Zircon reveals protracted magma storage and recycling beneath Mount St. Helens

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ABSTRACT

Current data and models for Mount St. Helens volcano (Washington, United States) suggest relatively rapid transport from magma genesis to eruption, with no evidence for protracted storage or recycling of magmas. However, we show here that complex zircon age populations extending back hundreds of thousands of years from eruption age indicate that magmas regularly stall in the crust, cool and crystallize beneath the volcano, and are then rejuvenated and incorporated by hotter, young magmas on their way to the surface. Estimated dissolution times suggest that entrained zircon generally resided in rejuvenating magmas for no more than about a century. Zircon elemental compositions reflect the increasing influence of mafic input into the system through time, recording growth from hotter, less evolved magmas tens of thousands of years prior to the appearance of mafic magmas at the surface, or changes in whole-rock geochemistry and petrology, and providing a new, time-correlated record of this evolution independent of the eruption history. Zircon data thus reveal the history of the hidden, long-lived intrusive portion of the Mount St. Helens system, where melt and crystals are stored for as long as hundreds of thousands of years and interact with fresh influxes of magmas that traverse the intrusive reservoir before erupting.

INTRODUCTION

Constraining time scales of magmatic processes of arc volcanoes is essential to understanding how magmas are transported, stored, and interact in the crust, and what may trigger volcanic eruptions. Recent studies of Mount St. Helens (Washington, United States) have established that melts and major phase crystals erupted from this arc system are generally relatively young, suggesting that only a few thousand years pass between generation and eruption of the magmas (Cooper and Donnelly, 2008; Cooper and Reid, 2003; Volpe and Hammond, 1991). This is in contrast to models of many other continental arc volcanic systems, where mafic magmas may be generally young, but intermediate to silicic magmas appear to have more protracted and complex histories (Zellmer et al., 2005). Evidence from the Aleutian Arc (Bacon et al., 2007), the Aegean arc (Zellmer and Turner, 2007; Bachmann et al., 2007), the Taupo Volcanic Zone (Charlier et al., 2003), and large volcanoes in the Cascade Arc (Bacon and Lowenstern, 2005; Reagan et al., 2003) suggest that these magmas require more extended time scales (tens to hundreds of thousands of years) for fractionation and accumulation, or may often be stored for these time scales and then remobilized before eruption. These protracted histories also correspond to the plutonic record, where zircon U-Pb studies indicate that accumulation and evolution of silicic magmatic bodies in the crust require hundreds of millions to thousands of years (Miller et al., 2007; Walker et al., 2007). Zircon provides a uniquely appropriate tool to address questions of duration and conditions of magma storage and evolution in young volcanic systems, through combined ²³⁰Th–²³⁴U disequilibria dating and elemental analysis of growth zones by ion probe. Uranium-thorium analysis of young zircon yields uncertainties of thousands to tens of thousands of years that allow us to investigate time scales of magmatic processes (e.g., Bacon and Lowenstern, 2005; Charlier et al., 2003), and corresponding elemental compositions provide an unprecedented time-correlated record of the evolving growth environment (e.g., Claiborne et al., 2010, 2006a). Using the U.S. Geological Survey (USGS)–Stanford sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG), we have applied these combined methods to zircons extracted from erupted products that span the 300 k.y. eruptive history of Mount St. Helens. Our unique data set illuminates the previously hidden intrusive component of the Mount St. Helens system, where magmas and their crystals are stored for as much as hundreds of thousands of years before being entrained by erupting magmas, and where magmatic processes and interactions begin that manifest themselves in surface products tens of thousands of years later.

MOUNT ST. HELENS BACKGROUND

Recent research has established that Mount St. Helens has been erupting for nearly 300 k.y., over which time volcanism has migrated 10 km eastward to the location of the current edifice (Clynne et al., 2008). The predominant eruptive products are dacites that appear to be lower crustal melts generated in response to intrusion of mantle basalts, which are also occasionally erupted; relatively sparse intermediate compositions are produced by mixing of the two end members (Pallister et al., 2008; Smith and Leeman, 1993, 1987). Trends in geochemistry and mineral assemblages suggest that the earlier erupted magmas were generally relatively silicic, cool, and wet, with no evidence for interaction with more primitive magmas (Clynne et al., 2008). As the system matured, mafic input apparently increased, and beginning ca. 20 ka the dacitic magmas that erupted became hotter and drier and showed more evidence of interaction with mafic end members (Clynne et al., 2008).

