



Three-dimensional seismic velocity structure of the northwestern United States

Jeffrey B. Roth,¹ Matthew J. Fouch,¹ David E. James,² and Richard W. Carlson²

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[1] We present a high-resolution, three dimensional, P-wave tomography model for the northwestern United States. Major features of the model include clear, well-resolved images of the Juan de Fuca–Gorda slab to depths of at least 500 km, reduced velocities beneath Newberry volcano and north-central Oregon, increased velocities beneath the Idaho batholith, and a deep, slab-like, eastward-dipping feature of increased velocities beneath Nevada. We find no evidence for a mantle plume in this region, and demonstrate that suggested disruption of the Juan de Fuca slab beneath Oregon in the vicinity of Newberry volcano is an inversion artifact. We interpret the primary features of this new model within the framework of post-Laramide tectonomagmatism and the continuing tectonic evolution of the Cascadia Subduction Zone. A model explaining the regional tectonomagmatic history consistent with the imaged seismic velocity structure is one driven by mantle flow responding to the evolving subduction system. **Citation:** Roth, J. B., M. J. Fouch, D. E. James, and R. W. Carlson (2008), Three-dimensional seismic velocity structure of the northwestern United States, *Geophys. Res. Lett.*, 35, L15304, doi:10.1029/2008GL034669.

1. Introduction

[2] The Cascadia subduction zone of northwestern North America, notably the descending Juan de Fuca and Gorda microplates (Figure 1a), are the remnants of an extensive convergent plate margin that spanned much of coastal western North America 30 million years ago. Tectonic reconstructions suggest that the subducting Farallon plate, once the major plate of the eastern Pacific Ocean, was consumed beneath the North American plate [Atwater and Stock, 1998]. On impact of the East Pacific Rise with North America, what became the southern edge of the descending oceanic plate margin has migrated northward along the San Andreas transform fault to its present location at the Mendocino triple junction [Atwater, 1970].

[3] The final stages of the purely convergent margin and the transition to a combination of subduction and strike-slip motion are expressed on the continent by magmatic and tectonic events that include the migrating silicic volcanism across most of the western U.S. in the Paleogene, known as the ignimbrite sweep [e.g., Lipman *et al.*, 1972], uplift and extension of Proterozoic crust of the central Basin and Range Province, and the Neogene large volume volcanism associated with the Columbia River and Snake River Plain

provinces. While the ignimbrite sweep is commonly interpreted as reflecting the transition from shallow- to normal-dip subduction [e.g., Lipman *et al.*, 1972], the cause of the continuing large-volume volcanism behind the shrinking Cascadia subduction system remains controversial. Beginning at ~17 Ma, over 200,000 km³ of Steens/Columbia River basalt was erupted near the Oregon-Washington-Idaho borders through terranes accreted along the western boundary of Precambrian North America [Camp and Ross, 2004]. Accompanying this volcanism near the Nevada-Oregon-Idaho borders were several large centers of silicic volcanism that by 12 Ma had developed into two geographically divergent, time-progressive tracks: (1) the Snake River Plain terminating at Yellowstone [Pierce and Morgan, 1992]; and (2) the High Lava Plains (HLP) of eastern Oregon terminating at Newberry Volcano [e.g., Jordan *et al.*, 2004]. The flood basalt and early ignimbrite activity have been widely interpreted to be the result of a plume impact at ~17 Ma [e.g., Camp and Ross, 2004; Jordan *et al.*, 2004; Xue and Allen, 2007], but models relating this, and the continuing volcanism along the tracks, to the evolving subduction system have also been developed [Christiansen and Lipman, 1972; Carlson and Hart, 1987; Humphreys *et al.*, 2000; Dickinson, 2002]. These different hypotheses for the late-Cenozoic tectonomagmatic evolution of the northwestern U.S. carry substantially different expectations for the structure of the mantle beneath this area. Constraining mantle structure through seismic imaging thus provides key evidence to help solve a decades-old debate of the relationship between continental volcanism/tectonism and the dynamics of the underlying mantle.

