

A Taxonomy of Upper-Mantle Stratification in the US

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Key Points:

- Upper mantle stratification is constrained using CRISP-RF and machine learning
- Stratification is classified into intra-lithospheric, transitional and sub-lithospheric
- High-resolution constraints allow the evaluation of different causal models.

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9 Abstract

10 The investigation of upper mantle structure beneath the US has revealed a growing diver-
 11 sity of discontinuities within, across, and underneath the sub-continental lithosphere. As
 12 the complexity and variability of these detected discontinuities increase - e.g., velocity in-
 13 crease/decrease, number of layers and depth - it is hard to judge which constraints are robust
 14 and which explanatory models generalize to the largest set of constraints. Much work has
 15 been done to image discontinuities of interest using S-waves that convert to P-waves (or re-
 16 flect back as S-waves). A higher resolution method using P-to-S scattered waves is preferred
 17 but often obscured by multiply reflected waves trapped in a shallow layer, limiting the visi-
 18 bility of deeper boundaries. Here, we address the interference problem and re-evaluate upper
 19 mantle stratification using filtered Ps-RFs interpreted using unsupervised machine-learning.
 20 Robust insight into upper mantle layering is facilitated with CRISP-RF: Clean Receiver-
 21 Function Imaging using Sparse Radon Filters. Subsequent sequencing and clustering of
 22 the polarity-filtered Ps-RFs into distinct depth-based clusters, clearly distinguishes three
 23 discontinuity types: (1) intra-lithosphere discontinuity with no base, (2) intra-lithosphere
 24 discontinuity with a top and bottom boundary (3) transitional and sub-lithosphere discon-
 25 tinuities. Our findings contribute a more nuanced understanding of mantle discontinuities,
 26 offering new perspectives on the nature of upper mantle layering beneath continents.

27 Plain Language Summary

28 Early investigations of the mantle rocks in the US indicate intricate layering. However,
 29 uncertainties remain regarding the origins of these structures. Here, we re-examine rock
 30 stratification using a fine-resolution approach. We use short waves that improve our ability
 31 to identify the depth of thin layers and sharp transitions in rock properties. Until now,
 32 these methods haven't been used due to interference with waves trapped in the near-surface
 33 layers. We address this problem with machine learning and the CRISP-RF (Clean Receiver
 34 Function Images Using Sparse Radon-Filters) method. CRISP-RF filters out the waves
 35 trapped in the crust and machine learning reveals spatially coherent patterns. We find
 36 evidence for three main classes of rock layering: (1) sharp transitions with no top or bottom
 37 boundary (2) a thin layer with a clear top and bottom boundary, and (3) a rare transition
 38 across and below a depth where the rocks are expected to transition from stiff to weaker
 39 properties. Our approach enables the test of hypotheses about the origins of upper mantle
 40 layering beneath continents.

41 1 Introduction

42 Seismological constraints on upper mantle layering beneath the contiguous US have
 43 revealed evidence for negative and positive velocity discontinuities hinting at a complex
 44 layering beneath the continental US (Abt et al., 2010a; L. Liu & Gao, 2018; T. Liu & Shearer,
 45 n.d.; Hopper & Fischer, 2018b; Kind & Yuan, 2018b; Hua et al., 2023). The mid-lithosphere
 46 discontinuities (MLDs) are the most widely detected and are defined by one or more negative
 47 velocity gradients confined to depths of 60-170 km (Abt et al., 2010a; T. Liu & Shearer,
 48 n.d.; Kind & Yuan, 2018b; Krueger et al., 2021b; Hopper & Fischer, 2018a). Beneath this
 49 discontinuity, within a depth range of 120-220 km, recent, but sporadic detections of positive
 50 velocity gradients (PVGs) have been reported and interpreted as the base of the MLDs
 51 (Hua et al., 2023; Luo, Long, Karabinos, & others, 2021). Slightly deeper still, underneath
 52 Proterozoic terranes, between 220-350 km depth, a negative velocity discontinuity has been
 53 detected and attributed to the base of the lithosphere (Tauzin et al., 2013). These constraints
 54 provide improved illumination on the complex layering within the upper mantle beneath the
 55 contiguous US; however the interpretations regarding their origins and causes, e.g., melt,
 56 anisotropy, relics of subduction-related hydration, elastically accommodated grain boundary
 57 sliding and metasomatism, are still vigorously debated, confounding a unified model (Karato,

2012; Ford et al., 2015; Wirth & Long, 2014b; Selway et al., 2015b; Rader et al., 2015; Saha et al., 2021).

The most common techniques for imaging the upper mantle discontinuities are long-period body-wave methods: (1) Sp converted waves (Hopper & Fischer, 2018b; Abt et al., 2010a; Kind & Yuan, 2018b; Chen et al., 2018; Krueger et al., 2021a) and (2) the top-side S reflections (T. Liu & Shearer, n.d.; Shearer & Buehler, 2019). As the data-volume has improved, the earliest observations using Sp converted waves (Abt et al., 2010a) have been supplemented by continent-wide studies (Hopper & Fischer, 2018b; Kind et al., 2012; Kumar, Yuan, et al., 2012; Kumar, Kind, et al., 2012) with improved signal-to-noise (Krueger et al., 2021a; Hua et al., 2023; Kind et al., 2020a) and better depth resolution using S-wave reflections (L. Liu & Gao, 2018; Shearer & Buehler, 2019). Both techniques have identified multiple upper mantle discontinuities (UMDs) within the contiguous US. In the tectonically active western US, a negative discontinuity is unambiguously detected and repeatedly verified by many authors (Kumar, Yuan, et al., 2012; Kind et al., 2020a; Abt et al., 2010a; T. Liu & Shearer, n.d.; Hopper & Fischer, 2018b; Krueger et al., 2021a). In the tectonically active western US, the velocity drop is inferred to coincide with slow velocities imaged with tomography, and has been interpreted as the boundary between the lithosphere and asthenosphere (Hansen et al., 2015; Hopper & Fischer, 2018b; Abt et al., 2010a; Kind & Yuan, 2018b; Rader et al., 2015). However, this interpretation is inconsistent with the thickness of stable continental lithosphere beneath Archean and Proterozoic terranes in the central and eastern US. Here the velocity drop is detected at shallower depths (Abt et al., 2010b; T. Liu & Shearer, 2021; Hopper & Fischer, 2018b; Krueger et al., 2021b). This is a distinct discontinuity internal to the lithosphere - the MLD rather than the LAB (Abt et al., 2010b; Hopper & Fischer, 2018a; T. Liu & Shearer, 2021).

To clarify the nomenclature and avoid confusion in our interpretation we define important terms: 1) the thickness of stable continental lithosphere and 2) the depth statistics and polarity of previously detected upper mantle discontinuities. The stable continental lithosphere is that portion of the crust and upper mantle that has remained intact since the Archean and Proterozoic era. Some of its distinct geophysical signatures are: high-velocities, low attenuation, and heat loss by conduction (Dalton et al., 2017; Fischer, Rychert, Dalton, Miller, & others, 2020; Priestley et al., 2018). Its thickness, as inferred from seismology and petrology, extends to a depth ~ 200 -250 km depth (Dziewonski & Anderson, 1981; Carlson et al., 2005; Gung et al., 2003). The seismic detection of a sharp boundary with the asthenosphere in this region is elusive, in contrast with the tectonically active regions (Eaton et al., 2009). This suggests that the bottom-boundary of stable continental lithosphere is marked by velocity gradients that are broad. Second, we categorize the previously detected upper mantle discontinuities (UMDs) into three groups without any biasing interpretation on their tectonic location or the rheological strength of the rock, that is lithosphere or asthenosphere (Figure 1b - 1d). The first group (UMD1) are characterized by a velocity drop, and typically detected at consistent depths (83 ± 28 km). The second group (UMD2) are positive velocity discontinuities that are slightly deeper (150 ± 30 km, often referred to as the PVG-150 (Hua et al., 2023)). The last and final group (UMD3) are deeper negative reflectors (>110 km) that are sporadically detected in some studies (T. Liu & Shearer, n.d.; Kind et al., 2020a; Ford et al., 2015) and deeper than their shallower counterpart.

Before evaluating which of the proposed models of upper mantle structure is most consistent with the growing observations, we point out that some authors (Kind & Yuan, 2018a) have raised doubts on whether the shallowest and most prevalent discontinuity, UMD1, exists as a real geological feature, especially underneath stable continents. They argued that these discontinuities could be artifacts from the signal processing with no real geological basis (Kind & Yuan, 2018a). On the contrary, (Krueger et al., 2021b) provide compelling evidence for its visibility within cratons globally. This they do by reprocessing data with rigorous data selection and robust signal processing. Apart from the details of signal processing, some of the differences in observation may be due, in part, to the

111 varying sensitivity and data quality of different imaging techniques as well as the spatial
 112 heterogeneity of these discontinuities. One way to address these short-comings is to improve
 113 spatial resolution by using short-period high-resolution converted or reflected body-waves
 114 (Guan & Niu, 2017; Luo, Long, Karabinos, Kuiper, et al., 2021; Ford et al., 2016; Wirth &
 115 Long, 2014b; Pugh et al., 2021; Rychert et al., 2007a). However, only a few observations
 116 use short-period body waves to image the upper mantle (Luo, Long, Karabinos, & others,
 117 2021; Wirth & Long, 2014b; Guan & Niu, 2017; Ford et al., 2016; Rychert et al., 2007a).
 118 Since the long-period body waves (e.g., Sp-RFs and S-reverberations) are often processed at
 119 frequencies less than 0.5Hz, it means that our insight into mantle layering is filtered through
 120 a low resolution lens (Shearer & Buehler, 2019). This limits the resolution on sharpness and
 121 ultimately the robustness of interpretations of UMD depths, sharpness and origins (mantle
 122 composition and dynamics).

123 Here, we achieve improved vertical resolution by utilizing Ps converted waves processed
 124 at a frequency higher than Sp-RFs or S-reflections. However, when using converted Ps waves
 125 to detect upper mantle discontinuities, crustal reverberations generated at shallow bound-
 126 aries like the Moho cause unwanted interference (Abt et al., 2010a; T. Olugboji, Zhang, et
 127 al., 2023; Kind et al., 2012). This confounds the interpretation of deeper mantle discontinu-
 128 ities. We illustrate this by comparing the UMD arrival times with that calculated for waves
 129 reverberated in the crust (red clouds in Figure 1a,1e). We use a continental Moho model
 130 (Schmandt et al., 2015) , and crustal velocities from (Schulte-Pelkum & Mahan, 2014). We
 131 observe that several UMDs reported in earlier studies (Abt et al., 2010a; T. Liu & Shearer,
 132 2021; Krueger et al., 2021a; Kind & Yuan, 2018b; Hopper & Fischer, 2018b) coincide with
 133 Moho multiples. In regions with thick crust, the deeper lithospheric discontinuities (UMD2
 134 and UMD3) are more likely to suffer interference. Even the shallow discontinuity (UMD1)
 135 can be affected in areas with a thin-layer crust where short reverberation paths allow mul-
 136 tiple to arrive at similar times. Therefore to make Ps-RFs suitable for mantle imaging
 137 we require a techniques that can isolate weak mantle conversions from Moho multiples
 138 that arrive at similar times. To address this issue, which has has long been a challenge
 139 in global geophysics, we employ the novel CRISP-RF technique (Clean Receiver-Function
 140 Imaging using Sparse Radon Filters)(T. Olugboji, Zhang, et al., 2023). This method lever-
 141 ages sparsity-promoting Radon transforms to effectively model and isolate mantle-converted
 142 energy from crustal multiples (T. Olugboji, Zhang, et al., 2023).

