RESOLVING UPPER MANTLE SEISMIC STRUCTURE BENEATH THE PACIFIC NORTHWEST AND INFERRED PLUME-LITHOSPHERE INTERACTIONS DURING THE STEENS-COLUMBIA RIVER FLOOD BASALT ERUPTIONS

by

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A THESIS

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THESIS ABSTRACT

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Title: Resolving Upper Mantle Seismic Structure Beneath the Pacific Northwest and Inferred Plume-Lithosphere Interactions During the Steens-Columbia River Basalt Eruptions

Cenozoic tectonics of the Pacific Northwest (PNW) and the associated mantle structures are remarkable, the latter revealed by EarthScope seismic data. In this thesis we model teleseismic body waves constrained by ambient-noise surface waves and teleseismic receiver function analysis in order to recover better-controlled higher resolution images of the PNW continuously from the surface of the crust to the base of the upper mantle. We focus on and have clearly imaged two major upper mantle structures: (1) the high-velocity Farallon slab (the "Siletzia curtain") extending vertically beneath the Challis-Kamloops-Absaroka volcanic flareup (~53-47 Ma) of western Idaho and central Washington; and (2) a high-velocity anomaly beneath the Wallowa Mountains of northeast Oregon associated with the main Columbia River flood basalts source region. The proximity of these two structures along with the magmo-tectonic history of the PNW leads us to reexamine the origin of the Columbia River Basalts ~ 16 Ma.

This thesis includes co-authored material submitted for publication.

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For my family whom has always supported my decisions in life no matter how off beat they may have been.

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CHAPTER I

INTRODUCTION

The research work throughout this thesis was executed entirely by me, Amberlee Darold. The writing has been in conjunction with my advisor, Eugene Humphreys, as second author on my paper, submitted for publication. This thesis contains unpublished co-authored materials in chapter I., Introduction, chapter IV., Discussion, and chapter V., Conclusions. Eugene Humphreys has contributed greatly through mutual conversations and editorial assistance to the background knowledge that supports my introduction, discussion and conclusions.

This thesis chapter includes co-authored material written in conjunction with Eugene Humphreys. Eugene Humphreys has contributed greatly through mutual conversations and editorial assistance to the background knowledge that support this introduction.

The EarthScope USArray provides the PNW with extensive teleseismic data coverage, facilitating numerous high-resolution seismic images of the crust and upper mantle (Roth et al., 2008; Sigloch et al., 2008; Burdick et al., 2009; Tian et al., 2009; Xue and Allen, 2010; Schmandt and Humphreys, 2010a). In this paper we discuss our tomographic inversion of teleseismic P and S body waves for PNW upper mantle structure produced under the constraints of a crustal structure derived from the ambient noise tomography and teleseismic receiver function analysis of Gao et al. (2011). Imaged mantle structures have large magnitudes and often correlate well with the major geologic structures. The major seismic structure imaged beneath the PNW is a high-velocity curtain-like structure interpreted by Schmandt and Humphreys (2011) as a fragment of ocean lithosphere abandoned beneath much of Idaho and northern Washington during the ~53 Ma accretion of Farallon lithosphere within the Columbia embayment. Also prominent is the high-velocity subducting Juan de Fuca slab, a low-velocity body in central Oregon and a high-velocity body beneath NE Oregon, directly below the source area for the ~16 Ma Columbia River flood basalt eruptions (CRB). This latter structure, its relation to the major high-velocity structure imaged beneath Idaho, and its relation to CRB event, are the foci of our paper.

1.1. Geologic context prior to Steens-CRB eruptions

By 125 Ma, the Blue Mountains accreted terrains (through which the CRB later erupt) had docked in the forearc of an active north-trending Cretaceous volcanic arc that extended from California through Idaho (the Idaho Batholith), to northern Washington and beyond (Fig. 1a and 1b). The arc became decreasingly active, becoming essentially amagmatic by ~53 Ma (Gaschnig et al., 2009) coinciding with the ending of the ~75-53 Ma northern Laramide Orogeny. The Larimide Orogeny was expressed by strong thrusting within and east of the volcanic arc (Dumitru et al., 1991; Humphreys et al., 2003;) and waning arc magmatism (Gaschnig et al., 2009) throughout Idaho and northeastern Washington. Magmatic quiescence and Laramide thrusting ended with the accretion of Farallon lithosphere into the Columbia embayment ~53 Ma (Fig. 1 and 2). During or very shortly after the accretion of Farallon lithosphere, a phase of extension created the northern Washington core complexes and opened the Pasco basin within the accreted lithosphere (Catchings and Mooney, 1988) (Fig 2a). Sudden onset of magmatism began with the Challis-Kamloops-Absaroka volcanic flareup ~53-47 Ma, primarily across Idaho and northern Washington, the Clarno volcanics erupted in north-central Oregon (Fig. 1), starting perhaps as early as 50-54 Ma (Bestland et al., 1999; Retallack et al., 2000) and certainly active by 45 Ma. Magmatism surrounded most of the expected boundary of the accreted Farallon lithosphere at or soon after accretion (fig. 1c). We take this period of extension and magmatism quickly following the Laramide Orogeny, ~53 Ma, as strong evidence for the removal or disruption of the Farallon slab from the base of North America in these areas. Alternatively these magmas could represent ridge-trench intersection and slab window formation (Madsen et al., 2006). The Blue Mountains region would have remained in contact with the Farallon lithosphere and the absence of volcanism from this forearc area of southeast Washington and northeast Oregon indicates that the Farallon slab remained in contact with the lithosphere, a condition that continued until the CRB eruptions.

Schmandt and Humphreys (2011) attribute this switch in magmatic and tectonic regime to a stalling and falling away of the flat subducting slab beneath Idaho and northern Washington, based in large part on the presence of a large curtain-like high-velocity structure imaged roughly beneath the areas of renewed magmatism (Fig. 1c and 4b). Magmas in this flareup include adakites and shoshonites, which Madsen et al. (2006) and Schmandt and Humphreys (2011) attribute to melting of the basaltic slab crust. The accretion of Farallon lithosphere also resulted in initiation of Cascadia subduction and Cascade Volcanic Arc ~45 Ma, although southern continuation of flat-slab subduction is evidenced by a near absence of magmatism until ~43 Ma and a continuation of Laramide thrust tectonics. This suggests that the subducting Farallon slab was torn between these two subduction domains, somewhere beneath southern Oregon (Fig 1c).

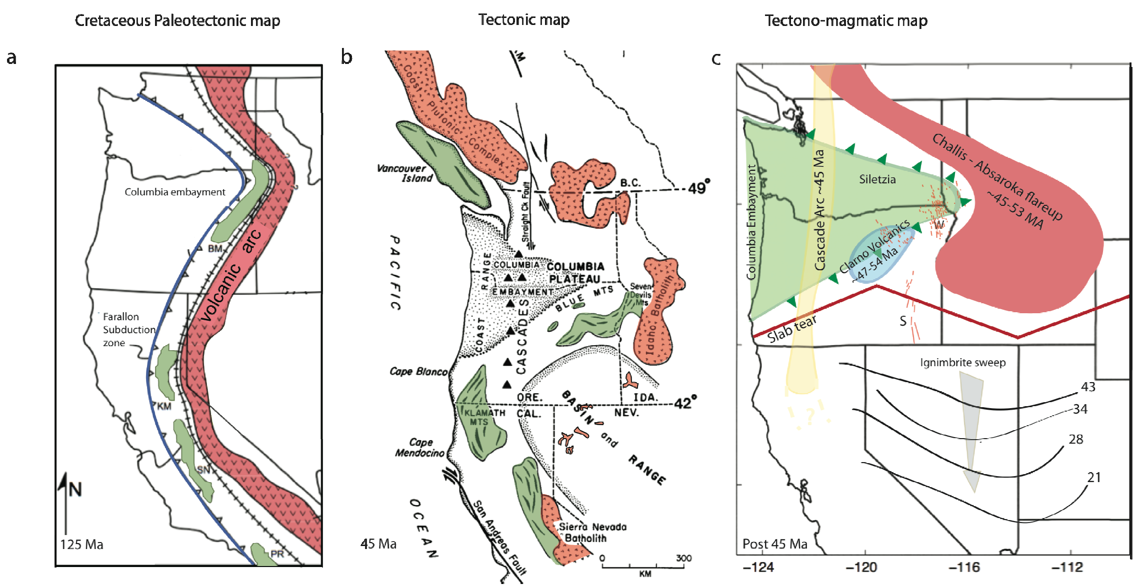


Figure 1. Tectonic setting of the U.S. Pacific Northwest without palinspastic restoration, (a) at 125 Ma, adapted by Dickinson (2006). Paleotectonic map of the Cretaceous volcanic arc and accreted oceanic arc terrains: the Blue Mountains (BM), western Klamath Mountains (KM), Sierra Nevada foothills (SN), and Peninsular Ranges (PR). Also showing configuration of the Farallon subduction zone and Columbia Embayment at ~125 Ma (solid blue line). (b) At 45 Ma, adapted from Riddihough et al., 1986, tectonic map after accretion of Farallon lithosphere into the Columbia Embayment (grey stipple): accreted oceanic arcs (green), and plutons of the Cretaceous arc (in pink). (c) Post 45 Ma, Tectono-magmatic map emphasizing main volcanic elements: Expected extent of accreted Farallon lithosphere (“Siletzia”, green); extent of Challis-Kamloops-Absaroka magmatic flareup ~45-53 Ma; Clarno volcanics ~47-54 Ma; Cascade volcanic arc ~45; proposed Farallon slab tear ~53-47 Ma; Southern ignimbrite flare up ~43-21 Ma; Steens Mountains (S); Wallowa Mountains (W); Steens-CRB dike swarms (red dashes).

