50	35.22	7.78
SM-2F			0.83011	0.510874	24.65	16.87	39.29	7.50
SM-2G			0.72092	0.509973	18.76	15.88	36.90	8.09
DM-103		2.57	0.73878	0.510853	—	—	—	7.93

Note: Oxygen isotope values for SRP crustal xenoliths are averages of whole-rock powder duplicates. Quartz and pyroxene phenocrysts were analyzed for samples CKI-1, 70-40, and SI-1, and $\delta^{18}\text{O}$ quartz-whole rock and $\delta^{18}\text{O}$ quartz-pyroxene are consistent with metamorphic fractionation temperatures of 700–800 °C: CKI-1 (qtz = 9.47‰), 70-40 (qtz = 8.40‰, pyx = 6.15‰), SI-1 (qtz = 7.43‰, pyx = 4.51‰). See GSA Data Repository for individual analyses and methods.

*U-Pb zircon ages were reported in Wolf et al., 2005.

GEOLOGIC BACKGROUND

The SRP-YP volcanic province extends from eastern Oregon to western Wyoming along a 700 km chain of northeast-trending volcanic fields defined by caldera centers (Fig. 1A). The Bruneau-Jarbridge, Twin Falls, Heise, and Yellowstone Plateau volcanic fields exhibit extreme heterogeneity and depletion in magmatic $\delta^{18}\text{O}$, with a total erupted volume of more than 10,000 km³ of low- $\delta^{18}\text{O}$ rhyolites, whereas nearly all rhyolites erupted to the west of the inferred Archean crust boundary ($^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ line) fall within a normal- $\delta^{18}\text{O}$ range (Figs. 1A and 1B). Despite their remarkable volume, evidence for suitable crustal sources for low- $\delta^{18}\text{O}$ magmas is scarce in the SRP. Available oxygen isotope data for crustal basement rocks that predate the SRP show a normal- $\delta^{18}\text{O}$ profile from west to east, ranging from ~6‰ to 10‰ (Fig. 1B; Data Repository). Oxygen isotope data for individual plutons that compose the Idaho batholith show that it is heterogeneous with a few sufficiently low- $\delta^{18}\text{O}$ regions to source the low- $\delta^{18}\text{O}$ magmas of the central SRP (Borroughs et al., 2005). However, the majority of the Idaho batholith is normal- to high- $\delta^{18}\text{O}$ (~8‰–11‰; Criss and Fleck, 1987).

XENOLITH SAMPLES

The 20 crustal xenoliths analyzed in this study are a representative subset of more than 260 samples collected by Leeman et al. (1985) at three localities in the SRP: Square Mountain–Magic Reservoir, Craters of the Moon, and Spencer–Kilgore (Fig. 1A). These xenoliths are granulite facies gneisses with varying proportions of quartz, plagioclase, alkali feldspar, orthopyroxene, clinopyroxene, Fe-Ti oxides, and interstitial glass. The freshest samples indicate equilibration at 700–800 °C and ~5 kbar, corresponding to a crustal depth of 15 km (Leeman et al., 1985). U-Pb zircon dating of xenoliths from each locality confirms that they are Archean in age, and documents the presence of the North American craton to a western extent of 114.5°W (Wolf et al., 2005). Among the samples analyzed, 14 xenoliths were previously analyzed for Sr and Nd isotopes, 10 were

analyzed for Pb isotopes, and 4 have been dated by U-Pb zircon geochronology (Leeman et al., 1985; Wolf et al., 2005).

RESULTS

Oxygen Isotopes

All xenoliths analyzed in this study have normal $\delta^{18}\text{O}$ values, ranging from ~6‰ to 9‰ (Table 1). Unlike the extremely heterogeneous Sr, Nd, and Pb isotope values, the O isotope values for the SRP crustal xenoliths define a narrow range and lack low- $\delta^{18}\text{O}$ values or supracrustal high- $\delta^{18}\text{O}$ values that are characteristic of crust elsewhere (e.g., Taylor, 1986). The xenoliths from the Spencer–Kilgore locality have slightly lower $\delta^{18}\text{O}$ values (~6‰–7‰) compared to those from the Craters of the Moon and Square Mountain–Magic Reservoir localities (~7‰–9‰), but all xenolith samples fall within the $\delta^{18}\text{O}$ range of crustal rocks exposed to the north and south of the SRP province, and thus, the $\delta^{18}\text{O}$ composition of the Archean crust sampled by the xenoliths is heterogeneous within a typical crustal range (Fig. 1B; GSA Data Repository).

