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Key Points:

- We investigated the Moho geometry beneath the Grenville-Appalachian transition using the scattered wavefield migration technique
- The Moho depth change is gradual beneath the central and southern Appalachians, but abrupt beneath New England
- Varied Moho geometries provide new insights into along-strike variations in tectonic settings before and during Appalachian orogenesis

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

Y. Luo,
yantao.luo@yale.edu

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Author Contributions:

Conceptualization: Yantao Luo, Maureen D. Long
Data curation: Yantao Luo
Formal analysis: Yantao Luo, Maureen D. Long, Stéphane Rondenay
Funding acquisition: Maureen D. Long
Investigation: Yantao Luo, Maureen D. Long, Paul Karabinos
Methodology: Yantao Luo, Stéphane Rondenay
Project Administration: Maureen D. Long
Resources: Yantao Luo, Maureen D. Long
Software: Yantao Luo, Stéphane Rondenay
Supervision: Maureen D. Long
Visualization: Yantao Luo, Paul Karabinos

First-Order Transition in Appalachian Orogenic Processes Revealed by Along-Strike Variation of the Moho Geometry

Yantao Luo[1], Maureen D. Long[1], Paul Karabinos[2], Stéphane Rondenay[3], and Roberto Masis Arce[4]

[1]Department of Earth and Planetary Sciences, Yale University, New Haven, CT, USA, [2]Geosciences Department, Williams College, Williamstown, MA, USA, [3]Department of Earth Science, University of Bergen, Bergen, Norway, [4]Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ, USA

Abstract Along-strike variation of the Laurentian rifted margin and the Appalachian orogen has long been recognized in the geologic record. We investigated the manifestation of this along-strike variation at depth by generating scattered wavefield migration profiles from four dense seismic arrays deployed across the Appalachian orogen at different latitudes. All profiles exhibit a similar crustal thickness decrease of 15–20 km from the Mesoproterozoic Grenville Province to the Paleozoic Appalachian accreted terranes, but the Moho architecture differs dramatically along strike. The profiles beneath the central and southern Appalachians show a smoothly varying Moho geometry; in contrast, there is an abrupt Moho depth offset beneath the New England Appalachians. This contrast in Moho geometry may result from variations in the Laurentian rifted margin architecture, changes in Taconic orogeny subduction polarity, and greater crustal shortening during the Acadian-Neoacadian orogeny in southern New England and the Alleghanian orogeny in the central and southern Appalachians. A first-order along-strike transition in the behavior of Appalachian orogenic processes is located between the central and New England Appalachians.

Plain Language Summary The Proterozoic Grenville Province and Paleozoic Appalachian domains are the two major tectonic units in eastern North America, associated with two past supercontinent cycles. The Grenville Province has generally thicker crust than the Appalachian domains, and a Moho depth decrease from Grenville to Appalachians has been observed throughout the Appalachian orogen by previous continental-scale seismic studies. The Moho beneath the Laurentian margin records how the Proterozoic rifted margin of Laurentia interacted with the Paleozoic Appalachian orogenesis at crustal levels. However, the detailed geometry of the Moho beneath the edge of Laurentia, and how it varies along the margin, have not been resolved by previous work. In this study, we apply a scattered wavefield migration imaging technique to four dense seismic arrays deployed at different latitudes across the Appalachian orogen to investigate the geometry of the Moho across the Grenville-Appalachian transition. The Moho depth change is smooth beneath the central and southern Appalachians but abrupt beneath New England. This distinction may result from a combination of a non-uniform Grenville rifted margin, different styles and directions of Appalachian subduction and terrane accretion episodes, and varied amount of crustal shortening along the Appalachian orogen.

1. Introduction

The eastern margin of North America has been shaped by Mesoproterozoic Grenville orogenesis, Neoproterozoic rifting, Paleozoic Appalachian orogenesis, and Mesozoic rifting. The nature of Paleozoic orogenic events varies along the strike of the Appalachian orogen (Hatcher, 2010; Hibbard & Karabinos, 2013). For example, the Ordovician Taconic orogeny involved the accretion of the Gondwana-derived Moretown terrane in New England (Macdonald et al., 2014), but peri-Laurentian crustal ribbons in the Canadian and southern Appalachians (Hibbard et al., 2007; van Staal et al., 2009). Also, subduction polarity during the Taconic orogeny may have varied along the orogen (Tull et al., 2014). Silurian and Devonian accretion of Ganderia, Avalonia, and Megumia in the northern Appalachians, and Carolina and Suwanee in the southern Appalachians, also accentuate the along-strike variability of Appalachian orogenesis (Hibbard et al., 2010). The Pennsylvanian-Permian Alleghanian orogeny involved the head-on collision of Gondwana with southeastern Laurentia, producing the Blue Ridge-Piedmont megathrust sheet that is absent in the northern Appalachians (Hatcher, 2010; Thomas & Hatcher, 2021). Furthermore, these Paleozoic tectonic events may have reactivated Neoproterozoic rift structures

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Writing – review & editing: Yantao Luo, Maureen D. Long, Paul Karabinos, Stéphane Rondenay, Roberto Masis Arce

produced during the breakup of Rodinia (Gates & Costa, 1998), which may have had varied geometries along the Laurentian margin, with promontories and recesses separated by numerous transforms (Thomas, 1993, 2006).

Seismic imaging of the deep crustal structure can be used to explore this along-strike variability of Appalachian orogenesis at depth. Seismic Ps receiver function studies have revealed that the crust of Appalachian terranes is typically 15–20 km thinner than the crust of the adjacent Grenville Province (e.g., Levin et al., 2017; Li et al., 2020). Li et al. (2018, 2020) reported a particularly sharp lateral gradient of Moho depth change in southern New England, which was further constrained by a subsequent study using a dense seismic array (Luo et al., 2021). The variable lateral gradients in crustal thickness change at different latitudes may shed light on along-strike variations of Paleozoic orogenies and their interactions with the rifted Laurentian margin. However, detailed Moho architecture involving dipping or structurally complicated geometry cannot be reliably resolved by receiver function techniques, which are based on a 1-D layered model (Rondenay, 2009). Therefore, other methods must be employed to take full advantage of the available dense seismic array data straddling the Grenville-Appalachian boundary.

In this study, we apply a scattered wavefield migration imaging technique to investigate the geometry of the Moho across the Grenville-Appalachians transition, and how this geometry varies along the Appalachian orogen. This imaging technique provides better resolution of 2-D Moho geometry than conventional 1-D receiver function analysis (Rondenay, 2009). We apply this technique to data from a dense seismic array in the central Appalachians and compare the result with uniformly reprocessed migration images beneath New England and the southern Appalachians based on previous work (Figure 1; Hopper et al., 2016; Luo et al., 2022). We find that although the total Moho depth change across each profile is similar, the transition is gradual and continuous beneath the central and southern Appalachians, whereas it is steep and abrupt beneath New England. The abrupt change in depth to Moho under southern New England coincides with an overlap between deep Moho beneath Grenville crust and shallow Moho under accreted Appalachian terranes. The contrast in Moho geometries may reflect some combination of along-strike variations in the architecture of the margin inherited from Neoproterozoic rifting (e.g., Thomas, 1993, 2006), changes in Taconic orogeny subduction polarity (e.g., Tull et al., 2014), the amount of crustal shortening during later collisions, particularly the Devonian Acadian orogeny (e.g., Hillenbrand et al., 2022) and the Pennsylvanian-Permian Alleghanian orogeny (e.g., Hatcher, 2010), and concentrated crustal thinning during Mesozoic rifting (e.g., Withjack et al., 2012).

