Mantle flow through the Northern Cordilleran slab window revealed by volcanic geochemistry

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ABSTRACT

The Northern Cordilleran slab window formed beneath western Canada concurrently with the opening of the Californian slab window beneath the southwestern United States, beginning in Late Oligocene–Miocene time. A database of 3530 analyses from Miocene–Holocene volcanoes along a 3500-km-long transect, from the northern Cascade Arc to the Aleutian Arc, was used to investigate mantle conditions in the Northern Cordilleran slab window. Using geochemical ratios sensitive to tectonic affinity, such as Nb/Zr, we show that typical volcanic arc compositions in the Cascade and Aleutian systems (derived from subduction-hydrated mantle) are separated by an extensive volcanic field with intraplate compositions (derived from relatively anhydrous mantle). This chemically defined region of intraplate volcanism is spatially coincident with a geophysical model of the Northern Cordilleran slab window. We suggest that opening of the slab window triggered upwelling of anhydrous mantle and displacement of the hydrous mantle wedge, which had developed during extensive early Cenozoic arc and backarc volcanism in western Canada. High heat flow throughout the western Canadian Cordillera is broadly coincident with the field of intraplate volcanism and is linked to slab window-induced mantle upwelling.

INTRODUCTION

Motions of the Earth's tectonic plates affect flow patterns in the upper mantle (Wiens et al., 2008). In turn, these flow patterns affect the thermal, physical, and chemical evolution of the plates; the most striking examples are located in slab window environments. Slab windows are gaps between subducted parts of oceanic plates at sites of mid-ocean spreading ridge subduction (Dickinson and Snyder, 1979; Thorkelson and Taylor, 1989). These breaches occur within an otherwise continuous layer of subducting oceanic lithosphere, which normally separates a wedge of hydrated mantle (Gill, 1981) from an underlying region of hotter, drier mantle (Thorkelson, 1996; Gorring and Kay, 2001). Consequently, slab window environments are expected to differ from those involving normal subduction in patterns of mantle flow, variations in mantle composition, flux of mantle-derived heat, and expressions of magmatism in both forearc and inboard regions (Hole et al., 1991; Haeussler et al., 1995; Cole and Stewart, 2009).

Approximately one-third of the present-day American Cordillera, from eastern Alaska to the Antarctic Peninsula, is underlain by slab windows (Fig. 1), all of which have contributed to variations in igneous and tectonic conditions in the continental margin. Two of the intersections occurred beneath North America, leading to the formation of two large slab windows (Thorkelson and Taylor, 1989): one beneath the southwestern United States, herein referred to as the Californian slab window, and the other beneath western Canada, herein called the Northern Cordilleran slab window. The Californian slab window has been the subject of much study, but its relationships to volcanism and patterns of asthenospheric flow have been complicated by oceanic microplate formation (Wilson et al., 2005), an inboard jump of the spreading ridge and transcurrent displacement along the San Andreas fault system, impingement of the Yellowstone hotspot, and widespread extension in the Basin and Range province (Atwater and Stock, 1998). In contrast, the crust of western Canada has undergone relatively little late Cenozoic deformation (Armstrong and Ward, 1991), making the Northern Cordilleran slab window (Fig. 2A) a more straightforward locale for evaluating the outcome of ridge subduction and slab window formation.

