

# Origin of the Newberry Hotspot Track: Evidence from shear-wave splitting

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Received 14 November 2005; received in revised form 30 January 2006; accepted 31 January 2006

Available online 9 March 2006

Editor: S. King

## Abstract

Located in the northwestern United States, the Newberry Hotspot Track consists of a sequence of age-progressive silicic volcanic domes and lava flows, showing a monotonic age progression from east to west ending at the Newberry Caldera. While mantle plumes are often called upon to explain hotspot tracks, the Newberry track cannot be the direct product of plate motion over a stationary mantle source as its orientation is  $\sim 120^\circ$  to plate motion, making it a good case study for alternative causal mechanisms of hotspot tracks. Four end-member tectonic models have been proposed: (1) subduction counterflow, (2) gravitational flow along the base of the lithosphere, (3) lithospheric faulting, and (4) extension of the Basin and Range. To get fabric information about the asthenosphere and constrain the possible flow fields beneath the Newberry track, SKS splitting measurements were made for 27 events at 12 stations of the Oregon Array for Teleseismic Study (OATS) along the track. A gradual rotation of the fast direction is observed from ENE–WSW at the northwest end of the array to E–W to the southeast and the delay times average 1.65 s. We infer that the SKS splits are the product of anisotropy in the asthenosphere and the anisotropy orientation does not vary with depth beneath the track. The average fast directions ENE–WSW to the northwest are consistent with generation by mantle shear parallel to the subduction of the Juan de Fuca Plate, and the more E–W fast directions to the east are perhaps due to shear caused by the Basin and Range extension. Since the observed fast directions are not parallel to the Newberry track, as the subduction counterflow model or the gravitational flow model suggests, the age-progressive volcanism is unlikely a direct product of asthenospheric flow. Instead, we propose that the Newberry track is the product of lithosphere-controlled processes.

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*Keywords:* Oregon; Newberry; Hotspot track; SKS splits; Lithospheric processes

## 1. Introduction

Located in the northwestern United States, the Newberry Hotspot Track, along the Oregon High Lava Plains, consists of a sequence of volcanic domes and lava flows. K–Ar dating of rhyolitic domes in the region shows they were widespread from 17 to 11 Ma but domes younger

than 10 Ma form two distinct belts each  $\sim 250$  km long and trending N75°W (Fig. 1) [1,2]. The northern belt of volcanism within the Newberry Hotspot Track is coincident with the Brothers Fault Zone (Fig. 1), a NW-trending fault zone running across the strike of the NE-trending normal faults of the Basin and Range. Isochrones of rhyolitic domes can be drawn across the region showing a monotonic age progression from east to west ending at the Newberry Caldera (Fig. 1). More recent  $\text{Ar}^{40}/\text{Ar}^{39}$  dating confirms these volcanism trends [3].