1.2. The Steens-CRB eruptions

Steens-Columbia River Basalt Group flows cover most of eastern Washington, northeast Oregon, and portions of western Idaho. The main phase eruptions, Steens, Imnaha and Grand Ronde, erupted a volume of ~ 220,500 km^3 (94% of the total volume [Camp and Hanan, 2008]). Eruptions began ~16.8 Ma with the Steens theolitic basalt eruptions in southeastern Oregon and migrated rapidly northward, erupting the Imnaha basalts ~16-2-16.0 Ma, and the Grande Ronde basaltic andesites ~16.0-15.6 Ma (Barry et al., 2010, Jarboe et al., 2010) from the north south trending Chief Joseph dike swarms (Fig. 1c and 2a). The Steens and Imnaha eruptions are composed of olivine theolites typical of flood basalt provinces worldwide. However, the Grand Ronde, which comprise ~65% of the flood basalt volume, are high silica (~52-58%) basaltic andesites unique to the bulk composition of all other flood basalt provinces (Camp and Hanan, 2008). The silica-rich Grande Ronde magmas are not primary mantle melts but can be produced by direct partial melting of a basalt-like source material (Takahahshi et al., 1998; Yaxley, 2000).

Steens-CRB volcanism generally is attributed to interaction of the Yellowstone plume with North America (Brandon and Goals, 1988; Hooper and Hawkesworth, 1993; Dodson et al., 1997; Takahahshi et al., 1998; Camp et al., 2003). However, this volcanic event presents puzzling complexities: (1) the eruptive centers define an elongated ~N-S trend roughly parallel to the Precambrian margin of North America (Fig. 2), which has been attributed to plume interaction with the old continental margin (Jordan et al., 2004; Camp, 2004); (2) the largest erupted volumes were produced by the CRB, far north of the location predicted by backtracking the Yellowstone volcanic track (Fig. 2), which has been attributed to slab deflection (Geist and Richards, 1993) or N-S tearing of the subducted slab (Liu and Stegman, 2012); (3) after an early basaltic phase the CRB magma composition changed rapidly to basaltic andesite, which is not a mantle melt and has been attributed to assimilation of the North American lower crust (Wolfe and Ramos, in press), melting of a eclogite entrained in a plume (Yaxley, 2000; Takahahshi et al., 1998; Hooper and Hawkesworth, 1993), or melting of the crust on the subducted Juan de Fuca slab (Camp, 2004); and (4) the CRB eruptions occurred largely within a quasi-circular area of relative uplift and subsidence, centered on a pluton that experienced local uplift of 2 km, which has been attributed to a coincident delamination event (Hales et al., 2005). It is unknown whether these peculiarities represent the sort of variations and complexities expected of plume-lithosphere interaction in the geologically complex Earth (Geist and Richards 1993; Camp and Ross 2004; Jordan et al., 2004), or if the CRB represent an unusually complex response to plume impingement, or if they are a result of local conditions unrelated to a plume (Carlson, 1984).

1.3. Major mantle structures

Seismic Imaging has been important for gaining new insight into the tectono-magmatic history of the PNW, and has progressed rapidly since the deployment of USArray. Several recent tomographic studies using USArray have imaged the mantle in the PNW (e.g., Roth et al., 2008; Sigloch et al., 2008; Burdick et al., 2009; Tian et al., 2009; Xue and Allen, 2010). In our area of interest, northeast Oregon, the imaging of Schmandt and Humphreys (2010a, 2011) is unsurpassed. They image a high-velocity mantle "curtain" extending vertically from beneath central Idaho to near the eastern edge of the Cascades in Washington along with a separate prominent elliptical body below the source area of the CRB's in northeast Oregon. This imaging was created by inverting 248,000 P and 84,000 S relative teleseismic travel-time residuals observed by USArray and more than 1700 additional stations. Schmandt and Humphreys' (2011) inversion uses a western U.S. crust model to isolate the mantle component of residual times and three-dimensional frequency-dependent sensitivity kernels to map residuals into velocity structures. They proposed that their imaged "curtain" reflects rollback-like foundering of flat-subducting Farallon slab initiated by the accretion of Farallon lithosphere within the Columbia embayment and consequent subduction termination. Schmandt and Humphreys (2011) argued that any upper mantle high-velocity anomaly of this volume must be subducted ocean lithosphere. Its shape and location support this contention by being consistent with Farallon ocean lithosphere subduction that ended beneath this area ~53 Ma. We agree with the conclusion of Schmandt and Humphreys and use their body wave data for our imaging. However, we use the ambient noise tomography and teleseismic receiver function model of Gao et al. (2011) specific to the PNW (Fig. 2c) instead of using the western U.S. crustal model in order to better image the relationship of the upper mantle with the lower crust.

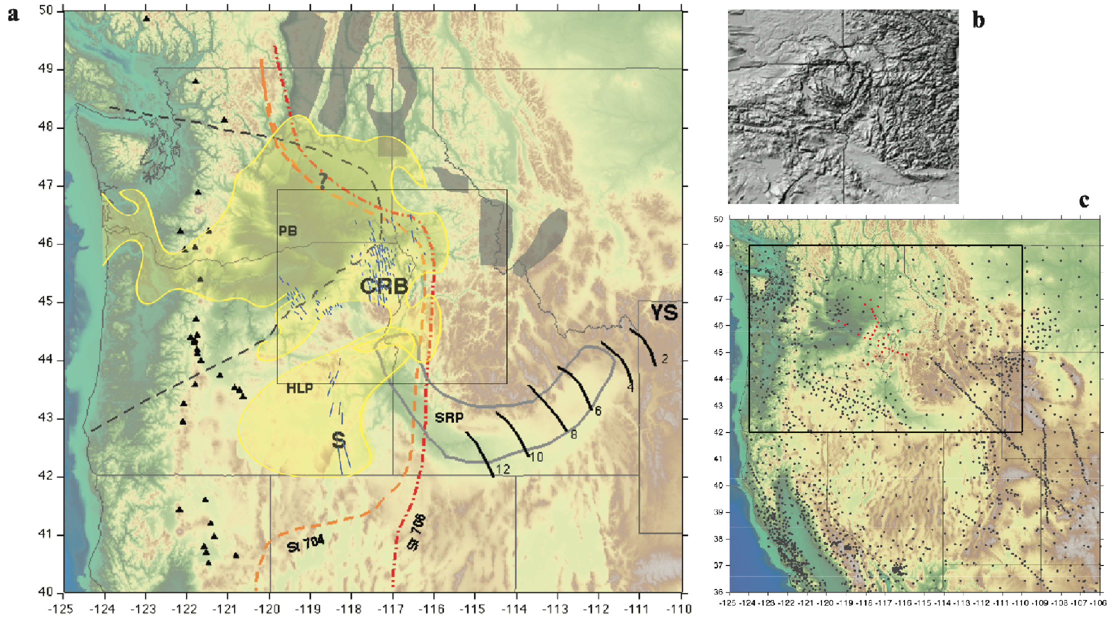


Figure 2. Physiographic maps of the U.S. Pacific Northwest emphasizing (a) geology modified from Gao et al. (2011), outline of inferred Farallon lithosphere (dashed green and blue line); Steens-CRB province (yellow outlined area); Steens-CRB dike swarms (blue dashes); main Columbia River flood basalt source area (CRB); Steens basalts source area (S); Steens Cenozoic metamorphic core complexes (shaded grey patches); isotopic $^{87}Sr/^{86}Sr$ 0.706 line (dashed red line) and isotopic $^{87}Sr/^{86}Sr$ 0.704 line (dashed orange line, location uncertain in eastern Washington (?)) isopleths define boundaries between Precambrian silicic continental crust east of the 706 line and Mesozoic and younger mafic accreted oceanic crust west of the 704 line; active High Cascade Arc and other Quaternary volcanoes (black triangles); Snake River Plain (SRP, grey outline); time-progressive Newberry and Yellowstone (YS) rhyolite eruptive progression across SRP and High Lava Plains (HLP) (black lines, in Ma); Pasco Basin (PB). (b) Northwest Oregon topography, USGS DEM image, focused on the bull's eye pattern of uplift in the Wallowa Mountains (area corresponds to black box in Fig. 1a). (c) Regional topography and the 1,715 broadband seismic stations used in this study: Red circles represent Wallowa Flexible array operated between 2006-2009. The black rectangle represents the expanse of Gao et al., crustal model (lat: 42° to 49°, lon: -124° to -110°) used to constrain our body-wave imaging.

CHAPTER II

DATA AND METHODS

This thesis chapter was written entirely by me, Amberlee Darold, with editorial assistance from Eugene Humphreys.

From the teleseismic travel-time data assembled by Schmandt and Humphreys (2010a), we use 155,134 P-wave delay times from 1,715 broadband stations and 50,298 S-wave delay times from 960 broadband stations recorded by seismic arrays operating in the Pacific northwestern United States between 2006-2010 (Fig. 2c). The regional coverage from the EarthScope Transportable array, with ~75 km station spacing, is augmented with stations of the Wallowa FlexArray (~10 km station spacing), and several other regional arrays located farther from our focus area and provides us with excellent ray path coverage. P waves are picked on the vertical component and S-waves are picked on the tangential component. We use teleseismic events with magnitudes $M_w > 5.0$, located at distances of 30°-90° for direct P and S phases, and 155°-180° for PKPdf phases. Waveforms are Gaussian band-pass filtered in up to four frequency bands with center frequencies of 1.0, 0.5, 0.3, 0.1 Hz for P waves and 0.4, 0.1, 0.05 Hz for S-waves, and arrival times are derived from cross-correlation of waveforms (VanDecar and Crosson, 1990). The root mean square (RMS) values of P and S residuals are 0.4154 s and 1.1591 s, respectively.

