Experimental constraints on magma ascent rate for the Crater Flat volcanic zone hawaiite

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ABSTRACT

Phase equilibria and isothermal, constant-rate decompression experiments conducted on a hawaiite from the Crater Flat volcanic zone near Yucca Mountain, Nevada, provide insight into the dynamics of magma transport for this magmatic province. H_2O contents up to 4.6 wt% in melt inclusions, the lack of plagioclase phenocrysts, and the presence of amphibole all suggest that phenocrysts and melt in the Crater Flat volcanic zone were equilibrated at near-water-saturated conditions during ascent. Comparison of decompression-induced crystallization of plagioclase microlites in experiments with natural tephra implies that magma ascent rates for the region are $>$0.04 m/s if the magmas are water saturated. Estimates of minimum ascent rates increase if the magmas are water undersaturated. A two-stage process is needed to generate reaction rims found on natural amphibole, suggesting that small batches of magma were briefly stored (3–5 days) at depths as shallow as 800 m prior to eruption.

Keywords: hawaiites, Crater Flat, Yucca Mountain, phase equilibria, magma ascent, volatiles.

INTRODUCTION

Long-term safety concerns about the proposed Yucca Mountain Nuclear Waste Repository in Nevada have generated significant interest in the volcanic activity of the Crater Flat volcanic zone (Crowe et al., 1983; Bradshaw and Smith, 1994). A better understanding of mineral-melt reactions occurring during transport (magma ascent) and eruption of Crater Flat magmas can aid in assessing the style and explosivity of future eruptions. Rutherford and Hill (1993) showed that the thickness of breakdown rims on amphibole crystals reacting with coexisting melt during ascent of dacitic magmas is a function of magma ascent rates. Earlier work on the volcanic rocks of Crater Flat (Vaniman et al., 1982) showed them to occasionally contain amphibole, with some of the amphiboles surrounded by reaction rims. Another result of ascent-related degassing of water-bearing magma is the crystallization of a microlite-rich groundmass, and the possibility of some phenocryst overgrowth. Microlite growth measurements (e.g., Cashman, 1992) can be used to estimate magma ascent rates by comparing crystal size in natural samples with data from decompression experiments (Geschwind and Rutherford, 1995; Martel and Schmidt, 2003). The first objective of this study was to experimentally determine the conditions of phenocryst-melt equilibration in typical amphibole-bearing Crater Flat hawaiite. These conditions are interpreted to represent those where the final stage of magma ascent began. We then performed decompression experiments to determine rates of magma ascent required to produce the amphibole and microlite textures, and compositions observed in natural tephra.

EXPERIMENTAL AND ANALYTICAL METHODS

The starting material used for our experiments is a hawaiite collected from a lava flow (LW-Ql2a) erupted from the Lathrop Wells (LW) volcanic center, the youngest vent in Crater Flat volcanic zone (77.3 ka, Heizler et al., 1999). Like the majority of the material erupted in Crater Flat, it is made up of 2–4 vol% phenocrysts of magnesian olivine ($<$4 mm) with occasional microphenocrysts of An_{69} plagioclase in a finely crystalline groundmass. The bulk chemical composition of the starting material is given in Table 1, along with the average