2. Method and Results

2.1. Scattered Wavefield Migration Technique

The scattered wavefield migration technique backpropagates scattered wavefields recorded at seismic stations to each potential scatterer beneath the profile, utilizing the similarity of its form with that of the 2-D generalized Radon transform (e.g., Beylkin, 1985; Miller et al., 1987). The migration resolves material property perturbations at the scatterer, including P-wave velocity perturbation $\delta\alpha/\alpha$, S-wave velocity perturbation $\delta\beta/\beta$, and density perturbation $\delta\rho/\rho$ (Bostock et al., 2001). In practice, this method performs best at resolving $\delta\beta/\beta$ (e.g., Rondenay et al., 2001; Rondenay et al., 2005), combining constraints from both the direct forward-scattered Ps phase and free surface reflected backscattered PPs, PSp, PSsv, and PSsh phases. The migration technique has a stricter requirement on the data quality compared with the traditional receiver function analysis, and it relies on very dense seismic arrays to reduce the spatial aliasing at shallow depths. Despite these limitations, this technique can resolve discontinuities with 2-D geometry in the deep crust and uppermost mantle using only a few high-quality events (Rondenay et al., 2005). The migration technique has been applied to image structure beneath subduction zones (e.g., Mann et al., 2019; Pearce et al., 2012), volcanic provinces (e.g., Chen et al., 2013), as well as ancient collision zones (e.g., Hopper et al., 2016; Luo et al., 2022).

2.2. Migration Profile Beneath the Central Appalachians

The Mid-Atlantic Geophysical Integrative Collaboration (MAGIC) seismic deployment consisted of 29 broadband seismic stations extending from Ohio to Virginia, cutting across the central Appalachians (Long et al., 2020). We applied the scattered wavefield migration to 20 stations (BB' line in Figure 1; Figure 2a), combining the denser eastern segment of the MAGIC array and nearby USArray stations (IRIS Transportable Array, 2003). To construct the migration image beneath the MAGIC profile, we searched for earthquakes with magnitudes larger than 5.5 at epicentral distances from 30° to 90°, occurring from October 2013 to November 2016. We then performed an automatic quality control process based on the signal-to-noise ratio (SNR), using the maximum

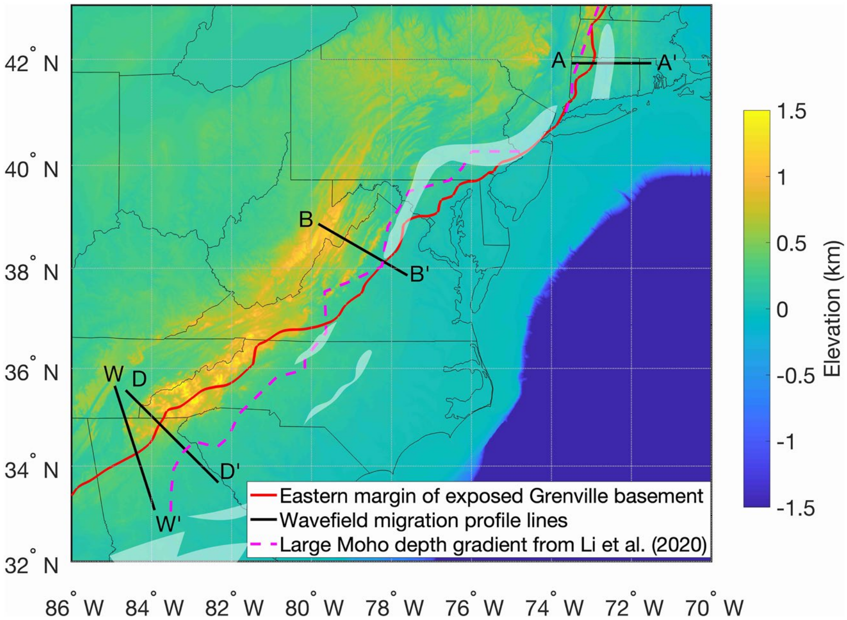

Figure 1. Map showing migration profile lines. AA' is based on the SEISConn array (Luo et al., 2022), and BB' is based on the eastern portion of MAGIC array and the USArray. DD' and WW' are based on the SESAME array and the USArray (Hopper et al., 2016). The naming convention of the DD' and WW' profiles is kept the same as in previous SESAME array studies (e.g., Parker Jr. et al., 2013), instead of following an alphabetical order with the profiles to the north. The red line is the approximate eastern margin of exposed Grenville basement, based on Hibbard et al. (2006). Note that there are small inliers of Grenville crust exposed east of the red line (Hibbard et al., 2006) and that accreted Appalachian terranes overlie Grenville crust, particularly in the southern Appalachians (Cook & Vasudevan, 2006; Hatcher, 2010). White patches show the approximate locations of major onshore Mesozoic rift basins modified from Withjack et al. (2012) and Gao et al. (2020). The magenta dashed line delineates the steepest gradient of west-to-east Moho depth decrease along the Appalachian orogen from Li et al. (2020).

squared amplitude from 0 to 7.5 s after the estimated onset of incident P wave as "signal" and the maximum squared amplitude from 5 to 22.5 s before the estimated onset of incident P wave as "noise" (as in Rondenay et al., 2017). The thresholds of SNR are 5 dB on the Z component and 4 dB on the R component. This SNR test was applied to 3 different frequency bands, 0.03–0.3 Hz, 0.03–0.6 Hz, and 0.03–1.0 Hz. Only events that

