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Slab melting and magma formation beneath the southern Cascade arc

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ABSTRACT

The processes that drive magma formation beneath the Cascade arc and other warm-slab subduction zones have been debated because young oceanic crust is predicted to largely dehydrate beneath the forearc during subduction. In addition, geochemical variability along strike in the Cascades has led to contrasting interpretations about the role of volatiles in magma generation. Here, we focus on the Lassen segment of the Cascade arc, where previous work has demonstrated across-arc geochemical variations related to subduction enrichment, and H-isotope data suggest that H_2O in basaltic magmas is derived from the final breakdown of chlorite in the mantle portion of the slab. We use naturally glassy, olivine-hosted melt inclusions (MI) from the tephra deposits of eight primitive ($MgO > 7$ wt%) basaltic cinder cones to quantify the pre-eruptive volatile contents of mantle-derived melts in this region. The melt inclusions have B concentrations and isotope ratios that are similar to mid-ocean ridge basalt (MORB), suggesting extensive dehydration of the downgoing plate prior to reaching sub-arc depths and little input of slab-derived B into the mantle wedge. However, correlations of volatile and trace element ratios (H_2O/Ce, Cl/Nb, Sr/Nd) in the melt inclusions demonstrate that geochemical variability is the result of variable addition of a hydrous subduction component to the mantle wedge. Furthermore, correlations between subduction component tracers and radiogenic isotope ratios show that the subduction component has less radiogenic Sr and Pb than the Lassen sub-arc mantle, which can be explained by melting of subducted Gorda MORB beneath the arc. Agreement between pMELTS melting models and melt inclusion volatile, major, and trace element data suggests that hydrous slab melt addition to the mantle wedge can produce the range in primitive compositions erupted in the Lassen region. Our results provide further evidence that chlorite-derived fluids from the mantle portion of the slab (~7–9 km below the slab top) cause flux melting of the subducted oceanic crust, producing hydrous slab melts that migrate into the overlying mantle, where they react with peridotite to induce further melting.

1. Introduction

Dehydration of subducted oceanic lithosphere drives arc magmatism at convergent plate margins. However, the thermal structure of an individual subduction zone controls the depths at which key dehydration reactions occur (Schmidt and Poli, 1998; Van Keken et al., 2011). Thermal structure is commonly assessed using the thermal parameter (ϕ), which is a function of downgoing plate age, dip angle, and convergence rate (e.g., Syracuse et al., 2010). Variability in ϕ globally is predicted to cause a wide range of slab surface temperatures beneath arcs (675–950 °C), as estimated from geodynamic models (e.g., Syracuse et al., 2010) and geochemical tools (e.g., Cooper et al., 2012). The results suggest a continuum of subduction zones between 'cold' (Tonga, Kamchatka) and 'warm' slabs (Cascades, Mexico). Fluids released from the subducting slab have been shown to become more solute-rich with increased temperature (Kessel et al., 2005; Hermann et al., 2006; Cooper et al., 2012; Ruscitto et al., 2012), and there is geochemical evidence for melting of the oceanic crust beneath some warm-slab endmembers such Mexico (Cai et al., 2014), the Cascades (Walowski et al., 2015), and SW Japan (Kimura et al., 2014). In addition, there is widespread geochemical evidence for melting of subducted sediment beneath arcs (e.g., Plank, 2005). However, whether the oceanic crust begins to melt beneath most arcs has

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been debated, and a consensus is emerging that the oceanic crust dehydrates and contributes fluids to the mantle wedge in arcs with cold to intermediate slab temperatures (e.g., Van Keken et al., 2011). To understand slab recycling and magma generation, it is imperative to differentiate the roles of different components in the subducted oceanic lithosphere (altered oceanic crust, sediment, serpentinized peridotite) and determine how these components are transferred to the overlying mantle wedge (as fluids, melts or a supercritical phase). The Cascade arc represents a global warm-slab endmember due to slow, shallow subduction of young oceanic crust (6–10 Ma at the trench; Wilson, 2002). Geodynamic models (Syracuse et al., 2010; Wada and Wang, 2009) and geochemical studies (Cooper et al., 2012; Ruscitto et al., 2012; Walowski et al., 2015) agree that slab surface temperatures beneath the arc axis are hotter, on average, than many other arcs globally. Previous work in the central Oregon Cascades has suggested that the mantle wedge beneath the arc receives a reduced flux of volatiles from the downgoing slab (Ruscitto et al., 2012), and H_2O concentrations in olivine-hosted melt inclusions (MI) from both the central and southern Cascades ($\sim$3.2 wt%; Ruscitto et al., 2010, 2011; Le Voyer et al., 2010) fall slightly below the global average ($\sim$3.9 wt%; Plank et al., 2013). Walowski et al. (2015) found that hydrogen isotope ratios of primitive magmas from the Lassen region of the southern Cascades are lighter than those for the Mariana arc. This is likely the result of waning dehydration of chlorite in the mantle portion of the downgoing slab ($\sim$7–9 km below the slab top) after the crustal portion of the slab has already dehydrated beneath the forearc. These results also provide evidence that flux-melting of the oceanic crust occurs when fluids released from the slab interior interact with oceanic crust that is above its wet solidus temperature (e.g., Spandler and Pirard, 2013).