2. Data and Methods

[4] Broadband seismic data for our study come from the EarthScope/USArray Transportable Array (TA), the High Lava Plains seismic experiment [Carlson *et al.*, 2005], the CASC93 array [Li and Nábělek, 1999], and nearby stations from several regional networks for a total of 438 stations (Figure 1b). We briefly summarize the data analysis and inversion methodologies used here and provide a detailed description in the auxiliary material.¹ The analysis follows that developed by VanDecar [1991] with modifications presented in several studies including James *et al.* [2001]. In this method, we first determine very precise (~0.03 sec) relative P-wave delay times using a multi-channel cross correlation (MCCC) method [VanDecar, 1991]. The data are quality checked to assure that they are free of timing errors and records are visually inspected to eliminate cycle skipping. We evaluated waveform data from earthquakes

¹School of Earth and Space Exploration, Arizona State University, Tempe, Arizona, USA.

²Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC, USA.

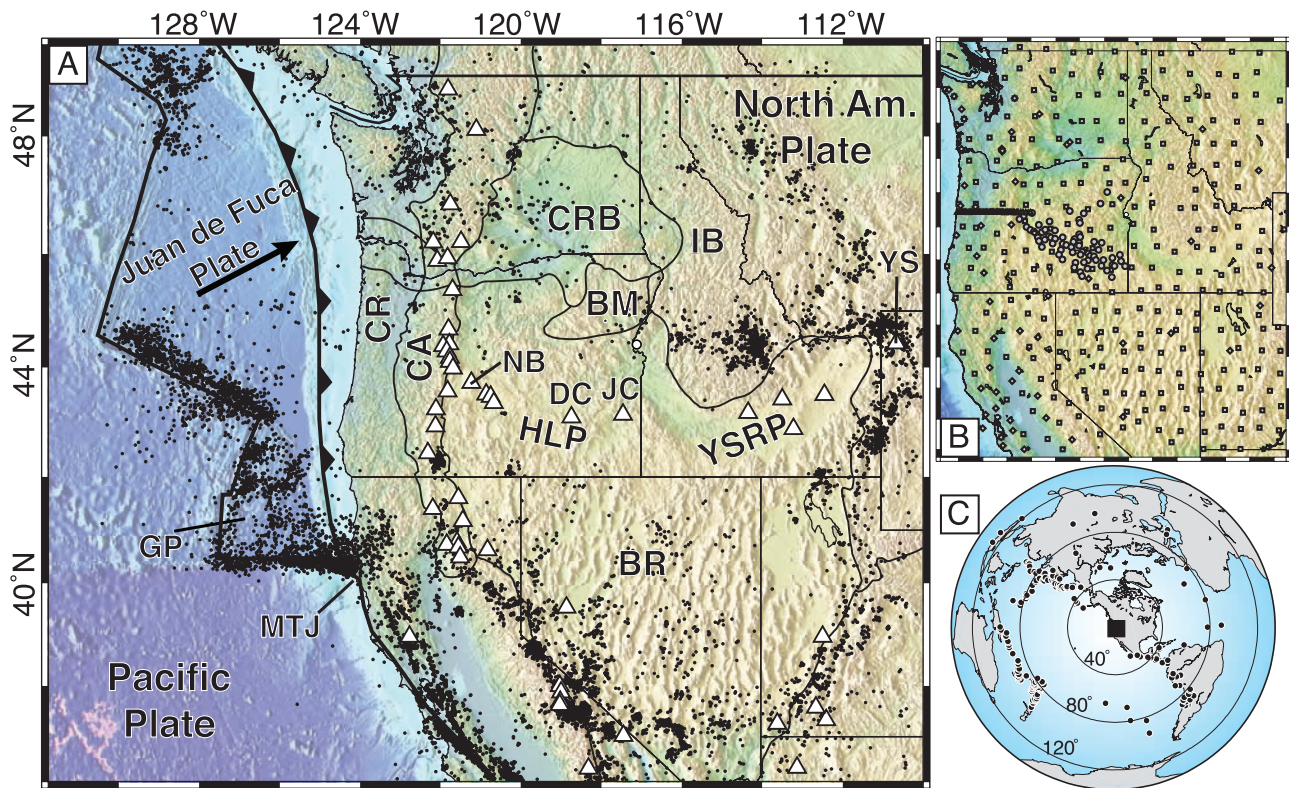


Figure 1. (a) Physiographic map of the northwestern United States indicating primary geologic features. Black dots denote historical earthquake hypocenters with $m_b \geq 4.0$, white triangles denote Holocene volcanoes including those of the Cascade arc (CA) and along the High Lava Plains (HLP) and Yellowstone-Snake River Plain (YSRP) volcanic provinces including the Newberry (NB), Diamond (DC) and Jordan Craters (JC) volcanoes along the HLP trace. BM = Blue Mtns; BR = Basin & Range; CR = Coast Range; CRB = Columbia River Basalts; GP = Gorda Plate; IB = Idaho Batholith; MTJ = Mendocino triple junction; YS = Yellowstone. (b) Locations of stations used in the inversion including stations from USArray Transportable Array (squares), High Lava Plains Seismic Experiment (circles), Cascadia Array (triangles), and other regional arrays (diamonds). (c) Locations of events used in the inversion (circles).

