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Evidence for trench-parallel mantle flow in the northern Cascade Arc from basalt geochemistry

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A B S T R A C T

Geochemical data for basalts from the Garibaldi Volcanic Belt (northern segment of the Cascade Arc) define arc-parallel gradients in trace elements and isotope ratios that extend at least 150 km into the arc from the northern margin of the subducting Juan de Fuca plate. Southerly increases in Zr/Nb, Ba/Nb, Th/La, Pb/Ce, $^{208}Pb/^{204}Pb$ and $^{176}Hf/^{177}Hf$ indicate greater mantle depletion and higher slab-derived contributions with distance from the slab edge. Temperatures and pressures of mantle melt segregation also decrease to the south. The gradients are most plausibly explained as a consequence of slab rollback-induced toroidal flow at the northern slab edge (Nootka fault zone), whereby enriched (OIB-type) NE Pacific asthenospheric mantle from beneath the slab is drawn into the mantle wedge in a trench-parallel southerly flow pattern. Melts of the enriched asthenosphere are progressively diluted to the south by melts of the slab-modified, depleted mantle wedge. Arc-parallel changes in slab thermal conditions cannot account for these gradients. Trench parallel geochemical gradients in the northern Cascade Arc are consistent with shear wave splitting data, numerical modeling, and experimental studies showing that trench-parallel mantle flow may be a common phenomenon near slab edges and slab gaps.

1. Introduction

Two-dimensional numerical models of subduction zone dynamics predict that viscous coupling between the subducting plate and overlying mantle will result in mantle wedge flow that is parallel to the convergence vector (e.g., van Keken et al., 2002). However, seismic anisotropy data, 3-D numerical modeling, and experimental studies have shown that mantle flow in subduction zones may be much more complex, especially at and near the terminations of the arcs (Kneller and van Keken, 2008; Long and Silver, 2009; Long and Wirth, 2013; MacDougall et al., 2014; Schellart, 2010, 2004). Because the compositions of primary arc magmas reflect the composition of the mantle wedge (variably modified by slab-derived components), spatial variations in the geochemistry of arc magmas provide independent evidence for circulation patterns in the mantle wedge.

In this study, we present new high precision Sr–Nd–Hf–Pb isotopic and trace element data for basalts from the Garibaldi Volcanic Belt (GVB), the northern segment of the Cascade Arc (Fig. 1). An arc-parallel gradient in basalt alkalinity (Fig. 2) was first documented by Green and Harry (1999) and attributed to an along-arc gradient in the age and temperature of the subducting plate. However, spatial gradients in basalt geochemistry that are oriented parallel to the arc axis have been interpreted as evidence for trench-parallel mantle flow in Central America (Hoernle et al., 2008), Tonga (Turner and Hawkesworth, 1998), and Vanuatu (Heyworth et al., 2011). Similar gradients are also associated with mantle influx at slab edges in Kamchatka (Portnyagin et al., 2005) and Central America (Johnston and Thorkelson, 1997). The goal of this study is to use the new geochemical data on GVB basalts to evaluate trench-parallel mantle flow as an alternative hypothesis for the gradient in GVB basalt alkalinity, and to explore the tectonic implications.

2. The Garibaldi Volcanic Belt

The ~1250 km long Cascade Arc is related to subduction of the young (<11 Ma) Juan de Fuca oceanic plate and represents a thermally 'hot' end-member in the global spectrum of subduction zones (Syracuse et al., 2010). A bend in the arc axis marks the boundary between the ~375 km long Garibaldi Volcanic Belt (GVB) in the north and the High Cascades in the south (Fig. 1a). The GVB includes the major volcanic centers, from south to north, of Glacier Peak, Mt. Baker, Mt. Garibaldi, Mt. Cayley, Mt. Meager, Salal Glacier, and Bridge River Cones (Fig. 1). In the GVB, basaltic lavas comprise only a small fraction of total eruptive volumes and are peripheral to the main volcanic edifices (Green, 2006). Basalts transition