TABLE 1. BULK AND MINERAL COMPOSITIONS OF STARTING MATERIAL AND EXPERIMENTAL PRODUCTS

Oxides (wt%)	Starting material LW-A	CFVZ avg. bulk composition*	Amphibole		Plagioclase	
			Experiment	Natural	Experiment	Natural
SiO_2	49.24	50.18 (1.46)	40.23	40.10	50.16	49.07
TiO_2	1.85	1.67 (0.40)	4.25	4.09	–	–
Al_2O_3	17.42	16.77 (0.39)	14.35	13.84	31.01	30.37
Cr_2O_3	–	–	0.09	0.06	–	–
FeO (total)	10.43	10.30 (0.86)	11.54	11.19	0.50	0.68
MnO	0.16	0.16 (0.00)	0.15	0.12	–	–
MgO	5.84	5.32 (0.33)	13.02	13.95	–	–
CaO	8.69	9.09 (0.10)	11.91	11.12	13.75	13.93
Na_2O	3.32	3.53 (0.14)	2.31	2.39	3.31	3.59
K_2O	1.69	1.73 (0.19)	0.81	1.21	0.23	0.24
P_2O_5	1.36	1.25 (0.14)	–	–	–	–
Total	100.00	100.00	98.65	98.07	98.95	98.31
Pressure (MPa)	–	–	180	–	175	–
Temperature (°C)	–	–	975	–	970	–
An	–	–	–	–	68.9	67.2

Note: CFVZ—Crater Flat volcanic zone.
*Calculated from compositions reported in Vaniman et al. (1982). Standard deviations in parentheses.

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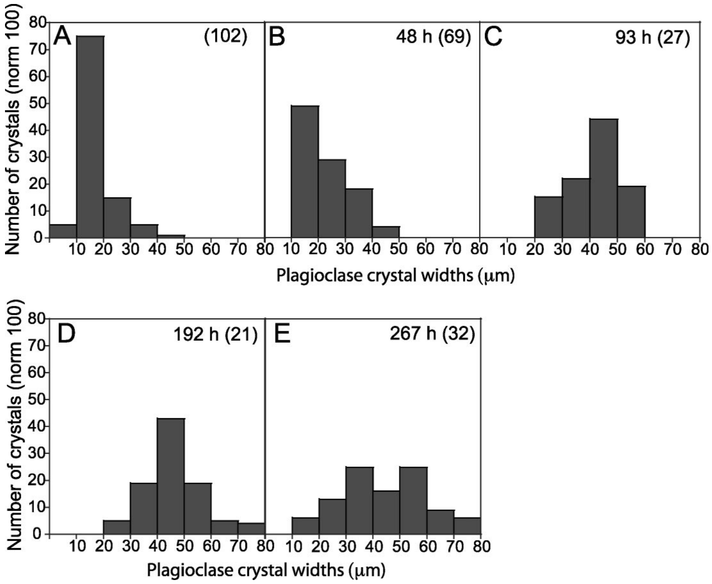

Figure 1. Modal size distribution of measured crystal widths normalized to 100 for (A) natural tephra from Little Cone NE and (B–E) decompression experiments. Decompression interval and number of crystals measured, shown in parentheses, are given for each sample. All experiments were decompressed from 180 to 15 MPa.

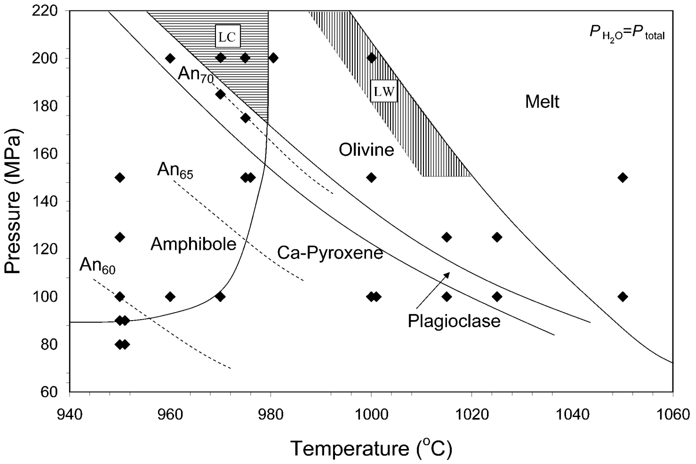

Figure 2. Phase-equilibria diagram for Crater Flat hawaiite. Solid diamonds represent constant pressure-temperature (*P-T*) experiments. Double diamonds illustrate reversal experiments. Solid lines are mineral liquidus curves. Dashed lines are contours of plagioclase composition (anorthite [An] content). Horizontal and vertical patterned areas are regions in *P-T* space where pre-eruption magmatic phenocryst assemblage and composition of Little Cone NE (LC) and Lathrop Wells (LW), respectively, are stable.

composition of lavas from five Crater Flat volcanic centers. Based on Lathrop Well's young age, relatively large eruption volume (0.14 km^3), and the compositional similarity of this sample to other rocks in this province, LW-Ql2a is considered to be a representative Crater Flat starting composition for an ascent-rate study.