with $m_b \geq 6.0$ for a total of 17,870 high-quality delay times from 216 events (Figure 1c). The data are corrected for station elevation and inverted for station terms, earthquake relocations, and slowness perturbations. The three-dimensional image of seismic velocity perturbations is the minimum structure necessary to satisfy the data after the effects of local structure beneath the stations and earthquake mislocations are removed.

3. Results

[5] The results of our inversion (model NWUS08-P) provide new constraints on mantle structure beneath the northwestern U.S. (Figure 2). Below we describe key features of the model with special emphasis on the structure of the subducting plate and mantle wedge. We evaluate model resolution in the auxiliary material and note that these tests demonstrate that the features described below are well resolved. The major features in this model are also consistent with preliminary results from S-waves to be presented in a future paper.

3.1. Morphology and Continuity of the Descending Plate

[6] The subducting oceanic plate is clearly imaged across the study region and is characterized by a plane of increased

($\sim+2\%$) velocity perturbations with a $\sim 50^\circ$ eastward dip and a signal strength that varies laterally along the strike of the Cascades arc. While we observe shallow reduced ($\sim-1\%$) velocities beneath the Coast Range west of the Cascades, we find no evidence for strongly reduced slab (underside) velocities as recently suggested by *Xue and Allen* [2007]. To the south, the slab signal is truncated abruptly near the eastward projection of the Mendocino triple junction (Figures 2a and 2b). Within the upper mantle beneath southern Oregon and northern California, the slab signature is continuous to depths of at least 500 km. Beneath central and northern Oregon, however, the plane of slab-related high velocities appears to vanish at ~ 200 km depth (Figures 2b, 2d, and 2e). Resolution tests show clearly that this apparent “hole” in the slab is an inversion artifact produced by the presence of low velocity material above the slab and is a consequence of limited raypath coverage unavoidable in this region of the world.

3.2. Variations in Mantle Wedge Structure and Surrounding Regions

[7] We observe a broad zone of considerably reduced ($\sim-3.0-3.5\%$) velocities beneath central and northern Oregon in the mantle wedge above the slab (Figures 2a, 2b, 2d, and 2e). This prominent anomaly has two areas of concentrated low velocities, including a shallow zone be-

neath the Newberry volcanic field extending to ~200 km depth (Figures 2a and 2e), and a slightly deeper zone that appears NE of Newberry and extends to just S of the Columbia River Basin. Less strong reduced velocities extend NE well into the Columbia River Basin (Figures 2b and 2d), ending at ~350 km beneath the SW tip of the Blue Mountain province (Figure 2d). Reduced velocities also form an E–W trending zone across the entire High

Lava Plains to depths of ~200 km, including regions near Jordan and Diamond Craters, sites of recent basaltic volcanism, consistent with the surface wave results of *Warren et al.* [2008]. The broad regions of reduced velocities are coincident with the notable aseismicity across central and eastern Oregon. Consistent with previous studies [e.g., *Schutt and Humphreys, 2004*], we note a band of reduced velocities extending to depths of ~250 km beneath southern