Inversion of damped least squares follows the methods of Schmandt and Humphreys (2010b). Using finite-frequency sensitivity kernels centered on rays located by tracing through the AK135 (Kennett et al., 1995) 1-D Earth model, and that extend out to the first Fresnel zone (based on the center frequency of the filter used during cross correlation). These sensitivities are calculated using the Born theoretical 'banana-doughnut' kernel approximation of Dahlen et al. (2000). Inversion is for slowness on a rectangular but variably spaced set of nodes (described below) using the LSQR algorithm (Paige and Sanders, 1982), which is regularized using gradient and norm damping and Laplacian smoothing. Smoothing and damping parameters were chosen to give high variance reduction and precise images.

Inside the region defined on Figure 2c, the upper ~75 km of our model is constrained by the velocity model of Gao et al. (2011), which is derived from fundamental-mode Rayleigh waves recovered from ambient noise and includes a velocity step at the Moho derived from receiver function analysis. This structure is enforced by its direct inclusion into our model and applying strong damping to model parameters above 50 km (with relaxed damping between 60-90 km). For the P-wave inversion, we multiply the surface wave model of Gao et al., (2011) by a Vp/Vs factor of 1.74 (scaling factor from Schmandt and Humphreys, 2010a). The RMS values of the P and S wave residuals from the model of Gao et al. (2011) are 0.0276 s and 0.0480 s, respectively. Outside this region we use crustal velocity and thickness models (elevation and Moho depths, [Gilbert and Fouch, 2007]) to calculate ray theoretical travel-time corrections for crustal heterogeneity (Schmandt and Humphreys, 2010b). The RMS values for P and S wave crustal corrections are 0.1826 s and 0.1783 s, respectively and have little effect on the RMS values of P and S residuals before crustal corrections. This could be due to a lack of correlation between observed traveltime residuals and the crustal corrections.

We choose a model domain that is much larger than our focus area, to improve resolution of the deep mantle structure and to reduce edge effects in our area of interest. Our model domain extends in depth from the surface to 900 km, in longitude from $^{-}$125°W (near the Pacific coastline) to $^{-}$106° W (the middle of Wyoming), and in latitude from 50°N (slightly north of the Canadian border) to 36°N (central California). Vertical node spacing increases gradually from 10 km in the crust to 60 km at depths of 565 km and below to account for both the increasing first Fresnel zone width and decreasing resolution with depth. The uppermost layer nodes are chosen to co-locate with those of Gao et al., (2011) ambient noise model to avoid interpolation. The horizontal node spacing is smallest in northeast Oregon and increases gradually away from this location, varying from 25 km to 40 km at the Earth's surface and dilating progressively with depth.

CHAPTER III

RESULTS

This thesis chapter Written entirely by me, Amberlee Darold, with editorial assistance from Eugene Humphreys.

Because we use the same data and similar methods of Schmandt and Humphreys (2010a and 2010b), our inversions are similar. However, our use of a better constrained crustal structure (Gao et al., 2011), anisotropic corrections, choice of node spacing and smoothing and damping optimized for the PNW, combine to create better constrained images of improved resolution for this area. This allows us to construct a well-resolved image that is continuous from the surface to ~800 km. Our inversion reduces overall travel-time residual variance by 89.5% for P waves and 86.4% for S waves. Overall variance reduction tends to be an optimistic indicator of image quality because resolution changes throughout the model space. A more reliable assessment of model quality is the variance reduction for the well-sampled portions of the model, which are 81.4% for P waves and 75.2% for S waves (portions of the model domain where nodes are sampled by several rays from at least 2 back azimuth quadrants [see Schmandt and Humphreys, 2010b]).

We use synthetic testing to test the resolvability of specific structures of interest with the available ray set. Figure 3 summarizes synthetic resolution tests for P and S waves to an initial structure consisting of three checkerboard depth layers. We include the model of Gao et al. (2011) in our synthetic testing to allow for a direct comparison of results. These tests show good recovery of our basic input model with minimal streaking.

The peak amplitude recovery is roughly 70-80% for P-waves and 40-50% for S-waves. Greater resolution P-wave amplitude recovery occurs owing to the fact that we have over three times more recorded P-wave residuals, 755 more stations than for S waves and few high quality S arrivals of high frequency (0.4 Hz for S-waves). Below we show tests of structures specifically designed to test specific aspects of the structures imaged.

Our imaging resolves four primary structures in the upper mantle beneath the PNW (Fig. 4, we focus our discussion primarily on P-wave images): (1) the high-velocity subducted Juan de Fuca oceanic lithosphere (JdF), (2) a strong low-velocity structure beneath north-central Oregon, (3) the high-velocity "curtain" inferred to be abandoned Farallon oceanic lithosphere beneath western Idaho and across central Washington (Schmandt and Humphreys, 2011), and (4) a smaller high-velocity structure in NE Oregon, termed here the Wallowa anomaly. We further examine the high-velocity structure beneath NE Oregon and its relationship with the high-velocity "curtain".

Vp and Vs heterogeneity dominate the PNW crust and upper mantle. The P and S wave amplitudes of heterogeneity are greatest in the upper 250 km with S wave models showing very little structure below this. The discrepancy between heterogeneity amplitude of the P and S inversions most likely results from smaller data set, difference in station density and, more notably, the effects of anisotropy.

We calculate the effect of upper mantle azimuthal anisotropy on P delays; correction times are estimated using a scaling relationship between SKS split times and teleseismic P-wave travel times (O'Driscoll et al., 2011). The effect of azimuthal anisotropy in a tomographic inversion is expected to cause P-wave anomalies that are too fast and S-wave anomalies that are too slow, and we see this disagreement in our inversions. However, azimuthal anisotropy may not be appropriate in areas of vertical flow such as subducting slabs, upwelling plumes, downwelling lithospheric instabilities or foundering slabs (O'Driscoll et al., 2011). We image these types of structures in the PNW and have processed our inversion with and without these travel time adjustments. We note that the correction times for the PNW are relatively small and their effect on the inversion is minor (the largest effect occurs in the uppermost mantle velocity beneath the HLP, where very strong SKS splits are observed [Long et al., 2009]). After careful consideration we conclude that the azimuthal anisotropy changes only complicate our analysis of northeastern Oregon and therefore we remove them from our final model.

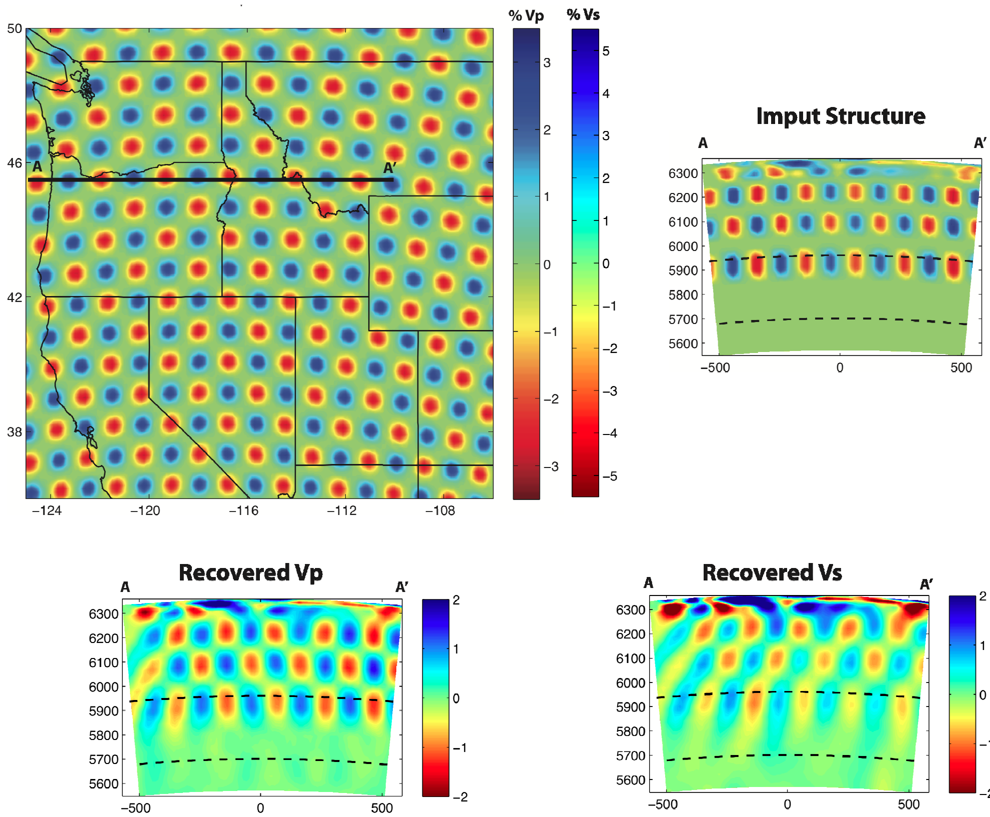


Figure 3. Checkerboard resolution tests results. Cross section labeled as A-A' on horizontal map view. Input structures (top row) include the crust model of Gao et al., from zero to 75 km (above dashed line) and alternating anomalous volume layers for Vp (+/- 3%) and Vs (+/- 5%) at depths of 125-170 km, 225-290 km, and 370-415 km. Recovered structures are +/- 2% for both Vp and Vs.

