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Ps mantle transition zone imaging beneath the Colorado Rocky Mountains: Evidence for an upwelling hydrous mantle

Zhu Zhang *, Kenneth G. Dueker, Hsin-Hua Huang

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ABSTRACT

We analyze teleseismic P-to-S conversions for high-resolution imaging of the mantle transition zone beneath the Colorado Rocky Mountains using data from a dense PASSCAL seismic broadband deployment. A total of 6,021 P-to-S converted receiver functions are constructed using a multi-channel minimum-phase deconvolution method and migrated using the common converted point technique with the 3-D teleseismic P- and S-wave tomography models of Schmandt and Humphreys (2010). The image finds that the average depths of the 410-km discontinuity (the 410) and 660-km discontinuity (the 660) at 408 $\pm$ 1.9 km and 649 $\pm$ 1.6 km respectively. The peak-to-peak topography of both discontinuities is 33 km and 27 km respectively. Additionally, prominent negative polarity phases are imaged both above and below the 410. To quantify the mean properties of the low-velocity layers about 410 km, we utilize double gradient layer models parameterization to fit the mean receiver function waveform. This waveform fitting is accomplished as a grid-search using anelastic synthetic seismograms. The best-fitting model reveals that the olivine–wadsleyite phase transformation width is 21 km, which is significantly larger than anhydrous mineral physics prediction (4–10 km) (Smyth and Frost, 2002). The findings of a wide olivine–wadsleyite phase transformation and the negative polarity phases above and below the 410, suggest that the mantle, at least in the 350–450 km depth range, is significantly hydrated. Furthermore, a conspicuous negative polarity phase below the 660 is imaged in high velocity region, we speculate the low velocity layer is due to dehydration flux melting in an area of convective downwelling. Our interpretation of these results, in tandem with the tomographic image of a Farallon slab segment at 800 km beneath the region (Schmandt and Humphreys, 2010), is that hydrous and upwelling mantle contributes to the high-standing Colorado Rocky Mountains.

1. Introduction

1.1. The Colorado Rocky Mountains

The Colorado Rocky Mountains (CRM) has ∼1700 m of excess topography with respect to the adjacent Colorado Plateau and High Plains (Hansen et al., 2013). It is commonly believed that the early Cenozoic uplift of the CRM was due to Farallon plate subduction during the Laramide Orogeny (e.g. Eaton, 1987). Hypothesized mechanisms for the late-Cenozoic uplift of the Colorado Plateau and CRM includes: post-Laramide removal and/or segmentation of the Laramie slab with asthenospheric upwelling between 50 to 20 Ma (e.g. Humphreys, 1995); or, convective sinking of the lower crust and lithosphere (Karlstrom et al., 2012; Levander et al., 2011). The Colorado Rockies Experiment and Seismic Transects (CREST) project addresses questions regarding how mantle convection beneath the CRM has influenced the tectonic history using seismology, geochronology, geochemistry and flexural modeling.

Teleseismic body wave tomography models reveal complicated mantle structure beneath the CRM with low velocity structure that extends into the lower mantle (e.g. Schmandt and Humphreys, 2010). Additionally, a tomographically imaged high velocity anomaly, interpreted to be a Farallon slab segment at 800 km depth, is found beneath the CRM that may produce mantle upflow beneath this region due to flow around the edge of the sinking slab segment (Faccenna and Becker, 2010; Liu and Stegman, 2011).

A recent study provides new constraints on the CRM crustal structure via receiver function imaging and finds that the CRM crust is thinner with respect to adjacent regions, therefore termed the “Rootless Rockies” (Hansen et al., 2013). Hence, the normal thickness CRM crust and the 1,700 m of the excess CRM topography is not supported by crustal Airy isostasy. Therefore, a low-density mantle buoyancy influx is an alternate hypothesis to explain these findings (e.g. Levandowski et al., 2014). A useful ap-

* Corresponding author.
E-mail address: zhuzhang@earth.sinica.edu.tw (Z. Zhang).

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proach to address mantle fluxes is to investigate the characteristics of the mantle transition zone seismic discontinuities beneath the CRM.

1.2. Mantle transition zone

The mantle transition zone (MTZ) is delimited by the 410-km discontinuity (410) and the 660-km discontinuity (660), and is potentially a hydrous reservoir globally (Thio et al., 2016). The 410 corresponds to phase transition of olivine (α) to wadsleyite (β). However, the 660 undergoes multiple phase transitions including the ringwoodite (γ) to perovskite and magnesiowüstite ($pv+mw$) (e.g. Bina and Helffrich, 1994) and majorite-garnet (gt) to ilmenite (il), to perovskite (pv) reactions (e.g. Akaogi and Ito, 1999). The Clapeyron slopes (dP/dT) of these phase transitions have been constrained from *in situ* X-ray diffraction experiments that find the opposing Clapeyron slopes range from +1.5 to +4.0 MPa/K for the $\alpha \rightarrow \beta$ reaction and from −3.1 to −0.4 MPa/K for the $\gamma \rightarrow pv+mw$ reaction (Fei et al., 2004; Katsura et al., 2003, 2004). For $ga \rightarrow il \rightarrow pv$, the Clapeyron slope is positive (Akaogi and Ito, 1999). In this study, we attribute the discontinuity topography primarily to olivine phase change as olivine is the dominant mineral in upper mantle.

