ABSTRACT

Varially melted granodiorite blocks ejected during the Holocene caldera-forming eruption of Mount Mazama were plucked from the walls of the climactic magma chamber at ~5 km depth. Ion-microprobe U-Pb dating of zircons from two unmelted granodiorite blocks with SHRIMP RG (sensitive high-resolution ion microprobe–reverse geometry) gives a nominal 238U/206Pb age of 101±28 ka, or 174±89 ka when adjusted for an initial 230Th deficit. SHRIMP RG U-Th measurements on a subset of the zircons yield a 230Th/238U isochron age of 112 ± 24 ka, considered to be the best estimate of the time of solidification of the pluton. These results suggest that the granodiorite is related to andesite and dacite of Mount Mazama and to magmas of the climactic eruption. The unexposed granodiorite has an area of at least 28 km². This young, shallow pluton was emplaced in virtually the same location where a similarly large magma body accumulated and powered violent explosive eruptions ~7700 yr ago, resulting in collapse of Crater Lake caldera.

Keywords: ion probe, zircon, geochronology, calderas, granodiorite.

INTRODUCTION

The caldera-forming, climactic eruption of Mount Mazama, during which Crater Lake caldera collapsed, ejected an exceptionally varied assemblage of cumulate and other mafic rocks (Williams, 1942; Druitt and Bacon, 1989) about 7700 yr ago (6845 ± 50 14C yr B.P.; Bacon, 1983). Among them are porphyritic granodiorite and related hypabyssal or plutonic blocks, many of which have been partially melted. None has juvenile magma adhering to its surface. The equilibrated partial melts and features indicative of catastrophic depressurization suggest that the granodiorite blocks were plucked from the walls or floor of the climactic magma chamber during the caldera-forming eruption (Bacon, 1992). Prior to partial melting, oxygen in much of the granodiorite exchanged with meteoric hydrothermal fluids, as shown by low δ18O values in most samples (Bacon et al., 1989).

We set out to determine the crystallization age of the granodiorite by ion-microprobe U-Pb dating of zircons separated from unmelted blocks using the SHRIMP RG (sensitive high-resolution ion microprobe–reverse geometry) operated by the U.S. Geological Survey and Stanford University. The U-Pb data indicate that most analyzed grains are ca. 100 ka, and none is older than Pleistocene. Subsequent U-Th measurements on a subset of these zircons support a crystallization age of ca. 110 ka. Here we report our results¹ and their significance for magmatic processes at Crater Lake.

GRANODIORITE BLOCKS EJECTED IN THE CALDERA-FORMING ERUPTION

The granodiorite and related rocks occur in all deposits of the climactic eruption of Mount Mazama but are most abundant in late-erupted proximal ignimbrite. The dense to pumiceous blocks that are the focus of the present study. The grain size, texture, and composition of the granodiorite are permissive of its being the crystallized remnants of a reservoir that fed the Quaternary volcanic center. The bulk chemical and radiogenic isotopic compositions of the granodiorite samples are similar to those of local eruptive rocks (Bacon, 1992; Bacon et al., 1994). Trace element concentrations and ratios suggested to Bacon (1992) that the granodiorite might be related to voluminous rhyodacite lavas that underlie Mount Mazama, the ca. 0.4 Ma Pre-Mazama rhyodacites described by Nakada et al. (1994). Bacon et al. (1994) suggested that the elevated 87Sr/86Sr ratios of glasses could indicate an age of ca. 10 Ma for the source pluton. The U-Pb and U-Th zircon ages refute this hypothesis.

GEOLOGIC CONTEXT OF THE PLUTON

The radial distribution of granodiorite blocks around Crater Lake caldera gives an indication of the minimum dimensions of their source pluton.

¹GSA Data Repository item 200051, Analytical data for the zircons, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

Data Repository item 200051 contains additional material related to this article.