3.1. Juan de Fuca and low-velocity anomaly

As imaged previously (e.g., Michaelsen and Weaver, 1986), the JdF slab is imaged dipping steeply to the east and extending only to depths of 100-300 km. An apparent gap in the Juan de Fuca plate is imaged in the central portion of the slab at the border of Oregon and Washington (Rasmussen and Humphreys, 1988; Roth et al., 2008). This gap appears as shallow as 60 km and widens with depth to include all of Oregon below ~250 km (Fig. 4). The N-S extent of the gap is ~90 km in length at 60 km depth (which also is the depth where the JDF slab first appears in our images) and increases to a width of ~550 km at 290 km depth. At this depth the entirety of the JDF (and "curtain") appear to be breaking up. This apparent gap in the slab is adjacent to the large low velocity anomaly directly to the east, which appears as shallow as the Moho at 30 km and extends in depth to at least ~300 km. Both features are well resolved (Fig. 4b) and aside from the Yellowstone anomaly (Fig. 4b), the low velocity anomaly is the strongest low-velocity anomaly in the PNW. This structure is centered adjacent to the JDF gap, dips eastward with the JDF slab, and is surrounded on three sides by high-velocity structures (the JDF slab and, to the north and east, the Siletzia curtain).

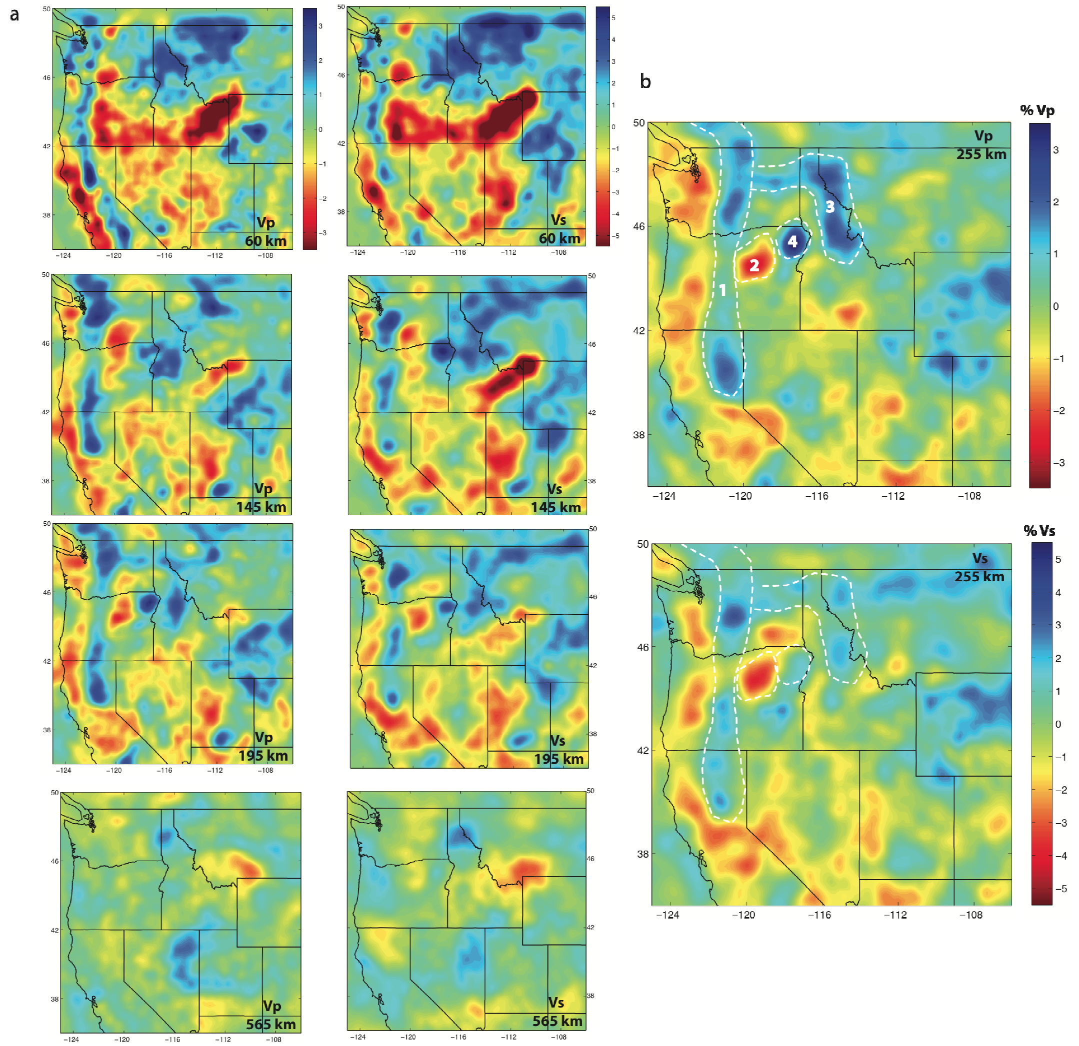


Figure 4. Horizontal upper-mantle map slices. (a) Vp (left column) and Vs (right column) tomograms at depths 60 km, 145 km, and 195 km (from top to bottom) images show horizontal map slices above and below connection of the Wallowa anomaly and the curtain anomaly (b) Major upper mantle seismic anomalies at 255 km depth (top Vp and below Vs), from left to right, (1) the high-velocity Juan de Fuca, (2) the low-velocity structure, (4) high-velocity Wallowa, and (3) the high-velocity curtain.

3.2. The curtain and Wallowa anomaly

The previously imaged high-velocity curtain-like structure (Schmandt and Humphreys, 2011) extends vertically from the base of North America lithosphere to depths of ~600 km beneath northern Idaho and western Montana, ~450 km beneath central Idaho and ~300 km beneath northern Washington (Fig. 4). The Wallowa high-velocity anomaly in NE Oregon lies just west of the southern extent of this structure. The Wallowa anomaly is circular in plan view ~80km wide and extends vertically from the base of NA lithosphere to ~350 km depth, ~250km in length.

3.3. Advanced synthetic structures

The high-velocity Wallowa structure in northeast Oregon lies beneath the topographic bull's eye with the Wallowa Mountains uplift at its center (Hales et al., 2005)(Fig. 2b). Figure 4b shows that this structure lies adjacent to the curtain-like structure that was interpreted by Schmandt and Humphreys (2011) to be Farallon slab. To assess the structural relationship between these two structures we perform a series of resolution tests. Figure 5 shows some of these tests. We are led to conclude that the Wallowa high-velocity structure is connected to the high-velocity curtain-like structure from 105 km to145 km across northeastern most Oregon and central Idaho at the curtains southeast segment. Figure 5b shows resolution of the structures connected while Figure 5c shows resolution of the structures separated. For the "curtain" we have placed a slab-like structure from 90km – 625 km depth that curves west with depth and shallows to the south, this structure is located in northern Idaho and across central Washington, surrounding Northeast Oregon. For the Wallowa anomaly we have placed an inverted funnel-like structure at 105–370 km depth beneath the northeastern corner of Oregon and attached it to the "curtain" between 105–145 km depth (Fig. 5b). The synthetic images of the connected structure are almost identical to our inversion images, whereas unconnected synthetic tests do not give similar images (Fig. 5a, 5b, and 5c).

The physical connection of the NE Oregon structure with the curtain-like structure suggests that it has the same origin; the curtain a part of the remnant Farallon slab. This suggests that just prior to the accretion of Farallon lithosphere, subducting Farallon slab may have been in contact with western U.S. lithosphere as far east as NE Wyoming (Humphreys, 2007). This would make the foundering Farallon slab at least ~600 km in length beyond the expected extent of Farallon lithosphere within the Columbia Embayment. Our imaging agrees with this hypothesis and confirms a foundering slab of ~300 km beneath central Idaho and northern Washington and ~600 km beneath northern Idaho. The Wallowa anomaly is ~250 km in length and likely represents a later episode of foundering Farallon slab, which propagated from south to north and was initiated by the arrival and ponding of the Yellowstone Plume beneath Southeastern Oregon.

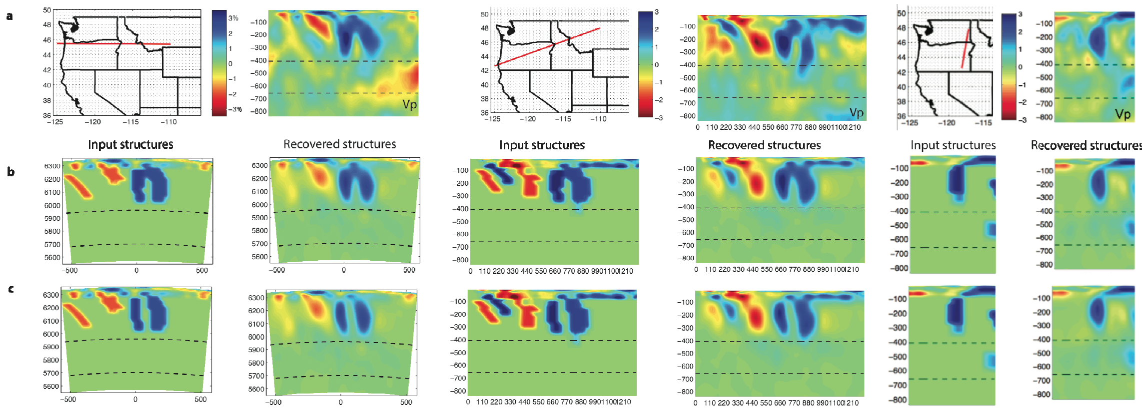


Figure 5. Advanced synthetic structures exhibiting, (a) map view and horizontal cross-sections of Vp tomographic inversion images of the Wallowa anomaly and the Siletzia curtain. (b) Input and output of synthetic tests connecting the Wallowa anomaly and the Siletzia curtain from 105km-145km. (c) Input and output of synthetic tests separating the Wallowa anomaly and the Siletzia curtain.