We measured the volatile contents, major element, trace element, and B isotope compositions of olivine-hosted MI and the radiogenic isotopic compositions of bulk tephra from the eruptive centers in the Lassen region studied by Walowski et al. (2015). We use these data to quantify the chemical contributions from the subducting oceanic lithosphere and to better understand how subduction of warm oceanic crust affects the composition of mantle melts and the productivity of melting in the mantle wedge. We also test the hypothesis of Walowski et al. (2015) that magma production beneath the southern Cascades involves a multi-stage process that includes flux melting of the subducted oceanic crust and hydrous slab melt addition to the overlying mantle wedge.

2. Geologic setting

The Lassen region is the southern terminus of the active Cascade arc (Guffanti et al., 1990). Volcanism is the result of oblique subduction of the Gorda micro-plate beneath the North American plate (Fig. 1; Wilson, 2002), producing dominantly calc-alkaline magmas (Clynne and Muffler, 2010). Westward expansion of the Basin and Range extensional province into the eastern flanks of the Cascade arc, including the Hat Creek and Lake Almanor Grabens, has produced many normal faults that provide pathways for mafic magmas to reach the surface (Guffanti et al., 1990; Clynne and Muffler, 2010). The Quaternary volcanics in the Lassen region sit above a broad platform of mafic to intermediate volcanoes and volcanic products 2–4 km thick (Berge and Stauber, 1987), which is underlain by Sierran and Klamath metamorphic/plutonic basement rocks (Berge and Stauber, 1987). Surrounding the Lassen Peak dacitic dome complex (Clynne and Muffler, 2010) is a large volcanic field containing over 500 cinder cones and small shield volcanoes erupted in the last 12 Ma (Guffanti et al., 1990). Previous work on the Quaternary mafic volcanoes has identified a range in compositions from low-K tholeiitic basalts (LKT; also called high-

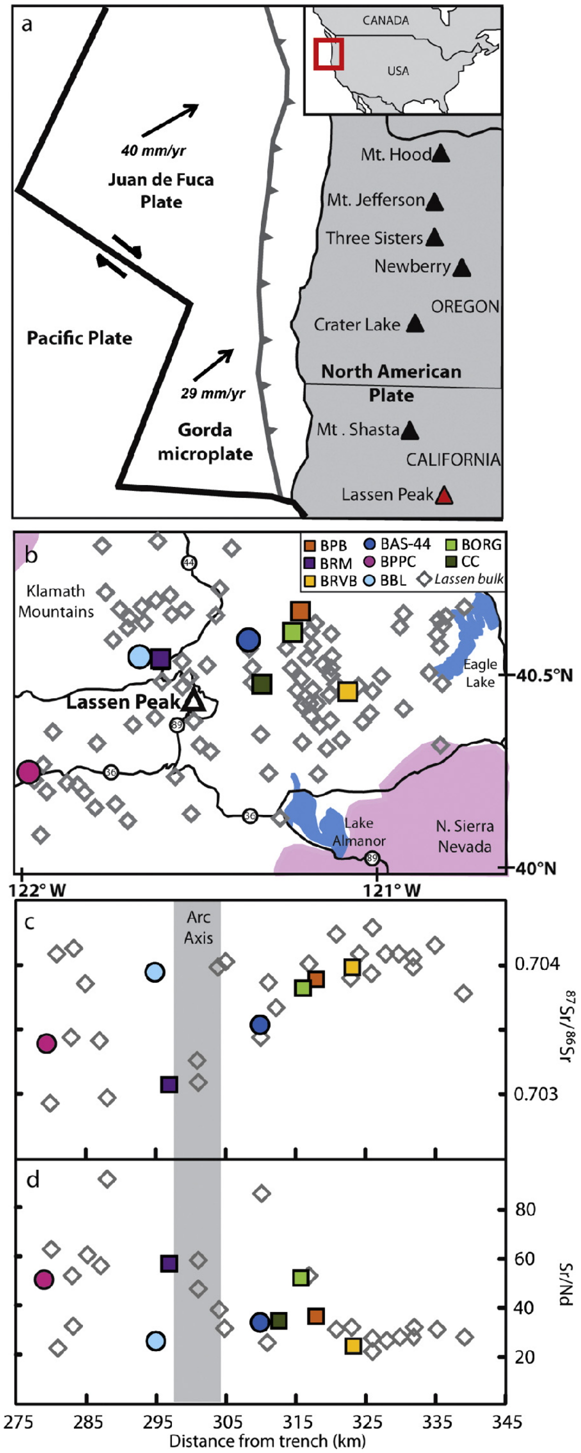

Fig. 1. a) Regional map of the Northwestern United States showing major tectonic boundaries. The Cascade volcanic arc is defined by the major peaks (black triangles). Lassen Peak is highlighted with a red triangle. Black arrows show convergence direction and are labeled with the convergence rate relative to North America. b) Larger scale map of the Lassen region with locations of vents sampled in this study (BRVB: Basalt of Round Valley Butte; BPB: Basalt of Poison Butte; BRM: Basalt of Red Mountain; BBL: Basalt of Big Lake; BAS-44: Basalt of Hwy 44; BPPC: Basalt of Paine Parasitic Cone; BORG: Basalt of Old Railroad Grade; CC: Cinder Cone; see Table 1 for details) and previously sampled by Clynne (1993) and Borg et al. (1997) (gray diamonds). Lassen Peak (large white triangle), outcropping basement rocks (shaded pink areas), major highways (thin black lines), and large lakes (shaded blue regions), are also highlighted. Distance from the trench vs. c) Sr/Nd and d) $^{87}Sr/^{86}Sr$ for samples in this study (colored symbols) and Borg et al. (1997) (gray diamonds). Symbols and colors for individual cinder cones are consistent throughout the manuscript. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)