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Notes

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Voluminous low $\delta^{18}O$ magmas in the late Miocene Heise volcanic field, Idaho: Implications for the fate of Yellowstone hotspot calderas

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ABSTRACT

We report oxygen isotope compositions of phenocrysts and U-Pb ages of zircons in four large caldera-forming ignimbrites and post-caldera lavas of the Heise volcanic field, a nested caldera complex in the Snake River Plain, that preceded volcanism in Yellowstone. Early eruption of three normal $\delta^{18}O$ voluminous ignimbrites with $\delta^{18}O_{quartz}$ = 6.4‰ and $\delta^{18}O_{zircon}$ = 4.8‰ started at Heise at 6.6 Ma, and was followed by a 2‰–3‰ ^{18}O depletion in the subsequent 4.45 Ma Kilgore caldera cycle that includes the 1800 km^3 Kilgore ignimbrite, and post-Kilgore intracaldera lavas with $\delta^{18}O_{quartz}$ = 4.3‰ and $\delta^{18}O_{zircon}$ = 1.5‰. The Kilgore ignimbrite represents the largest known low-$\delta^{18}O$ magma in the Snake River Plain and worldwide. The post-Kilgore low $\delta^{18}O$ volcanism likely represents the waning stages of silicic magmatism at Heise, prior to the reinitiation of normal $\delta^{18}O$ silicic volcanism 100 km to the northeast at Yellowstone. The occurrence of low $\delta^{18}O$ magmas at Heise and Yellowstone hallmarks a mature stage of individual volcanic cycles in each caldera complex. Sudden shifts in $\delta^{18}O$ of silicic magmas erupted from the same nested caldera complexes argue against any inheritance of the low $\delta^{18}O$ signature from mantle or crustal sources. Instead, $\delta^{18}O$ age trends indicate progressive remelting of low $\delta^{18}O$ hydrothermally altered intracaldera rocks of previous eruptions. This trend may be generally applicable to older caldera complexes in the Snake River Plain that are poorly exposed.

Keywords: oxygen isotopes, zircon, U-Pb age, caldera, remelting, low $\delta^{18}O$.

VOLUMINOUS RHYOLITES OF THE SNAKE RIVER PLAIN AND THE HEISE VOLCANIC FIELD

Patterns of basaltic and silicic volcanism of the Snake River Plain (SRP; Fig. 1) follow 2 cm/yr plate migration over a Yellowstone mantle plume (Christiansen, 2001; Yuan and Dueker, 2005) that taps progressively older, thicker, more differentiated, and more fertile silicic crust (Morgan et al., 1984; Nash et al., 2006). Partial melting of crust above the plume head caused the formation of large silicic magma bodies that erupted explosively and effusively in a series of 0.5–1 Ma caldera clusters yielding ~40 voluminous (>300 km^3) rhyolitic supereruptions since 16 Ma (e.g., Perkins and Nash 2002; Bonnichsen et al., 2007). These eruptive clusters, or nested caldera complexes, have a 2–3 m.y. lifespan that may reflect the duration of piecemeal assembly of batholithic bodies in the lower and upper crust. The silicic magma bodies are density traps for basaltic magma input from the Yellowstone mantle plume and thus provide a focused heat source for crustal melting.

The currently active and best-studied Yellowstone complex includes three nested calderas that formed since its inception ca. 2.1 Ma. Here we focus on the 6.6–4.0 Ma Heise caldera complex that directly precedes Yellowstone and includes four nested calderas (Table 1). The Heise volcanic field is far better preserved than any of the earlier caldera complexes within the Snake River Plain. It contains a distinct resurgent

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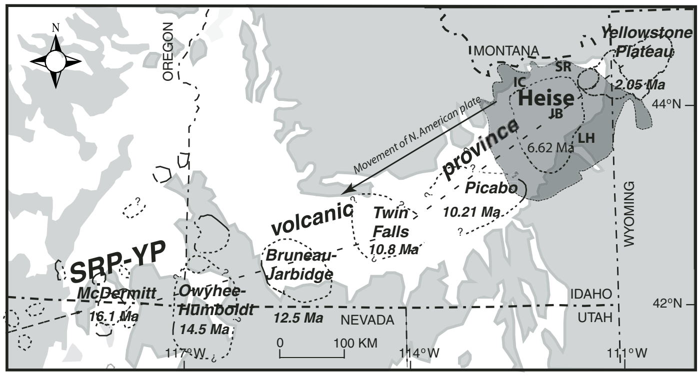

