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Evidence for a lithospheric step and pervasive lithospheric thinning beneath southern New England, northeastern USA

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ABSTRACT

In this study, we use data from the SEISConn seismic experiment to calculate Sp receiver functions in order to characterize the geometry of upper-mantle structure beneath southern New England (northeastern United States). We image robust negative-velocity-gradient discontinuities beneath southern New England that we interpret as corresponding to the lithosphere-asthenosphere boundary (LAB) and identify a well-defined step of 15 km in LAB depth at a longitude of 73°W, which we interpret to be the boundary between Laurentian and Appalachian lithosphere, although the offset may be larger if the putative LAB phase is reinterpreted to be a mid-lithospheric discontinuity. We infer that the lithosphere throughout the region is substantially thinner than elsewhere in the continental interior, consistent with regional tomographic studies and previously published Sp receiver function results. The presence of thinned lithosphere suggests that the low-velocity Northern Appalachian Anomaly (NAA) in the upper mantle may extend as far south as coastal Connecticut. The presence of regionally thinned lithosphere and a step in lithospheric thickness suggests that inherited structure may be preserved in present-day lithosphere, even in the presence of more recent dynamic processes associated with the NAA.

INTRODUCTION

Southern New England's (northeastern United States) geologic structure is the result of two Wilson cycles starting approximately one billion years ago (Hatcher, 2010). The effects of repeated rifting, accretion, and subduction on the (mantle) lithospheric structure of the continental margin are not well constrained. Global tomography finds some correlation between crustal age and inferred lithospheric thickness (e.g., Steinberger and Becker, 2018), although at shorter length scales, this relationship may break down (Simons et al., 2002). Structural deviations from this relationship may result from relatively recent tectonic processes, although it is unclear how long perturbations to lithospheric mantle structure can persist after the last thermotectonic event (Porter et al., 2019). A key question, then, is: to what extent (if any) have the repeated episodes of accretion and rifting in the northeastern U.S. been preserved in the lithospheric mantle?

Estimates of lithosphere-asthenosphere boundary (LAB) depth based on receiver function (RF) analysis range from 50 to 115 km beneath the northeastern U.S. (Hopper and Fischer, 2018), while estimates based on seismic tomography range from 50–85 km (Yang and Gao, 2018) to 60–150 km (Porter et al., 2016). Tomographic studies have also imaged a region of low upper-mantle velocities beneath the northeastern U.S., commonly referred to as the Northern Appalachian Anomaly (NAA). Due to the relatively sparse spacing of available seismic stations in eastern North America, it has proven difficult to observe definitive changes in mantle structure that can be directly linked to inherited structure associated with continental collision or rifting. The recently completed Seismic Experiment for Imaging Structure beneath Connecticut (SEISConn) experiment (Long and Aragon, 2020) was designed to image crust and mantle structure at a finer scale, crosscutting key tectonic features and geologic terranes in southern New England. These terranes include the Proterozoic-aged Grenville orogen to the west and terranes that were accreted during the Appalachian orogeny to the east, including the Ganderia and Avalonia terranes. Our study compared observations of mantle structure generated using Sp RF analysis to these tectonic boundaries in order to better understand to what extent present-day seismic structure is related to past plate-boundary processes.

DATA AND METHODS

The SEISConn deployment consisted of an east-west linear array spanning northern Connecticut and crosscutting several passive-margin terrane boundaries and the centrally located Hartford rift basin (Long and Aragon, 2020). We used seismic data from the SEISConn experiment and from 76 additional broadband stations (Fig. 1). Our highest-spatial-density data are in northern Connecticut, with good coverage extending into Massachusetts and New York (see Figs. S1 and S2 in the Supplemental Material[1]). We calculated >2000 individual Sp receiver functions (RFs; filtered to 2–100 s) and stacked them according to their common conversion point (CCP; e.g., Lekic et al., 2011). RF traces were migrated using a three-dimensional mantle velocity model (Schmandt and Lin 2014, Schmandt et al., 2015) and a global crustal model (Laske et al., 2013). RF uncertainties were calculated using a bootstrapping technique (Hopper and Fischer, 2018). See the Supplemental Material for a description of the methodology.

