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The lithosphere–asthenosphere boundary and the tectonic and magmatic history of the northwestern United States

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ABSTRACT

This study explores the properties of the lithosphere–asthenosphere boundary (LAB) and other shallow mantle discontinuities across the diverse geologic provinces of the northwest United States. Sp phases were used to image three-dimensional discontinuity structure by common conversion point stacking with data from 804 temporary and permanent broadband stations, including 247 from EarthScope's USArray Transportable Array. Substantial variations in mantle discontinuity structure are apparent over a variety of spatial and temporal scales. To the west of the Sevier Thrust Belt, a coherent Sp negative phase coincides with the LAB depth range inferred from tomographic models. To the east, within the stable craton, multiple negative phases typically occur in the high velocity lithospheric layer, although in places a single mid-lithospheric discontinuity is imaged. Sub-cratonic LAB phases are often absent, indicating an LAB velocity gradient that is distributed over >50 km and that is consistent with effects of temperature alone. Where weak and intermittent LAB phases appear, they suggest more vertically localized velocity gradients produced by other factors such as bulk composition, volatile content, or contrasts in grain size or melt. In the tectonically active west, a positive Sp phase at depths consistent with the base of the asthenospheric low velocity zone in tomography models is intermittently observed. Beneath magmatic provinces in the west, the LAB Sp discontinuity deepens by ∼10 km from the High Lava Plains, where magmatism has occurred from 0–10.5 Ma, to the northern region of the Columbia River Basalts, which has been magmatically quiet since 15 Ma. Here we suggest a model in which the negative LAB velocity gradient is created by a layer of partial melt ponding beneath a solidus-defined boundary. This model predicts that higher temperatures associated with more recent magmatism would result in a shallowing of the intersection of the geotherm with the solidus. Beneath the Yellowstone Caldera, the absence of an LAB Sp phase suggests that the contrast in seismic velocity between the lithosphere and asthenosphere has been erased by intrusion of partial melt and heat into the lithosphere.

1. Introduction

1.1. The lithosphere–asthenosphere boundary

The lithosphere is classically defined rheologically and kinematically as the rigid plate that translates coherently with surface plate motions. In this study we probe the properties of the mantle portion of the lithosphere as defined by its seismic wavespeed, i.e. the high velocity layer above the asthenospheric low velocity zone.

The primary mechanisms for the velocity decrease from lithosphere to asthenosphere are temperature, volatile content, bulk composition, partial melt, grain size, and anisotropic fabrics, all of which can be reset by tectonic and magmatic processes. Here we image the seismologically-defined lithosphere–asthenosphere boundary (LAB) and other shallow mantle discontinuities across the diverse geologic provinces of the northwest United States. Our goal is to better understand the mechanisms responsible for producing the seismically observed LAB and how the LAB and other mantle discontinuities relate to the region's tectonic and magmatic evolution.

1.2. Tectonic and magmatic setting and prior studies of seismological structure

The tectonic and magmatic evolution of the northwestern United States is expressed over several different temporal and spatial scales. At the broadest scales, our study region is divided along the Sevier Thrust Belt into a western region that

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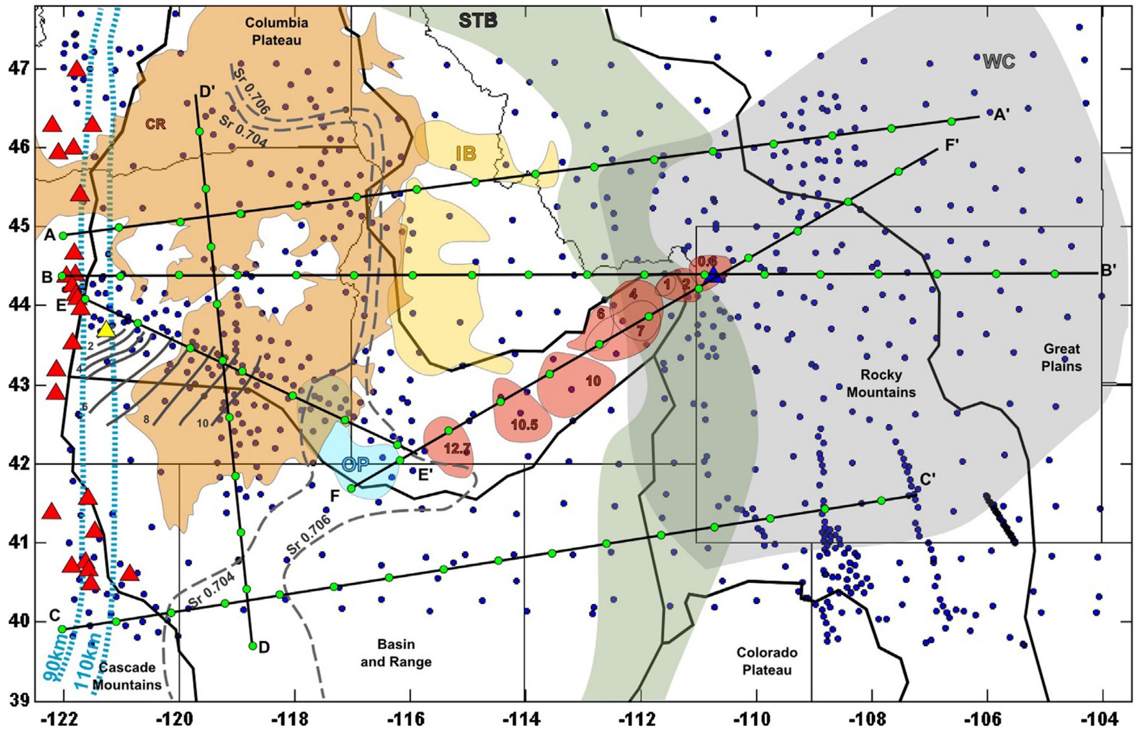

