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Lithospheric layering beneath the contiguous United States constrained by S-to-P receiver functions

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ABSTRACT

To image upper mantle seismic discontinuities beneath the contiguous United States, a total of 284,121 S-to-P receiver functions (SRFs) recorded by 3,594 broadband seismic stations in the EarthScope Transportable Array and other permanent and temporary deployments are stacked in circular bins of 2° in radius. A robust negative arrival, representing a sharp discontinuity of wave speed reduction with depth, is visible in virtually all the stacked traces in the depth range of 30–110 km. Beneath the western U.S., the mean depth of this discontinuity is 69 ± 17 km, and beneath the eastern U.S., it is 76 ± 5 km, both are comparable to the depth of the tomographically-determined lithosphere–asthenosphere boundary (LAB). In contrast, the depth of the discontinuity beneath the stable cratonic region of the central U.S. is 87 ± 6 km, which is significantly shallower than the $\sim$250 km LAB depth determined by seismic tomography. Based on the amplitude of the corresponding arrival in the SRFs and findings from previous seismic tomography and mantle xenolith studies, this discontinuity beneath the central U.S. is interpreted as the top of an intra-lithospheric low wave speed, probably phlogopite-rich layer. The observations provide new constraints on a number of regional scale tectonic processes, such as lithospheric stretching in the Texas–Louisiana Gulf Coastal Plain and the Basin and Range Province, and possible lithospheric basal erosion beneath the northeastern U.S.

1. Introduction

Reliably mapping the thickness and layering of the lithosphere, which is the outermost rigid shell of the Earth, is essential in understanding upper mantle structure and dynamics (McKenzie and Priestley, 2008). Two of the most frequently employed seismological techniques for investigating lithospheric thickness and layering are surface wave tomography (McKenzie and Priestley, 2008; Bedle and van der Lee, 2009; Schaeffer and Lebedev, 2014; Caló et al., 2016) and stacking of receiver functions which are P-to-S or S-to-P converted phases (P_s and S_p, respectively) from wave speed discontinuities at the bottom of or inside the lithosphere (Rychert and Shearer, 2009; Fischer et al., 2010; Kind et al., 2012). Surface wave tomography can detect gradual variations in wave speed gradient, but is insensitive to sharp discontinuities due to low vertical resolution (Li et al., 2007; Rychert et al., 2007). In contrast, P-to-S receiver functions are widely used for imaging the Moho and mantle transition zone discontinuities (Zhu and Kanamori, 2000; Gao and Liu, 2014; Liu et al., 2017), but are not effective to study lithospheric discontinuities because of the strong Moho multiples in the expected time window of the arrivals associated with the discontinuities (Faber and Müller, 1980). Instead, lithospheric discontinuities are commonly imaged using S-to-P receiver functions (SRFs), in which the S_p arrivals are precursors to the direct S-wave. Because the Moho multiples appear after the direct S-wave, a separation of the primary converted phases and the multiples is expected on the SRFs (Faber and Müller, 1980). Relative to surface wave tomography, SRF stacking has the disadvantage that only sharp discontinuities can be detected. Tests suggest that a discontinuity that is 50 km or thicker cannot generate observable S-to-P converted phases (Kumar et al., 2012).

Beneath the contiguous United States (Fig. 1), the observed lithospheric thickness from most surface wave tomography studies demonstrates similar spatial variations, with values as small as less than 70 km beneath the western U.S., 90–150 km along the Rocky Mountains, Colorado Plateau, and Appalachians, and about 250 km beneath the tectonically stable cratonic region of the central U.S. (McKenzie and Priestley, 2008; Bedle and van der Lee, 2009; Schaeffer and Lebedev, 2014). The observed spatial variations of lithospheric thickness correspond well with measurements from shear wave speed gradient (Yuan and Romanowicz, 2010), electrical conductivity (Murphy and Egbert, 2017), mantle xenolith

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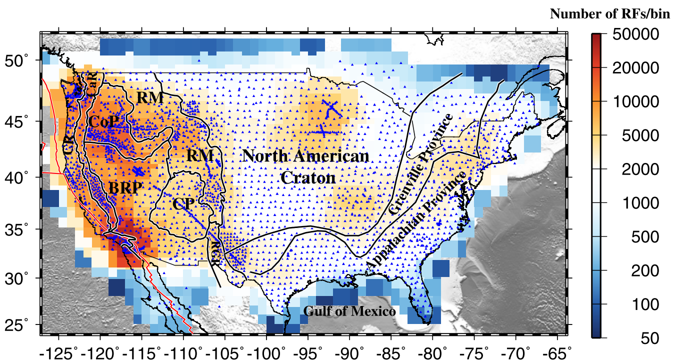

Fig. 1. Number of S receiver functions in radius = 2° circular bins and broadband seismic stations (blue triangles) used in the study. The thick black lines delineate major tectonic provinces. CR: Coast Ranges, CaR: Cascade Range-Sierra Nevada, CoP: Columbia Plateau, BRP: Basin and Range Province, RM: Rocky Mountains, CP: Colorado Plateau, and RGR: Rio Grande Rift (Hoffman, 1988). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

(Mareschal and Jaupart, 2004), and shear wave splitting (Yang et al., 2014).