RESULTS

Our results (Fig. 2) reveal a clear positive velocity gradient, corresponding to the Moho, as well as multiple negative velocity gradients within the mantle. A laterally continuous

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[1]Supplemental Material. Detailed description of methods and negative phase interpretation and *k*-means clustering analysis, along with figures demonstrating receiver function uncertainties, histograms of LAB depth, and a table of stations and events, station information, and profile data. Please visit https://doi.org/10.1130/GEOL.S.19879813 to access the supplemental material, and contact editing@geosociety.org with any questions.

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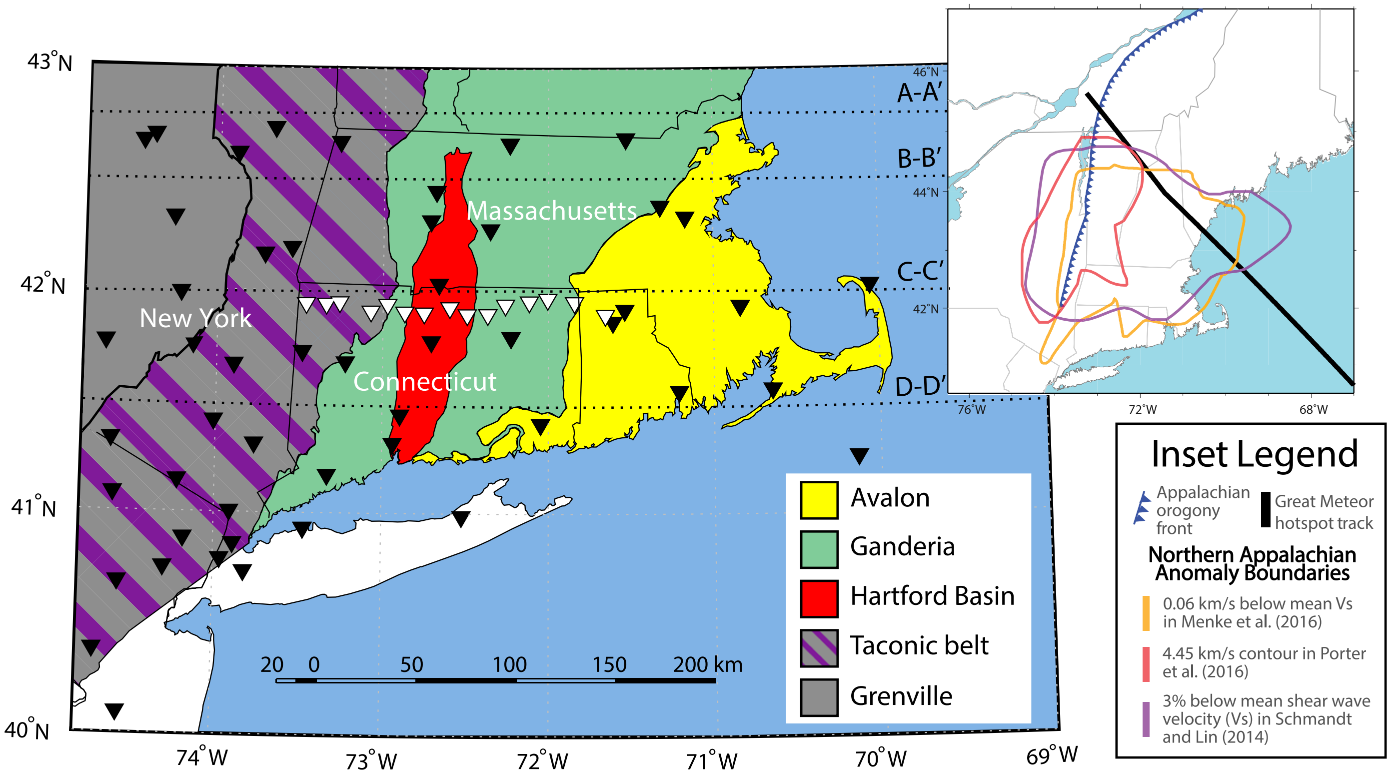

