

Supporting Information for

Crust and Upper Mantle Structure Beneath the Eastern United States

Chengping Chai¹, Charles J. Ammon², Monica Maceira¹, Robert Herrmann³

¹Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

²Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, U.S.A.

³Department of Earth and Atmospheric Sciences, Saint Louis University, St. Louis, Missouri, U.S.A.

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Introduction

This supplement includes paragraphs describing cross-sections B1-B2, D1-D2, E1-E2, F1-F2, G1-G2, and H1-H2 (Text S1); a figure showing the relative data variance of receiver functions (Figure S1); a figure showing example surface-wave dispersions (Figure S2); a figure showing Bouguer gravity maps before and after wavenumber filtering (Figure S3); a comparison of single-station receiver functions and smoothed receiver functions (Figure S4); a figure showing the convergence of the simultaneous inversion (Figure S5); a figure showing receiver function misfit (Figure S6); a figure showing surface-wave dispersion misfit (Figure S7); a comparison of observed gravity maps and predicted gravity maps (Figure S8); a comparison of EARS crust thickness smoothing (Figure S9); a comparison of crustal thickness maps from recent seismic velocity models (Figure S10); a figure showing the distributions of crustal and uppermost mantle P-wave velocities (Figure S11); a comparison of upper mantle shear speed at 63 km depth in western and eastern U.S. (Figure S12); maps showing cluster locations (Figure S13 and S15); Velocity profiles for each cluster (Figure S14 and S16); a map showing locations of cross-sections

(Figure S17); V_s cross-section B1-B2 (Figure S18); V_s cross-section D1-D2 (Figure S19); V_s cross-section E1-E2 and F1-F2 (Figure S20); V_s cross-section G1-G2 and H1-H2 (Figure S21); a comparison of the uppermost mantle V_s and earthquake focal mechanisms (Figure S22); the final seismic velocity model for the eastern United States in a text file (Data Set S1); the seismic velocity model for the western United States in a text file (Data Set S2); a list of seismic networks used in an excel file (Table S1); an animation compares the single-station-averaged receiver functions and the smoothed version (Movie S1); and interactive tools to view the seismic velocity model for the eastern United States (Visualization S1) and for the western United States (Visualization S2).

Text S1.

The cross-section B1-B2 (Figure S18) is parallel to the longer arm of the New Madrid seismic zone (NMSZ) and passes through the Wabash Valley seismic zone (WVSZ) of Illinois and Indiana. Compared to the region to the north (left in Figure), the crust hosting modern WVSZ seismicity is relatively faster, with a smaller velocity gradient in the mid-to-lower crust. The WVSZ is underlain by a slightly thicker crust than the NMSZ. However, the upper mantle beneath the WVSZ is faster than that beneath the NMSZ. A broad higher velocity anomaly is imaged beneath the WVSZ about 70-150 km depth, which agrees with a recent local study (Chen Chen et al., 2016). The continuation of a relatively fast lower crust beneath the NMSZ northward to the WVSZ may suggest these two seismic active regions are connected (Chen Chen et al., 2016). To the south-southwest of the NMSZ, deeper into the Mississippi Embayment, the sedimentary cover thickens to at least 10 km and the crust thins to roughly 30 km.

The cross-section D1-D2, E1-E2, F1-F2, G1-G2, and H1-H2 pass through and across the Appalachian Mountains. Cross-section D1-D2 (Figure S19) clearly shows a slower upper mantle beneath New England, which is consistent with other studies (Pollitz & Mooney, 2016; Schmandt et al., 2015; Shen & Ritzwoller, 2016). The decrease seismic velocity has been interpreted as due to interaction with the Great Meteor hotspot roughly 50 Ma (Eaton & Frederiksen, 2007). Along the profile, which samples the Valley and Ridge Province of central and eastern Pennsylvania, the crustal thickness increases by roughly 10 km from eastern Pennsylvania into the West-Virginia border. Crustal thicknesses in western Pennsylvania are comparable to those to the south (see Figure 6). Although the mid crust varies in speed along the profile, the change in crustal thickness appears to arise from an increase in thickness of lower crustal material. Depths of earthquakes along the profile are generally above 25 kilometers and show no systematic variation with the structure.

Cross-section E1-E2 (Figure S20) samples from southeastern Canada into New England and crosses the West Quebec seismic zone (WQSZ). Magnitude 3 and larger earthquakes extend to 20 km depth in the WQSZ region and appear to shallow slightly along the profile in New York and New England. Along this direction, the WQSZ locates near the edge of the Canadian Shield as is evident in the mantle speed cross-section. Cross-section F1-F2 (Figure S20) shows a crustal thickness change beneath central Pennsylvania. Crossing from the Appalachian Plateau to the Valley and Ridge Province, the upper crust slows and the lower crust thins. At roughly the same position the mantle speeds decrease.

79 Seismicity in the region shows transitions from reverse faulting in the thinner southeast
80 part of the state to strike-slip faulting in the northwest. Whether the stress change is
81 associated with the structure within the crust and/or upper mantle is difficult to tell. The
82 pattern of reverse faulting continues down the eastern seaboard along the area of
83 relatively thin crust. But reverse faulting in northern New York and southeastern Canada
84 occurs with crust with more typical interior thicknesses. The pattern is slightly better
85 matched with reverse faulting occurring above the regions of the relatively slow
86 uppermost mantle (see Figure S20), so perhaps the change (from South Carolina to
87 Ottawa) is a result of an overall variation in lithospheric strength.

88 Cross-section G1-G2 (Figure S21) crosses eastern Ohio and through central Virginia and
89 into northwestern North Carolina. Crustal thickness in eastern Ohio is comparable to that
90 under the Appalachians, or perhaps slightly thinner. As discussed earlier in the Results
91 section, the crustal thickness changes quickly as you exit the Appalachians to the east.
92 Mantle speeds decrease modestly, but steadily from Ohio to the Appalachians. The 2011
93 M5.7 Virginia earthquake was located near an edge of a faster lower crust anomaly and a
94 change in crustal and upper mantle structure. Cross-section H1-H2 (Figure S21) crosses
95 from the northeast WVSZ to the Charleston region and the South Carolina Seismic Zone.
96 The crustal thickness increases slightly from the midwest into the Appalachians, and
97 seismicity appears to extend slightly deeper in the ETSZ near the profile. Near the
98 southeastern margin of the Appalachians, into the coastal plain, the depth range of slower
99 crustal material increases. The material that could be called lower-mid crust in the
100 midwest and Appalachians disappears as the material with typical lower-crustal speeds
101 shallows with a thinning of the crust. At the same position, the mantle speeds decrease
102 along the east coast. Mantle speeds decrease modestly, but steadily from Indiana to the
103 Appalachians, crossing the region that (Chu et al., 2013) suggested a hidden hot-spot
104 track. Along the profile, we see no evidence for a slow upper mantle. However, our
105 model includes a slight reduction in average upper mantle speed in northeast Kentucky
106 and southwest Ohio (see Figure 6), directly above the turning points of the rays that
107 showed delayed travel times and frequency-dependent amplitudes analyzed by (Chu et
108 al., 2013) (the signals were generated by the Virginia earthquake and recorded on
109 midwest Transportable Array (TA) stations described in that work). Our average is
110 shallower than where they placed the anomaly but may reflect the same feature.
111 However, we do not see it extend to the west, towards the northern Mississippi
112 Embayment, as they suggested.

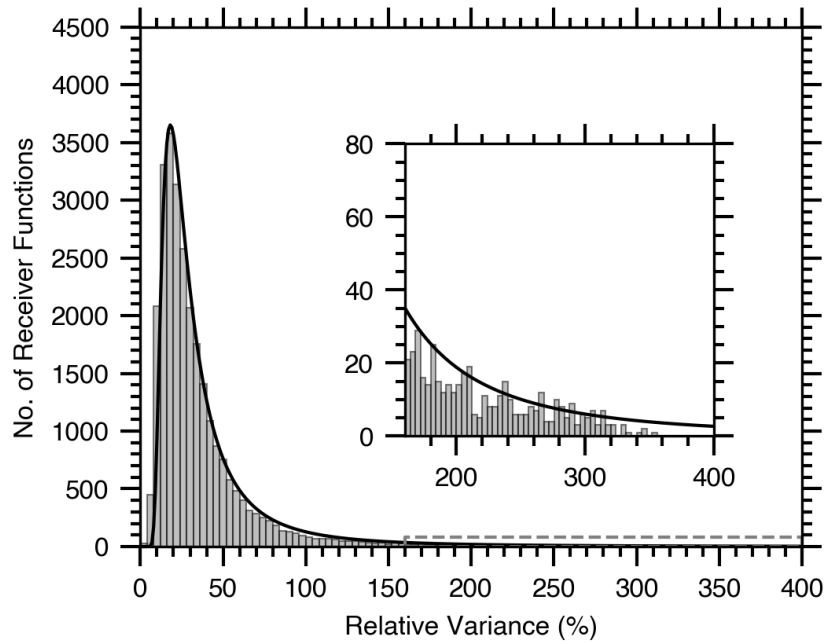


Figure S1. Relative data variance distribution of receiver functions recorded in the Eastern U.S. region. The insets show a detailed view for relative variance ranges between 165% and 400% (dashed box). Black lines indicate extreme value distributions. The relative data variance is computed as the signal variance between an individual receiver function and the single-station-averaged receiver function.