Figure 1. Map of Snake River Plain (SRP) showing Heise and Yellowstone Plateau (YP) caldera complexes. Dark shaded area in Heise volcanic field indicates extent of Kilgore ignimbrite from Morgan and Macintosh (2005). Post-caldera units dated in this study (Table 1) are indicated by bold letters: IC—Indian Creek; JB—Juniper Buttes; LH—Long Hollow; SR—Sheridan Reservoir.

dome, Juniper Buttes, and post-caldera rhyolitic lavas in the center and along the projected ring fracture of the caldera (Fig. 1). Therefore, the Heise field offers the second-best example of magmatism along the Snake River Plain and, along with Yellowstone, delineates general patterns for understanding the origin of rhyolites. Here we report oxygen isotope analyses of phenocrysts and ion microprobe U-Pb ages of zircons in the Heise volcanic field and discuss important similarities and differences with Yellowstone (Table 1). This work significantly expands the number and volume of severely ^{18}O depleted magmas in the Snake River Plain. The appearance of low $\delta^{18}O$ magmas seems to herald the terminal stages in the evolution of individual volcanic cycles.

Successive eruptions of four large-volume ignimbrite units in the 6.6–4.0 Ma Heise volcanic field (Table 1) resulted in the formation of four large and overlapping calderas: the 1200 km^3 Blacktail Creek tuff, ~750 km^3 Walcott tuff, ~300 km^3 Conant Creek tuff, and 1800 km^3 Kilgore tuff (ignimbrite) (volume estimates are from Morgan and McIntosh, 2005). The $^{40}Ar/^{39}Ar$ dating of widely distributed Kilgore samples yielded indistinguishable ages consistent with a single eruption event and inferred source vents in the north and in the south of the caldera (Morgan and McIntosh, 2005). Pre-caldera and post-caldera lavas and domes have been previously mapped, but few reliable age data are available. All magmas in Heise are high-silica rhyolites (74–76 wt% SiO_2) with similar phenocryst phases of sanidine, plagioclase, quartz, pyroxenes, opaques, zircon, ±biotite, but they exhibit variations in phenocryst abundance from nearly aphyric (Walcott) to more crystal rich (10%–20%; Blacktail Creek tuff).

OXYGEN ISOTOPE RESULTS AND U-PB AGES OF ZIRCON: HEISE VERSUS YELLOWSTONE

Oxygen isotope values of quartz, zircon, and sanidine phenocrysts of the major ignimbrites and post-caldera units differ dramatically despite

TABLE 1. U-PB ZIRCON AGES AND $\delta^{18}O$ VALUES OF PHENOCRYSTS IN SAMPLES OF MAJOR TUFFS AND LAVAS FROM THE HEISE VOLCANIC FIELD, IDAHO

Cycle, Unit	Sample	Volume (km^3)	Ar-Ar eruption age (m.y.)	U-Pb concordia age (m.y.) (n)	$\delta^{18}O$ (‰) average			Melt (‰) (Calc.)	Temperature (°C)		$^{86}Sr_i$/$^{86}Sr_i$
					Quartz	Zircon	Sanidine		Zrc sat	Liq	
I. Blacktail Creek	95–2001a	1200	6.62 ± 0.03	6.92 ± 0.28 (12)	6.4	4.81		6.0	848	824	0.7115
II. Walcott	06HS-18	750	6.27 ± 0.04		7.3*		5.48	5.9	786	856	0.7128
Wolverine Creek	06HS-16	<100?	5.59 ± 0.05	5.45 ± 0.14 (15)			6.08†	6.1	799	855	
III. Conant Creek	06HS-5	300	5.51 ± 0.13	5.70 ± 0.19 (10)	6.4*		5.43	5.8	859	942	
IV. Kilgore	TNP96–43	1800	4.45 ± 0.05	4.59 ± 0.26 (10)	4.46	**1.58**,1.69 *1.58*		3.3	842	845	0.7104-
	2000–17	"	4.45 ± 0.06	4.49 ± 0.25 (12)	4.33	1.50		3.3	874	843	0.7109
post-Kilgore, intracaldera lavas											
Long Hollow	626.1	<20	3.5 ± 0.4*	4.28 ± 0.18 (13)	4.68	1.92,*1.65*	3.78	4.2	816	780	
Indian Creek	06HS-1	<20	4.14 ± 0.09*	3.96 ± 0.18§ (6)	*1.40*	1.21,1.12	3.02	3.4	858	868	
				4.11 ± 0.27# (6) 4.46 ± 0.17‡ (21)							
Juniper Buttes	06HS-4	<20	3.3–3.7†	4.29 ± 0.15 (9)			3.80	4.2	811	778	
Sheridan Reservoir	06HS-19	<20		2.07 ± 0.19 (14)	4.55	2.51,2.37 2.25	3.74	4.1	886	857	

