Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL089316

Key Points:
- A high-resolution crustal shear-velocity model is constructed with full-wave ambient noise tomographic method in southern New England
- The crust beneath the central Hartford basin is thinner than its surroundings with the lower crust being seismically fast
- The high-velocity crustal root results from magmatic underplating during the formation of the Central Atlantic Magmatic Province

Supporting Information:
- Supporting Information S1

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Citation:
Gao, H., Yang, X., Long, M. D., & Aragon, J. C. (2020). Seismic evidence for crustal modification beneath the Hartford rift basin in the northeastern United States. *Geophysical Research Letters*, *47*, e2020GL089316. https://doi.org/10.1029/2020GL089316

Received 16 JUN 2020
Accepted 23 AUG 2020
Accepted article online 30 AUG 2020

Seismic Evidence for Crustal Modification Beneath the Hartford Rift Basin in the Northeastern United States

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Abstract Extensive Mesozoic rifting along the eastern North American margin formed a series of basins, including the Hartford basin in southern New England. Nearly contemporaneously, the geographically widespread Central Atlantic Magmatic Province (CAMP) was emplaced. The Hartford basin provides an ideal place to investigate the roles of rifting and magmatism in crustal evolution, as the integration of the dense SEISConn array and other seismic networks provides excellent station coverage. Using full-wave ambient noise tomography, we constructed a detailed crustal model, revealing a low-velocity ($V_s = 3.3$–3.6 km/s) midcrust and a high-velocity ($V_s = 4.0$–4.5 km/s) lower crust beneath the Hartford basin. The low-velocity midcrust may correspond to a layer of radial anisotropy due to extension and crustal thinning during rifting. The high-velocity crustal root likely represents the remnant of magmatic underplating resulting from the CAMP event. Our findings shed light on crustal modification associated with supercontinental breakup, rifting, extension, and magmatism.

Plain Language Summary A series of sediment-filled rift basins exist along the passive eastern North American margin, extending from Georgia to Newfoundland. The rift basins were formed during extension leading up to the breakup of the supercontinent Pangea at approximately 200 million years ago and have preserved critical information about modification of continental crust during supercontinent breakup. The coverage of seismic stations in southern New England is excellent, benefiting from the recent deployment of the EarthScope Transportable Array in the northeastern United States and the Seismic Experiment for Imaging Structure beneath Connecticut (SEISConn). Using an advanced seismic imaging method, we constructed a detailed model of the crust beneath the Hartford basin located in central Connecticut and western Massachusetts. We discovered that the lower crust (at the depths of 18–35 km) beneath the Hartford basin is seismically much faster than its surroundings. We suggest that this high-velocity layer may be the residual of the trapped magmas at the bottom of the crust, presumably during the formation of the Central Atlantic Magmatic Province at the time of the breakup of Pangea.

1. Introduction

The Eastern North American Margin (ENAM), a rifted passive margin, provides a record of continental evolution over the last 1.3 Ga from the formation and breakup of the supercontinent Rodinia through the multistage assembly of Pangea to the formation of the modern Atlantic Ocean (e.g., Hatcher, 2010; Thomas, 2006). The extensive Mesozoic rifting along the ENAM initiated at approximately 230 Ma and eventually led to the breakup of the supercontinent Pangea, with the rift/drift transition completed by approximately 185 Ma (Withjack et al., 1998, 2012). During rifting, the emplacement of the Central Atlantic Magmatic Province (CAMP) occurred over a period of less than one million years at approximately 200 Ma (e.g., Marzoli et al., 1999, 2018). Along the southern and central portions of the ENAM, rifting was accompanied by magmatic activity, as expressed in the presence of the offshore East Coast Magnetic Anomaly and seaward-dipping reflectors (e.g., Withjack et al., 2012). The CAMP is one of the Earth's largest igneous provinces (Blackburn et al., 2013; Dorais et al., 2005; Jourdan et al., 2009; McHone, 1996), but its origins remain enigmatic; various models invoke a deep mantle plume, edge-driven convection, thermal supercontinental insulation, lithospheric delamination, or some combination of these (e.g., Coltice et al., 2007; Marzoli et al., 2018; Whalen et al., 2015). The emplacement of CAMP postdates the onset of rifting in the eastern United States, but predates the breakup of Pangea and the completion of the rift/drift transition (e.g.,