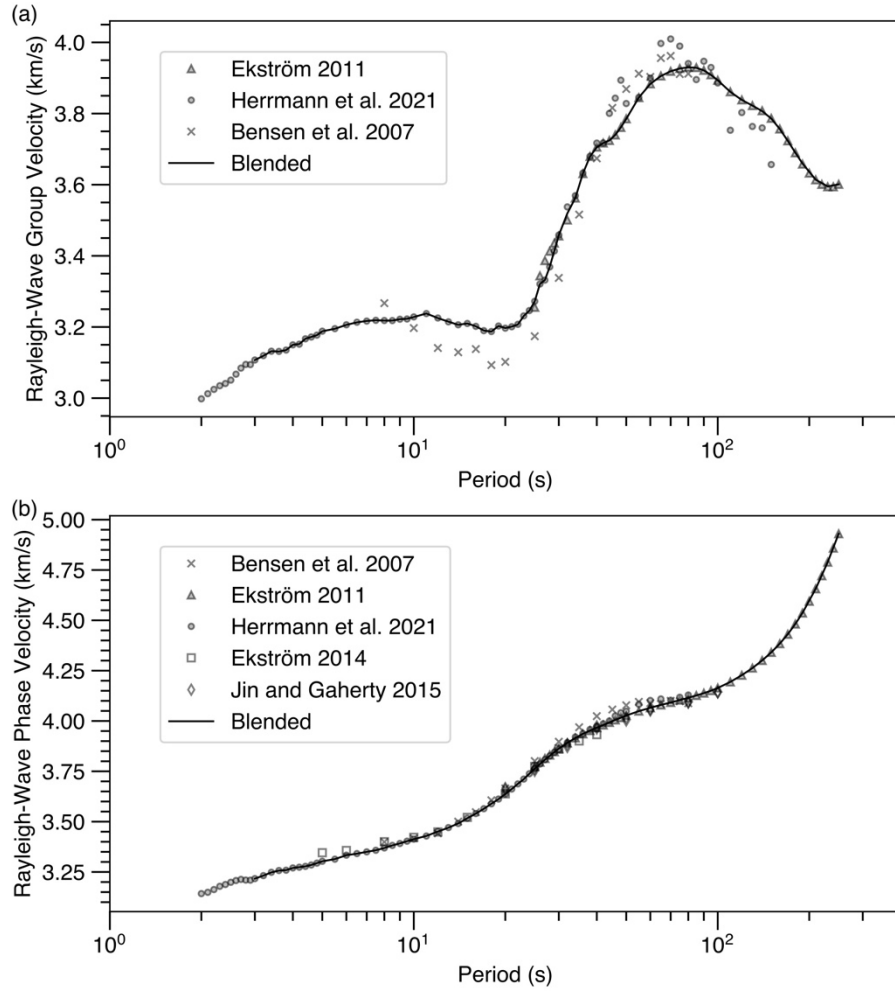


Figure S2. Example dispersion measurements and blended curves in the eastern U.S. (latitude 44.5N, longitude 73.5E) for Rayleigh-Wave group velocity (a) and Rayleigh-Wave phase velocity (b). The blended curves were computed using values from Ekström (2011) and Herrmann et al. (2021). Dispersion models from other sources (Bensen et al., 2007; Ekström, 2014; Jin & Gaherty, 2015) are only shown for reference.

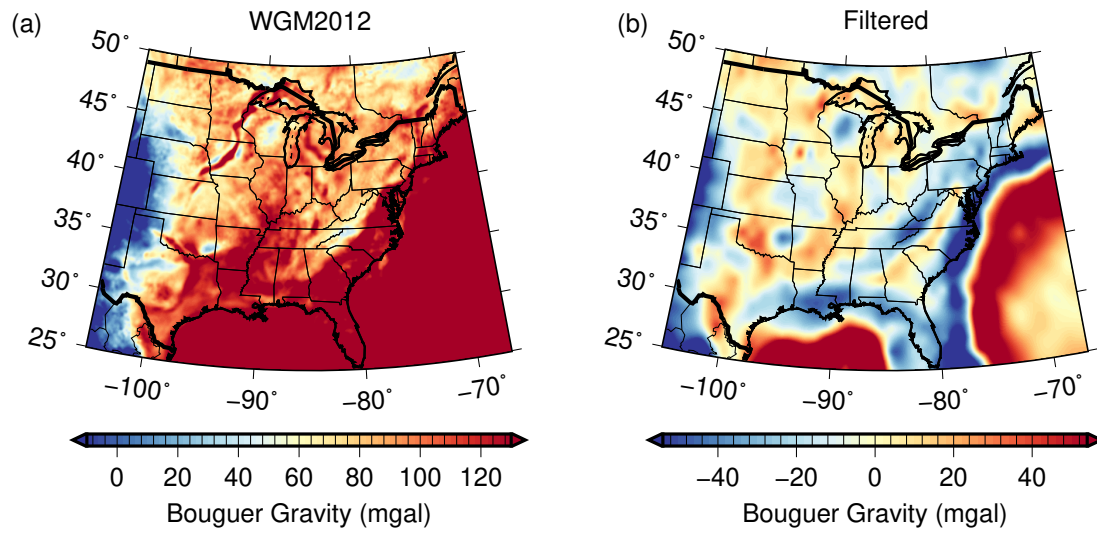


Figure S3. Bouguer gravity maps before (a) and after (b) wavenumber-filtering to emphasize shallow structure and features have spatial dimension larger than 1° . Note the color scale changes.

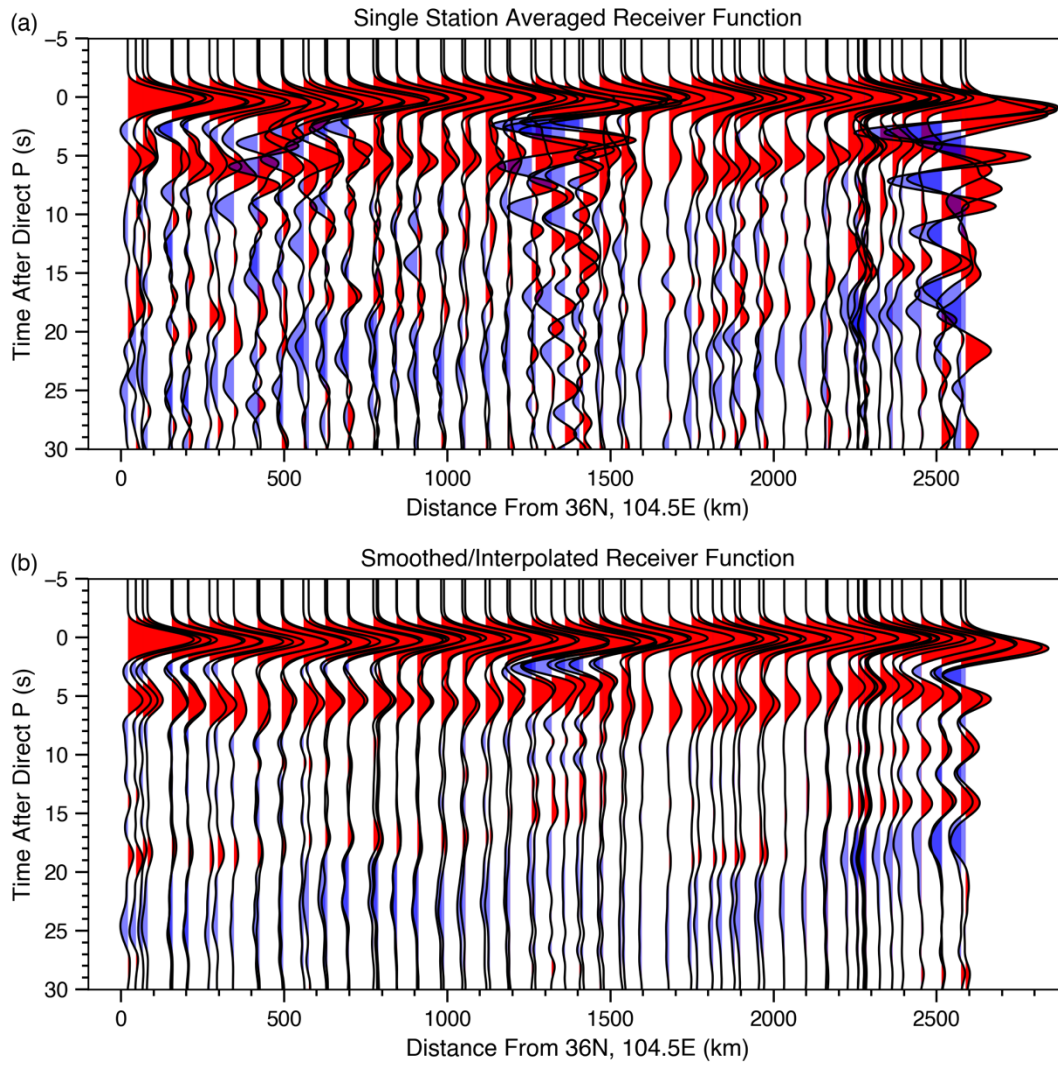


Figure S4. A comparison of (a) single station averaged and (b) smoothed/interpolated receiver functions in a cross-section view. The locations of the stations used are shown in Figure 1.