Note: see the GSA Data Repository (see footnote 1) for individual $\delta^{18}O$ and U-Pb analyses. Ages were corrected for the initial ($^{234}U/^{230}Th$) disequilibria using Scharer (1984). Zircon oxygen isotope analyses are by size fractions: bold = >150 µm, air abraded; underlined = >105 µm; normal font = bulk; italics = <53 µm. Liquidus (Liq) temperatures were determined in MELTS program at 4 wt% water and 1.5 kbar pressure; Zrc sat are calculated zircon saturation temperatures.

*Old K-Ar ages and Sr isotope values were reported in Morgan and McIntosh (2005).

†Fresh glass.

§Rims (0–2 µm).

#Rims (5–7 µm).

‡Cores.

overall compositional similarities (Fig. 2; GSA Data Repository[1]). Our new analyses demonstrate that the Blacktail Creek, Walcott, and Conant Creek large-volume tuffs have normal $\delta^{18}O$ values, while the youngest and the most voluminous ignimbrite in the sequence, the Kilgore tuff, and post-Kilgore lavas are strongly depleted in $\delta^{18}O$ by 3‰ (Fig. 2).

Zircon represents a near-liquidus phase in these crystal-poor high-silica rhyolites and thus provides a somewhat better, near-liquidus, proxy for $\delta^{18}O_{melt}$ than quartz, which crystallized last among all major phenocryst phases and is absent in crystal-poor varieties of tuffs. Using $\Delta^{18}O$(melt-zircon) of 1.8‰ applicable at magmatic temperatures of ~800 °C, we estimate Kilgore and post-Kilgore $\delta^{18}O_{melt}$ to be ~3.3‰ and ~3‰, respectively, lower relative to normal $\delta^{18}O$ rhyolites that result from mantle magma differentiation (Fig. 2). Zircons were sieved into large, intermediate, and small size fractions (>105 µm, <50 µm), and analyzed in bulk as described in Bindeman and Valley (2001). In addition, larger size fractions of zircons were air abraded in a corundum abrader that removed outermost ~20%–35% of zircons and yielded cores. However, no differences between large zircons or zircon cores and small zircons were found at Heise, suggesting that core to rim oxygen isotope zoning is either absent or very subtle (<0.4‰). Moreover, quartz-zircon and sanidine-zircon oxygen isotopic fractionations at Heise (Fig. 2; Table 1) are in equilibrium, and are consistent with temperatures of 700–800 °C using fractionation factors from Valley et al. (2003), and with liquidus and zircon saturation temperatures (Table 1). The lack of oxygen isotopic zoning in zircons distinguishes Heise from Yellowstone and Timber Mountain calderas (Bindeman and Valley, 2001; Bindeman et al., 2006), where isotopically zoned zircons are present in low $\delta^{18}O$ magmas. Post-caldera lavas show somewhat variable $\delta^{18}O_{zircon}$ values but lack a sawtooth pattern in the $\delta^{18}O$ versus eruption age plot for Yellowstone (Fig. 2).

