Seismically imaged relict slab from the 55 Ma Siletzia accretion to the northwest United States

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ABSTRACT

Teleseismic tomography images a large high-velocity "curtain" extending vertically beneath the ca. 50 Ma Challis magmatic trend to maximum depths of 230–600 km. We interpret this structure as subducted Farallon ocean lithosphere that stalled with the ca. 55 Ma accretion of the Siletzia microplate to North America within the Columbia Embayment, and we consider the regional tectonic implications. The abrupt switch ca. 53 Ma from Laramide thrusting and magmatic quiescence to extension and vigorous magmatism in the northwestern United States is evidence for foundering of the flat-subducting Farallon slab. To account for the imaged curtain, foundering apparently occurred by rollback after Siletzia accretion terminated subduction within the Columbia Embayment. The magnitude of the high seismic velocity curtain is approximately that expected for 20–50 m.y. old ocean lithosphere that stalled in the upper mantle ca. 50 Ma. We suggest that the stalled slab became nearly neutrally buoyant as a result of removal of its basaltic crust, the melting of which likely contributed to the short-lived vigor of Challis magmatism. After Siletzia accretion, normal dip Cascadia subduction initiated west of Siletzia, evidenced by arc volcanism in Oregon and Washington beginning ca. 45–40 Ma, while continued quiescence of the Sierra Nevada arc suggests persistence of flat subduction to the south. Kinematically, this requires a tear in the subducted Farallon slab near the latitude of southern Oregon. We propose that north to south propagation of this torn slab edge propagated the ignimbrite flare-up across what now is the northern Basin and Range and ended the Laramide orogeny.

INTRODUCTION

New western United States seismic images enabled by EarthScope's USArray provide for the first time high-resolution information on upper mantle structure over a large area of continent. In this paper we discuss the Pacific Northwest portion of our recent tomographic models (Schmandt and Humphreys, 2010a) to focus on a prominent but previously unresolved "curtain" of high-velocity mantle extending vertically from beneath central Idaho to near the eastern edge of the Cascades in northern Washington and extending down to depths of 230–600 km (Figs. 1 and 2). The only plausible explanation for this large volume of high-velocity mantle is recently subducted ocean lithosphere. We address here the seismic, tectonic, and magmatic evidence that this structure is subducted Farallon slab abandoned in the upper mantle during the ca. 55 Ma accretion of Siletzia, which we define as the fragment of Farallon lithosphere that filled the Columbia Embayment in the Eocene. We then consider the seismic and geodynamic plausibility that ocean lithosphere subducted in the early Cenozoic did not lose its seismic contrast or sink into the Earth. We then discuss the implications of this structure for early Cenozoic tectonic evolution of the western United States.

PACIFIC NORTHWEST TOMOGRAPHY

We created high-resolution P-wave (V_P) and S-wave (V_S) images of the upper mantle beneath the western United States by inverting 248,000 P and 84,000 S relative traveltime residuals of teleseismic earthquakes observed by USArray and more than 1700 additional stations (Schmandt and Humphreys, 2010a). The inversion uses recent advances in western U.S. crust models (Yang et al., 2008; Gilbert and Flesch, 2009) to better isolate the mantle component of residual times and three-dimensional frequency-dependent sensitivity kernels to map residuals (measured in multiple frequency bands) into velocity structure. Horizontal node spacing is 40 km within the footprint of the USArray, and vertical node spacing increases gradually with depth from 30 km at 60–90 km depth, to 65 km at >820 km depth. The method was described in detail in Schmandt and Humphreys (2010b). Resolution tests demonstrate excellent recovery of structures with length scales ≥70 km, with typical peak amplitude recovery of 70%–80% for V_P and 60%–70% for V_S (Fig. DR1 in the GSA Data Repository[1]). V_P resolution is slightly better than V_S resolution in the Pacific Northwest as a result of 150 additional short-period stations (Fig. 1), a greater number of high-quality teleseismic P arrivals, and shorter wavelength sampling of teleseismic P arrivals.