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Although the caldera is $8 \times 10$ km at the rim, the elliptical area sampled by vents for the climactic eruption is $\approx 4.5 \times 6.5$ km. Rare granodiorite in ejecta of older vents near the east rim of the caldera extend the dimensions to $\approx 4.5 \times 8$ km, or a minimum area of 28 km$^2$.

The depth to the source of granodiorite blocks is believed to be that of the climactic magma chamber. Vapor saturation pressures calculated from measurements of dissolved volatiles in melt inclusions trapped in phenocrysts of clinomagnetic rhyodacite pumice indicate a 5 km minimum depth (Bacon et al., 1992). The presence of unmelted blocks suggests that the granodiorite extends to shallower depth.

There are few independent constraints on the crystallization age of the granodiorite. Oxygen isotope data demonstrate that rocks of the pluton exchanged with meteoric hydrothermal fluid before partial melting by the climactic magma. The pluton had crystallized, but at least part of it had not yet been affected by hydrothermal exchange at the time of the ca. 70 ka eruption of the tephra of Pumice Castle (Bacon and Lanphere, 1990), from which a granodiorite clast with primary magmatic $\delta^{18}O$ values was recovered (Bacon, 1992).

**ZIRCON U-Pb GEOCHRONOLOGY WITH SHRIMP RG**

Analyses of zircons were carried out with SHRIMP RG. The RG signifies the reverse geometry of the doubly focusing mass spectrometer in which the electrostatic analyzer is downstream of the magnet, providing the capability for substantially higher mass resolution than in conventional ion microprobes. Zircons were mounted in epoxy, polished, and coated with ~10 nm of gold. An ~15 nA primary beam of $^{16}O_2$ ions was focused to produce ~30 × 45 μm flat-floored analysis craters. The intensity of the $^{238}U/^{206}Pb$ peak was monitored in order to identify relatively U-rich grains that had been targeted on the basis of scanning electron microscope cathodoluminescence images. Prior to analysis, the beam was rastered for 4 min to remove the gold coat and surface contamination. For each spot, data were collected for 7–30 scans of peaks at $^{96}Zr$, $^{204}Pb$, $^{206}Pb$, $^{207}Pb$, $^{238}U$, $^{232}Th$, $^{16}O$, and $^{238}U/^{206}O$. Results were referenced to the 1099 Ma zircon standard AS57 (Paces and Miller, 1993). Precision in U-Pb age determinations for the young zircons from Crater Lake is mainly limited by counting statistics for $^{206}Pb$ and $^{207}Pb$, not by calibration against the standard. U concentrations were obtained by comparison with zircon standard SL13.

In order to demonstrate that young zircons can be successfully dated by the U-Pb method with SHRIMP RG, we have analyzed grains from the granite of the Geysers previously analyzed by Dalrymple et al. (1999) with a CAMECA ims 1270. Dalrymple et al. (1999) reported a $^{238}U/^{206}Pb$ age of 1.13 \pm 0.04 Ma (MSWD [mean square of weighted deviates] = 1.1) and a $^{207}Pb/^{206}Pb$ ratio of 0.91 \pm 0.09 for common Pb for sample ANG1-11400 (determined by fitting a line to $^{207}Pb/^{206}Pb$ and $^{238}U/^{206}Pb$ data, uncorrected for common Pb, on a Tera-Wasserburg diagram; e.g., Baldwin and Ireland, 1995). Data were referenced to measurements on the AS3 zircon standard grains (1099 Ma) in the same mount and regressed with ISOPLOT, yielding a $^{238}U/^{206}Pb$ age of 1.11 \pm 0.06 Ma (95% confidence level; MSWD = 0.60) and a $^{207}Pb/^{206}Pb$ ratio of 0.80 \pm 0.06 for common Pb (Fig. 1). U concentrations in the 13 grains analyzed ranged from 300 to 3800 ppm.