Besides thermally induced discontinuity topography, hydration can affect both discontinuities depth and phase transformation width (Smyth and Jacobsen, 2006; Karato et al., 2006; Karato, 2011), and reduce P- and S-wave seismic velocities (Thio et al., 2016). In hydrous condition, the ratio of water partitioning between olivine, wadsleyite, ringwoodite and perovskite is 6:30:15:1 (Dai and Karato, 2009). The pressure interval of the olivine–wadsleyite phase transition is 1.0 ± 0.5 GPa in hydrous, near saturated condition, which is much broader than the anhydrous width; hence, the width of the phase transformation increases from 12 km to 40 km (Smyth and Frost, 2002). For the 660, the magnitude of the Clapeyron slope can increase from −0.5 MPa/K at anhydrous condition to −2.0 MPa/K at ~1 wt.% hydration (Litasov et al., 2005). Therefore, increasing hydration level has the same effect as reduced temperature: elevating the 410 and depressing the 660 while broadening the phase transformation of both discontinuities (Jacobsen and Smyth, 2006).

1.3. Low velocity layers surrounding mantle transition zone

A low velocity layer just above the 410 (410-LVL) has been observed in numerous seismic studies using a variety of seismic phases (e.g. Courtier and Revenaugh, 2007; Schmandt et al., 2011; Hier-Majumder and Tauzin, 2017; Tauzin et al., 2013). Because thermal and chemical heterogeneities are incapable of making the 410-LVL, the leading interpretation of the 410-LVL is that it manifests partially molten layer induced by dehydration flux melting. The 410-LVL phase has been recognized as a global feature with up to ~90 km thickness and ~10% S wave velocity reduction (Tauzin et al., 2010; Wei and Shearer, 2017). A 0.7% melt fraction containing 0.22 ± 0.02 wt.% water of total water content in the MTZ can be gravitationally stable at the base of upper mantle (Freitas et al., 2017).

Geodynamic calculations suggest that a 0.5% melt fraction across the western U.S. (1.5–2% localized) can extend up to 70 km above the 410 to explain the 410-LVL phase (Hier-Majumder and Tauzin, 2017) and this phase is consistent with the prediction of the transition zone water filter (TZWF) model (Bercovici and Karato, 2003; Leahy and Bercovici, 2007). If the MTZ is hydrated and flowing upwards, hydrous partial melting can be produced just above the 410 due to the water solubility contrast between olivine and wadsleyite. Correspondingly, in a down-flowing mantle a pre-existing melt layer above the 410 can be advected back down into the MTZ to produce a quenched hydrous wadsleyite layer (Leahy and Bercovici, 2007).

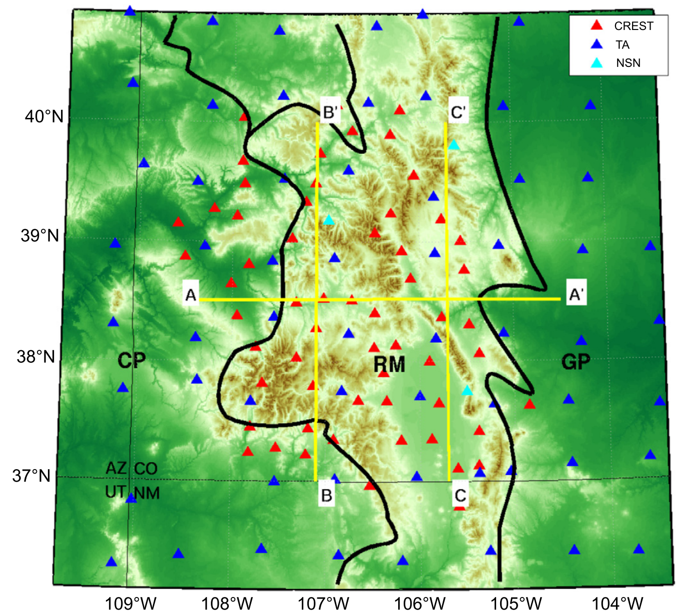

Fig. 1. Topography of the Colorado Rocky Mountains with locations of seismic stations. Seismic stations are: the CREST array (red triangles), USArray Transportable Array stations (blue triangles) and NSN stations (cyan triangles). Geologic provinces include the Colorado Rocky Mountains (RM), the Great Plains (GP), and the Colorado Plateau (CP). Province boundaries are outlined by black lines and the yellow lines denote cross sections. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

Additionally the existence of secondary discontinuities just above the 660 has been reported globally with 2.2% S-wave reduction (Shen et al., 2014) and at a regional scale (Eagar et al., 2010; Tauzin et al., 2013). Tauzin et al. (2017) speculated these converters are due to compositional heterogeneities from stagnant slabs or a possible phase transformation of ilmenite. Just below the 660, Schmandt et al. (2014) suggested that a negative velocity gradient discontinuity is due to dehydration melting in a downward mantle flow.

In this study, we use P-to-S receiver function (PRF) to investigate seismic structures surrounding the MTZ beneath the CRM region. One of our remarkable observations is the presence of low velocity layers both above and below the 410, and uppermost lower mantle beneath the CRM associated with high velocity anomalies. Together with the existence of low velocity anomalies in tomography models, we therefore speculate that the mantle is upwelling and hydrous.

2. Data set

We deployed 59 IRIS-PASSCAL three-component broadband seismic stations within the CRM from August 2008 to November 2009 to acquire 15 months of continuous seismic data. Additionally, the CREST array had nearly 100% temporal overlap with 35 EarthScope Transportable Array stations (Fig. 1). The combined arrays result in a 94-station seismic array with a station spacing of 25–40 km.

During the CREST deployment period, waveforms from 110 teleseismic events (Fig. 2) with magnitudes >5.5 and epicentral distance between 30° and 95° from the array center were obtained from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center. The events were manually selected based on the signal–noise ratio of the vertical components.

The seismic recordings were manually windowed from 10 s before to 130 s after the observed direct P arrivals. The three-