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Slab-plume interaction beneath the Pacific Northwest

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[1] The Pacific Northwest has undergone complex plate reorganization and intense tectono-volcanic activity to the east during the Cenozoic (last 65 Ma). Here we show new high-resolution tomographic images obtained using shear and compressional data from the ongoing USArray deployment that demonstrate first that there is a continuous, whole-mantle plume beneath the Yellowstone Snake River Plain (YSRP) and second, that the subducting Juan de Fuca (JdF) slab is fragmented and even absent beneath Oregon. The analysis of the geometry of our tomographic models suggests that the arrival and emplacement of the large Yellowstone plume had a substantial impact on the nearby Cascadia subduction zone, promoting the tearing and weakening of the JdF slab. This interpretation also explains several intriguing geophysical properties of the Cascadia trench that contrast with most other subduction zones, such as the absence of deep seismicity and the trench-normal fast direction of mantle anisotropy. The DNA velocity models are available for download and slicing at http://dna.berkeley.edu.

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1. Introduction

[2] The Pacific Northwest of western North America is unusual in that both a subducting slab and a hotspot occur within ~1000 km of one another. Globally, these geologic components are commonly separated into distinct provinces [*Davaille et al.*, 2005]. The Juan de Fuca plate that continues to subduct today (Figure 1) is a remnant corner of the Farallon plate and is terminated to the south by the Mendocino Triple Junction (MTJ). Subduction beneath the Pacific Northwest has been continuous for more than ~150 Ma [*Severinghaus and Atwater*, 1990; *Bunge and Grand*, 2000]. The westernmost US exhibits several major Neogene to Quaternary volcanic provinces. The Columbia River Basalts (CRB, Figure 1) is the product of a phase of massive volcanic outpouring that occurred ~17 Ma. The Yellowstone Snake River Plain (YSRP) hosts a bimodal volcanic trend that exhibits a time progressive sequence of volcanic centers (Figure 1). Two groups of hypotheses have been proposed to explain this surface geology: a stationary deep-seated whole mantle plume [*Morgan*, 1971; *Pierce and Morgan*, 1992; *Pierce et al.*, 2000; *Camp and Ross*, 2004; *Waite et al.*, 2006; *Smith et al.* 2009], or various lithospheric-driven processes of fracture and volcanism [*Dickinson*, 1997; *Humphreys et al.*, 2000; *Christiansen et al.*, 2002]. Nevertheless, seismic imaging efforts to constrain the geometry of any Yellowstone plume anomaly through the mantle have been inconclusive. Here we take advantage of the Yellowstone region being now well covered by the dense USAarray deployment to provide constraints on the source of the hotspot, the process of subduction, and the inevitable interaction between the two in the mantle beneath the Pacific Northwest.

2. Data and Method

[3] To image the earth's interior beneath the Pacific Northwest, we use all of the available Earthscope-USArray data recorded from January 2006 to July 2009 (Figure S1 of the auxiliary material).[4] The station coverage extends from the west coast to ~100°W and from the Mexican to the Canadian boarder. We also processed the data from two Earthscope temporary arrays (FACES and Mendocino Experiment) deployed along the Cascadia trench and permanent seismic networks in the western US, enhancing the resolution achieved for this region. The velocity structure of the mantle is retrieved through body wave finite frequency tomographic inversion. The dataset of our multi-frequency compressional model DNA09-P is derived from 58,670 traveltimes of direct P from 127 earthquakes measured in four frequency bands. The dataset used for our shear model DNA09-S includes 38,750 travel-time measurements, 34,850 S-wave observations from 142 events and 3,900 SKS observations from 24 events (see auxiliary material).

3. Results

[4] The structures displayed in our P- and S-wave models are consistent despite the difference in the wavelengths of the signals used (Figure S2). Checkerboard resolution tests show good recovery beneath the seismic array to a depth of 1200 km (Figures S3–S6) and we also performed specifically designed resolution tests to demonstrate the robustness of the features described below (Figures S7–S10). Aside from specific cases discussed in the next sections, our two models are in good agreement (see auxiliary material) with previous USAarray based models [*Roth et al.*, 2008; *Sigloch et al.*, 2008; *Burdick et al.*, 2009].