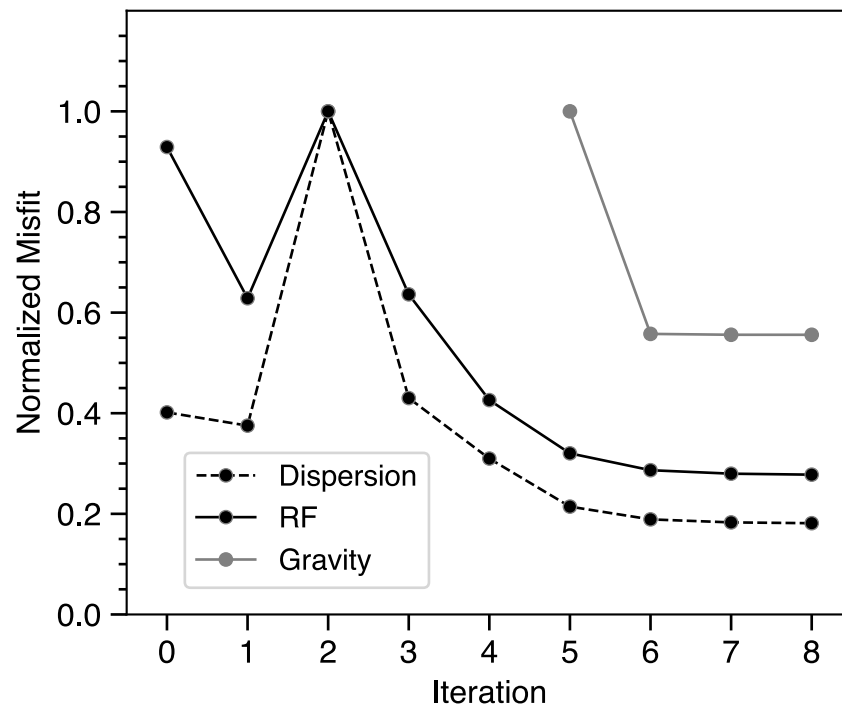


Figure S5. Convergence of the simultaneous inversion. The gravity observations were included in last three iterations. Misfits for each type of observations are normalized with the maximum. For each iteration, misfits were averaged over the grid. At each grid location, dispersion misfit was averaged between group and phase velocity measurements while receiver function misfit was averaged from all available receiver functions. RF stands for receiver function.

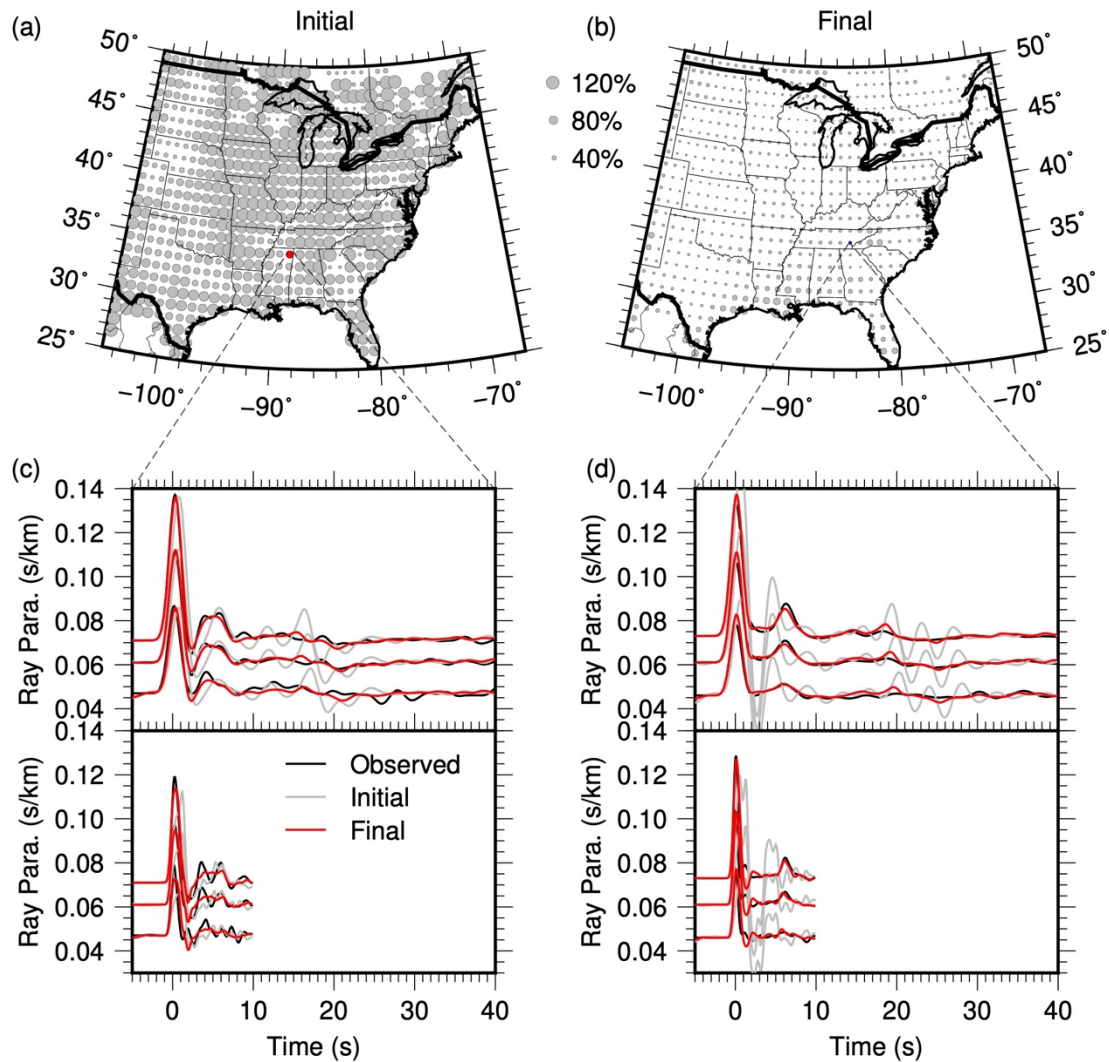


Figure S6. Receiver function misfit map for the initial model (a) and the inverted model (b). The size of dots represents the normalized misfit at each grid points. Receiver functions at two grid points (red and blue) are giving in (c) and (d) with the locations indicated by the dashed black lines. Receiver functions in different ray-parameter bins are displayed for both narrow-band (Gaussian 1.0, top frame) and broad-band (Gaussian 2.5, bottom frame). Since the broad-band receiver functions are noisier, we used a shorter time window.