Figure 1. Tectonic setting of southern New England (northeastern USA), after Hibbard et al. (2006), delineating major terranes (Grenville, Ganderia, and Avalon) as well as the Taconic belt, a zone of deformation during the Taconic orogeny that makes up the western edge of Laurentia. We include the Moretown terrane, which accreted onto Laurentia during the Taconic orogeny, as part of Ganderia. White triangles correspond to Seismic Experiment for Imaging Structure beneath Connecticut (SEISConn) stations (network XP); black correspond to all other seismic stations (networks LD, N4, NE, TA, U.S., XA, XO; all networks and stations are listed in Table S1 in the Supplemental Material [see footnote 1]) used. Dotted black lines correspond to cross sections in Figure 2. Inset (modified from Levin et al., 2017) outlines possible Northern Appalachian Anomaly boundaries based on seismic tomography models and the path of the Great Meteor hotspot.

negative phase is observed west of 73°W at depths of ~60–100 km. A similar, lower-amplitude negative phase is observed at depths of 50–70 km east of 73°W. We also observe large, discontinuous negative phases at depths of 150–200 km centered at ~73°–74°W. These negative phases are adjacent to large-amplitude positive phases in a region of poor data coverage (see the Supplemental Material for a data density plot), suggesting issues related to limited data. Secondary, laterally discontinuous negative phases are also present at mantle depths and may reflect the presence of real structure; however, we choose to focus our discussion on the largest-amplitude phases. We mark only the largest negative phase at <150 km depth (Hopper and Fischer, 2018), with the caveat that the phase must be exceed error bars defined by two standard deviations and have a resolvable positive phase (Moho) between 25 and 50 km. Multiple negative phases with similar amplitudes are occasionally observed in a zone of negative energy (e.g., 60–90 km depth at 74°–73°W). Our discussion is largely unaffected by the decision to pick only the largest-amplitude phase in these cases.

We observe a change in the amplitude and depth of the selected negative phases occurring at a longitude of ~73°W (Fig. 3). Along northern profiles (Fig. 2), the negative phase is observed at 70–80 km depth west of 73°W, gradually transitioning to shallower depths (60–70 km) east of 73°W. At cross section C-C′ (Fig. 2), the negative-phase depth increases beneath the western half of the study area, reaching a maximum depth of 90–100 km and average depths of ~75–85 km, and abruptly transitions to a weaker, shallower (55–60 km) negative phase east of 73°W. Longitude 73°W is roughly coincident with the boundary between the Taconic belt and Ganderia terrane, which corresponds to the eastern boundary of Laurentia. At cross section D-D′ (Fig. 2), the stepover at 73°W remains pronounced, although the step begins to diverge from the surface terrane boundary in southern Connecticut (Fig. 3). In order to better assess whether this correlation is meaningful, we employ *k*-means clustering, based only on amplitude and depth, and compare the clusters to results divided on the basis of the Laurentian boundary. We observe that the *k*-means clustering generates groupings similar to those dictated by terrane, indicating that a relationship between depth, amplitude, and terrane boundary may exist (see the Supplemental Material). Averaging depth values east and west of the Taconic belt–Ganderia terrane boundary yields an average depth offset across the terrane boundary of ~15 km.

