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Constraints on crystal storage timescales in mixed magmas: Uranium-series disequilibria in plagioclase from Holocene magmas at Mount Hood, Oregon

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ABSTRACT

Uranium-series crystal ages, interpreted within a textural and geochemical framework, can provide insight into crystal storage timescales, especially in cases where crystals may derive from multiple sources. We report here ^{230}Th–^{226}Ra model ages of two distinct populations of plagioclase from low silica dacites from Mount Hood, Oregon, a volcano where previous studies show that the compositions of erupted magmas are controlled by magma recharge, mixing, and incorporation of plagioclase derived from mafic and silicic end-member magmas. We have measured trace element concentrations and ^{238}U–^{230}Th–^{226}Ra disequilibria in four plagioclase size fractions from the Timberline (1500 a) and Old Maid (215 a) eruptive sequences. After correction for groundmass and apatite contamination, average ^{230}Th–^{226}Ra model ages of large (>500 μm) plagioclase are >4.5 ka (Timberline) and >5.5 ka (Old Maid), with ages of cores that are >10 ka in each case, indicating that plagioclase derived from silicic magmas crystallized thousands of years before eruptions. These model ages are longer than timescales of repose between eruptions, indicating that these crystals resided in the sub-surface over multiple eruptions, likely stored in a silicic crystal mush zone that periodically interacts with mafic recharge magmas, remobilizing a fraction of the large plagioclase crystals during each eruptive event. After correction for large plagioclase contamination, small (<500 μm) plagioclase, derived from mafic magmas, have high (^{226}Ra)/Ba relative to equilibrium with liquid proxies (groundmass and mafic inclusion), leading to ^{230}Th–^{226}Ra model ages that are <~3 ka for Old Maid and undefined for Timberline separates. However, the preservation of significant ^{230}Th–^{226}Ra disequilibria require that the majority of crystals in the separate are young (<<10 ka). The high (^{226}Ra)/[Ba] could potentially be explained by rapid crystallization immediately prior to and/or during mixing events, consistent with evidence of rapid crystallization of rims. Rapid crystallization of mafic intrusions may trigger eruption at Mount Hood by producing a partially-crystalline mafic magma capable of mixing with a reheated silicic crystal mush.

1. Introduction

Timescales of pre-eruptive magmatic processes are difficult to constrain, yet are critical for understanding the dynamics of shallow magmatic systems that lead to eruption. Phenocryst mineral phases can provide timescale information because they crystallize in the sub-surface, recording physical and geochemical characteristics of their source magmas. Detailed studies of textural and chemical heterogeneity within individual crystals and between crystal populations can reveal a more complex pre-eruptive magmatic history than suggested by whole-rock chemical trends (e.g. Davidson and Tepley, 1997; Eichelberger et al., 2006; Ginibre et al., 2002; Murphy et al., 2000; Salisbury et al., 2008; Tepley et al., 2000). In addition, recognition of distinct populations of crystals that have experienced different histories prior to eruption provides a means to probe the origin of different magmatic components that contribute to erupted magma compositions. These approaches are particularly useful for studying magmatic processes at Mount Hood and other andesite- and dacite-dominated arc volcanoes because magma mixing frequently combines contributions from mafic and silicic magmas present in the sub-surface (e.g. Browne et al., 2006; Eichelberger, 1978; Eichelberger et al., 2006; Kent et al., 2010; Murphy et al., 2000; Pallister et al., 1992), leaving crystal phases as the primary record of magmatic history. A recent study of plagioclase in andesitic and dacitic Mount Hood lavas has revealed the presence of two plagioclase populations in magmas erupted throughout the ~500 ka history of the volcano, which represent plagioclase crystallized from the distinct mafic and silicic end-member magmas prior to and during mixing events (Kent et al., 2010). Our study adds temporal constraints to the crystallization and storage histories of these two plagioclase populations in their respective source magmas.