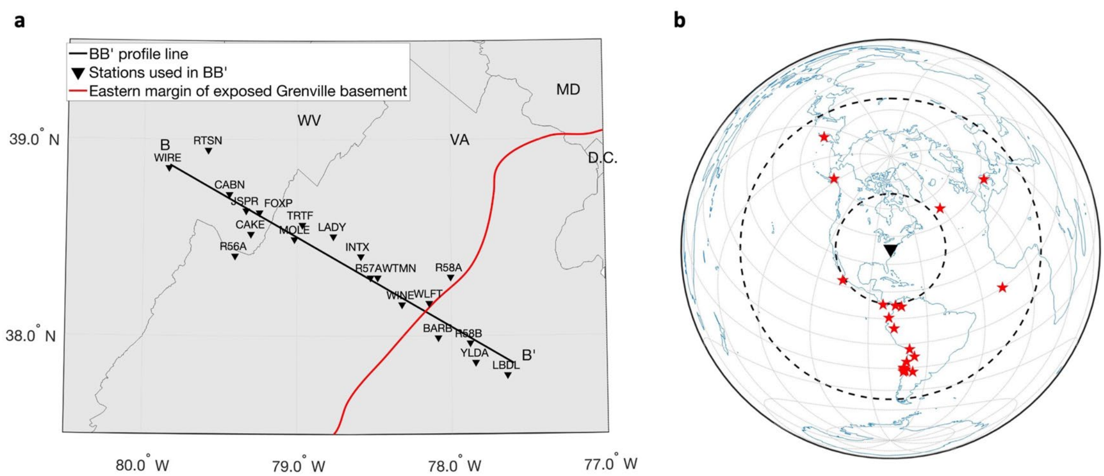

Figure 2. (a) Station map showing stations (black triangles) used in the migration of the BB' profile. The black solid line is the profile line, and the red solid line marks the eastern margin of exposed Grenville basement as in Figure 1. WV—West Virginia, VA—Virginia, MD—Maryland, D.C.—District of Colombia. (b) Event map for the migration of the profile BB'. The black triangle marks the midpoint location of the BB' line, and red stars are the teleseismic events used in the migration. The two black dashed circles mark 30° and 90° distances away from the midpoint of the BB' line.

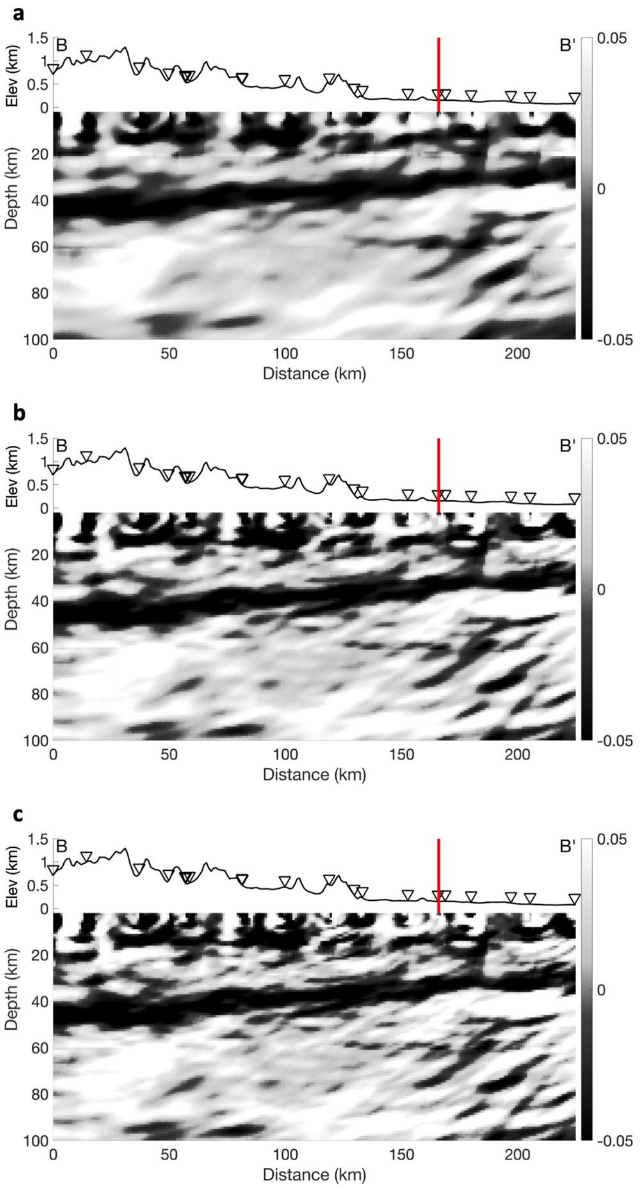

Figure 3. Composite migration images of profile BB', using data band-pass filtered between (a) 0.03 and 0.3 Hz, (b) 0.03 and 0.6 Hz, and (c) 0.03 and 1.0 Hz. Brighter shades represent positive S-wave velocity perturbations, and darker shades represent negative S-wave velocity perturbations. 20X exaggerated surface topography is plotted at top, and station locations are marked with triangles. Red vertical line marks the intersection of the profile with the eastern margin of exposed Grenville basement line shown in Figures 1 and 2.

passed the quality control in at least 1 frequency band for at least 14 stations (70% of the stations) were selected. A total of 69 events passed this automatic quality control process. We then followed the procedures described in Rondenay et al. (2005) and extracted scattered wave impulse responses for each event. We visually examined the extracted scattered wavefield and excluded poorly deconvolved, "ringy" traces. We also examined the migration result from each individual event and excluded the events that failed to reconstruct a potential Moho signal in the composite migration image. In the end, 24 events (Figure 2b) were retained for further analysis.

Figure 3 displays the composite migration images of the MAGIC array with data filtered at three different frequency bands (0.03–0.3 Hz, 0.03–0.6 Hz, and 0.03–1.0 Hz), showing $\delta\beta/\beta$ beneath the profile BB'. The perturbation and the migration to depth are based on a 1-D reference model (Table 1), and the perturbation is solved in a relative sense due to limited data coverage in practice (Rondenay et al., 2001). Composite migration images combine constraints from individual phases shown in Supplementary Figure S1, using the 0.03–0.6 Hz band images as an example. The Moho discontinuity, associated with a sharp increase of S-wave velocity with depth, is visible as a prominent transition from a darker band (negative perturbation) above to the brighter region (positive perturbation) below. The main trend of the Moho depth change is very smooth beneath BB', decreasing from ~55 to ~35 km from west to east. There may be a localized west-dipping feature branching out from the main Moho signal beneath the center part of the profile at about 40–45 km depth. Both the primary Moho geometry and the localized feature resolved in the migration are robust, with negligible uncertainty, as derived from a bootstrap test (Figure S2 in Supporting Information S1).

2.3. Comparison With Reprocessed Migration Profiles at Other Latitudes

Figure 4 compares the result of the BB' line with results reprocessed from the AA' line across the New England Appalachians (SEISConn; Luo et al., 2022) as well as the DD' and WW' lines across the southern Appalachians (SESAME; Hopper et al., 2016). The naming convention for the SESAME profile lines (e.g., DD', WW') is kept the same as in the original study. Data for all four profiles are filtered in the same frequency band (0.03–0.6 Hz), and images are plotted here with the same plotting convention as in Figure 3 for more straightforward comparison. One simplification made in previous applications of the migration method is simply adding the weights from all events together regardless of their scattering angles, instead of integrating over scattering angles. This simplification can result in a considerable underestimate of perturbation amplitudes when there is an ample amount of data. For example, in Hopper et al. (2016), the resolved S-wave velocity contrast across the Moho for both DD' and WW' profiles is less than 1%. In this study, a new weighting strategy based on the varied data abundance for each profile is applied to regulate the resolved perturbation to a reasonable range, and the S-wave velocity contrast across the Moho for all four profiles in Figure 4 is on the order of 10%.