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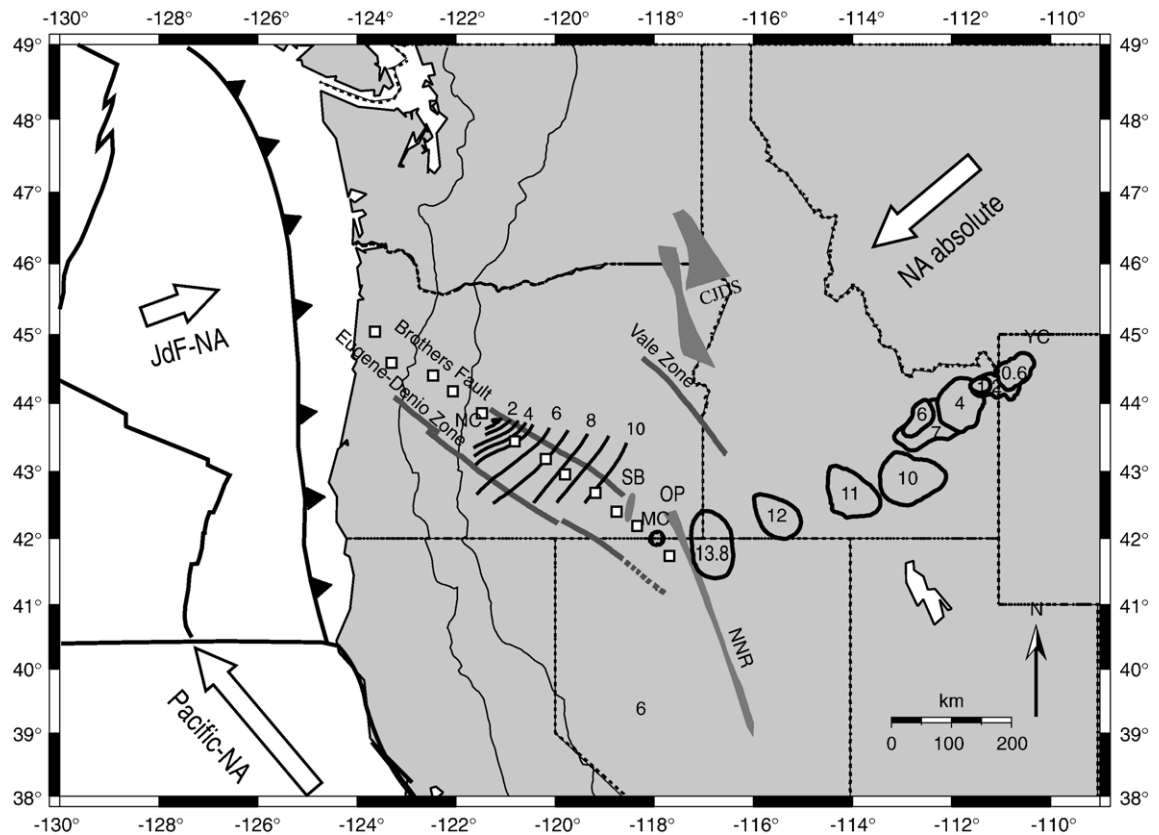


Fig. 1. Tectonic map for the study region. The age-progressive volcanic products of the Newberry and Yellowstone hotspots are shown in black. Both initiate in the region of the McDermitt Caldera (MC). Age contours of initial rhyolitic volcanism along the Newberry track are shown in 1 Ma increments extending to the Newberry Caldera (NC) [3]. Major rhyolitic caldera centers from Owyhee Plateau (OP) along the Yellowstone track are shown with age in Ma extending to the Yellowstone Caldera (YC) [5]. Dike swarms associated with the ~17Ma basaltic outpourings are shown in gray: Chief Joseph Dike Swarm (CJDS), Steens Basalt (SB), and Northern Nevada Rift Zone (NNRZ) [4,7]. Strike-slip fault zones across Oregon are shown in gray lines [48]. Twelve stations used in this study are shown as white squares, numbered from OT01 at the west end to OT12 at the east end. Plate motions are shown as white arrows.

The northwest-trending Newberry track crudely mirrors the better-known Yellowstone Hotspot Track, which is associated with northeastward migration of silicic volcanism along the Eastern Snake River Plain ending at the Yellowstone Caldera (Fig. 1) [2,4,5]. Initiation of the Newberry–Yellowstone hotspots occurred near the region of the McDermitt Caldera in northern Nevada and is coincident with outpouring of the Columbia River basalts at ~17Ma [2]. The Columbia River basalts extend throughout eastern Oregon, eastern Washington, and western Idaho, and are a series of flows with ages 17–6Ma, although primarily 17–14Ma [2,4,6]. The conduits for these flows lie along a NS-oriented trend, north of the McDermitt Caldera and a similar NS-oriented trend of magmatism occurs southward along the northern Nevada rift zone (Fig. 1) [7].

