Voluminous low $\delta^{18}O$ magmas in the late Miocene Heise volcanic field, Idaho: Implications for the fate of Yellowstone hotspot volcanic 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 $\delta^{18}O_{\text{quartz}} = 6.4\%e$ and $\delta^{18}O_{\text{diamon}} = 4.8\%e$ started at Heise at 6.6 Ma, and was followed by a 2‰–3‰ $\delta^{18}O$ depletion in the subsequent 4.45 Ma Kilgore caldera cycle that includes the 1800 km$^3$ Kilgore ignimbrite, and post-Kilgore intracaldera lavas with $\delta^{18}O_{\text{quartz}} = 4.3\%e$ and $\delta^{18}O_{\text{diamon}} = 1.5\%e$. 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 reintroduction 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 melting 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, melting, 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 seems progressively older, thicker, more differentiated, and more fertile basaltic 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 $\sim$40 voluminous ($>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 dome, Juniper Buttes, and post-caldera rhylitic 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 $\delta^{18}O$ 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, $\sim$750 km$^3$ Walcott tuff, $\sim$300 km$^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 δ18O VALUES OF PHENOCRYSTS IN SAMPLES OF MAJOR TUFFS AND LAVAS FROM THE HEISE VOLCANIC FIELD, IDAHO

<table>
<thead>
<tr>
<th>Cycle, Unit</th>
<th>Sample</th>
<th>Volume (km³)</th>
<th>Ar-Ar eruption age (m.y.)</th>
<th>U-Pb concordia age (m.y.)</th>
<th>818O (%) average</th>
<th>Melt (%) (Calc.)</th>
<th>Temperature (°C)</th>
<th>δ18O (‰)</th>
<th>Zr sat</th>
<th>Liq</th>
<th>a Sr/a Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Blacktail Creek</td>
<td>95–2001a</td>
<td>1200</td>
<td>6.6±0.03</td>
<td>6.9±0.28 (12)</td>
<td>6.4</td>
<td>4.81</td>
<td>848</td>
<td>824</td>
<td>0.7115</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II. Walcott</td>
<td>06HS-18</td>
<td>750</td>
<td>6.27±0.04</td>
<td>7.3*</td>
<td>5.48</td>
<td>5.9</td>
<td>786</td>
<td>856</td>
<td>0.7128</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III. Conant Creek</td>
<td>06HS-16</td>
<td>&lt;100</td>
<td>5.59±0.05</td>
<td>5.45±0.14 (15)</td>
<td>6.0*</td>
<td>6.1</td>
<td>799</td>
<td>855</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV. Kilgore</td>
<td>TNP96–43</td>
<td>1800</td>
<td>4.45±0.05</td>
<td>4.59±0.26 (10)</td>
<td>4.46</td>
<td>1.58, 1.58</td>
<td>842</td>
<td>845</td>
<td>0.7104</td>
<td></td>
<td></td>
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<tr>
<td>post-Kilgore, intracaldera lavas</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Long Hollow</td>
<td>626.1</td>
<td>&lt;20</td>
<td>3.5±0.4*</td>
<td>4.28±0.18 (13)</td>
<td>4.68</td>
<td>1.92, 1.92</td>
<td>816</td>
<td>780</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indian Creek</td>
<td>06HS-1</td>
<td>&lt;20</td>
<td>4.1±0.09*</td>
<td>3.96±0.18 (6)</td>
<td>1.21</td>
<td>1.21, 1.21, 1.21</td>
<td>858</td>
<td>868</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Juniper Buttes</td>
<td>06HS-4</td>
<td>&lt;20</td>
<td>3.3–3.7†</td>
<td>4.29±0.15 (9)</td>
<td>3.80</td>
<td>4.2</td>
<td>811</td>
<td>778</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheridan Reservoir</td>
<td>06HS-19</td>
<td>&lt;20</td>
<td>2.07±0.19 (14)</td>
<td>4.55</td>
<td>2.51, 2.37, 2.25</td>
<td>2.37</td>
<td>4.1</td>
<td>886</td>
<td>857</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: see the GSA Data Repository (see footnote 1) for individual δ18O and U-Pb analyses. Ages were corrected for the initial (234U/230Th) disequilibria using Scharer (1984). Zircon oxygen isotope analyses are by size fractions: bold = >150 µm, air abraded; underlined = >105 µm, normal font = <55 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).
1Fresh glass.
2Rims (0–2 µm).
3Rims (5–7 µm).
4Cores.

Overall compositional similarities (Fig. 2; GSA Data Repository¹). Our new analyses demonstrate that the Blacktail Creek, Walcott, and Conant Creek large-volume tuffs have normal δ18O values, while the youngest and the most voluminous ignimbrite in the sequence, the Kilgore tuff, and post-Kilgore lavas are strongly depleted in δ18O 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 δ18O melt than quartz, which crystallized last among all major phenocryst phases and is absent in crystal-poor varieties of tuffs. Using Δ50O (melt-zircon) of 1.8‰ applicable at magmatic temperatures of ~800 °C, we estimate Kilgore and post-Kilgore δ18O melt to be ~3.3‰ and ~3‰, respectively, lower relative to normal δ18O 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 δ18O magmas. Post-caldera lavas show somewhat variable δ18Ozircon values but lack a sawtooth pattern in the δ18O versus eruption age plot for Yellowstone (Fig. 2).