3.1. Juan de Fuca Slab

[5] The north-south elongated fast anomaly associated with the JdF slab is clearly imaged in our P- and S-wave models (Figures 2a and S2). At 200 km depth, its signature is strong (up to 2%) in Northern California and Washington, and weak in Oregon (less than 1%). The strong-to-weak fast

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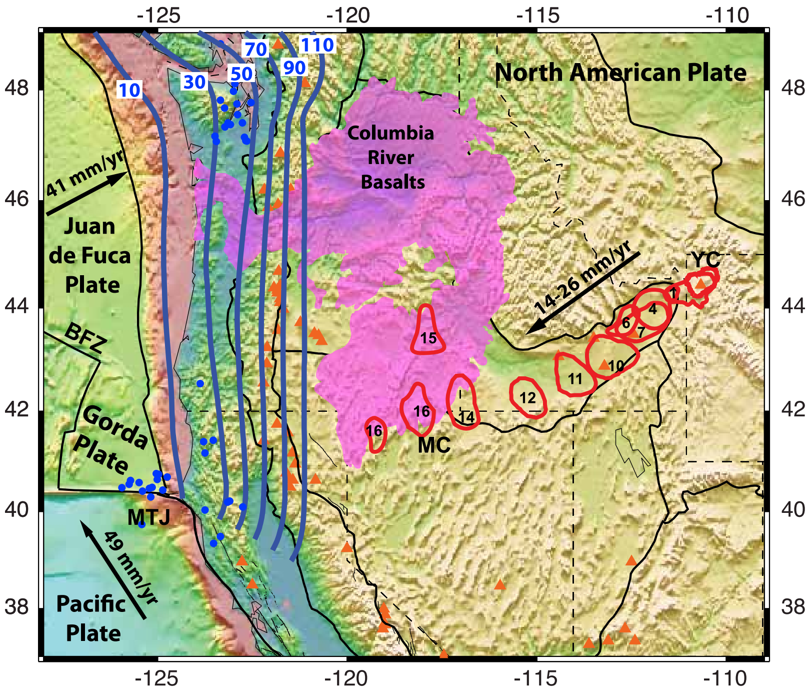

Figure 1. Geologic-tectonic features of the Pacific Northwest of the United States overlaid on topography and bathymetry. North from the Mendocino Triple Junction (MTJ), the Gorda and JdF plates, separated by the Blanco Fracture Zone (BFZ), are subducting beneath the North American plate with an oblique convergence rate of 41 mm/yr. The estimated depth of the top of subducting slab is shown with blue contours labelled in km. The location of all M > 4 earthquakes with depth ≥35 km since 1970 are shown as blue dots. Volcanoes are shown as orange triangles. The Yellowstone Hotspot Track exhibits a series of time-progressive regions of caldera-forming eruptions (red outline) from McDermitt (MC) to the currently active Yellowstone Caldera (YC). The track is approximately parallel to the absolute plate motion of North America, which is estimated to be 14–26 mm/yr to the southwest. Numbers indicate the age of the calderas (in Ma). The Columbia River Flood Basalt Province was a massive outpouring of basalt from ~16.6 to ~15.0 Ma and is shown in pink [*Camp and Ross*, 2004].

anomaly transition in southern Cascadia coincides with the Blanco Fracture Zone that divides the Gorda and JdF sections of the slab (Figures 1 and 2a). Figures 2 and 3 show that the slab is surprisingly short compared to the several thousand kilometers of slab we would expect to observe considering the 150 Ma long history of Farallon-JdF subduction. The slab extends to only 300 km depth beneath Oregon (Figures 2h and S7). The Gorda section of the slab is continuously imaged to greater depths around 600 km (Figure 2i). East of the Gorda slab, our model shows several fast features with amplitudes comparable to that of the Gorda slab (Figures 2i and S8, “F1” and “F2” in Figure 3). The shallow part of the fast feature immediately east of the Gorda slab and with a similar dip (Figure 2i, “F1” in Figure 3) was previously interpreted as lithospheric drip [*West et al.*, 2009]. The more horizontal fast anomaly further east (F2, Figures 2h, 2i, and 3f) has been previously imaged and interpreted as the Farallon plate foundering in the mid-mantle [*Sigloch et al.*, 2008]. Regionally, similar fast anomalies are not observed south of the southern boundary of the Gorda plate, i.e. south of ~38°N and the MTJ (Figures 2a and S2). We therefore interpret the fast bodies east of the presently subducting Gorda-JdF slab (anomalies F1 and F2) as possible fragments of the Farallon-JdF slab.