The main trend of the Moho discontinuity beneath each profile is marked as a yellow dashed line (Figure 4), and any potential additional interfaces near the Moho are marked as yellow dotted lines. Beneath the New England Appalachians (AA'), there is a steep gradient in the Moho depth offset. The Moho is ~46 km deep in the west end and abruptly shallows to ~30 km depth across the offset. As shown by the dotted yellow line, the shallower Moho east of the offset may extend westward above the deeper Moho, forming a doubled Moho structure. The abrupt Moho offset and the potential Moho overlap are not located directly beneath the Grenville-Appalachian boundary

Table 1
1-D Reference Velocity Models Used for the Four Migration Profiles

	Layer thickness (km)	Vp (km/s)	Vs (km/s)
AA'	20	5.8	3.36
	30	6.5	3.75
	N/A	8	4.6
BB'	15	6.09	3.53
	45	6.5	3.79
	N/A	8.18	4.73
DD'&WW'	60	6.6	3.8
	N/A	8.2	4.8

Note. The model for the AA' profile is based on the IASP91 model (Kennett & Engdahl, 1991); the model for the BB' profile is based on a data set in Mooney and Boyd (2021) in the central Appalachians; the model for the DD' and WW' profiles is the same one used in Hopper et al. (2016).

(red vertical line), but more than 20 km to the west, within the Grenville Province. Beneath the southern Appalachians (DD' and WW'), the Moho is deepest beneath the topographic highs at ~58 km depth and gradually shallows to ~38 km depth at the southeast end of the profile, sharing a similar smooth geometry as beneath the central Appalachians (BB').

In Figure 5, we plot the Moho geometry together with the surface topography as well as the Bouguer gravity anomaly variation for all four profiles for comparison. The profiles are aligned at 0 km horizontal distance according to the deepest points in their respective Moho depths. The profiles can be divided into two groups with distinct behaviors in Moho geometry, topography, and gravity variations. For the BB', DD', and WW' profiles, the Moho depths vary smoothly, and they correlate well with surface topography (but not Bouguer anomaly variations). Between 0 and 100 km horizontal distances, the amounts of Moho depth decrease (from the deepest points) and topography decrease (from the highest points) are the greatest, while the Bouguer anomalies are nearly constant over the same interval. Between 100 and 200 km distances, the amounts of Moho depth and topography decrease become smaller, and the Bouguer anomalies increase drastically. In contrast, the AA' profile beneath New England shows an abrupt Moho depth offset at ~30 km horizontal distance, which is accompanied by a steep change of Bouguer anomaly but no large surface topography change. To the east of the abrupt Moho offset, the Moho depth minimum and Bouguer anomaly maximum are both located at ~50 km distance. Farther to the east, the minimum elevation, associated with the Hartford rift basin, occurs at ~70 km distance. The thinnest crust is not located beneath the center of the Hartford basin but rather to the west of it, at 50–60 km distance.

3. Discussion

The overall depth to Moho in eastern North America is substantially greater beneath the Grenville province than beneath accreted Appalachian terranes (e.g., Levin et al., 2017; Li et al., 2018; Li et al., 2020). Furthermore,

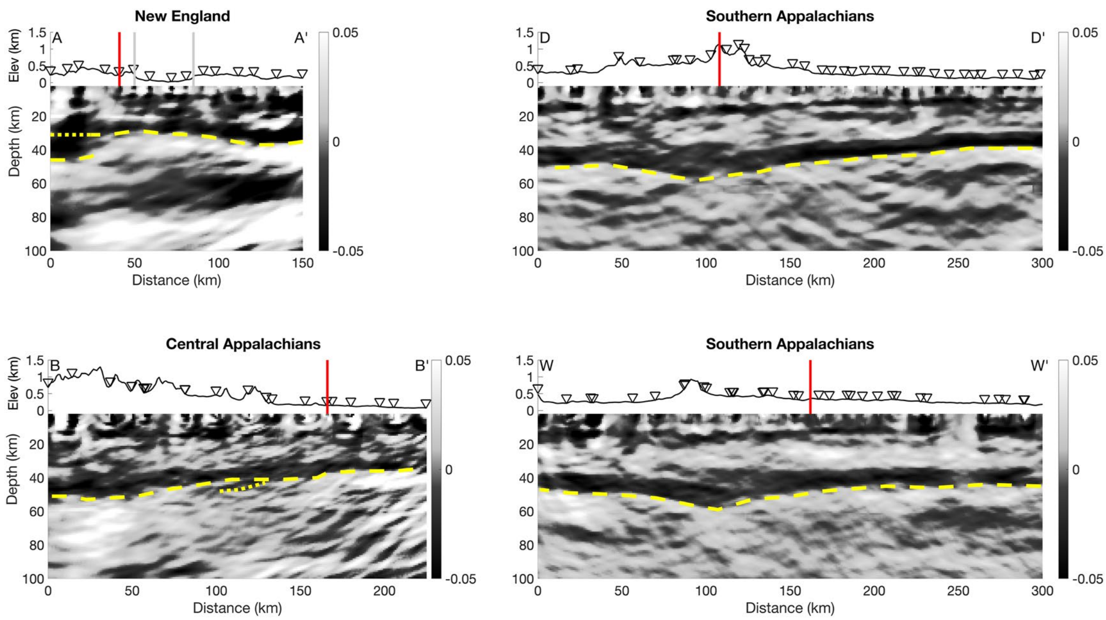

Figure 4. Annotated migration images of profiles AA' (reprocessed from Luo et al., 2022), BB' (this study), DD', and WW' (reprocessed from Hopper et al., 2016), using data band-pass filtered between 0.03 and 0.6 Hz. General trends of the Moho geometry are marked with yellow dashed lines. Potential additional structures are marked with yellow dotted lines, which include the potential extension of the shallower Moho to the west over the deeper Moho beneath AA', and a localized west-dipping feature branching out from the main Moho beneath BB'. Red vertical lines mark the intersection of each profile with the eastern margin of exposed Grenville basement line shown in Figure 1. Gray vertical lines on profile AA' denote the borders of the Hartford basin. Other plotting conventions are as in Figure 3.