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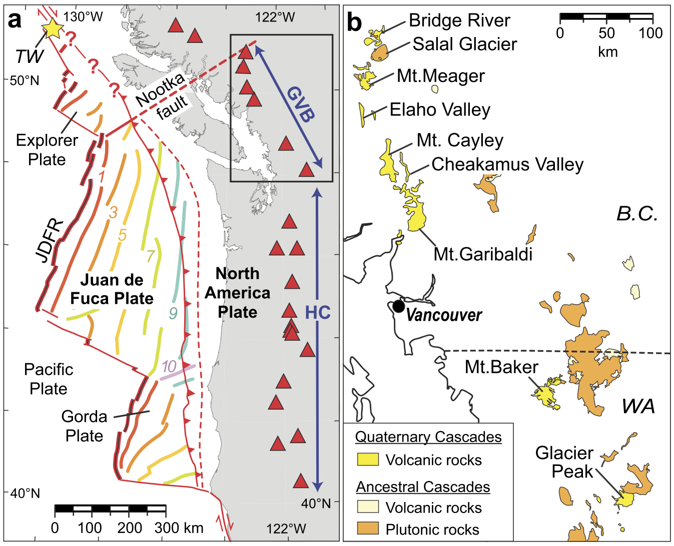

Fig. 1. a: Map of the Cascade Arc. Red triangles—major volcanoes. Contours (1, 3, 5, 7, 9, 10) indicate the age (in Ma) of the Juan de Fuca plate from Wilson (2002). Dark blue arrows indicate the extents of Garibaldi Volcanic Belt (GVB) and High Cascades (HC). Garibaldi Volcanic Belt is also enclosed in rectangle (enlarged in b). JDFR—Juan de Fuca ridge. Yellow star labeled TW (at upper left) is the Tuzo Wilson volcanic field. b: Garibaldi Volcanic Belt with sample localities indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

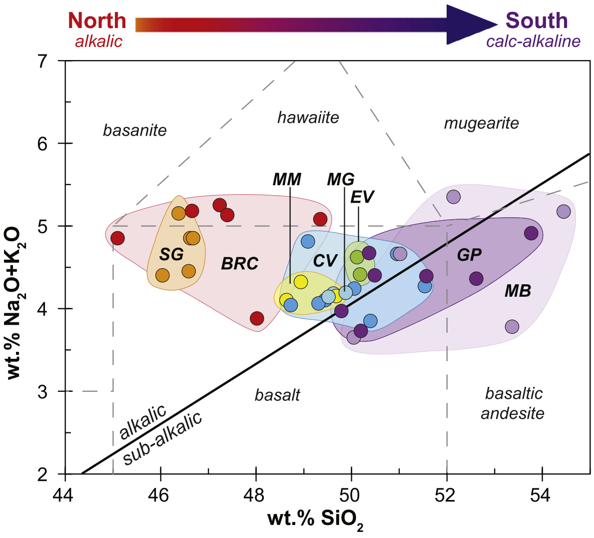

Fig. 2. Total alkalis vs. silica diagram after Le Bas (1986) with data for the GVB basalts analyzed in this study (from Table S1). The GVB basalts become more alkalic to the north. BRC—Bridge River Cones; SG—Salal Glacier; EV—Elaho Valley; MM—Mt. Meager; CV—Cheakamus Valley; MG—Mt. Garibaldi; MB—Mt. Baker; GP—Glacier Peak.

from calc-alkaline and tholeiitic compositions in the southern GVB, with major element compositions typical for arc magmas, to alkalic compositions in the northern GVB (Fig. 2). The most highly alkalic GVB basalts, at Salal Glacier and Bridge River, display only a minor trace element arc signature and bear compositional similarities to oceanic intraplate basalts (OIB) (Mullen and Weis, 2013).