DISCUSSION

While the depth and amplitude of the prominent negative phase can be clearly identified in our CCP images, its origin is less evident. We considered whether contrasts in seismic anisotropy within the upper mantle may contribute to our observations. However, given the complex nature of lithospheric anisotropy beneath our study region (e.g., Li et al., 2021; Lopes et al., 2020), it is likely that the negative phases we image reflect largely isotropic velocity decreases with depth. Numerous studies of continental lithosphere have found evidence for mid-lithospheric discontinuities (MLDs) (e.g., Fischer et al., 2010; Wirth and Long, 2014; Abt et al., 2010) at depths of ~80–150 km. We compare our negative phases to the regional S-wave velocity model of Yang and Gao (2018) and find that our negative phases predominantly fall within the depth range suggested by a tomographically inferred potential LAB depth range, which we define as the depth of the first maximum in velocity downward to the first minimum in velocity (Birkey et al., 2021; Fig. 4; see the Supplemental Material). Our results are also consistent with observations of lithospheric thinning (78–67 km) from west (75°W) to east (71°W) using data from the USArray seismic array (Hopper and Fischer, 2018), but we infer slightly thinner lithosphere than studies using Ps

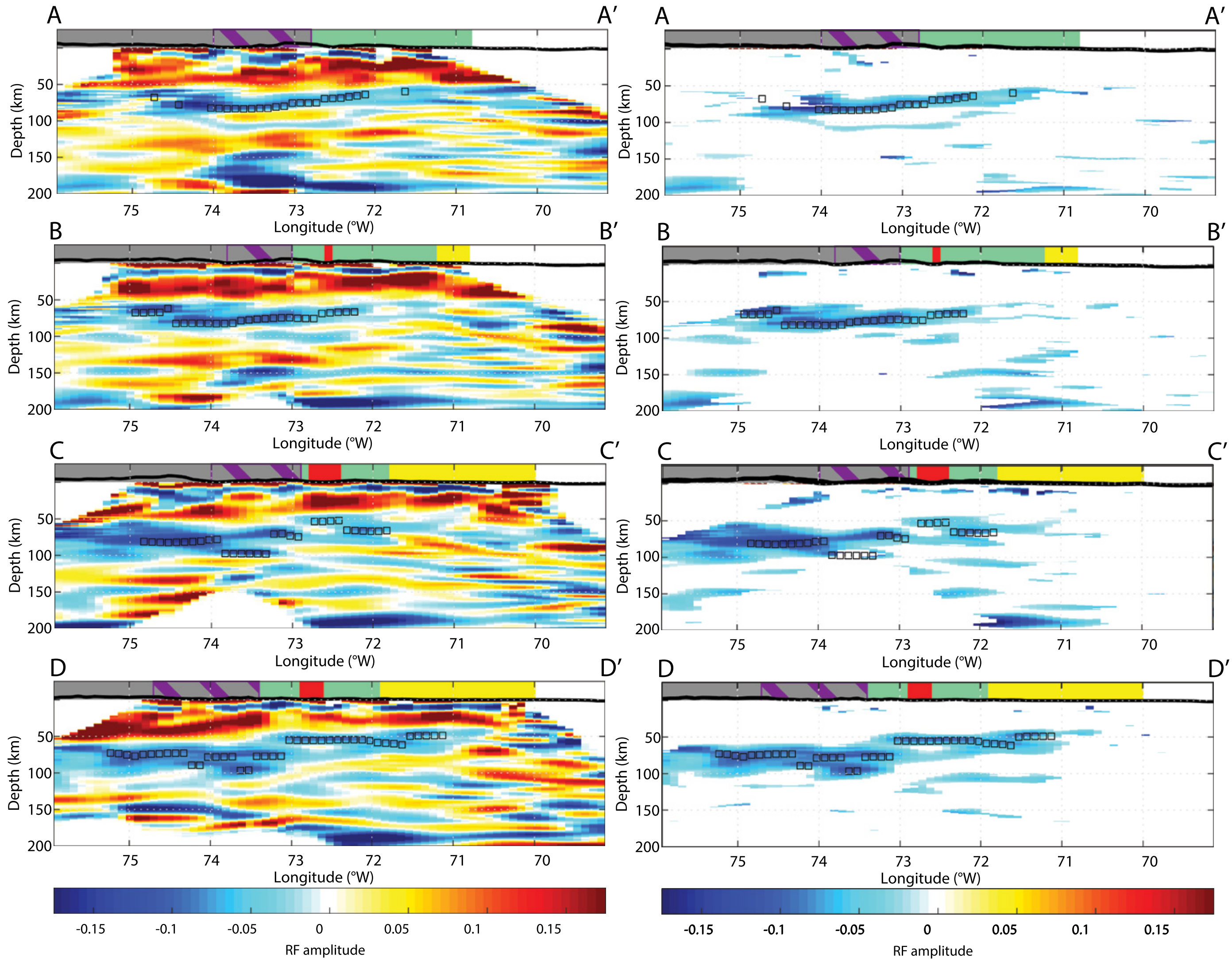

Figure 2. (Left) Vertical cross sections through Sp common conversion point (CCP) stacked receiver functions (RFs); see Figure 1 for location. Negative phases (blue) indicate presence of negative velocity gradient; positive phases are shown in red. Open black squares show location of selected negative phases, likely corresponding to lithosphere-asthenosphere boundary (LAB), picked using criteria discussed in text. Colored boxes at top of each section mark extent of tectonic terranes (Fig. 1). Note pronounced change in depth of LAB phase at ~73°W in cross sections C-C′ and D-D′. (Right) Masked Sp CCP stacked RF results where only negative-amplitude phases with uncertainties of 0.08 or less are shown.

receiver functions (Rychert et al., 2005) and heat-flow data (Artemieva, 2006). If the negative phase does in fact correspond to the LAB, this suggests that LAB depths in our study area are comparable to those of the tectonically active western U.S. and that an abrupt change in LAB properties is closely aligned with the eastern edge of pre-Appalachian Laurentia over much of the study area, with the exception of southern Connecticut.

