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Amphibole reaction rims as a record of pre-eruptive magmatic heating: An experimental approach

S.H. De Angelis [a,*], J. Larsen [a], M. Coombs [b], A. Dunn [a], L. Hayden [c]

[a] *Department of Geology and Geophysics, University of Alaska Fairbanks, Reichardt Building, 900 Yukon Drive, Fairbanks 99775, United States*
[b] *Alaska Volcano Observatory, United States Geological Survey, 4230 University Drive Anchorage, AK 99508-4667, United States*
[c] *United States Geological Survey, 345 Middlefield Rd, MS 910, Menlo Park, CA 94025, United States*

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ABSTRACT

Magmatic minerals record the pre-eruptive timescales of magma ascent and mixing in crustal reservoirs and conduits. Investigations of the mineral records of magmatic processes are fundamental to our understanding of what controls eruption style, as ascent rates and magma mixing processes are well known to control and/or trigger potentially hazardous explosive eruptions. Thus, amphibole reaction rims are often used to infer pre-eruptive magma dynamics, and in particular to estimate magma ascent rates. However, while several experimental studies have investigated amphibole destabilization during decompression, only two investigated thermal destabilization relevant to magma mixing processes. This study examines amphibole decomposition experimentally through isobaric heating of magnesio-hornblende phenocrysts within a natural high-silica andesite glass. The experiments first equilibrated for 24 h at 870 °C and 140 MPa at H_2O-saturated conditions and $fO_2 \sim$ Re–ReO prior to rapid heating to 880, 900, or 920 °C and hold times of 3–48 h. At 920 °C, rim thicknesses increased from 17 µm after 3 h, to 55 µm after 12 h, and became pseudomorphs after longer durations. At 900 °C, rim thicknesses increased from 7 µm after 3 h, to 80 µm after 24 h, to pseudomorphs after longer durations. At 880 °C, rim thicknesses increased from 7 µm after 3 h, to 18 µm after 36 h, to pseudomorphs after 48 h. Reaction rim microlites vary from 5–16 µm in size, with no systematic relationship between crystal size and the duration or magnitude of heating. Time-averaged rim microlite growth rates decrease steadily with increasing experimental duration (from 3.97×10^{-7} mm s^{-1} to 3.1 to 3.5×10^{-8} mm s^{-1}). Time-averaged microlite nucleation rates also decrease with increasing experimental duration (from 1.2×10^3 mm^{-3} s^{-1} to 5.3 mm^{-3} s^{-1}). There is no systematic relationship between time-averaged growth or nucleation rates and the magnitude of the heating step. Ortho- and clinopyroxene together constitute 57–90 modal % mineralogy in each reaction rim. At constant temperature, clinopyroxene abundances decrease with increasing experimental duration, from 72 modal % (3 h at 900 °C) to 0% (48 h at 880 °C, and 36 h at 900 and 920 °C). Fe–Ti oxides increase from 6–12 modal % (after 3–6 h) to 26–34 modal % (after 36–48 h). Plagioclase occurs in relatively minor amounts ($<$1–11 modal %), with anorthite contents that increase from An56 to An88 from 3 to 36 h of heating. Distal glass compositions ($>$500 µm from reacted amphibole) are consistent with inter-microlite rim glasses (71.3–77.7 wt.% SiO_2) within a given experiment and there is a weakly positive correlation between increasing run duration and inter-microlite melt SiO_2 (68.9–78.5 wt.%). Our results indicate that experimental heating-induced amphibole reaction rims have thicknesses, textures, and mineralogies consistent with many of the natural reaction rims seen at arc-andesite volcanoes. They are also texturally consistent with experimental decompression reaction rims. On this basis it may be challenging to distinguish between decompression and heating mechanisms in nature.