Geophysical studies of the crust and petrologic studies of recently erupted products of Mount St. Helens provide clues to the size, shape, conditions, and timing of processes in the modern magma reservoir. Uranium-series disequilibria of glasses indicate that melts are generated within a few thousand years of eruption, and feldspars appear to have grown from days (Blundy and Cashman, 2001) to <20 k.y. before eruption (Cooper and Donnelly, 2008; Cooper and Reid, 2003; Volpe and Hammond, 1991). The complex compositional zoning and multiple populations of pyroxene, amphibole, and plagioclase indicate that magma mixing, crystal recycling on the scale of thousands of years, and convection in the chamber are common (Cooper and Donnelly, 2008; Cooper and Reid, 2003; Rutherford and Devine, 2008; Streck et al., 2008). Iron-titanium oxides indicate storage at temperatures from 820 °C to 940 °C (Rutherford and Devine, 2008; Rutherford et al., 1985). Seismic and petrologic studies indicate that melt-rich magma is stored in a widened conduit at 5–12 km depth (Pallister et al., 2008; Gardner et al., 1995). This information creates a vivid model of the upper part of the modern magmatic system: magmas generated in the lower crust ascend into a widened conduit at 5–12 km depth, ~4 km² in volume, in which they convect, mingle, and partially crystallize on short time scales before eruption, as well as recycle phenocrysts from crystal mushes that have been stored on the scale of thousands of years (Pallister et al., 2008).
METHODS

We used the SHRIMP-RG at the Stanford-USGS Microanalytical Center to measure U-Th and U-Pb isotopes and trace elements in zircons (following Bacon and Lowenstern, 2005; Walker et al., 2007; Claiborne et al., 2006a, 2010; Mazdab and Wooden, 2006). These data provided crystallization ages and chemical composition of zircon from 18 erupted units that span the eruptive history of Mount St. Helens, 9 of which compose a study focusing on one eruptive period (9–16 ka). Uranium-thorium data were collected for samples erupted more recently than 300 ka; U-Pb data were collected for the sample erupted ca. 300 ka and for spots proved older than 300 ka by U-Th analyses. Since the zircon is not cognate to the melt in which it erupted (see Discussion), we cannot directly use whole rock or glass (\(^{230}\text{Th}/^{232}\text{Th}\)) to establish the initial ratio. We chose an initial (\(^{230}\text{Th}/^{232}\text{Th}\)) of 1.2, reported in Cooper and Donnelly (2008) for the 2004–2006 eruption and within 0.15 of all previously published values (Cooper and Reid, 2003; Volpe and Hammond, 1991; Bennett et al., 1982), as a likely average for the Mount St. Helens dacites. Likely variability of this ratio introduces uncertainty on the scale of thousands of years into our model ages, particularly those with low U/Th, but this is not sufficiently large to affect our main conclusions. We use Ti concentration to constrain temperature, following the Ti-in-zircon thermometer (Ferry and Watson, 2007), assigning \(a_{\text{Zr}} = 1\) and \(a_{\text{Fe}} = 0.7\). Quartz is a common phenocryst in the more silicic lavas, and we interpret most zircon growth to have occurred at or near quartz saturation. Compositions of Mount St. Helens glasses suggest high \(a_{\text{Zr}}\) (>0.5), calculated following Hayden and Wafson (2007; cf. Claiborne et al., 2006a, 2010). Assuming too high \(a_{\text{Fe}}\) or too low \(a_{\text{Zr}}\), results in underestimation of temperature, and an error of 0.2 in activity estimates yields an error of \(\pm 30^\circ\text{C}\); this uncertainty does not affect our main conclusions.