CHAPTER IV

DISCUSSION

This thesis chapter includes co-authored material written in conjunction with Eugene Humphreys. Eugene Humphreys has contributed greatly through mutual conversations and editorial assistance to the background knowledge that support this discussion.

The eastern Oregon Steens-CRB flood basalt event generally is thought to be the initiation of the Yellowstone hotspot within North America. While hotspots typically initiate with a flood basalt event (Richards, et al., 1989), the eastern Oregon flood basalts are peculiar in that the main eruptions, the CRB, are far off track, and the main phase of the CRB eruptions, the Grande Ronde, are basaltic andesite. Three independent lines of reasoning, discussed in the following paragraphs, lead us to conclude that the CRB eruptions, and their abnormalities, were related to a northward propagating delamination-style foundering of Farallon lithosphere from the base of Cretaceous accreted terrains of North America ~16 Ma.

4.1. Seismic evidence

First, Our upper mantle imaging and resolution tests demonstrate that the high-velocity Wallowa structure is connected to the large sheet-like high-velocity curtain structure imaged beneath much of Idaho and Washington. Schmandt and Humphreys (2011) argue that the curtain-like structure is subducted Farallon ocean lithosphere, based on its large volume and slab-like shape. If so, then the high-velocity Wallowa structure also is likely to be foundered Farallon lithosphere. This is consistent with the volume of the Wallowa structure, which is to be too large to be delaminated North America lithosphere and too deep to be basalt-depleted upper mantle.

The Wallowa anomaly at depths of 195-330 km is circular in map view and is nearly perfectly aligned with the circular bull's eye topography (Fig 2b), which is the source area for most of the CRB. This uplift pattern was created during and after the CRB eruptions (Hales et al., 2005), suggesting that the Wallowa structure is related to the CRB event. The Wallowa anomaly is connected with the Idaho sheet-like anomaly below the north-northeast side of topographic bull's eye at depths of 60-150 km (Fig. 2a and 4), as would occur if the Wallowa anomaly were foundered Farallon lithosphere that delaminated with a with a hinge on its north-northeast side.

4.2. Tectono-magmatic evidence

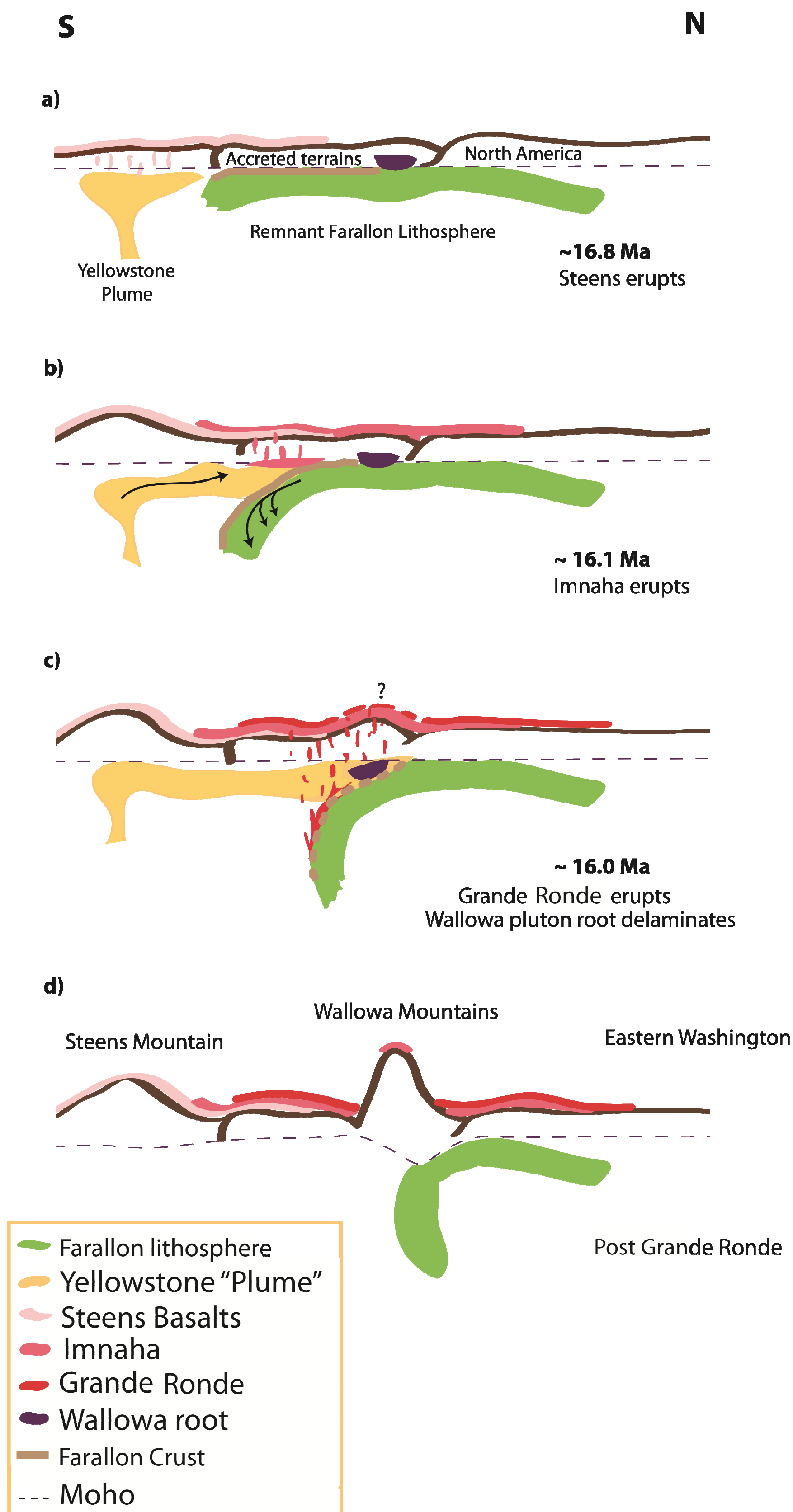
The tectonic and magmatic history of the region provides the second type of evidence that Farallon lithosphere was at the base of North America prior to CRB volcanism. We assume that waning magmatism in the well-established Idaho Cretaceous arc and the occurrence of strong backarc thrusting represents Laramide-age flattening of the Farallon slab. The ~53 Ma accretion of Farallon lithosphere within the Columbia Embayment and resulting initiation of Cascadia subduction would have abandoned the Farallon slab within the Embayment and at the base of North America east of the accreted Farallon lithosphere. We interpret the absence of magmatism from northeast Oregon and southeast Washington from the time of accretion until the time of CRB eruptions to indicate that the Farallon slab prevented magmatism by remaining at the base of the North America lithosphere. This is in strong contrast to the sudden and vigorous magmatism that initiated ~53 Ma in all regions around this amagmatic area (Fig. 1c). This presumably indicates slab removal or disruption from the surrounding areas (Absaroka-Challis-Kamloops magmatism across northwestern Wyoming and from central Idaho through northern Washington [Feeley, 2003; Schmandt and Humphreys, 2011]; Pasco basin magmatism [Catchings and Mooney, 1988]; and the Clarno volcanism of north-central Oregon [Bestland et al., 1999]). The initiation of Cascadia subduction west of Farallon lithosphere following accretion occurred during a time when the amagmatic Laramide Orogeny continued to the south of central Oregon suggesting a continuation of flat-slab subduction south of central Oregon. This would require an ~E-W tear in the subducted Farallon slab extending across central Oregon and east to the southern extent of the Idaho anomaly. The south to southwest propagation of slab removal from the base northwestern Nevada is thought to follow the sweep of magmatism that is the expression of the ignimbrite flareup (Humphreys, 1995) and Ancestral Cascade arc (Cousens et al., 2008).

4.3. Physical and chemical evidence

Our third line of reasoning for Farallon slab removal beneath northeast Oregon at ~16 Ma comes from the physical and chemical nature of the Steens-CRB flood basalt event. The eastern Oregon flood basalt event initiated with the Steens theolitic basaltic eruptions ~16.8 Ma (Wolff et al., 2012; Camp et al., 2012, Jarboe et al., 2010) across southeastern Oregon. Magmatism migrated rapidly northward, erupting the Imnaha basalts ~16.1-15.9 Ma (Barry et al., 2010), and then the massive Grande Ronde basaltic andesites ~16.0-15.5 Ma (Barry et al., 2010). The Grande Ronde flows erupted from dike swarms concentrated nearly 400km north-northeast of the initial Steens eruptions (Fig. 1c and 2a) Assuming pre-CRB magmatic quiescence was due to Farallon slab against the base of North America, CRB magmatism suggests a south-to-north removal of this lithosphere. In addition, the rapid exposure of the Farallon ocean crust to the asthenosphere makes available the large amounts of basalt-like rock required to produce the composition and volume of Grande Ronde magma. The fact that none of the Grande Ronde lavas express melting in the presence of garnet suggests that this crust had not metamorphosed to eclogite. This would not be surprising considering northeast Oregon was in a forearc position when the Farallon lithosphere accreted, and the subduction interface may well have been above the depth of garnet stability, ~35 km.

