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Post-caldera volcanism: in situ measurement of U–Pb age and oxygen isotope ratio in Pleistocene zircons from Yellowstone caldera

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Abstract

The Yellowstone Plateau volcanic field, the site of some of the largest known silicic volcanic eruptions, is the present location of NE-migrating hotspot volcanic activity. Most volcanic rocks in the Yellowstone caldera (0.6 Ma), which formed in response to the climactic eruption of 1000 km^3 of Lava Creek Tuff (LCT), have unusually low oxygen isotope ratios. Ion microprobe analysis of both U–Pb age and δ^{18}O in zircons from these low-δ^{18}O lavas reveals evidence of complex inheritance and remelting. A majority of analyzed zircons from low-δ^{18}O lavas erupted inside the Yellowstone caldera have cores that range in age from 2.4 to 0.7 Ma, significantly older than their eruption ages (0.5–0.4 Ma). These ages and the high-δ^{18}O cores indicate that these lavas are largely derived from nearly total remelting of normal-δ^{18}O Huckleberry Ridge Tuff (HRT) and other pre-LCT volcanic rocks. A post-HRT low-δ^{18}O lava shows similar inheritance of HRT-age zircons. The recycling of volcanic rocks by shallow remelting can change the water content and eruptive potential of magma. This newly proposed mechanism of intracaldera volcanism is best studied by combining in situ analysis of oxygen and U–Pb isotope ratios of individual crystals.

Keywords: Yellowstone Hot Spot; zircon; SHRIMP data; calderas; O-18/O-16

1. Introduction

In situ U–Th–Pb dating of individual zircon grains as young as 0.1 Ma provides quantitative constraints on mechanisms of magma generation and storage, duration of volcanism, phenocryst growth time, and recycling of volcanic materials [1–3]. In young calderas, these processes are the subject of active monitoring and drilling programs, pertinent to volcanic hazard assessment.

Yellowstone National Park and vicinity contains three of the largest Quaternary calderas in the world. Voluminous ash-flow eruptions, each accompanied or followed by caldera collapse, happened at 2.0, 1.3, and 0.6 Ma producing the Huckleberry Ridge Tuff (HRT, >2500 km^3), Mesa Falls Tuff (MFT, ~ 300 km^3) and Lava Creek Tuff (LCT, ~ 1000 km^3) [4–6]. The youngest, post-LCT caldera (Fig. 1) hosts a spectacular

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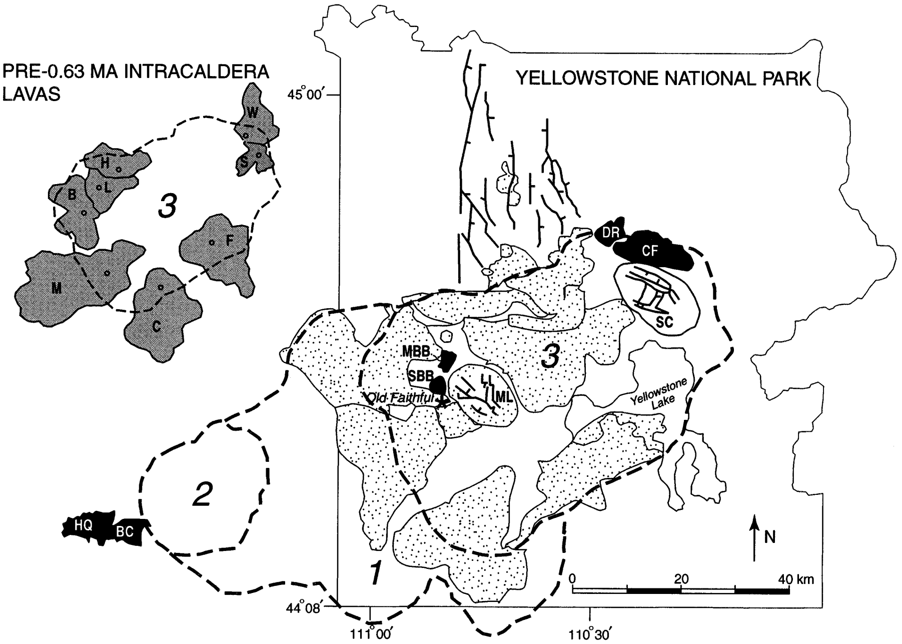