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Uranium-series crystal dating (using ^{238}U–^{230}Th–^{226}Ra disequilibria) is one of few methods capable of providing absolute ages for young (<350 ka) crystals (Allègre and Condomines, 1976; Charlier and Zellmer, 2000; Charlier et al., 2005; Condomines et al., 1995; Cooper and Donnelly, 2008; Cooper and Reid, 2003, 2008; Cooper et al., 2001; Reagan et al., 1992; Rogers et al., 2004; Schaefer et al., 1993; Tepley et al., 2006; Turner et al., 2003a,b; Volpe, 1992; Volpe and Hammond, 1991; Zellmer et al., 2008). This method is especially useful for dating bulk separates of major phases, such as plagioclase (Cooper and Reid, 2008). Plagioclase is resistant to dissolution and diffusive re-equilibration (Cherniak, 2002, 2003; Grove et al., 1984), and it crystallizes throughout much of the cooling history of most magmas. ^{238}U–^{230}Th disequilibrium is useful for constraining the longer-term histories of crystals and crystal populations (~10 ka up to ~350 ka), while ^{230}Th–^{226}Ra disequilibrium is capable of constraining more recent crystallization events (up to 10 ka). We focus on the two most recent eruptive events at Mount Hood, the Old Maid (eruption age ~215 a) and Timberline (eruption age ~1500 a) sequences (Crandell, 1980; Priest et al., 1982; Scott et al., 1997; Wise, 1969), because they are young enough to preserve ^{230}Th–^{226}Ra disequilibrium. In this study, we present measurements of (^{226}Ra)/(^{230}Th) in plagioclase from Mount Hood dacites and use these data, in conjunction with new and existing trace element data, to constrain the age and origin of plagioclase in these lavas. Our findings document that it is possible to use uranium-series techniques in conjunction with other approaches to constrain the age and origin of different mineral populations in mixed magmas.

2. Geological background

Mount Hood is a stratovolcano with 500 ka history of eruptive activity located in the Cascade arc ~80 km east of Portland, Oregon (Scott et al., 1997). In comparison to other stratovolcanoes in the Cascade arc, Mount Hood exhibits minimal compositional heterogeneity in its eruptive products, with lavas having a restricted compositional range (andesites to dacites of 58–64 wt.% SiO_2; Cribb and Barton, 1997; Hildreth, 2007; Kent et al., 2010). This remarkable homogeneity is primarily the result of magma mixing with possible minor fractional crystallization and crustal assimilation (Cribb and Barton, 1997; Kent et al., 2010). Evidence for magma mixing is widespread and includes simple linear compositional trends evident in Harker plots, the common presence of mafic inclusions in many lavas, complex mineral textures and zoning patterns, kinked crystal size distribution (CSD) plots for plagioclase (e.g. Fig. 1), and the presence of crystals in individual lavas with compositions showing that they derived from multiple magmatic sources (e.g. Cribb and Barton, 1997; Darr, 2006; Eichelberger, 1978; Kent et al., 2010; Woods, 2004).

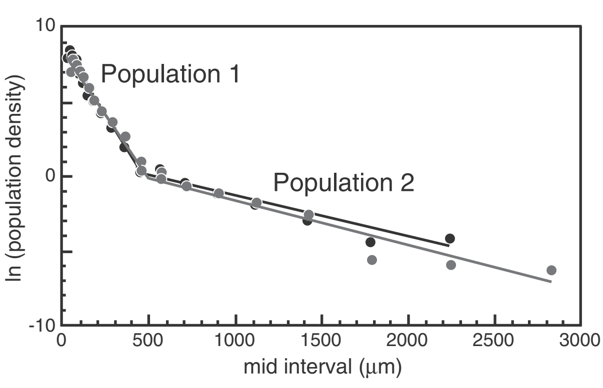

Fig. 1. Plagioclase crystal size distribution diagram, modified from Kent et al. (2010). Black symbols, Timberline; grey symbols, Old Maid. Kent et al. (2010) defined plagioclase with maximum crystal lengths 44.8–448 μm and >710 μm as Population 1 and Population 2, respectively.

