

Slab portal beneath the western Aleutians

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ABSTRACT

Tomographic images of the distribution of shear-wave speed beneath the northwestern Pacific delineate the configuration of the subducted oceanic lithosphere beneath the western Aleutian arc. At ~ 100 km depth, a fast shear-wave speed anomaly is beneath the Aleutian arc everywhere east of 173°E . Between 164°E and 173°E , however, seismic velocities at this depth are slow relative to the surrounding mantle. The lateral termination of the fast shear-wave speed anomaly at depth coincides with a gap in deep seismicity beneath the Aleutians. The absence of these two distinctive traits of subducting slabs leads us to conclude that this segment of the Aleutian arc overlies a very large window in the otherwise continuous lithospheric slab that we term a “slab portal.” This portal is likely to facilitate the production of distinctive volcanic rocks (adakites or high-Mg# andesites) by partially melting the adjacent edges of the slab. The Miocene age of most adakites in the westernmost Aleutians where no slab is present may indicate that the portal formed relatively recently. The chemistry of western Aleutian adakites approximates that of typical continental crust, so their genesis and subsequent lateral transport toward Kamchatka is a plausible mechanism for new continent formation.

Keywords: adakites, Aleutians, mantle structure, seismic tomography, slab melting.

INTRODUCTION

The Aleutian arc forms a boundary between the North American and Pacific plates. From east to west, the relative motion between the plates changes progressively from normal convergence to highly oblique convergence to pure transform motion (Fig. 1). At the arc termination against the Kamchatka peninsula, the plate boundary turns sharply to the southwest and once again becomes a subduction zone.

The chemistry of some volcanic andesites near the Aleutian-Kamchatka junction as well as in the westernmost active volcanoes of the Aleutian arc suggests that a large slab window is beneath the westernmost Aleutians (Yogodzinski et al., 2001). Characterized by relative Mg enrichment and elevated Sr/Y ratios, such rocks commonly are referred to as adakites and are interpreted to be products of melting of the young (younger than 25 Ma) subducted oceanic lithosphere (Defant and Drummond, 1990). The presence of adakites is often taken as evidence for a disruption in the subducting plate (e.g., Johnston and Thorkelson, 1997; Abratis and Wörner, 2001; Kinoshita, 2002; Bourgois and Michaud, 2002).

Pacific lithosphere that subducts beneath Kamchatka and the Aleutian arc is ca. 50 Ma (Kelemen et al., 2003). To explain the production of adakite-like rocks in the western Aleutians and at the Aleutian-Kamchatka junction, Yogodzinski et al. (2001) proposed melting at the side edges of disrupted subducted lithosphere. Citing exposures of these rocks on the surface and on the seafloor, combined with qualitative arguments about earthquake distribution, they estimated the extent of the gap in the subducting Pacific lithosphere. They concluded that subducted lithosphere is largely absent beneath the entire transform section of the Aleutian arc.

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In previous work (Levin et al., 2002) we documented the lack of northward subduction of the Pacific lithosphere at the western edge of the slab window proposed by Yogodzinski et al. (2001). We showed that relocated seismic activity beneath southern Kamchatka coincides with a high seismic velocity body associated with the subducted Pacific