Fig. 1. Map of Yellowstone National Park and vicinity showing positions of calderas and studied lava flows. Big Bend Ridge and related caldera segments (1) formed as a result of the climactic eruption of HRT. Henry Fork caldera (2) formed by eruption of MFT. Yellowstone caldera (3) formed by eruption of LCT. Source maps are from [4–6,8]. Flows shown in black are the most ^{18}O-depleted, post-caldera lavas (CF – Canyon flow, DR – Dunraven Road flow, MBB and SBB are Middle and South Biscuit Basin flows which post-date LCT and the Yellowstone caldera). BC (Blue Creek flow) and HQ (Headquaters flow) which originated within the Big Bend Ridge caldera segment (#1) but later were truncated by the Henry Fork caldera (#2) [20]. Other post-LCT flows and domes are in speckled pattern. ML and SC are post-LCT Mallard Lake and Sour Creek Resurgent Domes. The inset shows the position of reconstructed pre-LCT lava flows and their inferred vent centers, truncated by the present caldera walls [5]. Inset flows (abbreviation, K–Ar age, Ma [13]): (H, 0.61–0.64) – Mount Haynes; (L, 0.8–0.84) – Harlequin Lake; (B) – Big Bear Lake; (M, 1.22–1.24) – Moose Creek Butte; (C, 0.93–0.97) – Lewis Canyon; (F, 0.92–0.94) – Flat Mountain; (S) – Stonetop Mountain; (W, 1.17–1.22) – Wapiti Lake.

modern hydrothermal system, responsible for large-scale ^{18}O depletion of volcanic rocks. The 0.7 Ma periodicity in caldera-forming eruptions and the 0.6 Ma period since the last catastrophic eruption raise concerns about future volcanic activity [4–6]. Thus, it is important to understand whether intracaldera volcanism relates to a dying cycle that started 0.6 Ma ago or a new cycle that may lead to another catastrophic eruption.

More than 900 km^3 of rhyolite has erupted within the Yellowstone caldera since its collapse at 0.6 Ma, and many of these lavas are unusually depleted in ^{18}O as a result of meteoric water involvement in magma genesis. The mechanisms of water–rock interaction and post-LCT intracaldera volcanism are a subject of debate. It has been proposed that ^{18}O-depleted magmas originated either from direct meteoric water influx into the magma chamber [7,8], or by assimilation of rocks previously altered by hydrothermal fluids of meteoric origin [6]. Both cases may lead to water saturation and gas-driven explosions. However, low-$\delta^{18}O$ rocks (units Canyon flow (CF), Middle Biscuit Basin (MBB), South Biscuit Basin (SBB), Dunraven Road flow (DR), Blue Creek flow (BC)) (see Fig. 1) contain isotopically zoned crystals of zircon and quartz with cores that are several permil higher in $\delta^{18}O$ than rims [9,10]. This oxygen isotope zoning provides critical evidence that zircon and quartz in low-$\delta^{18}O$ magmas are older and inherited from normal-$\delta^{18}O$ rocks or magmas and that the possible mechanisms of genesis of low-$\delta^{18}O$ magmas can be tested by in situ dating of individual zircons.

The carefully delineated $^{40}Ar/^{39}Ar$ and K/Ar eruption ages of most Yellowstone volcanic units ([11–13], M.A. Lanphere, written communication, 2000) create a geochronological framework for U–Pb dating of zircons. The age of these volcanics exceeds several half-lives of ^{234}U–^{230}Th disequilibria; hence direct $^{206}Pb/^{238}U$ dating, using correction for common ^{207}Pb [14,15], is possible. We report results of in situ ion microprobe (SHRIMP-RG (sensitive, high-resolution, ion microprobe, reverse geometry)) analyses of 83 individual zircons (95 analyses) from post-LCT intracaldera low-$\delta^{18}O$ lavas, the BC flow (post-HRT), and zircons from LCT and HRT (table 1 of the **EPSL Online Background Dataset**[1]). These zircons are from samples that have previously been analyzed (in situ and in bulk) for $\delta^{18}O$ [9]. We demonstrate that most zircons in post-LCT and post-HRT lavas contain cores that are significantly older than their $^{40}Ar/^{39}Ar$ age of eruption, and the age of caldera formation. The especially voluminous HRT (>2500 km^3) appears to be the main source of these zircons.