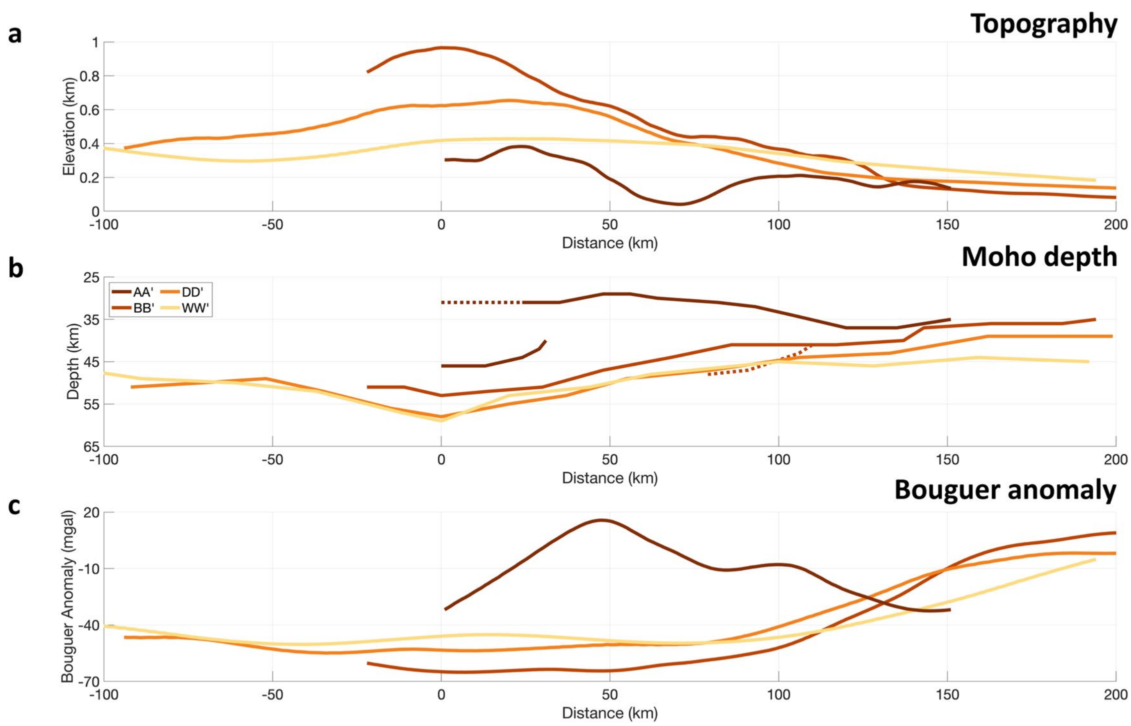

Figure 5. Plots of (a) surface topography from Amante and Eakins (2009), (b) Moho depth from each migration image, as shown in Figure 4, and (c) the Bouguer gravity anomaly (Kucks, 1999) for each profile are shown for comparison. Here both the topography and Bouguer anomaly values at each point are calculated as the average over a circular area with a 10-km radius for better comparison on the general trends and fewer distractions from local heterogeneities. Figure S3 in Supporting Information S1 shows a version of this figure in which the topography and Bouguer anomaly values are not locally averaged. Distance (x-axis) is the horizontal distance relative to the deepest point of the Moho profiles, so that the locations of deepest Moho beneath AA', BB', DD', and WW' profiles are aligned at 0-km distance. The dark brown lines show the surface topography, the Moho depth, and the Bouguer anomaly variation across the AA' profile, in panels a, b, and c respectively; the light brown, orange, and yellow lines are those of the BB', DD', and WW' profiles.

the variation in Moho geometry at different latitudes (Figures 4 and 5) suggests the abrupt Moho depth offset in the New England Appalachians is unusual compared to the rest of the orogen. Li et al. (2020) proposed that the along-strike variation of Moho geometry is determined by changes in the steepness of the subsurface boundary between Grenville and accreted Appalachian terranes. However, this subsurface boundary was likely affected by later tectonic events, which varied along the strike of the margin, and might have contributed to the development of different Moho geometries. For example, substantial Acadian-Neoacadian crustal shortening and thickening might have given rise to an Acadian orogenic plateau whose spatial extent was limited to southern New England (e.g., Hillenbrand & Williams, 2021); in contrast, farther to the south, the Alleghanian orogeny had a more dominant impact on the lithospheric architecture (e.g., Thomas & Hatcher, 2021). Furthermore, the Grenville-Appalachian boundary is not necessarily the crustal boundary where the Moho depth offset developed. High-resolution scattered wave analyses focused on the AA profile (Luo et al., 2021, 2022) revealed that the abrupt Moho depth offset beneath southern New England is located to the west of the Grenville-Moretown suture, along with a potentially doubled Moho. Luo et al. (2022) suggested that the abrupt offset beneath southern New England was initiated by westward thrusting of rifted Grenville crust and the Moretown terrane over unrifted Grenville crust. Also, if the lateral extent of doubled Moho is as large (~20 km) as suggested by Luo et al. (2022), it would require the crustal boundary to have a listric geometry, with a steep angle in the upper portion that soles into a low-angle detachment at lower crust depths (van Staal & Zagorevski, 2023).

Here, we build upon previous observations and models from Li et al. (2020), Hillenbrand et al. (2021), and Luo et al. (2022), taking advantage of additional new and/or reprocessed migration images for the central and southern Appalachians. We conduct a more comprehensive and integrated analysis of the potential origins of the observed along-strike variability in the Moho geometry along the Appalachian orogen. One consensus view among the mentioned previous studies is that an abrupt Moho offset, or the lack thereof, is ultimately the result of different amounts of relative vertical displacement between two crustal blocks of interest. Any relative vertical

