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Why do mafic arc magmas contain ~ 4 wt% water on average?Terry Plank^{a,*}, Katherine A. Kelley^b, Mindy M. Zimmer^c, Erik H. Hauri^d, Paul J. Wallace^e^a Lamont–Doherty Earth Observatory of Columbia University, Palisades, NY 10960, USA^b Graduate School of Oceanography, University of Rhode Island, Narragansett Bay Campus, Narragansett, RI 02882, USA^c Los Alamos National Laboratory, Los Alamos, NM, USA^d Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington DC 20015, USA^e Department of Geological Sciences, University of Oregon, Eugene, OR 97403, USA

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ABSTRACT

The last 15 yr have seen an explosion of data on the volatile contents of magmas parental to arc volcanoes. This has occurred due to the intense study of melt inclusions trapped in volcanic phenocrysts, aliquots of magma that have presumably escaped degassing during eruption. The surprising first-order result is the narrow range in H₂O concentrations in the least degassed melt inclusions from each volcano. Nearly all arc volcanoes are sourced with mafic magmas that contain 2–6 wt% H₂O. The average for each arc varies even less, from 3.2 (for the Cascades) to 4.5 (for the Marianas), with a global average of 3.9 ± 0.4 wt% H₂O. Significant variations occur from volcano to volcano within each arc, but the means are indistinguishable within one s.d. The narrow range and common average value for H₂O are in stark contrast to the concentrations of most other subduction tracers, such as Nb or Ba, which vary by orders of magnitude. A modulating process, either in the crust or mantle, is likely responsible for the restricted range in the H₂O contents of arc melt inclusions. One possibility is that melt inclusion H₂O values reflect vapor saturation at the last storage depth in the crust prior to eruption. In this scenario, magmas rise from the mantle with variable H₂O contents (> 4 wt%), become vapor-saturated and start degassing, and continue to degas up until the depth at which they stall. If the stalling depths are ~ 6 km, which is common for storage depths beneath volcanoes, magmas would be saturated at ~ 4 wt% H₂O, and melt inclusions, most of which become closed during further ascent, would thus record ≤ 4 wt% H₂O. Another possibility is that the mantle melting process modulates water content in the melt such that magmas rise out of the mantle with ~ 4 wt% H₂O. A strong relationship between the water content of the source, H₂O_(o) and the degree of melting (F) maintains nearly constant water contents in the melt for a restricted range in mantle temperature. Magmas with 3–4 wt% H₂O can be generated at $\sim 50^\circ$ below the dry solidus for a wide range in F and H₂O_(o). The narrow range in wedge temperatures may be another manifestation of a planet with average upper mantle of 1400 °C potential temperature. The characteristic mean and range of H₂O contents of arc magmas has implications for both the volatile fuel for explosive eruptions and the mass balance of H₂O recycled through subduction zones.

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1. Introduction

Water affects every part of a magma's history, from its origins in the mantle to its eruption from a volcano. Water dramatically lowers the solidus temperature of the mantle, and so drives melting (e.g., Katz et al., 2003). It has a major effect on the rheological properties of both magmas and crystals, depolymerizing melt and weakening olivine (e.g., Gonnermann and Manga, 2007; Hirth and Kohlstedt, 1996). Water cycles chemical components between the

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hydrosphere, mantle, and crust at subduction zones (e.g., Wallace, 2005; Ruscitto et al., 2012). Magmas crystallize and differentiate in unique ways when water is a major dissolved component (e.g., Grove et al., 2003; Zimmer et al., 2010). And water exsolves dramatically from melt at low pressure, causing the vesiculation which fuels explosive eruptions (e.g., Cashman, 2004).

Despite these critical phenomena, the quantitative measurement of the concentration of water in magmas has been an on-going challenge in igneous petrology. The primary difficulty stems from the near complete degassing of magmas during ascent, eruption and cooling. The only bits of magma that escape such near-complete degassing at the surface of the earth are trapped inside crystals. Roberto Clochiatti, Alfred Anderson and Alexander Sobolev pioneered the petrological utility of such melt

inclusions (e.g., Clocchiatti, 1968; Clocchiatti et al., 1975; Anderson 1973, 1976; Sobolev et al., 1983) and this, together with experimental phase equilibrium (see Grove et al. (2012)), are the primary approaches used today for determining pre-eruptive volatile contents of magmas. Another hurdle is in the quantitative measurement of H₂O or H species in such inclusions. Early inferences were based on the absence of measurement—the deficit from 100% on the sum of the oxides measured by electron microprobe. Such sum deficits were not very precise, but they turned out to provide an accurate view of the water-rich nature of arc magmas. FTIR and SIMS ion microprobe techniques now provide higher precision and information on H speciation.