2. Methods

Zircons were mounted in epoxy, polished and gold-coated. Before gold coating, they were photographed in transmitted light to identify undesirable near-surface melt or mineral inclusions and imaged by cathodoluminescence (CL) in order to select darker (and U-richer) areas for analysis. SHRIMP-RG provides high transmission at a higher mass resolution than ion microprobes with a smaller radius. The ~ 8 nA primary beam of $^{16}O_2^-$ ions produced ~ 30 μm diameter, ~ 1 μm deep, flat-bottomed analysis pits. Prior to each analysis, the beam was rastered for 3 min to remove the gold coat and surface contamination. For each spot, data were collected for seven scans of peaks of $^{90}Zr_2O$, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{238}U, $^{232}Th^{16}O$, and $^{238}U^{16}O$. Zircon standard AS-57 (1099 Ma) was analyzed every four analyses. Zircon standard SL13 was used as a check for U concentrations. Yellowstone zircons tend to be U-rich, allowing for high precision age determination despite their young age (table 1 of the **EPSL Online Background Dataset**[1]). U-richer zircons or cores were preferentially chosen for analysis because they provided better counting statistics for these young ages. The $^{206}Pb/^{238}U$ age is most reliable for zircons of a young age. Common lead correction was made using the $^{207}Pb/^{206}Pb$ ratio, which can be measured more reliably than the $^{204}Pb/^{206}Pb$ ratio. High Th concentrations allowed us to determine the $^{208}Pb/^{232}Th$ age in many cases, but with larger errors than the $^{206}Pb/^{238}U$ age, given the lower ^{208}Pb concentration. Therefore, the ^{207}Pb-corrected $^{206}Pb/^{238}U$ ages are used in further discussion.

Since the zircon/melt partition coefficient is higher for U than for Th, an initial deficit of ^{230}Th may occur in zircon during its crystallization [16], creating a temporal gap in the $^{230}Th/^{234}U$ secular equilibrium of the ^{238}U decay series. Unless corrected, this leads to underestimation of the true age of crystallization. For Yellowstone, the Th/U (whole rock) ratio in volcanics is typically in the 4–5 range, with an average of 4.5 (analyses from [6,8]). The Th/U (zircon) ratio varies from 0.16 to 1.66 (0.4–1.25 for 90% of analyses; table 1 of the **EPSL Online Background Dataset**[1]), and thus determines the correction. The Th–U ratio of each zircon analysis (a measure of the magnitude of the initial ^{230}Th–^{234}U disequilibria) was used to calculate the ratio $(U/Th)^{zircon}$–$(U/Th)^{melt}$ for each analysis (typically in the 0.1–0.35 range). The age correction resulting from the initial Th–U disequilibria due to crystallization was in the +0.07 to +0.1 Ma range. The corrected $^{206}Pb/^{238}U$ ages and the measured $^{208}Pb/^{232}Th$ ages (less accurately determined because of the longer half-life of ^{232}Th) plot on a 1:1 slope, signifying concordance. No crystallization disequilibrium is expected in the $^{232}Th/^{208}Pb$ decay series, since intermediate daughter products of ^{232}Th are short-lived. Therefore, Th/U-corrected ages give a better estimate of the age of zircon crystallization.

[1] http://www. elsevier.nl/locate/epsl; mirror site: http://www. elsevier.com/locate.epsl