Fig. 1. Map of the study area. Thick black lines with green circles: cross-section locations. Dark blue circles: broadband stations that contributed data to this study. Red triangles: arc volcanoes. Yellow triangle: Newberry Volcano. Blue triangle: Yellowstone Caldera. Red shaded areas: rhyolitic calderas in the eastern Snake River Plain, with age in Ma, after Smith et al. (2009). Grey shaded area (WC): Wyoming Craton, after Foster et al. (2006). Green shaded area (STB): Sevier fold and thrust belt, after DeCelles and Coogan (2006). Orange shaded area (CR): Columbia River flood basalts and Steens basalts, after Camp and Ross (2004). Yellow shaded area (IB): Idaho Batholith, after Gaschnig et al. (2011). Blue shaded area (OP): Owyhee Plateau, after Shoemaker (2004). Dashed grey lines (Sr 0.704 and Sr 0.706): Sr lines, after Eagar et al. (2011). Solid grey lines: isochrons showing age progression of the High Lava Plains silicic volcanism, labeled with earliest age in Ma, after Eagar et al. (2011). Hatched light blue lines: contours of depth to top of Juan de Fuca slab, labeled with depth, after McCrory et al. (2006). Thick black lines: boundaries between tectonic provinces, labeled in black, from Fenneman and Johnson (1946). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

has experienced significant deformation and magmatic activity throughout the Phanerozoic, and an eastern region where deformation has been less extensive, particularly in the last 50 My (Fig. 1). The Archean Wyoming Craton forms the core of the eastern region, though there are also other ancient, stable continental blocks, including the Medicine Hat Block and the Colorado Plateau (Foster et al., 2006; Fig. S3). The ancient continental blocks extending several hundreds of kilometers west of the Sevier Thrust Belt – i.e. the Paleoproterozoic Selway Terrane and Archean Grouse Creek Block – underwent greater degrees of tectonic and magmatic reworking (Foster et al., 2006). These blocks are bounded on the west by Phanerozoic accreted terranes, a boundary often associated with strontium isopleths, with $^{87}Sr/^{86}Sr$ decreasing westwards (Armstrong et al., 1977; Coney et al., 1980).

Phanerozoic tectonism was dominated first by subduction and orogenesis. Convergence has included the Cretaceous to Eocene Sevier and Laramide Orogenies. While the Sevier Thrust Belt marks the eastern limit of the Sevier Orogeny, Laramide deformation extended further east, building the Rocky Mountains (Dickinson, 2004; Saleeby, 2003; Tikoff and Maxson, 2001). By the Early Miocene, part of the convergent boundary on the continental margin had converted to the San Andreas transform. Consequent Basin and Range extension is estimated to have reached values of 50% or more within the study area (Dickinson, 2004; McQuarrie and Wernicke, 2005).

One feature common to many recent tomography models is the marked transition from shallow upper mantle with low seismic velocities in regions that have experienced high degrees of tectonic reworking and magmatism to a thick, high velocity mantle layer elsewhere (e.g. Burdick et al., 2012; Darold and Humphreys, 2013; James et al., 2011; Obrebski et al., 2011; Schmandt and Humphreys, 2010; Shen et al., 2013; Sigloch, 2011; Yuan et al., 2011). South of ∼45° N, this transition appears at the eastern margin of the Basin and Range and Snake River Plain, with the exception of lower velocity upper mantle beneath the High Rockies south of the Wyoming Craton. In the northern portion of our study region, the transition typically occurs further west at longitudes of 118°–119° W.

The region has experienced a long and varied magmatic history. The Columbia River Flood Basalts, emplaced between 16.6 and 15.0 Ma (Camp et al., 2003; Hooper et al., 2002), outcrop in the northwest of the study region (Fig. 1). Their southern lobe was overprinted by later High Lava Plains volcanism. In the High Lava Plains, a wave of silicic volcanism started at ∼15.5 Ma and has propagated towards the northwest (e.g. Jordan et al., 2004). Recent work extends this trend into the northwest Basin and Range to 12 Ma (Ford et al., 2013). Along the eastern Snake River Plain, silicic volcanics decrease in age from 12–0 Ma in the direction opposite to North American plate motion, culminating in the active volcanism beneath Yellowstone Caldera (e.g. Christiansen et al., 2002; Pierce and Morgan, 2009, 1992; Shervais and Hanan, 2008). In both the High Lava Plains and eastern Snake River Plain, basaltic magmas have erupted since 10.5 Ma with no age-progressive trend (e.g. Christiansen et al., 2002; Jordan et al., 2004; Till et al., 2013a).

In the High Lava Plains area, low velocities are observed to shallow mantle depths, implying small lithospheric thicknesses (Wagner et al., 2010; Obrebski et al., 2011; Hanson-Hedgecock et al., 2012; Gao and Shen, 2014). Furthermore, temperatures and pressures of basaltic melt equilibration indicate that asthenospheric conditions exist at very shallow mantle depths