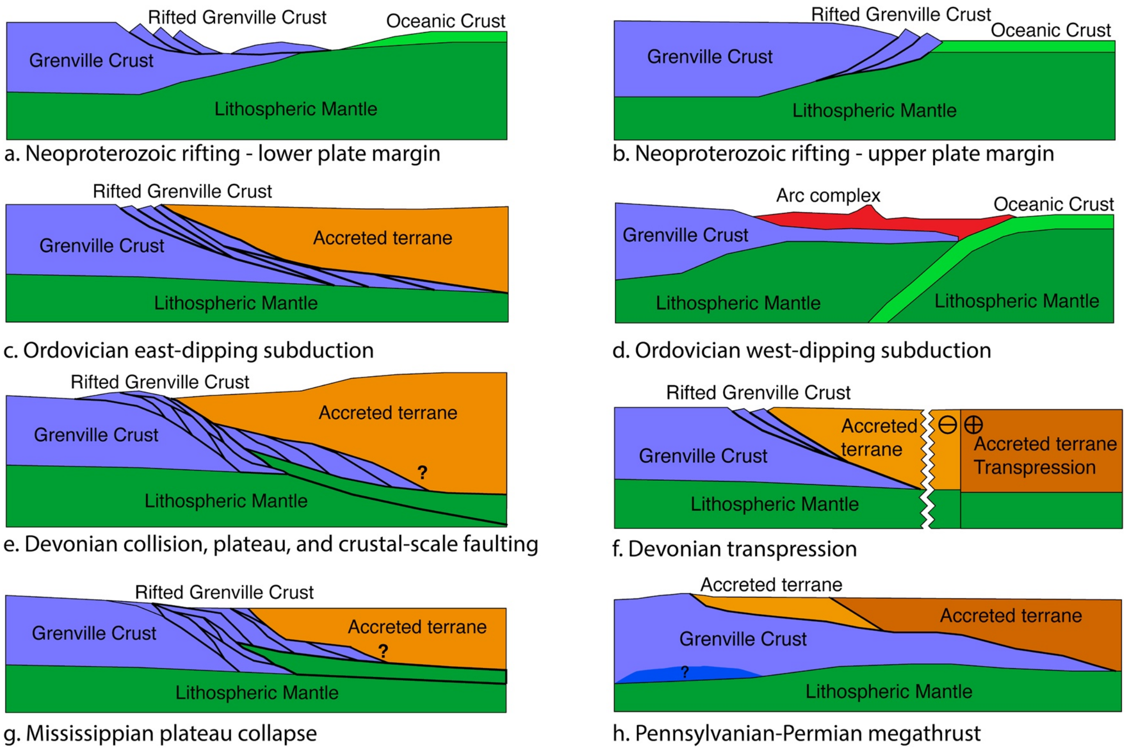

Figure 6. Schematic cross-sections showing variations in the Neoproterozoic to Permian evolution of the Appalachian orogen. The diagrams are not intended to encompass and categorize all possible evolution paths. Instead, two end-member scenarios related to the Moho geometry development during each time period of interest are shown as examples, with panels on the left showing possible scenarios that lead to an overthrust-type Moho structure, and panels on the right showing possible trajectories that lead to a smoothly varying Moho. These events include Neoproterozoic rifting of the Laurentian margin showing a (a) lower plate and (b) upper plate geometry. Subsequently, we depict Ordovician Taconic (c) accretion of a Gondwanan-derived terrane above an east-dipping subduction zone and (d) west-dipping subduction under the Laurentian margin and formation of an arc complex. Next, we illustrate Devonian Acadian-Neoacadian (e) collision and plateau formation and (f) transpression parallel to the orogen. Subsequently, we envision (g) Mississippian plateau collapse in accreted terranes; the question mark beneath the accreted terrane denotes the unknown potential extension of the rifted Grenville crust beneath the accreted terrane, and (h) Pennsylvanian-Permian Blue Ridge-Piedmont megathrust of accreted terranes over Grenville crust; the question mark in the dark blue patch near the bottom of the Grenville crust denotes the potential existence of a dense crustal root (Fischer, 2002; Hopper et al., 2016). Cross-sections (a) and (b) were adapted from Lister et al. (1986), (d) from Tull et al. (2018), and (h) from Cook and Vasudevan (2006).

displacement is likely controlled by the amount of shortening caused by the corresponding compressional events, the location of the crustal boundary/fault that accommodated the shortening (which may or may not be the Grenville-Appalachian boundary), and the steepness of that crustal boundary. In the following discussion, we focus on several major tectonic events and their along-strike variations (Figures 6 and 7), and discuss how they could have potentially affected the development of the Moho geometry observed at different latitudes.

3.1. Proterozoic Rifted Margin Configuration

Because the observed Moho depth offset beneath AA' is located farther west than the eastern margin of exposed Grenville basement (Figures 4 and 5), Luo et al. (2022) suggested that the offset marks the boundary between Grenville crust that was unaffected by Neoproterozoic rifting and Paleozoic deformation, and Grenville crust that was rifted and overprinted by Paleozoic deformation (Figure 6g). Thrust faults along the western margins of the Green Mountain and Berkshire massifs in Vermont, Massachusetts, and Connecticut have been interpreted as reactivated Neoproterozoic normal faults (Karabinos, 1988; Stanley & Ratcliffe, 1985). Because the Moho offset is located near the eastern margin of unrifted Grenville crust, we suggest that it may have been initiated by the reactivation of crustal-scale Neoproterozoic normal faults, formed during the rifting of Rodinia, as Paleozoic thrust faults during the Taconic or Acadian-Neoacadian orogeny. This model requires the reactivated Neoproterozoic normal faults to have penetrated the entire crust and be east-dipping during reactivation, so that westward thrusting/reverse faulting of rifted Grenville crust and the Moretown terrane could create the Moho depth offset. Lister et al. (1986) proposed a detachment faulting model for continental rifting in which the lower

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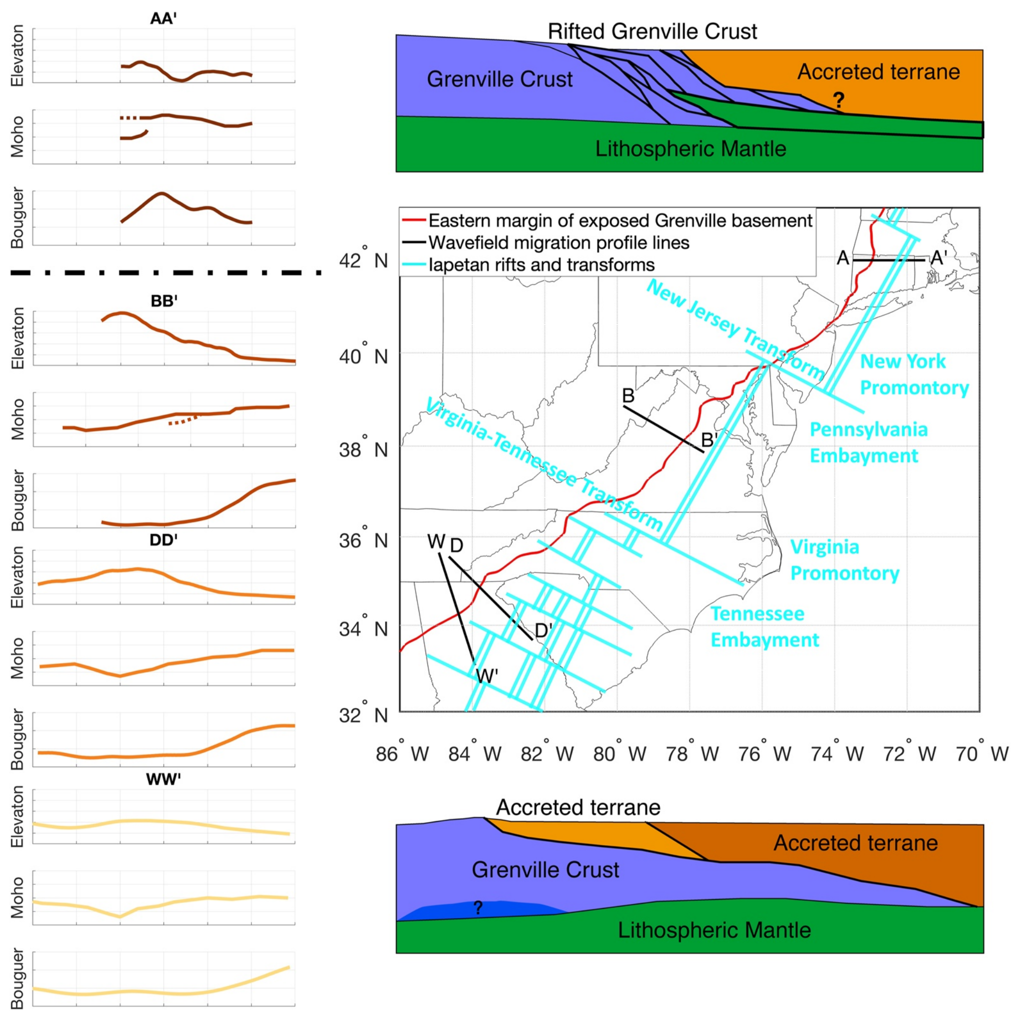