Evidence for multiple crystal populations is particularly strong for plagioclase, the dominant phenocryst phase. Kinked CSD patterns occur in most Mt. Hood samples, including those used in this study (Fig. 1; Kent et al., 2010). CSD patterns of this type are commonly interpreted to result from juxtaposition of crystals from separate magmas as the result of magma mixing (e.g. Higgins, 1996; Marsh, 1988, 1998; Salisbury et al., 2008), although other explanations are possible. Using the CSD plots, two populations of plagioclase at Mount Hood can be distinguished: Population 1 plagioclase is 44.8-448 μm (where length refers to the longest crystal dimension in the stereologically-corrected CSD data) and Population 2 plagioclase is >710 μm (Kent et al., 2010). For Mount Hood, the mixing interpretation is supported by consistent chemical differences between the two plagioclase types: Population 1 crystals are higher in FeO*, MgO, and typically have $X_{An} > 0.55$. The larger Population 2 crystals tend to have lower X_{An} (as low as ~0.3, although some values as high as 0.7 are also present) and lower FeO* and MgO. In addition, two populations are also distinguishable on the basis of crystal textures. Population 2 crystals are subhedral to anhedral, tabular, complexly zoned, and have high X_{An} rims. Population 1 crystals are euhedral and acicular, lack complex zoning, and have low X_{An} rims. Overall, the differences between these two plagioclase populations are most simply explained by crystallization in separate, chemically-distinct magmas (e.g., Humphreys et al., 2009; Kent et al., 2010; Martel et al., 2006; Ruprecht and Cooper, in press). Population 1 crystals precipitated from mafic magmas (basalt to basaltic andesite) and Population 2 crystals crystallized from silicic magmas (low-SiO_2 rhyolite, Kent et al., 2010).

Magma mixing hybridized the liquid components of the end-member magmas without substantially altering the textural and geochemical characteristics of the two plagioclase populations (Kent et al., 2010). Late-stage syn- and post-mixing plagioclase growth also occurred, resulting in the crystallization of 25–50 μm An-rich rims on An-poor Population 2 crystals (and in some cases, <5 μm An-poor rims on Population 1 crystals; Darr, 2006). Diffusion modeling of Mg distributions across Population 2 rims demonstrate that they crystallized within days to weeks of eruption, suggesting a clear cause-and-effect relationship between mixing events and eruptions (Kent et al., 2010), consistent with eruption driven by recharge of a mafic magma into a cooler silicic magma reservoir.

3. Samples and methods

The samples used in this study were collected from dacite block-and-ash flow and pyroclastic flow deposits exposed on the southern side of Mount Hood; see Supplementary Table 1 of Kent et al. (2010) for whole-rock major element results. Timberline sample MH-08-08 was collected from an in-situ block in a dome collapse deposit located between the White River and Salmon River (N 45° 19.889′, W 121° 42.194′). Old Maid sample MH-08-12 was collected from an in-situ block in a pyroclastic flow unit located along the WSW bank of the White River (N 45° 18.666′, W 121° 41.021′). Both samples are porphyritic, containing 35–45 vol.% phenocrysts (plag + hbl + opx + cpx + ox) with a matrix of intergrown microcrystalline plagioclase and glass. Mafic inclusion MH-09-04A from the Old Maid sequence was collected from a different block than MH-08-12 but within the same deposit. Inclusion MH-09-04A contains 50–60 vol.% plagioclase phenocrysts (+px + hbl), but with smaller crystals than in the host rock.

The rocks were crushed by hand and sieved to prepare plagioclase and groundmass separates and whole-rock chips for trace element and uranium-series analyses. We prepared plagioclase separates of sizes 125–250 and 250–500 μm, representative of Population 1