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 206Pb/238U zircon crystallization ages overlap within uncertainty with 40Ar/39Ar 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. 40Ar/39Ar eruption 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 δ18O values in each caldera cluster, interpreted here to represent remelting of hydrothermally altered rocks progressively buried by caldera collapses. Zircons in low δ18O Kilgore ignimbrite and post-caldera lavas are in isotopic equilibrium with quartz and feldspar and do not show δ18O 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.
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 δ18O post-Kilgore intracaldera lava may represent residual low δ18O Kilgore magma that was still remaining in the magma body after caldera collapse. The latest post-Kilgore low δ18O 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 δ18O values. Furthermore, U-Pb zircon age of Sheridan Reservoir rhyolite overlaps the age of Huckleberry Ridge tuff of Yellowstone. This suggests that dying low δ18O volcanism at Heise was contemporaneous with the initially high δ18O 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 δ18O 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 low δ18O depleted rhyolites erupted at Yellowstone: (1) Heise zircons have crystallization ages that are comparable to the Ar-Ar eruption ages; (2) zircons are in δ18O isotopic equilibrium with quartz and sandine, and zircon size fractions are homogeneous in δ18O, while Yellowstone zircons are zoned by 5%ε (3) post-Kilgore volcanic units retain levels of δ18O depletion similar to those of Kilgore for more than 2 m.y. of post-caldera activity; and (4) the low δ18O Kilgore ignimbrite has lower 87Sr/86Sr ratios (Table 1) compared to the preceding tuff units, while the low δ18O post-caldera Yellowstone rhyolites always show higher 87Sr/86Sr values, interpreted by Hildreth et al. (1991) as evidence for high 87Sr/86Sr, low δ18O brines entering the magma chamber.

Bindeman and Valley (2001) estimated that in Yellowstone low δ18O 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 δ18O pre-Kilgore zircons became annealed of δ18O zoning through diffusion, solution-reprecipitation, and new growth in a voluminous low δ18O Kilgore magma body.

Figure 3. Origin of large-volume low δ18O magmas in caldera settings. A: δ18O values of bulk magma plotted against its eruptive volume, where low δ18O, ~0‰ hydrothermally altered rock or magma are bulk mixtures between normal δ18O 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 δ18O rocks are confined to the intra-caldera block. In A, Yellowstone magmas define a trend of mixing between most δ18O depleted, ~0‰ Canyon flow (CF) rhyolites of small 40 km3 volume and normal δ18O, ~8‰ Huckleberry Ridge tuff (HRT)-type magma. The most δ18O depleted CF rhyolite from Yellowstone represents 100% remelting of the low δ18O hydrothermally altered rocks, while HRT-type magma that erupted at the inception of volcanism at Yellowstone represents the lower crust-derived normal δ18O component. Intermediate δ18O 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 δ18O diluting) trend. The voluminous 1600 km3 low δ18O 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 δ18O units (Boroughs et al., 2005) with poorly defined volumes plot variably. VSMOW—Vienna standard mean ocean water. B: Conceptual model of mixing of low δ18O carapace melt with normal δ18O magma from below in caldera settings. The low δ18O end member is diluted over progressively larger magma volumes when vertical and horizontal sizes of the magma chamber increase. Bulk δ18O of final magma results from volumetric contributions from the low δ18O cap and the normal δ18O magma chamber as indicated by the ellipsoids. Based on these constraints, the more voluminous Kilgore magma body taps a greater proportion (~40%) of low δ18O carapace compared to Yellowstone. Alternatively, if δ18O depletion in the carapace is greater compared to Yellowstone, smaller proportions of low δ18O melts will suffice.

LOW δ18O MAGMATISM: SOURCE-RELATED FLUKE OR PREDETERMINED OUTCOME OF CALDERA CLUSTER EVOLUTION?

Boroughs et al. (2005) interpreted the newly discovered abundant low δ18O 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 δ18O Eocene–Cretaceous source rocks of the Idaho batholith, 200 km west of Heise. Melting of an older low δ18O 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 δ18O values of 4.8‰–5.2‰ (Fig. 2), precluding a mantle low δ18O source. What caused the formation of >1800 km3 of low δ18O magmas at Heise?

Here we attempt to connect the level of δ18O depletion with erupted magmatic volumes as a model for genesis of low δ18O rhyolites in caldera settings. Figure 3 plots the inferred volumes of known low δ18O magmas in caldera settings throughout the western United State and the level of their δ18O depletion that show an overall positive correlation of volume with δ18O. 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 δ18O (6.5‰–7.5‰), while subsequent Yellowstone units Mesa Falls and Lava Creek tuffs are moderately δ18O depleted...
and contain some carapace-derived low δ¹⁸O component. Eruptive volumes of low δ¹⁸O 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 altitudes 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 shallow magma body that has digested a significant proportion of a low δ¹⁸O 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 δ¹⁸O 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 shallow magma body that has digested a significant proportion of a low δ¹⁸O 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.

LOW δ¹⁸O MAGMAS: WHY ARE THEY SO ABUNDANT?

The significant level of depletion of Kilgore magma requires tens of percent of hydrothermally altered assimilated 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 km³ of silicic magma from a protolith that cooled below solids to ~500–600 °C, and was altered by low δ¹⁸O hydrothermal fluids, is estimated to be 250–500 km³. At high (Hawaiian) magma production rates of 0.001 km³/km²/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 δ¹⁸O MAGMAS

This study demonstrates that despite the outlined differences between Yellowstone and Heise, a systematic trend emerges: volcanism starts with the eruption of normal δ¹⁸O magmas by partial melting of preexisting crust, results in formation of several partially overlapping calderas, and terminates with the appearance of low δ¹⁸O magmas. The low δ¹⁸O 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 δ¹⁸O, 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 δ¹⁸O 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 δ¹⁸O magmas, is initiated at a new location of fertile crust. The first cycle of caldera-forming eruptions at Yellowstone produced normal δ¹⁸O 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.

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