Although both tracks are located on the North American Plate, the Yellowstone track is parallel to the

absolute plate motion, while the Newberry trend is oblique to it. The Yellowstone track has been commonly considered as the result of a mantle plume [5,8,9]. This interpretation is consistent with the associated gravity high, topographic high, high heat flow, and geochemical signature, which are characteristic of many hotspots. Yet, despite these features, evidence for an upwelling conduit through the upper mantle beneath Yellowstone remains unclear and the debate continues as to whether a mantle plume is the origin [3,10–15]. The Newberry hotspot is far less studied than Yellowstone and many of its characteristics have yet to be quantified, such as its source, its causal mechanism, and its relation to the Yellowstone track. While the Newberry Hotspot Track is also associated with bimodal age-progressive volcanism, high topography and high heat flow [2,3,16], it cannot be the direct product of a stationary deep mantle plume or any other stationary source, as the hotspot path is northwesterly at

~120° to plate motion. Geochemical analyses of Newberry are also limited, but the high  $^3\text{He}/^4\text{He}$  ratios often associated with mantle plumes are lacking. Instead there are notable enrichments in Ba, Sr, and Pb, compared with that of mid-ocean ridge basalts, consistent with a subduction component in the source [17].

## 2. Tectonic models proposed

Four end-member tectonic models have been proposed for the formation of the Newberry Hotspot Track: (1) subduction counterflow. Counterflow associated with the subduction of the Juan de Fuca Plate beneath North America draws material westward across the base of the continental lithosphere [3,10,17,18]. (2) Gravitational flow along lithospheric topography. Westward flow associated with topography change on the base of the lithosphere. Possible sources of topography include the edge of the craton and the Yellowstone “plume” head or its residuum [3,10,17]. (3) Lithospheric faulting. Progressive faulting in the lithosphere, initiating near the McDermitt Caldera [19–21]. (4) The extension of the Basin and Range. The enhanced extension at the northern margin of the Basin and Range that propagated with extensional widening of the province [2,11].

If the Newberry track is a product of asthenospheric processes as model 1 and/or 2 propose, then astheno-

spheric flow is expected along the length of the hotspot track. Alternatively, if lithospheric processes as proposed by model 3 and/or 4 are responsible for the hotspot track, asthenospheric flow along the hotspot is not required. SKS splits can provide fabric information about the asthenosphere, which constrains the possible flow fields beneath the Newberry Hotspot Track and discriminates between these models.

## 3. Shear-wave splits

Data were collected from the Oregon Array for Teleseismic Study (OATS). The OATS array includes eleven 3-component broadband seismic stations (Guralp CMG-3ESPD) with average station spacing of 50 km, which were installed in May 2003 and will operate till May 2006. The permanent station COR at Corvallis represents a twelfth station. The array extends from the McDermitt Caldera to the southeast along the Newberry track, past the Newberry Caldera, over the High Cascades and on to the coast within ~100 km of the trench (Figs. 1 and 2).

Using data from the first one and half years of the OATS deployment, teleseismic events with magnitude equal or greater than 6.3 and epicentral distances greater than 85° were carefully examined. A total of 27 events provide clear SKS or SKKS phases (Fig. 2 inset). A low-

