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Effects of water, depth and temperature on partial melting of mantle-wedge fluxed by hydrous sediment-melt in subduction zones

Ananya Mallik[a,b,*], Rajdeep Dasgupta[a], Kyusei Tsuno[a], Jared Nelson[a,c]

[a] *Department of Earth Science, Rice University, 6100 Main Street, MS 126, Houston, TX 77005, USA*
[b] *Bayerisches Geoinstitut, Universität Bayreuth, 95440 Bayreuth, Germany*
[c] *Department of Physics and Astronomy, Texas A & M University, 4242 TAMU, College Station, TX 77843, USA*

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Abstract

This study investigates the partial melting of variable bulk H_2O-bearing parcels of mantle-wedge hybridized by partial melt derived from subducted metapelites, at pressure–temperature (P–T) conditions applicable to the hotter core of the mantle beneath volcanic arcs. Experiments are performed on mixtures of 25% sediment-melt and 75% fertile peridotite, from 1200 to 1300 °C, at 2 and 3 GPa, with bulk H_2O concentrations of 4 and 6 wt.%. Combining the results from these experiments with previous experiments containing 2 wt.% bulk H_2O (Mallik et al., 2015), it is observed that all melt compositions, except those produced in the lowest bulk H_2O experiments at 3 GPa, are saturated with olivine and orthopyroxene. Also, higher bulk H_2O concentration increases melt fraction at the same P–T condition, and causes exhaustion of garnet, phlogopite and clinopyroxene at lower temperatures, for a given pressure. The activity coefficient of silica (Υ_{SiO_2}) for olivine-orthopyroxene saturated melt compositions (where the activity of silica, a_{SiO_2}, is buffered by the reaction olivine + SiO_2 = orthopyroxene) from this study and from mantle melting studies in the literature are calculated. In melt compositions generated at 2 GPa or shallower, with increasing H_2O concentration, Υ_{SiO_2} increases from <1 to ~1, indicating a transition from non-ideal mixing as OH^- in the melt (Υ_{SiO_2} <1) to ideal mixing as molecular H_2O (Υ_{SiO_2} ~1). At pressures >2 GPa, Υ_{SiO_2} >1 at higher H_2O concentrations in the melt, indicate requirement of excess energy to incorporate molecular H_2O in the silicate melt structure, along with a preference for bridging species and polyhedral edge decorations. With vapor saturation in the presence of melt, Υ_{SiO_2} decreases indicating approach towards ideal mixing of H_2O in silicate melt. For similar H_2O concentrations in the melt, Υ_{SiO_2} for olivine-orthopyroxene saturated melts at 3 GPa is higher than melts at 2 GPa or shallower. This results in melts generated at 3 GPa being more silica-poor than melts at 2 GPa. Thus, variable bulk H_2O and pressure of melt generation results in the partial melts from this study varying in composition from phonotephrite to basaltic andesite at 2 GPa and foidite/phonotephrite to basalt at 3 GPa, forming a spectrum of arc magmas. Modeling suggests that the trace element patterns of sediment-melt are unaffected by the process of hybridization within the hotter core of the mantle-wedge. K_2O/H_2O and H_2O/Ce ratios of the sediment-melts are unaffected, within error, by the process of hybridization of the mantle-wedge. This implies that thermometers based on K_2O/H_2O and H_2O/Ce ratios of arc lavas may be used to estimate slab-top temperatures when (a) sediment-melt from the slab reaches the hotter core of the mantle-wedge by focused flow (b) sediment-melt freezes in the overlying mantle at the slab-mantle interface and the hybridized package rises as a mélange diapir and partially melts at the hotter core of the mantle-wedge. Based on the results from this study and previous studies, both channelized and

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[*] Corresponding author at: Bayerisches Geoinstitut, Universität Bayreuth, 95440 Bayreuth, Germany. Fax: +49 921 55 3769.
E-mail address: Ananya.Mallik@uni-bayreuth.de (A. Mallik).

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porous flow of sediment-melt/fluid through the sub-arc mantle can explain geochemical signatures of arc lavas under specific geodynamic scenarios of fluid/melt fluxing, hybridization, and subsequent mantle melting.

