The 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 lies beneath the Aleutian Arc everywhere east of 173^{O}E. Between 164^{O}E and 173^{O}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 portal in the otherwise continuous lithospheric slab. The 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 adakites above the westernmost Aleutians may indicate that the portal was formed relatively recently.

1. Introduction

The Aleutian Arc forms a boundary between the North American and Pacific plates. The relative motion between the plates changes progressively, from east to west, from normal convergence to highly oblique convergence to pure transform motion [Figure 1]. At the western termination of the Aleutian Arc against the Kamchatka peninsula the plate boundary turns sharply to the southwest, and once again becomes a subduction zone.

The chemistry of some volcanic rocks near the Aleutian-Kamchatka Junction (AKJ) as well as in the westernmost active volcanoes of the Aleutian Arc suggests that a large slab window lies beneath the westernmost Aleutians (Yogodzinski et al., 2001). The rocks in question are andesites 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 (under 25 Ma) subducted oceanic lithosphere (Defant and Drummond, 1990). Their presence in erupted lavas is often taken as evidence for a disruption in the subducting plate (e.g., Johnston and Thorkelson, 1997; Abratis and Worner, 2001; Kinoshita, 2002; Bourgois et al., 2002).

The Pacific lithosphere subducting beneath Kamchatka and the Aleutian Arc is roughly 50 Ma old (see a review by Kelemen et al., 2004). To explain the production of adakite-like rocks in the western Aleutians and at the AKJ, Yogodzinski et al. (2001) proposed melting at the side edges of disrupted subducted lithosphere. They used known exposures of these rocks on the surface and on the sea floor and qualitative arguments about the distribution of seismic activity to estimate the extent of the resulting window in the subducting Pacific lithosphere. They concluded that subducted lithosphere is largely absent beneath the entire transform section of the Aleutian Arc.

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 carefully relocated seismic activity beneath southern Kamchatka coincided with a high seismic velocity body associated with the subducted Pacific lithosphere. The absence of a high-velocity body north of the AKJ argued 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. 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 ~173^{O}E, approximately beneath the Near Islands. In recognition of its size we term the opening in the subducted Pacific lithosphere a "slab portal". Finally, we consider the implications of this portal for the origin of adakite-like rocks in the Aleutian Arc, and also the time frame for the opening of the portal.

2. Tomographic Imaging Method

The tomographic model presented here is an update of the model previously described by Levin et al. (2002). It is constructed by inverting surface-wave dispersion (frequency-specific travel times) data that are most suited to image uppermost mantle in the depth range of our interest (50-200 km). The 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 more than 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 found with 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 (Vs) models of the crust and the uppermost mantle on a $1^{O}x1^{O}$ grid across the region of study.

3. Evidence for a Slab "Portal"

Subducting oceanic lithosphere is cooler than the surrounding mantle, and is therefore seismically faster. Tomographic images (Figures 1, 2a) show that at a depth of ~150 km a fast shear wave speed anomaly is present beneath the Aleutians everywhere east of 173^{O}E . Between 164^{O}E and 173^{O}E, however, seismic velocities at this depth are not higher than average for mantle at this depth. Rather, they are anomalously slow. 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 AKJ.

The lateral resolution of our 3D 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 recovery tests show that, with the available surface-wave data, 50 Ma old oceanic lithosphere should be imaged with a positive (fast) shear-velocity anomaly. Therefore, the observed low-velocity anomaly indicates that the subducted lithosphere is absent in this region or is significantly thinner and hotter than expected from the age of the oceanic lithosphere subducting beneath the Aleutian Arc (~50 Ma, see Kelemen et al., 2004).

It is instructive to compare images of shear wave speed distribution at depth with a catalog of high-quality earthquake locations compiled by Engdahl et al. (1998) seen in Figure 2. Note that the region of lower seismic velocities beneath the western Aleutians is characterized by a well defined gap in deep (over 100 km) earthquake hypocenters. The absence of the subducted lithosphere beneath this section of the western Aleutians from the AKJ to 173^{O}E explains this observation.

An alternative explanation for anomalously low shear wave speed beneath the western Aleutians would be that the subducting lithosphere, while present, is significantly thinner and hotter than its age (~50 Ma) would suggest. As a result, it may be invisible to the relatively long wavelength seismic waves used to construct the tomographic images. Anomalously warm subducted lithosphere could result from an extreme oblique angle of subduction and the longer residence time the slab would have in contact with the ambient mantle. The lithosphere entering this section of the subduction zone could have been additionally heated by a mantle plume for which there is evidence in this area from telesesmic P-waves (Gorbatov et al., 2001).