Lithospheric thickness estimates typically show a pronounced contrast between the western and eastern U.S., which may be attributed to differences in thermotectonic age (e.g., Porter et al., 2019). Regional tomography models show clear evidence for an upper-mantle low-velocity anomaly (the NAA) located beneath central New England, with depth extent estimated at 60–140 km (Li et al., 2003) to 60–300 km (Schmandt and Lin, 2014). These values overlap with the depth of our inferred LAB, providing independent evidence that the lithosphere may be thinned throughout southern New England. Our inference is also consistent with recent evidence from shear-wave splitting suggesting that the NAA may extend south to the latitude of the SEISConn array (Levin et al., 2017; Lopes et al., 2020), at least in eastern New England. The origin of the NAA is debated; it has been attributed to the Great Meteor hotspot (Eaton and Frederiksen, 2007) or to edge-driven small-scale convection (Menke et al., 2016). In any case, our results and others (Lopes et al., 2020; Luo et al., 2021) suggest that the NAA may be associated with lithospheric thinning as far south as southern New England.

While the regionally shallow LAB suggests a relationship to ongoing dynamic mantle processes, the change in depth and amplitude (a function of velocity gradient across the LAB) across the western edge of the accreted Appalachian terranes suggests that some lithospheric properties may be tectonically inherited. In the Ps RF imaging by Luo et al. (2021), a similar abrupt change in negative phase energy at mantle depths across the western edge of Laurentia was observed; however, the negative phase west of 73°W was interpreted to be an MLD, not the LAB. This alternative interpretation is possible, given that the presence of MLDs in the Grenville province is well documented (Wirth and Long, 2014; Abt et al., 2010). If true, then the lithospheric step would be even more pronounced than the ~15 km vertical offset we propose here. If a lithospheric thickness of 100–150 km for Grenville-aged lithosphere (Porter and Reid, 2021) is assumed, this would imply an inferred LAB step of ~35–85 km. We also cannot exclude the possibility that the negative phase east of 73°W may represent an MLD. Regardless of whether the phase is an MLD or the LAB, we are left with the same observation, which is that the properties of the mantle litho-