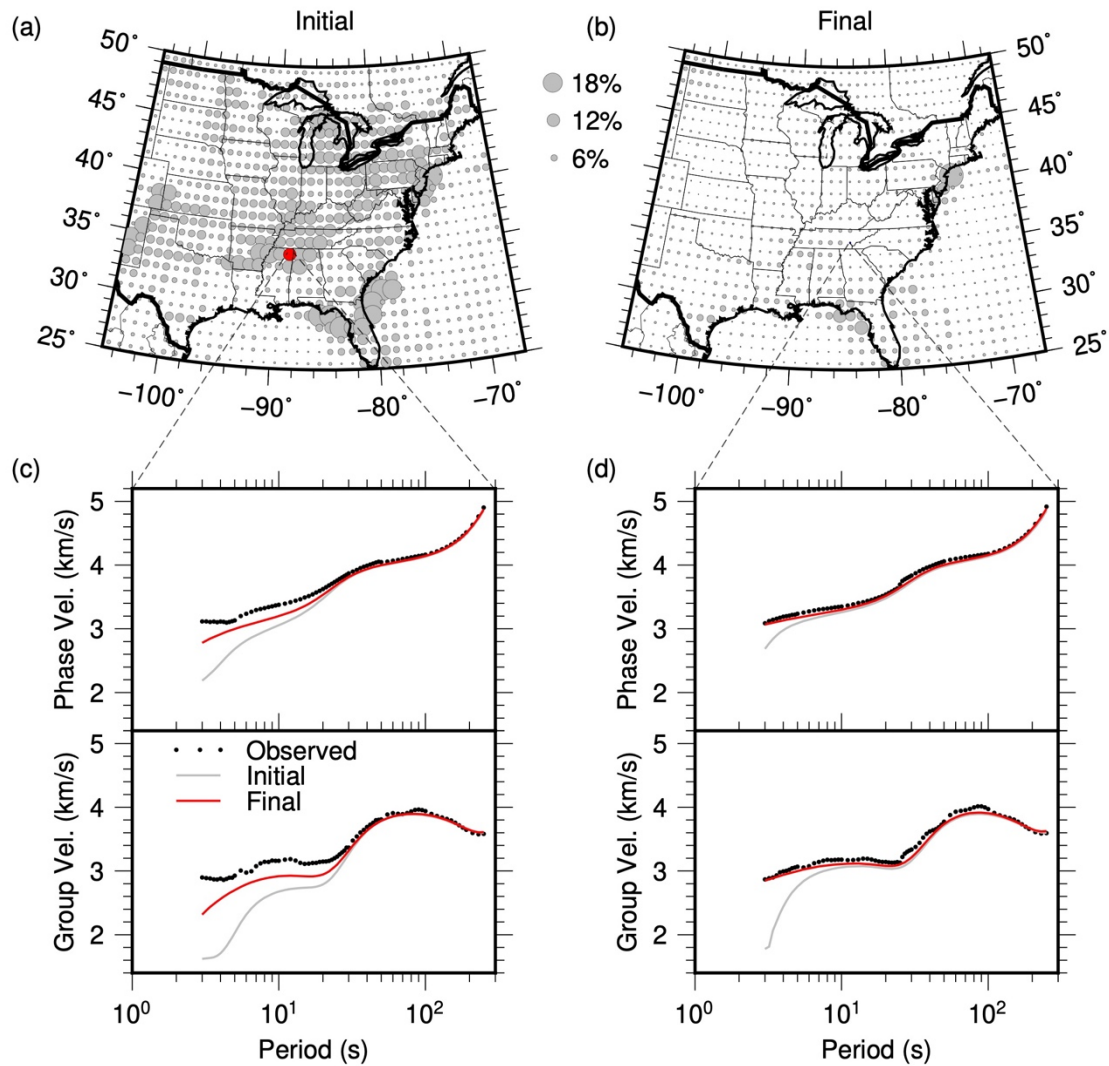


Figure S7. Surface-wave dispersion misfit map for the initial model (a) and the inverted model (b). The size of dots represents normalized misfit at each grid points. Rayleigh-wave dispersion curves at two grid points (34.5, -88.5) and (35.5, -84.5) (optimal and less-optimal data fits, respectively) are shown in (c) and (d) with the location indicated by the dashed black lines. The upper panel of (c) and (d) shows phase velocities while the lower panel shows group velocities.

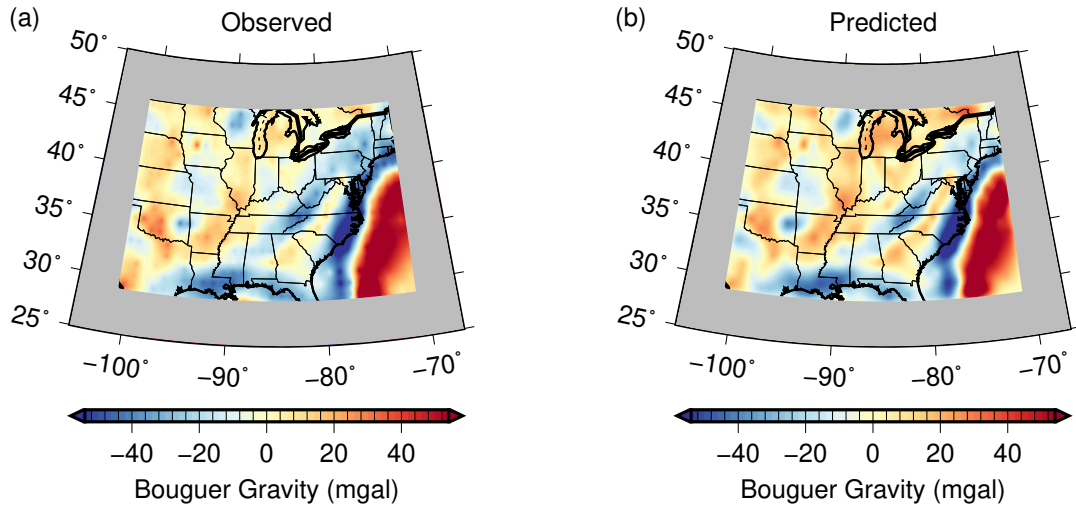


Figure S8. Comparisons of observed gravity maps (a) and predicted gravity maps (b) for the eastern U.S.

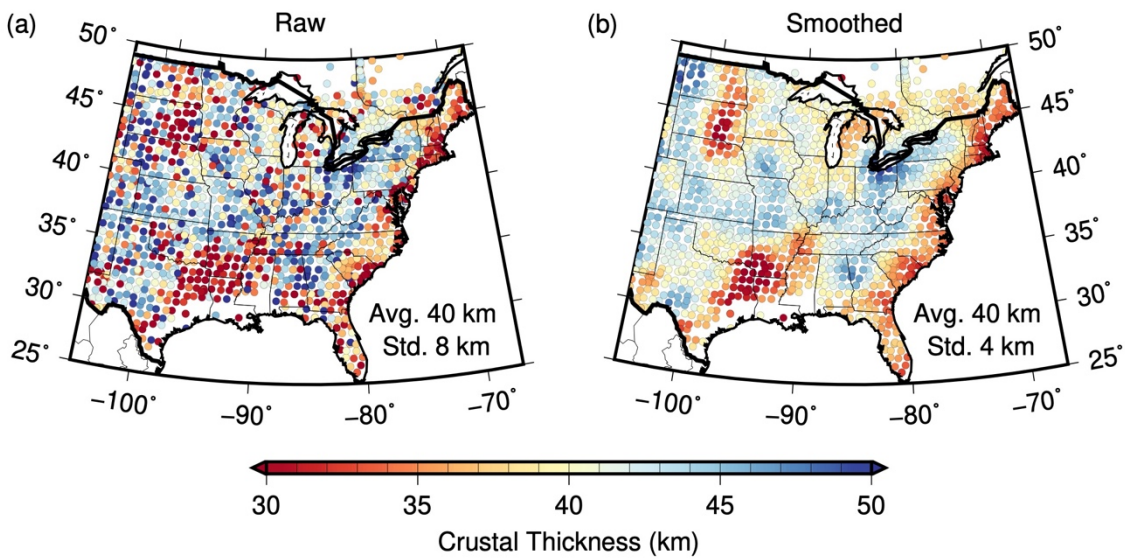


Figure S9. A comparison of EARS crustal thickness results (Crotwell & Owens, 2005) from the raw data (a) and the spatially smoothed version (b).

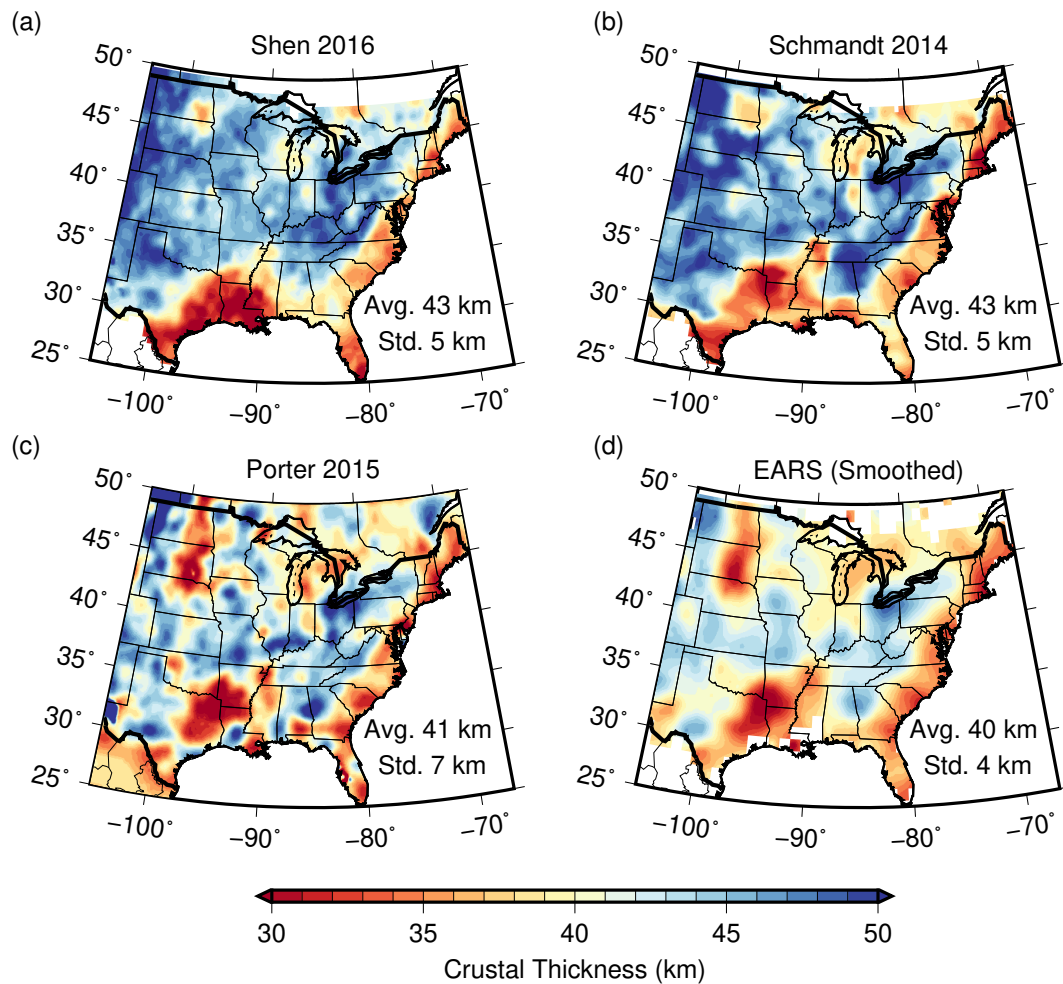


Figure S10. A comparison of crustal thickness maps from four recent models, Shen-2016 model (Shen et al., 2016), Schmandt-2014 model (Schmandt et al., 2015), Porter-2015 model (Porter et al., 2016), and EARS model (Crotwell & Owens, 2005). The results of this paper are shown in Figure 5.