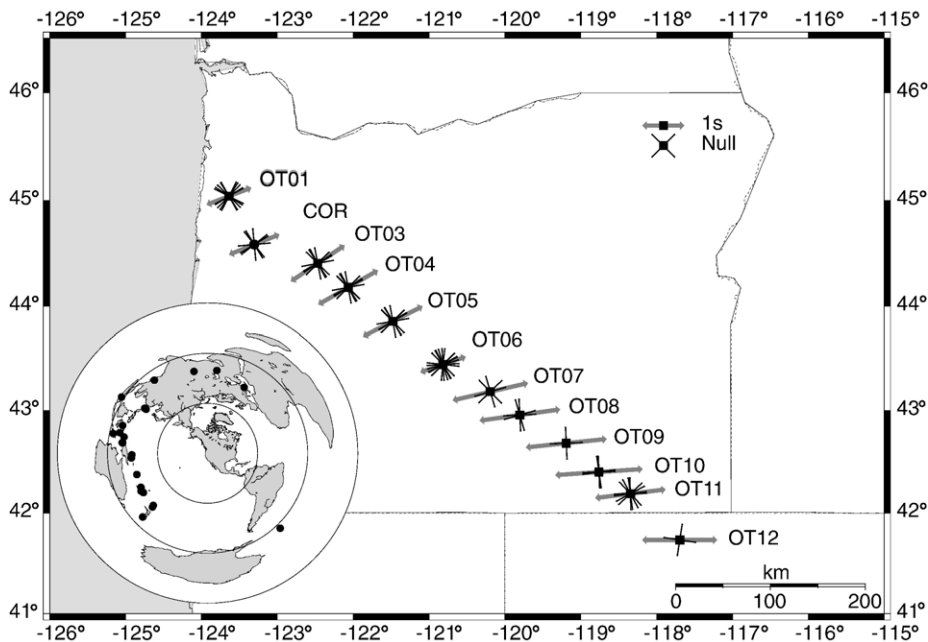


Fig. 2. Splitting results across Oregon. The thick gray line indicates the result after stacking all useful events at each station. The line orientation gives the fast splitting direction, and its length is linearly proportional to the splitting time. The thin black crosses indicate null results. Inset: distribution of the 27 events used in the SKS splitting study, where the black dots indicate the locations of earthquakes.

pass filter at 10s was applied to reduce microseismic noise before making splitting measurements. Splitting parameters were determined by minimizing the tangential energy of SKS or SKKS arrivals [22]. As a quality control, events were discarded if their splitting parameters have errors greater than 1s in splitting time  $\delta t$  and/or greater than  $22.5^\circ$  in fast direction  $\phi$  at the 95% confidence level. Average splitting parameters at each station were then determined through a stacking procedure [23] and are shown in Fig. 2. The station-averaged fast directions for the OATS array show a gradual rotation from ENE–WSW at the northwest end of the array to E–W to the southeast and the delay times average 1.65s.

The splitting fast directions  $\phi$  for individual events from different event back azimuths show small variations at each station, suggesting a relatively simple anisotropy orientation beneath the array. Splitting times  $\delta t$  show more variation scattered around the stacked splitting time at each station. Fig. 3a and b gives an example of the splitting parameters of  $\phi$  and  $\delta t$  as a function of event back azimuth at station OT09. Neither  $\phi$  nor  $\delta t$  show a  $\pi/2$  periodicity as a function of event back azimuth, which would be expected if there were two-layers of anisotropy [24,25]. Instead, the fast directions do not vary with event back azimuth suggesting orientation of anisotropy does not vary with depth. The scatter of  $\delta t$  versus event back azimuth may indicate either thickness variations of anisotropic layers, incidence angle variations, or errors in splitting measurements. The latter is likely more influential as splitting times measured for different events from similar back azimuths also show some variation. Null results were

also observed at all 12 stations when the event back azimuth was parallel or perpendicular to the fast direction determined from other events at the same station (Fig. 2). The combination of null observations and well-resolved fast directions from other events at the same station indicates that a single layer of anisotropy dominates the splitting observations. Low-pass filtering of the SKS waveforms, and errors in splitting measurements, limit our ability to detect small variations of splitting parameters that would result from the presence of thin layer of anisotropy. However, such small structures, if they exist would be small compared with the likely thickness of a layer necessary to generate  $\sim 1.6$ s delays. Accordingly, we interpret our splitting results in terms of a single layer of anisotropy beneath the Newberry track.