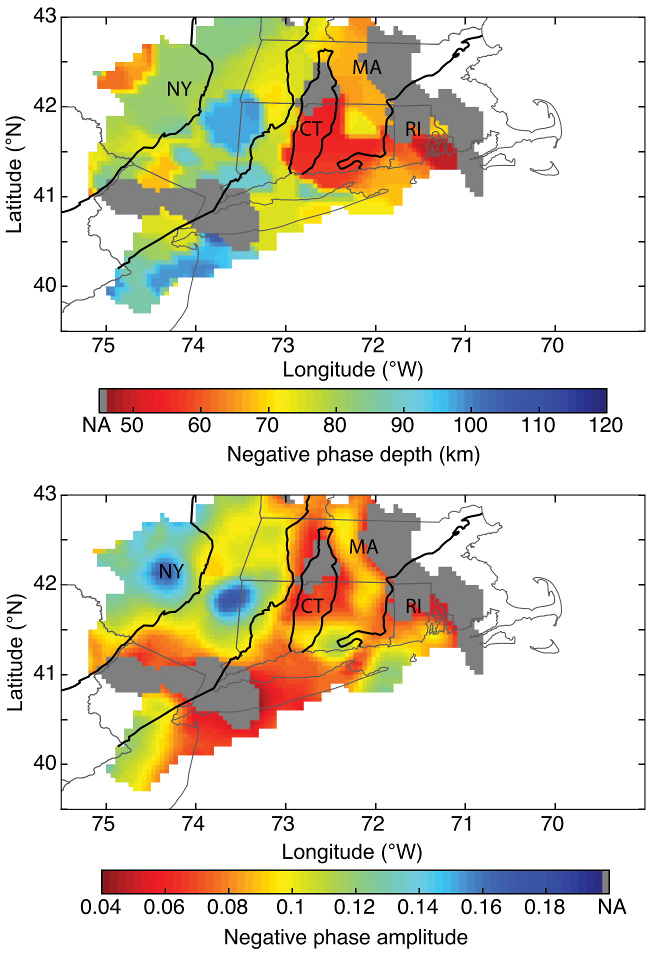

Figure 3. Maps of depth (top) and amplitude (bottom) of selected negative phase interpreted as lithosphere-asthenosphere boundary (LAB). Regions of common conversion point (CCP) image for which phases were not selected are marked in gray. Thick black lines mark edges of terrane boundaries; thin black lines mark state boundaries. Pronounced change in LAB depth (top) and amplitude (bottom) is approximately coincident with Taconic belt–Ganderia terrane boundary. NY—New York; MA—Massachusetts; CT—Connecticut; RI—Rhode Island.

sphere change at the boundary between Laurentia and the accreted Appalachian terranes to the east. Li et al. (2018) and Luo et al. (2021) also documented a sharp "step" in crustal thickness across the same boundary beneath the SEISConn line; this is also broadly consistent with heat-flow data, which indicate that western Connecticut is cooler than central and eastern Connecticut (Artemieva, 2006).Taken together, the co-located changes in crustal and mantle lithospheric structure has important implications for isostatic compensation and density structure that will be explored quantitatively in future work.

Our observations provide evidence that lithospheric structure can be inherited and maintained over long time scales. Complementary observations from elsewhere in eastern North America provide a similar argument; Wagner et al. (2018) argued for a role for inherited structures, including cratonic edges and suture zones, beneath the southeastern U.S. based on seismic tomography. Our inference of lithospheric thinning beneath eastern New England associated with the NAA also provides a basis for comparison with other structures in eastern North America, notably the Central Appalachian Anomaly (CAA), a region with thin lithosphere and slow upper-mantle velocities (e.g., Evans et al., 2019; Byrnes et al., 2019). While it is plausible that a different set of processes has operated beneath the CAA and NAA to produce thinned lithosphere, detailed comparisons between the regions are instructive (e.g., Long et al., 2021), particularly in light of our new constraints on lithospheric structure beneath New England.