143 In the rest of this paper we describe how we improve our understanding of upper mantle
 144 layering in the continental US by analysing body-wave conversions free of crustal reverber-
 145 ations and noise. We process a large dataset by scanning all available data across the con-
 146 tiguous US. We then apply CRISP-RF processing to produce high-resolution, multiple-free
 147 Ps-RFs. This enables tighter constraints on discontinuity depths and sharpness. We orga-
 148 nize the filtered Ps-RFs into depth-dependent clusters based on an unsupervised machine
 149 learning algorithm: a hybrid of the Sequencer and hierarchical k-means algorithm (Baron
 150 & Ménard, 2020). This process is crucial for revealing coherent and striking patterns in the
 151 data-space of body-wave conversions. We discuss the new insight into upper mantle strati-
 152 fication revealed by our filtered and ordered Ps converted waves: (1) tighter estimation on
 153 the depth and polarity of mantle discontinuities, (2) improved visibility of discontinuities
 154 across and beneath the stable continental lithosphere, (3) detection of mantle layering with a
 155 top and bottom-boundary and the estimation of its thickness (4) a preliminary evaluation
 156 of proposed models to explain upper mantle stratification, that is, melt, metasomatism, and
 157 elastically accommodated grain-boundary sliding.

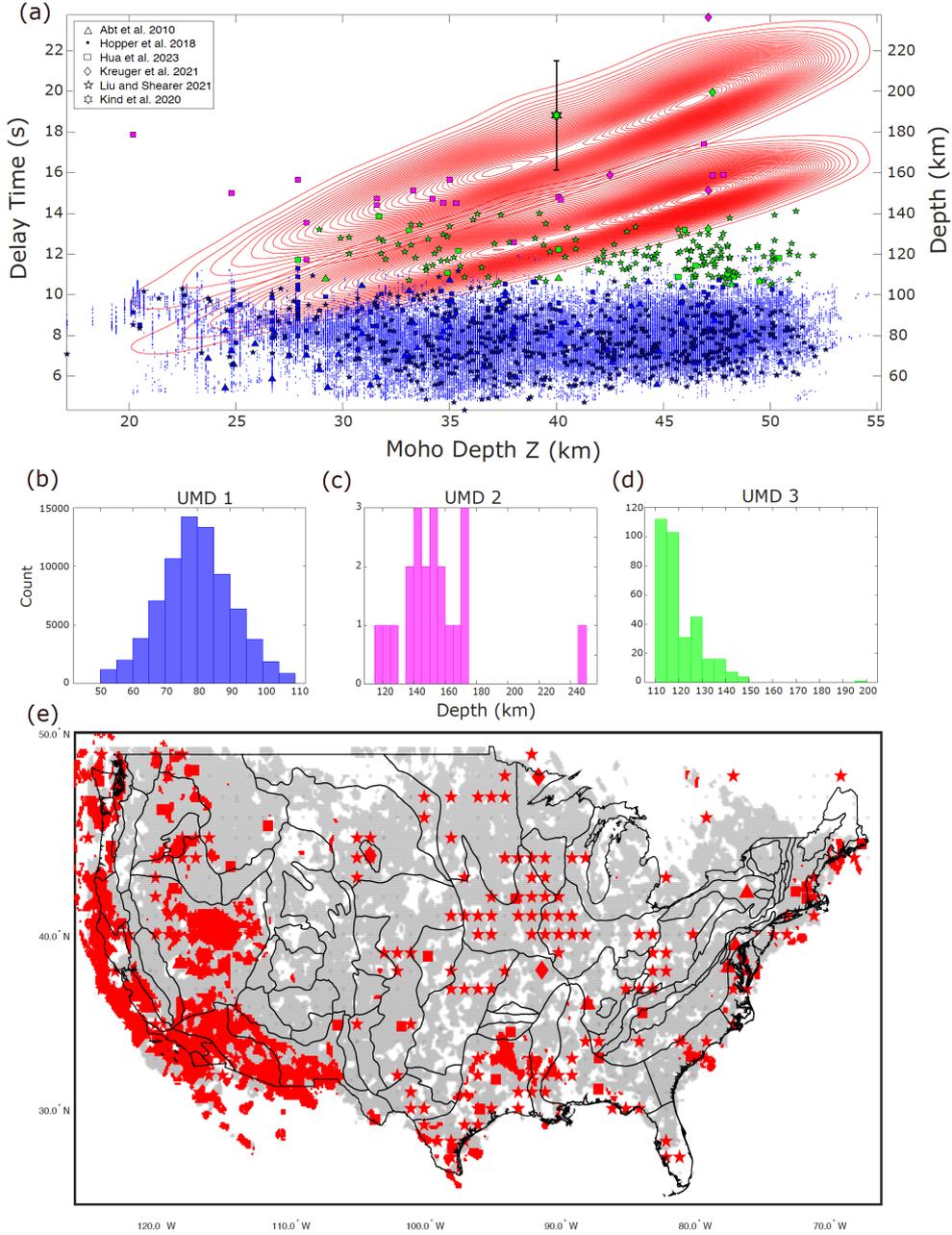


Figure 1. Compiled depths of US upper mantle discontinuities (UMD) highlighting the interference with crustal reverberation when imaging with Ps-RFs. (a) A scatter plot of UMD depth (right y-axis) overlaid on the Ps delay time (left y-axis) of Moho multiples (red contours: pPmS and pSmS arrivals). This region delineates depth-range (and timing) of crustal interference with mantle conversions. The Ps-delay of mantle conversions and crustal reverberations are calculated using a continental-scale Moho model from (Schmandt et al., 2015) and mantle velocities from (Schulte-Pelkum & Mahan, 2014). (b,c,d). Histogram of UMDs grouped by category. (e). Location where UMDs in (a) are observed anticipating locations where the Ps-RF imaging of UMDs are masked by crustal multiples (red). The symbols are same as in (a) and are from (Abt et al., 2010b; Kreuger et al., 2021a; Hopper & Fischer, 2018b; Hua et al., 2023; T. Liu & Shearer, 2021; Kind & Yuan, 2018b)

2 Data

We download and process three-component earthquake waveforms from the Incorporated Research Institution for Seismology (IRIS) database. The majority of the waveforms were recorded by stations that are part of the transportable array (TA) with additional contributions from all the major regional seismic networks within the contiguous US. The initial waveform database comprised approximately $\sim 500,000$ earthquake events recorded on $\sim 2,389$ seismic stations (Figure 2). This represents earthquakes with magnitude >5.5 spanning the period of 1989 to 2022. We select teleseismic earthquakes located at distances between 30 and 90 degrees from the recording stations. This range is specifically chosen to exclude earthquakes that may be affected by diffraction effects in the core shadow zone (Hosseini et al., 2019), as well as non-planar and triplicated waves from the mantle transition zone (Stähler et al., 2012).

We apply several data cleaning and preconditioning procedures to ensure data quality. The seismograms are rotated from the geographic (Z, N, E) to the earthquake coordinate system: vertical (Z), radial (R), and transverse (T) orientation (Rondenay, 2009). We apply an automated quality selection criteria to obtain the best data. We select records with good signal-to-noise ratio (SNR), automatically rejecting all waveforms with SNR less than 2 (calculated with a signal window of 120 s and a noise window of 25 s around the predicted P-arrival time). We ensure consistent sampling rates across all waveforms for each station. This requires resampling the waveforms to the highest frequency for each station. Through these quality control measures, a total of 83,697 earthquake waveforms passed initial quality checks. This is a total of $\sim 17\%$ of the initial preprocessed data.

After the initial quality checks, we organize the seismograms recorded at each station into discrete slowness values. In a radially symmetric earth the body-waves propagating from the hypocenter to the station travel with a distinct ray parameter (slowness values) and sample the receiver-side structure with different arrival angles. Optimal slowness-sampling and epicentral distance coverage is required for stable CRISP-RF processing (Figure S2). This restriction reduces our station catalog from 2,389 to a final set of 417 stations (17.5 % of total station inventory). This also culls the seismograms to a final selection of 20,460 of the best three-channel recordings. When compared to the discarded seismograms the final dataset comprise the highest quality (SNR > 16) seismograms. Despite this strict data-selection criteria the final set of stations are widely distributed across the contiguous US ensuring a comprehensive coverage across different tectonic domains (Figure 2).

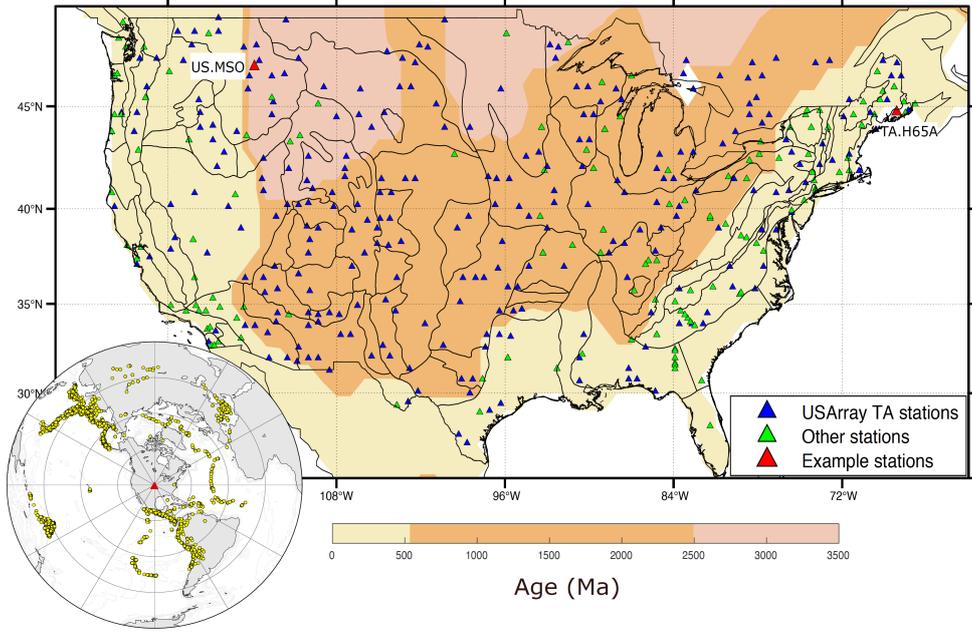


Figure 2. Distribution of seismic stations used in this study. The inset shows the distribution of teleseismic earthquakes that are used. Red triangles mark the locations of the two example stations (TA.H65A, US.MSO) used in our analysis. A full description of all 2389 stations and data statistics can be found in Figure S1 and S2

3 Methods

3.1 RFs at High-Frequency: Contaminated Radial Stacks

We image upper mantle discontinuities using high-frequency receiver functions. We analyse teleseismic P-waves for signature of conversion from seismic discontinuities beneath the stations (Langston, 1977). Radial Ps-RF traces are calculated with a cut-off frequency of 1.5 Hz using the extended-time multi-taper cross-correlation method (ETMT) (Helffrich, 2006). This approach extends the traditional cross-correlation receiver function technique (Park & Levin, n.d.) by applying multiple Slepian tapers to window the waveform data before spectral estimation and deconvolution. To improve the detection of late arriving low-magnitude sub-crustal mantle conversions, we employ a re-normalization procedure, where we implement a 6-second time-shift (τ_s) on the radial component traces to remove early arriving crustal conversions before deconvolution (Equation 1a) (Helffrich, 2006; Shibutani et al., 2008; Park & Levin, 2016d). This step ensures that high-amplitude crustal phases do not overshadow the weaker and deeper sub-Moho conversions of interest. The time-shift is implemented in the frequency domain:

$$\tilde{U}_\kappa^r(\omega, p) = W_\kappa * [U_\kappa^r(\omega, p)e^{i\omega\tau_s}] \quad (1)$$

where $U^r(\omega, p)$ is the Fourier-transformed radial seismogram and W_k are the Slepian tapers, and p is the horizontal slowness. The receiver functions are then computed by deconvolving the shifted radial seismogram from the vertical (both seismograms are tapered with W_k):

$$\tilde{\mathbf{D}}(\omega, p) = \left[\frac{\sum_{\kappa=0}^{\kappa-1} \tilde{U}_\kappa^z(\omega, p) * \tilde{U}_\kappa^r(\omega, p)}{\sum_{\kappa=0}^{\kappa-1} \tilde{U}_\kappa^z(\omega, p) * \tilde{U}_\kappa^z(\omega, p) + \zeta(\omega)} \right] \quad (2)$$

209 We then stack the radial receiver functions in slowness bins with one-degree spacing to
 210 enhance signal quality (Park & Levin, 2000, 2016c):

$$\mathbf{D}(\omega, p_s) = \left(\sum_{l=0}^{n_p} (1/\sigma_l^2) \right)^{-1} \left(\sum_{l=0}^{n_p} 1/\sigma_l^2 \tilde{\mathbf{D}}(\omega, p_l) \right) \quad (3)$$

211 where p_s are the slowness bins, p_l are the individual slowness values in each bin, and σ_l^2
 212 are the frequency-dependent stacking weights derived from coherence (Park & Levin, 2000,
 213 2016c). The frequency domain receiver functions are then transformed back to the time
 214 domain using the inverse Fourier transform

$$\mathbf{d}(t, p_s) = \mathcal{F}^{-1} \left[\mathbf{D}(\omega, p_s) \right] \quad (4)$$

215 where \mathcal{F}^{-1} is the inverse Fourier transform. The Ps-RF data is a 2-D matrix in which each
 216 row represents traces stacked into slowness bins. Each row is a distinct horizontal slowness
 217 and each column is a discrete-time sample.