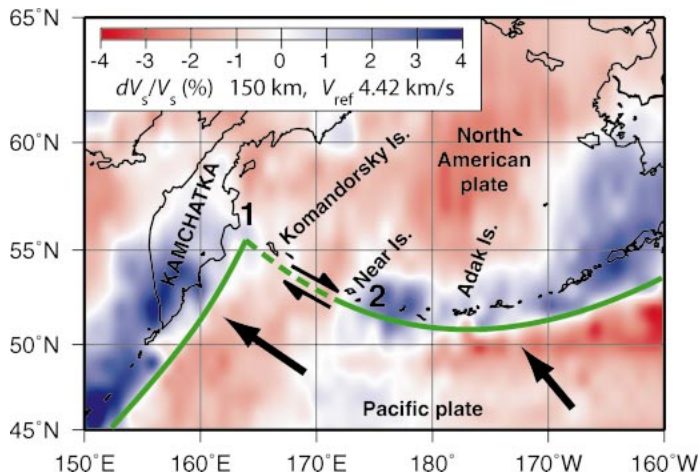


Figure 1. Horizontal slice through three-dimensional shear-velocity (V_s) model (Levin et al., 2002) at depth of 150 km, showing lateral extent of slab portal with respect to ambient geographic features. Green line—convergent (solid) and transcurrent (dashed) plate boundaries. Solid arrows—direction of Pacific plate motion relative to North America. Solid half-arrows—sense of motion in western segment of Aleutian arc. 1—Cape Kamchatka; 2—approximate location of youngest known Aleutian adakite (sample 70-B29, Scholl et al., 1976).

lithosphere. The absence of a high-velocity body north of the Aleutian-Kamchatka junction argues strongly against aseismic subducted material beneath the inactive convergence zone in northern Kamchatka.

In this paper we focus on the eastern edge of the proposed slab window. By using new tomographic images of seismic velocity and high-quality locations of seismic events, we show that the westernmost extent of the subducted Pacific lithosphere is at $\sim 173^\circ\text{E}$, approximately beneath the Near Islands. In recognition of its large size we term the opening in the subducted Pacific lithosphere a “slab portal.” We consider the implications of this portal for the origin of adakite-like rocks in the Aleutian arc and the time frame for the opening of the portal. We conclude by examining the possible mechanism of new continental crust accretion in the northwestern corner of the Pacific.

TOMOGRAPHIC IMAGING METHOD

The tomographic model presented here (Figs. 2 and 3; Data Repository Fig. DR1¹) is an update of the model previously described by Levin et al. (2002). It is constructed by inverting surface-wave dispersion (frequency-specific traveltimes) data that are most suited to image uppermost mantle in the depth range of our interest (50–200 km). Data for the tomographic model consist of a global set of broadband surface-wave group (Ritzwoller and Levshin, 1998) and phase (Trampert and Woodhouse, 1995; Ekström et al., 1997) velocity measurements, complemented with group velocity measurements on >2000 source-receiver paths from a year-long deployment of portable seismic stations in Kamchatka (Peyton et al., 2001). We used a two-step inversion procedure. First, period-specific dispersion maps were constructed using a “diffraction tomography” method (Ritzwoller et al., 2002) that is based on a physical model of surface-wave lateral sensitivity kernels. Subsequently, these dispersion maps were subjected to nonlinear Monte-Carlo inversion (Shapiro and Ritzwoller, 2002) to estimate an ensemble of acceptable shear-velocity (V_s) models of the crust and the uppermost mantle on a $1^\circ \times 1^\circ$ grid across the region of study.

EVIDENCE FOR A SLAB PORTAL

Subducting oceanic lithosphere is cooler than the surrounding mantle and has faster seismic wave speed. Tomographic images (Figs. 1 and 2A; Fig. DR1 [see footnote 1]) show that at a depth of ~ 150 km, a fast shear-wave speed anomaly is present beneath the Aleutians everywhere east of 173°E . Between 164°E and 173°E , however, seismic velocities at this depth are anomalously slow for mantle at this depth, not fast. As seen in Figure 1, and documented in more detail by Levin et al. (2002), a return to high values of shear-wave speed takes place in the west only at the Aleutian-Kamchatka junction.

The lateral resolution of our three-dimensional tomographic model beneath the western Aleutians for the depth range of interest varies between 200 and 500 km, generally deteriorating with depth. Therefore, the width of the reported slab portal is larger than the resolution limit of our data. Moreover, synthetic tests show that, with the available surface-wave data, 50 Ma oceanic lithosphere should be imaged with a positive (fast) shear-velocity anomaly. Therefore, the observed low-velocity anomaly indicates that subducted lithosphere is absent in the western Aleutians or is significantly thinner and hotter than expected from the age of the Pacific lithosphere entering the mantle (ca. 50 Ma; see Kelemen et al., 2003).