This alternative hypothesis, however, is difficult to reconcile with the lack of seismic activity at depth. Even young (<25 Ma) oceanic lithosphere subducts with seismic activity that typically extends beyond 100 km depth (e.g., subduction beneath Central America (Husen et al., 2003), the Andes (e.g., Husen et al., 2000) or the Cascades (e.g., Tabor and Smith, 1985)). The absence of the Wadati-Benioff zone combined with the current transform faulting tectonic regime of the western Aleutians (e.g., Yogodzinski et al., 1993) makes the alternative scenario unlikely. In addition, the thermal structure of the thermal structure of the incoming plate is observed to be consistent with its lithospheric age (Ritzwoller et al., 2004).

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 about 100 and 200 km. The westernmost Aleutians lie 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 Figure 2a), we term this opening a "slab portal".

4. 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., 2004) 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 pre-existing continental material (Kelemen et al., 2004).

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. It is thus encouraging that tomographic images and relocated eartquakes agree with this expectation from the spatial distribution of rocks with distinct geochemical signatures. Taking into consideration the lateral resolution of the tomographic image (>200 km), the location of the youngest identified Aleutian adakite, dredge sample 70-B29 (Scholl et al., 1976; Kelemen et al., 2004), is either directly above the eastern edge of the slab portal or very close to it (see Figure 1).

Older (Miocene-age) adakites and adakite-like rocks are found throughout the western Aleutians (Yogodzinski et al., 1995; Yogodzinski and Kelemen, 1998). These localities do not at present 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; Ave Lallemant, 1996). Finally, geodetic measurements throughout the western Aleutians (Ave Lallemant and Oldow, 2000; Burgmann et al., 2000) show a progressively increasing westward drift of western Aleutian terranes.

It is interesting to note that the island of Adak that gives its name to the distinctive volcanic rocks is relatively far from the slab portal imaged by seismic tomography (Figure 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 else caused by the eastward influx of hot asthenospheric rock from the portal, similar to the scenario proposed in Central America (Abratis and Worner, 2001) and the Lau Basin (Smith et al. 2001).

Kelemen et al. (2004) recently proposed an alternative mechanism for the origin of high Mg # andesites in the Aleutians which postulates a multistage 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 depressed temperature within the supra-slab mantle wedge achieved via heat transfer to obliquely subducting lithosphere. At face value this scenario is compromised by the absence of a subducted plate beneath the Western Aleutians, as the maintenance of the "cold" mantle wedge becomes problematic. However, numerous adakites 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 at ~15 Ma, while Wessel and Kroenke (2000) describe an even younger (~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 detach and sink to form the modern portal. Evidence of a foundered slab can be found in body-wave tomography. In the mantle transition zone north of the western Aleutian slab portal Gorbatov et al. (2000) found high-velocity bodies that they interpreted as remnant detached slabs that have stalled above the 670-km mantle discontinuity.

Their unusual chemistry makes western Aleutian high Mg # andesites prime candidates for the building blocks of continental crust (Kelemen et al., 2004), but the mechanism for accreting sufficient material to form a continent remains uncertain. In this regard, the history of recent terrane accretion in eastern Kamchatka may be of interest. Geist and Scholl (1994) argue 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 AKJ has not been stationary through time, but has migrated northeast over ~10-30 Ma. Consequently, the arc-volcanic terranes that form the eastern "capes" of Kamchatka may represent other former fragments of the Aleutian arc that were attached to the growing continental lithosphere of Kamchatka. In this scenario, the northwestern Pacific region may be viewed as a prime example of ongoing continent building, with raw materials (adakites), the transport system (the western Aleutians strike-slip zone) and the assembly site (Kamchatka) all in evidence.

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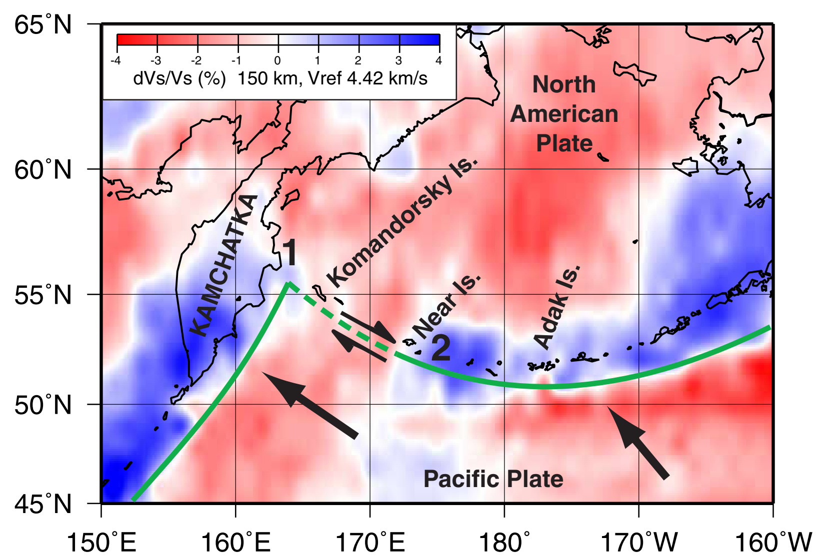
Figure captions