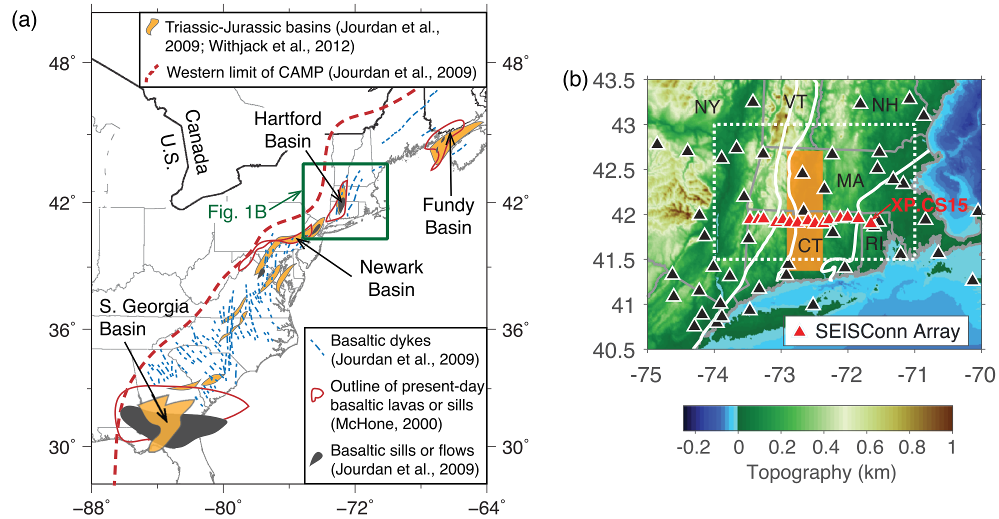

Figure 1. (a) Major rifting-related tectonic features along the eastern north American margin. The red dashed line marks the western limit of the Central Atlantic Magmatic Province (CAMP) from Jourdan et al. (2009). The black line marks the United States-Canada border. The orange patches outline the Triassic-Jurassic basins along the passive margin (only continental basins are shown) based on Jourdan et al. (2009) and Withjack et al. (2012). Basaltic dikes (short dashed blue lines) and basaltic sills/lavas (red outlines and black patch) are highlighted. Thin gray lines indicate state boundaries. (b) Distribution of seismic stations in southern New England used in this study, including the dense SEISConn array (red triangles) and other seismic networks (black triangles). The orange shaded area shows the location of the Hartford basin. The three white lines compiled by Li et al. (2018) mark the Grenville-Taconic, Taconic-Gander, and Gander-Avalon tectonic boundaries from west to east, respectively. The gray lines indicate state boundaries and coastlines. The dotted box marks the image area shown in Figure 2. Background colors indicate topography/bathymetry.

Withjack et al., 1998). In the eastern United States, CAMP covers most of the Appalachian Mountains and the Atlantic coastal plain to the east (Figure 1a), though the volume of magma appears to differ significantly along strike (e.g., Marzoli et al., 2018). The onshore portion of the ENAM region thus provides an ideal setting to investigate the evolution of continental lithosphere and how continental rifting and extension interacted with CAMP magmatism to shape the present-day crustal structure.