**U-Pb RESULTS**

We analyzed a total of 47 points on zircons from the two granodiorite samples from Crater Lake. The U concentrations in the zircons were typically 100–600 ppm (total range = 59–1230 ppm). Zircons range in maximum dimension from 30 to 550 μm. Higher U concentrations were found in small euhedral grains (50–100 μm) that were dark in inverse cathodoluminescence (CL). Among hundreds of zircons, we found no evidence in CL images for inherited cores. Concentric and sector zoning detected by CL appears to be consistent with crystallization from the granodiorite magma.

Ratios of $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ for both samples, uncorrected for common Pb, are plotted on a Tera-Wasserburg concordia diagram (Fig. 2), but with a log scale for the $^{238}U/^{206}Pb$ ratio in order to illustrate clearly the extrapolation to concordia. Because of the youth of the Crater Lake zircons, $^{207}Pb/^{206}Pb$ ratios are dominated...
by common Pb. The $^{206}\text{Pb}/^{208}\text{Pb}$ ratio of $0.86 \pm 0.02$ for common Pb determined by regression of the data is comparable to a whole-rock value of 0.8240 (Bacon et al., 1994). The small amount of radiogenic $^{206}\text{Pb}$ present forces a long extrapolation to concordia that results in imprecise, analytically identical crystallization ages for the two samples of 60 ± 120 and 130 ± 100 ka (95% confidence level). An age much younger than 1 Ma clearly is required in comparison to our results for the granite of the Geysers. The $^{238}\text{U}/^{206}\text{Pb}$ age for the pooled data from the two granodiorite samples is 101±28 ka (95% confidence level). It is doubtful that recent Pb loss can explain the young age of the zircons because the analyzed granodiorite samples show little evidence of alteration, are not partially melted, and, in the case of sample 461 (which yielded the younger nominal age), have primary magmatic $^{81}\text{O}_{\text{plagio}}$ and $^{81}\text{O}_{\text{quartz}}$ values. The $^{238}\text{U}/^{206}\text{Pb}$ age, however, must be adjusted for initial disequilibrium in U-series intermediate daughter products.

**EFFECT OF U-Th DISEQUILIBRIUM ON U-Pb AGE**

The zircons are sufficiently young that an initial $^{230}\text{Th}$ excess or deficit, owing to igneous U-Th fractionation, could result in erroneous $^{235}\text{U}/^{208}\text{Pb}$ ages (Mattinson, 1973; Ludwig, 1977). Mattinson (1973) pointed out that zircon has a much lower Th/U ratio than the melt from which it crystallizes, and thus zircons initially will have $(^{230}\text{Th})/(^{238}\text{U})$ (parentheses indicate activity ratios) significantly less than the secular equilibrium value $(^{230}\text{Th})/(^{238}\text{U}) = 1$. The effect on the measured $^{238}\text{U}/^{206}\text{Pb}$ age can be calculated if Th/U ratios are known for zircon and melt, assuming secular equilibrium at the time of crystallization (Schärer, 1984) or, more accurately, if zircon initial $(^{230}\text{Th})/(^{238}\text{U})$ is known (Wendt and Carl, 1985). Combining a typical Crater Lake zircon Th/U ratio of 0.7 and initial $(^{230}\text{Th})/(^{232}\text{Th})$ of ~0.3 based on U-Th measurements on zircons with SHRIMP RG (see next section) gives an initial $(^{230}\text{Th})/(^{238}\text{U})$ of 0.2 and permits calculation of a representative adjusted concordia curve in Figure 2B, assuming initial magmatic $(^{234}\text{U})/(^{238}\text{U}) = 1$. Intersection of the linear fit to the pooled Crater Lake data and this concordia curve yields a “true” $^{238}\text{U}/^{206}\text{Pb}$ age of 174 ± 115 ka. The maximum possible adjustment to 196 ± 115 ka results from assuming initial $(^{230}\text{Th})/(^{238}\text{U}) = 0$.