As the globally averaged crustal contribution to the SKS splitting is small with an average value of 0.2s [26], crustal anisotropy is absent in the adjacent Eastern Snake River Plain [27], and we see evidence for one layer of anisotropy only, it is unlikely that the crust is contributing significantly to our observations along the Newberry track. Since anisotropy in the lower mantle and transition zone is typically less than 0.2s [26,28–30], the upper mantle is the most important source of our anisotropic signal. Given that the lithosphere is thin beneath the array [31–33], the observed splits are most likely from an asthenospheric source. This interpretation is consistent with previous studies in the Pacific Northwest [33–36].

Although high stress plus enriched water content or melt-rich layers can cause a  $90^\circ$  rotation of the fast axis of olivine with respect to strain [37,38], these conditions are uncommon in natural environments [39–41]. Along the

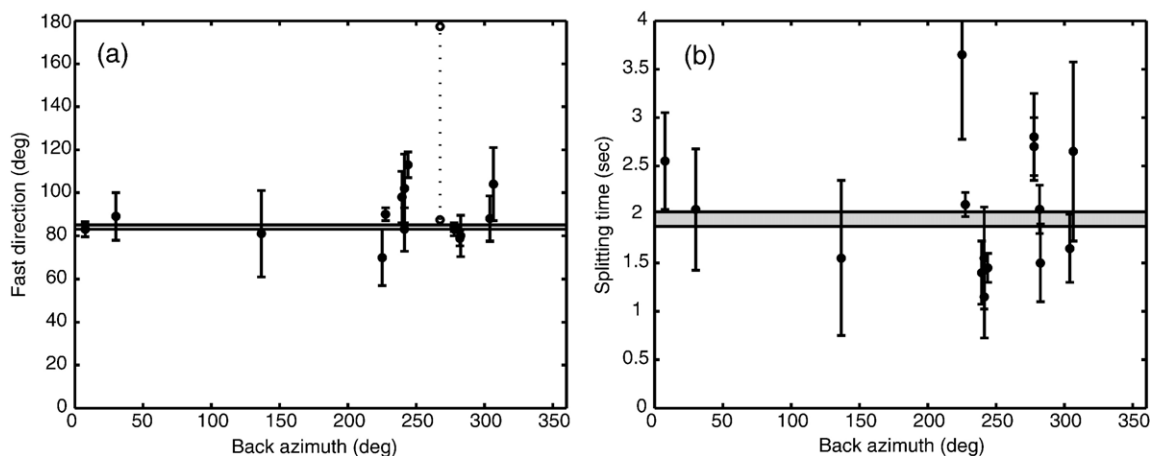


Fig. 3. Splitting parameters (a) the fast splitting direction and (b) the splitting time as a function of event back azimuth for station OT09. Black dots and vertical solid lines indicate splitting parameters and corresponding uncertainties, respectively. Circles connected by dot lines indicate two candidate fast directions for null results. Horizontal gray bars illustrate the best-fit  $\phi$  and  $\delta t$  calculated from stacking all splitting observations at OT09.