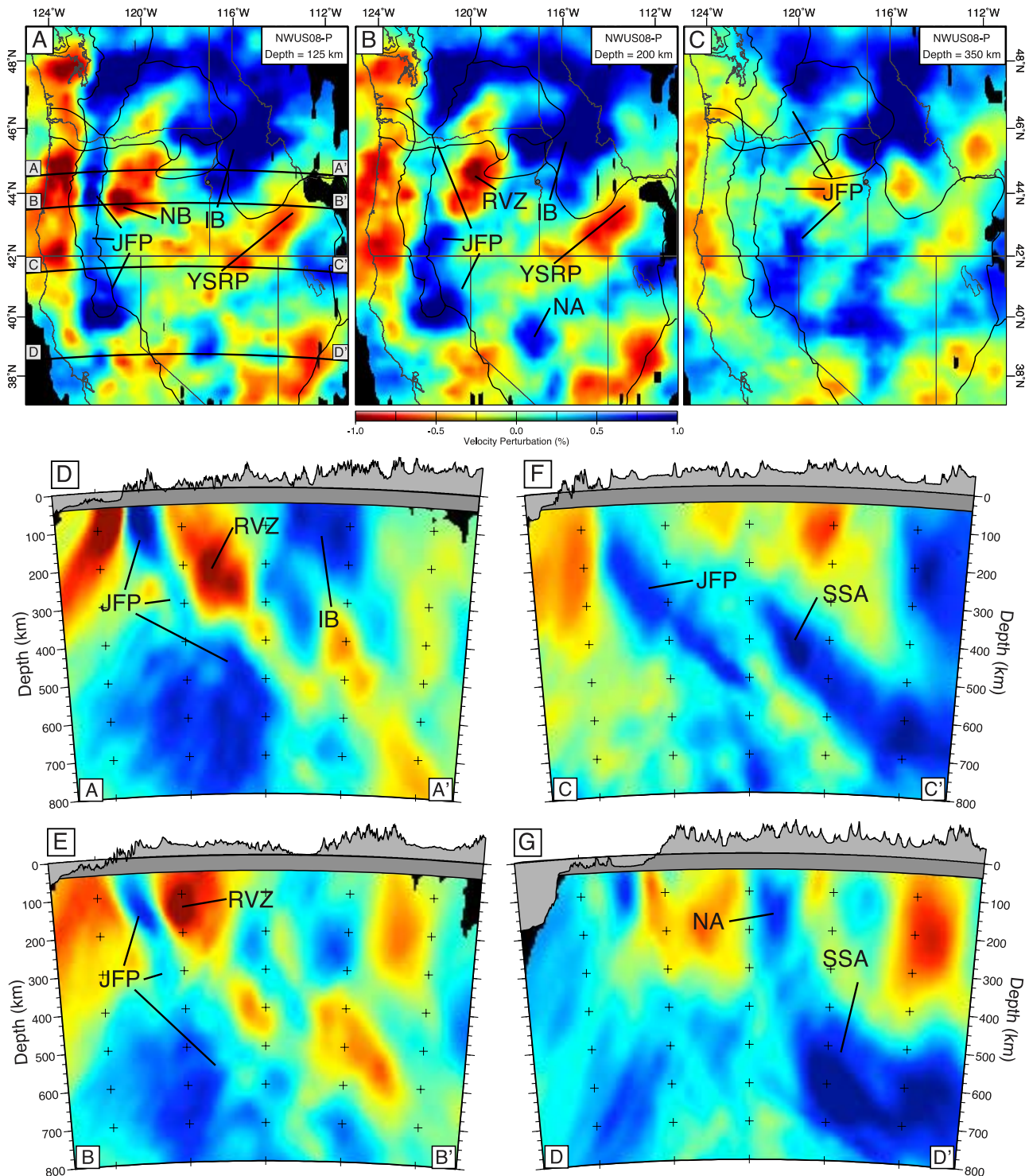


Figure 2

Idaho along the Snake River Plain hotspot track (Figures 2a and 2b).

[8] We observe increased ($\sim+2\%$) velocities beneath northeastern Oregon and into northern Idaho, underlying the Idaho Batholith and the Wallowa Mountain range near the margin of Precambrian North America. The region of increased velocities extends to depths of ~ 400 km, considerably greater than expected for continental lithosphere, and may at least partly be due to downward smearing, given the currently limited data coverage in the model for that region. We also observe a well-resolved prominent band of high velocities beneath northern Washington State, trending E–W from Cascadia into Precambrian North America.

3.3. “Nevada Cylinder” and Large Scale Structure in the Deeper Mantle

[9] We image an isolated, and well-resolved, cylindrical zone of increased velocities extending between ~ 100 and 300 km depth beneath central Nevada (Figures 2a, 2b, and 2g), but it does not connect directly to deeper increased velocities. We also observe an apparent offset in the slab at ~ 500 km depth near the southern terminus of the Juan-de-Fuca/Gorda plate, which appears as a plane of increased velocities parallel to the descending plate ~ 100 km to the east (Figure 2f). This slab-like feature continues along strike to the south and penetrates into the lower mantle to at least 700 km depth.