In the southern GVB, the age of the Juan de Fuca plate at the trench is ~9 Ma, but decreases northward to ~5 Ma (Fig. 1a) (Wilson, 2002). Green and Harry (1999) predicted that the northerly decrease in slab age should result in higher slab temperatures to the north and correspondingly smaller additions of slab-derived hydrous components to the mantle wedge. A less hydrated mantle would produce smaller melt fractions more enriched in alkali elements, thus accounting for the arc-parallel gradient in basalt alkalinity. However, Salal Glacier and Bridge River alkalic basalts are isotopically distinct from other Cascade Arc basalts, recording a source more similar to enriched NE Pacific asthenospheric mantle (Mullen and Weis, 2013). Salal Glacier and Bridge River also coincide with the trace of the Nootka fault zone (Fig. 1a) that forms the boundary between the subducting Juan de Fuca plate and the nearly stagnant Explorer microplate (Audet et al., 2008; Riddihough, 1984). These characteristics are more consistent with generation of the northern GVB alkalic basalts by decompression melting of NE Pacific asthenosphere flowing into the Cascadia mantle wedge through a slab gap at the Nootka fault (Mullen and Weis, 2013).

To track mantle compositional variations and slab contributions along the length of the GVB, we measured high-precision Sr–Nd–Hf–Pb isotopic ratios and trace element abundances on the most primitive samples (i.e., highest Ni, Cr, and Mg/Mg+Fe values, indicating minimal modification since segregating from the mantle) from all Quaternary GVB eruptive centers (Fig. 1b).

3. Materials and methods

3.1. Samples analyzed

Although the samples analyzed for this study are not 'primary' magmas, i.e., unmodified since segregating from the mantle source, they represent the most primitive magmas identified in eight volcanic centers in the GVB. Data reported here for 4 of the volcanic centers (Mt. Baker, Bridge River, Salal Glacier, and Mt. Meager) include previously published data from Mullen and McCallum (2014) and Mullen and Weis (2013) and are indicated as such in Table S1. We utilized splits of the same GVB basalt sample powders previously analyzed by Green (2006), Green and Sinha (2005), and Mullen and McCallum (2014), supplemented by one additional sample from Bridge River (THEC1) and one from Glacier Peak (GP11-01). Samples obviously affected by crustal contamination, as indicated by xenocrysts and/or xenoliths, were omitted from this study and are discussed further in Mullen and Weis (2013). The analyzed samples have 45–54 wt.% SiO_2, $Mg/(Mg+Fe^{2+})$ values of 0.44 to 0.71 (Table S1) and all have olivine phenocrysts or microphenocrysts. Ni and Cr contents range from 301 to 25 ppm and 373 to 24 ppm, respectively (Table S1). Petrographic details are discussed further in Green (2006), Green and Sinha (2005), Mullen and McCallum (2014), and Mullen and Weis (2013). Stratigraphic relationships and $^{40}Ar/^{39}Ar$ and K–Ar ages indicate all analyzed samples are less than 1 Myr old (details in Green, 2006 and Mullen and McCallum, 2014).

Northern GVB samples (Salal Glacier, Bridge River Cones) are olivine phyric, nepheline-normative alkalic basalts and hawaiites erupted from monogenetic vents. Central GVB basalts are predominantly hypersthene-normative and include the Mosaic Assemblage peripheral to Mt. Meager, isolated vents of Elaho Valley, the Cheakamus Valley flows that erupted from a vent east of Mt. Cayley, and the Helm Creek flow and associated scoria erupted from The Cinder Cone ~15 km north of Mt. Garibaldi. Because the Cheakamus Valley flows are ~35 km long, in all plots Cheakamus samples are shown at the latitude of the eruptive vent (50.25° N) rather than the sample sites from Table S1. In the southern GVB, Mt. Baker and Glacier Peak basalts are predominantly calc-alkaline basalts and basaltic andesites (CAB). Two high alumina olivine tholeiites (HAOT), a basalt type that is common in the High Cascades, have also been identified in the GVB and both were analyzed for this study (Park Butte at Mt. Baker, White Chuck cinder cone at Glacier Peak) (Green, 2006; Mullen and McCallum, 2014).