A series of rift basins, including the South Georgia, Newark, Hartford, and Fundy basins, had been formed along the ENAM since the late Triassic, extending from Georgia to Newfoundland (Figure 1a). These rift basins demonstrate different shapes and scales (Withjack et al., 2012), with the South Georgia basin being one of the oldest and largest (e.g., McBride et al., 1989). The Hartford basin is located in central Connecticut and western Massachusetts (Roden-Tice & Wintsch, 2002; Withjack et al., 2012), and is bounded by uplands with higher topography to its west and east (e.g., Farrell, 2015; Hillenbrand, 2018; Roden-Tice & Wintsch, 2002). The Hartford basin is ~4 km deep (Schlische & Olsen, 1989) and is elongated in the south-north direction, roughly parallel to the geologically defined Taconic Belt-Gander terrane boundary (Figure 1b). Magmatism associated with the CAMP was contemporaneous with extension in the Hartford basin and spans across it, with extensive synrift basalt flows that are interbedded with sedimentary units; furthermore, northeast-trending basaltic dykes are exposed within and outside the basin (e.g., Jourdan et al., 2009; Schlische, 1993; Withjack et al., 2012). The relative timing of CAMP and extension in the Hartford basin is different than in some other ENAM rift basins, particularly in the southeastern United States, where CAMP magmatism postdates the deposition of synrift sediments (e.g., Withjack et al., 1998). Recent receiver function studies (Li et al., 2018; Long et al., 2018) revealed a west-to-east decrease in the depth of Moho of up to 15 km near the western boundary of the Hartford basin. This geological setting makes the Hartford basin an ideal target to study the spatial distribution of magmatic intrusion within the crust, the role of magmatism in continental rifting, and the interplay between extension and magmatism beneath southern New England.

Benefiting from the EarthScope USArray Transportable Array (TA) deployment in eastern North America in 2013–2015, the crustal structure beneath the northeastern United States has been much better constrained by a variety of seismic methods in recent years (e.g., Li et al., 2018; Yang & Gao, 2018). However, the ~70-km interstation spacing of the EarthScope TA is too sparse to characterize the small-scale crustal structure in this region. The Seismic Experiment for Imaging Structure beneath Connecticut (SEISConn; ~10-km spacing; Figure 1b) has significantly increased the spatial density of broadband seismic observations in southern New England (Long & Aragon, 2020). This provides a new opportunity to investigate the detailed crustal structure of the Hartford basin and its surrounding region. In this study, we construct a high-resolution crustal velocity model for southern New England using the advanced full-wave ambient noise tomography. We integrate the dense SEISConn array with other seismic networks to maximize the data coverage. Our velocity model reveals a low-velocity midcrust and a high-velocity lower crust beneath the central Hartford basin, where the Moho defined by teleseismic receiver functions is relatively shallow. We suggest that the seismic features imaged beneath the Hartford basin reflect crustal modification by extension during Mesozoic rifting and by magmatic emplacement during the CAMP event.

2. Data and Method

We collected the vertical-component seismic waveforms from 2013 to 2018 recorded by 64 broadband stations within southern New England (Figure 1b; see supporting information). The empirical Green's functions show high-quality Rayleigh wave signals at 3–40 s periods (Figure S1; supporting information). The full-wave ambient noise tomography method includes three major procedures (Gao, 2018; Gao & Shen, 2014; Yang & Gao, 2018): (1) simulation of wave propagation in the 3-D spherical Earth using the nonstaggered-grid, finite-difference method (Zhang et al., 2012). We parameterized the model domain into $0.007° \times 0.007°$ in the longitudinal and latitudinal directions. The model grid extends from $-75°$ to $-69.8°$ in longitude, from 40.5° to 43.48° in latitude, and from the Earth's surface down to 131 km depth; (2) measurement of the Rayleigh wave phase delays between the observed empirical Green's functions and the synthetic waveforms through cross-correlation in seven overlapping period bands, including 20–40, 15–30, 10–20, 8–15, 5–10, 4–8, and 3–5 s; and (3) calculation of three-dimensional, finite-frequency sensitivities of Rayleigh waves and inversion for velocity perturbations. We chose the regional shear-wave velocity model of the northeastern United States that was recently constructed by Yang and Gao (2018) as the initial reference model, which extends from the surface down to the depth of about 220 km, with the best vertical resolution at the depth range of 15–120 km.

The reference model was progressively and iteratively updated for a total of five iterations of wave simulation and inversion. When measuring the phase delays, we require the signal-to-noise ratio of the empirical Green's functions to be $\geq$4, and the correlation coefficients to be $\geq$0.5 for the first three iterations and $\geq$0.7 for the last two iterations. To minimize the asymmetric effect of the empirical Green's functions, we first calculate separately the phase delays for the positive and negative segments, and then take the average as the final phase delays between each station pairs. In comparison with the work by Yang and Gao (2018), this study includes the dense SEISConn array in northern Connecticut, making it feasible to achieve a higher-resolution crustal-scale velocity model for this portion of southern New England. The phase delays have been significantly decreased using the final model compared to the initial model, particularly at periods shorter than 10 s (Figures S2–S4). Because the sediment in the Hartford basin is ~4 km thick, it does not express itself directly in our velocity models; resolution tests that probe its possible expression in our model are presented in Figure S6. Although the velocity perturbation of a sedimentary layer is not fully recovered, we do not see any significant artifacts at greater depths.