Samples of powdered basalt were sealed in $Ag_{70}Pd_{30}$ tubing along with a sufficient amount of distilled H_2O to ensure melt saturation ($P_{total} = P_{H_2O}$) at the initial experimental pressure (P) and temperature (T). All experiments were carried out in tungsten-zirconium-molybdenum pressure vessels with a pressurizing mixture of Ar and CH_4, which maintained the oxygen fugacity just below the quartz-fayalite-magnetite fO_2 buffer.

A series of experiments was conducted at constant P and T in order to determine phase stability fields. To ensure that chemical equilibrium was achieved, several reversal experiments were conducted in which the same phase assemblage was attained for both melting and crystallization processes. Run durations of 24–48 h were needed to achieve equilibrium. Experimental charges were divided into two aliquots, one for thin sections used for optical and electron microprobe analyses and the other for use as starting material in further experiments. Isothermal decompression experiments used aliquots of samples quenched from constant P and T experiments as a starting material. These experiments were held at initial P of 175–185 MPa for 6 h before decompression to ensure that all microlites produced during the previous quench were dissolved, and that only the phenocryst assemblage was present. Pressure was released at one of several constant rates to simulate possible magma ascent paths. All runs were quenched at a final P of 15 MPa.

Standard electron microprobe calibration techniques outlined by Devine (1995) were used to analyze mineral and glass compositions.

RESULTS

Melt Inclusion Analysis

We analyzed 21 olivine melt inclusions from Lathrop Wells tephra in order to estimate pre-eruption melt volatile content and composition, and to further evaluate the conditions required to create the observed phenocryst-melt assemblages (olivine ± amphibole). Using the volatiles by difference method (Devine et al., 1995), we obtained estimates of H_2O contents of 1.2–1.7 wt% for 19 of 21 melt inclusions. Two inclusions, however, had volatile contents of 2.9 and 3.5 wt%. These two melt inclusions also had less-evolved silicate melt compositions, with Mg#s of 51 and 53, respectively, compared to an average Mg# of 46 for all others [Mg# = MgO/(MgO + FeO_T)]. These results are within the findings of Luhr and Housh (2002), who established a mean total water content of 3.5 wt% (range of 1.9%–4.6%) from Fourier transform infrared analyses of nine olivine melt inclusions from two vents in Crater Flat (Lathrop Wells and Red Cone). Six of their inclusions also contained dissolved CO_2 ranging from 230 to 930 ppm.

Plagioclase Microphenocrysts

A textural analysis of natural tephra samples (e.g., Cashman and Marsh, 1988; Armienti et al., 1994; Higgins, 1996; Hammer and Rutherford, 2002) erupted from the Little Cone NE vent was done to determine crystal sizes. Direct measurements of plagioclase were made from both backscattered electron and optical images. These analyses yielded a dominant width of 10–20 μm; some crystals, however, were as narrow as 5 μm, and others were as wide as 50 μm (Fig. 1A). Crystal-size distribution (CSD) analysis was used to determine the mean crystal width. CSD slopes generated with the CSD Corrections program (Higgins, 2000) corresponded to a mean width of 32 μm.