Based on the magmatic volume, production rate and isotopic evidence (Camp and Ross, 2004; Hooper and Hawkesworth, 1993; Wolff and Ramos, 2012), we attribute the Steens magmatism to arrival of the Yellowstone mantle plume beneath southeast Oregon. This is an area where we do not expect Farallon lithosphere at the base of North America. But northward eruptive dike propagation enters an area underlain by Farallon lithosphere, and the evidence outlined above suggests a delamination style of foundering of this lithosphere occurred. Initial (Imnaha) CRB magmas were the first to invade northeast Oregon, and they have the isotopic signature of plume-derived melts. We envision sills of Imnaha basalt intruding at the density step between the Farallon crust and its mantle; this density profile would promote sill intrusion and could propagate magmatism northward rapidly, and the presence of such a magma layer would mechanically decouple the ocean lithosphere from North American and enable the delamination of the negatively buoyant lithosphere. Rapid northward propagation was driven by the negative buoyancy of the Farallon lithosphere and the positive buoyancy of the plume asthenosphere and its melt, and was enabled by the mechanical decoupling provided by magmatic sills. This mechanism is similar to the plume-driven delamination discussed by Burov et al. (2007) and Camp and Hanan (2008). These invading magma sills and, with Farallon delamination, the inflowing hot buoyant plume mantle would also allow the garnet-rich Wallowa plutonic root (Johnson et at., 1997; O'Driscoll and Johnson, 2008) to detach. Like Hales et al. (2005), we attribute the ~2 km of Wallowa pluton uplift to the delamination of its root. The circular pattern of topographic uplift pattern could result from the underplating of magmas derived from the upflowing decompressing asthenosphere driven by the sinking of the Farallon lithosphere or the Wallowa pluton root, in a manner similar in form to that modeled by Elkins-Tanton (2000) for the Siberian Traps.

Figure 6 (next page). Yellowstone plume induced delamination model of remnant Farallon lithosphere from the base of Cretaceous accreted terrains producing the CRB's. Cross-sections a-d corresponds with age-progressive evolution of the CRB's starting with the Steens basalt eruptions and concluding post Grande Ronde. (a) Steens theolitic basalts erupt from southeastern Oregon ~16.8 my and plume encroachment and destabilization of the Farallon lithosphere begins. (b) Plume activation of mechanical delamination and slab rollback of Farallon lithosphere from base of Cretaceous accreted terrains by the emplacement of magmatic sills and eruption of the Imnaha basalts ~16.1Ma. (c) Sill migration triggers Wallowa pluton root delaminate, melting of Farallon basaltic crust, and Grande Ronde andesitic basalt eruptions ~16.0 Ma. (d) Post Grande Ronde mantle structure with exaggerated topography (Figure 5a, column 5 represents map cross-sesction and figure 5a, column 6 represents current Vp mantle structure).


S
N
a)
Accreted terrains
North America
Remnant Farallon Lithosphere
Yellowstone
Plume
~16.8 Ma
Steens erupts
b)
~ 16.1 Ma
Imnaha erupts
c)
?
~ 16.0 Ma
Grande Ronde erupts
Wallowa pluton root delaminates
d)
Wallowa Mountains
Steens Mountain
Eastern Washington
Post Grande Ronde
Farallon lithosphere
Yellowstone "Plume"
Steens Basalts
Imnaha
Grande Ronde
Wallowa root
Farallon Crust
--- Moho

CHAPTER V

CONCLUSIONS

This thesis chapter includes co-authored material written in conjunction with Eugene Humphreys. Eugene Humphreys has contributed greatly through mutual conversations and editorial assistance to the background knowledge that support these conclusions.

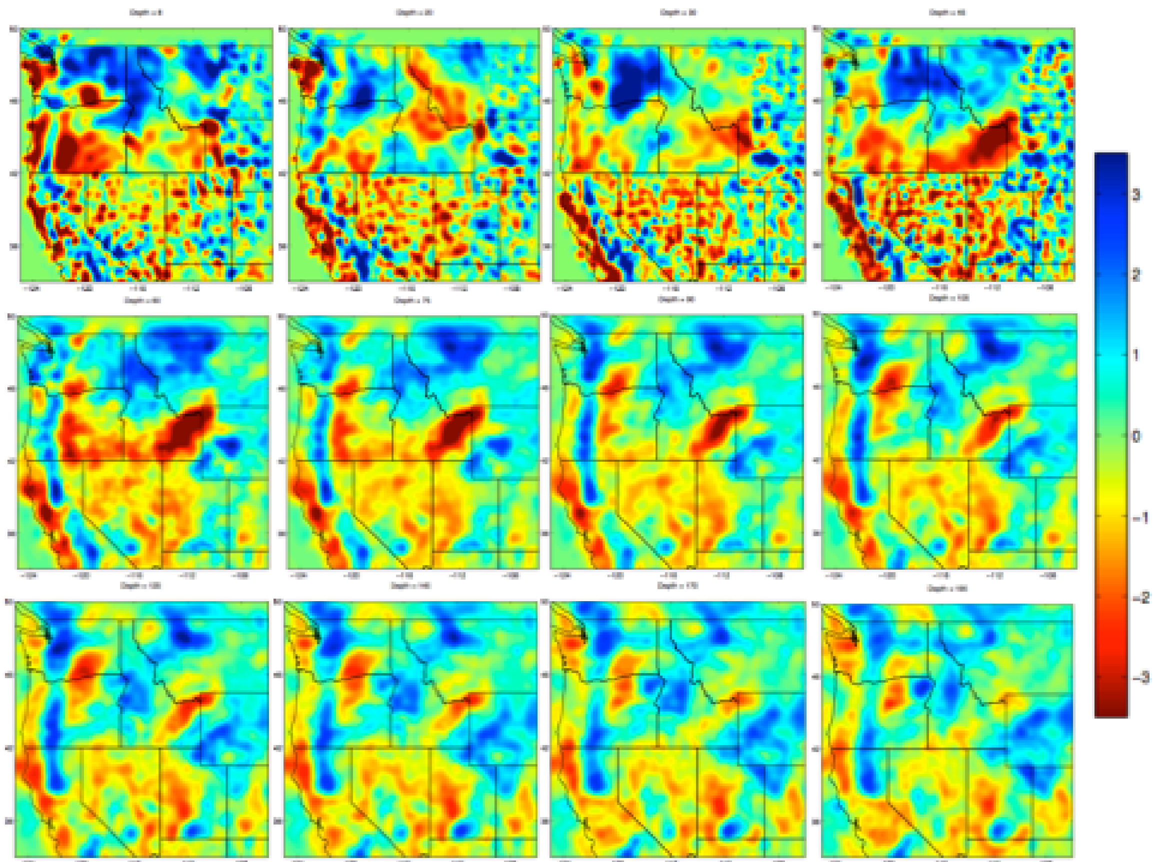
By combining constraints derived from our tomographic imaging, the geologic history, and the evolution of flood basalt magmatism in northeast Oregon and surrounding regions, we conclude the following (depicted in figure 6): (1) northeast Oregon and southeast Washington were directly underlain by subducting (~120-53 Ma) and abandoned (53-16 Ma) Farallon slab until the beginning of CRB magmatism (Fig. 6, green Farallon slab); (2) Yellowstone plume impingement beneath the southern Oregon lithosphere initiated flood basalt activity with the Steens eruptions (16.8 Ma, Barry et el., 2010), which destabilized the Farallon lithosphere ~16.1 Ma (Fig. 6a); (3) the Farallon lithosphere foundered in a delamination style, with a hinge rolling rapidly toward the north-northeast. This was driven by the negative buoyancy of the slab and positive buoyancy of the hot, partially molten plume asthenosphere, and was mechanically enabled by the emplacement of magmatic sills between the dense Farallon lithosphere and the less dense overlying crust, and propagating northward following the pressure gradient created by delamination (Fig. 6b); (4) this initial basaltic magmatism, derived from plume-rich asthenosphere, gave rise to the northward-propagating Imnaha flows of the early CRB (Fig. 6b); (5) The voluminous Grande Ronde flows were largely sourced from the basaltic oceanic crust of the Farallon lithosphere (Fig. 6c); (6) Wallowa pluton root delamination, driven by its dense garnet-rich restitic root (Johnson et at., 1997; O'Driscoll and Johnson, 2008) and enabled by the emplacement of basaltic sills above this body (Fig. 6c). The intense CRB magmatism is attributed to the forced overturn of an unusually hot asthenosphere and the presence of large volumes of basalt.