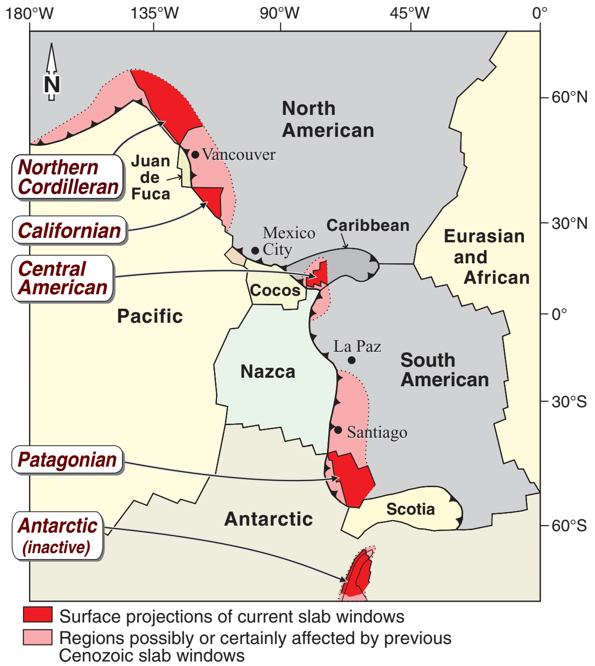

Figure 1. Current slab windows and plausible locations of previous windows beneath Americas and Antarctic Peninsula (Dickinson and Snyder, 1979; Forsythe and Nelson, 1985; Thorkelson and Taylor, 1989; Johnston and Thorkelson, 1997; Gorring and Kay, 2001; Sisson et al., 2003; Madsen et al., 2006; Breitsprecher and Thorkelson, 2009).

We describe the mantle response to the formation of the Northern Cordilleran slab window using volcanic geochemistry as a proxy for mantle composition. Using a 3500-km-long transect through inboard areas of eastern Alaska, western Canada, and the northern conterminous United States, we document spatial and temporal changes in mantle composition, particularly in the degree of hydration. We demonstrate how these changes are related to slab window formation and describe a unifying model for the modern plate tectonic environment of northwestern North America.

VOLCANIC ARC AND SLAB WINDOW ENVIRONMENTS

Metasomatism of the mantle wedge beneath volcanic arcs involves release of hydrous fluids and mobile elements from the downgoing slab, stabilization of Ti-rich minerals, and production of arc magma (Gill, 1981). Consequently, arc magmas have a distinctive geochemical signature in which alkalies, alkaline earth elements, and light rare earth elements are enriched over high field-strength elements (HFSEs), particularly Ti, Nb, and Ta. The metasomatism occurs within a wedge of mantle between the downgoing slab and the overriding plate (Gill, 1981). In contrast, other parts of the upper mantle are nearly anhydrous, as reflected by higher ratios of HFSEs to other elements. These differences are critical in the evaluation of mantle flow in slab window environments.

As a mid-ocean spreading ridge enters a trench the framework of subduction is disturbed, leading to a new regime of physical, thermal, and chemical conditions (Hole et al., 1991; Thorkelson, 1996; Gorring and