Phase Equilibria

Experimental run products define an equilibrium phase diagram (Fig. 2) for an H_2O-saturated hawaiitic composition. Olivine is the liquidus phase, appearing at 1040–1000 °C with increasing P_{H_2O}. At $P < 175$ MPa, decreasing T produces olivine crystallization followed by plagioclase, clinopyroxene, Ti-rich amphibole, and then iron-titanium oxide. Above 175 MPa, the plagioclase and clinopyroxene stability fields are suppressed, and a phenocryst assemblage of olivine plus amphibole is stable at $T < 975$ °C. At $P < 90$ MPa amphibole does not crystallize at any temperature. Amphiboles produced in our experiments are compositionally similar to those found in the natural tephra and lava flows from the Little Cone NE vent (Table 1). Plagioclase compositions at 175 MPa are similar to those of microlites found in the natural tephra. With decreasing pressure, at a given temperature, the crystallizing plagioclase changes from An_{70} to An_{60}.

Decompression Experiments

The Little Cone volcanic center, like other vents in Crater Flat, is a dike-fed system. There is no evidence that suggests the presence of a shallow magma reservoir. A simple ascent model for the amphibole-bearing Little Cone magmas is an isothermal (970 °C), constant-rate decompression path from an initial *P* of 180 MPa to 15 MPa. Several decompression experiments were done for various ascent rates to simulate such an ascent path.

Upon decompression, plagioclase microphenocryst nucleation and growth in the melt is triggered at $P < 175$ MPa, and growth tends to continue with decreasing pressure. The rim compositions on plagioclase microlites ranged from An_{70} for short decompression times (12 h) to An_{50} in longer decompressions (267 h). All of the decompression experiments produced euhedral, tabular plagioclase crystals, except for one 12 h run, which grew rod-shaped morphologies. Measurements indicated that crystal widths increased with increasing duration of decompression (Figs. 1B–1E). Decompression times of 93–267 h produced crystal widths ranging from 10 to 90 μm, with a dominant mode at 30–60 μm. A 48 h decompression time resulted in crystal widths of 10–50 μm, with a dominant mode at 10–30 μm. A 12 h experiment produced even smaller crystal widths (≤5 μm).

Constant-rate decompression times of 12–267 h failed to produce any rim growth on amphibole crystals in the hawaiite samples. Instead, amphibole dissolution was extensive, particularly in longer-duration (>96 h) decompression experiments, and this reaction was accompanied by coarsening of nearby plagioclase, clinopyroxene, and iron-titanium oxide crystals that grew during decompression.

DISCUSSION

Pre-eruption Conditions for Little Cone and Lathrop Wells

The occurrence of plagioclase microphenocrysts and the stability field of the olivine + amphibole phase assemblage fix the minimum *P-T* conditions for phenocryst-melt equilibration in the amphibole-bearing Crater Flat magma just prior to ascent and eruption. Our constant *P* and *T* experiments showed that the natural phenocryst assemblage found in the amphibole-bearing Little Cone tephra is stable only at $P > 175$ MPa and $T < 975$ °C. The temperature range over which this phase assemblage is stable increases with increasing pressure (Fig. 2). Experimental plagioclase microlite compositions indicate that their natural counterparts must have crystallized during the magma ascent to the surface. Plagioclase in the natural samples is almost exclusively a groundmass phase, consistent with this conclusion. The small size and limited range in compositions (An_{66-69}) found in natural tephra correspond to compositions crystallized near the plagioclase liquidus in relatively rapid (≤2 days) decompressions. Longer decompression times produce plagioclase crystal sizes (30–60 μm) that are larger and more evolved (An_{50}–An_{60}) than those observed in the natural samples.

The minimum *P* of 175 MPa for phenocryst-melt equilibration in the amphibole-free Lathrop Wells magmas is similar to that of Little Cone. Our experiments show that the different phase assemblages at the two vents are likely a result of a 25–35 °C higher temperature for the magmas erupted at Lathrop Wells (Fig. 2).