218 Since the crust-mantle boundary is often the most prominent discontinuity in the litho-
 219 sphere, top-side reflections bouncing off the Moho (Ppms and Psms) are visible in most of the
 220 stacked radial receiver functions (Figure 3). This presents a significant obstacle when inter-
 221 preting converted waves from sub-crustal lithosphere discontinuities (100-200 km) arriving
 222 at ~ 10 -20 secs (Figure 1 and 3). The moho multiples can be identified in the receiver func-
 223 tion stacks by their characteristic time-distance(slowness) behavior. Earthquakes located
 224 closer to the station (and traveling with large horizontal slowness) arrive slightly earlier than
 225 those further away (Figure 3c). This is the opposite behavior for the Ps-converted waves
 226 that do not experience top-side reflections. These conversions arrive later for earthquakes
 227 located closer to the station (Shi et al., 2020; Ryberg & Weber, 2000). Depending on the
 228 station location, data quality, and depth to other discontinuities beneath a station, crustal
 229 multiples may not always be easily identified in the receiver function stacks. This makes
 230 it harder to interpret the final stacked receiver functions (Figure 3a,b,g,h). For a clear
 231 and accurate interpretation of the Ps-RFs, it is crucial to distinguish crust-mantle top-side
 232 reflections from mantle conversion. Only when these multiply reflected waves have been
 233 properly filtered out can we confidently proceed with the interpretation for upper mantle
 234 layering.

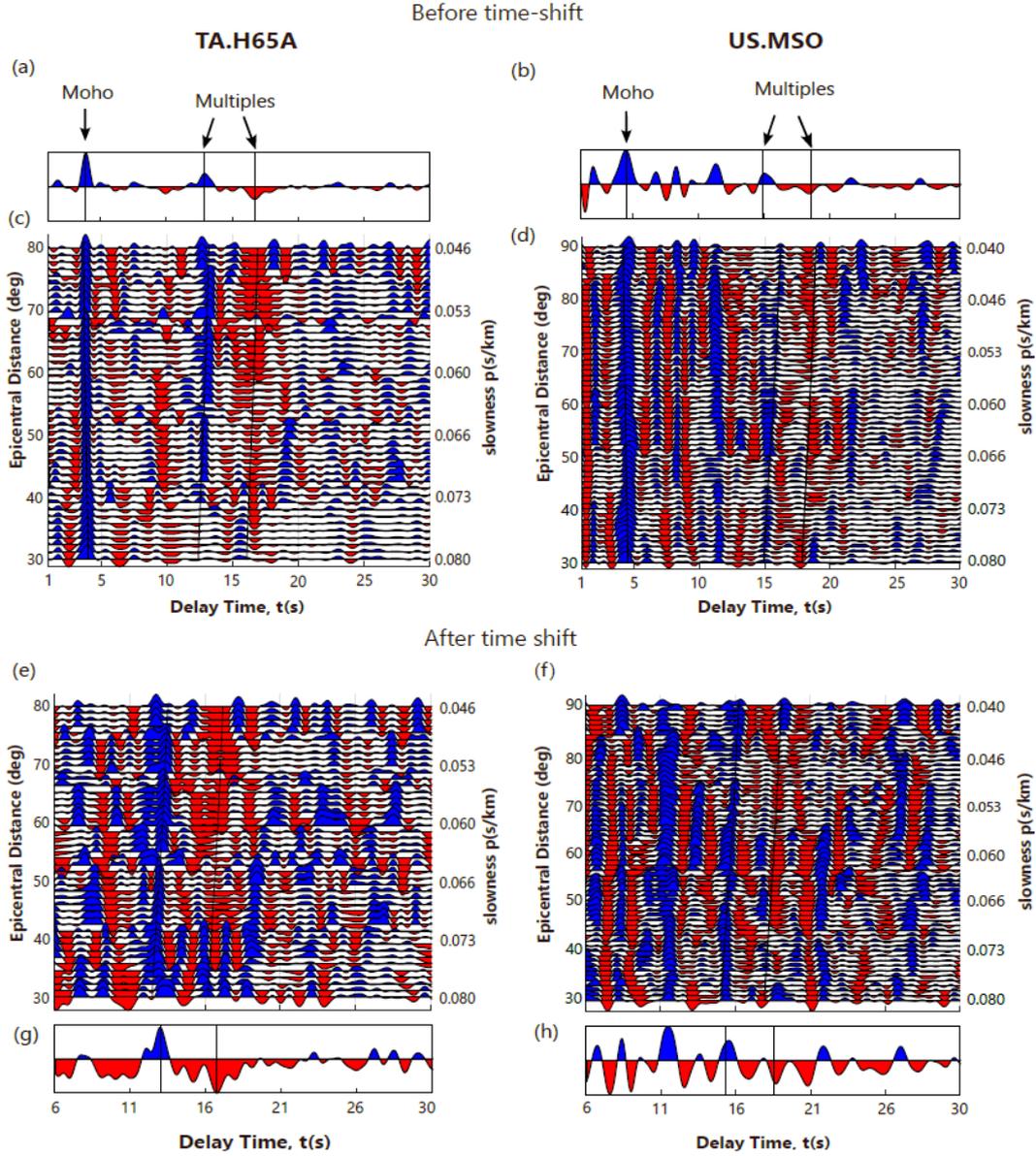


Figure 3. Radial receiver functions for two stations showing Moho arrivals and multiples - top-side reflections in the crust. (a-b) Full stack of all radial receiver functions for stations TA.H65A and US.MSO showing Moho and multiples. (c-d) The radial receiver functions for each station, sorted and stacked by station-earthquake distance in angular degrees. (e-f) Time-shifted radial receiver functions same as (c-d) but starting at 6 secs. (g-h) Full stack of the time-shifted receiver functions corresponding to (e-f). Blue and red shading indicate positive and negative amplitudes

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3.2 Filtered RFs: CRISP-RF for Denoising

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We briefly present our approach to removing top-side reflections and other non-coherent noise. This is the method called Clean Receiver-function Imaging using Sparse Radon Filters (CRISP-RF) (T. Olugboji, Zhang, et al., 2023). This method enhances the clarity of Ps-RFs allowing for a more accurate interpretation of sub-crustal mantle discontinuities. For a more detailed description, we refer the reader to (T. Olugboji, Zhang, et al., 2023). The

241 technique involves three main steps: The initial step applies the sparse Radon transform to
 242 the Ps-RF data:

$$\mathfrak{R}_{\text{sp}}(\mathbf{d}) : \underset{\mathbf{m}}{\operatorname{argmin}} \left\{ \frac{1}{2} \|\mathcal{F}^{-1}\{\mathbf{L}\mathcal{F}\{\mathbf{m}\}\} - \mathbf{d}\|_2^2 + \lambda\psi(\mathbf{m}) \right\} \quad (5)$$

243 where $\mathfrak{R}_{\text{sp}}(\mathbf{d})$ maps the Ps-RF data \mathbf{d} to the Radon model \mathbf{m} . The transform can be
 244 viewed as finding a predictive Radon model, \mathbf{m} , using the forward operator \mathbf{A} and subject
 245 to regularization $\psi(\mathbf{m})$ (recasting as $\mathbf{d} = \mathbf{A}\mathbf{m}$). Therefore the transform is an optimiza-
 246 tion problem to find \mathbf{m} using a sparsity-enforcing regularization: ℓ_1 -norm $\psi(\mathbf{m}) = \|\mathbf{m}\|_1$
 247 (Equations 5). This optimization is solved using the SRTFISTA algorithm: a fast iterative
 248 shrinkage-thresholding approach that promotes the sparsity of the Ps-RFs in both the time
 249 and frequency domains (forward and inverse fourier operators: $\mathbf{A} = \mathcal{F}^{-1}\mathbf{L}\mathcal{F}$) and yields
 250 a cleaner representation of the Ps-RF data (Beck & Teboulle, 2009; Gong et al., 2016).
 251 Here, \mathbf{L} , is a frequency-domain projection matrix that maps the Ps-RF arrivals in \mathbf{d} from
 252 the time-slowness data-space to the Radon model, \mathbf{m} , which is now in the intercept-time-
 253 curvature model-space. Top-side reflections are mapped into the negative curvature while
 254 direct conversions show up in the positive curvature (Figure 4c & 4d).

255 The second step applies a selective masking filter, \mathbf{K} , to the Radon model \mathbf{m} . The filter
 256 is designed to extract only direct mantle conversions by removing contributions representing
 257 top-side reflections (red dashed lines in Figure 4c & 4d). By setting the amplitudes with
 258 negative curvatures (squares in Figure 4c & 4d) to zero and preserving those with positive
 259 curvatures (circles in Figure 4c & 4d), the masking filter retains only Ps-conversions from
 260 the upper mantle. The third and final step transforms the now filtered Radon model back to
 261 the data-space using the adjoint Radon transform $\mathfrak{R}_{\text{sp}}^+$. This is the required filtered Ps-RF
 262 data $\tilde{\mathbf{d}}$ free of unwanted reflections and incoherent noise (Figure 4e & 4f):

$$\mathbf{d} \xrightarrow[\text{step1}]{\mathfrak{R}_{\text{sp}}} \mathbf{m} \xrightarrow[\text{step2}]{\mathbf{K}} \mathbf{m}\mathbf{K} \xrightarrow[\text{step3}]{\mathfrak{R}_{\text{sp}}^+} \tilde{\mathbf{d}} \quad (6)$$

263 A comparison between the original and CRISP-RF processed Ps-RF stacks for our two
 264 example stations shows that the CRISP-RF technique has successfully isolated the mantle-
 265 converted phases by attenuating crustal multiples and noise (compare Figure 4a,b to 4e,f).
 266 This is evident in the filtered stacks, where mantle conversions are easily and unambiguously
 267 identified.