Keywords: Subducted sediments; Mantle-wedge hybridization; Arc magmatism; Hydrous partial melting; Phase equilibria

1. INTRODUCTION

Arc lavas have typical geochemical signatures such as enrichment in Large Ion Lithophile Elements, H_2O, U and Th due to input from subducted slab in their source. The slab component involved maybe aqueous fluid and/or melt from subducted sediments and altered oceanic crust. The involvement of subducted sediments in the formation of arc lavas has been demonstrated by the presence of the cosmogenic isotope ^{10}Be (e.g. Morris and Tera, 1989) in arc lavas (that suggests addition of recent surface material), and with similarity in trace element patterns and ratios between arc lavas and corresponding subducted sediments. Although geochemical evidence does indicate sediments being involved in the formation of arc lavas, the process by which their geochemical signature is transferred to arc magmas is not well understood. The sedimentary contribution in cold subduction zones is likely in the form of aqueous fluids, whereas, in intermediate to hot subduction zones, it is likely in the form of hydrous melts (Hermann and Rubatto, 2009). The melt compositions of metapelitic sediments are siliceous and may contain variable water contents in subduction zone conditions (e.g. Johnson and Plank, 2000; Auzanneau et al., 2006; Hermann and Spandler, 2008; Thomsen and Schmidt, 2008; Tsuno and Dasgupta, 2012); hence, they metasomatize the mantle-wedge to form orthopyroxene at the expense of olivine ± hydrous minerals such as phlogopite and amphibole. Although the process of hybridization of sediment-melt with mantle-wedge peridotite has been studied, there remain the following outstanding questions on melting of the arc source, which require further investigation.

(a) How do pressure (P), temperature (T), and importantly bulk H_2O content of the zone of production of primitive arc magma as well as the flux of sediment-melt to peridotite affect the phase equilibria of hybridization? In the study by Mallik et al. (2015), the authors had studied the phase equilibria of hybridization of sediment-melt with mantle-wedge peridotite containing a fixed H_2O content of 2 wt.% in the bulk sediment-melt + peridotite mixture. They had found that such a process of hybridization produced ultrapotassic leucitites, similar to ultrapotassic lavas from several post collisional settings and active arcs. However, what effect does bulk H_2O content have on the magmas derived from sediment-melt fluxed mantle-wedge? Can it, along with P and T, explain the wide range of alkalic to tholeiitic arc lavas?

(b) H_2O being the most abundant volatile species in arc magmas, what effect does it have on the melting systematics of the hybridized arc source? Hydrous partial melts of spinel peridotite (pressure $\leqslant$2 GPa) are andesitic due to expansion of olivine stability with respect to dry systems (Kushiro, 1972; Nicholls and Ringwood, 1973), whereas, hydrous partial melts of garnet peridotite are more silica-poor than their anhydrous partial melt counterparts. Why is there a difference in the influence of H_2O on mantle melting with pressure?

(c) The presence of slab-input in the source of primary arc lavas are inferred based on geochemical tracers. In fact, K_2O/H_2O and H_2O/Ce ratios of arc lavas have been used as thermometers to determine slab-top temperatures for various arcs (Hermann and Spandler, 2008; Plank et al., 2009; Cooper et al., 2012). If the primary arc lavas are generated by reactive infiltration of slab-derived component through the mantle-wedge, or, by hybridization of the slab-component with the mantle within a mélange, the geochemical tracers can be tied back to slab-derived components or used to estimate slab-top temperatures either, (a) they are unaffected by the process of hybridization, or, (b) the effect of the process of hybridization on the geochemical tracers are known. Hence, it is important to investigate the effect of trace element systematics of slab components on the process of metasomatism/hybridization of the mantle-wedge.

(d) A recent study by Pirard and Hermann (2015) investigated the hybridization of sediment-melt with the mantle at the slab-mantle interface via porous and channelized flow. However, it needs to be investigated how the melt compositions produced by hybridization at the slab-mantle interface continue to affect the composition of equilibrated magma at the hotter mantle-wedge core.

In this study, we investigate the phase equilibria of a mixture of sediment-melt and sub-arc fertile mantle, across a P–T range and variable bulk H_2O concentrations, but with fixed sediment-melt:mantle ratio. We simulate the reactive infiltration of a mass of sediment-melt through the mantle-wedge, and explore the closed system partial melting behavior of the parcel of mantle hybridized by the sediment-melt, similar to that explored by Mallik et al. (2015) and Pirard and Hermann (2015). The experiments of Mallik et al. (2015) were performed with fixed water content. Here we explore the phase equilibria of a similar reactive process but focus on the effect of variable H_2O on the partial melt chemistry and melting reactions. In particular, we explore how variable water content affects the silica activity and other major element compositions of magmas generated from sediment-melt infiltrated peridotite. We also model the trace element concentrations of