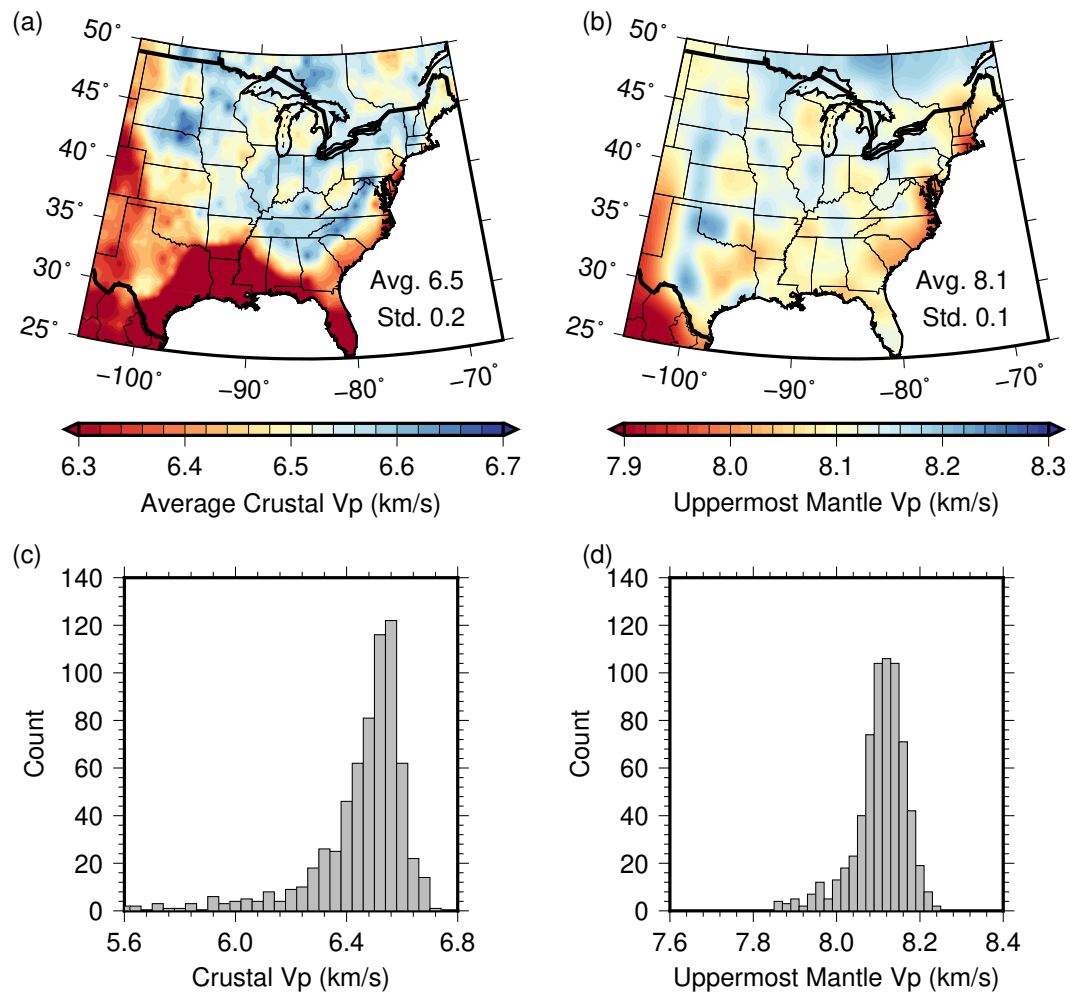


Figure S11. Average crustal Vp speed map, uppermost mantle Vp speed map and histograms of crustal and uppermost mantle Vp velocity.

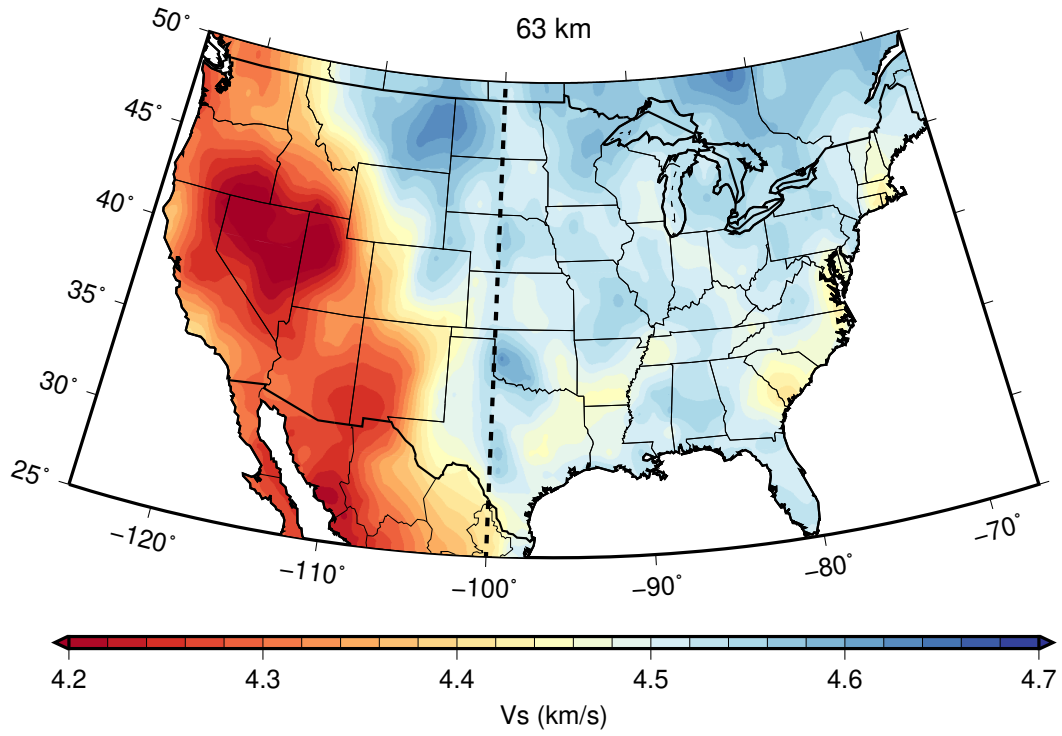


Figure S12. A comparison of upper mantle shear speed at 63 km in western and eastern U.S. The dashed line indicates the transition from the western U.S. model (Chai et al., 2015) to the eastern U.S. model (this study).

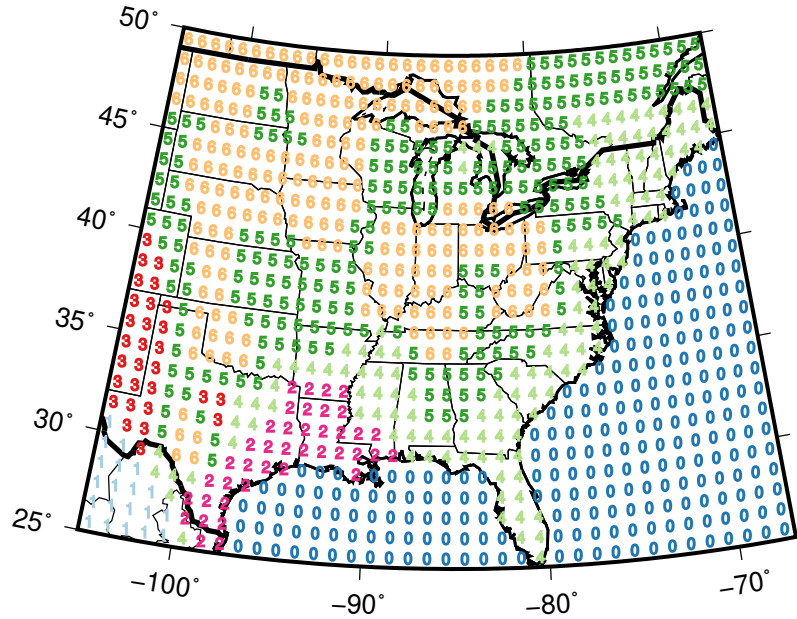


Figure S13. Locations of the automated model clusters generated using a simple hierarchical clustering algorithm. The shear velocities between 6 km and 200 km in depth was used for the clustering. Note the oceanic profiles were assigned based on location. The rough correspondence of the clusters to geologic regions are (0) Oceanic; (1) Southern Basin and Range Region; (2) Western Mississippi Embayment; (3) Central Basin and Range Region; (4) Atlantic Plain and Northern Appalachian Highlands; (5) and (6) Interior Plains, Central and Southern Appalachian Highlands, and Southern Canadian Shield. The velocity profiles within each cluster are summarized in Figure S14.