[1]GSA Data Repository item 2007250, oxygen isotopes, U-Pb ages, and XRF analyses of volcanic rocks from the Heise volcanic field in Idaho, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

U-Pb zircon ages were determined in nine samples: two samples of Kilgore ignimbrite, four samples of post-Kilgore rhyolites, and one sample each of Blacktail Creek, Conant Creek, and Wolverine Creek tuffs (Table 1). The U-Pb ages in most samples are normally distributed and therefore are treated as single populations. Disequilibrium-corrected $^{206}Pb/^{238}U$ zircon crystallization ages overlap within uncertainty with $^{40}Ar/^{39}Ar$ sanidine eruption ages. Post-Kilgore rhyolite of Long Hollow erupted at the inferred ring fracture, and rhyolites of Juniper Buttes in the

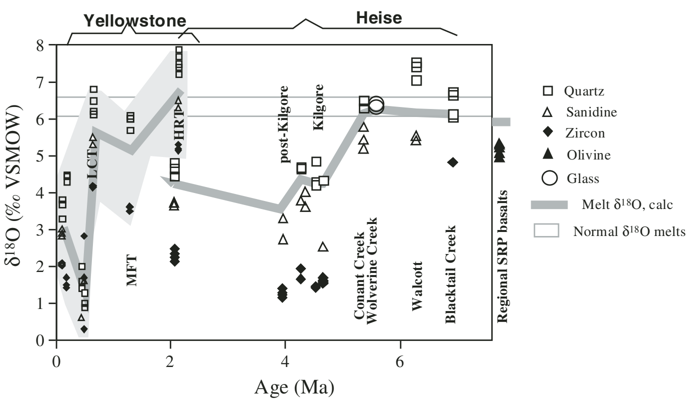

Figure 2. Oxygen isotope phenocryst values vs. $^{40}Ar/^{39}Ar$ eruptive age for volcanic rocks of Heise volcanic field (this work; see footnote 1), as compared to Yellowstone (data from Bindeman and Valley, 2001). Major episodes of caldera formation are labeled by the name of the caldera-forming ignimbrite (see Table 1). Note progressive depletion of $\delta^{18}O$ values in each caldera cluster, interpreted here to represent remelting of hydrothermally altered rocks progressively buried by caldera collapses. Zircons in low $\delta^{18}O$ Kilgore ignimbrite and post-caldera lavas are in isotopic equilibrium with quartz and feldspar and do not show $\delta^{18}O$ variation as a function of size (Table 1). Abbreviations: HRT—Huckleberry Ridge tuff; MFT—Mesa Falls tuff; LCT—Lava Creek tuff. VSMOW—Vienna standard mean ocean water.