One potential explanation for the presence of both the vertical step and thinner-than-predicted lithosphere is that the processes associated with the NAA may have thermally eroded the base of the lithosphere beneath terranes east and west of the Grenville front. If so, fundamental differences in the rheology between Grenville-aged lithosphere and the Appalachian accreted terranes may have resulted in lateral contrasts in LAB depth and velocity gradient. Subduction and the introduction of water are one proposed mechanism for weakening of the cratonic lithosphere (e.g., Bedle et al., 2021). A potential consequence of the addition of water could be a reduction in wave speeds in the lithosphere and a corresponding reduction in velocity gradient between the lithosphere and asthenosphere, resulting in diminished LAB amplitudes in RFs; we speculate that this mechanism may explain some of the amplitude observations in our study, although debate exists over the extent to which water affects wave speeds (e.g., Cline et al., 2018). Several westward-dipping structures have been observed in the uppermost mantle beneath the eastern half of the SEISConn array using high-frequency Ps RF analysis; these structures generally terminate along the Grenville front (Luo et al., 2021). These structures have been interpreted as either relic slabs or shear zones associated with past subduction, suggesting the possibility that the step in lithospheric thickness that we observe results from the eastern half of southern New England being more significantly impacted by metasomatism, and thus more susceptible to later lithospheric loss associated with NAA-related asthenospheric upwelling, than the western half. Importantly, this model is plausible regardless of whether the phase imaged west of the Laurentian boundary is the LAB or an MLD, because in either case, a stronger and thicker lithosphere likely exists west of the boundary.

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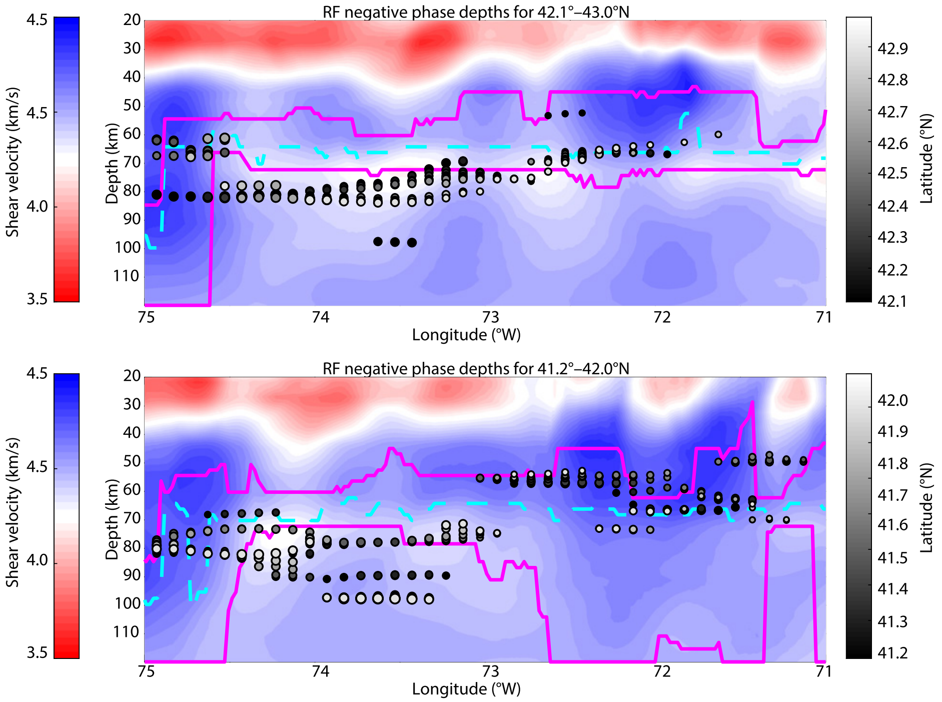

Figure 4. Cross sections of receiver function (RF) picks (solid circles with grayscale indicating latitude) from Figure 2 superimposed on averages of the Vs tomography model for the same latitudes (IRIS DMC, 2011; Yang and Gao, 2018). At latitudes of 42.1°–43°N (top), lateral changes in negative phase depth are more gradual, while at 41.2°–42°N, lateral changes in negative depth are more abrupt (bottom). Dashed cyan line marks depth of the maximum negative velocity gradient of the averaged tomography model, and solid magenta lines mark the potential LAB depth range as defined by Birkey et al. (2021). In most regions, the selected phases fall within or below the potential LAB depth range.

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