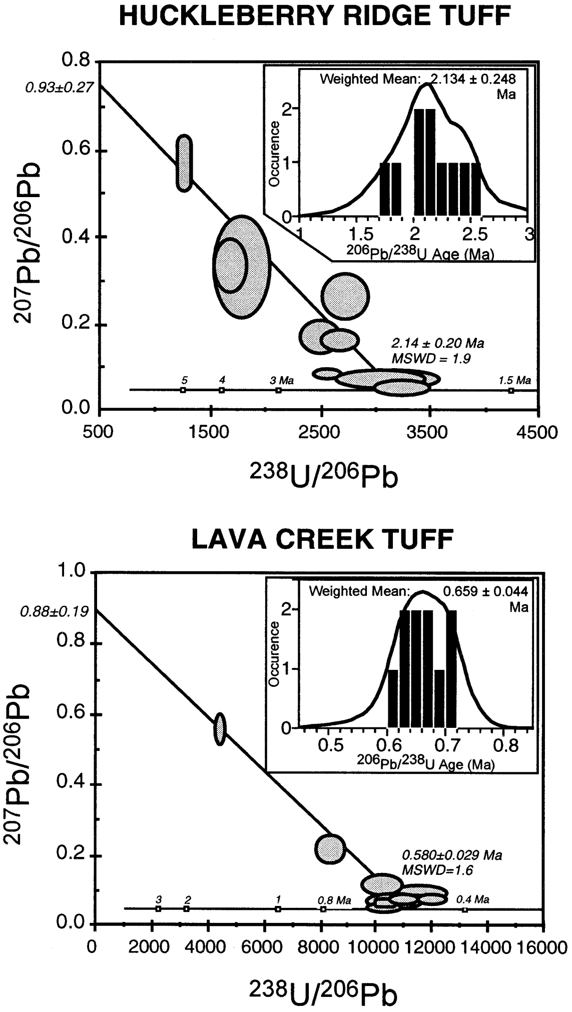


Fig. 2. Tera–Wasserburg concordia diagram for individual zircons determined by SHRIMP-RG from HRT (unit B, sample HRT-2) and LCT (unit A, sample LCT-3a). The intercept with the *Y*-axis gives the composition of common lead, the intercept with the nearly horizontal concordia determines ages (Th/U partition-uncorrected). Each oval represents $\pm 1\sigma$ error. Error-weighted line is shown. Histogram of inset suggests normal distribution for HRT and LCT ages. Note that Th/U partition-corrected ages ([16], see Section 2) on the inset are preferred and represent the best estimate of age for time of zircon crystallization in HRT and LCT.

3. Ages of zircons in major caldera-forming tuffs

Zircon ages approximate a normal distribution for LCT and HRT samples (Fig. 2) suggesting that they represent a single population. Tera–Wasserburg concordia diagrams were used to regress York error-weighted and unweighted lines [17], and to demonstrate that the majority of analyses are concordant, while the others represent mixing of radiogenic lead and common Pb with $^{207}Pb/^{206}Pb = 0.88$–0.92. LCT and HRT yielded error-weighted ages of 0.58 ± 0.03 Ma (2σ, $n = 10$, MSWD = 1.6, probability of fit = 0.11) and 2.14 ± 0.20 Ma (2σ, $n = 10$, MSWD = 1.9, probability of fit = 0.055), respectively. Error-unweighted ages for LCT and HRT are 0.57 ± 0.03 and 2.04 ± 0.20. These ages are either similar within error, or younger than the eruption age of LCT and HRT from $^{40}Ar/^{39}Ar$ in sanidine ([12], M.A. Lanphere, written communication, 2000).

When corrected for the initial Th–U partition (see Section 2 and [16]), the ages of LCT and HRT are 0.659 ± 0.044 Ma and 2.134 ± 0.248 Ma, and these ages provide the best estimate for time of zircon crystallization. They can be compared with eruption ages from $^{40}Ar/^{39}Ar$ in sanidine (M.A. Lanphere, written communication, 2000). Analyses of zircons in LCT (0.659 ± 0.044 Ma) are only 0.02 Myr older than the 0.640 ± 0.002 Ma sanidine $^{40}Ar/^{39}Ar$ ages of LCT. Zircons in HRT (2.134 ± 0.248 Ma) are 0.08 Myr older, compared to a sanidine $^{40}Ar/^{39}Ar$ age of 2.057 ± 0.002 Ma. Thus, the zircon U/Pb ages agree within error with $^{40}Ar/^{39}Ar$ sanidine ages. Zircons in MFT tend to be U-poor and we report only analyses of four U-rich zircons (table 1 of the **EPSL Online Background Dataset**[1]) which yielded a weighted average of 1.463 ± 0.046 Ma, 0.15 Ma older than $^{40}Ar/^{39}Ar$ sanidine ages of 1.304 ± 0.011 Ma. Earlier investigators [12] obtained $^{40}Ar/^{39}Ar$ ages that are somewhat younger: 2.003 ± 0.014 Ma for HRT, 1.293 ± 0.012 Ma for MFT, and 0.602 ± 0.004 for member B of LCT. Nevertheless, the similarity of sanidine $^{40}Ar/^{39}Ar$ and zircon U/Pb ages shows that these zircons crystallized close in time and space with the sanidine and do not significantly predate the eruption (e.g. [18]). Hence, the zircons in the major caldera-forming eruptions were not inherited from older rocks or magma.

4. Ages of individual zircons in post-LCT and post-HRT low-$\delta^{18}O$ lavas

4.1. Post-LCT low-$\delta^{18}O$ lavas

In contrast to zircons in the caldera-forming ash-flow tuffs, ages of individual zircons in low-$\delta^{18}O$ lavas show a wide range, varying from the inferred eruption ages to the age of HRT (Fig. 3). Age maxima are defined by cumulative probabilities, taking into account errors associated with each age (Fig. 3). The youngest peak in each sample is younger than LCT and, therefore, reflects the last episode of zircon crystallization prior to eruption. These ages, when corrected for the initial U–Th disequilibria [16], are nominally 0.084–0.044 Myr older than the feldspar $^{40}Ar/^{39}Ar$ eruption ages [10] for the same units. We interpret these age differences as also being largely analytical, as is the case with LCT and HRT discussed above.