3.2. Yellowstone Anomaly

[6] The YSRP is underlain by an elongated northeast-southwest oriented low velocity anomaly (Figure 2a) that extends as deep as 300 km (Figures 2d–2g). The shallow anomaly is connected to an elongated low velocity body that extends continuously downward to a depth of 900 km (Figures S9 and S10). This observation contrasts with previous large-scale models [*Sigloch et al.*, 2008; *Burdick et al.*, 2009] for which no slow material is imaged in the transition zone. However, it is consistent with regional models in which the slow anomaly is continuously observed down to ~660 km where resolution is lost due to the limited aperture of the arrays [*Waite et al.*, 2006; *Yuan and Dueker*, 2005; *Smith et al.*, 2009]. The low-velocity anomaly dips to the northwest in the upper 400 km and to the southeast from 400 to 800 km depth (Figures 2f and 2g). The “S”-shape structure of the anomaly is similarly observed in both our P- and S-wave models (Figures 2d–2g).

4. Discussion

4.1. Juan de Fuca Slab

[7] The geometry of the Cascadia subduction zone, especially its north-south variation and the absence of a slab deeper than 300 km beneath Oregon, carries important implications for the tectonic setting of the Pacific Northwest. Beneath Oregon, the slab is too short to act as a mechanical barrier to upper-mantle flow and may allow the mantle underlying the JdF plate to flow eastward beneath the plate margin as the North American plate moves southwestward above it. This provides a possible explanation for the trench-