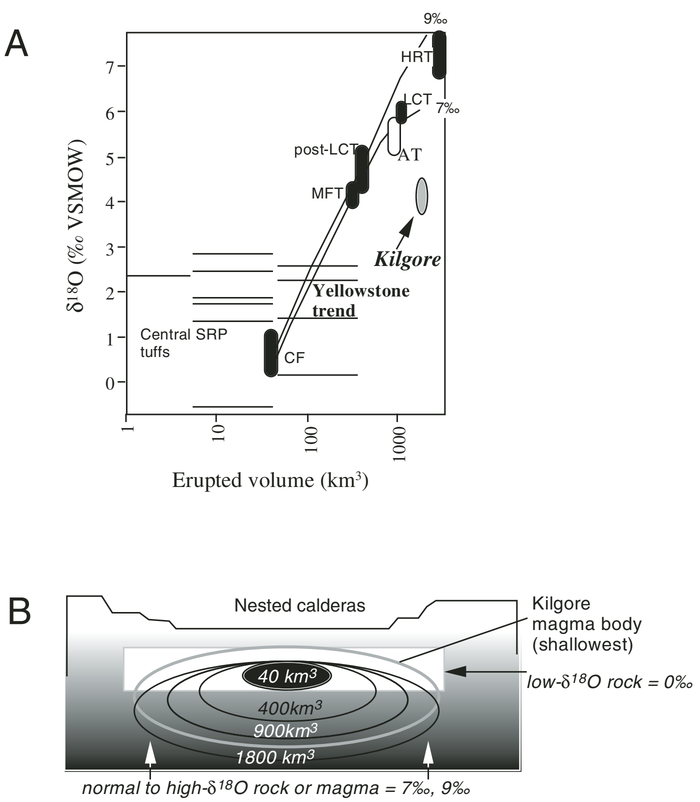

Figure 3. Origin of large-volume low $\delta^{18}O$ magmas in caldera settings. A: $\delta^{18}O$ values of bulk magma plotted against its eruptive volume, where low $\delta^{18}O$, 0‰ hydrothermally altered rock or magma are bulk mixtures between normal $\delta^{18}O$ magma and 7‰ (lower curve) and 9‰ (upper curve) lower crustal magma, respectively. Mixing lines are drawn assuming ellipsoidal geometry of magma chambers from panel B, in which low $\delta^{18}O$ rocks are confined to the intracaldera block. In A, Yellowstone magmas define a trend of mixing between most $\delta^{18}O$ depleted, ~0‰ Canyon flow (CF) rhyolites of small 40 km^3 volume and normal $\delta^{18}O$, 8‰ Huckleberry Ridge tuff (HRT)–type magma. The most $\delta^{18}O$ depleted CF rhyolite from Yellowstone represents 100% remelting of the low $\delta^{18}O$ hydrothermally altered rocks, while HRT-type magma that erupted at the inception of volcanism at Yellowstone represents the lower crust–derived normal $\delta^{18}O$ component. Intermediate $\delta^{18}O$ magmas such as Lava Creek tuff (LCT), Mesa Falls tuff (MFT), and post-LCT 0.2 Ma Yellowstone rhyolites are plotted vs. their respective eruptive volumes and plot on the overall Yellowstone mixing (or low $\delta^{18}O$ diluting) trend. The voluminous 1000 km^3 low $\delta^{18}O$ Ammonia Tanks tuff (AT) of Timber Mountain Caldera complex, Nevada (Bindeman et al., 2006), also plots on this mixing trend. Thin lines are central Snake River Plain (SRP) low $\delta^{18}O$ units (Boroughs et al., 2005) with poorly defined volumes plot variably. VSMOW—Vienna standard mean ocean water. B: Conceptual model of mixing of low $\delta^{18}O$ carapace melt with normal $\delta^{18}O$ magma from below in caldera settings. The low $\delta^{18}O$ end member is diluted over progressively larger magma volumes when vertical and horizontal sizes of the magma chamber increase. Bulk $\delta^{18}O$ of final magma results from volumetric contributions from the low $\delta^{18}O$ cap and the normal $\delta^{18}O$ magma chamber as indicated by the ellipsoids. Based on these constraints, the more voluminous Kilgore magma body taps a greater proportion (~40%) of low $\delta^{18}O$ carapace compared to Yellowstone. Alternatively, if $\delta^{18}O$ depletion in the carapace is greater compared to Yellowstone, smaller proportions of low $\delta^{18}O$ melts will suffice.

resurgent dome are identical in age. In the earliest post-Kilgore lava, the Indian Creek rhyolite, the outermost ~3–5 µm zircon rims yield U-Pb zircon crystallization ages that agree with the K-Ar eruption age and are ~0.5 m.y. younger than cores that have Kilgore tuff age (ca. 4.5 Ma). This earliest low $\delta^{18}O$ post-Kilgore intracaldera lava may represent residual low $\delta^{18}O$ Kilgore magma that was still remaining in the magma body after caldera collapse. The latest post-Kilgore low $\delta^{18}O$ Heise rhyolite, Sheridan Reservoir, has a U-Pb zircon age of 2.07 Ma that significantly postdates the Kilgore tuff eruption and has ~0.7‰ higher $\delta^{18}O_{zircon}$ values. Furthermore, U-Pb zircon age of Sheridan Reservoir rhyolite overlaps the age of Huckleberry Ridge tuff of Yellowstone. This suggests that dying low $\delta^{18}O$ volcanism at Heise was contemporaneous with the initially high $\delta^{18}O$ volcanism at the newly developing Yellowstone center. Pre-Heise xenocrysts are extremely rare in lavas and tuffs, and were found in only one sample (Juniper Buttes), where two zircons yielded ages of 49 and ca. 55 Ma.