A number of SRF studies have been conducted over the past decade to image lithospheric discontinuities beneath North America (Li et al., 2007; Rychert et al., 2007; Abt et al., 2010; Lekić et al., 2011; Kind et al., 2012; Kumar et al., 2012; Levander and Miller, 2012; Lekić and Fischer, 2014; Hansen et al., 2015; Hopper and Fischer, 2015; Reeves et al., 2015). Most previous work report a sharp negative-wave speed discontinuity (NVD) in the depth range of 40–180 km beneath the contiguous U.S. The NVD beneath the western and eastern U.S. has a depth ranging from 40 to 110 km, which is similar to the depth of the lithosphere–asthenosphere boundary (LAB) revealed by surface wave tomography, and is consequently considered as the bottom of the lithosphere (Rychert et al., 2007; Abt et al., 2010; Hansen et al., 2015). In contrast, the depth of the NVD beneath the central U.S. ranges from 80 to 180 km (Kumar et al., 2012; Hansen et al., 2015), which is significantly smaller than the ∼250 km depth determined using surface wave tomography (McKenzie and Priestley, 2008; Bedle and van der Lee, 2009). The NVD is therefore regarded as a mid-lithospheric discontinuity (MLD) rather than the LAB beneath most areas of the central U.S.

The current study is motivated by a number of factors. First, previous SRF studies used none or only part of the EarthScope Transportable Array (TA) stations (Fig. 1), leading to limited station coverage especially for the eastern U.S. Second, there are apparent discrepancies among existing SRF investigations in the resulting depth of the NVD (see Fig. 8 in Hansen et al., 2015 for a comparison of results from four SRF studies). For instance, in the stable cratonic region of the central U.S., the depth is ∼100 km in Kumar et al. (2012) and Hopper and Fischer (2015), but is as large as 160 km in Hansen et al. (2015). Such discrepancies are most likely caused by the different methodologies used by the different studies, as well as the weak signal from the target discontinuities and the consequent uncertainties in reliably identifying the correct arrivals, especially when a small bin size for stacking is used to reach a high lateral resolution (e.g., the radius is about 0.4° in Hansen et al., 2015). In this study, we use a relatively large bin size (radius = 2°) to obtain more reliable results with a comparatively lower resolution for the whole contiguous U.S. Third, while it is known that the stacking amplitude of the negative arrival from the NVD is a significant parameter to quantify the sharpness of the interface to provide additional constraints on the nature of the discontinuities (Abt et al., 2010), spatial variation of the amplitude over the entire study area remains absent. Finally, some of the SRF studies (Li et al., 2007; Kumar et al., 2012; Hansen et al., 2015) briefly discussed the possibility that the negative arrival beneath the Moho could be a side-lobe of the strong S-to-P conversion from the Moho. Although this possibility has been considered as unlikely based on the strong amplitude of the negative arrival and the occasionally independent structure of the Moho and the NVD, a systematic synthetic study to confirm this is still lacking.

In this study we use all the available broadband seismic data recorded prior to January, 2016, including those from all the TA stations, to image the depth of and SRF stacking amplitude associated with lithospheric discontinuities beneath the contiguous U.S., with an unprecedented station coverage for the area. Additionally, we perform synthetic test on the possibility that the observed negative arrival corresponding to the NVD is an artifact from the Moho.

2. Data and methods

The broadband seismograms used in the study are obtained from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) using BREQ_FAST. A total of 3,594 stations contributed to the dataset, including 1,667 TA stations which sample the study area with an ∼70 km interval. The seismograms are recorded within a duration of up to 28 yrs, from January 1988 to January 2016, during which all the USArray TA stations have finished their recording in the study area (125°W–65°W and 25°N–50°N). We use the following empirical formula for the cutoff magnitude (M_c) similar to that used by Liu and Gao (2010) to balance the quantity and quality of the requested seismograms, i.e., $M_c = 5.2 + (\Delta - 30.0)/(180.0 - 30.0) - D/700.0$, where Δ is the epicentral distance in degree which is between 60° and 85° for the study, and D is the focal depth in km. The requested seismograms are then trend-removed and band-pass filtered in the frequency band of 0.06–0.6 Hz. Those with a direct S-wave signal-to-noise ratio of 1.5 or greater on the radial component are selected to compute SRFs. The three-component ZNE (vertical, N-S, E-W) seismograms are rotated to LQT (P, S_V, S_H) components on the basis of theoretical back-azimuth and incident angle (Farra and Vinnik, 2000). The L component is in the propagation direction of the incident S-wave, primarily containing S_p energy and nearly zero direct S-wave energy for horizontally layered homogeneous media. The Q component, which is perpendicular to the L component, contains significant direct S_V-wave energy that can partially convert to P-wave at sharp wave speed discontinuities (Farra and Vinnik, 2000). The rotated seismograms are time-reversed so that the S_p wave arrives after the direct S-wave and the crustal multiples prior to the S-wave. Subsequently, the L component is deconvolved in the time-domain by the S signal on the Q component to generate SRFs for the purpose of eliminating the influence of the source (Langston, 1979; Kumar et al., 2012). The arrival time of the S_p wave in the SRFs depends on the depth of the discontinuity, the wave speeds in the overlying layer, and the ray parameter of the direct S-wave, whereas its amplitude is proportional to the wave speed contrast across and the sharpness of the discontinuity.

The procedure to moveout correct and stack the SRFs follows the common conversion point (CCP) technique (Dueker and Sheehan, 1997), and is similar to the one that Gao and Liu (2014) used for imaging the mantle transition zone discontinuities across the contiguous U.S. To remove the influence of the ray parameter on the arrival times, moveout correction is applied prior to stacking the SRFs using (Sheriff and Geldart, 1982; Dueker and Sheehan, 1997)

$$T_{Sp} - T_S = \int_{-h}^{0} \left[\sqrt{(V_s(z)^{-2} - p^2} - \sqrt{V_p(z)^{-2} - p^2}\right] dz, \qquad (1)$$