Figures 1 and 2 show three distinctive high-velocity structures beneath the Pacific Northwest. A prominent, relatively small and approximately elliptical body is imaged below the source area of the Columbia River flood basalts in northeast Oregon (Fig. DR2). This structure may owe its creation to basalt depletion or lithospheric delamination (Hales et al., 2005). A second high-velocity feature is the slab-like structure beneath the Cascade Arc, which must be the steeply dipping subducted Juan de Fuca slab. The subject of this paper is the high-velocity curtain extending vertically from the base of North America lithosphere to depths of ~230 km beneath eastern Washington and 450–600 km beneath northern Idaho and westernmost Montana (Figs. 1 and 2). Several recent tomography studies using USArray data found a large volume of vertically elongated high-velocity mantle in this region (e.g., Roth et al., 2008; Sigloch et al., 2008; Burdick et al., 2009; Tian et al., 2009; Xue and Allen, 2010), although not

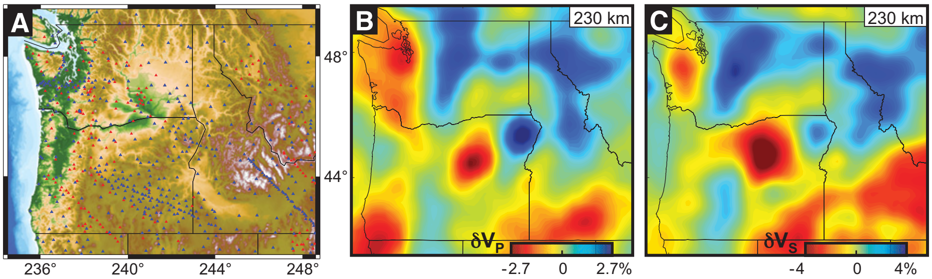

Figure 1. A: Regional topography and stations used in our study. Blue indicates stations used for P and S data; red indicates short-period stations used only for P data. Backarc area underlain by Siletzia is well approximated by low-lying Columbia basin (see Fig. 2). B: P-wave velocity variations. C: S-wave velocity variations.

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[1] GSA Data Repository item 2011073, supplemental figures, 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.

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as a feature distinct from the smaller anomaly beneath northeast Oregon. Our better resolution in this area is a result of data from 30 stations in the Wallowa Mountains array. Based on the excellent recovery of input structure in synthetic tests (Fig. DR1), we consider the high-velocity curtain and its separation from the Wallowa Mountains anomaly to be robust features. The maximum depth of the curtain being in the transition zone beneath northern Idaho is supported by receiver function results indicating a spatially correlated upward deflection of the 410 km discontinuity and no strong deflection of the 660 km discontinuity (Eagar et al., 2010).

VOLCANIC AND TECTONIC CONTEXT

Prior to the Laramide orogeny, subduction of Farallon ocean lithosphere beneath western North America generated arc magmatism along the entire plate margin. In the Pacific Northwest of the United States, magmatism was concentrated in the Idaho batholith (Giorgis et al., 2005), with this inboard setting related to subduction beneath the northeast margin of the Columbia Embayment (Fig. 2C). Starting ca. 80 Ma, magmatism in the Idaho batholith lost most of its mantle geochemical signature and became increasingly lower crustal in composition and decreasingly active, finally becoming amagmatic at 54 Ma (Fig. 2A; Gaschnig et al., 2009). This commonly is attributed to Farallon slab flattening against the base of North America (Feeley, 2003), similar to accountings for Laramide-age magmatic quiescence to the south (Coney and Reynolds, 1977). The magmatic lull coincided with Laramide thrusting in the Rocky Mountains of the United States and Canada that continued until ca. 53 Ma in Montana (van der Pluijm et al., 2006). The Laramide-style episode was followed by a magmatic flare-up, starting ca. 55 Ma in southern British Columbia (Gehrels et al., 2009) and ca. 52 Ma in the United States (Gaschnig et al., 2009), with the initiation of compositionally and isotopically diverse (Madsen et al., 2006) Challis-trend magmatism and associated core-complex extension (Foster et al., 2007). Siletzia ocean lithosphere accreted to North America within the Columbia Embayment about that time, necessitating initiation of Cascadia subduction on the west side of Siletzia (Fig. 2C) (Wells et al., 1984).