It is remarkable that only 38–45% of zircon core analyses in each sample define the peak at eruption age (Fig. 3), and even these proportions may be overestimated due to sampling bias. During analysis, we choose crystal cores that are dark in CL and are U- and Th-richer. Cores of eruption-age zircons tend to be most U- and Th-rich (typically up to 1 wt%) and also have the most varied Th/U ratios (from 0.1 to 1.7).

The majority of zircons analyzed in each post-LCT lava are older than the eruption age. Nine zircons, three from each flow, cluster at 2.1 ± 0.3 Ma, coinciding with the age of HRT within uncertainty (Fig. 3). These are elongated, medium-size zircons with medium-dark CL, commonly overgrown by thin light-CL rims. The 2.1 Ma zircons contain the lowest concentrations of U and Th (100–1500 ppm) and have rather restricted Th/U (0.4–0.8), similar to those of HRT.

The third group of zircons forms a broad age range from 0.7 to 1.0 Ma and possibly has a mixed origin. These ~0.9 Ma zircons are similar in age to the pre-LCT Harlequin Lake and Mount Haynes flows, which are truncated by the western rim of the Yellowstone caldera (north of MBB, Fig. 1), and to the voluminous Lewis Canyon and Flat Mountain flows on the southern edge of the caldera. These crystals are dark to medium-dark in CL, contain moderate concentrations of U and Th (1000–200 ppm each), and have restricted Th/U ratios between 0.3 and 0.8. Several analyses were made on one large zircon grain from DR: the darker-CL, U/Th-richer core of resorbed morphology has ages 0.99 ± 0.09, 0.93 ± 0.19 and 0.86 ± 0.16 Ma, the intermediate zone is 0.59 ± 0.1 Ma, and rims are near the eruption age (0.43 ± 0.2 Ma). This single zircon crystal records a 0.5 Myr history.

The fourth group of zircons has ages similar to LCT (0.60–0.70 Ma) and constitutes only 13% of analyzed grains in CF and DR, both from the eastern part of the caldera. Only one grain of this age range is found in MBB, from the western part of the caldera. Their CL images are similar to those of the 0.7–1.0 Ma zircons, and they form a continuum in age with pre-LCT zircons.

4.2. BC flow (post-HRT)

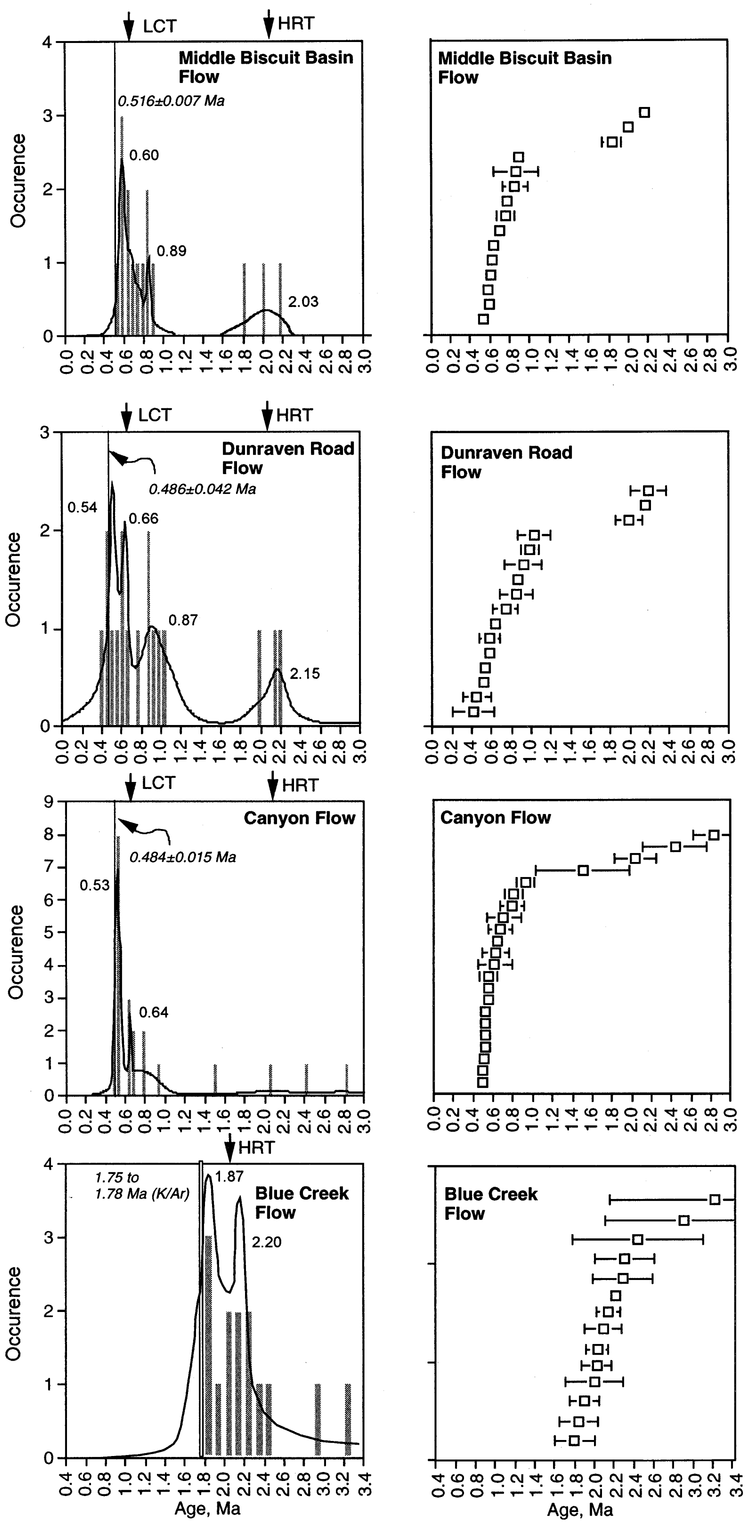
Zircons in the post-HRT low-$\delta^{18}O$ BC flow form a tightly clustered spectrum of ages (Fig. 3). The youngest four zircons give a 1.87 ± 0.09 Ma weighted average age peak which is close to the K/Ar eruption age of 1.75–1.78 Ma [13]. These zircons are gray in CL, and have a Th/U ratio of 0.4–0.7. The older group of nine zircons cluster around 2.20 ± 0.27 Ma, close to the age of HRT. These zircons have a broader Th/U of 0.5–1.15 and exhibit variable CL intensity.