In the mid-90s, a series of seminal papers brought these new analytical methods to melt inclusion and submarine glass studies of subduction zone magmas (Danyushevsky et al., 1993; Sisson and Layne, 1993; Stolper and Newman, 1994; Sobolev and Chaussidon, 1996; Roggensack et al., 1997). Together, this work demonstrated unequivocally that subduction zone magmas are initially wet, with primary water concentrations being at least 2 wt%, and more evolved basalts containing up to 6 wt% H₂O. The new techniques developed in these papers spawned a flurry of studies on magmatic water, leading to a wave of new understanding on subduction water fluxes (Sadofsky et al., 2008; Ruscitto et al., 2012), wet melting in the mantle (Kelley et al., 2006, 2010; Langmuir et al., 2006; Portnyagin et al., 2007; Johnson et al., 2009; Ruscitto et al., 2010), cross-arc water variations (Walker et al., 2003) the ascent of arc magmas (Blundy and Cashman, 2005), their differentiation (Zimmer et al., 2010) and eruption (Blundy et al., 2006; Metrich et al., 2010; Spilliaert et al., 2006). Complementary phase equilibria studies also supported very high water contents in some parental arc magmas (6–16 wt% H₂O; Grove et al., 2005; Carmichael, 2002). The future will see further development of Raman spectroscopy, with single micron spatial resolution on unexposed inclusions (Mercier et al., 2010), and nanoSIMS, with the potential for single micron spatial resolution and single ppm detection limits in nominally anhydrous phenocrysts (Hauri et al., 2011; Mosenfelder et al., 2011).

Approximately 15 yr later, focused efforts by many groups have now provided baseline data for a number of volcanic arcs. The surprising result is how little the H₂O concentration varies in the least degassed mafic melts from each volcano. The purpose of this paper is to present this observation, and then explore mechanisms that could lead to similar average water contents for different arcs.

2. The data

Magmas lose their dissolved H₂O as a natural consequence of ascent and eruption. A magma with 7 wt% H₂O (the maximum observed in olivine-hosted inclusions, from Klyuchevskoy, Kamchatka; Auer et al., 2009 and Augustine, Alaska; Zimmer et al., 2010) will reach pure H₂O-vapor saturation at ~400 MPa, or ~15–16 km in the crust (assuming an upper crustal density of 2.6 g/cc, and using the solution models of Newman and Lowenstern (2002) and Witham et al. (2012)). As magmas ascend to depths shallower than their point of H₂O-saturation, they will continually degas H₂O to vapor, striving to reach equilibrium during decompression, eruption, and cooling. At the earth's surface (1 atm pressure), mafic melts can hold ~0.1 wt% H₂O. Thus, all wet magmas lose H₂O to vapor upon ascent; only melt inclusions trapped in early formed crystals that are brought to the surface and cooled rapidly stand some chance of preserving original H₂O concentrations. Olivine is the vessel of choice, as it is one of the first minerals to crystallize in arc basaltic magma, and contains minor concentrations of incompatible elements that can exchange with melt inclusions. Clinopyroxene-hosted melt inclusions or phenocrysts themselves may also preserve information about undegassed water concentrations (Zimmer et al., 2010; Wade et al., 2008). Tephra clasts ≥ 3 cm in diameter cool slowly enough (~10 min) that a significant fraction of H₂O (~1 wt%) may be lost by diffusion through the olivine (Lloyd et al., 2013), and so only melt inclusions in small diameter scoria lapilli or ash retain pre-eruptive H₂O contents. CO₂ and S generally have a lower solubility in arc magmas than H₂O (Wallace, 2005;

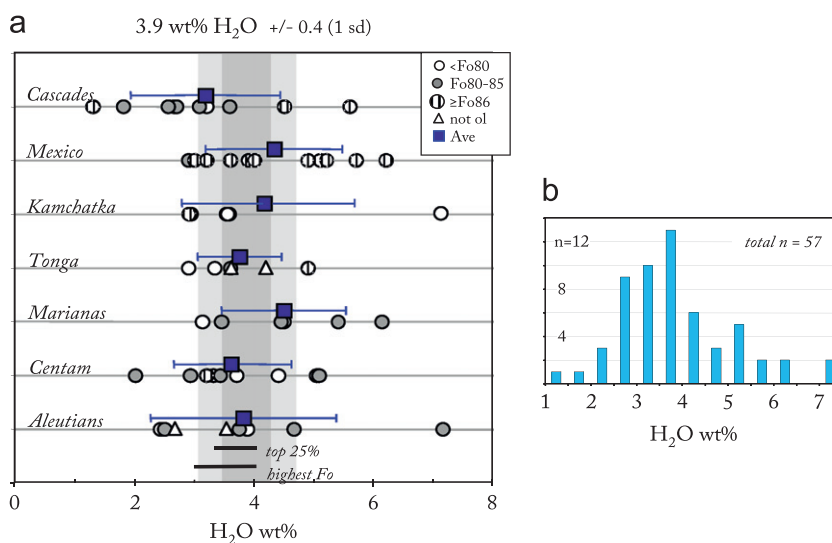


Fig. 1. (a) Water concentration in melt inclusions from 7 volcanic arcs (data and references in Table 1 and Appendix). Each point plotted is the maximum water concentration measured in mafic melt inclusions from a single volcano or cinder cone. Most inclusions are hosted in olivine; symbols reflect forsterite (Fo) content and non-olivine hosts (clinopyroxene and plagioclase). Blue boxes are averages of volcanoes within each arc (error bars are one standard deviation). Grey vertical bar reflects average of all arcs (dark grey is one s.d.; light grey is two). Heavy black lines are global averages (± 1 s.d.) calculated using two other approaches: averaging the top 25% of the water contents within a given melt inclusion population, and selecting the maximum H₂O content within the highest Fo olivines (top 2 Fo units) in a given population. (b) Histogram of maximum water concentrations in each volcano or cinder cone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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