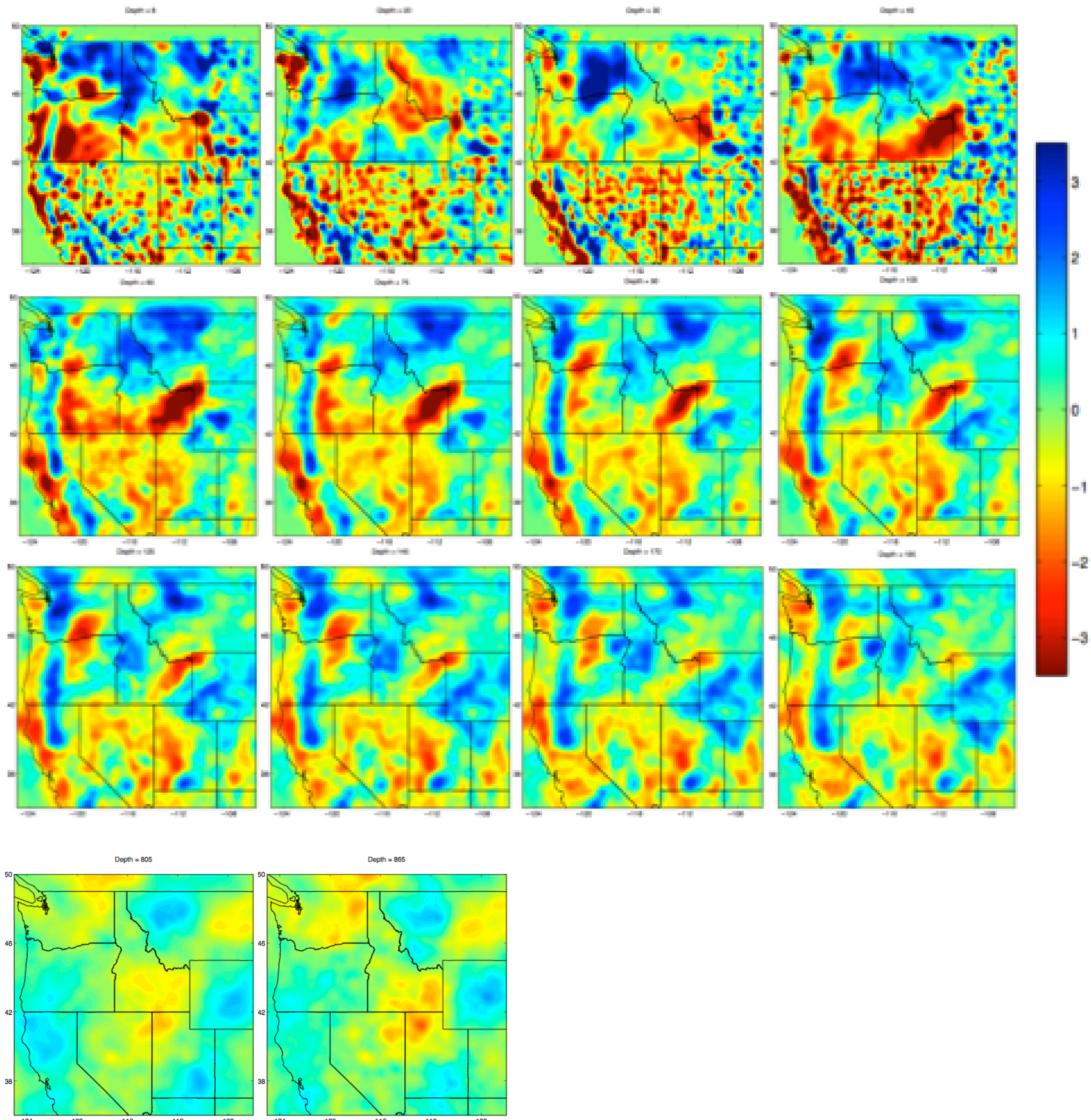
We view the eastern Oregon flood basalt eruptions and Wallowa Mountain uplift as a plume amplified and accelerated version of western U.S. magmatic and tectonic activity. Throughout the western U.S., flat-slab Farallon subduction applied Laramide-driving basal tractions (Coney and Reynolds, 1977; Bird, 1994, Saleeby, 2003), lithospheric cooling (Dumitru et al., 1991) and hydration (Dixon et al., 2004) of the lithosphere. The subsequent, protracted foundering of the flat slab and assent of asthenosphere to the base of a thinned (Spencer, 1996) and hydrated (Humphreys et al., 2003) North American lithosphere created a vigorous ignimbrite flareup (Coney, 1978; Ward, 1995) and initiated lithospheric instability and associated uplifts [e.g., southern Sierra Nevada (Saleeby and Foster, 2004; Zant et al., 2004) and the southwest Colorado Plateau (Levander et al., 2011)]. The activity that occurred ~16 Ma in eastern Oregon presents a microcosm of all this, although with its local peculiarities and made especially intense by the impingement of Yellowstone plume asthenosphere. In particular, magmatic decoupling of the gravitationally unstable Farallon fragment and Wallowa pluton root enabled their foundering, which both drove uplift centered on the Wallowa Mountains and dragged anomalously hot mantle far north of its arrival location in southern Oregon.

APPENDIX A

P-WAVE TOMOGRAPHY

(8 km – 865 km)



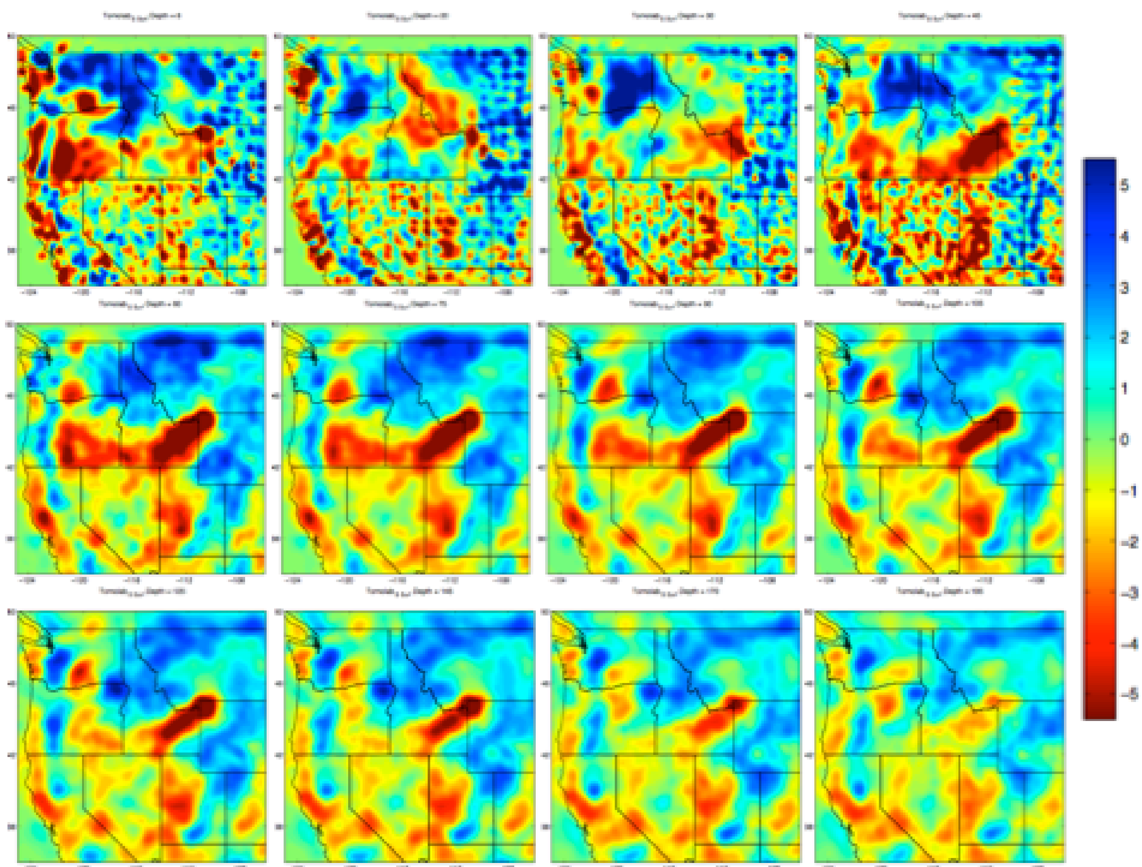


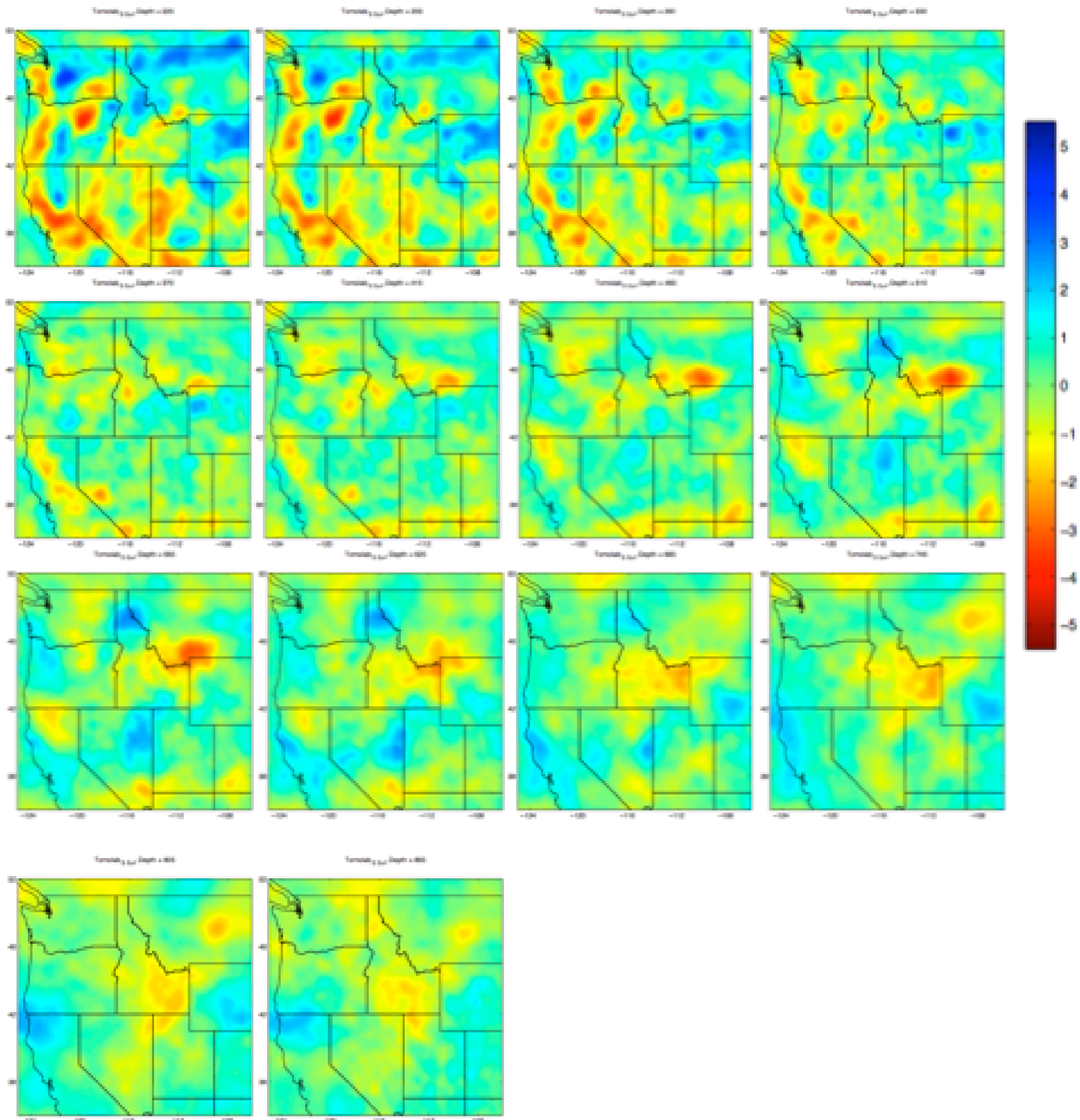
Depth = 805
Depth = 865
50
46
42
38
-124
-120
-116
-112
-108
3
2
1
0
-1
-2
-3