Correlated Sr and O isotopes define separate but overlapping fields of SRP crustal xenoliths and magmas (Fig. 2A). The Sr isotope ratios of all rhyolites at Yellowstone, Heise, and Bruneau–Jarbridge (normal- and low- $\delta^{18}\text{O}$) and all SRP basalts overlap with the average xenolith values, which is an expected result for large-volume magma genesis from crustal sources. However, the Nd isotope ratios of Cenozoic SRP rhyolites and basalts are higher than any analyzed Archean xenoliths and require a significant proportion of low Sm/Nd juvenile mantle (Fig. 2B). Similar trends are apparent in plots of Pb isotopes versus O, with Pb isotope ratios that are intermediate between a crust and mantle source (GSA Data Repository).

Considering only normal- $\delta^{18}\text{O}$ rhyolites, which are the earliest eruptive units of the Yellowstone and Heise caldera centers, we observe that they can be produced by averaging the xenoliths with normal- $\delta^{18}\text{O}$ basalt (Figs. 2A and 2B). However, voluminous low- $\delta^{18}\text{O}$ rhyolites from the Yellowstone Plateau, Heise, Bruneau–Jarbridge, and Twin Falls volcanic fields do not have $\delta^{18}\text{O}$ counterparts among the xenoliths (Figs. 1B, 2A, and 2B). Their formation requires remelting of hydrothermally altered (low- $\delta^{18}\text{O}$) rocks—either shallow parts of the basement or earlier magmatic precursors that were strongly modified by meteoric/hydrothermal fluids. This dramatic shift in $\delta^{18}\text{O}$ value does not lead to significant changes in Sr, Nd, or Pb isotopes, compared to the extremely heterogeneous xenolith range.

Sr-O and Nd-O Mixing Models

Sr-O and Nd-O mixing models presented in Figures 3A and 3B define a three-component mixing field between the crust, the mantle, and a low- $\delta^{18}\text{O}$ source in the genesis of Yellowstone and Heise rhyolites. The Sr-Nd-O isotopic composition of an isotopically intermediate xenolith sample (DM-103) best approximates the xenolith average and thus was selected as the crust end member. The Sr-Nd-O isotopic composition of the mantle end member is the average of SRP basalts, which represent a combination of plume and lithospheric mantle components (Graham et al., 2009). All normal- $\delta^{18}\text{O}$ Yellowstone and Heise rhyolites plot within the Sr-O and Nd-O mixing fields established by the crust and mantle end members and possess variable crust and mantle contributions that are specific to each rhyolite, ranging from ~30% to 50% crust and ~50% to 70% mantle (Figs. 3A and 3B). This result is consistent with previous estimates of crust and mantle proportions in SRP rhyolites (e.g., Bonnicksen et al., 2008; Nash et al., 2006; McCurry and Rodgers, 2009). U-Pb zircon age inheritance establishes genetic ties between normal- and low- $\delta^{18}\text{O}$ Yellowstone rhyolites (Bindeman et al., 2008), and we used these known correlations and published O, Sr, and Nd isotope ratios to construct mixing curves between normal- and low- $\delta^{18}\text{O}$ rhyolite end members (Figs. 3A and 3B; GSA Data Repository). As

