A comparative study of continental vs. intraoceanic arc mantle melting: Experimentally determined phase relations of hydrous primitive melts

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ABSTRACT

It is widely recognized that H_2O and other volatile components play a crucial role in mantle melting in subduction zones in both continental and intraoceanic arc settings. Here we report the results of a study aimed at determining the H_2O-undersaturated, near-liquidus phase relations for two primitive arc magma compositions with the goal of determining the P–T–H_2O conditions of mantle melt segregation beneath an arc of each type. These samples, JR-28, a basaltic andesite ($SiO_2 = 53.2$ wt.%) from Volcán Jorullo, Mexico, and ID-16, a basalt ($SiO_2 = 48.9$ wt.%) from Okmok Volcano, Aleutian Islands, have compositions consistent with near-primary, mantle-derived origins. H_2O-undersaturated (2–7 wt.% added H_2O) piston-cylinder experiments have been carried out at upper mantle pressures and temperatures (1.0–2.0 GPa and 1100–1350 °C). The near-liquidus mineralogy of these compositions was mapped in P–T–H_2O space to constrain the conditions under which these melts are multiply saturated with a mantle residue (lherzolite or harzburgite). Previous measurements of dissolved H_2O in olivine-hosted melt inclusions suggest pre-eruptive H_2O-contents for JR-28 of ≥ 5.5 wt.% H_2O. Inverse and forced saturation experiments show JR-28 melts to be saturated with a harzburgite assemblage at ~1175 °C and ~1.2 GPa with 5 wt.% H_2O and ~1150 °C and ~1.4 GPa with 7 wt.% H_2O. The experimentally determined phase relations of ID-16 suggest equilibrium with a lherzolite residue with ~2 wt.% H_2O at 1280 °C and 1.4 GPa. The presence of Ca-rich pyroxene in these latter experiments likely reflects the higher bulk CaO content of ID-16 (~10.7 wt.% CaO) relative to JR-28 (~8.3 wt.% CaO). The temperatures of melt–mantle equilibration for both samples are higher than those predicted by steady-state geodynamic models at the inferred equilibration depths. Our results thus support the hypothesis that ascent of melts from the hottest region of the mantle wedge perturbs the isotherms upward to create a hot region in the shallow mantle beneath the arc. We propose that final melt–mantle equilibration of primitive, H_2O-undersaturated melts occurs in the shallow mantle prior to their ascent into the crust and that heterogeneities in uppermost mantle mineralogy therefore influence the compositions of erupted primitive melts. We suggest that basalt ID-16 last equilibrated with lherzolite, whereas the primitive basaltic andesite JR-28 formed by melting of a depleted source and last equilibrated with a harzburgite residue.

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1. Introduction

It is well established that H_2O from the subducted oceanic plate plays a crucial role in basaltic magma genesis within the mantle wedge beneath arcs. Experimental studies have shown that the introduction of a slab-derived hydrous fluid or melt to the mantle wedge significantly lowers the peridotite solidus. One possible model is that rising fluids initiate melting at the vapor-saturated solidus in the deep part of the wedge, and as the hydrous melt continues rising through the inverted thermal gradient, the higher temperatures cause further melting of peridotite and dilution of the initial H_2O content of the melt (e.g., Grove et al., 2006). The details of this process are poorly understood, however, and there are still few high-pressure experiments that investigate the H_2O-undersaturated equilibration conditions of hydrous primitive arc melts (Hesse and Grove, 2003; Medard and Grove, 2008; Muntener and Ulmer, 2006; Parman and Grove, 2004; Pichavant and Macdonald, 2007; Ulmer, 2007).

Furthermore, the origins of primitive melts that are elevated in SiO_2 relative to MgO (high-Mg andesites and boninites) are uncertain. The extent to which slab-derived fluids or melts, source depletion, and melt reaction in the subarc mantle contribute to their generation has been debated (Kelemen et al., 2003b; Parman and Grove, 2004; Wood and Turner, 2009), and in some cases their mantle origin has been questioned (Streck et al., 2007). An additional question is whether refractory sources beneath arcs (harzburgite) form by large degrees of melting due to fluxing of fluids from the subducted plate (e.g., Grove et al., 2002) or from reactions between ascending basaltic melt and mantle lherzolite in which clinopyroxene is dissolved and orthopyroxene is precipitated (e.g., Kelemen et al., 1992).

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Here we present new results from H_2O-understaturated piston-cylinder rock melting experiments on two primitive but chemically distinct arc magma compositions: a basaltic andesite from Central Mexico ($SiO_2 = 53.2$ wt.%) and a basalt from the Central Aleutians ($SiO_2 = 48.9$ wt.%). The geochemistry of these samples (e.g., Mg#, MgO and Ni contents) suggests they are both mantle-derived. The goal of this work is to constrain the P–T–H_2O conditions of mantle melt segregation and describe the mantle mineralogy with which these melt compositions last equilibrated. We present our data with those of other rock-melting experiments to constrain the range of primitive melt compositions produced by melting various mantle lithologies, from fertile lherzolite to refractory harzburgite. Our experimental results support the interpretation that fluid-fluxed melting of, or shallow reequilibration with, harzburgite can produce SiO_2-rich primitive melts (e.g., Grove et al., 2003).