4.3. Xenocrysts

Among 95 analyzes of zircons in Yellowstone lavas, only three gray CL zircon crystals are older than the onset of volcanic activity at Yellowstone: 64 ± 1 Ma in BC, 92–97 Ma in CF, and 3.52 ± 0.2 Ma in DR.

5. $\delta^{18}O$ values of zircons in post-LCT and post-HRT low-$\delta^{18}O$ lavas

Bindeman and Valley [9,10] have determined that post-LCT low-$\delta^{18}O$ lavas (units CF, DR, MBB, and SBB) and post-HRT low-$\delta^{18}O$ lava



LCT
HRT
Middle Biscuit Basin Flow
0.516±0.007 Ma
0.60
0.89
2.03
Occurence
Middle Biscuit Basin Flow
LCT
HRT
Dunraven Road Flow
0.486±0.042 Ma
0.54
0.66
0.87
2.15
Occurence
Dunraven Road Flow
LCT
HRT
Canyon Flow
0.484±0.015 Ma
0.53
0.64
Occurence
Canyon Flow
HRT
1.75 to 1.78 Ma (K/Ar)
1.87
Blue Creek Flow
2.20
Occurence
Age, Ma
Blue Creek Flow
Age, Ma

Fig. 3. Histograms of in situ $^{206}Pb/^{238}U$ ages of individual Yellowstone zircons determined by ion microprobe in post-LCT lavas and post-HRT BC flow. Vertical lines and numbers in italics show $^{40}Ar/^{39}Ar$ and K/Ar (BC) sanidine eruption ages for these units [11,13]. Arrows represent the average $^{40}Ar/^{39}Ar$ age of caldera-forming eruptions of LCT, and HRT (M.A. Lanphere, written communication, 2000). DR erupted on top of CF, and therefore is geologically younger. The youngest peaks of U/Pb age correspond to eruption and are analytically indistinguishable from $^{40}Ar/^{39}Ar$ eruption ages [10]. On the right, analyses are plotted with their error bars (table 1 of the **EPSL Online Background Dataset**[1]) against sample number.
←

(unit BC) contain heterogeneous populations of quartz and zircon, with 5‰ core-to-rim zoning in zircon as determined by the laser fluorination of air-abraded zircons (precision ±0.1‰). Here, we report ion microprobe analyses on cores and rims of individual zircons from the DR that exhibit the largest interval of core-to-rim zoning, resolvable with an ion microprobe with precision ±1‰ (Fig. 4). The age patterns (Fig. 4) correlate with the $\delta^{18}O$ values of individual zircons in the same samples. Analyses of zircon rims and cores in DR (Fig. 4) demonstrate a more than 5‰ range in $\delta^{18}O$, with cores exhibiting the largest variation, consistent with the zircons being inherited from variably ^{18}O-depleted volcanics and with the processes of oxygen isotope exchange (overgrowth and volume diffusion). The $\delta^{18}O$ histogram mimics the zircon age pattern, strengthening the conclusion that older inherited zircon cores (in Fig. 3) are also higher in $\delta^{18}O$ [9].