RESULTS

Uranium-thorium and U-Pb analyses of 325 spots on zircon collected from 18 samples, ranging from the oldest known (ca. 300 ka) to most recent (December 2005) eruptions, provide a contrasting but complementary and more complex view of magma storage and interaction beneath Mount St. Helens than previously established. All samples have multiple age populations, including ages at least 150 k.y. older than their eruption age (Figs. 1 and 2). Age groups, which range from ca. 6 to 600 ka, generally appear in multiple, but not all, samples. Younger ages generally dominate over older, but it is common for the youngest identified ages for a sample to be at least tens of thousands of years older than the eruption age; only 3 of 18 samples contain ages within error (\(\sim 5–20\) k.y.) of eruption age as defined by \(^{40}\text{Ar}/^{39}\text{Ar}, \text{K-Ar, or radiocarbon data}\) (Clynne et al., 2008). Ten of the analyses reveal xenocrystic zircons that range from 12 to 96 Ma; these are most common in the earlier eruptions.

Just as the zircons from any one sample are a composite of many ages, many of the zircons record more than one growth episode. In grains large enough for multiple U-Th analyses, the magmatic ages vary from core to rim by as much as 200 k.y. Age and compositional variations usually correspond to zones visible in cathodoluminescence images of the zircon grains (Fig. 3) that are sometimes separated by resorption surfaces. Rounded external morphology suggests that most zircons from some samples underwent resorption prior to eruption, whereas all zircons from some other units are euhedral.

Concentrations of Ti and Hf correlate inversely (Fig. 4). Older zircon is more restricted in composition, with lower Ti (\((-3–10)\) ppm) and higher Hf (\((-11,000–14,000)\) ppm) than the younger zircon, which ranges to a maximum of \((-40)\) ppm Ti and a minimum of \((-6200)\) ppm Hf. A distinct increase in variability and in maximum Ti and minimum Hf corresponds to zircon ages beginning ca. 100 ka (Fig. 4).

DISCUSSION AND CONCLUSIONS

As the only mineral identified as more than a few thousand years older than its eruption, zircon records a different, more extended part of the Mount St. Helens magmatic history than any other phase. This could be due to its relatively slow growth and dissolution (Watson, 1996), low diffusivities (Cherniak et al., 1997), and resulting ability to survive reheating events intact while other phases are dissolved or have their age and chemical systems reset. Furthermore, zircon is sufficiently small that it will behave as a physical tracer in the melt (Claiborne et al., 2006b), segregating from rejuvenated, crystal-rich, sluggishly mobile mushes with interstitial melt while the major phases coeval with the zir-
ported Mount St. Helens zircons to the surface [36x90]. Furthermore, the magmas that trans-
lent to melt compositions [cf. Harrison et al.,
ture of initiation of growth is not necessarily
that a close coincidence between whole-rock
atures (Ferry and Watson, 2007; Fig. 4). (Note
with dominant estimated Ti-in-zircon tempera-
tures for given Ti (ppm) from Ti-in-zircon
Figure 2 for typical 2σ uncertainties on age
data. Gray and black curves show boundar-
ies of fields containing >95% of Hf and >90%
of Ti concentrations, respectively. Horizontal
dashed lines represent approximate tempera-
tures for given Ti (ppm) from Ti-in-zircon
thermometry (Ferry and Watson, 2007).

At the probable thermal interval of dominant
zircon growth for Mount St. Helens dacites
based on both thermometers, these magmas
would have been crystal-rich mushes or immo-
bile, rigid sponges, indicating that episodes of
zircon growth correspond to cooling and crys-
tallization events in the subvolcanic system.
These could correspond to posteroactive cooling
or intrusive events during periods of reduced
replenishment and eruption, but magnitudes of
uncertainties on eruption ages and zircon ages
and the possibility of unidentified eruptive units
prohibit direct correlation on a large scale.