Figure 7. Summary of main results and interpretations of this study. The surface topography, the Moho depth, and the Bouguer anomaly profiles for each line are as in Figure 5. The schematic cross-sections showing the interpreted structure beneath southern New England and beneath central and southern Appalachians are from Figure 6. On the map, the location of each line and the approximate eastern margin of exposed Grenville basement from Hibbard et al. (2006) are as in Figure 1. The approximate locations of Iapetan rifts and transforms (transfer faults) are shown as cyan lines, where rifts are doubled lines and transforms are single lines, based on Thomas (2006, 2019).

plate margin is greatly extended, with numerous seaward-dipping normal faults (Figure 6a), and the upper plate margin is less extended, with widely scattered steep normal faults (Figure 6b). An upper plate margin usually has thinner synrift rocks and postrift successions than a lower plate margin (Thomas, 1993). A continental margin may have both lower and upper plate segments separated by transfer faults, which could be inherited and have profound influence on the future tectonic processes (Thomas, 2006, 2019). Thomas (1993) applied this model to the rifted Laurentian margin, and the along-strike change in crustal architecture (Figure 7) could be one of the tectonic controls on the Moho geometry.

In particular, line AA’ (abrupt Moho offset) and line BB’ (smooth Moho) are separated by the proposed New Jersey transform of Thomas (1993) (Figure 7). If the Moho depth offset beneath southern New England was indeed controlled by reactivated Neoproterozoic faults, the Laurentian margin at that latitude was likely a lower plate margin. The Green Mountain and Berkshire massifs have been widely interpreted as Neoproterozoic fault blocks of rifted Grenville basement with unconformably overlying rift-drift sediments that were transported westward during Paleozoic deformation, when normal faults were reactivated as reverse or thrust faults (e.g., Karabinos, 1988; Karabinos et al., 2017; Stanley & Ratcliffe, 1985). In this case, the east-dipping detachment fault could have been reactivated as west-directed thrusts during Paleozoic orogenesis, and this fault could be progressively steepened by later accretional and collisional events (Hillenbrand et al., 2021; Li et al., 2018). Although Thomas (1993) suggested that the lack of synrift rocks and the thin postrift succession near the New York Promontory implied an upper-plate margin for this segment of the rifted margin, a lower-plate margin was inferred for the New England Rift Zone farther to the north (Allen et al., 2010). The well-documented presence of rift clastic rocks unconformably overlying Grenville basement rocks in western Vermont and Massachusetts along the margins of the Green Mountain and Berkshire massifs (Ratcliffe et al., 2011; Zen et al., 1983) is consistent with the segment near line AA' being part of a lower plate margin. Thomas (1993) proposed upper-plate margins at the latitudes of line BB', DD', and WW', which would imply that there are no east-dipping, listric Neoproterozoic detachment faults to be reactivated to form abrupt Moho depth offset and potentially doubled Moho. However, we suspect that the Neoproterozoic rift margin configuration is not the sole tectonic control of the present-day Moho geometry, because that would suggest the presence of abrupt Moho depth offset at any latitudes with a lower-plate Neoproterozoic rift margin, which is not supported by observations (e.g., Levin et al., 2017; Li et al., 2020).

3.2. The Taconic Orogeny

Many tectonic models have suggested that the rifted Laurentian margin in New England was partially subducted beneath an Ordovician arc during the Taconic orogeny (e.g., Karabinos et al., 1998; Rowley & Kidd, 1981; Stanley & Ratcliffe, 1985). More recent models suggested that the Taconic arc was built on a Gondwanan-derived microcontinent, the Moretown terrane, above an east-dipping subduction zone, with a subsequent subduction polarity reversal (Karabinos et al., 2017; Macdonald et al., 2014). Alternative models involving collision with a single arc complex, without a subduction polarity reversal, also exist (Hildebrand & Whalen, 2021; Valley et al., 2019). Taconic collision between the Laurentian margin and the Moretown terrane above an east-dipping subduction zone could have thrust the Moho at the base of the Moretown terrane crust over the Laurentian Moho. If such a crustal-scale overthrust in fact occurred, then the abrupt offset in depth to Moho and the overlap between the deep and shallow Moho boundaries observed could be relics of the Taconic orogeny (Figure 6c). The Taconic crustal thickening that postdated the accretion of Moretown terrane (Hames et al., 1991; Hillenbrand et al., 2022) may also have contributed to the development of the Moho offset. East-dipping faults formed during Ordovician subduction could also have been reactivated during later collisions to accommodate crustal-scale thrusting of the Moho beneath the Moretown terrane over Grenville crust. However, based on the location of the abrupt Moho offset, to the west of the Laurentia-Moretown suture, it is more likely that it was developed on reactivated Neoproterozoic rift faults.

The Taconic orogeny is recognized throughout the Appalachian orogen, but its timing and style are thought to have varied. Tectonic models of the Taconic orogeny in other parts of the orogen typically invoke east-dipping subduction of the Laurentian margin under arcs or accreted terranes for the Canadian Appalachians (van Staal & Barr, 2012; van Staal et al., 2007), for the central Appalachians (Hughes et al., 2014; Wise & Ganis, 2009) and for the southern Appalachians (Hatcher, 2010; Thigpen et al., 2022). However, Tull et al. (2014, 2018) suggested a northwest-dipping subduction polarity throughout the Taconic orogeny in the Appalachians of Georgia and Alabama (Figure 6d). Along-strike changes in the polarity of Taconic subduction could be one factor controlling the Moho geometry near the Laurentian margin, because crustal-scale west-directed thrusting would be unlikely if the accreted arcs and/or terrane had been subducted to the northwest, as in Figure 6d. Similarly, northwest-dipping subduction beneath the Laurentian margin would not have created east-dipping faults suitable for reactivation during later collisions, as would have been necessary to produce the Moho offset and overlap observed in southern New England (Figure 4a). Tull et al. (2014) speculated that the transform boundary separating regions with oppositely dipping early Taconic subduction zones was located somewhere in the central Appalachians. Our observation that the Moho geometry beneath the BB' line in the central Appalachians is smooth, similar to the DD' and WW' lines in the southern Appalachians, might suggest that the proposed Taconic transform boundary was north of the BB' line, assuming that subduction polarity was indeed a controlling factor in how the Moho geometry developed. Intriguingly, there is a west-dipping feature beneath the BB' line just beneath the prominent Moho boundary (Figure 4; yellow dotted line), which may plausibly represent a relict structure from a west-dipping Taconic subduction. However, Wise and Ganis (2009) and Hughes et al. (2014) proposed tectonic models for the Taconic orogeny in the central Appalachians involving east-dipping subduction. Because the evidence does not favor a change in Taconic subduction polarity between the New England Appalachians and the central and southern Appalachians, we conclude that subduction polarity is unlikely to have been a key factor controlling the Moho geometry.