1. Introduction

The style and explosivity of volcanic eruptions are controlled by the mass eruption rate. In turn, mass eruption rate is controlled by the magmatic ascent rate and the physical and chemical properties of the magma (e.g., density, viscosity, crystallinity, and

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[*] Corresponding author at: School of Earth, Ocean and Ecological Sciences, University of Liverpool, 4 Brownlow Street, Liverpool, L69 3GP, United Kingdom. Tel.: +44 151 794 4974.
E-mail address: pelee83@gmail.com (S.H. De Angelis).

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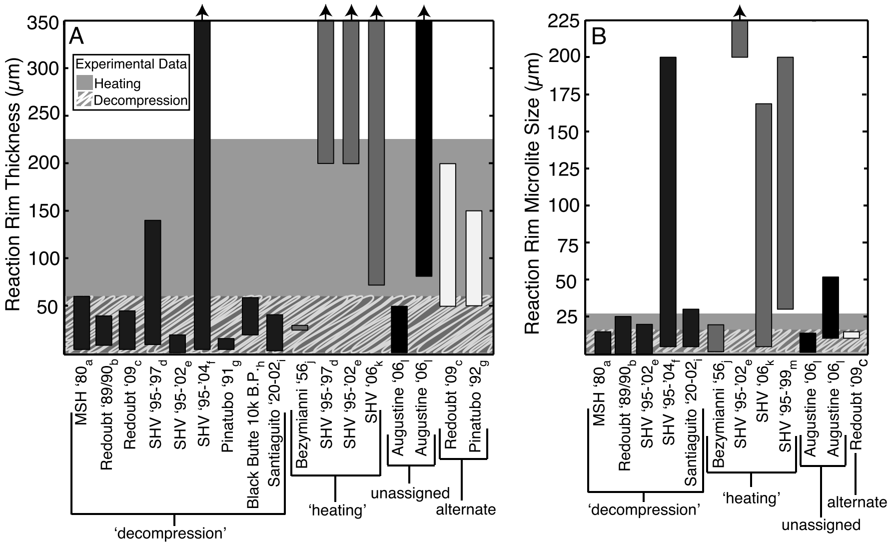

Fig. 1. Textural characteristics of natural amphibole. Ranges natural reaction rim (A) thickness (μm) and (B) microlite sizes (μm), as reported by previous studies. Data are classified by the inferred cause of reaction rim formation (decompression, heating, unassigned, and 'alternate'). Data on very thin oxidation or 'black type' (Garcia and Jacobsen, 1979) reaction rims are not included. Diagonal crosshatched shading denotes data ranges for experimental reaction rims formed through decompression (Browne and Gardner, 2006; Rutherford and Devine, 2003; Rutherford and Hill, 1993). Grey shading denotes data ranges for experimental reaction rims formed through heating (Browne, 2005; this study). Arrows indicate datasets where the data range exceeds the axes of the figure. Volcano abbreviations: SHV = Soufrière Hills Volcano; MSH = Mount St Helens. Data sources: a = Rutherford and Hill (1993); b = Browne and Gardner (2006); c = Coombs et al. (2013); d = Devine et al. (1998); e = Rutherford and Devine (2003); f = Buckley et al. (2006); g = Daag et al. (1996); h = McCanta et al. (2007); i = Scott et al. (2012); j = Plechov et al. (2008); k = Humphreys (personal communication); l = De Angelis et al. (2013); m = Murphy et al. (2000).

composition; Rutherford, 2008). Thus, understanding pre-eruptive processes that can influence magmatic ascent rates and eruption triggering is important for research into active and potentially hazardous volcanic eruptions. Magmatic ascent and eruption triggering processes are likely influenced by the pre-eruptive processes occurring within the shallow magma storage region, such as: magma mixing and mingling, heating, and/or changes in gas pressure. Phenocryst phases, including hydrous amphibole, residing in the subvolcanic plumbing system are well-known to be sensitive recorders of pre-eruptive magmatic processes.