Figure 1. A horizontal slice through the 3D shear velocity model (Levin et al., 2002) at a depth of 150 km, showing the lateral extent of the slab portal with respect to ambientgeographic features. A green line shows the convergent (solid) and transcurrent (dashed) plate boundaries. Solid arrows show the direction of the Pacific plate motion relative to North America, solid half-arrows indicate the sense of motion in the western segment of the Aleutian Arc. 1 - Cape Kamchatka; 2 - the approximate location of the youngest known Aleutian adakite (sample 70-B29, Scholl et al., 1976).

Figure 2. (a) Vertical cross-section through the tomographic Vs model along the profile shown with the white line in (b). Colors indicate the percent perturbation relative to the regionally averaged one-dimensional profile. White circles show earthquakes (EHB catalog, Engdahl et al., 1998) located within the area shown with the dashed line in (b). The low-velocity anomaly between 164^{O}E and 173^{O}E at depths below 100 km (the approximate thickness of the oceanic lithosphere) coincides with the region devoid of deep earthquakes. This is what we call the "slab portal", where subducting oceanic lithosphere is absent. (b) A topographic map of the Aleutian-Kamchatka junction. Circles show epicenters of earthquakes from the EHB catalog. Hypocentral depths are indicated with the color scale.

Figure 3. Isosurface representation of the Vs model beneath the Western Aleutians, in which the model is laterally smoothed with a gaussian filter (σ = 100 km) to highlight the dominant large-scale features. The dark blue surface (+1.2%) represents the high seismic velocity oceanic lithosphere subducting beneath the Aleutians East of 173^{O}E and beneath southern Kamchatka. The

red surface (-1.2%) indicates low seismic velocities associated with asthenospheric material that penetrates through the "slab portal" beneath the western Aleutians. Vertically exaggerated topography is shown with a colored isosurface on the top. The dashed green line shows the locations of Aleutian and Kamchatka trenches. Light blue surfaces show the projection of the subducted oceanic lithosphere on the trenches.



-4 -3 -2 -1 0 1 2 3 4
dVs/Vs (%) 150 km, Vref 4.42 km/s
North American Plate
KAMCHATKA
Komandorsky Is.
1
Near Is.
2
Adak Is.
Pacific Plate
65˚N
60˚N
55˚N
50˚N
45˚N
150˚E
160˚E
170˚E
180˚
170˚W
160˚W