The crystal-rich storage zone suggested by
our data has been repeatedly remobilized by hot,
young magmas that reheat, mix, and incorporate
older Mount St. Helens magmas shortly before
eruption (e.g., Charlier et al., 2003; Bacon and
Lowenstern, 2005; Zellmer and Turner, 2007;
Zellmer et al., 2003). The zircon ages present
in any eruption would then partly depend on
the physical distribution of zircon populations
in the storage zone relative to the path that
the replenishing magma took on its way to erup-
tion, resulting in complex age populations that
vary from eruption to eruption. The paucity of
eruption-age zircon is likely a consequence of erup-
ting magmas that were undersaturated in
zircon. The fact that the entrained and/or
recycled zircons have not been completely dis-
solved constrains the amount of time they have
been in contact with the undersaturated melt
to <=100 yr (following the models of Watson
[1996] and assuming grains with radii of ~50
µm in undersaturated melt with 4 wt% water
at ~900 °C; cf. Zellmer et al. [2003]), delimit-
ing the time scale between rejuvenation and
eruption and corroborating other evidence that
the Mount St. Helens erupted magmas are not
stored in the upper crust for long periods of time
prior to eruption (Cooper and Donnelly, 2008).

Using Hf as an indicator of fractionation
(Claijborne et al., 2006a) and Ti as a proxy for
temperature (Ferry and Watson, 2007), varia-
tions in zircon geochemistry clearly illustrate
that the early melts from which zircon grew
were generally cool (most ≤750 °C) and rela-
tively silicic. These were followed by more
variable but generally hotter (most ~720 °C to
850 °C), less fractionated melts (Fig. 4), pre-
sumably a consequence of the increasing mafic
input through time recognized by Clyne et al.
(2008). However, zircon records modification
of the magmatic system ca. 100 ka, ~80 k.y.
before increased thermal influx manifested in
the whole-rock and major phase chemistry of
erupted products. We interpret this to mean that
higher thermal flux was introduced to the intru-
sive portion of the system and influenced mag-
mas stored there for tens of thousands of years
before erupting magmas were significantly modified. The zircon record is also unique in
that much of this geochemical and thermal
history is commonly revealed in grains from a
single sample.

Zircon data from Mount St. Helens reveal
an intrusive body beneath the edifice with a
melt fraction that varies in volume and location
through time from solid rock through melt-rich
zones. The locations of these melt-rich or crys-
tal mush zones not only affect the distribution
of zircon ages in any one sample, but could
potentially dictate the path erupting magmas
take through the crust. Except for the eruption
process, this model is remarkably similar to pro-
cesses thought to occur in incrementally assem-
bled plutonic bodies and larger volcanic systems
(Bacon and Lowenstern, 2005; Charlier et al.,
2003; Walker et al., 2007). While the major min-
eral phases in Mount St. Helens rocks document
the volcanic aspects of the system (convection,
mixing, and decompression and degassing of
the magma just prior to and during eruption), zircon
records its intrusive behavior: the input, inter-
araction, repeated rejuvenation, and slow, cool

crystallization of unerupted magma that reflects
the growth of a volcanic center. The information
from these zircons indicates that each erupted
magma interacts with older, rejuvenated parts
of the system on its relatively rapid journey from
source to eruption, and suggests that active plu-
tonic bodies are essential components of the
magmatic plumbing systems of small, arc vol-
canoes such as Mount St. Helens.

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REFERENCES CITED

Bachmann, O., Charlier, B.L.A., and Lowenstern,
J.B., 2007, Zircon crystallization and recycl-
ing in the magma chamber of the rhyolitic Kos Plateau Tuff (Aegean arc): Geology, v. 35,
Bacon, C.R., and Lowenstern, J.B., 2005, Late Pleis-
tocene granodiorite source for recycled zircon
and phenocrysts in rhyodacite lava at Crater
Lake, Oregon: Earth and Planetary Science
Bacon, C.R., Sisson, T.W., and Mazdab, F.K., 2007,
Young cumulate complex beneath Veniami-
caldera, Aleutian arc, dated by zircon
uranium and thorium decay series nuclides
in erupted plutonic blocks: Geology, v. 35,
Bennett, J.T., Krishnaswami, S., Turekian, K.K.,
uranium and thorium decay series nuclides in
Mt. St. Helens effusives: Earth and Plan-
etary Science Letters, v. 60, p. 61–69, doi:
10.1016/0012-821X(82)90020-6.
Blundy, J., and Cashman, K., 2001, Ascent-driven
crystallisation of dacite magmas at Mount St.


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