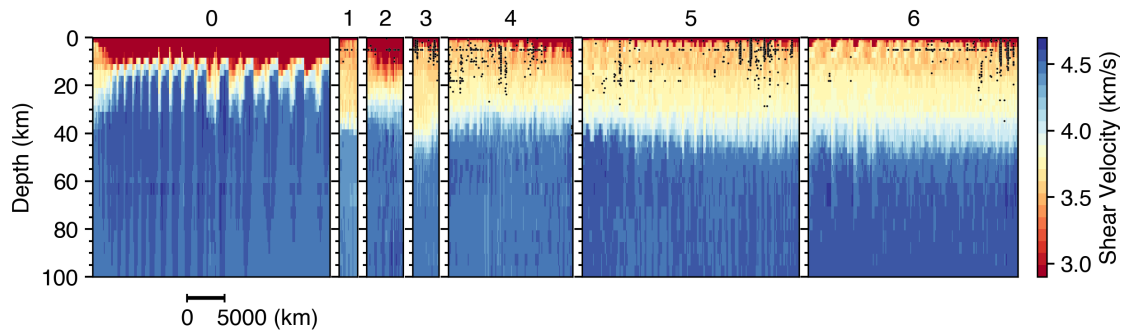


Figure S14. Shear velocity profiles of Earth model clusters constructed using a hierarchical clustering algorithm. The shear velocities between 6 km and 200 km in depth was used for the clustering. The label above each panel correspond to that in Figure S13. Southern regions are shown on the left, regions from the interior of North America toward the right. Velocity profiles within the cluster are sorted from north to south by row (like in a book). Dots shows seismicity (magnitude 3 and larger) from the USGS NEIC catalog before May 2021.

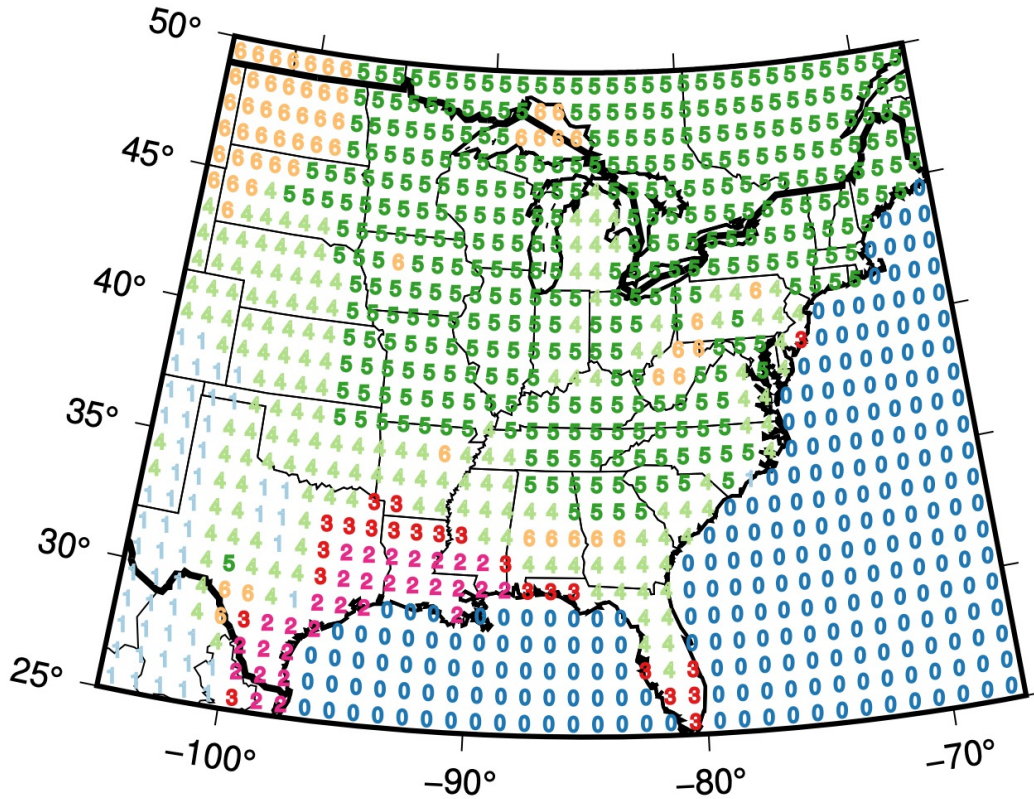


Figure S15. Same as Figure S13 but used the shear velocities of the upper 20 km. Similar to Figure 11 from Herrmann et al. (2021), this figure can be used to select a 1D local model for further analysis.

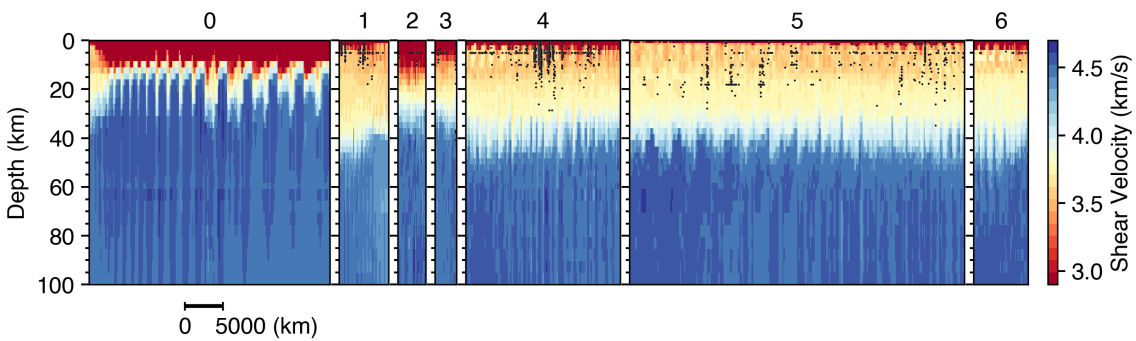


Figure S16. Same as Figure S14 but the clustering used the shear velocities of the upper 20 km. The label above each panel correspond to that in Figure S15.

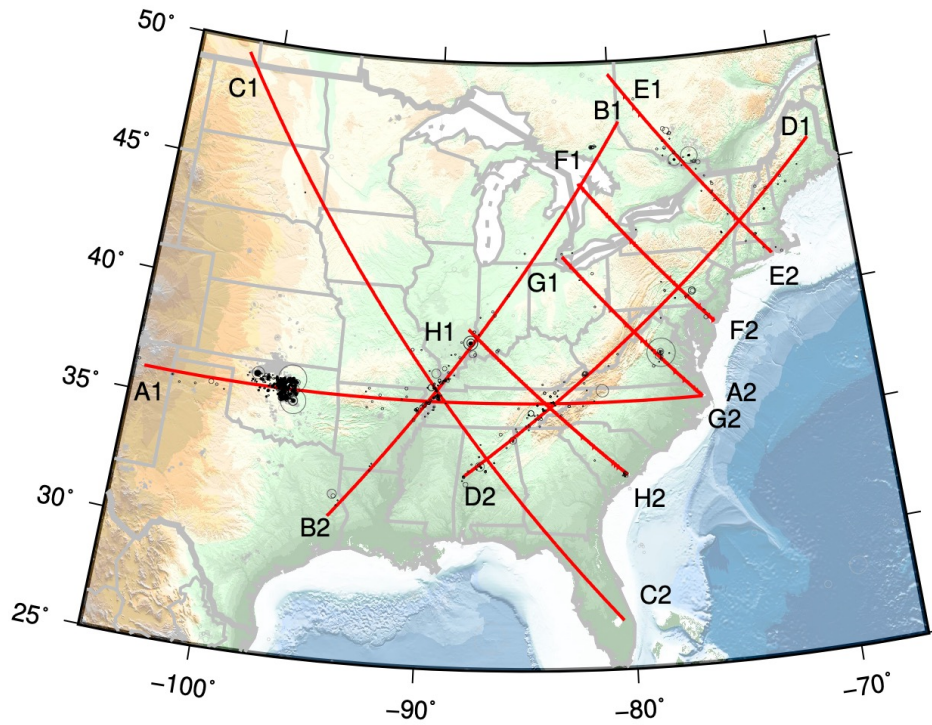


Figure S17. Seismicity (black and gray circles, magnitude 3 and larger prior May 2021) and cross-section locations (red lines). Black circles represent earthquakes that are shown in cross-sections. Gray circles are earthquakes that located 100 km away from any cross-sections. Larger circles correspond to larger magnitudes. The earthquake data were downloaded from USGS NEIC catalog.