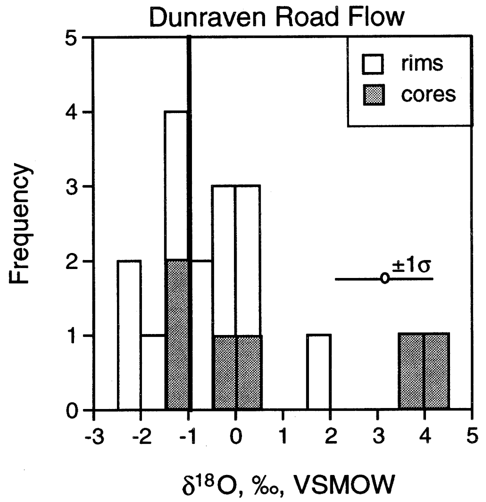


Fig. 4. Histogram of $\delta^{18}O$ values of individual zircon cores and rims in DR, determined in situ by ion microprobe (±1‰, see [19] for analytical details, and [10] for analyses). Vertical line denotes $\delta^{18}O$ value for zircons in equilibrium with host obsidian (+1‰).

6. Discussion

Long residence times (>100 kyr) of zircons have been reported in large silicic magma reservoirs [1,2], as well as contrasting examples of short residence time (<50 kyr) [18]. In Yellowstone, we see no evidence of long residence time. Large volume LCT and HRT magmas contain only eruption-age zircons, while smaller volume post-caldera rhyolites contain heterogeneous populations of zircons, varying in age, and oxygen isotope ratios [9]. However, the youngest age peak in each case is always in agreement with the $^{40}Ar/^{39}Ar$ eruption age. These eruption-aged zircons must have grown less than 0.05–0.1 Myr before the eruption.

The main conclusion of the present study is that of zircon recycling. The absolute majority of recycled zircons were ultimately derived from Yellowstone rocks or magmas and not from rocks that predate the onset of volcanism at Yellowstone. In particular, among 95 analyses of low-$\delta^{18}O$ lavas, in LCT and HRT we find no zircons from the Archaean basement or the Eocene Absaroka volcanics, and only three older xenocrysts (two Cretaceous and one Miocene) are present. This suggests that basement rocks were not importantly involved in remelting.

There is evidence of geographic and age control on inheritance. Particularly abundant and ubiquitous are zircon cores with ~2.1±0.4 Ma ages, similar to the age of the most voluminous eruption (HRT, >2500 km^3), which underlies the whole suite of later intracaldera lavas and tuffs. BC, a post-HRT intracaldera lava, contains an especially large proportion of HRT-age zircons.

Zircons in three post-LCT lavas are characterized by the abundance of HRT, and a variety of pre-LCT, post-MFT zircons, but do not contain MFT- or BC-age zircons, likely because the Yellowstone caldera is located northeast of those units (Fig. 1). It is notable that all three analyzed post-LCT intracaldera lavas, erupted as far apart as 45 km, contain the same zircon age groups (Fig. 3). This suggests that both the source rocks for the zircons and the mechanism of melt segregation were similar throughout the Yellowstone caldera. It is also noteworthy that post-LCT lavas contain only a limited number of LCT-age zircons suggesting that LCT is not a parent for post-LCT lavas. LCT appears not to be the main source of contamination in post-LCT lavas based on $^{40}Ar/^{39}Ar$ age data and on the difference in major element compositions of pyroxenes in LCT and the low-$\delta^{18}O$ lavas [6]. Therefore, we interpret zircon age spectra (in Fig. 3) as largely inherited from pre-caldera source rocks, erupted in the same area.

At Yellowstone, this evidence for zircon recycling and inheritance is independently confirmed by oxygen isotope zoning in zircon and quartz. Pre-caldera lavas are characterized by normal $\delta^{18}O$ values, while the analyzed post-caldera lavas are low in $\delta^{18}O$ and exhibit $\delta^{18}O$ core-to-rim zoning in zircon (Fig. 4, [9,10]). The absolute majority of zircons in post-LCT and post-HRT low-$\delta^{18}O$ lavas contain inherited higher $\delta^{18}O$ cores, similar to the pre-caldera zircons (e.g. Fig. 4, [9,10]). This suggests that these lavas were largely derived by remelting of ^{18}O-depleted source rocks. Alteration-resistant quartz and zircon were not modified by prior hydrothermal alteration, which depleted groundmass and feldspars in $\delta^{18}O$. Zircon and quartz later survived a relatively short episode of groundmass melting and eruption. There was not enough time for zircons to exchange oxygen with the rapidly formed host low-$\delta^{18}O$ melt, and thus zircons preserved $\delta^{18}O$ zoning as well as the older cores.