**U-SERIES MEASUREMENTS WITH SHRIMP RG**

A subset of the zircons dated by U-Pb was analyzed for $^{230}\text{Th}$, $^{232}\text{Th}$, and $^{238}\text{U}$ (Reid et al., 1997) using a 30 nA primary beam of $^{16}\text{O}$. Data were collected in 10 scans per point for $^{90}\text{Zr}$,$^{160}$O, $^{230}\text{Th}$,$^{160}$O, $^{232}$Th,$^{160}$O, $^{232}$Th,$^{160}$O, $^{238}$U,$^{160}$O, and $^{238}$U,$^{160}$O. Results for the oxides were converted to an atomic mass in Figure 3. Results for the oxides were converted to an atomic mass in Figure 3.

**U-SERIES RESULTS**

The U-Th data for zircons from the two unmelted granodiorite samples are plotted on $(^{230}\text{Th})/(^{232}\text{Th})$ versus $(^{238}\text{U})/(^{232}\text{Th})$ activity ratio diagrams in Figure 4. Pooled results for samples 461 and 1627 yield a 112 ± 24 ka isochron (MSWD = 1.1). The isochron is mainly defined by four euhedral, high $(^{238}\text{U})/(^{232}\text{Th})$ zircon crystals or crystal fragments in sample 1627 (Fig. 4A) that range in size from ~70 to ~150 µm. Relatively low U-Th ratios and scatter in the data for sample 461 preclude fitting an independent isochron. However, nearly all of the zircons analyzed from the two samples are significantly below the $(^{230}\text{Th})/(^{232}\text{Th})$ versus $(^{238}\text{U})/(^{232}\text{Th})$ equiline in Figure 4B. That the majority of analyzed crystals show a $^{230}\text{Th}$ deficit is taken as corroboration of the young age indicated by the U-Pb measurements. We suggest that the U-Th isochron age is the most accurate date for solidification of the granodiorite.

**ZIRCON RECYCLING**

Zircon crystals in the granodiorite may have crystallized at different times. Phenocrysts in porphyritic intermediate to silicic volcanic rocks may be recycled from earlier crystallized magmas or cumulate mush at the margins of magma bodies (e.g., Mahood, 1990; Nakada et al., 1994). Reid et al. (1997) showed that zircons in young rhyolites at Long Valley, California, had $^{230}\text{Th}$-$^{232}\text{Th}$ crystallization ages as much as 230 k.y. in excess of independently determined eruption times. It is possible that some zircons in the granodiorite at Crater Lake crystallized well before they were incorporated into the magma. However, the relatively U-rich zircons that we analyzed probably crystallized late, during final solidification of the granodiorite. Unless substantially older, the U-Pb ages of recycled zircons, particularly those of comparatively low-U crystals, might not be resolved from those of late-nucleated zircons by ion-microprobe U-Pb analysis. For example, the three zircons from sample 461 that plot low in Figure 2

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**Figure 3. U-series activity ratio diagram for ion microprobe analyses of zircon standards AS57 (1099 Ma) and SL13 (572 Ma).** Data for these ancient zircons plot within error of equiline because U-series intermediate daughter products are in secular equilibrium. Line fit to data (solid) is virtually indistinguishable from equiline (dotted). Large analytical uncertainties in $(^{230}\text{Th})/(^{232}\text{Th})$ ratios for SL13 zircons result not only from low $^{230}\text{Th}$ but also from low Th contents (20–25 ppm). MSWD—mean square of weighted deviates.

**Figure 4. U-series activity ratio diagrams for zircons from granodiorite blocks from Crater Lake caldera.** A: Isochron (112 ± 24 ka) fit to data for zircons from both samples is mainly defined by four analyses of crystals from sample 1627. This result is believed to be best estimate of crystallization age of granodiorite. B: Detail of low $(^{238}\text{U})/(^{232}\text{Th})$ part of activity ratio diagram. Most data plot significantly below equiline, corroborating young $(^{238}\text{U})/(^{206}\text{Pb})$ age and suggesting that all zircons analyzed crystallized at about same time. MSWD—mean square of weighted deviates.
have low U concentrations (59–116 ppm). Because of large analytical uncertainties in the U-Pb ages, it is unclear whether these crystals are older than the majority of the zircons in the granodiorite.