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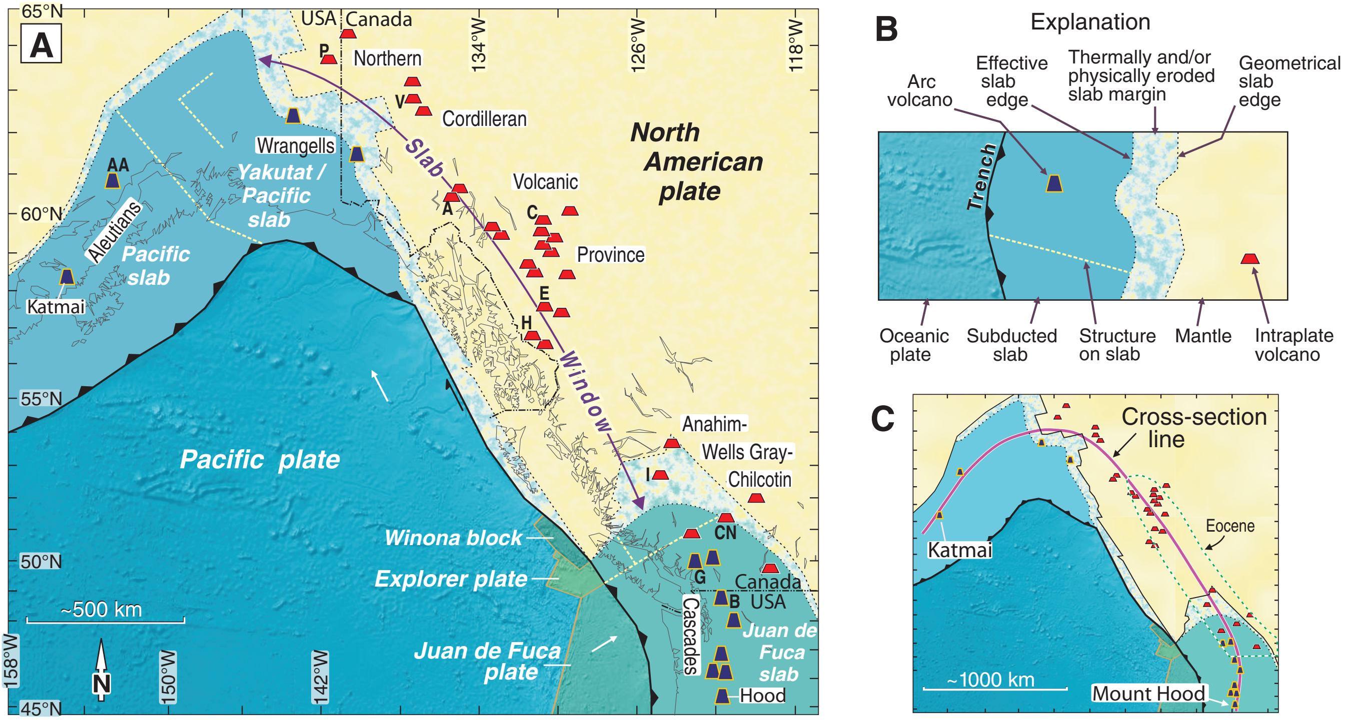

Figure 2. Northern Cordilleran slab window and late Cenozoic to Holocene volcanic regions. A: Tectonic plates and subducted slabs to depth of ~250 km beneath North American plate, showing Northern Cordilleran slab window. Mottled pattern along margins of slabs represents subducted crust that is likely to have been physically or thermally degraded, or removed by slab breakoff (Frederiksen et al., 1998; Thorkelson and Breitsprecher, 2005; Harder and Russell, 2006; Fuis et al., 2008) relative to model of uneroded slab edges (Madsen et al., 2006). Volcano symbols represent clusters of volcanoes or individual volcanoes. Columbia River basalts and Neogene forearc volcanic centers were not included in study. Volcano abbreviations: B—Mount Baker, G—Mount Garibaldi, CN—Chilcotin North, I—Mount Itcha, H—Hoodoo Mountain, E—Mount Edziza, C—Canyon Creek, A—Alligator Lake, V—Volcano Mountain, P—Mount Prindle, AA—Aleutians near Anchorage. B: Visual explanation of key features shown in A. C: Location of geochemical transect line on simplified version of A, used to construct Figures 3 and 4. Area of Eocene volcanism represented by data in Figure 4 is shown in labeled field.

Kay, 2001). Near the trench, the subducting ridge imparts a thermal pulse that commonly involves emplacement of magma akin to mid-ocean ridge basalt, high-temperature metamorphism, and melting of forearc sediment (Haeussler et al., 1995; Sisson et al., 2003). Farther inboard, the ridge separates into a slab window bounded by thin slab edges, which are prone to deformation and thermal erosion, including partial melting (Thorkelson and Breitsprecher, 2005). Above the slab window, arc magmatism is typically interrupted and replaced by a broader volcanic field with largely intraplate characteristics (Hole et al., 1991; Thorkelson, 1996). Microplate formation and tearing of the subducted slabs may occur, complicating the shape and extent of the slab window (Wilson et al., 2005).