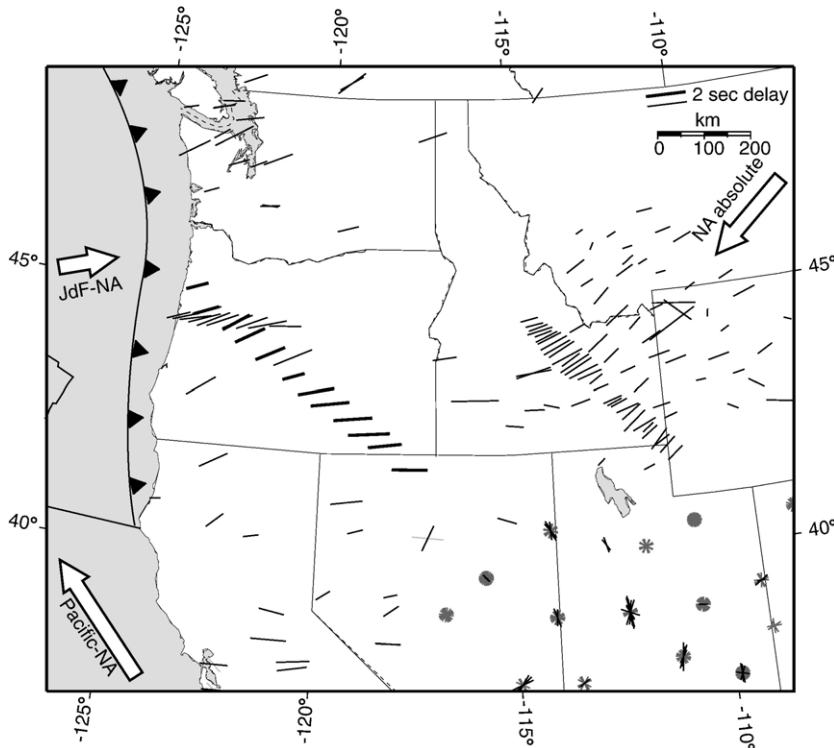


Fig. 4. Oregon splits shown in regional context. Oregon splits are plotted as thick black lines; other measured splits are shown with thin, solid lines; and null splits are plotted as short light gray lines [33–36,44–47,53,54].

OATS array, if such conditions exist, they are most likely at the NW end, which is adjacent to the trench where the subducting slab may introduce water and increase the stress level. However, the influence of the subduction zone on the asthenosphere would not extend beneath the entire array to the SE. Considering the similarity of the fast directions observed along the OATS array from the NW to the SE, and also the consistency with regional results further inland to the east (Fig. 4), it is unlikely that subduction is causing a  $90^\circ$  rotation of the fast axis with respect to the flow direction. We therefore interpret our observed fast directions as aligned with the mantle flow direction [30,42,43].

#### 4. Discussion

The observed fast directions along the Newberry Hotspot Track are consistent with the contiguous regional pattern of anisotropy (Fig. 4). The ENE–WSW fast direction of OATS adjacent to the coast is consistent with splitting observations from other studies west of the Cascades and parallel to the subduction direction of the Juan de Fuca Plate [44–47]. The fast direction rotates to E–W inland along the OATS array consistent with observations in the Western Snake River Plain [35].

Further east, uniform southwest orientation of SKS splits has been observed in Yellowstone and the Eastern Snake River Plain, and has been interpreted as a single asthenospheric layer of anisotropy due to the southwesterly motion of North American Plate [33,34,36,46].

Our uniform splitting orientations suggest a relatively simple anisotropic structure beneath the OATS array, and they are not parallel to the absolute plate motion of the North American Plate, as observed to the east around Yellowstone and the Eastern Snake River Plain [33,34,36,46]. Our splitting orientations are generally parallel to the subduction direction of the Juan de Fuca Plate west of the Cascades, and more E–W to stations east of OT05, which marks the west boundary of Basin and Range extension. Therefore, the E–W orientation of fast axes may reflect west-directed Basin and Range extension, which is generally E–W to NW–SE [2]. However, we should be aware of that there may be a more complex interaction, and other tectonic processes, such as the flow associated with the subduction of the Gorda slab, Oregon’s clockwise rotation, and the influence of nearby Pacific–North America shear or slab roll back, etc., may generate or contribute to the observed anisotropy pattern, which are beyond what our data can constrain.



The first order observation is that the orientation of fast axes along the OATS array are not aligned with the Newberry Hotspot Track, indicating that either the splits are not sensitive to mantle flow oriented along the track or the track is not the product of asthenospheric flow. We prefer the second explanation as our SKS splits show that the orientation of fast axes do not vary with depth. If the Newberry track was the product of asthenosphere flow moving northwest across Oregon, as the subduction counterflow model or the gravitational flow model suggests, we would expect fast splitting directions parallel to the track. Instead our splitting orientations are generally parallel to Juan de Fuca Plate subduction and fit into a much broader regional picture. Given these preliminary observations we suggest that the progressive volcanism across Oregon is more likely a product of lithosphere-controlled processes.