Figure 1

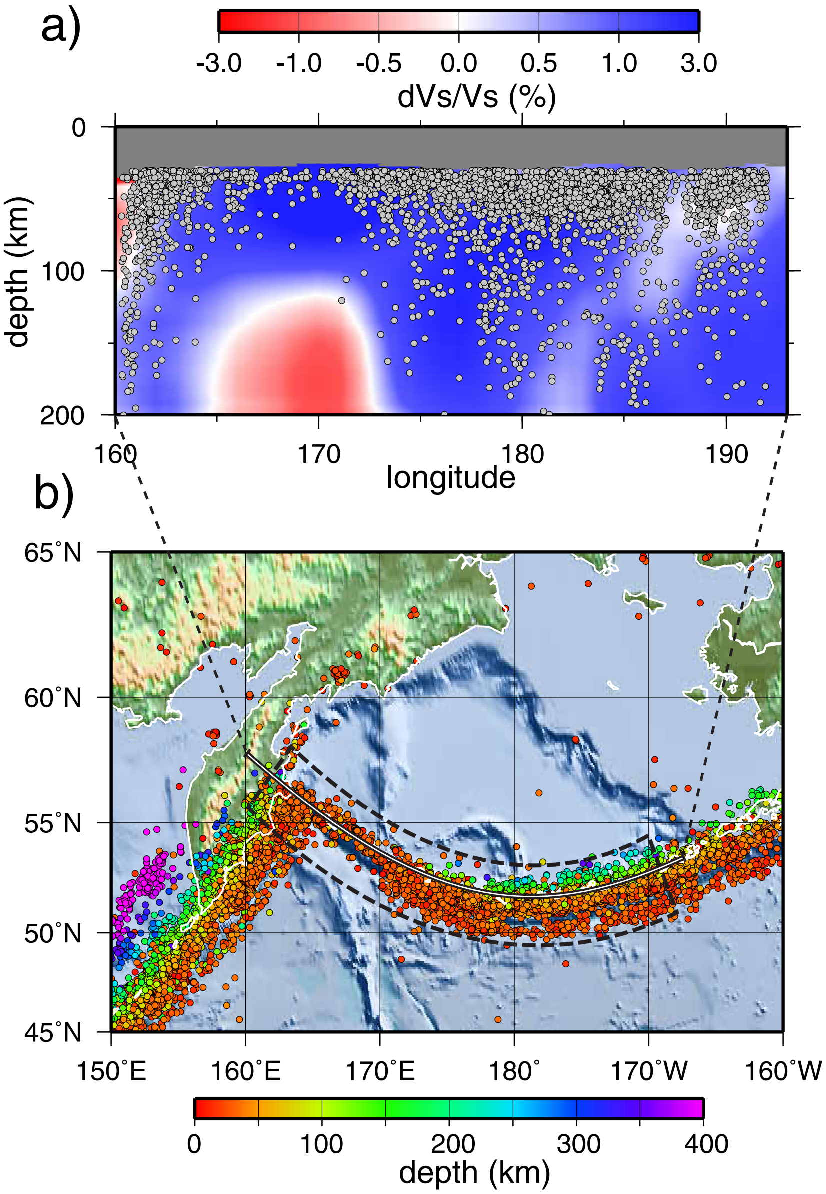
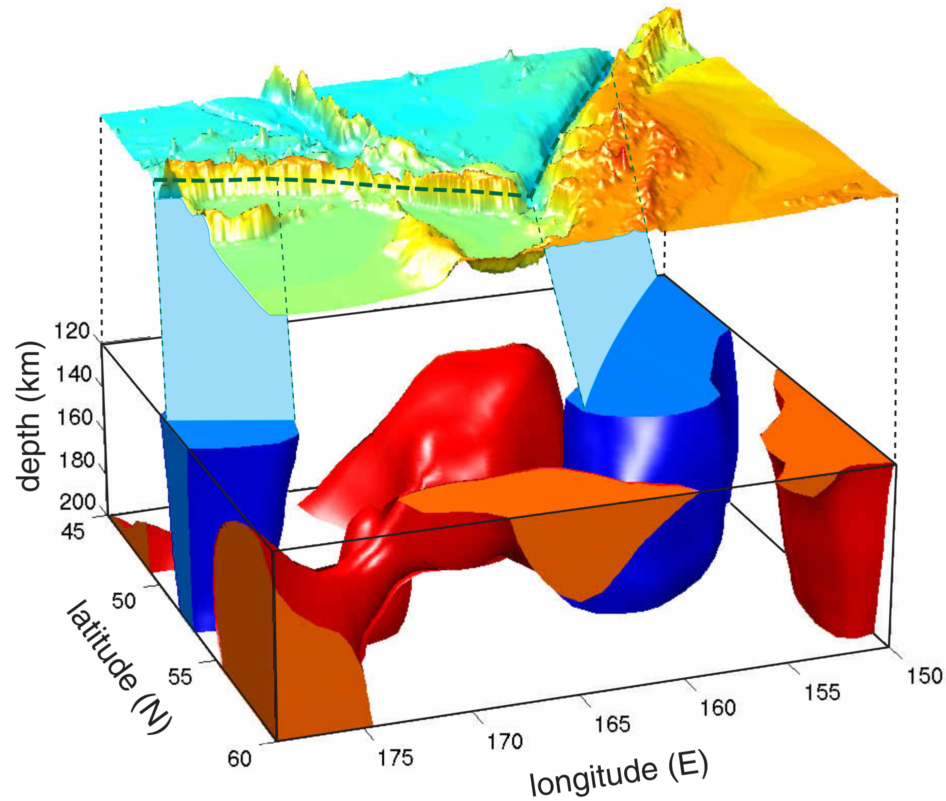

a)
-3.0
-1.0
-0.5
0.0
0.5
1.0
3.0
dVs/Vs (%)
0
100
200
depth (km)
160
170
180
190
longitude
b)
65˚N
60˚N
55˚N
50˚N
45˚N
150˚E
160˚E
170˚E
180˚
170˚W
160˚W
0
100
200
300
400
depth (km)

Figure 2



120
140
160
180
200
depth (km)
45
50
55
60
latitude (N)
175
170
165
160
155
150
longitude (E)

Figure 3