GEOCHEMICAL IMAGE OF THE SLAB WINDOW

A geochemical transect of Neogene to Holocene volcanic centers from the Cascade Arc to the Aleutian Arc (Fig. 2C) was carried out using data compiled from the literature (Appendix DR1 in the GSA Data Repository[1]). The data were filtered to eliminate evolved compositions ($SiO_2 > 60\%$), which may reflect crustal rather than mantle sources, and samples with extreme trace element ratios, which may reflect analytical error, misreporting of data, or anomalous source compositions or processes. The resulting data set of 3530 analyses was divided into 41 groups representing individual volcanoes or clusters of volcanic centers, from Mount Hood in Oregon to the Katmai volcanic field in Alaska (Figs. 2 and 3; Appendix DR2). For each group, average values and standard deviations were determined and plotted against distance along the transect. The plume-generated Columbia River flood basalts were not included in the study.

Element abundances and ratios varied along the transect, with MgO/SiO_2 indicating that volcanic rocks of the Cascade and Aleutian Arcs are less mafic than those from volcanoes in the intervening region (Fig. 3A). The influence of subducted slab was evaluated using tectonically sensitive ratios, including TiO_2/MnO and Nb/Zr (Figs. 3B and 3C; Appendix DR2; Sun and McDonough, 1989). These ratios reveal a clear pattern of arc character in the Cascade Arc, intraplate character throughout most of British Columbia and Yukon, and a return to arc character in the Wrangell Mountains and Aleutians. When this pattern is compared to a cross section through the crust and upper mantle, the volcanic centers with intraplate affinity closely register with a physical model of the slab window (Figs. 2 and 3D) from Thorkelson and Taylor (1989) and Madsen et al. (2006), modified by constraints from seismic studies (Fuis et al., 2008; Audet et al., 2009). The rocks with intraplate affinity also have high incompatible element abundances.

In the north, the change from arc to intraplate character occurs where the torn and structurally complicated Pacific-Yakutat plate assemblage (Fuis et al., 2008) passes eastward into the slab window. The Wrangell volcanics, which were partly derived from slab melting (Preece and Hart, 2004), are near the eastern, tomographically imaged slab edge (Frederiksen et al., 1998). In the south, the transition from arc to intraplate signatures is gradual; the northern Cascade Arc is trenchward from coeval intraplate centers of the Anahim–Wells Gray–Chilcotin volcanic field (Fig. 2A). This gradation may reflect faulting of the downgoing slab during formation of the Explorer microplate at 4 Ma, and thermal erosion of

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[1] GSA Data Repository item 2011094, Appendix DR1 (bibliography of geochemical data for Miocene–Holocene volcanic rocks, northwestern North America) and Appendix DR2 (average values and standard deviations of geochemical ratios from Miocene–Holocene volcanoes, northwestern North America), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