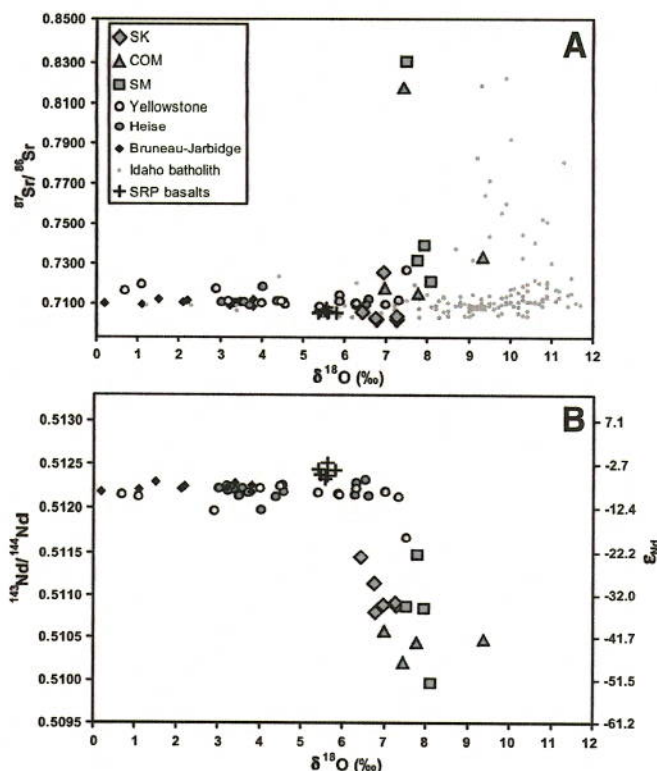


Figure 2. O, Sr, and Nd isotopic compositions of Spencer-Kilgore, Craters of the Moon, and Square Mountain-Magic Reservoir crustal xenoliths, Yellowstone, Heise, and Bruneau-Jarbridge rhyolites, and Snake River Plain (SRP) basalts. The symbol key applies to Figures 2 and 3. A: $^{87}\text{Sr}/^{86}\text{Sr}$ plotted against $\delta^{18}\text{O}$. Note that $^{87}\text{Sr}/^{86}\text{Sr}$ of the crustal xenoliths bracket $^{87}\text{Sr}/^{86}\text{Sr}$ of all SRP rhyolites, and that normal- $\delta^{18}\text{O}$ ($\delta^{18}\text{O} > 6\text{‰}$) Yellowstone and Heise rhyolites have O isotope compositions that are bracketed by the normal- $\delta^{18}\text{O}$ xenoliths and SRP basalts, whereas low- $\delta^{18}\text{O}$ rhyolites do not. Isotopic data for the Idaho batholith are from Criss and Fleck (1987) and are similar in $^{87}\text{Sr}/^{86}\text{Sr}$ to SRP crustal xenoliths and magmas, but generally higher in $\delta^{18}\text{O}$. B: $^{143}\text{Nd}/^{144}\text{Nd}$ plotted against $\delta^{18}\text{O}$. Note that all SRP rhyolites have higher $^{143}\text{Nd}/^{144}\text{Nd}$ than SRP crustal xenoliths, and require contribution from a higher $^{143}\text{Nd}/^{144}\text{Nd}$ mantle component—SRP basalts. Note: See the GSA Data Repository for O, Sr, Nd, and Pb isotope data and references, and additional plots of $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $\delta^{18}\text{O}$.

isotope-isotope mixing models depend on element concentration ratios and define hyperbolas in the mixing space, we used second-order polynomial least-squares regression lines to approximate each mixing curve and then projected these fit lines along the Sr-O and Nd-O axes.

An important result of this modeling is that the fit lines converge at $\delta^{18}\text{O}$ values of -1.5‰ to -0.4‰ (Sr-O) and -1.0‰ to 0.7‰ (Nd-O), overlapping at $\delta^{18}\text{O} \approx -1\text{‰}$ (Figs. 3A and 3B). Because O, Sr, and Nd isotope ratios and concentrations of the rhyolite end members are fixed from published values, and the fit lines were constructed for three independent mixing curves in two separate isotopic systems (Sr-O and Nd-O), this is a robust result. All low- $\delta^{18}\text{O}$ Yellowstone and Heise rhyolites fall along or within these projected mixing curves (Figs. 3A and 3B). The relative proportions of low- $\delta^{18}\text{O}$ versus normal- $\delta^{18}\text{O}$ components in these rhyolites were estimated with binary mixing curves between the modeled low- $\delta^{18}\text{O}$ source compositions and published isotopic compositions of normal- $\delta^{18}\text{O}$ rhyolite end members (GSA Data Repository). The results indicate $\sim 20\text{--}80\%$ of low- $\delta^{18}\text{O}$ ($\delta^{18}\text{O} = -1.5\text{‰}$ to -1.0‰) and normal- $\delta^{18}\text{O}$ ($\delta^{18}\text{O} = 7.0\text{‰}$ to 7.5‰) components. The majority of low- $\delta^{18}\text{O}$ rhyolites of the central SRP Bruneau-Jarbridge volcanic field also fall