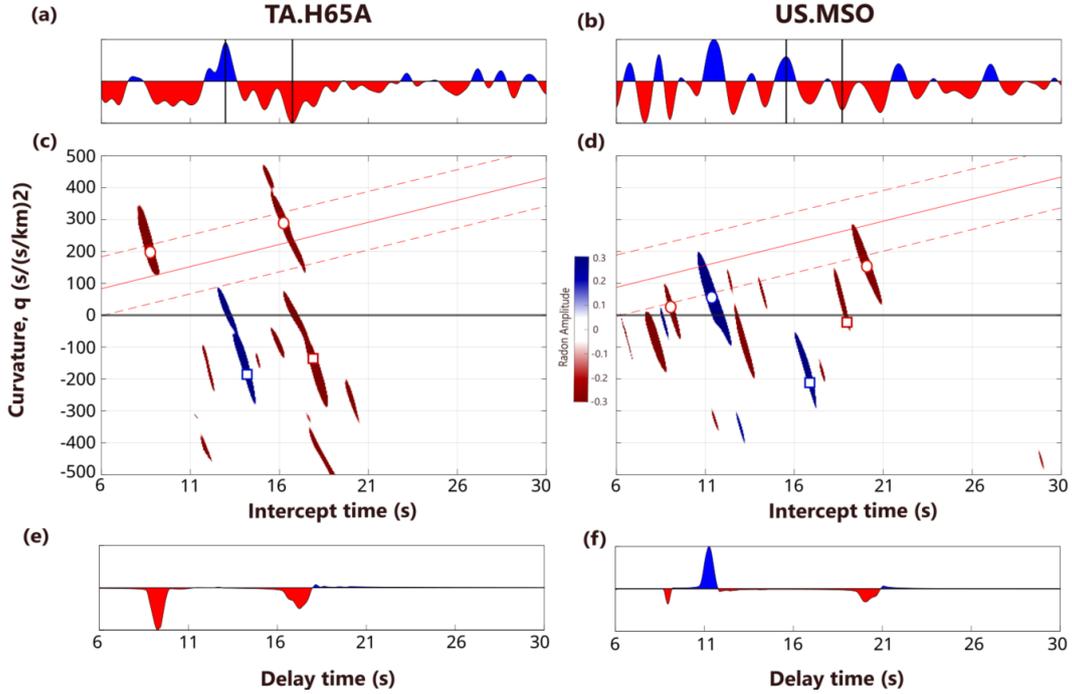


Figure 4. CRISP-RF denoising steps for filtering receiver functions obtained from stations TA.H65A and US.MSO. (a-b) Time-shifted unfiltered receiver function stacks, with predicted Moho arrival times indicated by black lines. (c-d) Radon model (after applying step 1) showing direct mantle conversions along the positive curvature axis (circles), and multiples in the negative curvature (squares). The masking filter are the red lines - they retain all arrivals between the dashed lines (step 2). (e-f) The final filtered Ps-RFs after transforming the filtered Radon model to data domain (step 3). The top-side reflections in the crust have been removed leaving only the direct conversions

3.3 Machine Learning (Sequencing & Clustering) on Filtered RFs:

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Since our aim is to produce a detailed map of coherent scattering across discontinuities located in the upper mantle, we employ a two-tiered machine learning approach to find repeatable patterns in the receiver function signature of upper mantle conversions across all our 417 stations. This approach integrates the Sequencer algorithm (Baron & Ménard, 2020) with hierarchical clustering, each serving a distinct but complementary role in uncovering patterns in our denoised Ps-RFs. The sequencer algorithm is necessary for sorting the CRISP-RF filtered receiver functions before applying the correlation-based hierarchical clustering algorithm. The Sequencer algorithm is an unsupervised machine learning tool that reveals hidden sequential structures often obscured within complex multivariate datasets (Baron & Ménard, 2020). It leverages a variety of distance metrics to systematically reorder datasets based on similarity. It has shown promise in sequencing earthquake waveforms to discern spatial patterns in lower mantle scattering (Kim et al., 2020), the analysis of seismic noise to detect temporally coherent signals (Fang, n.d.), and classification of seismic velocities for guiding discovery of tectonic influences on crustal architecture (T. Olugboji, Xue, et al., 2023). In our application of the sequencer algorithm, the data objects to be sequenced are the single-station Ps-RF stacks obtained before or after CRISP-RF processing (vertical lines in the images of Figure 5).

First, we apply the Sequencer to the unfiltered single-station receiver function stacks (Figure 5a). The performance is very poor (Figure 5b). A slight improvement in the

288 detection of positive amplitude arrivals can be seen at ~ 60 km and ~ 100 km but not
289 much information is gained from ordering the unfiltered data. This is probably due to the
290 complex mixed-mode scattering within the highly heterogeneous crust across the US. As a
291 result, it is hard for the sequencer algorithm to find interpretable patterns within the data.
292 On the other hand, when we separate CRISP-RF filtered receiver function into two subsets:
293 a set containing only negative amplitudes, and another with only positive amplitudes, the
294 algorithm performed much better. This is possible because we have filtered out the top-side
295 reflections in the crust as well as other incoherent noise. The additional simplification using
296 polarity-dependent filtering also helps considerably (Figure 5c,d). We use an appropriate
297 measure of dissimilarity (Kullback-Leibler (KL) divergence) and a scale (sixteen) to find
298 the most optimal ordering of each of the two data subsets. The importance of filtering
299 and de-noising with CRISP-RF before sequencing is another strong argument for why we
300 are able to improve our detection of upper mantle layering using Ps-RFs that are clearly
301 overprinted by a highly scattered wave-field within the continental crust (Figure 1 and 5a).

302 After sequencing the filtered Ps-RFs, we apply a hierarchical clustering algorithm that
303 independently delineates the seismic stations into groups based on polarity-filtered receiver
304 function signature of upper mantle layering. Hierarchical clustering starts by measuring
305 pair-wise cross-correlation across all the filtered Ps-RFs. This measure of similarity is then
306 used to create binary clusters in a hierarchical manner where the third object is merged
307 into the binary cluster containing the first and second object and so on until all objects are
308 merged sequentially until a final cluster is built. This cluster tree (a dendrogram) shows how
309 (dis-)similar each of the Ps-RFs are compared to the others. The most similar (consistent)
310 Ps-RFs have linkages that are short while the dissimilar ones (and large clusters of dis-
311 similar Ps-RFs) have linkages that are longer. Through an iterative routine guided by the
312 depth coherence, we choose a linkage threshold that separates the dendrogram into 4 final
313 clusters one cluster each for the positively and negatively filtered Ps-RFs (Figure 6 & 7).
314 Each cluster is a natural grouping of single-station polarity-filtered Ps-RFs whose traces are
315 most coherent and therefore reflect the signature of scattering from coherent upper mantle
316 structure.

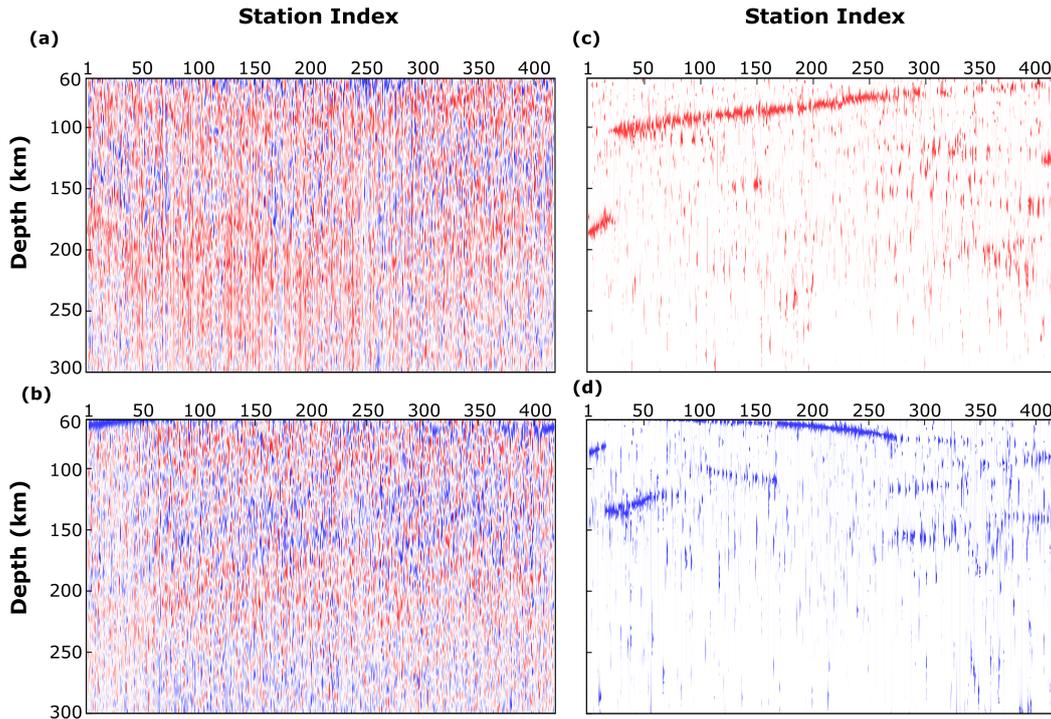


Figure 5. Enhanced pattern recognition of upper mantle discontinuities through polarity-based filtering and sequencing of Ps-RF traces. (a) Single-station radial Ps-RF stacks without CRISP-RF processing illustrating minimal interpretive content (b) Single-station radial Ps-RF traces, same as in (a), but processed through the sequencer algorithm. The image is still hard to interpret due to the presence of multi-mode scattering in a heterogeneous crust (c) Negatively filtered and sequenced Ps-RF traces (d) Positively filtered and sequenced Ps-RF traces. The CRISP-RF filtered traces in (c) and (d) show clear and coherent arrivals.

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4 Results

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Unsupervised machine learning, applied to Ps-RF traces that have been filtered based on polarity, offers a window into upper mantle structure beneath the contiguous US. Based on our analysis we observe a more complicated stratification of upper mantle structure. Beneath each station, three types of upper mantle discontinuities are observed, classified based on depth: (1) intra-lithospheric discontinuities (velocity drop and increase), (2) transitional discontinuities (velocity drop) and (3) sub-lithospheric discontinuities (velocity increase). This observation presents a departure from the simple view of a single uniform and ubiquitous middle lithosphere discontinuity expressed as a rapid velocity drop. Note that the relationship of the discontinuity depth to location within, across or beneath the lithosphere is only straightforward for stable continental lithosphere east of the Rocky mountain front. That said, this detailed perspective on upper mantle layering may reflect changes in composition, metasomatism, phase change, or rheology.

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4.1 Transitional and Intra-lithosphere discontinuities: Velocity drop

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The most striking results is the detection of phases with negative polarity visible across all the stations and within depth internal to the lithosphere (< 200 km) and at a depth that marks a transition from the lithosphere to asthenosphere (> 200 km). These phases with negative polarity on the filtered Ps-RF traces indicate discontinuities marked by a velocity

335 drop. After coherence-based clustering of these negative discontinuities, we observe four
 336 distinct station groupings: N1-N4 (Figure 6 % S3). The group index is sorted based on
 337 total number of stations and depth of each group’s representative centroid (average Ps-RF
 338 trace in each cluster).

339 The first and largest cluster, N1, (45 % - 189 of 417 stations) is the one with a pro-
 340 nounced Ps-RF arrival at a depth between 60 to 100 km , i.e. spanning a depth of ~40
 341 km (Figure 6a,6b & S3a). This intra-lithosphere discontinuity is within the depth-range
 342 traditionally associated with the mid-lithosphere discontinuity reported in previous studies
 343 (see Figure 1b) (Abt et al., 2010b; Hopper & Fischer, 2018a; Krueger et al., 2021a; Hua et
 344 al., 2023; T. Liu & Shearer, n.d.). Our independent confirmation of this discontinuity using
 345 a slightly different approach, Filtered and Sequenced Ps-RFs instead of Sp-RFs, provides
 346 extra validation that this discontinuity is real and not an artifact of deconvolution.

347 The second largest cluster, N2, (24 % - 101 of 417 stations) represents all stations with
 348 slightly deeper Ps arrivals compared to N1: 100 km - 135 km. This discontinuity is more
 349 depth-confined. Half of the stations see the discontinuity at a depth of 100 km and another
 350 half 35 km deeper at ~ 135 km (Figure 6c,6d & S5b). Compared to its shallower counterpart
 351 in N1 (Figure 6a), the deeper reflector lack a substantial depth variability and hints at
 352 a relatively consistent physical process across this limited depth range. While sporadic
 353 detections of such a relatively deeper intra-lithosphere discontinuity have previously been
 354 reported especially within the Achaean and Proterozoic terrains of central and eastern US,
 355 (T. Liu & Shearer, n.d.; Hua et al., 2023), the consistency of this seismic signal in a quarter
 356 of our stations implies a more widespread occurrence.

357 The third cluster, N3, (18% - 77 of 417 stations) represent stations with the deepest
 358 intra-lithosphere reflectors located at a depth range from ~150 km to ~190 km (Figure
 359 6e, 6f & S3c). Coherent signals in this depth range coincide with the lowermost region
 360 of the thermal boundary layer within cratonic lithosphere (Kind et al., 2020a) and may
 361 mark the transitional zone where a non-mobile lithosphere transitions to a convection
 362 upper mantle asthenosphere. Although these group of stations are consistent in having
 363 deeper discontinuities, we observe a few stations with shallower discontinuities which are
 364 not located at a consistent depth. This complicated pattern reduces the overall correlation
 365 value across the entire group. as indicated by the smearing in the final cluster average
 366 (Figure 5f).