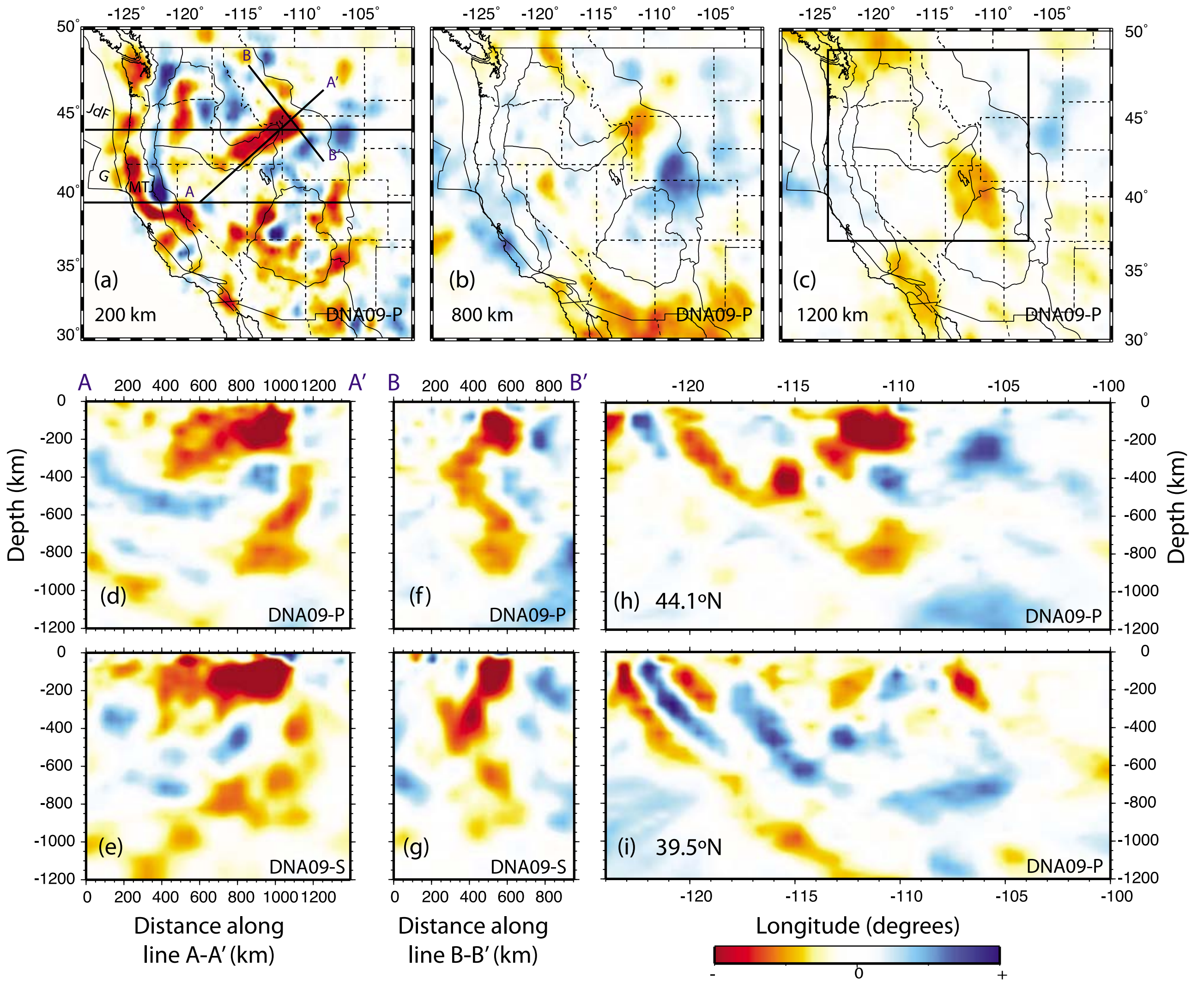

Figure 2. Map views and vertical cross sections showing the velocity structure of the Cascadia subduction zone and the Yellowstone anomaly. Constant depth slices at 200 km, 800 km and 1200 km extracted from our P-wave model. (a) Slow elongated anomaly beneath the YSRP and the along strike variation in amplitude of the north-south JdF slab anomaly. (b and c) Slow lower mantle beneath the Yellowstone Caldera as deep as the base of our model. (d and e) SW-NE cross-sections through our P- and S-wave models, respectively, along the YSRP (AA′, location shown in Figure 2a). These slices illustrate the deflection of the top of the Yellowstone anomaly by the southwestward moving North American plate. The amplitude of the slow anomaly increases to the northeast, where volcanism is younger. (f and g) NW-SE cross-sections though the Yellowstone Caldera along line BB′. They show the tilted low-velocity anomaly extending continuously from the surface to depth of 900 km. (h and i) Vertical slices at latitudes 39.5°N and 44.1°N, respectively. Figures 2h and 2i illustrate the fragmentation of the Gorda slab to the south and the shortness of the JdF Slab beneath Oregon. The color scale shown is −2 to +2% and −3 to +3% for our P- and S-wave models, respectively.

normal fast direction of anisotropy retrieved from SKS splitting analysis in central and northern Cascadia [*Long and Silver*, 2009, *Long et al.*, 2009; *Eakin et al.*, 2010]. The orientation of the fast direction in central and northern Cascadia differs from most other subduction zones where the fast direction is trench-parallel [*Long and Silver*, 2009]. The Gorda-Juan de Fuca slab is thought to be in trench rollback, and it has been suggested that the Gorda slab plays a significant role [*Humphreys and Coblentz*, 2007]. This is consistent with our model where the Gorda slab dives deeper into the mantle and exhibits a faster anomaly, potentially indicative of cooler and denser material. The retrograde motion of the Gorda-Juan de Fuca plate is also likely responsible for toroidal flow of the upper mantle around its southern edge as suggested by SKS splitting observations [*Zandt and Humphreys*, 2008]. Finally, the Cascadia subduction zone is also unusual due to the near-absence of deep seismicity (Figure 1). This has been previously associated with its young age and warm temperature [*Severinghaus and Atwater*, 1990]. The fragmentation of the slab may also play a role. There is no recorded seismicity >35 km depth beneath Oregon where the depth extent of the slab is only 300 km thereby reducing the slab pull force usually responsible for intermediate depth down-dip-tension earthquakes.