It is instructive to compare images of shear-wave speed distribution at depth with a catalog of high-quality earthquake locations (Fig. 2) compiled by Engdahl et al. (1998). The region of lower seismic velocities beneath the western Aleutians correlates with a well-defined

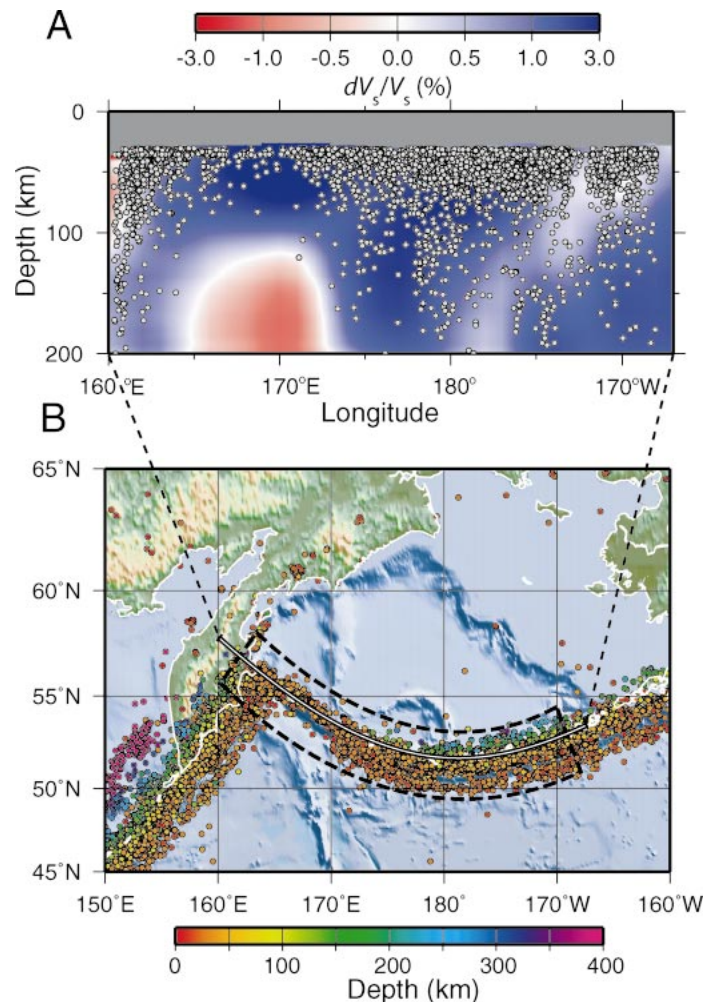


Figure 2. A: Vertical cross section through tomographic shear velocity (V_s) along profile shown with white line in B. Colors indicate percent perturbation relative to regionally averaged one-dimensional profile. White circles show earthquakes (EHB catalog, Engdahl et al., 1998) located within area shown between dashed lines in B. Low-velocity anomaly between 164°E and 173°E at depths below 100 km (approximate thickness of oceanic lithosphere) coincides with region devoid of deep earthquakes. We call this section of Aleutian arc, where subducting oceanic lithosphere is clearly absent, slab portal. B: Topographic map of Aleutian-Kamchatka junction. Circles show epicenters of earthquakes from EHB catalog (Engdahl et al., 1998). Hypocentral depths are indicated with color scale.

gap in deep (>100 km) earthquake hypocenters. The absence of the subducted lithosphere beneath this section of the western Aleutians from the Aleutian-Kamchatka junction to 173°E can explain this correlation.

An alternative explanation for anomalously low shear-wave speed beneath the western Aleutians would be that the subducting lithosphere is significantly thinner and hotter than its age (ca. 50 Ma) would suggest. To be invisible to the seismic surface waves used to construct the tomographic images, anomalously warm subducted lithosphere could result from an extremely oblique angle of subduction. The lithosphere entering the western Aleutian subduction zone could have been additionally heated by a mantle plume. Gorbатов et al. (2001) argued for a plume in this area from teleseismic P-wave tomography.