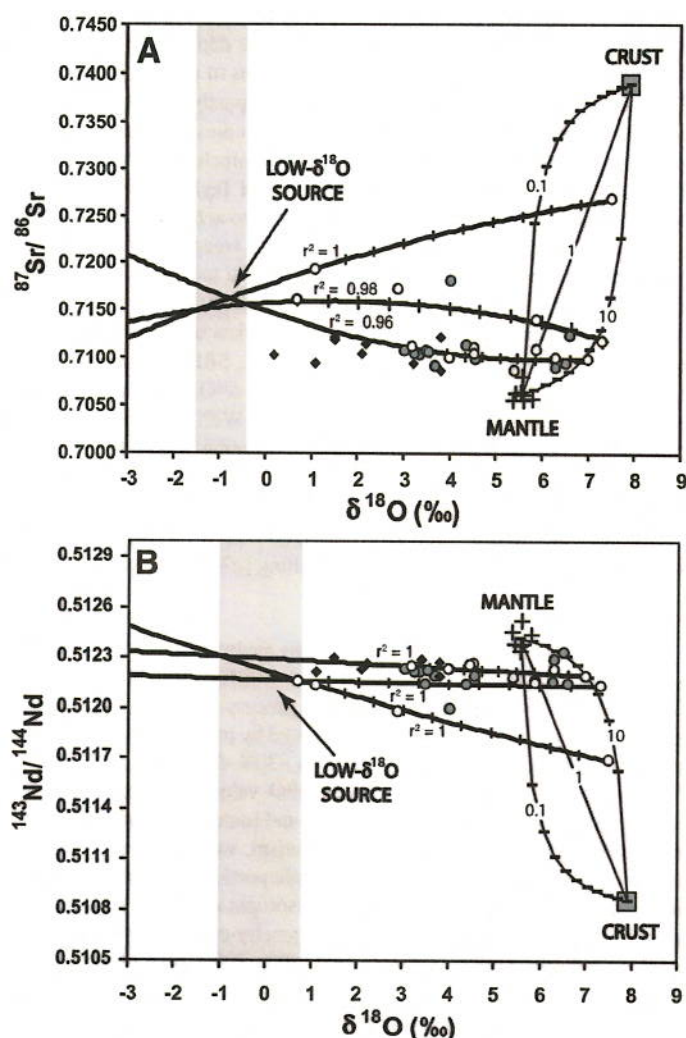


Figure 3. Sr-O and Nd-O mixing models. The crust end member (square) was estimated with the crustal xenoliths of this study, from which sample DM-103 is the most representative of the xenolith average: $\delta^{18}\text{O} = 7.9\text{‰}$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7388$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5109$. Snake River Plain (SRP) basalts (crosses) were used as the mantle end member: $\delta^{18}\text{O} = 5.6\text{‰}$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7063$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5124$. O, Sr, and Nd concentration ratios for binary mantle-crust mixing curves vary from 0.1, 1, and 10, where R = O/Sr (A) and O/Nd (B) are concentration ratios of crust/mantle. Normal- $\delta^{18}\text{O}$ Yellowstone and Heise rhyolites plot within the crust-mantle binary mixing field. Second-order polynomial least-squares regression lines ($r^2 \geq 0.96$) were fit to hyperbolic mixing curves between genetically related normal- $\delta^{18}\text{O}$ and low- $\delta^{18}\text{O}$ Yellowstone rhyolite end members, and these converge at $\delta^{18}\text{O}$ values of -1.5‰ to -0.4‰ (A) and -1.0‰ to 0.7‰ (B). The $\delta^{18}\text{O}$ fields of convergence (shaded) overlap at $\delta^{18}\text{O} \approx -1\text{‰}$, which serves as a constrained estimate for the low- $\delta^{18}\text{O}$ source of low- $\delta^{18}\text{O}$ rhyolites. Heterogeneity in $\delta^{18}\text{O}$ and homogeneity in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ of low- $\delta^{18}\text{O}$ rhyolites can be explained by varying proportions ($\sim 20\text{--}80\%$) of normal- $\delta^{18}\text{O}$ rhyolitic components and this low- $\delta^{18}\text{O}$ source (see text and GSA Data Repository for more detail on mixing models).

along the main Yellowstone-Heise mixing trend; however, this correlation could be fortuitous because the mixing lines were generated with eastern SRP data, and the Bruneau-Jarbridge volcanic field possesses no normal- $\delta^{18}\text{O}$ rhyolites.