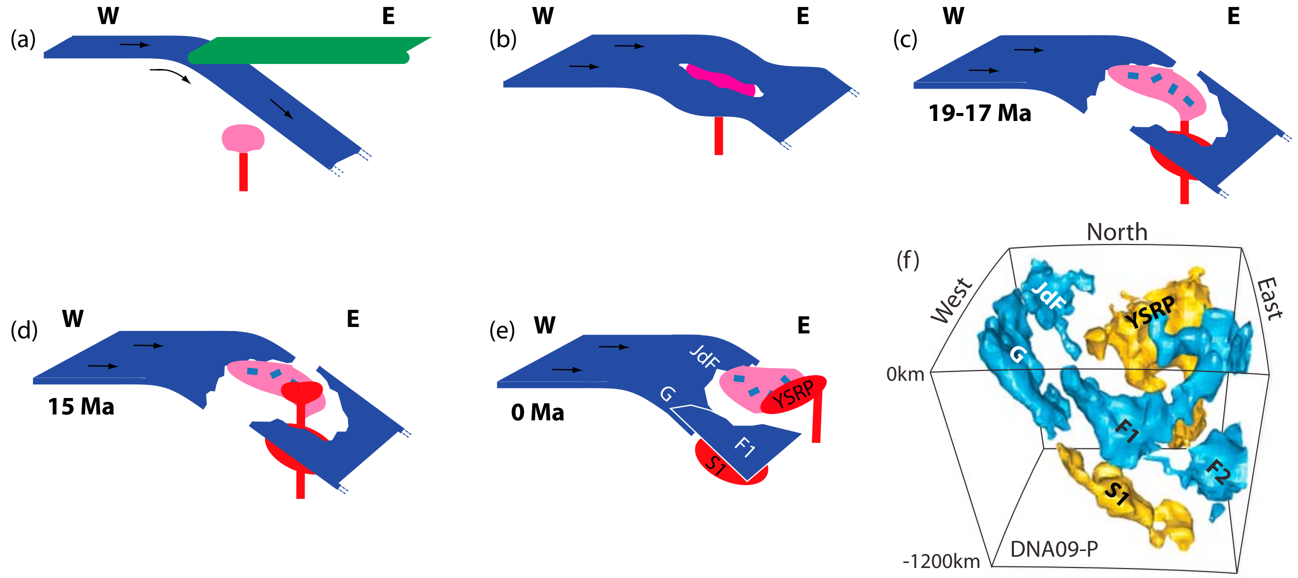

Figure 3. Illustrated time-history for the Pacific Northwest leading to today's mantle structure. (a) Any Yellowstone plume (pink plume head, red plume tail) would have to break through the subducting slab (blue) to reach the base of the continental lithosphere (green). (b) While the arrival of the buoyant plume likely precipitated break-up of the slab, pre-existing weaknesses and fractures may have facilitated the break. (c) The weakened slab eventually broke resulting in a reduction of slab pull and a decrease in the convergence rate at the trench at 19 Ma. Fragments of subducted oceanic crust (blue blocks) were assimilated by the plume head. The plume continued to the surface triggering the Columbia River Basalt outpouring. Some of the plume material may have remained trapped beneath remnants of the slab. (d) By ~15 Ma, the plume tail immerged to the south of the plume head and started propagating to the NE with respect to the North American plate. (e) As subduction continued, the fragment of the old slab (F1) and the currently subducting slab (G) began to overlap (as in Figure 2i). (f) Simplified 3D views (looking to the east) of our P-wave model. The depth of the box is 1200 km and the area plotted is that included in the box in Figure 2c. 3D isosurfaces that emphasize the structure of the JdF slab fragments and that of the Yellowstone plume are drawn at −0.3% and +0.45% (see also Figure S12).

There is some sub-crustal seismicity beneath Northern California and beneath Northern Washington where the slab is imaged deeper into the mantle (Figure 3).

4.2. Yellowstone Plume

[8] We interpret the low velocity anomaly beneath the YSRP as a mantle plume with a lower mantle origin. Our interpretation, based on geometrical observations of our P- and S-wave models, is also supported by the high He^3/He^4 isotopic ratio typical of the YSRP volcanism [*Graham et al.*, 2009], which is often interpreted as indicative of lower mantle source. The low-velocities are consistent with high temperatures and low-density. A hot plume with a large volume of low-density material, as observed in our models, accounts for the high heat flow, the broad topographic swell, the geoid high and the large free air gravity anomaly observed in the YSRP area [see *Smith et al.*, 2009, and references therein]. At 410 km depth the conduit is offset to the northwest of the Yellowstone Caldera and coincides with a region where the 410 km discontinuity deepens by 10 km [*Fee and Dueker*, 2004] as predicted when a high-temperature plume interacts with the transition zone. The geometry and structure of the elongated slow anomaly beneath the YSRP is consistent with the predictions of numerical models for the deflection of a plume head by the motion of an overlying lithospheric plate [*Lowry et al.*, 2000; *Steinberger et al.*, 2004]. It is elongated in the SW-NE direction parallel to the motion of the North American plate, the amplitude of the slow anomalies decrease to the southwest with increasing age of the calderas, and the plume conduit today coincides with active volcanism in the Yellowstone Caldera. This shallow, elongated part of the plume head exhibits a larger amplitude velocity anomaly than the conduit. The estimate we obtained for the Vp/Vs ratio from the comparison of our P-wave and S-wave models is also high for the shallow, elongated part of the anomaly (Figure S11). Both these observations are consistent with the presence of partial melt, which decreases preferentially S-wave velocities.