[10] We note that a recent global P-wave model by *Burdick et al.* [2008], which utilizes travel times hand-picked by analysts at both the International Seismic Centre (ISC) and the USArray Array Network Facility (ANF), exhibits many of the same features presented in this paper. In particular, the position and extent of the Juan de Fuca slab, the putative uppermost mantle “hole” in the slab beneath Oregon, the reduced velocities beneath the Yellowstone-Snake River Plain, and the increased velocity anomalies associated with the Idaho Batholith, are consistent with the strength and geographical extent of the anomalies published here. However, our model provides higher resolution in key regions of the northwestern United States both from the additional data from the CASC93 and HLP arrays and from the greater accuracy of the cross-correlation method for determining relative delay times, and reveals several important anomalies that have not been observed previously. For instance, the extremely reduced velocities we image beneath

the High Lava Plains and Newberry Volcano have important implications for the interpretation of the “hole” in the Juan de Fuca slab. Similarly, the discovery of the high-velocity column beneath central Nevada has important implications for upper mantle dynamics, as discussed by J. D. West et al. (Geophysical detection of lithospheric delamination beneath the Great Basin, submitted to *Science* 2008).

4. Tectonomagmatic Interpretation

[11] We frame the discussion of these tomographic images around the broad outlines of post-Laramide tectonics, with particular emphasis on the dynamic nature of a rapidly evolving subduction system. We recognize the difficulty of placing current-day structures in the context of the migrating geodynamic processes that have driven the tectonomagmatic evolution of the western U.S. We therefore focus on the relationship between Juan de Fuca subduction, Columbia River/Steens Mountain flood volcanism, and the Yellowstone-Snake River Plain and HLP/Newberry migrating volcanic trends.

4.1. Subducting Juan de Fuca/Gorda Slab

[12] The lateral continuity of the subducting plate has been a topic of significant debate and has fundamental implications for interpreting models of regional intraplate tectonomagmatism. For example, in order for a plume to supply the flood basalt volcanism at 17 Ma, it would have to have penetrated, and presumably severely disrupted, the slab that was present beneath eastern Oregon at this time. Previous studies have reported suggestions of a “hole” or “break” in the descending slab beneath central Oregon [e.g., *Michaelson and Weaver*, 1986]. As we demonstrate through tests with synthetic models, the inversion would produce a structural artifact (a slab “hole”), even for a continuously intact slab. We therefore conclude that while the dip of the slab varies somewhat along strike, there is no evidence for significant slab disruption at shallow (<200 km) depths beneath central Oregon.

[13] Figure 2f exhibits what appears to be a slab-like object, sub-parallel to and E of the downgoing plate, similar to structures in S-wave velocity model NA00 [*van der Lee*, 2002], and raises the possibility of slab break and enechelon subduction. If so, and if the break is associated with near-surface reorganization of subduction, at the current convergence rate of ~ 40 mm/yr [*Gripp and Gordon*,

Figure 2. Cross sectional slices (horizontal and vertical) through tomographic model NWUS08-P. Warm colors represent regions of reduced velocities; cool colors represent regions of increased velocities. Cells with 5 rays or fewer are indicated by black. Note that while the color range extends to $\pm 1\%$, there are anomalies beyond those values that are saturated in the figure. Top row: horizontal slices at depths of (a) 125 km, (b) 200 km, and (c) 350 km. Labeled lines in Figure 2a represent the locations of cross sections presented in Figures 2d–2g. The Juan de Fuca plate (JFP) is evident as a N–S trending band of relatively high velocities paralleling the coast in all panels. In Figure 2a, reduced velocities exist beneath Newberry (NB) and the Yellowstone-Snake River Plain (YSRP). Increased velocities are evident across N Washington State and beneath the Idaho Batholith (IB). In Figure 2b the slab signature is muted in the vicinity of the reduced velocity zone (RVZ) beneath the Newberry region. Both the descending plate and the reduced velocity zone are still evident at 200 km depth, as is the cylindrical increased velocity Nevada anomaly (NA). (d–g) Vertical (cross section) slices through model NWUS08-P. $40\times$ vertically exaggerated topography is plotted for each section; top 50 km is not shown due to lack of resolution at shallow depths. Crosses are plotted every 100 km in depth and 2° in radial distance. Figures 2d and 2e show that the apparent disruption in the descending slab is paired with reduced velocities above the slab in the mantle wedge. In Figure 2f the slab appears to be detached at ~ 500 km depth, with a secondary, slab-like anomaly (SSA) extending to >700 km depth. In Figure 2g, subducting slab terminates at these latitudes; Nevada anomaly and SSA are clearly evident.