3. Results

In comparison with the initial reference model (Yang & Gao, 2018), our new shear-wave velocity model in this study provides more detailed structure of the southern New England crust (Figure 2). Beneath the SEISConn array, we are able to resolve seismic features at a horizontal scale of 30–40 km (Figure S5), a significant improvement over the horizontal resolution (~50 km) of Yang and Gao (2018). At depths greater than about 30 km, the major velocity features in our velocity model are primarily inherited from the reference model (Figure S6). In order to investigate the crustal structure beneath the Hartford basin and its surroundings, we present the shear-wave velocities at depths of 6, 11, 18, and 25 km (Figure 2), a west-east velocity profile along the SEISConn array (Figure 3a), the crustal thickness defined by teleseismic *P* wave

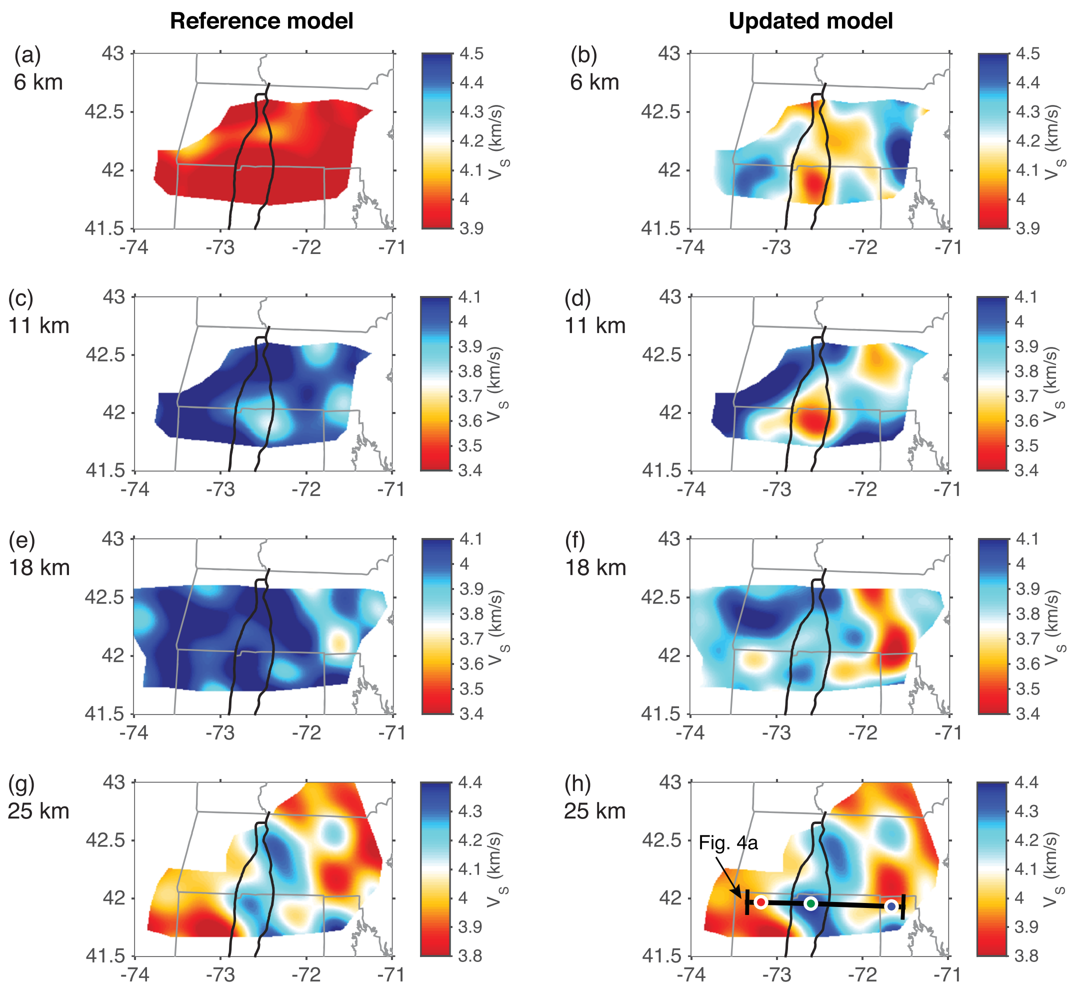

Figure 2. Comparisons of the reference model by Yang and Gao (2018) (left column) and the new model in this study (right column). The shear-wave velocities are demonstrated at the depths of (a–b) 6, (c–d) 11, (e–f) 18, and (g–h) 25 km. Only areas with a horizontal resolution scale of 30–35 km are shown based on the checkerboard resolution tests at the corresponding depths (Figure S5); the resolution is highest beneath the SEISConn array. The west-east line in (h) marks the profile location in Figures 3a and 3b. The three color-coded dots along the line mark the locations of the three 1-D velocity profiles in Figure 3c. The black solid outline represents the Hartford basin. The gray lines indicate state boundaries.