The sudden onset of intense, geochemically diverse, and relatively alkalic magmas, including adakites, led Breitsprecher et al. (2003) and Madsen et al. (2006) to attribute this activity to asthenospheric upwelling through a Kula-Farallon slab window, incorporating slab crust in the process. We attribute this magmatism to asthenospheric upwelling as the flat-subducting Farallon slab fell away from the base of North America (Feeley, 2003; Coney and Reynolds, 1977). This phase of magmatism ended in British Columbia ca. 48 Ma (Gehrels et al., 2009) and Challis magmatism waned 48–45 Ma (Gaschnig et al., 2009). Subsequently, magmatism swept west across Oregon (the Clarno volcanics, ca. 45–40 Ma; Retallack et al., 2000) and the Cascade arc initiated ca. 45–40 Ma (Fig. 2A; Christiansen and Yeats, 1992) as a response to outward stepping of subduction required by Siletzia accretion.

This geologic record supports a history in which Farallon slab subducted flat against North America during the Laramide and fell away shortly after Siletzia accretion, at the time of Challis magmatism. We suggest that the imaged curtain is Farallon slab that fell away from basal North America ca. 50 Ma, still present beneath an area roughly coincident with Challis magmatism.

PHYSICAL ORIGIN OF THE SILETZIA CURTAIN

Seismically fast upper mantle may be attributed to subducted ocean lithosphere, thick continental lithosphere, or small-scale convective downwelling or delamination of continental lithosphere (Bird, 1979). The imaged high-velocity curtain extends below a belt of Cretaceous plutons and Cenozoic core complexes, where lithosphere is expected to be thin, and convective removal of basal lithosphere could not create an anomalous volume as large as that imaged. We infer that the imaged curtain must be subducted ocean lithosphere, an idea supported by its slab-like form and location near where the last subducted slab would have been in this area.

We calculate the seismic structure expected for stalled ocean lithosphere to evaluate this idea. The age of the Farallon plate upon subduction in the Columbia Embayment is ≤55 m.y. (Müller et al., 2008). Using the thermal parameters of van Keken et al. (2002), we represent a reasonable range of possibilities by calculating the thermal structure for ocean lithosphere of two ages (20 and 50 m.y.) and then letting these evolve conductively in asthenosphere for 50 m.y. The older slab is 350 °C cooler than the asthenosphere across its core (50 km width) and has a width of 180 km (at 50 °C cooler than asthenosphere); the younger slab is 250 °C cooler than asthenosphere and has a width of 160 km. Assuming mean upper-mantle shear quality factor, $Q_{S,}$ = 100 (Dalton et al., 2008), these core temperatures predict core seismic anomalies δV_P = 2.3%–3.3% and δV_S = 3.8%–5.3% (Karato, 1993). For structures 150–200 km wide, our P and S models recover ~80% and ~70% of the actual amplitudes. Hence, we expect the thermal anomaly of our modeled slabs would be imaged as seismic anomalies of δV_P = 1.8%–2.6% and δV_S = 2.7%–3.7%. This compares well with our observed core seismic anomalies of δV_P = 1.5%–2.5% and δV_S = 2.5%–4.0%.

Other factors contributing to the expected seismic contrast of the slab with the asthenosphere include effects caused by dehydration upon formation of lithosphere at the spreading center and seismic anisotropy, although we have little knowledge about either of these properties. For the effects of water, if we assume a 50 km thickness of dehydrated slab to be seismically faster by an amount equivalent to temperature decrease of 100 °C (Karato, 2003), it can increase the expected imaged velocities by δV_P = 0.6% and δV_S = 1.0%. If ocean lithosphere anisotropy is preserved upon subduction and the fast axis is oriented downdip, teleseismic P and S waves would be advanced in the curtain and predicted velocity anomalies would be even larger. However, local SKS splitting suggests a fast axis generally in the horizontal plane (Liu, 2009). We conclude that the seismic magnitude of the Siletzia curtain is within the expected range for slab that stalled ~50 m.y. ago.

If the imaged curtain is stalled ocean lithosphere, any of its crust that was not underaccreted to North America during flat subduction would warm quickly after stalling and melt. The loss of what would have become an eclogitic crust would eliminate most of the slab's negative buoyancy (Cloos, 1993), helping to explain why the slab has not sunk. Melting of either underaccreted or still-attached slab crust is consistent with the vigor and diversity of Challis magmatism, and a contribution from melting of oceanic crust has been suggested (e.g., Madsen et al., 2006).

