Earth and Planetary Science Letters 365 (2013) 232–242

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Upper mantle seismic structure beneath the Pacific Northwest: A plume-triggered delamination origin for the Columbia River flood basalt eruptions

Amberlee Darold *, Eugene Humphreys

Department of Geological Sciences, University of Oregon, Eugene, OR 97403, USA

A R T I C L E I N F O

Article history:
Received 20 July 2012
Received in revised form
11 January 2013
Accepted 20 January 2013
Editor: Y. Ricard
Available online 1 March 2013

Keywords:
tomography
delamination
Columbia River basalt
flood basalt

A B S T R A C T

We invert teleseismic P and S body waves constrained by an ambient-noise surface wave model and Moho depth inferred from receiver function analysis (Gao et al., 2011) to image mantle structures continuously from the surface to the base of the upper mantle. The major structures coincide with prominent geological features. We focus on a NE-Oregon structure, termed here the Wallowa anomaly, which coincides with the source area for the ~16 Ma Columbia River flood basalt eruptions and a circular area of topographic relief created during and after these eruptions. Resolution tests indicate that the curtain-like structure previously interpreted as Farallon lithosphere connects with the Wallowa anomaly above 150 km along the northeast margin of the Wallowa anomaly. This connection, along with the pre-flood basalt magmatic and tectonic history of the Pacific Northwest, lead us to conclude that arrival of the Yellowstone plume to south-central Oregon initiated delamination of remnant Farallon lithosphere from the base of NE Oregon, exposing ocean crust to Yellowstone asthenosphere. This hypothesis accounts for the propagation of flood basalt volcanism far north of the Yellowstone hotspot track, and for the high-silica composition of most of the flood basalt magmas.

1. Introduction

The EarthScope USArray provides extensive teleseismic data coverage of the Pacific Northwest (PNW) for the first time, facilitating seismic images of the crust and upper mantle with greatly improved resolution (Roth et al., 2008; Sigloch et al., 2008; Tian et al., 2009; Xue and Allen, 2010; Schmandt and Humphreys, 2010a; Gao et al., 2011, Levander and Miller, 2012). In this paper we discuss our tomographic inversion of teleseismic P and S body waves for PNW upper mantle structure that are created under the constraints of 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 structures imaged beneath the PNW are a low-velocity volume beneath the Snake River Plain (Fig. 1a) that is thought to be created by the passage of the Yellowstone hotspot (Stachnik et al., 2008), and 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 are the high-velocity subducting Juan de Fuca slab, a strong low-velocity anomaly beneath north-central Oregon, and a high-velocity body beneath northeast Oregon, directly below the source area for the ~16 Ma Columbia River basalt (CRB) eruptions. This latter structure, its relation to the major high-velocity structure imaged beneath Idaho, and its relation to the CRB event, are the foci of our paper.

We conclude that the CRB eruptions were caused by a plume-triggered foundering of a fragment of Farallon lithosphere that was left at the base of North American lithosphere beneath northeast Oregon and southwest Washington at the end of the Laramide orogeny. This hypothesis is based on three observations and their straightforward interpretations. First, tectonic considerations place Farallon lithosphere at the base of North America beneath most of the Pacific Northwest at the end of the Laramide. Second, strong post-Laramide magmatism occurred shortly after the Laramide orogeny everywhere in the region except NE Oregon and SW Washington, suggesting that at this time the slab was removed from the base of North America everywhere except NE Oregon and SW Washington. Third, our upper mantle imaging finds a high-velocity anomaly beneath northeast Oregon that is connected with the high-velocity curtain-like structure thought to be the foundered Farallon lithosphere beneath Idaho. Below we outline the geologic history of the area with our hypothesis in mind, which we follow with discussion of the imaged upper mantle structure.

* Corresponding author.
E-mail address: adarold@uoregon.edu (A. Darold).