The experiments reported here are also useful for testing hydrous olivine-melt thermometers (Medard and Grove, 2008; Sugawara, 2000) and petrologic models that constrain the pressures (P) and temperatures (T) of mantle–melt equilibration (Katz et al., 2003; Lee et al., 2009; Sugawara, 2000; Wood and Turner, 2009). In addition, we can compare our experimental P–T estimates with geodynamic models of arcs that provide P–T profiles through the mantle wedge (Manea et al., 2004; Peacock, 1991; Peacock and Wang, 1999; Syracuse et al., 2010; van Keken, 2003; van Keken et al., 2002). A complete experimental data set that explores the P–T conditions of melt generation and subsequent melt extraction is also important for development of geodynamic models that couple mantle and melt flow (e.g., Cagnioncle et al., 2007). This investigation adds to this data set by constraining the P–T–H_2O conditions of near-primary melt extraction from two contrasting subduction zones, the continental arc of Central Mexico and the intraoceanic island arc of the Central Aleutians.

2. Geologic setting and starting materials

This work focuses on two primitive compositions: a basaltic andesite from central Mexico and a basalt from the central Aleutian volcanic arc (Table 1). JR-28, collected and provided by Dr. J. Roberge (UNAM), is a basaltic andesite (similar in composition to JOR-44 of Luhr and Carmichael, 1985) from the earliest lava flows of Volcán Jorullo, a monogenetic cinder cone in the Michoacán-Guanajuato Volcanic Field (MGVF) of the Trans-Mexican Volcanic Belt (TMVB).

The TMVB is an east–west trending belt of volcanic features resulting from the subduction of the Cocos and Rivera plates beneath the North American plate. Volcanism along this arc has produced rock compositions that range from primitive basalt and basaltic andesite to rhyolite (Hasenaka and Carmichael, 1985; Luhr et al., 1989). The MGVF contains abundant cinder cones of basalt and basaltic andesite (Hasenaka and Carmichael, 1985, 1987). JR-28 contains olivine phenocrysts (~5 vol.%) with Cr-spinel inclusions and a groundmass of plagioclase, augite, olivine, spinel and glass (Luhr and Carmichael, 1985). It is among the most primitive and hydrous of the magmas erupted within this arc (Luhr, 1997). Olivine-hosted melt inclusions from early erupted tephra at Jorullo (olivine phenocrysts up to Fo_{91}) have H_2O contents as high as 5.7 wt.%, providing a minimum value for the H_2O content of the primitive melt (Johnson et al., 2008). Accordingly, the majority of the experiments with this sample were run with 5 and 7 wt.% added H_2O.

The second sample, ID-16, is a primitive basalt erupted at Okmok Volcano in the Central Aleutian arc. This shield volcano is located between the Four Mountains and Cold Bay arc segments, where the Pacific plate transitions from subducting beneath the oceanic part of the North American plate in the west to subducting beneath the continental Alaskan Peninsula in the east (Kay et al., 1982). Quaternary basaltic lavas comprise the early-formed part of the volcano (Byers, 1959). Nye and Reid (1986) collected and analyzed the least fractionated basalts from Okmok, including ID-16, which Dr. C. Nye kindly provided to ADJ. ID-16 has olivine phenocrysts (Fo_{88-89} cores) in a groundmass of olivine, plagioclase, clinopyroxene, and glass. This sample is characteristic of a near-primary mantle melt. Draper and Johnston (1992) investigated the anhydrous phase relations of ID-16, though by comparison with other arc magmas, it is likely that it contained some dissolved H_2O. We note that there have been two previous attempts to determine the hydrous phase relations for ID-16, Dewey (1996) and Weaver (2007), but the former suffered from uncertainties in the experimental H_2O contents and the latter suffered from unacceptable Fe loss to the Au–Pd capsules. Reliable hydrous phase relations for this sample are needed to provide more accurate P–T estimates of melt equilibration than have been suggested in previous work (Draper and Johnston, 1992; Nye and Reid, 1986). Although we do not have melt inclusion data to estimate the pre-eruptive H_2O content for ID-16 melts, we chose to investigate its near liquidus phase relations with 2 and 5 wt.% H_2O based on the range of water contents

Table 1
Bulk composition of starting materials. JR-28: Analysis 1 provided by J. Roberge (unpublished data), analysis 2: average glass composition of all superliquidus experiments ($n = 14$) normalized to 100% anhydrous. ID-16 analysis 1: XRF analysis from Nye and Reid (1986) FeO calculated by assuming $Fe^{3+}/Fe^{2+} = 0.12$. Analysis 2: Average of 9 microprobe analyses of glass of superliquidus run product reported by Draper and Johnston (1992). Parentheses indicate 1σ standard deviation where available.

Oxide	JR-28		ID-16	
	1	2	1	2
SiO_2	53.16	52.44 (0.55)	48.94	49.32 (0.99)
TiO_2	0.77	0.77 (0.02)	0.7	0.60 (0.08)
Al_2O_3	16.18	16.84 (0.25)	16.01	15.84 (0.48)
FeO	7.57	7.47[a] (0.42)	7.95	8.81[a] (0.22)
Fe_2O_3			1.06	
MnO	0.13	0.13 (0.01)	0.17	0.165 (0.05)
MgO	9.43	9.40 (0.09)	11.42	11.35 (0.31)
CaO	8.41	8.43(0.42)	10.89	10.67 (0.16)
Na_2O	3.42	3.44 (0.18)	2.21	2.10 (0.09)
K_2O	0.79	0.80 (0.02)	0.52	0.51 (0.03)
P_2O_5	0.15	0.24 (0.03)	0.12	0.10 (0.04)
Total	100.00	100.00	99.99	99.46
Ni (ppm)	261[b]		266	
Cr (ppm)	564[b]		662	
Mg#[c]	0.70		0.70	

[a] Total Fe calculated as FeO.
[b] Values for JOR-44 of Luhr and Carmichael (1985).
[c] molar MgO/(MgO + FeO[a]).