Amphibole reaction rims are often used to unravel complex magma ascent and mixing processes. For example, researchers use ascent-driven dehydration and decomposition of amphibole to calibrate models for assessing magma ascent timescales in intermediate arc magmas (Browne and Gardner, 2006; Rutherford and Devine, 2003; Rutherford and Hill, 1993). However, other factors also trigger amphibole breakdown (e.g., oxidation, fluxing of the melt with a CO_2 rich fluid, or heating; Rutherford and Hill, 1993). The role of heating is particularly important because many arc magmas display disequilibrium textures that record the heating of one magma by another during pre-eruptive mixing (e.g., Clynne, 1999; Devine et al., 2003; Eichelberger, 1975; Feeley and Sharp, 1996; Murphy et al., 2000; Ruprecht and Bachmann, 2010; Tepley et al., 2000; Venezky and Rutherford, 1999). This process may lead to the breakdown of amphibole as temperatures exceed its typical thermal stability boundary of ~880–900 °C (Browne and Gardner, 2006; Henton de Angelis, 2013).

Many studies have used experimentally derived models of amphibole decomposition during controlled decompression to ascertain magma ascent rates from natural samples (e.g., Coombs et al., 2013; Devine et al., 1998; McCanta et al., 2007; Nicholis and Rutherford, 2004; Scott et al., 2012; Wolfe and Eichelberger, 1997; Plechov et al., 2008; Rutherford and Hill, 1993). In contrast, amphibole breakdown as a result of heating has only been systematically studied in a small number of experiments (Browne, 2005; Rutherford and Devine, 2003). Thus, there is no comparable tool to use for estimating timescales of amphibole decomposition triggered by heating. Furthermore, this lack of experimental data on heating induced amphibole breakdown makes the identification of reaction rims formed by heating in natural rocks problematic.

1.1. Natural amphibole reaction rim classifications

Natural amphibole reaction rims display a broad range of textures and mineralogies (Fig. 1; Browne, 2005; Browne and Gardner, 2006; Buckley et al., 2006; Coombs et al., 2013; Daag et al., 1996; Devine et al., 1998; Garcia and Jacobsen, 1979; Humphreys et al., 2009; McCanta et al., 2007; Murphy et al., 2000; Plechov et al., 2008; Rutherford and Devine, 2003; Rutherford and Hill, 1993; Scott et al., 2012; Tepley et al., 2013). In addition to polycrystalline reaction rims, other studies have described amphibole mantled by or replaced by pseudomorphs of augite, formed as a single continuous crystal around the host amphibole (e.g., Holocene deposits of El Chichón; Andrews et al., 2008). Garcia and Jacobsen (1979) describe two reaction rim types: 'black' and 'gabbroic'. In 'black' type reaction rims the amphibole is replaced by 'very fine-grained' Fe–Ti oxide and pyroxene microlites. They conclude that 'black' rims result from dehydrogenation and oxidation during magma extrusion. This type of amphibole replacement is easily identified and commonly observed around phenocryst edges and along interior cracks and cleavage planes (Rutherford and Hill, 1993).

In 'gabbroic' reaction rims the amphibole is replaced by 'fine–medium' orthopyroxene, clinopyroxene, plagioclase, and Fe–Ti oxide microlites. Garcia and Jacobsen (1979) concluded that these reaction rims form as a result of dehydration. Rutherford and Hill (1993) further recognized that this rim type forms only when the amphibole directly contacts the host melt. In subsequent studies on Soufrière Hills Volcano, Montserrat (e.g., Devine et al., 1998; Humphreys et al., 2009; Rutherford and Devine, 2003) a third rim type was identified: 'thick', coarse-grained clinopyroxene-rich reaction rims thought to be the result of heating.

While there are some exceptions, decompression-induced reaction rims are generally described as thin (<60 μm), fine-grained (5–30 μm microlite size), and containing predominantly orthopyroxene, clinopyroxene, plagioclase, and Fe–Ti oxides (Fig. 1; Browne and Gardner, 2006; Rutherford and Hill, 1993). Experimental stud-