However, a number of factors make this scenario unlikely. First, the seismic structure of the incoming Pacific plate is consistent with its thermal age (Ritzwoller et al., 2004), and conductive heating of 50 Ma oceanic lithosphere held in contact with asthenosphere is too slow to obliterate its temperature anomaly in fewer than 100 m.y. (Ritz-

¹GSA Data Repository item 2005044, Figure DR1, cross sections through the tomographic model, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

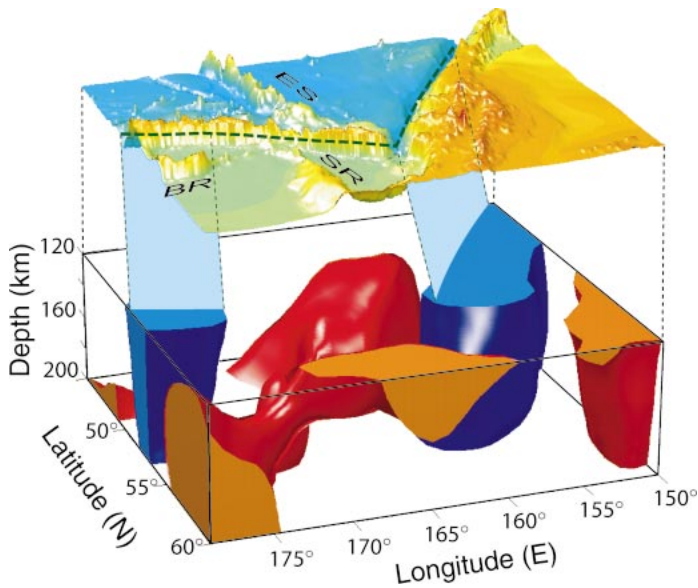


Figure 3. Isosurface representation of shear-velocity model beneath western Aleutians, in which model is laterally smoothed with Gaussian filter ($\sigma = 100$ km) to highlight dominant large-scale features. Dark blue surface (+1.2%)—high seismic velocity oceanic lithosphere subducting beneath Aleutians east of 173°E and beneath southern Kamchatka. Red surface (-1.2%)—low seismic velocities associated with asthenospheric material that penetrates through slab portal beneath western Aleutians. Vertically exaggerated topography is shown with colored isosurface on top. Dashed green line—locations of Aleutian and Kamchatka Trenches. Emperor Seamounts (ES) and Bowers and Shirshov Ridges (BR and SR) are also shown. Light blue surfaces show projections of subducted oceanic lithosphere on trenches.

woller et al., 2003, their Fig. 12). Second, a slab's thermal anomaly would diffuse laterally for ~ 300 km, and remain detectable to the surface-wave tomography. Third, even young (younger than 25 Ma) oceanic lithosphere subducts with accompanying seismic activity that typically extends beyond 100 km depth—e.g., Central America (Husen et al., 2003), the Andes (e.g., Husen et al., 2000), or the Cascades (e.g., Tabor and Smith, 1985). If frictional heating renders the subducted oceanic plate both aseismic and thermally similar to the surrounding mantle, the slab is unlikely to retain enough strength to translate intact sideways, which is required to follow the current transform faulting of the western Aleutians (e.g., Yogodzinski et al., 1993).

We therefore conclude that the segment of the western Aleutians where the shear-wave speeds are low and deep earthquakes are absent is devoid of subducted Pacific lithosphere at depths between ~ 100 and 200 km. The westernmost Aleutians are above an opening in a vertical barrier that divides the upper mantle beneath the Pacific and the North American plates from the Kuriles to Alaska. In recognition of its significant width (see Fig. 2A), we term this opening a slab portal.

IMPLICATIONS OF THE SLAB PORTAL

The presence of a slab portal beneath the western Aleutians has implications for the origin of volcanic rocks (variously referred to as adakites [Yogodzinski et al., 2001] or high-Mg# andesites [Kelemen et al., 2003]) found in the western Aleutian arc. These rocks are interesting because their composition is similar to average continental crust, and consequently they have been hypothesized as examples of how to create continental crust without involvement of preexisting continental material (Kelemen et al., 2003).

