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Invited research article

Primitive arc magma diversity: New geochemical insights in the Cascade Arc

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ABSTRACT

The origin of the large range of compositional diversity encompassed by primitive arc magmas and the respective roles of mantle heterogeneity versus slab-derived contributions are the center of ongoing debate. The Cascade Arc of western North America is a global endmember hot subduction zone and an ideal setting in which to examine fundamental questions about the origin of arc magmas. Cascade Arc primitive magmas define several distinct compositional endmembers, the most widespread of which are high alumina olivine tholeiite (HAOT), calc-alkaline basalt (CAB), and intraplate-type basalt (IPB). New high precision Sr-Nd-Hf-Pb isotopic and trace element data for 49 of the most primitive magmas from seven major High Cascades volcanic centers are used to assess whether the basalt groups are derived from geochemically distinct mantle sources. Along with recently published data for the Garibaldi Volcanic Belt (GVB), the northern and other major segment of the Cascade Arc, and Mt. Rainier, the new data expand the high-precision isotopic coverage to seventeen volcanic centers spanning the ~1300 km length of the arc. In all investigated isotopic systems, the new High Cascades data allow for finer resolution with much less scatter than previous data. HAOT mantle sources are systematically more depleted in incompatible elements than CAB sources, yet High Cascades CABs and HAOTs are isotopically indistinguishable, defining a remarkable linear Pb isotopic array consistent with a single mantle endmember that is similar to the source of Juan de Fuca mid-ocean ridge basalts. This mantle has been variably modified by contributions from a single subducting sediment endmember that is a close isotopic match to average Northern Cascadia basin sediment. Although Astoria Fan sediment was previously used as a proxy for the subducting sediment composition in the Cascadia subduction zone, the isotope ratios of Cascades basalts record no input from Astoria Fan sediment. High Cascades CABs and HAOTs both contain subducting sediment input in the form of a melt, but CABs also contain melts of subducting oceanic crust which is most apparent in the southern Cascades high-Sr/P suite and in the GVB. The least sediment input is recorded by GVB basalts, which also become progressively lower in $^{208}Pb^*/^{206}Pb^*$ and Hf isotope ratios to the north, reflecting the influx of an isotopically distinct enriched mantle component that generates IPBs at the northern slab edge. Enriched mantle with a composition trending towards HIMU is also recorded by a distinct isotopic array that is defined by IPBs from the Mt. Adams-Simcoe back arc region. We propose that slab gaps permit the influx of sub-slab asthenospheric mantle in both the northern GVB and Mt. Adams-Simcoe back-arc. Otherwise, western North America is underlain predominantly by isotopically homogeneous, MORB-type depleted mantle from which both the CAB and HAOT basalt groups are derived. Our results from the Cascades imply that most of the compositional heterogeneity encompassed by primitive arc magmas is not related to the presence of multiple mantle components but to variability in the composition and quantity of slab contributions. This study highlights the importance of high precision Sr-Nd-Hf-Pb isotope and trace element data in obtaining new insights on the petrogenesis of arc magmas.

1. Introduction

Primary magmas in subduction settings encompass a wide range of compositional variability on local to global scales (e.g., Kelemen et al., 2014; Arculus, 1994). Deciphering the factors responsible for this diversity is difficult because these magmas are likely to contain contributions from a compositionally heterogeneous array of fluids and/or melts derived from several reservoirs in the subducting plate during prograde

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metamorphism. These reservoirs include altered oceanic crust, overlying sediment, and underlying hydrated mantle lithosphere (e.g., Schmidt and Poli, 2014). Pre-existing compositional variabilities within the mantle wedge are an additional potential source of diversity among primary arc magmas. Many studies concur that the sub-arc mantle primarily consists of depleted mantle that is similar in composition to the sources of mid-ocean ridge basalts (MORBs) (e.g., Green, 1976; Pearce and Peate, 1995; Perfit et al., 1980). However, enriched ocean island basalt (OIB) source mantle has been proposed to play an important role in controlling magma compositions in some arcs (Central America: Reagan and Gill, 1989; Mexico: Petrone et al., 2003; Sulu: Macpherson et al., 2010; Castillo et al., 2007; Izu-Bonin: Hochstaedter et al., 2000; Marianas: Woodhead et al., 2012; Aleutians: Morris and Hart, 1983; Fiji: Gill, 1984; Ellam and Hawkesworth, 1988).

The Cascade Arc of western North America offers a particularly interesting case in which to examine the factors contributing to arc magma compositional diversity because several genetically distinct primitive magma lineages have been identified on the basis of major and trace elements. The most widespread of these suites are referred to in this paper as high alumina olivine tholeiite (HAOT), calc-alkaline basalt (CAB), and intraplate-type basalt (IPB). Previous studies have concluded that these lineages reflect a sub-arc mantle that is composed of geochemically and mineralogically distinct domains of lithospheric and asthenospheric mantle, ranging in composition from MORB- to OIB-source-type, that have been modified by a spectrum of slab-derived components on multiple occasions (Righter, 2000; Hildreth, 2007; Bacon et al., 1997; Leeman et al., 1990, 2005; Borg et al., 1997, 2002; Conrey et al., 1997; Grove et al., 2002; Schmidt et al., 2008; Green and Harry, 1999; Hughes, 1990; Baker et al., 1994). The Cascades is also considered an endmember 'hot' subduction zone, and the relatively high temperatures predicted for the subducting Juan de Fuca plate (Syracuse et al., 2010; Wada and Wang, 2009) imply nearly complete dehydration of the slab at sub-arc depths (e.g., van Keken et al., 2011; Hacker et al., 2003; Harry and Green, 1999). In turn, several workers have proposed that some Cascade Arc magmas may be little-influenced by modern slab-derived components (e.g., Leeman et al., 1990, 2004, 2005; Conrey et al., 1997; Borg et al., 1997, 2002). In this study, we use new high-precision Sr-Nd-Hf-Pb isotope and trace element data to test the hypothesis that the major endmember primary magma suites in the Cascade Arc represent isotopically distinct mantle sources on a regional scale. The high precision geochemical data that have recently become available for subducting sediment on the Juan de Fuca plate (Carpentier et al., 2013, 2014; Prytulak et al., 2006) and oceanic crust of the Explorer plate (Cousens et al., in review) further allow us to ascertain which slab-derived components have contributed to Cascade Arc magmas.