2002] this break would have occurred at $\sim 16\text{--}17$ Ma, coincident with flood basalt activity in this area. While the slab-like feature is not continuous along strike in our model, perhaps due to a lack of ray coverage, it remains possible that a small section of slab has detached, presumably in response to rapid plate restructuring and ridge subduction. Alternatively, this break could be associated with the now subducted portion of the Surveyor Fracture Zone [Severinghaus and Atwater, 1990], suggesting that fracture zones may serve as plate weaknesses facilitating dismemberment during subduction.

4.2. Reduced Velocity Zones Beneath Newberry and the Columbia River Basalts

[14] Newberry volcano often is highlighted as the western terminus of the northwestward propagating High Lava Plains volcanic lineament and is characterized by bimodal basalt and rhyolitic volcanism more typical of the HLP than the Cascades. Yet Newberry basalts carry a geochemical signature of a mantle source strongly influenced by subducted slab-derived fluids [Carlson *et al.*, 2008], a characteristic it shares with Cascade magmas. The strength of the reduced velocity anomaly beneath Newberry might be explained by the presence of melt, perhaps concentrated in this area due to the release of fluids from the downgoing slab that results in partial melting of the hotter asthenospheric mantle beneath the High Lava Plains.

[15] The broad region of reduced velocities extends to the NE of Newberry beneath the western edge of the Blue Mountains and continues beneath the thick sections of Columbia River basalts in south-central Washington. This is one of the more unexpected features of our tomographic imaging, as its location does not correlate directly either with the eruptive centers of the Columbia River basalts, with the High Lava Plains volcanic trend, or with areas of active Quaternary volcanism. There is almost certainly a strong thermal component to the strong and well localized seismic anomaly, but its position and shape does not obviously match predictions from plume outflow models for volcanism in this area [e.g., Camp and Ross, 2004].

4.3. Precambrian North America

[16] We observe a prominent, regionally extensive, increased velocity anomaly that trends $\sim E\text{--}W$ across the northern part of Washington state and bends down along the western boundary of northern Idaho. The higher velocities follow roughly a geographic outline consistent with the western edge of Precambrian North America as indicated by a zone in which the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios of Mesozoic and Cenozoic igneous rocks rapidly increase from west to east [Armstrong *et al.*, 1977]. We note that the abrupt transition from lower to higher velocities in the vicinity of the Wallowa Mountains of NE Oregon, recently interpreted as a region of lithospheric delamination [Hales *et al.*, 2005], actually coincides with the western edge of a much larger-scale feature extending eastward from the Wallowa Mountains across into the Idaho Batholith. While this description of the high velocity perturbation anomaly is consistent with much of what is known from surface geology, the images at depth are less interpretable if this anomaly actually extends to depths of 400 km, but this portion of the image likely suffers from some amount of smearing at present.

[17] The Yellowstone-Snake River Plain reduced velocity anomaly lies within Precambrian lithosphere and is a linear feature that exhibits little variation in strength with distance from Yellowstone, and terminates near 250 km depth. The relatively constant velocity contrast in the underlying upper mantle is consistent with pervasive and long-lived basaltic volcanism observed along the length of eastern Snake River Plain and perhaps contrary to what might be expected of a plume tail track. Moreover, at shallow mantle depths, the lower velocities associated with the eastern Snake River Plain are contiguous and parallel to a band of somewhat reduced velocities that extend southwestward to the Mendocino triple junction. As that track also coincides with the edge of the descending slab based on angles of plate convergence, it remains an open question as to whether the Snake River Plain magmatism is the result of absolute lithospheric plate motion over a hotspot, or perhaps the result of ascending mantle flowing around the southern edge of the descending Gorda/Juan de Fuca plate.

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- R. W. Carlson and D. E. James, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015-1305, USA.
- M. J. Fouch and J. B. Roth, School of Earth and Space Exploration, Arizona State University, P.O. Box 871404, Tempe, AZ 85287-1404, USA. (jeffrey.roth@asu.edu)