[9] The continuous body of the plume seems to bottom at 900 km. Below, we image another slow feature offset to the southwest of the Yellowstone Caldera (Figures 2c and S7, "S1" in Figure 3). A similar slow feature is also imaged in global tomographic models. This anomaly is offset from the plume conduit today (Figure 3) and sits beneath a region of the mantle that is dominated by fast features (Figure 2i and "F1", "F2" in Figure 3). Its origin is unclear. One possibility is that it is a remnant of the early plume that is now trapped beneath the string of high velocity slab fragments.

4.3. Plume Slab Interaction

[10] The existence of a whole-mantle plume and an active subduction zone within 1000 km of one another as imaged in our models makes the tectonic setting of the Pacific Northwest unique [*Davaille et al.*, 2005]. Also striking is the substantial fragmentation of the slab. The latitude where the

slab is absent coincides with that of the Yellowstone plume (Figure 3). Around 19 Ma there was a substantial change in the spreading rate at the Pacific-JdF ridge and also in the convergence rate of the Cascadia trench [*Wilson*, 1988]. This change could result from a reduction in slab pull. The change also shortly predates the massive magma outpouring of the Columbia River Basalts (CRB) and the onset of volcanism along the YSRP which have been interpreted as the manifestation of Yellowstone plume head emplacement [*Smith et al.*, 2009] around 17 Ma. We thus propose that the ascent of the Yellowstone plume, and its necessary encounter with the JdF slab, contributed to a rupture of the slab [*Xue and Allen*, 2007] (Figure 3) and the subsequent reduction of slab pull in the Cascadia trench. The composition of the CRB requires the presence of oceanic crust in the source [*Takahahshi et al.*, 1998], which supports the hypothesis that the Yellowstone plume interacted with the JdF slab and carried fragments of oceanic crust back up to the melting zone.

[11] How did the plume manage to pass through an oceanic slab? The proximity of the Pacific-JdF ridge to the Cascadia trench means that the slab was (and is) very young (~10 Ma at the trench) and therefore thin and warm. Erosion and fragmentation of the slab by the plume may have been facilitated and guided by preexisting weaknesses or tears in the slab. In the Oligocene-Miocene context of regional plate reorganization, the subducting slab may have been torn due to offshore fragmentation of the Pacific-JdF ridge when it approached the North American trench [*Severinghaus and Atwater*, 1990]. The Blanco Fracture zone (Figure 1) is located at the transition from very short slab (300 km) in central and northern Cascadia, to longer slab (600 km) in southern Cascadia. Earlier tearing of the slab may also have been caused by the accretion of the Siletzia terrane ~48 Ma and the induced trench jump at the end of the Laramide Orogeny (45 Ma) that occurred at the latitude of today's Oregon-Washington border [*Humphreys*, 2008], precisely where the slab is missing.

[12] Fragmentation of the slab presumably occurred just prior to the arrival of the plume at the surface, around 19–17 Ma. The trench-perpendicular subduction rate in southern Cascadia is 30 mm/yr, and has been relatively constant [*Wilson*, 1988] for the last 19 Ma. Slab subducted since the arrival of the plume at the surface would be expected to have reached ~500 km depth given the 60° dip, similar to the depth extent observed. The original obstruction to the plume by the slab, and the continuing presence of slab fragments in the mantle, mean that the plume's buoyancy-driven ascent path will deviate from vertical as it interacts with these obstructions. This plume-slab interaction may be responsible for the S-geometry of the plume depicted in Figures 2e and 2h.

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