The comparison between Heise and its immediate successor Yellowstone is instructive: both produced high-silica, low $\delta^{18}O$ rhyolites with similar magmatic temperatures (Table 1; Nash et al., 2006). However, there are several features of the Heise rhyolites that are different from smaller-volume but more strongly $\delta^{18}O$ depleted rhyolites erupted at Yellowstone: (1) Heise zircons have crystallization ages that are comparable to the Ar-Ar eruption ages; (2) zircons are in $\delta^{18}O$ isotopic equilibrium with quartz and sanidine, and zircon size fractions are homogeneous in $\delta^{18}O$, while Yellowstone zircons are zoned by 5‰; (3) post-Kilgore volcanic units retain levels of $\delta^{18}O$ depletion similar to those of Kilgore for more than 2 m.y. of post-caldera activity; and (4) the low $\delta^{18}O$ Kilgore ignimbrite has lower $^{87}Sr/^{86}Sr$ ratios (Table 1) compared to the preceding tuff units, while the low $\delta^{18}O$ post-caldera Yellowstone rhyolites always show higher $^{87}Sr/^{86}Sr$ values, interpreted by Hildreth et al. (1991) as evidence for high $^{87}Sr/^{86}Sr$, low $\delta^{18}O$ brines entering the magma chamber.

Bindeman and Valley (2001) estimated that in Yellowstone low $\delta^{18}O$ small-volume post-caldera rhyolites zircon resided for 5–10 k.y., while larger volume tuffs of the Mesa Falls tuff and Lava Creek tuff lack inherited cores, perhaps due to longer accretion times. We interpret the origin of zircons in the Kilgore tuff and post-caldera units as representing longer magmatic residence in which inherited high $\delta^{18}O$ pre-Kilgore zircons became annealed of $\delta^{18}O$ zoning through diffusion, solution-reprecipitation, and new growth in a voluminous low $\delta^{18}O$ Kilgore magma body.

LOW $\delta^{18}O$ MAGMATISM: SOURCE-RELATED FLUKE OR PREDETERMINED OUTCOME OF CALDERA CLUSTER EVOLUTION?

Boroughs et al. (2005) interpreted the newly discovered abundant low $\delta^{18}O$ magmas in the older 12–10 Ma central Snake River Plain volcanic systems of Bruneau-Jarbidge and Twin Falls (Fig. 1) as due to melting of low $\delta^{18}O$ Eocene–Cretaceous source rocks of the Idaho batholith, 200 km west of Heise. Melting of an older low $\delta^{18}O$ crustal source cannot apply to Heise or Yellowstone because of the sharp isotopic contrast between early and late tuffs erupted from their respective nested caldera complexes (Fig. 2). Furthermore, our analyses of olivine phenocrysts in seven high $^3He/^4He$ Snake River Plain basalts erupted through and around the Heise field returned expected $\delta^{18}O$ values of 4.8‰–5.2‰ (Fig. 2), precluding a mantle low $\delta^{18}O$ source. What caused the formation of >1800 km^3 of low $\delta^{18}O$ magmas at Heise?

Here we attempt to connect the level of $\delta^{18}O$ depletion with erupted magmatic volumes as a model for genesis of low $\delta^{18}O$ rhyolites in caldera settings. Figure 3 plots the inferred volumes of known low $\delta^{18}O$ magmas in caldera settings throughout the western United State and the level of their $\delta^{18}O$ depletion that show an overall positive correlation of volume with $\delta^{18}O$. The most depleted post-caldera Yellowstone lavas at 0‰ represent pure remelting of the hydrothermally altered carapace around the magma chamber. The first voluminous erupted unit of Yellowstone, the Huckleberry Ridge tuff, is normal $\delta^{18}O$ (6.5‰–7.5‰), while subsequent Yellowstone units Mesa Falls and Lava Creek tuffs are moderately $\delta^{18}O$ depleted and contain some carapace-derived low $\delta^{18}O$ component. Eruptive volumes of low $\delta^{18}O$ central Snake River Plain rhyolites (data from Boroughs et al., 2005) are loosely defined, but it appears that larger units plot on the western U.S. caldera trend while smaller units are displaced toward lower eruptive volumes for a given $\delta^{18}O$ value (Fig. 3). This may either reflect underestimation of the eruptive volumes or suggest the influence of some other low $\delta^{18}O$ source such as the Idaho Batholith. In contrast, the Kilgore tuff is more $\delta^{18}O$ depleted relative to its peers, and plots to the right of the main "diluting" trend. Note that the $\delta^{18}O$ value of meteoric hydrothermal fluids at Heise should be either comparable to that of Yellowstone or somewhat higher due to the lower altitude of the Heise field.