receiver function analysis of the SEISConn stations by Long et al. (2018) (Figure 3b), and the extracted 1-D velocity profiles at three points along the SEISConn array (Figure 3c). Receiver function analysis (Long et al., 2018; Figure 3b) revealed a relatively shallow (30 ± 5 km) Moho beneath the central Hartford basin in comparison with its western and eastern uplands (40–45 km, with particularly thick crust at the western end of the array).

Our full-wave ambient noise tomographic model reveals a low-velocity anomaly at the depth range of 5–16 km, beneath the central Hartford basin and extending to the east and west across Connecticut (Figures 2 and 3). The shear velocity of this anomaly is about 3.3–3.6 km/s, which is up to 12% lower than the average crustal velocity of the northeastern United States (Shen & Ritzwoller, 2016). The west-east velocity profile (Figure 3a) and the extracted 1-D velocities along the SEISConn array (Figure 3c) further confirm the presence of a 10- to 15-km-thick low-velocity midcrustal layer beneath the central Hartford basin. The low-velocity layer extends into and deepens beneath the western and eastern uplands on either side of the Hartford basin, forming a domal seismic feature. The shear velocities in the shallowest part of our model are up to 4.2–4.3 km/s, forming a high-velocity lid over the low velocity zone (Figure 3a). While a