0012-821X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsl.2013.01.024

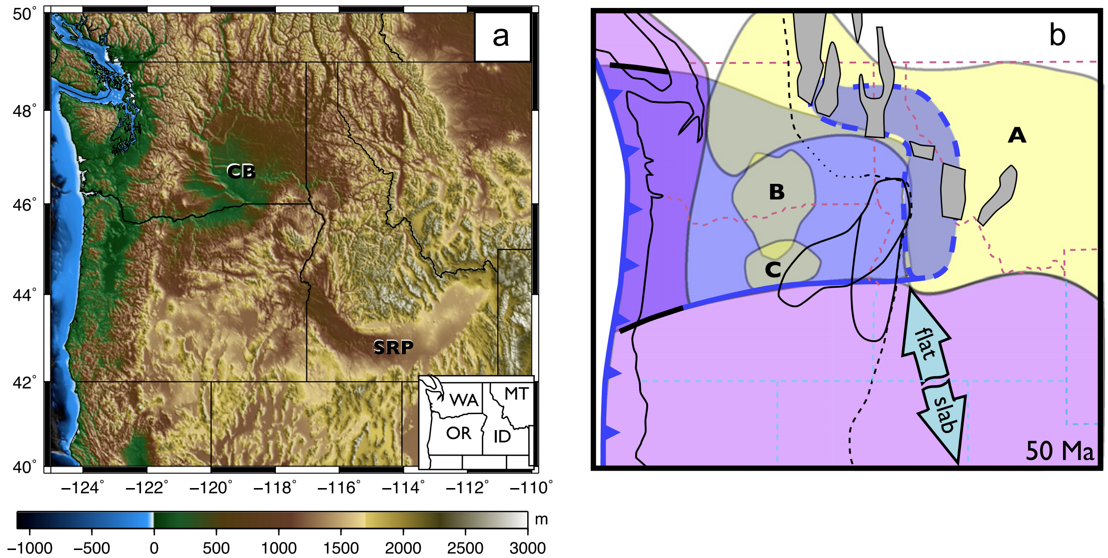

Fig. 1. (a) PNW topography (Simpson and Anders, 1992), with state lines. Notice circular range of mountains around the central Wallowa Mountains uplift at the NW end of the Snake River Plain (SRP) and SE of the Columbia Basin (CB). (b) Tectonic and magmatic elements at 50 Ma, shown on a present-day map (i.e., without palinspastic restoration). Purple is actively subducting Farallon lithosphere in contact with the base of North America, and blue is the Farallon lithosphere that accreted ~53 Ma. The Heavy blue line trending east across Oregon indicates location of slab tear between accreted Farallon lithosphere and flat-subducting Farallon lithosphere. The accreted Farallon lithosphere (blue) is present: at or near the surface beneath the costal ranges (bold black lines exposed Siletzia sutures); abandoned at the base of North America lithosphere beneath eastern Oregon and Washington; foundered from North America beneath Idaho and western Montana, where it is imaged hanging vertically (shown with dashed heavy blue outline, from Schmandt and Humphreys (2011)) and still attached to the flat-lying slab beneath eastern Oregon and Washington. Grey areas indicate active core complexes (generally above the foundered portion of slab) and yellow areas show regions of active magmatism, thought to be caused by slab foundering and rifting of the North America lithosphere. Note that SE Washington and NE Oregon remained amagmatic. Magmatic areas include (A) Absaroka–Challis–Kamloops (Madsen et al., 2006; Feeley, 2003; Schmandt and Humphreys, 2011), (B) Pasco Basin (Catchings and Mooney, 1988; area from region of inferred underplate, Gao et al., 2011), and (C) Clarno (Bestland et al., 1999). $^{87}Sr/^{86}Sr$ 0.706 line (from Van Buer and Miller (2010)) is dashed (dotted where inferred), and Blue Mountains terrain is shown with black outline (as accreted to North America and, to the west, in its present position). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.1. Geologic context prior to Steens–Columbia River basalt eruptions

By 120 Ma, the Blue Mountains terrain (through which the CRB later erupt) had docked in the forearc of an active north-trending volcanic arc that extended from California through Idaho (the western Idaho Batholith, Giorgis et al., 2005), northern Washington and beyond. The arc became decreasingly active during the course of the Laramide Orogeny, becoming essentially amagmatic by 55–60 Ma (Gaschnig et al., 2009). The Laramide Orogeny is expressed by strong thrusting within and east of the volcanic arc (Bird, 2002; Burchfiel et al., 1992; Wells et al., 2012) and the waning of arc magmatism throughout Idaho and northeastern Washington (Christiansen and Yeats, 1992; Gaschnig et al., 2009). Laramide thrusting and magmatic quiescence ended with the accretion of Farallon lithosphere ~53 Ma (the blue area in Fig. 1b). This lithosphere is exposed in the Coast Range of Washington and Oregon, where it has been given the name Siletzia. The timing of Siletzia accretion is based off geologic studies of the exposed sutures (bold black lines in Fig. 1b) in southern Vancouver Island and west-central Oregon (Wells et al., 2000). Gao et al. (2011) conclude that Farallon lithosphere occupies the lower crust beneath the Columbia Basin (Fig. 1a).

A phase of intense volcanism and extension occurred throughout most of the PNW during or very shortly after the accretion of Farallon lithosphere. This involved crust around most of the accretionary margin, including within and inboard of the Cretaceous arc in Washington, Idaho and Montana (Madsen et al., 2006; Christiansen and Yeats, 1992; Foster and Fanning, 1997). Magmatism began abruptly with the Challis–Kamloops–Absaroka volcanic flareup ~53 across Idaho and northern Washington, and the Clarno volcanics in north-central Oregon (Fig. 1b), starting perhaps as early as 54 Ma (Bestland et al., 1999; Retallack et al., 2000). Extension near the Cretaceous arc was dominated by core complexes (Armstrong and Ward, 1991; Coney and Harms, 1984; Foster et al., 2007). Challis–Kamloops–Absaroka lavas include adakites and shoshonites, which Madsen et al. (2006) and Schmandt and Humphreys (2011) attribute to melting of the basaltic slab crust. Extension and magmatism also involved the just-accreted Farallon lithosphere. This extension is most well known in the Pasco Basin (Catchings and Mooney, 1988; Gao et al., 2011), where it appears to be related to the extension in northern Washington (Wells et al., 1984; Miller and Bowering, 1990), and may include the Clarno volcanics in north-central Oregon (Fig. 1b). Within the broad region around the site of the CRB eruptions, northeast Oregon and southwest Washington standout as the one region that remained amagmatic following Farallon lithosphere accretion, and this area remained amagmatic until the CRB eruptions.

A commonly cited explanation for the PNW Eocene magmatic flareup (the magmatism labeled "A" in Fig. 1b) is the subduction of a spreading center that separated the Farallon plate from a "Resurrection plate" that was inferred to exist immediately north of the Farallon plate (Madsen et al., 2006; Breitsprecher et al., 2003). While accounting for the diverse magmas and the timing of this magmatism, we prefer a model in which accretion of Farallon lithosphere within the Columbia embayment left this slab abandoned at the base of North America, leading to a rollback-like foundering of this dynamically unsupported slab from the base of North America. Unlike the ridge subduction model, this model is consistent with the upper mantle curtain-like high-velocity structure imaged roughly beneath the areas of renewed magmatism in northern Washington and Idaho (Fig. 1b; Schmandt and Humphreys, 2011). They argue that an upper mantle high-velocity anomaly of this volume must be subducted ocean lithosphere, and its shape and location support this contention by being consistent with Farallon ocean lithosphere