APPENDIX B

S-WAVE TOMOGRAPHY

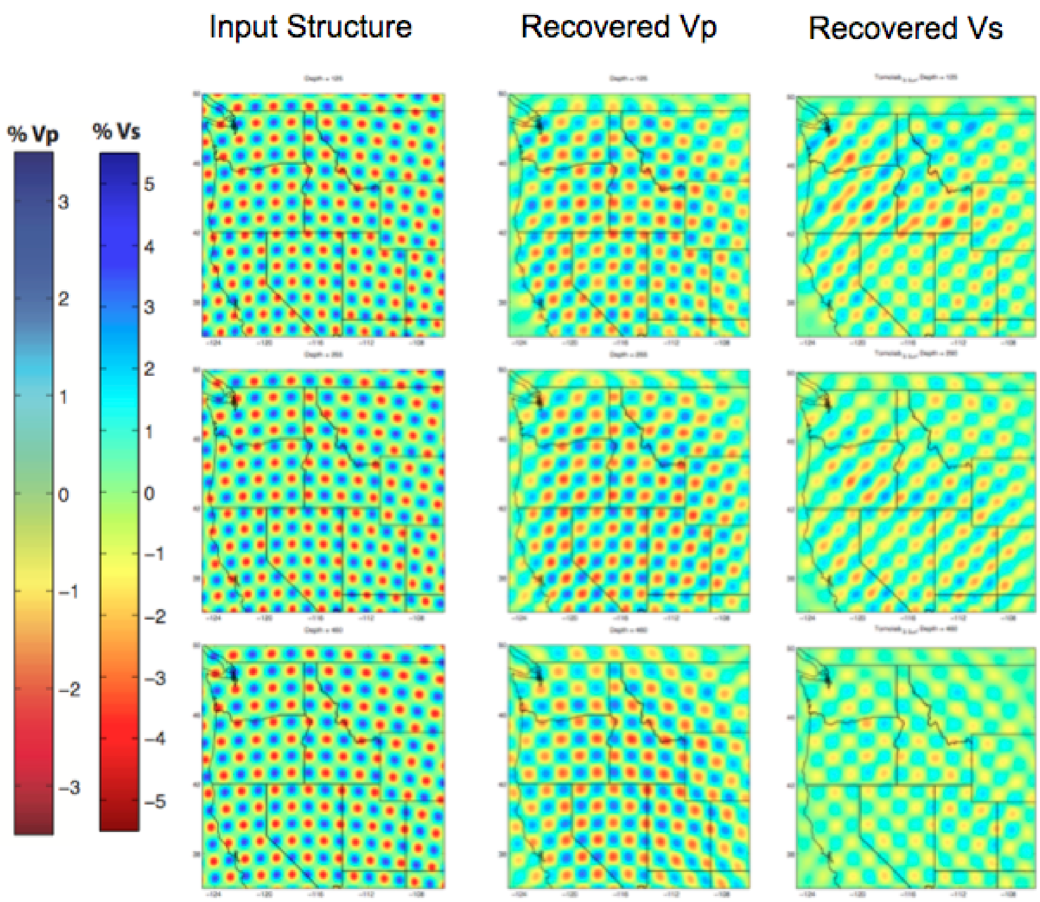
(8 km – 865 km)




5
4
3
2
1
0
−1
−2
−3
−4
−5

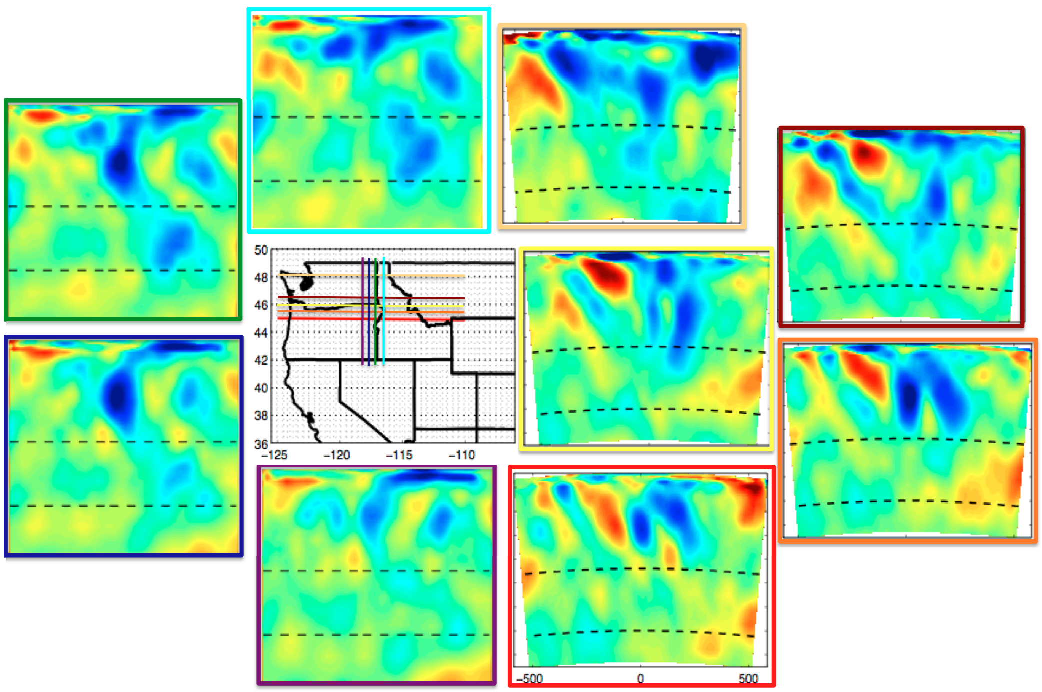
APPENDIX C

CHECKERBOARD SYNTHETICS



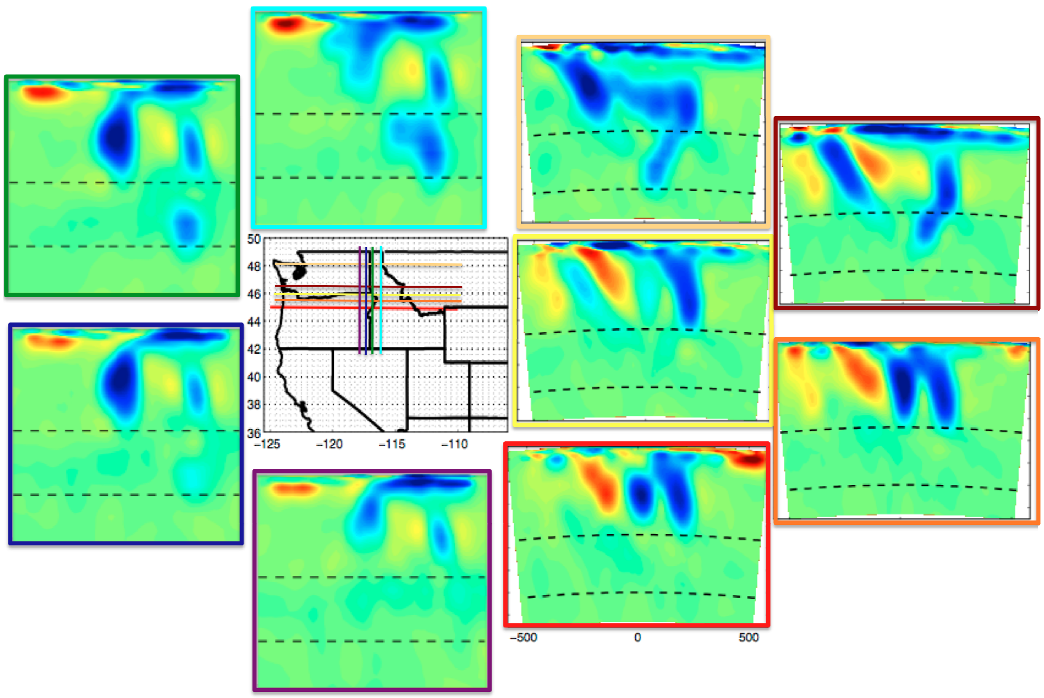
APPENDIX D

VERTICAL CROSS SECTIONS THROUGH THE CONNECTION OF THE WALLOWA ANOMALY AND THE CURTAIN



APPENDIX E

SYNTHETIC VERTICAL CROSS SECTIONS THROUGH THE CONNECTION OF THE WALLOWA ANOMALY AND THE CURTAIN



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