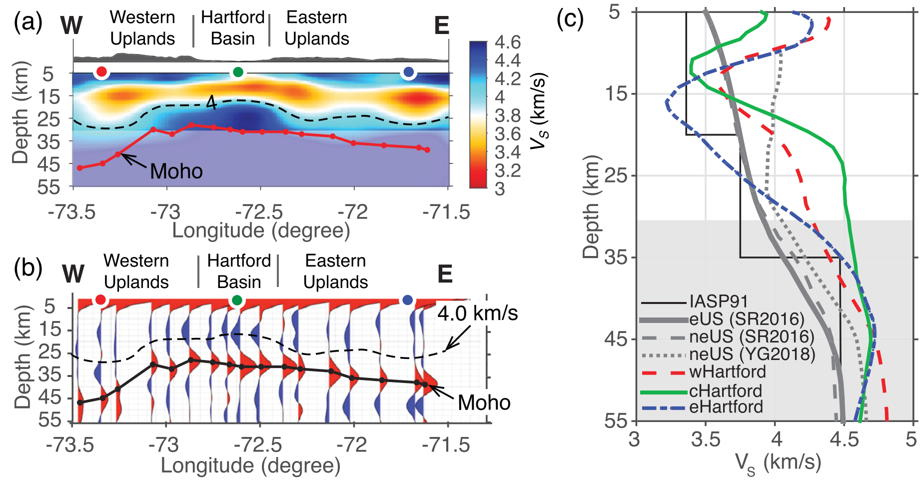

Figure 3. West-east seismic profile across the central Hartford basin. (a) Shear-wave velocity profile approximately along the SEISConn array within a depth range of 5–55 km. The dot-connected solid line is the estimated crust-mantle boundary (Moho) from teleseismic receiver function analysis by Long et al. (2018), and each red dot represents one seismic station and corresponds to the migrated receiver function traces in (b). The dashed line shows the velocity contour at 4.0 km/s to highlight the high-velocity crustal root. The red, green, and blue dots at the top of the figure correspond to the spatial locations of the extracted 1-D velocity profiles in (c). The velocity model below the depth of 30 km is mainly carried from the initial reference model by Yang and Gao (2018) and is masked with the translucent shade. See Figure 2h for the profile location. (b) Migrated stacked *P* wave receiver functions along the SEISConn seismic array from Long et al. (2018). The dot-connected solid line is the same as in (a). (c) Extracted 1-D shear-wave velocity profiles at three locations (color-coded dots in (a) and (b)). Similar to (a), the velocity below the depth of 30 km is marked with the shaded background. For the purpose of comparison, we plotted the 1-D shear velocity profiles from the 1-D global IASP91 model (thin black solid line; Kennett & Engdahl, 1991), the model by Shen and Ritzwoller (2016; SR2016) averaged within the eastern United States (east of longitude −90°; thick black solid line) and within the northeastern United States (east of longitude −76° and latitude within 40–46°; black dashed line), the averaged model by Yang and Gao (2018) (YG2018; black dotted line), respectively.

high-velocity lid seems to be required by the data, those very high upper crustal velocities are likely not well constrained and are probably overestimated (Figure S6).

A generally circular high-velocity anomaly lies immediately beneath the low-velocity midcrust of the central Hartford basin (Figure 2) and extends down to the bottom of the crust (Figure 3a), where crustal thinning is observed (Figure 3b). The shear velocity of this lower-crustal layer is about 4.0–4.5 km/s, which is nearly equivalent to the velocity of mantle lithosphere and is at least 10% higher than the average velocity of the lower crust in the northeastern United States (Shen & Ritzwoller, 2016; Yang & Gao, 2018). The thickness of this high-velocity lower-crust layer is up to nearly 20 km beneath the central Hartford basin. Beneath the western and eastern uplands, particularly at the far eastern and western ends of the SEISConn array, we also see evidence for relatively fast velocities at the base of the crust, but the thickness of the fast layer is much less than beneath the Hartford basin (Figures 3a and 3c). Beneath the Moho (as estimated from receiver functions), the shear velocity of our study region is on average about 4.6 km/s, similar to the average uppermost mantle velocities of the 1-D global model IASP91 (Kennett & Engdahl, 1991) and the northeastern United States (Shen & Ritzwoller, 2016; Yang & Gao, 2018).

4. Discussion

The key observations of this study include the spatial correlation of the high-velocity crustal root and the shallow Moho immediately beneath the central Hartford rift basin, along with the low-velocity midcrustal layer that extends across Connecticut. We also observe relatively high velocities in the shallow part of our model (depths between 5 and 10 km; Figure 3a); this may be related to the presence of basaltic dykes, which are distributed throughout much of Connecticut, although it is unclear whether the relatively low volume of basaltic material can explain the high velocities. Low-velocity midcrustal layers have been observed in different tectonic settings, such as in the North China Craton (Zheng et al., 2015), Eastern Siberia and Central Mongolia (Zorin et al., 2002), and the Tibetan Plateau (Kind et al., 1996; Yang et al., 2012). Correspondingly, a few mechanisms have been proposed to explain the presence of such low-velocity layers. For example, it may be a consequence of crustal rejuvenation in cratonic regions (Zheng et al., 2015), crustal flow or partial melting in tectonically active settings (Kind et al., 1996), a layer of relatively felsic composition (e.g., Guo & Chen, 2016), or strong radial seismic anisotropy (Shapiro et al., 2004; Yang et al., 2012). Possible intracrustal seismic structures that involve an apparent decrease in velocity with depth have also been imaged in the eastern United States with the use of teleseismic receiver functions (e.g., Hopper et al., 2017; Li et al., 2018; Long et al., 2019), and have generally been interpreted as subsurficial extensions of the tectonic boundaries. Moreover, a number of numerical and conceptual models for rift development suggest a very weak middle crust that decouples deformation in the upper and lower crust (e.g., Buck, 1991; Huismans & Beaumont, 2002).