SIGNIFICANCE OF LATE PLEISTOCENE AGE OF THE PLUTON

The U-Pb and U-Th results for zircon establish that a sizable pluton crystallized in the upper crust beneath Mount Mazama in late Pleistocene time ca. 110 ka. The depth of the pluton overlaps that of the magma chamber for the climactic, caldera-forming eruption, from which ~50 km$^3$ of magma was explosively ejected. Yet, prior to eruption of the granodiorite-bearing dacite of Pumice Castle ca. 70 ka, there is no geologic evidence for voluminous late Pleistocene explosive eruptions, such as might have been fed by a shallow felsic magma body. Pre-Mazama rhyodacite, formerly considered the most likely erupted relative of the pluton (Bacon, 1992), is >300 k.y. older (Nakada et al., 1994) than the probable age of the granodiorite.

The U-Pb and U-Th ages of the zircons in the granodiorite require that the pluton was emplaced during the eruptive lifetime of Mount Mazama, a complex of overlapping basaltic andesite to dacite lava shields and composite cones active between ca. 400 ka and ca. 35 ka (Bacon and Lanphere, 1990). Much of the Mazama edifice was constructed by central-vent fountaining and effusion of basaltic andesite to dacite prior to ca. 210 ka. Between that time and ca. 70 ka, the record preserved (i.e., that not destroyed by caldera collapse) indicates that eruptive activity was limited to vents near the present northwestern and northeastern walls of the caldera, outside the area defined by the ring-vent system that fed the 7.7 ka climactic eruption and sampled the granodiorite. A large, partially molten silicic magma body beneath Mount Mazama would have prevented denser mafic to intermediate magmas from reaching the surface except beyond its margins. After ca. 70 ka, andesite and dacite were erupted from many vents on the west edge and within the presumed area of the granodiorite pluton.

Accepting the age of the granodiorite to be 112 ± 24 ka as indicated by the U-Th measurements, the magma from which the granodiorite crystallized logically would be related to the dacite and silicic andesite flows preserved on the north caldera wall that erupted between 130 and 100 ka (Bacon and Lanphere, 1990). The crustal reservoir(s) that fed these lavas could have produced a substantial volume of dacitic magma that stagnated beneath Mount Mazama at the appropriate time to account for the granodiorite pluton. Before growth of Mount Mazama, rhyodacite and dacite domes had been emplaced widely between ca. 470 and ca. 415 ka and locally between ca. 1300 ka and ca. 600 ka. The few zircons from the granodiorite that have apparent U-Pb ages much older than 100 ka may have crystallized from these silicic magmas.

The zircon U-Pb results help to illuminate the origin of the granodiorite magma. The lack of any ancient cores in CL images or any pre-Pleistocene apparent ages measured by ion microprobe suggests that partial melting of basement rocks either did not contribute greatly to generation of the granodiorite magma or that any zircons were entirely consumed. The zircon data might support a minor component of melt derived by partial fusion of intrusive rocks equivalent to the ca. 1.3–0.6 Ma dacites and rhyodacites noted herein or recycling of zircons in middle to late Pleistocene forerunners of the granodiorite magma. It appears more likely that the analyzed zircons crystallized during solidification of the granodiorite pluton. The ion-microprobe measurements demonstrate that the source of the granodiorite blocks is a young pluton that solidified in virtually the same location where a similarly large, shallow, and slightly more differentiated magma body later accumulated and powered a violent series of eruptions, resulting in collapse of Crater Lake caldera. Perhaps the granodiorite pluton provided a relatively impermeable and rigid container for the climactic magma chamber that facilitated magmatic vapor accumulation and, thus, the ensuing catastrophic eruption.

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