Although all of our constant *P* and *T* experiments were run at water-saturated conditions, we do not assume that Crater Flat magmas necessarily began their ascent to the surface as water-saturated magmas. There is, however, evidence to indicate that the magmas erupted in the Crater Flat volcanic zone were volatile rich and were at or near volatile saturation during the phenocryst growth stage. Our phase-equilibria experiments have shown that to crystallize amphibole requires at least 3.0 wt% dissolved H_2O in the coexisting hawaiitic melt. Volatile data from Luhr and Housh (2002) and our own analyses of olivine-hosted melt inclusions indicate that magmas erupted at Lathrop Wells contained 1.9–4.6 wt% H_2O, well above the constraint imposed by amphibole stability. Some of the measured H_2O contents are likely to be low compared to H_2O trapped originally because of loss by diffusion and/or leakage (e.g., Mackwell and Kohlstedt, 1990; Hauri, 2002). Therefore, the saturation pressure derived from such analyses should be considered a minimum estimate.

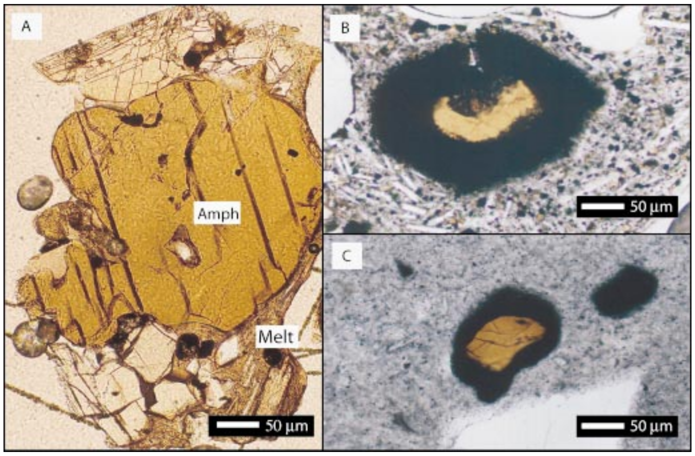

Figure 3. Optical photomicrographs. A: Amphibole phenocryst found in Little Cone South tephra (with no reaction rim) in direct contact with melt. Cusps along grain boundary indicate that some dissolution has taken place. B: Example of amphibole found in Little Cone NE with 70-μm-thick fine-grained reaction rim. C: Similar fine-grained textures found on amphiboles in "blast dacite" erupted from cryptodome that formed within Mount St. Helens in 1980.

A second reason the saturation pressure should be taken as a minimum value comes from the confirmed presence of a significant amount of dissolved CO_2 (Luhr and Housh, 2002) in melt inclusions. The observed CO_2 abundances would induce volatile saturation at greater depths in melt that contains only water. Upon formation of a CO_2-rich vapor phase in a rising magma, H_2O will partition into the vapor along with CO_2, thereby reducing the H_2O in the melt (Holloway and Blank, 1994). Assuming that the H_2O values (1.9–4.6 wt%) from the melt inclusions are the dissolved volatile contents, computed saturation (pre-eruption) *P* of 40–180 MPa (Moore et al., 1998) gives the last equilibration conditions for magmas erupted at Lathrop Wells (vertically shaded field in Fig. 2). However, the CO_2-bearing inclusions would have to be trapped from a melt crystallizing at even higher pressures (Newman and Lowenstern, 2002).

Magma Ascent Rates

Unlike the decompression-induced reaction that takes place in high-silica melts, amphibole breakdown in hawaiitic magma did not result in reaction rims. However, dissolution of amphibole clearly occurs, as indicated by the decrease in modal amphibole in the decompression experiments. Due to the low viscosity of the hawaiitic melt, the amphibole breakdown reaction is apparently slower than the transport of material away from the rim. The result is amphibole dissolution and growth of new anhydrous phases such as plagioclase, clinopyroxene, and iron-titanium oxide away from the amphibole-melt boundary. The lack of rim development is not just an experimental phenomenon; amphibole in contact with melt in the natural samples is rounded and apparently undergoing dissolution (Fig. 3A). As in our experiments, there is no indication of any rim development on some of the natural amphiboles, while on others there is a thick (~65 μm) fine-grained rim (Fig. 3B). The amphibole-melt textures in the experiments clearly indicate that the reaction rims found on amphiboles at Little Cone NE and Red Cone did not form during decompression.