We cannot rule out any of the possible explanations for the low-velocity midcrustal layer beneath our study region. The most likely explanation, however, is that it is due to strong radial anisotropy in the crust, as there is no supporting evidence for the presence of partial melt in the midcrust beneath the northeastern United States today, and no particular reason to expect a localized layer of felsic composition beneath Connecticut, in contrast to elsewhere beneath the northeastern United States (Figure 3c). We hypothesize that crustal extension and thinning during the Mesozoic rifting could have resulted in deformation of a weak midcrustal layer, forming crystallographic preferred orientation of midcrustal minerals (e.g., Brownlee et al., 2017) and yielding a radially anisotropic fabric that manifests as a slow layer in a model based on vertically polarized Rayleigh waves. Specifically, the crystallographic preferred orientation of crustal minerals, such as micas and amphiboles, may lead to an anisotropic geometry such that the slow axis of symmetry is vertical and the fast axis is horizontal; many elastic tensors measured from crustal rock samples exhibit a best-fit hexagonal tensor with such a slow-axis symmetry (Brownlee et al., 2017). A radially anisotropic layer with $V_{SH} > V_{SV}$ has been documented in other regions associated with extension, such as the Basin and Range in the western United States (Moschetti et al., 2010). If this hypothesis is true, it suggests that deformation associated with extension and continental breakup may have been more distributed (and less localized) in the midcrust than in the shallower crust, as the low-velocity layer is observed throughout Connecticut rather than localized directly beneath the Hartford basin. Future investigations of radial anisotropy beneath the northeastern United States will be able to test this idea.

A few recent seismic observations have revealed the presence of faster-than-average lower crust along the ENAM. For example, Marzen et al. (2019, 2020) demonstrated a fast lower-crustal velocity (Vp up to 7.2 km/s) beneath the South Georgia rift basin, where a relatively thin (~33 km) crust is observed in comparison with its surroundings (~47 km). As demonstrated by many existing tomographic models (e.g., Golos et al., 2018; Schmandt et al., 2015; Shen & Ritzwoller, 2016), the seismic velocity of the lower crust beneath the eastern United States is generally faster than the global average (Figure 3c). It has been proposed that metamorphic reactions after the formation of continental lithosphere may have densified and strengthened the lower crust (Fischer, 2002; Williams et al., 2014) and consequently increased the seismic velocities (Thybo & Artemieva, 2013). Notably, the high-velocity crustal roots localized beneath the Hartford and South Georgia basins are up to 10% higher than the average lower-crustal velocity of the northeastern United States. These new seismic observations of faster-than-average lower crust beneath ENAM rift basins thus provide further geophysical constraints on our understanding of the modification of continental crust due to processes such as rifting and magmatism.

Given the strong spatial correlations among the location of the Hartford sedimentary basin, the region of most intense crustal thinning, and the volume of fast lower crust, our preferred interpretation is that extension during rifting, along with the emplacement of the CAMP magmatics, has significantly modified the crust beneath the rift basin (Figure 1a). In this scenario, extension and crustal thinning in the late Triassic due to the ENAM rifting (Withjack et al., 2012) may have resulted in midcrustal radial anisotropy and provided the accommodation for the voluminous intrusion of the CAMP magmas into the lower crust. The high-velocity crustal root beneath the central Hartford basin, where crustal thinning is observed (Li et al., 2018; Long et al., 2018), reflects the remnant of mafic magmatic underplating during the CAMP event. After the intense short-period CAMP activity ceased in the early Jurassic, rifting along the Hartford basin continued for another 5–10 million years (Withjack et al., 2012), which may have resulted in further thinning of the previously underplated crust.