We propose that the Kilgore tuff represents the eruption of a comparatively shallow magma body that has digested a significant proportion of a low $\delta^{18}O$ carapace formed by down-dropped caldera fill and shallow intrusives from earlier caldera cycles (Fig. 3). Shallow venting of the Kilgore magma body is evident from a series of low-altitude vents located in the circumference of the caldera that operated in a fire-fountaining mode, as suggested by Morgan (1988). In addition, the large aerial extent of the Kilgore caldera suggests a high aspect ratio of the collapsed caldera and therefore a rather small vertical drawdown (Fig. 1; Morgan, 1988).

LOW $\delta^{18}O$ MAGMAS: WHY ARE THEY SO ABUNDANT?

The significant level of depletion of Kilgore magma requires tens of percent of hydrothermally altered assimilant to be added to the initial pre-Kilgore, post–Conant Creek mantle-derived magma. By mass balance, the 3‰ depletion would require a process more in line with bulk melting, digestion, or reactive assimilation (e.g., Bindeman and Valley, 2001; Beard et al., 2005) rather than conventional assimilation–fractional crystallization (e.g., Balsley and Gregory, 1998). The amount of basalt required to generate ~1000 km^3 of silicic magma from a protolith that cooled below solidus to ~500–600 °C, and was altered by low $\delta^{18}O$ hydrothermal fluids, is estimated to be 250–500 km^3.[2] At high (Hawaiian) magma production rates of 0.001 $km^3/km^2/yr$, the assembly of a Kilgore-size magma body would require a minimum of 10–20 k.y., and this time may be sufficiently long to dissolve and reprecipitate inherited zircons, explaining the lack of inherited cores.

FATE OF YELLOWSTONE HOTSPOT CALDERA COMPLEXES: FROM NORMAL TO LOW $\delta^{18}O$ MAGMAS

This study demonstrates that despite the outlined differences between Yellowstone and Heise, a systematic trend emerges: volcanism starts with the eruption of normal $\delta^{18}O$ magmas by partial melting of preexisting crust, results in formation of several partially overlapping calderas, and terminates with the appearance of low $\delta^{18}O$ magmas. The low $\delta^{18}O$ magmas hallmark the final stages of individual volcanic cycles, when volcanic cannibalism last taps down-dropped hydrothermally altered volcanic and subvolcanic rocks associated with earlier successive caldera collapses. After that, the melting potential of the crustal block becomes exhausted and voluminous silicic magma extraction ceases, even if thermal input from the mantle remains similarly high. However, lingering small-volume, low $\delta^{18}O$, post-caldera volcanism such as Sheridan Reservoir rhyolite, driven by fresh basalt input, is possible and is produced by wholesale remelting of the solidified low $\delta^{18}O$ Kilgore batholith, contemporaneous with formation of Huckleberry Ridge batholith nearby. Due to progressive plate migration relative to the mantle plume (Fig. 1), large-volume crustal melting, starting with normal $\delta^{18}O$ magmas, is initiated at a new location of fertile crust. The first cycle of caldera-forming eruptions at Yellowstone produced normal $\delta^{18}O$ magma much like the first-cycle magmas at Heise. We suggest that this crustal evolution scenario demonstrated for Yellowstone and Heise serves as a model for older caldera complexes along the Snake River Plain and perhaps elsewhere, pending better dating, volume estimation, and oxygen isotope analysis.

[2]This calculation is based on 1.5 kJ/kg K heat capacity of basalt, 600 °C basalt cooling from 1250 °C liquidus to 550 °C ambient temperature, 400 kJ/kg latent heat of its crystallization, yielding a total of 1450 kJ/kg for basalt. It takes ~300–400 kJ/kg to melt a granitic rock by reheating it by 300 °C and increasing the melt fraction by 50%, or only ~200 kJ/kg if the initial rock is already a glassy high-silica rhyolite with few crystals, and so little or no latent heat of fusion is required. At assumed heat transfer efficiency (e.g., Dufek and Bergantz, 2005) of 40%–20% for the preheated near solidus rhyolite, the basalt can melt 2–5 times the volume of rhyolite.

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