367 The fourth and final cluster, N4, (12% - 50 of 417 stations) represents stations situated
 368 above mantle that have a discontinuity that is very clearly transitional between lithosphere
 369 and asthenosphere. This is seen as a clear negative arrival on the Ps-RFs at a depth
 370 consistently between 200 to 260 km (Figure 6g). This depth range coincides with the
 371 expected base of thick depleted rigid mantle lithosphere underneath cratons (Kind et al.,
 372 2020a). As such, this cluster of stations reflect a deeper lithosphere-asthenosphere transition,
 373 and may detect a strong signature of a impedance contrast between the rigid lithospheric
 374 mantle and the weaker asthenospheric mantle. Stations that belong to these group, and in
 375 part N3, are consistent with upper mantle structure previously reported by (Kind et al.,
 376 2020a) in the central and eastern US referred to as the cratonic lithosphere-asthenosphere
 377 boundary (LABc). Here, our results show that these stations are mostly located in the
 378 Eastern US , for N4, with some stations in the western US for N3 (see Figure S5c & S5d)

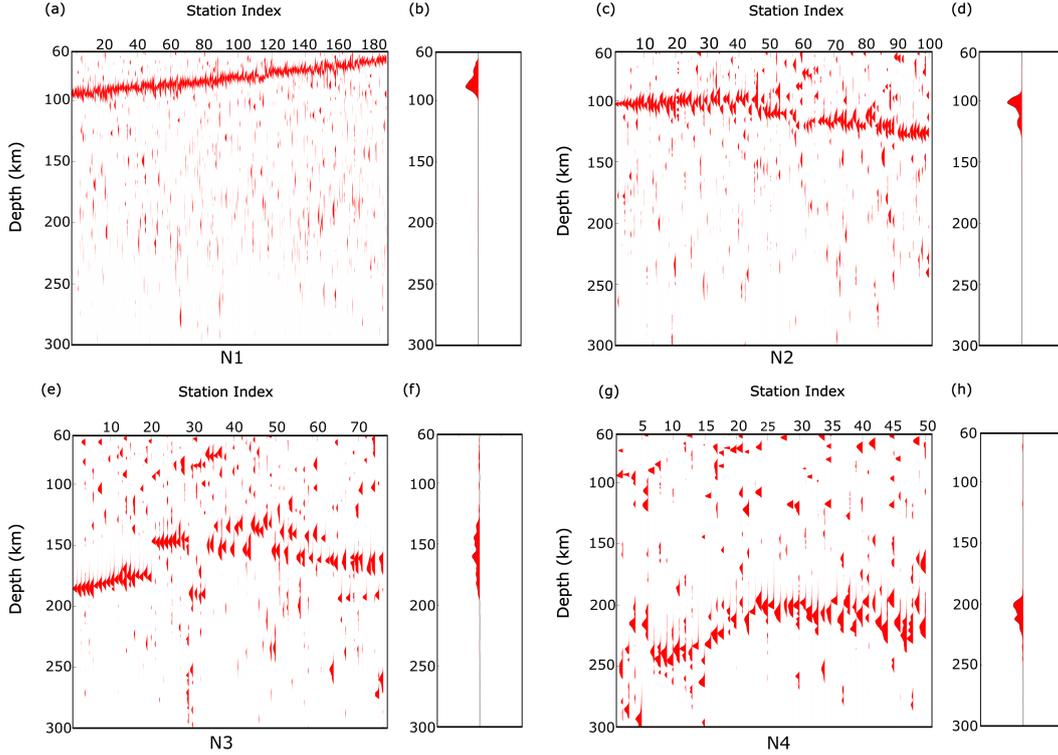


Figure 6. Stations with upper mantle discontinuities marked by a velocity drop and grouped by the hierarchical clustering of filtered and sequenced Ps-RFs (a) Shallow intra-lithosphere discontinuity (60-100 km) sorted from the deepest to shallowest station with the depth spanning 40-km. This discontinuity is similar to the previously identified mid-lithospheric discontinuities in Figure 1b. (b) Semblance-weighted stacks of the individual single-station filtered Ps-RFs (c) A relatively consistent and shallow intra-lithospheric discontinuity (100 km & 135 km) (d) Semblance-weighted stack, same as in b, showing the average Ps-RF signature across all stations in the cluster. (e) A transitional discontinuity (150-190 km) located at a depth consistent with the bottom of a thermal boundary layer. (f) The semblance weighted stack showing a more diffuse trace due to larger variance across stations in the cluster (g) A transitional discontinuity (200-250 km) located at a depth consistent with the transition from a conductive to adiabatic thermal gradient in a cold cratonic lithosphere. (h) The semblance weighted stack, is impulsive (~ 200 km) when the within-cluster variance is small and suggests that the sporadic negative amplitudes (~ 100 km) are not spatially coherent. A full statistic of the depths can be found in Figure S3. The spatial clustering can be found in S5.

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4.2 Intra and Sub-lithosphere discontinuities: Velocity increase

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In addition to upper mantle discontinuities marked by a velocity drop, we present results for discontinuities marked by a velocity increase. The Ps-RF signature of a velocity increase is a positive amplitude on the filtered Ps-RF traces. With the Ps-RFs filtered for positive amplitudes (Figure 5d) and processing through the hierarchical clustering algorithm, we observe two main types of upper mantle discontinuities marked by a velocity increase: (1) intra-lithospheric and (2) sub-lithospheric. The first cluster, P1, represents 22% of the stations with the shallowest intra-lithospheric discontinuity between ~ 80 to ~ 120 km (Figure 7a). This discrete jump in velocities is at a depth range overlapping with the intra-lithospheric discontinuities marked by a velocity drop in clusters N1 and N2 (Figure 6 a,c).

389 Slightly deeper (by ~ 40 km) is a second cluster, P2, of 32% of the stations located above
390 a velocity increase located between ~ 120 to ~ 180 km (Figure 7c). This intra-lithosphere
391 layer coincides with the previously reported positive velocity gradient-150km discontinuity
392 (PVG-150) which has been hypothesized to be the base of a melt layer embedded within
393 the lithosphere (Hua et al., 2023). When paired with the intra-lithosphere reflectors marked
394 by a velocity drop, this discontinuity reveals a potentially stratified lithospheric mantle in
395 some regions (Figure S6). Detection of such a top and bottom interfaces is only separable
396 using these two-tier filtering and clustering approach.

397 A third cluster, P3, unlike the other two, indicates the detection of an elusive sub-
398 lithosphere discontinuity at ~ 250 to 300 km (Figure 6e). Only a few stations ($\sim 5\%$)
399 show clear Ps-RF arrivals at these depths (Figure 7e). This observation is consistent with
400 the reported depth of the previously detected X-discontinuities (Pugh et al., 2021, 2023),
401 which has remained elusive in prior studies of upper mantle layering across the contiguous
402 US. The final and largest cluster, P4, is a null detection for lithosphere or sub-lithosphere
403 discontinuities with a velocity drop. This is $\sim 41\%$ of the station population. In this cluster,
404 the positive amplitudes observed at depths $< \sim 60$ km (Figure 7g and 7h) are most likely
405 the side-lobe of a crust-mantle conversion or evidence of thickened crust or terrain sutures
406 . Further analysis confirms this designations (Figure S7 & S8. see also 'X' discontinuity in
407 (Kind et al., 2020a)) and therefore we categorize these stations as belonging to stations
408 without a clear upper mantle discontinuity with a velocity increase. These structures may
409 be associated with complexes formed during extended Paleozoic assembly of the North
410 American continent.

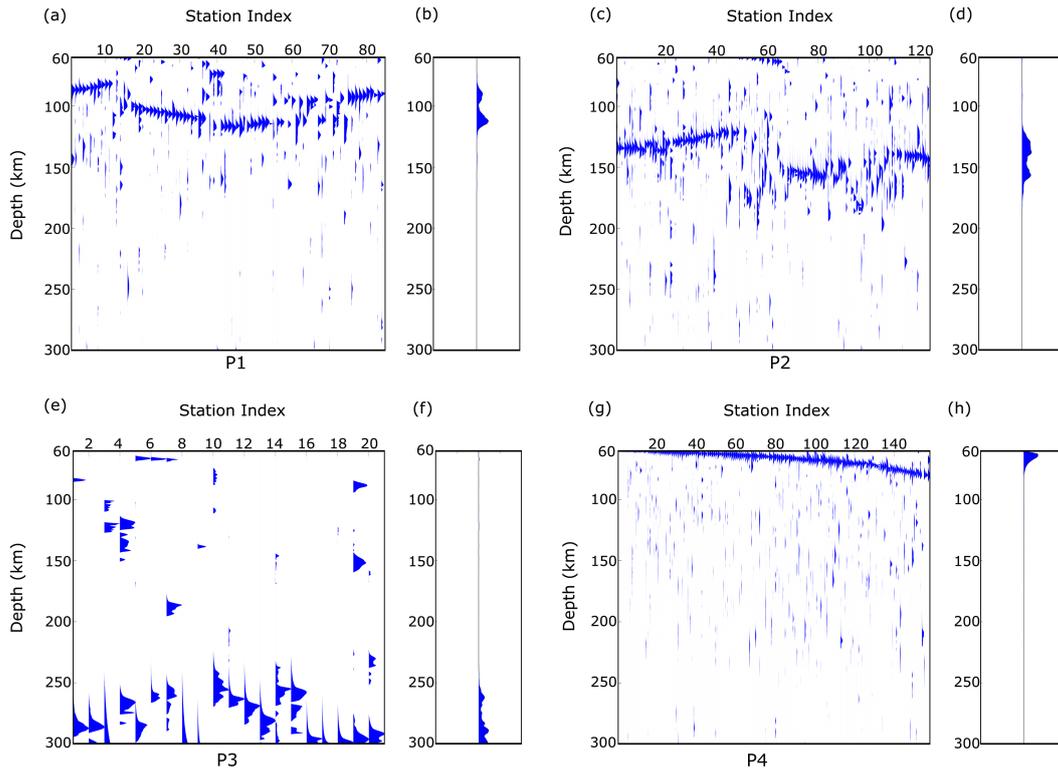


Figure 7. Similar to Figure 6 but for upper mantle discontinuities marked by a velocity increase. (a) P1: intra-lithosphere discontinuity depth of $\sim 80 - 120$ km (c) P2: intra-lithosphere discontinuity at a depth of $\sim 120 - 180$ km (e) P3: sub-lithosphere discontinuity at a depth of $\sim 250 - 300$ km (g) P4: Null detection caused by crustal side-lobes or terrane sutures. (b,d,f,h) Semblance-weighted stacks summarizing mean Ps-RF signal for P1-P4. A full statistic of the depths can be found in Figure S4. The spatial clustering can be found in S6.

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4.3 Spatial Clustering of Stations and Ps-RF Centroids

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Up until now, we've grouped our filtered Ps-RF results by looking at the data-similarity without any concern for geology or tectonics. Now, we examine how the stations belonging to each cluster are distributed in space. We do this by color-coding each station by the cluster index it belongs to using a color-coding scheme that interpolates stations into a 1-degree bin (Figure 8b and 8d). The mantle-discontinuity structure (velocity increase or decrease) beneath each station is then best described by the representative Ps-RF centroid for each group. The centroid is a semblance-weighted stack for all the polarity-filtered Ps-RFs for all the stations in the group. This summarizes the data variance in each group to a set of archetype receiver function reflecting the depth-dependent discontinuity structure across the US (Figure 8a and 8c). This spatial analysis of the station clustering reveals a striking diversity in upper mantle layering. It shows a mosaic of negative and positive seismic structures distributed in a largely stochastic fashion (Figures 8b, 8d). We observe that no single boundary or transition predominates continent-wide. Instead, a spectrum of seismic discontinuities emerges, segmented across variable depths. This random distribution does not conform to simple geographical or tectonic boundaries.