Radiogenic isotope ratios can be effective tracers of potential mantle heterogeneities and the fate of slab-derived materials, particularly when measured with modern analytical techniques that offer higher accuracy and precision. For example, multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) coupled with advances in sample preparation techniques have led to significant improvements over TIMS (thermal ionization mass spectrometry) in accuracy and precision, particularly in the case of lead isotopes, and to the routine analysis of Hf isotopic ratios (Albarède et al., 2004; Blichert-Toft et al., 1997; Weis et al., 2006). In the Garibaldi Volcanic Belt (GVB), the northern segment of the Cascade Arc (Fig. 1), high-precision Sr-Nd-Hf-Pb isotopic studies have demonstrated that IPBs and CABs tap two geochemically distinct mantle sources (Mullen and Weis, 2013, 2015). In the main segment of the arc, the High Cascades (Fig. 1), numerous Sr-Nd-Pb radiogenic isotope studies have been conducted over the past 4+ decades. However, it has not been possible to conclusively resolve whether the Cascade primary magma groups originate from isotopically distinct mantle domains on a whole-arc scale because few of the data are associated with the requisite precision. Published high-precision Pb isotope data are limited to the Mt. Rainier area (Sisson et al., 2014), and Hf isotope data, which can be particularly useful in arc settings because Hf is mobilized to a lesser extent in slab-derived fluids than are Sr, Nd and Pb (Woodhead et al., 2012), are available only for Lassen Peak and Mt. Adams (Borg et al., 2002; Jicha et al., 2009a).

We have measured new high-precision Sr-Nd-Hf-Pb isotopic and trace element data for magmas from seven High Cascades volcanic fields. The samples analyzed from Lassen Peak, Medicine Lake, Crater Lake, Mt. Shasta, Mt. Adams, and Simcoe (Fig. 1) were identified by Bacon et al. (1997) as representative of the most primitive magmas in the High Cascades. We also analyzed a suite of the distinctive North Sister-type basaltic andesites from the Three Sisters region (Fig. 1) to examine the isotopic effects of crustal contamination because these magmas record pervasive assimilation of mafic deep crust (Schmidt and Grunder, 2011; Schmidt et al., 2013). We also present several new analyses of GVB magmas to augment the existing high-precision isotopic database (Mullen and Weis, 2013, 2015; Mullen and McCallum, 2014) and to strengthen our comparison between the GVB and High Cascades segments. The new GVB dataset includes the first published geochemical data for the Silverthrone volcanic field, which was proposed to be the northernmost volcano in the Cascades by Green et al. (1988) but has been excluded from the arc by others (e.g., Hildreth, 2007).

Our new isotopic data differ significantly from previously published data on the same samples, particularly in Pb isotopes, which are associated with a ten-fold increase in analytical precision. Most importantly, the new data show that all CABs and HAOTs from the High Cascades are derived from a single isotopic mantle endmember that has been variably modified by subduction components. Factors other than mantle heterogeneity must be responsible for the differences between HAOTs and CABs. In contrast, IPBs sample isotopically distinct mantle components.

2. Cascadia subduction system: High Cascades and Garibaldi Volcanic Belt

The active Cascade Arc extends ~1300 km between southwestern British Columbia and northern California (Fig. 1). Magmatism initiated at ~4 Ma (du Bray and John, 2011) and is a consequence of northeasterly subduction of the Juan de Fuca plate system beneath the North American plate. Rates of convergence increase northward along the trench from 30 to 45 mm/year (Wilson, 2002). The southern portion of the Juan de Fuca plate, known as the Gorda sub-plate, has been internally deforming for the past ~3 Ma (Wilson, 2002). The northern portion of the Juan de Fuca plate became detached at ~4 Ma to form the Explorer microplate, which in the time since has nearly ceased subducting (Riddihough, 1984; Audet et al., 2008).

The Cascade Arc is subdivided into two main geographical segments, the High Cascades in the south and Garibaldi Volcanic Belt (GVB) in the north, by a change in the strike of the arc axis in the vicinity of Glacier Peak that follows a bend in the trench (Fig. 1). Convergence is consequently oblique in the High Cascades and orthogonal in the GVB. The High Cascades segment is nearly 900 km long and strikes roughly north-south, extending from Lassen Peak to Mt. Rainier (and possibly to Glacier Peak, as we discuss in this study). The High Cascades is characterized by a near-continuous array of mafic vents between larger composite volcanoes (Hildreth, 2007). In Oregon, magmatism is closely associated with development of an axial graben that is related to the encroaching extensional regime from the Basin and Range province to the east (Rogers, 1985; Conrey et al., 1997).

The NNW-trending, ~375 km-long GVB segment (Fig. 1) extends from Glacier Peak in the south to at least as far north as the Bridge River Cones, and perhaps as far north as the little-known Franklin Glacier and Silverthrone centers that lie above the Explorer microplate (Green et al., 1988). Compared to the High Cascades, volcanic vents are considerably sparser in the GVB and composite volcanoes are spatially separated by large non-magmatic gaps. Only a small proportion