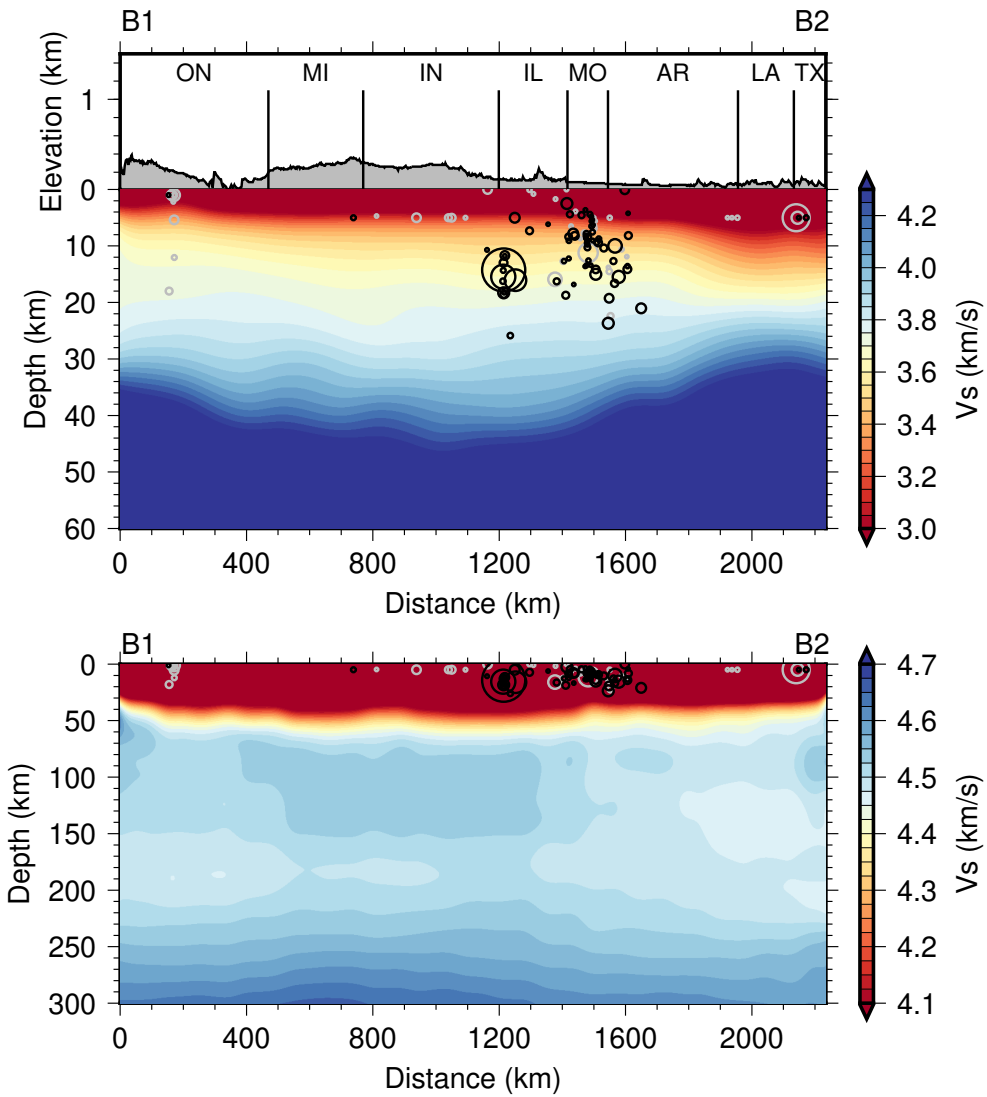


Figure S18. Shear velocity cross-sections along B1-B2. Top panel used a color palette for suitable for crustal speeds. The lower panel shows shear-wave velocity changes in the upper mantle. Circles are earthquakes located within 100 km of the cross-section. Black circles are events with depth uncertainties less than 5 km. Gray circles represent earthquakes with larger depth uncertainties or without uncertainties. Note the image is vertically exaggerated.

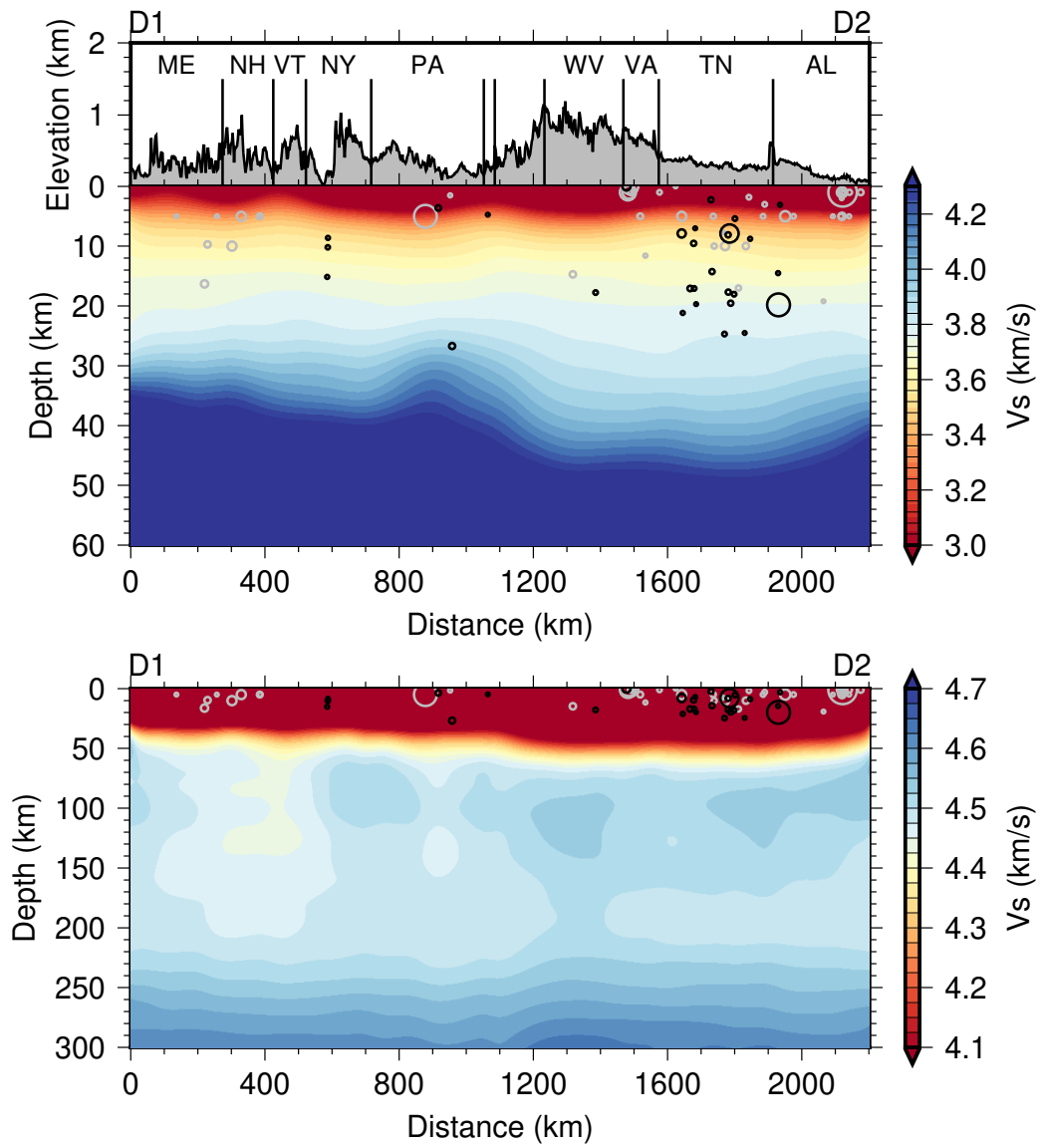


Figure S19. Same as Figure S18 but for cross-section D1-D2.