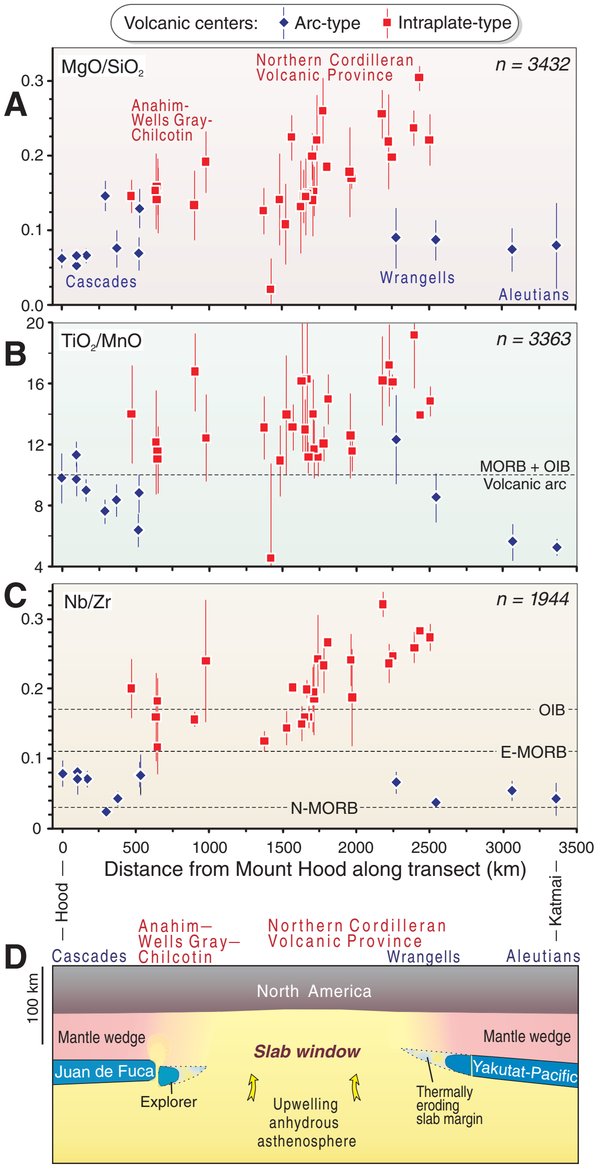

Figure 3. Geochemical transects and corresponding tectonic model. Transect line is shown in Figure 2C. Average values of geochemical ratios for Miocene–Holocene volcanic centers are plotted against distance from Mount Hood. Rocks with SiO_2 >60% were not included in study. Error bars at 1 standard deviation. Number of analyses used in each plot is indicated by *n*. A: MgO/SiO_2 ratios and locations of main volcanic fields. B: TiO_2/MnO ratios showing approximate division between volcanic arc and MORB (mid-oceanic ridge basalt) + OIB (ocean island basalt) compositions, based on Mullen (1983). C: Nb/Zr ratios showing values for N-MORB (N—normal), E-MORB (E—enriched), and OIB from Sun and McDonough (1989). In all plots, lower ratios are typical of volcanic arcs, with higher values common in intraplate fields, Nb/Zr being most sensitive tectonic discriminant. D: Tectonic model showing subducted Juan de Fuca–Explorer and Yakutat-Pacific slabs, intervening slab window, and locations of arc and intraplate volcanic fields. Vertical exaggeration ~5×.

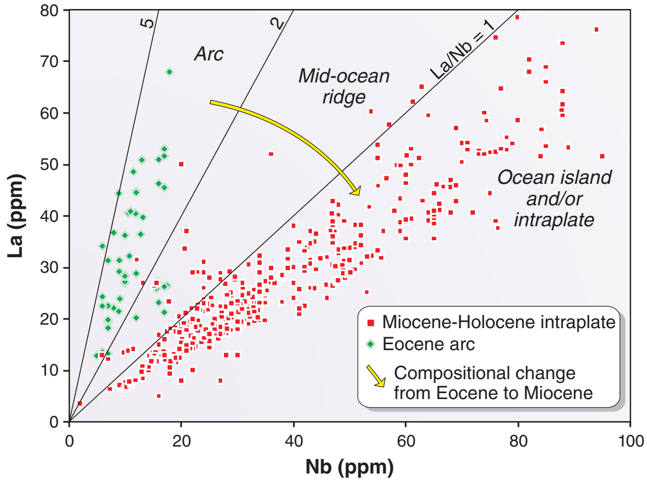

Figure 4. La/Nb tectonic discrimination diagram (Gill, 1981) showing change in tectonic affinity of igneous rocks in western Canada from Eocene (volcanic arc) to Miocene–Holocene (ocean island and/or intraplate) indicated by arrow. Eocene data are from Morris and Creaser (2003), Ickert et al. (2009), and Breitsprecher et al. (2003). Miocene–Holocene data sources are in Appendix DR1; data are in Appendix DR2 (see footnote 1).

both the Juan de Fuca and Explorer plates (Figs. 2 and 3; Madsen et al., 2006; Audet et al., 2009).