One possible explanation for the naturally rimmed amphiboles is that the crystals were picked up from hawaiitic wall rock as an erupting batch of magma moved to the surface through a previously established hawaiitic feeder dike. The fine-grained nature of the amphibole rim material in the Crater Flat volcanic zone magmas is similar to the texture observed in the Mount St. Helens cryptodome samples (Fig. 3C). The fine-grained rims in the latter are interpreted to have grown as a result of near-surface reaction and oxidation when ascending magma stalled in a shallow crustal reservoir (Rutherford and Hill, 1993). In the Crater Flat basin, the regional structure, along with the large-scale density contrast ($\sim$280 kg/m^3) found at shallow depths (0–5 km), provides the opportunity for limited localized storage of ascending magma (Connor et al., 2000). This setting may have created a scenario similar to that of the Mount St. Helens cyptodome, where earlier stalled batches of magma were exposed to conditions well outside the amphibole stability field. Such a process would suppress the rate of diffusion and transport of breakdown components away from the amphibole-melt boundary, and enhance the conditions needed for development of a fine-grained rim. This suggestion is strongly supported by preliminary experiments in which fine-grained rim textures were produced after rapid decompression (9 h) and stagnation for up to 5 days at low pressures (20 MPa) corresponding to shallow depths of $\sim$800 m.

Although amphibole reaction-rim growth apparently did not occur during ascent of Crater Flat magmas, the size and composition of plagioclase microlites in these experiments can be compared to those from natural basalts to constrain magma ascent rates. In shorter experimental decompression runs, lower SiO_2 melt compositions were accompanied by smaller plagioclase crystal widths compared to longer runs. In the longer decompression runs (93–267 h), plagioclase crystal widths were found to be 30–60 μm, much larger than the main mode (10–20 μm) found in erupted Little Cone tephra. In both the 12 and 48 h experiments, plagioclase growth was limited, as reflected in the width of the crystals ($\leq$5–30 mm). It is clear that the low viscosity of hawaiitic magmas helps promote crystal growth during the decompression process; doubling the magma's decompression time from 2 to 4 days results in a two- to threefold increase in plagioclase microlite crystal widths.

Comparison of the textures of our experimental decompression products with the natural samples, as well as the evidence of volatile-rich magma, strongly suggests that relatively rapid ascent rates are characteristic of the Crater Flat volcanic zone. The 175 MPa phenocryst-melt equilibration pressure of the magma before its ascent is equivalent to a depth of $\sim$7 km, assuming an average crustal density of 2560 kg/m^3 for the upper 10 km of crust (Brocher et al., 1998; Connor et al., 2000). In order to create the textures found in tephra at the volcanic centers of Crater Flat, magma ascent rates need to be $\geq$0.04 m/s. Depending on the amount of volatiles lost through the conduit (dike) walls, these magmatic conditions enhance the possibility for an explosive eruption that would produce tephra-fall deposits.

Even if these Crater Flat volcanic zone magmas were not initially water saturated ($P_{H_2O} < P_{total}$), the lack of plagioclase phenocrysts in the natural samples indicates that magma ascent had to be very rapid. Constant P and T experiments run at $P_{H_2O} < P_{total}$ conditions confirm that the plagioclase stability field would expand with increasing water undersaturation, pushing the stability of the natural phase assemblage of olivine + amphibole to higher pressures and temperatures. Thus undersaturation would require even higher magma ascent rates ($\gg$0.04 m/s) in order to suppress the decompression-induced microlite growth to the level observed in naturally erupted tephra.

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