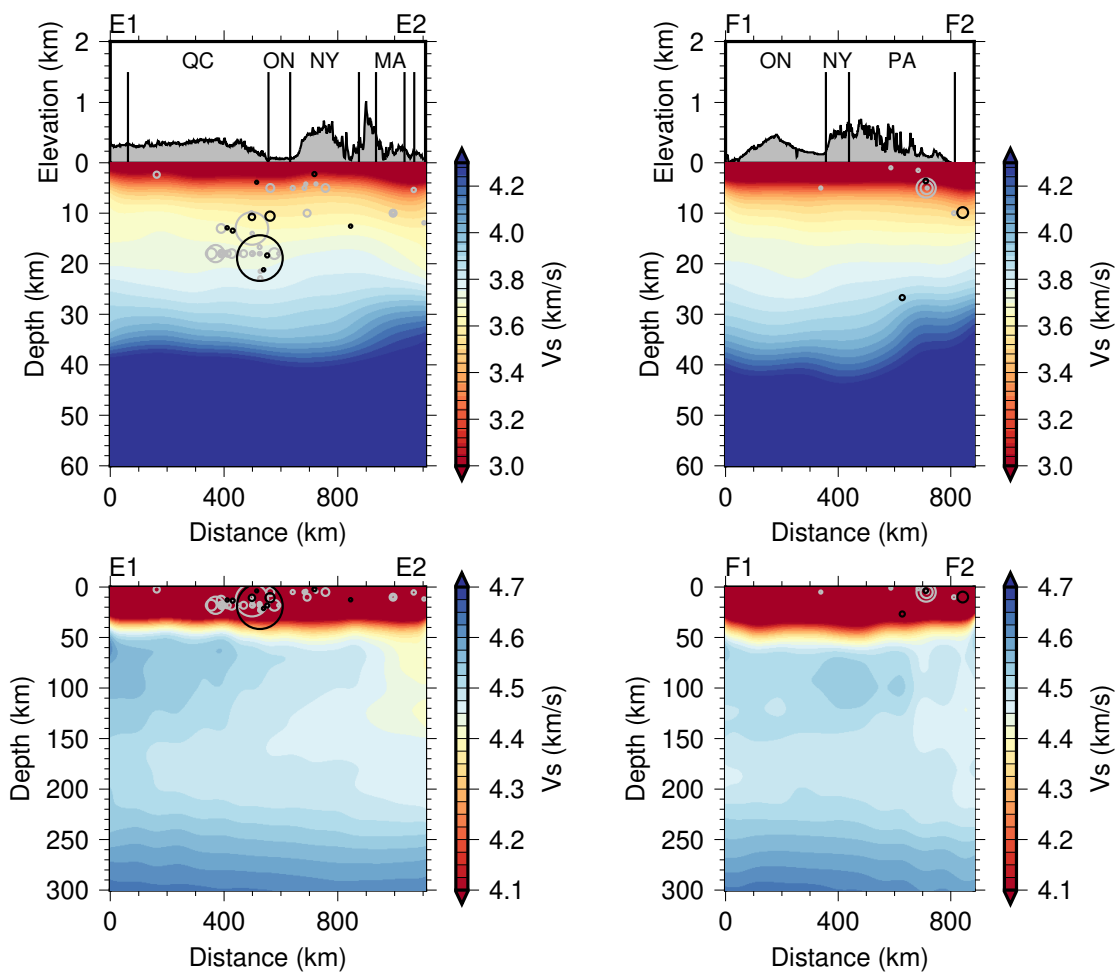


Figure S20. Same as Figure S18 but for cross-sections E1-E2 and F1-F2.

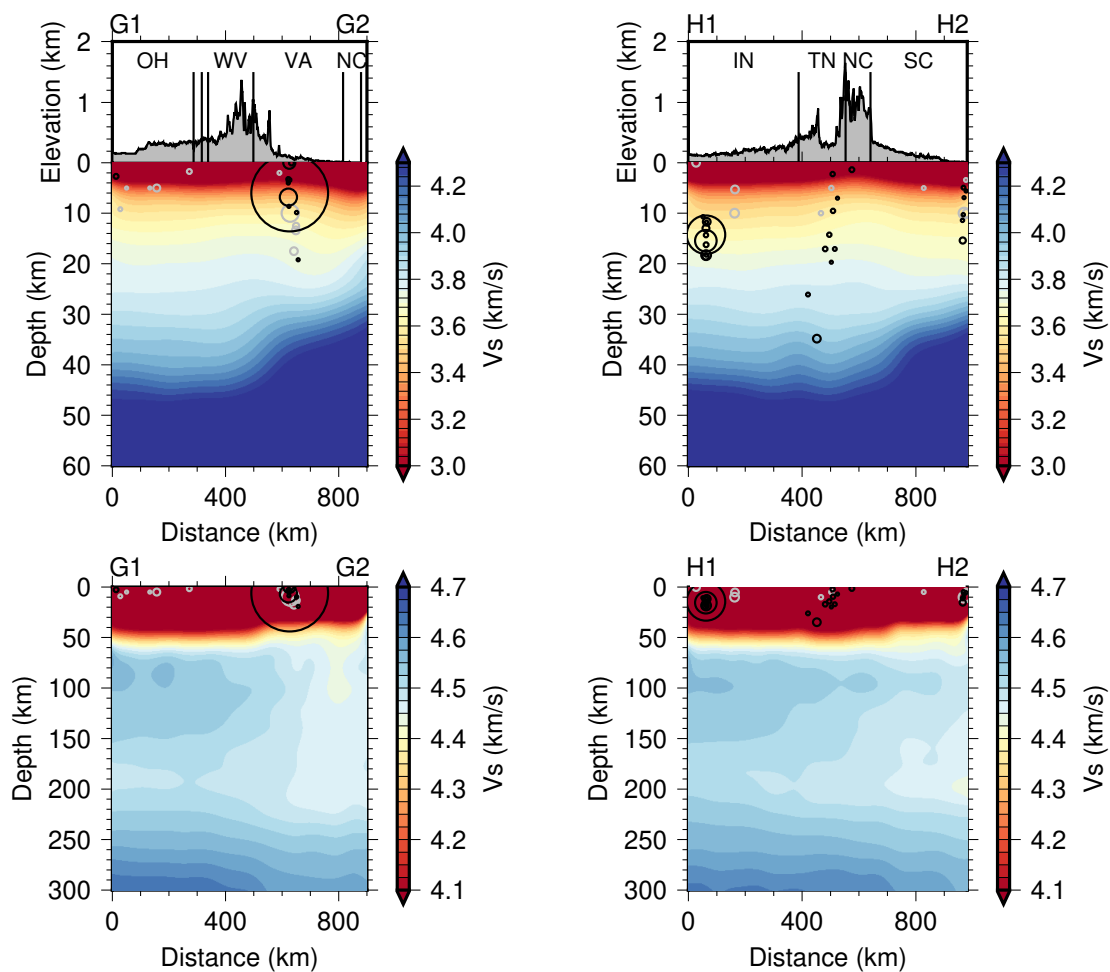


Figure S21. Same as Figure S18 but for cross-section G1-G2 and H1-H2.

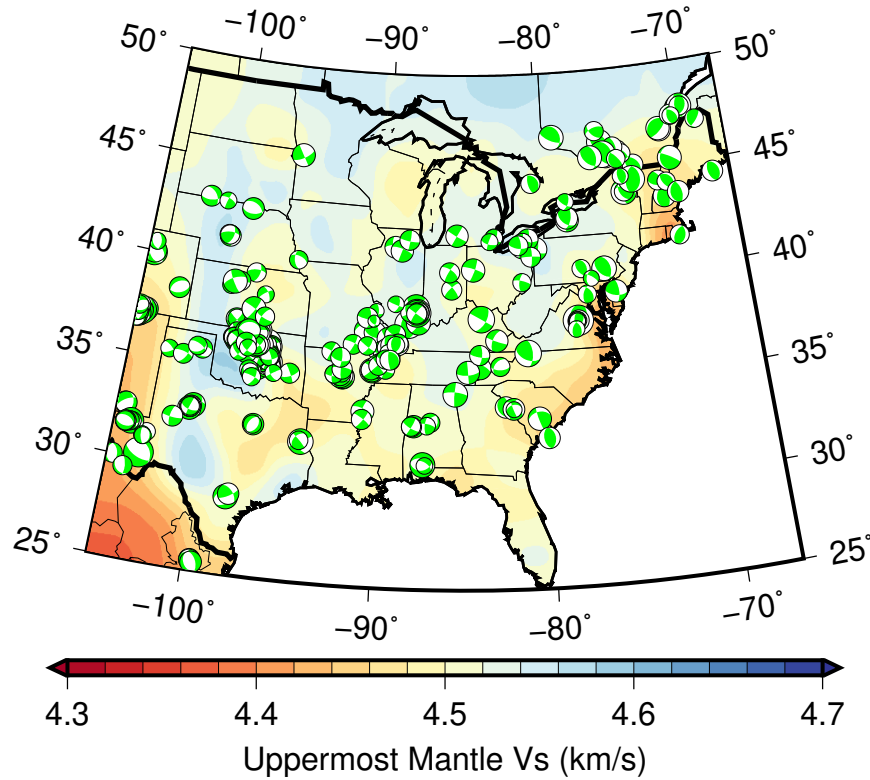


Figure S22. A comparison of the uppermost mantle V_s and focal mechanisms from the Saint Louis University (SLU) catalog (prior 2021/05/01).

Table S1. A list of seismic networks used for the receiver function calculation.

Data Set S1. The final seismic velocity model for the eastern United States derived from the inversion. The first column is latitude. The second column is longitude. The third column is depth (top of the cell) in kilometers. The fourth, fifth and sixth column are P-wave velocity (km/s), S-wave velocity (km/s), and density (g/cm^3), respectively.

Data Set S2. The seismic velocity model for the western United States from Chai et al. (2015). The first column is latitude. The second column is longitude. The third column is depth (top of the cell) in kilometers. The fourth, fifth and sixth column are P-wave velocity (km/s), S-wave velocity (km/s), and density (g/cm^3), respectively.

Movie S1. An animation compares the single-station-averaged receiver functions against the spatially smoothed/interpolated receiver functions.

Visualization S1. An interactive tool to view S-wave velocities of the 3D model for the eastern United States as depth slides and depth profiles side by side. The visualization was created with a Python script developed by Chai et al. (2018).

Visualization S2. An interactive tool to view S-wave velocities of the 3D model for the western United States (from Chai et al., 2015) as depth slides and depth profiles side by side. The visualization was created with a Python script developed by Chai et al. (2018).