Our detailed observations of a localized zone of fast crustal velocities beneath the Hartford basin shed new light on the interplay of extension, rifting, crustal thinning, and CAMP-related magmatism during the breakup of Pangea. Following Marzen et al. (2020) and using the linear mixing method (White et al., 2008), we estimate the thickness of magmatic intrusion in the lower crust based on our velocity model (see supporting information). For a range of reasonable assumptions, the layer thicknesses of the intrusions vary between 8 and 18 km beneath the Hartford basin, with most likely values of ~13 km (Figure S7). Our seismic imaging of a significant volume of magmatic intrusions in the lower crust beneath the Hartford basin (Figure S7) is consistent with suggestions by Marzoli et al. (2018), based on the compositions of CAMP basalts, that a significant volume of mafic material must also have intruded into the deep crust. Despite the fact that CAMP-related dykes are widespread throughout the eastern United States (Figure 1a), and are found in Connecticut both within and outside of the Hartford basin, the production of melt volumes sufficient to emplace large volumes of mafic material in the lower crust appears to have been localized beneath the basin itself. The localization of CAMP intrusions in the lower crust directly beneath the Hartford basin suggests that rifting, extension, and crustal thinning played a role in focusing upwelling and melt generation during the emplacement of CAMP magmatic material, similar to suggestions by Marzen et al. (2020).

It is likely that similar scenarios of magmatic underplating and crustal thinning occurred beneath other rift basins (e.g., Ai et al., 2019), including elsewhere in the ENAM. For example, recent results from the South Georgia rift basin (e.g., Marzen et al., 2019, 2020) also indicate colocated sedimentary basins, thin crust, and fast lower crustal velocities, and are consistent with our observations beneath the Hartford basin. Interestingly, we find similarities in structure between the South Georgia and Hartford basins, despite the differences in relative timing between extension and CAMP magmatism in these two regions (Marzen et al., 2020; Withjack et al., 1998). Detailed knowledge of crustal structures beneath other ENAM rift basins are needed to test and clarify the hypothesis that extension and rifting played a key role in focusing upwelling and/or melt beneath sedimentary basins during the CAMP event. Of course, in addition to magmatic emplacement from the CAMP event, tectonomagmatism prior to, during, and after rifting may have also contributed to the modification of the crust in the central Hartford basin and other eastern U.S. rift basins.

5. Conclusions

We constructed a high-resolution crustal velocity model for the Hartford basin and its surroundings using full-wave ambient noise tomography by combining the dense SEISConn array with other seismic networks in southern New England of the northeastern United States. We integrated our shear-wave velocity model with teleseismic *P* wave receiver function analysis to further constrain our observations and possible interpretations. The tomographic image revealed a 10- to 15-km-thick low-velocity midcrust beneath Connecticut and an up to 15-km-thick high-velocity lower crust directly beneath the Hartford basin, where the crust is thinner compared to the surroundings. We suggest that the midcrustal low velocities likely correspond to a layer of strong radial anisotropy, perhaps associated with deformation due to crustal extension and thinning during Mesozoic rifting. The high velocities in the lower crust likely delineate a localized volume of dense, mafic underplated material associated with the emplacement of the CAMP magmatics. Taken together, the evidence for crustal thinning, strong radial anisotropy in the midcrust, and the emplacement of high-velocity mafic material in the lower crust beneath the Hartford basin sheds light on crustal modification of the ENAM associated with supercontinental breakup, rifting, extension, and magmatism during the Mesozoic.

Data Availability Statement

All the seismic data used in this study were downloaded via the Data Management Center (https://ds.iris.edu) of the Incorporated Research Institutions for Seismology (IRIS).

Acknowledgments
This research was supported by the National Science Foundation (grant EAR-1736167) to the University of Massachusetts Amherst. The SEISConn experiment was supported by the National Science Foundation (grant EAR-1800923) to Yale University. The computer codes for full-wave ambient noise tomography were developed and maintained by Yang Shen's group at the University of Rhode Island (https://sites.google.com/view/seismo). The codes are available through requests to the authors or to Yang Shen. The velocity model generated by this study will be available through the IRIS Earth Model Collaboration (https://ds.iris.edu/ds/products/emc-earthmodels). We are grateful to Rachel Marzen for useful discussions on seismic structure beneath the rift basins of the eastern United States, and to Donna Shillington and an anonymous reviewer for thoughtful comments that greatly improved the paper.

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