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Despite this broad characterization, we observe that the most prevalent mantle discontinuity is the *intra-lithospheric discontinuity with a velocity drop* which is observed at $\sim 70\%$ of our stations (N1+N2). The semblance-weighted mean stacks reflect a discontinuity

430 at ~ 100 km for both clusters. In the first cluster, N1, the precursory arrival reflects the
 431 systematic depth variation across the individual Ps-RFs and for the second cluster, N2,
 432 the post-cursor arrival represents the slight depth offset for half of the station. Regardless
 433 these two clusters represent most of the data-variance for a negative-amplitude Ps-RFs.
 434 The filtered Ps-RF traces from these stations show a high correlation coefficient which is
 435 visually confirmed in the data grouping (compare Figures 6a and 6c). Beneath 18.36% of
 436 our stations we observe that the deepest intra-lithosphere discontinuity, N3 is less coherent
 437 (Figure 8a). The last group of stations, only 12 %, provide evidence for a discontinuity
 438 that is transitional between the lithosphere and asthenosphere - N4 - with a representative
 439 Ps-RF that is ~ 200 km (Figure 8a). The inter-station coherence for this group is lightly
 440 better than that of N2 but less than N1 and N2. The stations detecting this deeper transi-
 441 tional discontinuity are more prevalent in the stable continental lithosphere of the eastern
 442 US (Figure S5d) .

443 For upper mantle marked by a velocity increase, we observe only intra-lithospheric
 444 and sub-lithospheric discontinuities. We do not observe velocity increases at depths tran-
 445 sitional between lithosphere and asthenosphere. While the station distribution shows no
 446 clear separation by geology or tectonics, we observe that the largest cluster (41 %), P4,
 447 is a null detection for upper mantle discontinuities (Figure 7h and 8d).. This means that
 448 intra-lithosphere discontinuities (P1 + P2 = 53%) are only half as less likely than the
 449 counterpart velocity drop (N1+N2 = 70%). The discontinuity structure beneath stations in
 450 cluster P1 is slightly shallower (~ 100 km \pm 20 km), more self-similar (higher correlation)
 451 than those in P2 (~ 150 km \pm 30 km), which are deeper. Unlike the intra-lithosphere
 452 discontinuity the detections of sub-lithospheric discontinuity is rare. Only 5.21% of stations
 453 belonging to cluster 3 (Figure 7e). The depth range is confined to (~ 270 km \pm 30 km).
 454 The detection of upper mantle discontinuities with variable depth and spatial distribution
 455 reflects a complexity inconsistent with a simple view of a laterally continuous boundary.
 456 This complexity underscores their detection by higher resolution Ps-RFs after appropriate
 457 filtering and sorting.

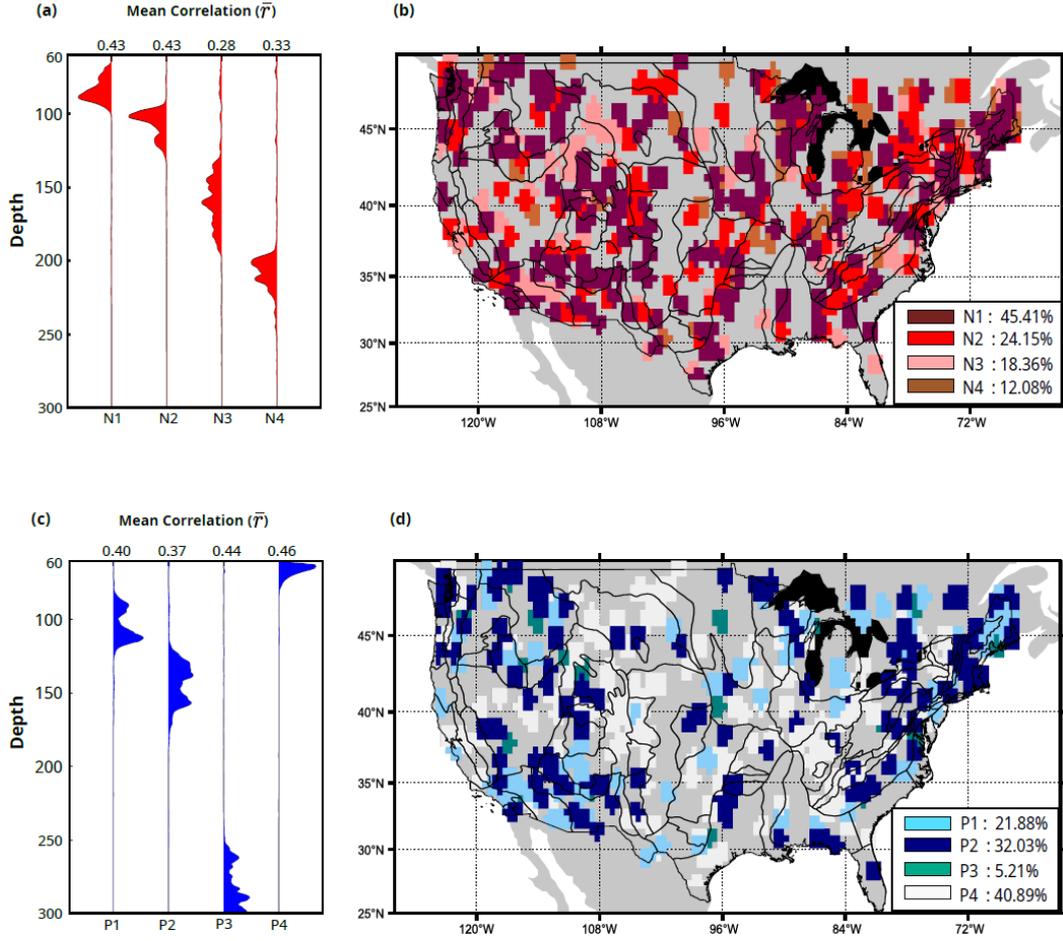


Figure 8. Station location, cluster index, centroid, and statistics for each Ps-RF filtered by polarity. (a) Semblance-weighted stacks for negative Ps-RF traces (N1-N4) representing discontinuities within and across the lithosphere (b) Location of stations (and counts) belonging to cluster N1-N4 (c) Semblance-weighted stacks for positive Ps-RF traces (P1-P3) representing discontinuities within and beneath the lithosphere. P4 represents null detections unrelated to upper mantle structure (d) Location of stations (and counts) belonging to cluster P1-P4

4.4 Synthesis: Architecture of Upper Mantle Stratification

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459 The analysis of polarity-filtered single-station Ps-RF traces resulted in their classifica-
 460 tion based on the upper mantle structure beneath the station. When each individual station
 461 was processed through the CRISP-RF filter and sorted into an exclusive group: N1-N4 or
 462 P1-P4 based on similarity to other stations, we were able to distinguish depth and type of
 463 the discontinuity (e.g. shallow, deep, velocity drop or intra-lithospheric). However, it is im-
 464 portant to note that each station can belong to either an ‘N-type’ cluster, a ‘P-type’ cluster,
 465 or both. Therefore looking beneath each station and identifying the ‘N-type’ or ‘P-type’
 466 discontinuity structure leads to a view of upper mantle architecture across the US. The first
 467 class is the *intra-lithosphere discontinuities without a discernable base* (green circles in Figure 9).
 468 These are stations whose Ps-RFs belong to the shallow ‘N-type’ (N1-N3) but do not indicate a
 469 deeper discontinuity marked by a velocity increase and so do not have a ‘P-type’ signature (do
 470 not belong to P1-P3). Crucially, these stations are coincident with the P4-type (null detection),
 471 where deep crustal reflectors and no positive intra-lithosphere

472 discontinuities are observed. The absence of a velocity increase below the velocity drop indicates that this is a strict discontinuity rather than a layering with a discernible top and
 473 bottom base. This type of upper mantle structure is prevalent and widespread (38.7%)
 474 suggesting a ubiquitous feature of the lithosphere.
 475

476 In contrast, we observe a second class of upper mantle architecture which can be
 477 described as *intra-lithosphere layering with a top and a base*. This type of upper
 478 mantle stratification is as prevalent as the previous type (44.8% of recording sites). This
 479 upper mantle architecture is observed for stations that belong to both an ‘N-type’ (N1-N3)
 480 and a ‘P-type’ (P1-P3) cluster. Therefore beneath these stations the mantle has both an
 481 upper and lower impedance contrast as you cross through an intra-lithosphere layer. It is
 482 important to note that two potential stratifications can arise in this conjunction of ‘N-type’
 483 and ‘P-type’ discontinuities: (i) a layer bounded by a velocity drop on top and a velocity
 484 increase below (yellow circles in Figure 9), and (ii) the reverse, a layer bounded by a velocity
 485 increase on top and a velocity drop below (yellow squares in Figure 9). The latter is a
 486 special case of mid-lithosphere stratification that has not previously been resolved.

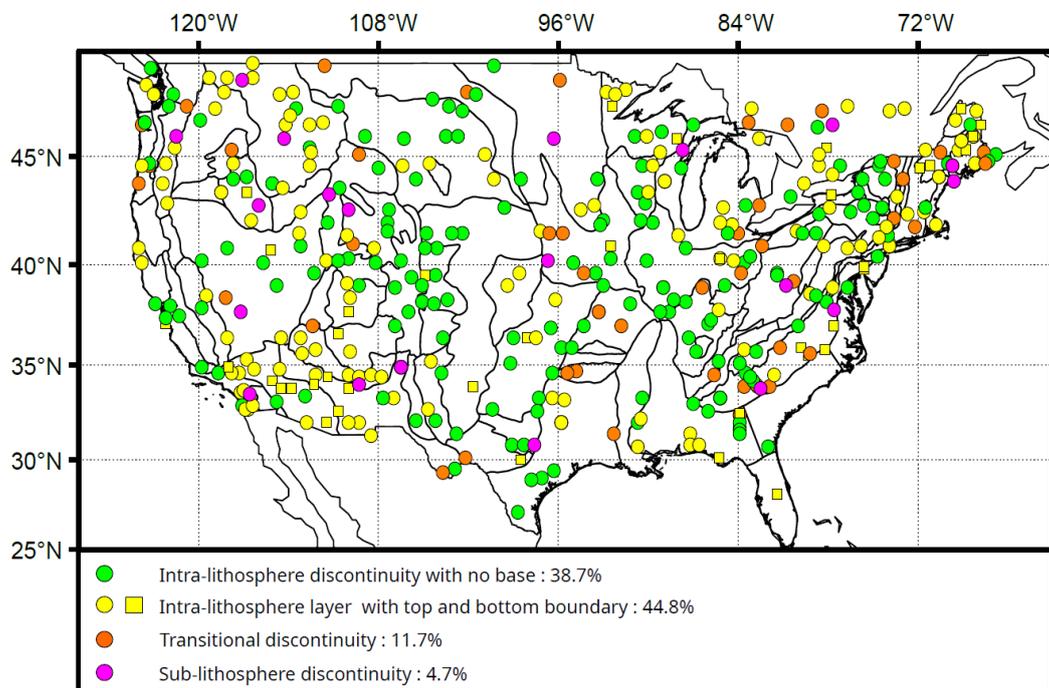


Figure 9. Upper mantle stratification beneath the US. Green circles represent stations with intra-lithosphere discontinuities without a discernible base. Yellow circles represent stations detecting a negative reflector with a deeper positive reflector. Yellow squares represent stations detecting a deeper negative reflector beneath a shallower positive reflector. Magenta-colored stations denote observed transitional discontinuities while orange stations mark sub-lithospheric positive reflectors

487 The two last classes of upper mantle stratification is: *transitional discontinuities*
 488 (across the lithosphere and asthenosphere) and *sub-lithosphere discontinuities*. Both
 489 types are not widespread - only 12 % show the detection of transitional discontinuities
 490 within the upper mantle. These can either be deeper ‘N-type’ clusters (N3 and N4) which
 491 lack a corresponding shallow ‘P-type’ Ps-RF signature (P1 or P2) at the same station
 492 (magenta-colored stations in Figure 9). Additionally, these stations lack any deep prominent
 493 positive reflectors from sub-lithosphere ‘P-type’ (P3) discontinuities. We therefore classify

494 these clusters as transitional discontinuities. Lastly, sporadic detection of sub-lithosphere
 495 discontinuities (4.7% of stations) with cluster ‘P-type’ (P3) signature constitutes the final
 496 class of upper mantle stratification. These are velocity increases confined to a depth of ~ 280
 497 $\text{km} \pm 30 \text{ km}$.