Assimilation (bulk or partial) and magma mixing can create low-$\delta^{18}O$ magmas and zircon inheritance (e.g. [2,6]), but it is unlikely at Yellowstone because: (1) the level of $\delta^{18}O$ depletion is too great (down to 0 to +3‰) and would require an unknown ultra-low-$\delta^{18}O$ (< -5‰) magma or rock to participate, but no ultra-low-$\delta^{18}O$ country rocks or individual phenocrysts of quartz and zircon have been found [9,10]; (2) this would require a remaining LCT magma in the magma chamber after eruption, but only few zircons of LCT age have been found in post-LCT lavas; (3) it is difficult to mix tens to hundreds of cubic kilometers of two viscous rhyolite magmas and achieve the textural, chemical, and isotopic homogeneity observed in volcanic glass of Yellowstone lavas [10].

Two lines of evidence suggest that post-caldera volcanism requires a nearly total remelting of hydrothermally altered rocks: abundance of inherited zircons in low-$\delta^{18}O$ lavas, and extremely low-$\delta^{18}O$ whole rock values, more consistent with wholesale melting of older, altered rhyolites rather than their assimilation or partial melting [9,10]. The remelting could have sampled either older volcanic rocks or subvolcanically crystallized plutons of the same age (e.g. [2]). The critical evidence comes from the level of ^{18}O depletion in each unit. For glassy, extremely ^{18}O-depleted post-LCT lavas the more likely scenario is the alteration, melting and subsequent eruption of a previously erupted volcanic rock.

The possibility of shallow remelting of previously erupted rocks is justified by the multiple caldera-forming events, the nesting of successive calderas (Fig. 1), and the large vertical displacement associated with each caldera collapse. For example, the 0.6 Ma Yellowstone caldera is largely enclosed within the larger and older (2.0 Ma) Big Bend Ridge caldera related to the eruption of HRT (Fig. 1). The Henry Fork caldera, the source of MFT, is entirely enclosed within the larger Big Bend Ridge caldera, segment related to HRT. The minimum vertical displacement (depression) of Yellowstone caldera, related to eruption of the 1000 km^3 of LCT, is estimated to be > 500 m based on the eruptive volume–caldera area ratio [8]. Vertical displacement after the 2500 km^3 HRT eruption could be several times larger. The post-HRT rhyolitic lavas and tuffs, including nearly 300 km^3 of the 1.3 Ma MFT, were deposited inside the first cycle (HRT) caldera on top of intracaldera HRT. Some of these lavas are truncated by the 0.6 Ma old Yellowstone caldera and are overlain by intracaldera LCT, and younger lavas. The zircon age spectra suggest that post-LCT melting has recycled HRT and a variety of post-HRT lavas. It is likely that LCT was too far above the magma chamber to be tapped significantly by heating and remelting, as evidenced by the small proportion of LCT-aged zircons in post-LCT lavas.

Therefore, based on the large proportion of inherited zircons (Fig. 3) and the abundance of high-$\delta^{18}O$ cores (Fig. 4, [9,10]), wholesale melting of previously hydrothermally altered HRT and a variety of post-HRT volcanics can be called upon to explain the origin of early post-LCT intracaldera volcanism. This conclusion may explain the genesis of other magmas from around the world, that might be produced by shallow remelting of pre-existing source rocks. The process is especially evident at Yellowstone because it is fortuitously fingerprinted by low-$\delta^{18}O$ magmas. If we are correct that intracaldera volcanism in Yellowstone is caused by remelting of erupted rhyolite and not by residual magma in the post-climactic magma chamber, a new look is provided on the origin of intracaldera volcanism and may link it to potential volcanic hazard. Two mechanisms are likely: (1) is the wholesale shallow melting of previously erupted and outgassed rocks, driven by the heat but not directly involving magma from the chamber; (2) is assimilation of precursor rocks. The first is predicted to produce less explosive volcanism because it involves previously outgassed rocks reheated at low pressure. This conclusion may explain the mostly effusive character of intracaldera volcanism of the Yellowstone and other similar calderas.

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