A mechanism put forward to explain the generation of these rocks (Yogodzinski et al., 2001) relies on the melting of the subducted slab material adjacent to its side edge. A slab window that allows through

flow of hot mantle material from beneath the subducted plate will facilitate this mechanism. The tomographic images and relocated earthquakes, together with the spatial distribution of rocks with distinct geochemical signatures, seem to follow this mechanism. Taking into consideration the lateral resolution of the tomographic image (>200 km), the location of the youngest (<600 k.y.) identified Aleutian adakite (dredge sample 70-B29 [Scholl et al., 1976; Kelemen et al., 2003]) is either directly above the eastern edge of the slab portal or very close to it (see Fig. 1).

Miocene adakites and adakite-like rocks are found throughout the western Aleutians (Yogodzinski et al., 1995; Yogodzinski and Kelemen, 1998). These localities do not overlie a subduction zone. It is plausible that adakitic and similar rocks formed above the eastern edge of the portal, and were subsequently transported to their present position. Significant westward transport of the western Aleutian Islands is supported by sedimentary evidence (Rostovtseva and Shapiro, 1998). Geochemical and structural evidence supports arc-parallel extension in the western Aleutians (Yogodzinski et al., 1993; Avé Lallemant, 1996). Geodetic measurements throughout the western Aleutians (Avé Lallemant and Oldow, 2000; Bürgmann et al., 2001) show a progressively increasing westward drift of western Aleutian terranes.

Notably, the island of Adak (which gives its name to the distinctive volcanic rocks) is relatively far from the slab portal imaged by seismic tomography (Fig. 1). Thus, the origin of the original adakites does not appear to be directly related to the slab portal of the western Aleutians and the associated melting of the slab material at the edge of the plate. It may be related to a local disruption of the lithosphere, or caused by the eastward influx of hot asthenospheric rock from the portal, similar to the scenario proposed in Central America (Abratis and Wörner, 2001) and the Lau Basin (Smith et al., 2001).

Kelemen et al. (2003) proposed an alternative mechanism for the origin of high-Mg# andesites in the Aleutians that postulates a multi-stage evolution of melts that originate when oceanic crustal basalt undergoes a transformation to eclogite and subsequently melts. This scenario would not be restricted to the area where the plate has an open-ended lateral termination. The key element of this mechanism is reduced temperature within the supraslab mantle wedge, achieved via heat transfer to obliquely subducting lithosphere. This scenario is compromised by the absence of a cool subducted plate beneath the western Aleutians, as the maintenance of the cold mantle wedge becomes problematic. However, numerous adakites have erupted in the Miocene, and the slab portal may have formed more recently. Yogodzinski et al. (1993) postulated a change in the plate-boundary regime ca. 15 Ma, whereas Wessel and Krönke (2000) argued for an even younger (ca. 6 Ma) change in the motion of the Pacific plate. Either of these plate reorganizations could have halted active convergence in the western Aleutians, after which the slab could have detached and sunk, forming the modern portal. Evidence of a foundered slab can be found in body-wave tomography. In the mantle transition zone north of the western Aleutians, Gorbatov et al. (2000) found high-velocity bodies that they interpreted as remnant detached slabs that stalled above the 670 km mantle discontinuity.

The unusual chemistry of western Aleutian high-Mg# andesites makes them prime candidates for the building blocks of continental crust (Kelemen et al., 2003). The mechanism for accreting sufficient material to form a continent remains uncertain. One plausible scenario for new continental growth may be represented by the history of recent terrane accretion in eastern Kamchatka. Geist and Scholl (1994) argued that Cape Kamchatka is an Aleutian island that is accreting to the continental lithosphere of the Kamchatka peninsula. Park et al. (2002) proposed that the Aleutian-Kamchatka junction has not been stationary through time, but migrated northeast between 30 and 10 Ma. Consequently, the arc-volcanic terranes that form the eastern capes of Kam-

chatka may represent other former fragments of the Aleutian arc that were attached to the growing continental lithosphere of Kamchatka. Thus, the northwestern Pacific region may be viewed as a good example of ongoing continent building, with raw materials (adakites), the transport system (the western Aleutians strike-slip zone), and the assembly site (Kamchatka) present.

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