The vertical orientation of the curtain 50 m.y. after it stalled in the upper mantle may be explained by locally stagnant flow owing to its location near the transition from westward flow of asthenosphere into the mantle wedge beneath Oregon (Long et al., 2009) and Washington to northeastward flow of asthenosphere beneath the continental interior (Humphreys et al., 2000).

DISCUSSION

We propose a model for Siletzia accretion (Fig. 2D) that is consistent with both Pacific Northwest tectonic and magmatic history and our tomography. The explanation prior to our upper mantle imaging invoked end-on subduction of the Kula-Farallon spreading center, creating a slab window that caused asthenospheric upwelling and melting of slab crust (Breitsprecher et al., 2003). This model appears inconsistent with the location of the imaged mantle curtain and does not account for the preceding magmatic lull. We propose an alternative history that involves rollback of flat-subducting Farallon slab following Siletzia accretion, which ascribes magmatism to asthenospheric flow into the opening mantle wedge and to melting of the stalled Farallon slab crust. Pre-accretion mag-

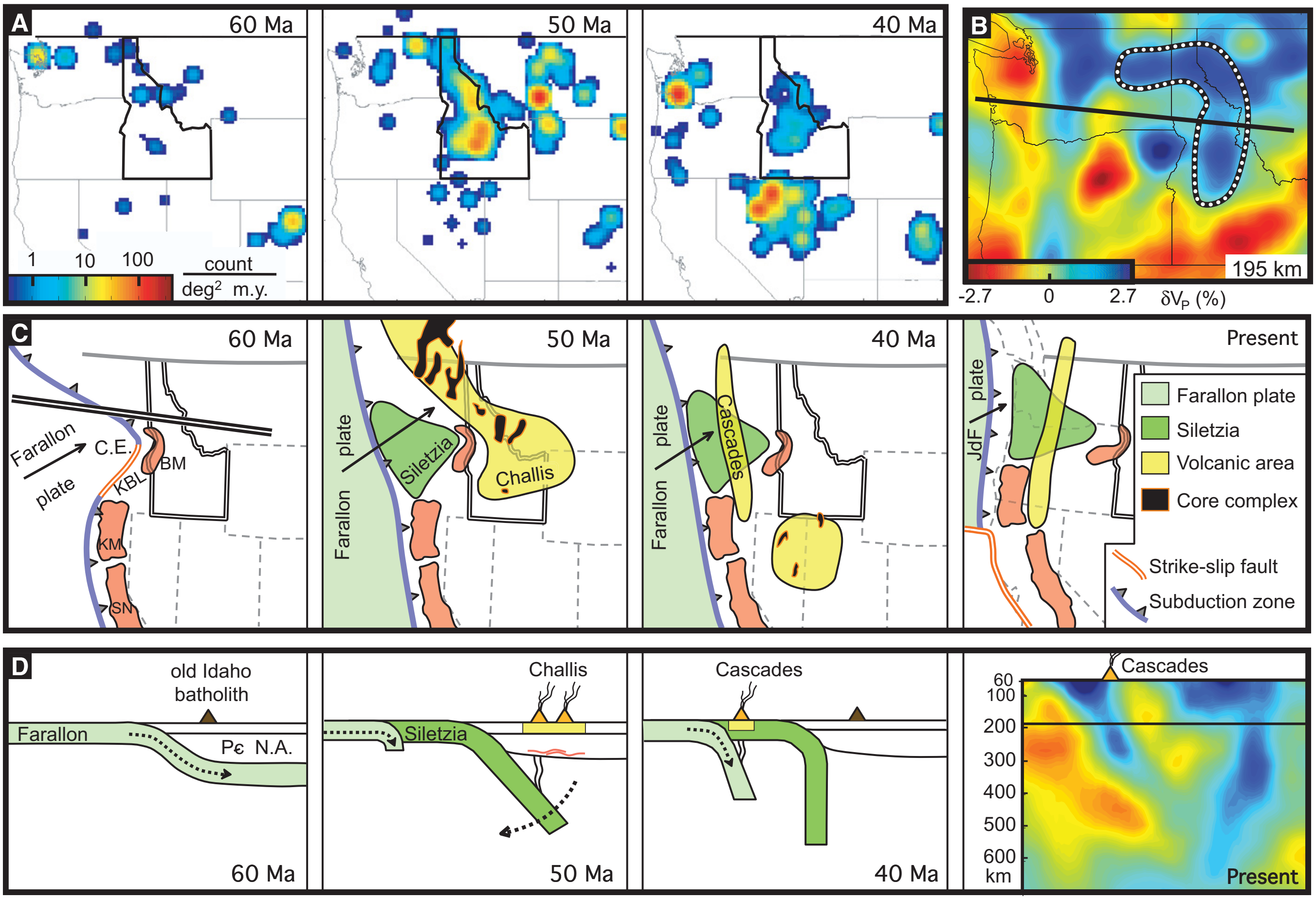

Figure 2. Maps and cross sections of northwestern United States at 60, 50, 40, and 0 Ma. Border of Idaho is highlighted. A: Maps showing density of reported dated igneous rocks from NAVDAT (North American volcanic and intrusive rock database; Walker et al., 2004). Data are binned in time and space (age data distributed equally over reported range, and age uncertainty >10 m.y. rejected). Results are smoothed over 50 km in space and 1 m.y. in time. Large dynamic range requires log scale and indicates variations between lulls and flare-ups. B: P-wave tomography, emphasizing correlation between imaged curtain and Challis magmatism. Dotted line—Siletzia curtain outline. Dark line—location of cross-section A–A′. C: Maps illustrating regional tectonic and magmatic evolution, modified after Dickinson (2006). Intact and coherent units defined by presence of Mesozoic to Cretaceous plutons and associated arc-related rocks are shown in pink; Klamath Mountains (KM), Blue Mountains (BM), and Sierra Nevada (SN). Prior to accretion, 60 Ma, Klamath–Blue Mountains lineament (KBL) is shown as transform boundary (Riddihough et al., 1986). At 60 Ma Farallon plate subducted to northeast in Columbia Embayment (C.E.). Siletzia accreted and subduction stepped west ca. 55–53 Ma, and by 50 Ma Challis magmatism was strong (JdF—Juan de Fuca). D: Cross sections (along B–B′ shown in C, left panel) show our interpretation of subduction history. At 60 Ma, Farallon slab subducts flat against Precambrian (Pє) North America (N.A.). Then, shortly after Siletzia accretion (50 Ma), Cascadia subduction initiates and abandoned, previously flat Farallon slab rolls back, exposing basal North America and Farallon crust to inflowing asthenosphere, causing melting. Event is over by 40 Ma, and little has changed to present, represented by tomography cross section, A–A′.

matic quiescence and the thrusting of basement-cored uplifts in Montana prior to ca. 53 Ma are attributed to flat subduction. Rapid ca. 53 Ma initiation of magmatism and extension is attributed to a rollback-like foundering of ocean lithosphere (Feeley, 2003), and we infer that Siletzia accretion within the Columbia Embayment preceded slab foundering, ca. 55 Ma. In this context, Challis-trend magmatism is thought to result from asthenospheric inflow, decompression melting, and heating of the hydrated base of North America lithosphere, likely accompanied by melting of oceanic crust. Sudden initiation of core complexes is attributed to gravitational collapse of a preexisting crustal welt (Coney and Harms, 1984), enabled by cessation of the compression created by flat subduction and seamount collision, and by subduction initiation at Cascadia (Fig. 2C) creating extensional stresses (Gurnis, 1992). The modern Pacific Northwest tectonic configuration was largely established by 40 Ma (Fig. 2D).

Siletzia accretion and creation of a normal-dip subduction zone at Cascadia must have torn the Pacific Northwest slab to separate it from the adjacent southern portion of flat-subducting slab responsible the continued quiescence of the Sierra Nevada arc and the ongoing Laramide orogeny. Following accretion, the ignimbrite flare-up propagated north to south across the Great Basin (ca. 45–21 Ma) (Fig. 2C); we attribute this to north to south retreat of the northern margin of the flat slab (Humphreys, 1995). Hence, Siletzia accretion appears to have triggered the northern sweep of the ignimbrite flare-up and perhaps the end of the Laramide orogeny. Abandonment of ocean lithosphere beneath continental margins during subduction termination may not be a rare occurrence; recent studies find relict slab beneath Baja California (Zhang et al., 2009; Wang et al., 2009). If not unusual, such events may be important for understanding diversity in convergent margin volcanism and the fate of subducted slabs.

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