498 **5 Discussions and Interpretations**

499 Our results, using filtered Ps-RFs, show that the upper mantle beneath the US is
 500 stratified. In the broadest sense, this view of the upper mantle’s stratification, particularly
 501 within and across the lithosphere, is consistent with previous regional and continent-wide
 502 (Abt et al., 2010b; Hopper & Fischer, 2018b; Kind et al., 2020a; Lekic et al., 2011; Lekić &
 503 Fischer, 2014; Levander & Miller, 2012; T. Liu et al., 2023) and single-station observations)
 504 (Ford et al., 2016; Hua et al., 2023; Krueger et al., 2021a; Long et al., 2017; Luo, Long,
 505 Karabinos, & others, 2021; Rychert et al., 2005, 2007b). However, our work differs in some
 506 specific details, especially across and below the lithosphere. First, our results refine the
 507 sharpness, depth variation, and complexity of intra-lithosphere discontinuities. Second, we
 508 show that some of these discontinuities have a top and bottom boundary, while others do not.
 509 Lastly, we can show a rare detection of a class of discontinuity transitional between the upper
 510 mantle lithosphere and asthenosphere (Kind et al., 2020b) and an elusive sub-lithosphere
 511 discontinuity that might be consistent with the X-discontinuity (Pugh et al., 2021). In what
 512 follows, we: (1) provide a justification for a new taxonomy of upper mantle stratification,
 513 (2) summarize our revised constraints providing the reasoning for why our approach to
 514 mantle imaging enables a refined view of upper mantle stratification (in contrast with S-
 515 wave conversions or reflections), and (3) discuss the implications of our revised constraints
 516 for causal models for upper mantle stratification.

517 **5.1 A New Taxonomy and its Justification**

518 In describing upper mantle structure, we introduce a new taxonomy – a way of organiz-
 519 ing and describing how upper mantle stratification varies across the US. This new taxonomy
 520 is informed by the descriptive patterns visible in the cluster analysis (Figure 10). We observe
 521 that most of the variability in the upper mantle stratification can be organized in three main
 522 ways: (1) intra-lithosphere discontinuities with no base, (2) intra-lithosphere layering with
 523 a top and bottom-boundary (P-type and N-type), and (3) transitional and sub-lithosphere
 524 discontinuities. In previous work by (Abt et al., 2010b; Fischer et al., 2010a; Fischer,
 525 Rychert, Dalton, Miller, Beghein, & Schutt, 2020; Kind et al., 2015; Kumar, Yuan, et al.,
 526 2012; L. Liu & Gao, 2018; T. Liu & Shearer, 2021) much effort has focused on detecting the
 527 mid-lithosphere discontinuities (MLD) using S-wave conversions or S-reverberations. Much
 528 of these observations belong to the class of mantle stratification we are calling the intra-
 529 lithosphere discontinuity with no base. This discontinuity, which is marked by a velocity
 530 drop, has initially been disputed to be an artifact of deconvolution by (Kind et al., 2020a).
 531 Here, we confirm this to be a robust detection consistent with the re-analysis of (Krueger
 532 et al., 2021b) but now verified across a wider footprint of stations. Apart from the MLD,
 533 we observe other discontinuities internal to the lithosphere, some of which look more like
 534 layering, hence introducing a new naming scheme that captures this diversity.

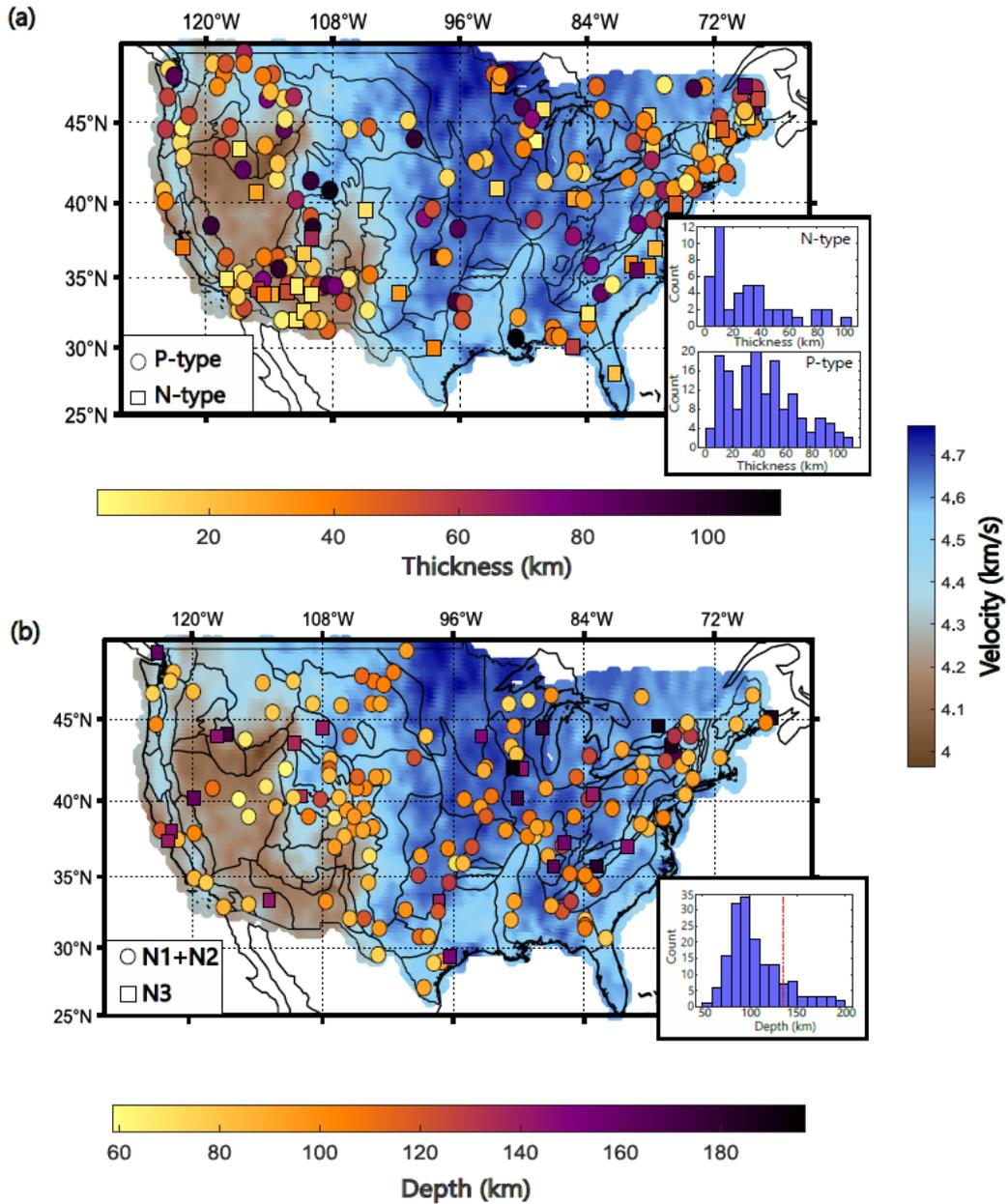


Figure 10. The most common upper mantle stratification across the US. (a) Stations located above mantle with an intra-lithosphere layer with a top or bottom boundary. Inset histogram shows layer thickness and symbols denote P-type and N-type layering (b) Stations located above mantle with an intra-lithosphere discontinuities with no detectable base. Inset histogram shows depth and symbols for N1+N2 and N3 discontinuities (compare with Figure 8). The red line marks the minimum depth for N3 discontinuities

535 For example, a recent global study conducted by (Hua et al., 2023) revealed a positive
 536 velocity gradient located at 150 km. They interpret this to be the base of a global molten
 537 asthenosphere layer. In our survey of the continental upper mantle, such a discontinuity is
 538 detected across the US, but this type of upper mantle stratification is more likely to be the
 539 base of an intra-lithosphere layer (P-type). Our taxonomy here is justified because when ob-

540 served in the eastern US, this P-type base is within the cold continental lithosphere and can-
 541 not be associated with the base of an asthenosphere layer (Figures 9 and 10a). In some rare
 542 cases, in the western US, which is more tectonically active, the thermal and shear-velocity
 543 structure may argue for a thinner lithosphere with a P-type base reflecting the bottom of an
 544 asthenosphere layer (Hansen et al., 2015; Hopper et al., 2014; Priestley et al., 2018). Our
 545 final classification – the transitional and sub-lithosphere discontinuities – could be the same
 546 discontinuities as that called the lithosphere-asthenosphere boundary in (Kind et al., 2020b)
 547 or the X-discontinuity in (Pugh et al., 2021; Srinu et al., 2021). Here, we choose to use the
 548 term transitional discontinuity because it does not impose a rheological interpretation to a
 549 seismological observation without a clear model. The term sub-lithospheric discontinuity
 550 encompasses all possibilities: the Lehmann, the X-discontinuity, and other types of upper
 551 mantle stratification.

552 **5.2 Revised Constraints on Upper Mantle Stratification**

553 *Re-evaluation of UMD1+3 (Intra-lithosphere discontinuity with no base):*
 554 The detection of an intra-lithosphere discontinuity with no base is most consistent with
 555 the previous observation of a mid-lithosphere discontinuity (MLD) in the eastern US, often
 556 referred to as the lithosphere-asthenosphere boundary (LAB) in the west (Hopper & Fischer,
 557 2018b; Krueger et al., 2021b; T. Liu & Shearer, 2021). Across the US, this discontinuity has
 558 previously been reported at a depth of 100 - 140 km (UMD1 and UMD3 in Figures 1b).
 559 As pointed out, our new results confirm those obtained using reflected and S-p converted
 560 body waves: SP-RFs, SS reflections (Figure 11). The confirmation of this discontinuity with
 561 our newly improved Ps-RF technique demonstrates that this type of mantle stratification
 562 is a feature that varies little with depth and is sharp enough to be visible at different
 563 wavelengths (Figure 6a,6b & 10b). Higher-resolution Ps-RF imaging provides the following
 564 revised constraints on this discontinuity: (1) it is more likely to be observed east of the
 565 Rockies, (2) the depth varies systematically, over 40 km, with the shallowest discontinuities
 566 (60 km) in the west and the deepest (~135 km) to the east (3) the velocity gradient is
 567 as sharp as 10 km regardless of region (Figure 10b). These constraints are important
 568 for evaluating causal models. Note also that to the west of the US the intra-lithosphere
 569 discontinuities are mostly marked by a bottom boundary, unlike to the east (Figure 10a).
 570 This observation rules out the need for a distinction between MLD and LAB and suggests
 571 that intra-lithosphere discontinuities with no base are a clear feature of cold continental
 572 lithosphere that has not been thermally modified over much of the US's tectonic history and
 573 yet can maintain a near-universal discontinuity that seems to be unrelated to the history of
 574 continental formation.

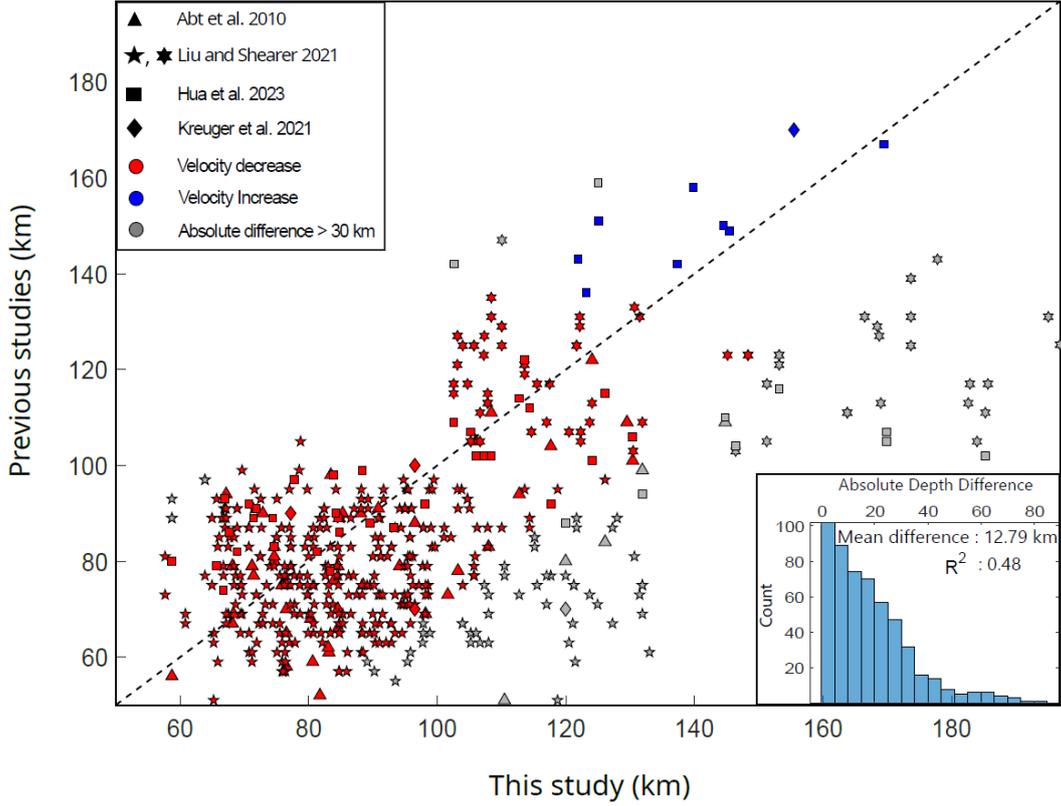


Figure 11. A comparison of previous body-wave studies of upper mantle discontinuities and this study. The scatter plot shows depth estimates for negative and positive discontinuities for similar locations. A one-to-one line (black dashed line) means that our results are consistent with previous work. Outliers are indicated in grey. Sample filtered Ps-RFs for two stations US.ECSD and IU.RSSD previously studied by (Krueger et al., 2021b; T. Liu et al., 2023) can be seen in Figure S9.

