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Influence of slab thermal structure on basalt source regions and melting conditions: REE and HFSE constraints from the Garibaldi volcanic belt, northern Cascadia subduction system

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Abstract

Garibaldi volcanic belt (GVB) basalts were erupted above the relatively young ($\leq$24 Ma) Juan de Fuca plate, which comprises the subducted oceanic lithosphere that becomes progressively younger (22–13 Ma), and presumably hotter, northward along the northern Cascadia convergent margin. Primitive and near-primitive mafic lavas of the 15-km-wide volcanic belt change from high-alumina olivine tholeiites and magnesian andesites near Glacier Peak, northwestern Washington, through transitional basalts to alkali-olivine basalts and basanites in the Bridge River-Salal Glacier areas, southwestern British Columbia. The distribution of different basalt types is consistent with varied source conditions imposed by differences in the thermal structure of the underlying subducted plate.

Significant arc-parallel variations characterize REE and HFSE contents in GVB basalts and suggest that source enrichment processes and melting conditions vary within the mantle wedge as the age and thermal state of the underlying subducted plate changes. More northerly GVB basaltic suites tend to have higher TiO_2, Nb, Ta, total REE, La, Sm/Yb, Nb/Yb, Ti/V, Y/Sc and Zr/Yb and lower Th/U, Zr/Ti and Zr/Nb than their southern counterparts. The basalts have sub-chondritic to chondritic Nb/Ta (6–21) and super-chondritic Zr/Hf (up to 55.90) ratios that exhibit positive correlation. Only Mount Baker and Glacier Peak basalts exhibit the distinctive negative Nb–Ta anomalies associated with arc lavas. Inter-HFSE and REE fractionations (including La/Yb, La/Nb and Ce/Pb) show significant correlations with the inferred age of the underlying subducted plate. Proportions of slab-derived HFSE-REE components (SC) transferred to basalt sources in the Cascadia mantle wedge appear to vary from negligible (Ti, Nb, Ta, Zr, Hf, Y, Sm, Eu and Tb: less than 15% SC) to perceptible (Nd: up to 35% SC) through moderate (La: up to 75% SC) to substantial (U, Th and Pb: up to 95% SC).

Arc-parallel HFSE-REE variations in primitive GVB basalts cannot be explained by variable degrees of depletion produced during prior episodes of melt generation in the mantle wedge. Instead, these differences in basalt chemistry probably reflect different extents of melting of a regionally homogeneous, locally heterogeneous, mantle wedge under conditions influenced by the thermal structure of the underlying subduction zone. Phase relationships and REE systematics of the primitive to near-primitive basalts argue that conditions of magma generation beneath the Bridge River, Salal Glacier, Meager Mountain and Cheakamus Valley lava fields involved lower degrees of melting, higher pressures, and mantle sources richer in garnet than

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those beneath Mount Baker and Glacier Peak. In addition, Nb/Ta in the Glacier Peak basalts exhibits slight positive correlations with Nb, Ta, La/Yb, and Th/Yb but not Nb/La or Nb/Th, implying that a residual mineral, most likely rutile, controlled extremely low HFSE partitioning into subduction-related fluids that equilibrated with mantle source regions above older, colder portions of the subducted plate.

Keywords: Basalt; Mantle wedge; Slab age; Thermal structure; Melting conditions

1. Introduction

Subduction zone magmas are characterized by depletions in high-field-strength elements (HFSE) relative to other incompatible elements. HFSE depletion of the magma sources may be both absolute (compared to MORB) and relative (compared to LILE and LREE). The depletions may originate in the mantle wedge or may be transferred to the mantle wedge via fluids or melts from the subducting plate or slab. Where proposed to originate in the mantle wedge, relative HFSE depletion in subduction zone magmas has generally been attributed to partial melting leaving a residual Ti-bearing mineral, especially rutile and amphibole (Green and Pearson, 1986; Ryerson and Watson, 1987), to magma-peridotite interactions during ascent from mantle sources (Kelemen et al., 1990), or to prior melt extraction (Ewart and Hawkesworth, 1987). Rutile or amphibole, however, are unlikely to be residual to mantle melting (Ayers et al., 1997). ^{226}Ra studies further suggest that rapid ascent of arc magmas may provide little opportunity for prolonged interaction between the melt and larger volumes of wall-rock (Turner et al., 1997). In addition, magma–peridotite interactions may produce intra-HFSE element fractionations which are not characteristic of most arc magmas (Davidson, 1996). Woodhead et al. (1998) noted that incompatible element abundances in New Britain arc basalts may indicate melting of mantle wedge material that had become progressively more depleted during previous melt extraction episodes. Highly depleted spinel-bearing harzburgites in Bataan lavas have been interpreted to reflect such mantle HFSE depletion before subduction-related metasomatism (Maury et al., 1992). Alternatively, radiogenic isotope and trace element signatures in some arc lavas may reflect varied proportions of enriched and depleted source material in the mantle wedge (Leeman et al., 1990; Stolz et al., 1996).

Relative HFSE depletion in arc magmas may also originate through partial melting of depleted mantle peridotite fluxed by slab-derived fluids/melts enriched in more mobile incompatible elements, such as the LILE and LREE (McCulloch and Gamble, 1991). Limited HFSE transfer from the subducted slab has been attributed to partial melting and/or dehydration of subducted oceanic crust or sediments in the presence of residual rutile (Brenan et al., 1994, 1995; Elliot et al., 1997). Overall Nb and Ta depletion may also reflect low fluid/rock partitioning of HFSE in comparison to LREE and LILE during dehydration of the slab, so that participation of accessory phases may not be required (e.g. Brenan et al., 1995; Keppler, 1996). The relative HFSE depletions, however, may not be directly related to slab-derived fluids, because arc lavas are often more depleted in absolute HFSE contents (not only relative to LILE enrichments) than associated back-arc basin counterparts (Woodhead et al., 1998). Some combination of slab- and wedge-based processes may therefore be necessary to explain HFSE distributions in arc magmas.

The Cascadia subduction system of western North America shares tectonic and geochemical relationships with many other convergent plate boundaries, but represents an end-member ‘hot’ subduction environment. Green and Harry (1999) demonstrated that the subducted Juan de Fuca plate becomes progressively younger and hotter northward along strike of the Cascadia margin. They examined possible relationships between slab thermal structure and onset of metamorphic dehydration/devolatization reactions beneath the seismogenic zone, and proposed that a northward decrease in volatile fluxing to the Cascadia mantle wedge would strongly influence melting conditions in basalt source regions. Reduced slab contributions to the wedge above the hotter and drier northern portions of the subducted plate were interpreted to result in basaltic magmas generated by lower