Propagation of lithospheric faulting [19–21] and the extension of Basin and Range [2,11] are two candidate lithospheric processes which have been suggested as responsible for the formation of the Newberry Hotspot Track. Oregon has several NW-trending strike-slip faults oriented parallel to the trend of the Newberry track (Fig. 1). The Brothers Fault Zone is coincident with the northern belt of volcanism within the Newberry track, and has been interpreted as the northern termination of the Basin and Range accommodating the right-lateral, strike-slip motion between areas of significant extension to the south and areas of much less extension to the north [2,48,49]. The transcurrent motion is accommodated by short, small offset, and NE-trending normal faults arranged en echelon to the NW-trending Brothers Fault Zone [50]. Field relations show that extension of these faults is coeval with the eruption of relatively young basalts [18], leading to the interpretation that extensional/transensional deformation is facilitating the Newberry volcanic progression [20]. However, new field evidence suggests that the faulting has not propagated across the province in the time frame of migrating volcanism, but rather has occurred throughout the province since at least 7.5 Ma [3,17].

Alternatively, the extension of Basin and Range has been proposed as the cause of the Newberry track [2,11]. In this scenario, the interaction of the North American, Pacific, and Farallon plates formed two separate transform zones between the Pacific and North American plates, separated by the remnant subduction of Farallon Plate (i.e. the Juan de Fuca Plate) beneath North American Plate. By 17 Ma, the remnant subduction zone became so short due to the migrating triple junction of these three plates and the two transform zones became partially coupled. This coupling produced an E–W to

NW–SE extension within part of the North American Plate with an axis parallel to the continental margin through the present Great Basin to the Columbia Plateau. This extension initiated a melting anomaly along the western margin of the Archean craton, forming the kernel from which both the Yellowstone hotspot and the Newberry melting anomaly could propagate. As the central extending region approached a stable configuration, active extension and basaltic magma generation became increasingly concentrated outward toward the margins. The extension was further enhanced where the extending margin intersected the transform boundary with thicker, cooler, more rigid lithosphere to the north. The enhanced extension at the north margin of the extending and thinning lithosphere produced crustal melting at the western side of the melting kernel, and which propagated northwestward with extensional widening to form the Newberry Hotspot Track. While this model is consistent with previous estimates of ~10–35% extension across the Great Basin during the past ~17 Ma [2,51], Jordan [2005] argues that the deformation in the High Lava Plain was minor, probably about 1% extension over ~8 m.y., insufficient to drive a magmatic system by adiabatic decompression.

## 5. Conclusion

SKS splitting observations across Oregon suggest a simple pattern of anisotropy which varies smoothly across the region. We infer a single layer of anisotropy beneath the Newberry Hotspot Track that is most likely in the asthenosphere. The fast directions are oriented ENE–WSW to the west of the Cascades which is consistent with mantle shear parallel to subduction of the Juan de Fuca Plate. To the east, fast directions are more E–W, perhaps due to shear caused by Basin and Range. Since the observed fast directions are not parallel to the Newberry track, it is unlikely that asthenospheric flow is responsible for the age-progression volcanism. Instead, we suggest the Newberry track is the product of a lithosphere-controlled process. While progressive lithospheric faulting and the extension of Basin and Range have also been called upon to explain the formation of the Newberry track previously, supporting field evidence is still lacking.

## Acknowledgments

This work was supported by the Graduate School of the University of Wisconsin – Madison, the University of California – Berkeley, and the NSF (EAR-0539987). Helpful reviews were provided by Eugene Humphreys

and an anonymous reviewer. We thank Cecily J. Wolf and Paul G. Silver for their shear-wave splitting codes. The figures were produced with SAC and GMT [52].

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