575 **Re-evaluation of UMD2 (Intra-lithospherelayering):** The observation of an
 576 intra-lithospheric layering with a discernible top and bottom boundary may be consistent
 577 with the PVG-150 km detected by (Hua et al., 2023). However, this interpretation is only
 578 consistent for stations located to the west of the Rockies. The spatial clustering along regions
 579 with recent magmatic activity – south of the Colorado Plateau and within the Columbia
 580 River basalt suggests that in these regions alone – not in the eastern US – do you have a
 581 lithosphere that may be thermally modified in such a way as to produce a partial molten
 582 layer that results in a shallow velocity drop with a discernable velocity increase at the bot-
 583 tom boundary of a rheological weak asthenosphere layer. In the eastern US, however, such
 584 an interpretation is not consistent with the observations, and a new model is required. Also,
 585 in a few locations we observe an even puzzling layering that is opposite of the partial melt
 586 interpretation—a velocity increase above a velocity increase (N-type).

587 **5.3 Improved Visibility of the Transitional and X-Discontinuity**

588 As we have seen, discontinuities internal to the lithosphere are easily detectable. How-
 589 ever, the high-frequency body-wave signature of the boundary between a lithosphere and an
 590 asthenosphere has proved elusive, especially beneath the Archean or Proterozoic lithosphere
 591 in the eastern US. This is probably due to the gradual thermal and compositional structure

592 leading to the lack of a sharp boundary at a depth of 250 km (Dalton et al., 2017; Fischer,
 593 Rychert, Dalton, Miller, Beghein, & Schutt, 2020; Priestley et al., 2018). In the continent-
 594 wide and single-station studies (Kind et al., 2020a; Krueger et al., 2021b; Mancinelli et al.,
 595 2017) the detections of a transitional discontinuity marked by a velocity drop are referred
 596 to as the craton LAB and are most clearly observed by (Kind et al., 2020a) in the south-
 597 eastern region of the US and on craton boundaries by (Krueger et al., 2021b). In our case,
 598 the detection of a deep discontinuity is rare and spatially variable (Figure 9, S5c, S5d, and
 599 S6c, S6d). As a result, we hesitate to make any inference on the driving mechanisms for its
 600 visibility.

601 Similarly, positive velocity gradients have previously been detected within and beneath
 602 the lithosphere. For detections within the lithosphere, the favored interpretation is the
 603 signature of paleo-subduction beneath the Superior craton, craton assembly through im-
 604 brication and underplating (Kind et al., 2020a). Although we observe these discontinuities
 605 in the lithosphere, the spatial resolution is not high enough to place constraints on their
 606 tectonic drivers. Most of our detections are associated with the top or bottom boundary
 607 of a lithospheric layer rather than a structural feature of continental assembly. The most
 608 compelling observation is the rare detections of sub-lithosphere discontinuities at 250 -300
 609 km (Figures 7c and S4c). We interpret these as an X-discontinuity similar to that seen glob-
 610 ally by (Pugh et al., 2021). The correspondence between the location of our detection and
 611 the yellow-stone hotspot lends further strength to this interpretation (Figure S6c). We note
 612 that the interpretation of a shallower positive discontinuity as the Lehmann discontinuity
 613 is not supported by our results. Future work is needed to evaluate if this discontinuity is
 614 preferably associated with anisotropy (Ford et al., 2016; Gaherty & Jordan, 1995; Gung et
 615 al., 2003).

616 **5.4 A Case for Models consistent with Revised Constraints**

617 Based on our new constraints we re-evaluate the different models proposed to explain
 618 intra-lithosphere and transitional discontinuities (Karato & Park, 2018; H. Yuan & Ro-
 619 manowicz, 2018). They include partial melting (Hua et al., 2023; Rader et al., 2015) chem-
 620 ical stratification or metasomatism (Krueger et al., 2021b; T. Liu et al., n.d.; Rader et al.,
 621 2015; Saha et al., 2021; Selway et al., 2015a), variable anisotropy (Wirth & Long, 2014a;
 622 H. Yuan & Levin, 2014; H. Yuan & Romanowicz, 2010), and elastically accommodated
 623 grain-boundary sliding (Karato et al., 2015). Many of these models were proposed shortly
 624 after the early detection of lithosphere discontinuities when a detailed view of upper mantle
 625 stratification was unavailable (Saha et al., 2021; Saha & Dasgupta, 2019). The new obser-
 626 vations suggest that some models are more consistent with discontinuities without a base
 627 while others are more consistent with those with a base.

628 **5.4.1 Intra-Lithosphere Discontinuities with no Base**

629 The simplest class of mantle stratification is the intra-lithospheric discontinuity with
 630 no base. This discontinuity, more likely to be observed in cold continental lithosphere, has
 631 a very systematic behavior that makes it hard to reconcile with models that prescribe a
 632 unique tectonic history – e.g., metasomatism or imbrication and underplating during craton
 633 assembly. For example, a discontinuity that is relatively sharp with no bottom boundary and
 634 is more likely to be observed east of the Rockies at a depth that varies systematically: the
 635 shallowest discontinuities (60 km) to the west and deepest (135 km) to the east. This near-
 636 universal discontinuity in the cold continental lithosphere leads us to prefer the attenuation-
 637 related model of (Karato et al., 2015) for this class of mantle stratification. As conceived,
 638 this model can reduce velocities across the US at sub-solidus temperatures either through
 639 thermal relaxation or hydration, without the need for a deeper increase in velocities, ruling
 640 out the need for a bottom base. The depth dependence of temperature and hydration in
 641 the grain-boundary sliding model can explain the deepening of this discontinuity. It is hard
 642 to reconcile this observation with the metasomatic model.

5.4.2 *Intra-Lithosphere Layering with a Top and Bottom Boundary*

The second class of mantle stratification is the intra-lithospheric discontinuity with a top and bottom boundary. In this class, the easiest to explain is the P-type boundary – a velocity increase below a velocity decrease. Because this discontinuity is more likely to be observed in the tectonically active and recently magmatic regions or along the Appalachians, we are inclined to prefer the partial melt or metasomatic model to explain this class of mantle stratification. If the lithosphere is significantly thermally perturbed, with the infusion, into the mantle, of low-velocity iron-rich or fluid-rich minerals, partial melting or metasomatism might lead to a reduction in velocity, below which an increase in velocity, detected as a bottom base, will be observed (Karato & Park, 2018; Saha et al., 2021). The reason why this bottom base has gone undetected until now might be related to the low-frequency content of Sp-RFs with or without deconvolution (Kind & Yuan, 2018b; X. Yuan et al., 2006) compared to the higher-resolution Ps-RFs (T. M. Olugboji et al., 2013; T. Olugboji, Zhang, et al., 2023). Also, in the S-reflection technique used by (T. Liu & Shearer, 2021; T. Liu et al., 2023) the resolution is limited to shallow discontinuities (≤ 150 km) due to the ambiguity of distinguishing source-side and receiver-side reflections. The N-type boundary – velocity decrease below a velocity increase is harder to explain. One simple model is that this reflects relics of craton assembly or crustal underplating. A thickened crust, or subducted lithosphere embedded within a lower velocity layer is one way to explain this observation. The geological preference for regions where such a tectonic scenario can be envisioned is another reason for our preference for this model.

5.4.3 *Transitional Discontinuities and the X*

The final class of mantle stratification is transitional and sub-lithosphere discontinuities. Strictly speaking, these discontinuities are of different types and are rare: negative velocity gradients for the transition across a lithosphere to asthenosphere transition and a positive velocity gradient for the sub-lithosphere discontinuity. For the discontinuity associated with the lithosphere-asthenosphere transition, the current statistics suggest that this discontinuity is more likely to be observed in the cold continental lithosphere in the eastern US (Figures 9 and S6d). The sparsity of observations should be related to the small velocity drop at these depths due to weak thermal and compositional gradients at these depths (Fischer et al., 2010b). The rarity of the sub-lithosphere X-discontinuity at 300 km is also a clear indication that phase transformations or recycling of basalts at hotspots are very unlikely across the US (Figure S6c).

5.5 *Current Limits, Next Steps: Hales, Lehmann and Anisotropy*

In our current assessment of upper mantle stratification, the CRISP-RF approach has produced a higher-resolution and improved view of upper mantle stratification. This success is due to improvements in frequency content as well as the availability of long-running stations that allow for wavefield separation of deep mantle conversions from shallow crustal reverberations. Despite these improvements, our taxonomy of upper mantle stratification does not yet explore anisotropy as do some recent studies using anisotropic Ps-RFs (Abt et al., 2010b; Ford et al., 2016; Park & Levin, 2016a; Wirth & Long, 2014a; H. Yuan & Levin, 2014). This is because the radon-transformed Ps-RFs we use assume isotropic layering. A generalization of the CRISP-RF methodology to investigate anisotropy is a natural next step. We do argue that in future generalization of our methodology to investigating anisotropy, back-azimuthal harmonic decomposition, as described in (Levin & Park, 1998; Park & Levin, 2016b; Bostock, 1997, 1998) should be applied only after isotropic layer-stripping and attenuation of crustal reverberations using CRISP-RF. An improved method for investigating anisotropy not contaminated by shallow crustal reverberations will allow us to evaluate models that invoke anisotropy for both intra-lithosphere and sub-lithosphere discontinuities, e.g. Lehmann, Hales, and Gutenberg discontinuities (Ford et al., 2016; Gaherty & Jordan, 1995; Gung et al., 2003; Deuss, 2009; Deuss & Woodhouse, 2004)

6 Conclusions

The stratification of the upper mantle beneath the US is investigated using high-resolution Ps-converted waves after filtering out shallow crustal reverberations. After careful data curation, using 417 of the best stations that span a diversity of physiographic provinces, followed by polarity-dependent filtering, sequencing, and clustering, we obtain a new and improved taxonomy of upper mantle stratification. We observe that the most dominant type of upper mantle stratification (84% of station inventory) is within the lithosphere – about half of which are discontinuities without a base and the other half are layers with a top and bottom boundary. A re-evaluation of causal models based on our revised constraints suggests that some class of models better explain the former than they do the latter. The remainder of our stations (16%) show rare detections of discontinuities transitional between the lithosphere and the asthenosphere and an X-type sub-lithosphere discontinuity. This suggests a limited role of such discontinuities in explaining upper mantle stratification. Future work should evaluate our taxonomy on a global scale and revisit the evaluation of causal models, especially with regards to anisotropy.

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8 Open Research

The dataset used in this study can be retrieved from IRIS using Obspy’s routines for mass download. The codes and results for waveform processing is accessible in the Github repository linked to the <https://doi.org/10.5281/zenodo.10452228>. The repository contains all metadata information, Ps-RF results and station classification.

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