The modestly depleted $\delta^{18}\text{O}$ value of -1‰ is not nearly as low as some estimates for hydrothermally altered source rocks at Yellowstone (-10‰) or the maximum theoretical depletions based on measured meteoric water values and high water/rock ratios (-15‰) (Hildreth et al., 1984), and this

may reflect the difficulty in achieving maximum depletion in ^{18}O due to limitations in permeability and/or thermal profiles of crustal source rocks (Taylor, 1986). It is notable that this value is comparable to measured $\delta^{18}\text{O}$ values of hydrothermally altered rocks from drill cores in modern volcanic geothermal systems in Iceland (0‰–2‰) and Kamchatka (–1‰) (Bindeman et al., 2004). We adopt the early argument of Taylor (1986) that large percentages of oxygen exchange are impossible to achieve at great depths by naturally percolating groundwaters, even in areas with high thermal gradients, because these waters are rapidly shifted to normal $\delta^{18}\text{O}$ values in shallow conditions. The fact that low- $\delta^{18}\text{O}$ magmas do not appear in stratovolcanoes or single calderas supports our view that vertical motions associated with multiple caldera collapses (e.g., SRP, Kamchatka) and/or rifting (e.g., Iceland) are key to bringing low- $\delta^{18}\text{O}$ source rocks to the temperature conditions appropriate for melting. (With average subsidence depths of 2–5 km per caldera collapse event [Lipman, 1997], two to three overlapping caldera collapses would result in 4–15 km of vertical draw-down. A synvolcanic geothermal gradient of 50–65 °C/km [Leeman et al., 2008] increases ambient temperatures by 200–975 °C, yielding temperature conditions appropriate for rhyolite melting [≥ 700 °C].)

CONCLUSIONS

The normal- $\delta^{18}\text{O}$ SRP crustal xenoliths analyzed in this study could not have directly sourced the voluminous low- $\delta^{18}\text{O}$ magmas of the SRP. We advocate a two-stage magma genesis process in eastern SRP volcanism, whereby the first rhyolites are generated by partial melts of the crust and mantle, creating hybrid magmas with ~30%–50% crust and ~50%–70% mantle contributions, and normal $\delta^{18}\text{O}$ values constrained by the oxygen isotope compositions of the crust and mantle reservoirs. Following this first phase of normal- $\delta^{18}\text{O}$ magmatism, subsequent magmas tap hydrothermally altered volcanic and plutonic portions of phase one rhyolites, maintaining the original Sr and Nd isotopic signatures, but recording variable $\delta^{18}\text{O}$ values. The $\delta^{18}\text{O}$ heterogeneity of phase two, low- $\delta^{18}\text{O}$ rhyolites reflects varying proportions (~20%–80%) of hydrothermally altered source rocks ($\delta^{18}\text{O} \approx -1$ ‰) and normal- $\delta^{18}\text{O}$ rocks and magmas ($\delta^{18}\text{O} \approx 7$ ‰). We suggest that the moderately depleted $\delta^{18}\text{O}$ value of –1‰ for this common low- $\delta^{18}\text{O}$ source is a geologically constrained, “typical” value for SRP caldera source rocks, in which $\delta^{18}\text{O}$ heterogeneities of variably hydrothermally altered intracaldera and subvolcanic rocks are averaged on a caldera-wide scale. We discourage the use of extremely low $\delta^{18}\text{O}$ values (i.e., <–5‰) when modeling assimilation/crustal melting. The derived –1‰ value requires that larger proportions of (–1‰) crust be present in magmas, and this warrants consideration of the “room problem,” accommodated through a combination of bulk remelting (Bindeman et al., 2007) caldera collapses and Basin and Range extension (e.g., Bonnichsen et al., 2008). At Yellowstone and Heise, low- $\delta^{18}\text{O}$ rhyolites dominate after ~2 million years, three caldera collapses, and 2500 km³ of normal- $\delta^{18}\text{O}$ rhyolitic eruptions (Bindeman et al., 2007), which may be a direct indicator of the time required for melting, assembly, and homogenization of large volumes of crust and mantle components in phase one magmatism, and concurrent accumulation, fracturing, and hydrothermal alteration of sufficient volumes of volcanic rock to source the voluminous second phase of low- $\delta^{18}\text{O}$ rhyolites. This model of magma genesis may be applicable to other large nested caldera centers in the SRP-YP volcanic province and elsewhere. Importantly, the higher (–1‰) value that we estimate for typical low- $\delta^{18}\text{O}$ source components means that many nominally “normal” rhyolites may in fact be subtly depleted. Recognition of time-progressive ^{18}O depletion is key to evaluating this model on a global scale.

ACKNOWLEDGMENTS

This work was supported by the U.S. National Science Foundation (grant EAR/CAREER-844772). We thank H. Cathey, S. de Silva, and an anonymous reviewer for thoughtful comments on the manuscript draft.

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Manuscript received 30 September 2009

Revised manuscript received 23 December 2009

Manuscript accepted 3 January 2010

Printed in USA