SLAB WINDOW–INDUCED MANTLE FLOW

In Eocene time, magmatism in western Canada was broadly arc-like with element ratios consistent with subduction and mantle metasomatism (Morris and Creaser, 2003; Breitsprecher et al., 2003; Fig. 4). In western Canada, a shift in tectonic affinity from volcanic arc to intraplate began after cessation of the Eocene arc ca. 47 Ma (Ickert et al., 2009) and a hiatus in magmatism during the Oligocene. Intraplate volcanism began in the Late Oligocene to Early Miocene (ca. 24 Ma; Edwards and Russell, 2000), was widespread by the Middle Miocene (ca. 10 Ma; Bevier et al., 1979; Carignan et al., 1994; Shi et al., 1998; Madsen et al., 2006), continued until a few hundred years ago (Edwards and Russell, 2000), and may resume in the future. This geochemical transition occurred synchronously with the opening of the Northern Cordilleran slab window and disappearance of the subducted oceanic lithosphere that had underlain much of western Canada in the Paleogene (Fig. 4). The window continued to grow throughout the Neogene–Holocene and is currently ~1500 km long, extending from southern British Columbia to near the Alaska-Canada border (Figs. 2 and 3).

The temporal shift in geochemical character reflects a change in the composition of the underlying magma sources, from slab-metasomatized mantle in the Paleogene to anhydrous asthenosphere or veined lithospheric mantle in the Neogene (Carignan et al., 1994; Edwards and Russell, 2000). This wholesale displacement of arc-type mantle is herein viewed as a passive response to the northward motion of the Pacific slab away from the eastward-moving Juan de Fuca slab (Fig. 2A). As the slabs diverged, they induced uprising of anhydrous asthenosphere through the growing slab window to fill the void (Fig. 3D). The upwelling asthenospheric mantle underwent decompressional melting, and thermally eroded the North American lithospheric mantle; both asthenosphere and lithosphere served as sources to parts of the intraplate volcanic field (Carignan et al., 1994; Shi et al., 1998; Edwards and Russell, 2000). Previous workers have used mantle plume activity, crustal extension, and backarc convection to explain specific features of the intraplate field (Bevier et al., 1979; Edwards and Russell, 2000; Currie and Hyndman, 2006), but the geochemical similarities among the volcanic centers are arguably greater than their differences. We therefore appeal to asthenospheric displacement of the mantle wedge as the fundamental explanation while recognizing that specific processes may have played important roles in certain parts of this extensive intraplate province.

THERMAL EFFECTS

The western Canadian Cordillera has a lithospheric thickness of only 52–66 km, with temperatures at the Moho from 800 to 850 °C (Harder and Russell, 2006). The association of a slab window with (1) intraplate volcanism involving partial melting of lithospheric and asthenospheric mantle, (2) thin lithosphere, (3) low seismic velocities, and (4) high heat flow is best explained by mantle upwelling, advective transfer of heat, and thermal erosion of the lithospheric mantle. In an alternative model, subduction-induced flow of asthenospheric mantle behind the northernmost Cascade Arc was used to explain the high heat flow in southern British Columbia (Currie and Hyndman, 2006). However, that model cannot explain the high heat flow above the neighboring slab window (Hyndman et al., 2005; Harder and Russell, 2006), which is devoid of both volcanic arc and subducting slab. We argue that widespread asthenospheric upwelling through the slab window and across the broken and eroded slab edges (Figs. 2 and 3D) is a more suitable model for the entire region.

CONCLUSIONS

The Northern Cordilleran slab window developed beneath western Canada in the Early Miocene, following an Eocene regime dominated by subduction and related mantle metasomatism. Opening of the window led to displacement of the hydrated mantle wedge by uprising asthenospheric mantle. This process is consistent with compositional patterns of magmatism beneath the Americas and worldwide. Slab windows are potent modifiers of convergent plate margins, involving regional displacement of the mantle wedge, production of intraplate magma, and thinning of the overriding lithosphere. Their current abundance suggests that slab windows have been common and important modifiers of convergent plate margins throughout Earth history.

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