Assessing the importance of Taconic subduction polarity in shaping the observed Moho geometry is particularly challenging for the central and southern Appalachians because significant displacement of accreted terranes occurred during westward Alleghanian thrusting in this region (Figure 6h) (Cook & Vasudevan, 2006; Foster et al., 2023; Hatcher, 2010; Ma et al., 2019). The Alleghanian thrusting displaced crustal rocks deformed during the Taconic orogeny approximately 350 km westward over Grenville basement, far from the rifted Laurentian margin (e.g., Hatcher, 2010; Hatcher et al., 2007). Thus, it is difficult to correlate Taconic structures exposed at the surface with potentially coeval features in geophysical images at or near the Moho.

3.3. The Acadian-Neoacadian Orogeny

Significant crustal shortening and thickening in southern New England during the Acadian-Neoacadian orogeny are typically interpreted to be the result of the accretion of Avalonia (Hatcher, 2010; Robinson et al., 1998). Hillenbrand and Williams (2021) suggested the existence of an Acadian orogenic plateau bordered to the west by Grenville crust. Thick and strong Grenville crust may have acted as a buttress during compression (e.g., Wintsch et al., 2014). Crustal shortening on the margin of the plateau could reactivate existing faults in western New England, including numerous thrusts in the classic “Taconic” orogen (Webb et al., 2020). The collapse of this orogenic plateau due to reduced compressional stress after the Neoacadian orogeny likely involved deep crustal ductile flow (Hillenbrand et al., 2022; Massey et al., 2017; Massey & Moecher, 2013), orogen-parallel escape (Karabinos et al., 2010), and significant crustal thinning (Hillenbrand et al., 2021), which could have further contributed to the present-day configuration of the Moho depth offset (Figure 6g). Furthermore, lithospheric foundering (Levin et al., 2000; Moecher et al., 2020) might have played a role in shaping the crust and lithospheric structure beneath southern New England. A potential association between the crustal thickness variation with variation in deeper lithospheric mantle structure was also suggested by Goldhagen et al. (2022), who identified regionally thinned lithosphere beneath southern New England from Sp receiver function analysis.

The timing and intensity of the Acadian-Neoacadian orogeny varied dramatically along the Appalachian orogen; the northern margin was undergoing collision and the accretion of Avalonia, but the southern margin experienced less orogen-perpendicular crustal shortening (Hibbard et al., 2010). Hibbard et al. (2010) and Hibbard and Karabinos (2013) suggested that this first-order along-strike transition took place near the New York Promontory, where the Devonian clastic wedge is thickest (Faill et al., 1985). Furthermore, there might also be a change of Acadian-Neoacadian subduction polarity near the southern end of the New York Promontory, with the Laurentian margin obliquely subducted beneath the Carolinia in the central and southern Appalachians (Hatcher & Merschat, 2006; Merschat et al., 2023). The lack of significant Acadian crustal shortening and clastic wedge formation in the central and southern Appalachians suggests that accreted terranes were juxtaposed with Laurentia via transpression (e.g., Dennis et al., 2007), without significant crustal shortening perpendicular to the orogen, as shown in Figure 6f. Evidence for Acadian-Neoacadian tectonism visible today in the central and southern Appalachians might possibly reflect metamorphism and deformation that actually occurred to the north near the New York Promontory, with these rocks of the Inner Piedmont being displaced southward to their present locations by transpression (Dennis et al., 2007; Merschat et al., 2012). Our observation of the abrupt Moho depth offset beneath southern New England and the smoothly varying Moho beneath the central and southern Appalachians (Figures 4 and 5) correlates well with the greater crustal shortening and thicker foreland clastic wedge development during the Devonian in southern New England than farther to the south. Nevertheless, it is uncertain how far south the inferred Acadian orogenic plateau extended, because high paleoelevations suggested by the sedimentological data continue further south along the orogen (Ettensohn et al., 2019; Hillenbrand et al., 2021), and related evidence might be overprinted by later tectonic events (including the Alleghanian orogeny, discussed below; Hatcher, 2002).

Previous receiver function studies (e.g., Levin et al., 2017; Li et al., 2018) reported a gradual Moho depth change across the Grenville-Moretown terrane suture to the north of the AA’ line, without an abrupt offset. If this gradual change in crustal thickness in northern New England is confirmed using high-resolution imaging from dense seismic arrays, it will strengthen the case that the Moho offset observed in southern New England is an unusual feature of the Appalachian lithosphere, and that there is a first-order transition both to the south and to the north of southern New England. Crustal shortening during the Acadian-Neoacadian orogeny appears to have been greater in southern New England than in regions farther north (Karabinos et al., 2010; Moecher et al., 2020; van Staal & Zagorevski, 2023), where the Taconic and Acadian orogenic belts are significantly wider (Hibbard et al., 2006) and the crust of the Acadian plateau was not as thick (Hillenbrand & Williams, 2021). Thus, there is a striking correlation between the greatest Acadian-Neoacadian crustal shortening, the thickest crust in the Acadian plateau, and the only segment of the Appalachian orogen with a well-documented offset in depth to Moho in southern New England.

3.4. The Alleghanian Orogeny

The Alleghanian orogeny was the culminating event in the formation of the Appalachians, when Laurentia collided with Gondwana to form Pangea (Hatcher, 2010; Thomas & Hatcher, 2021). In the New England Appalachians, the Alleghanian record is best preserved in Rhode Island and eastern Massachusetts and Connecticut (Getty & Gromet, 1992; Goldstein, 1989; Wintsch et al., 1992). Alleghanian deformation is also observed locally in high strain zones around the Willimantic dome (Getty & Gromet, 1992), the Pelham dome (Gromet & Robinson, 1990), and the eastern margin of the Connecticut Valley basin (McWilliams et al., 2013). Notably, there is no evidence that Alleghanian deformation extended as far west as the Moho offset that we observe today in southern New England. Thus, it seems unlikely that the Alleghanian orogeny was a controlling factor in the creation of the offset in Moho observed in line AA'.

In contrast, the Alleghanian orogeny played a major role in shaping the present-day lithospheric architecture in the central and southern Appalachians (Thomas & Hatcher, 2021). One of the most dramatic features of the Alleghanian orogeny is the Blue Ridge-Piedmont megathrust sheet, which translated the internal deformation zone of the Blue Ridge and Piedmont westward as much as 350 km over Grenville basement rocks (Figure 6h; Cook & Vasudevan, 2006; Hatcher et al., 2007; Hopper et al., 2017). Thus, Grenville crustal rocks below the megathrust sheet may extend all the way to the southeastern end of lines BB', DD', and WW' (Figure 1), even though these lines cross the surface boundary of the Laurentian suture with accreted terranes as shown in Figures 4 and 5. In comparison, Ando et al. (1984) inferred rifted Grenville basement rocks extending east of the Grenville-Moretown terrane suture in the subsurface beneath New England, but it is unclear how far to the east Grenville crust extends (denoted by question mark in Figure 6g). The large displacement of the Blue Ridge-Piedmont megathrust sheet in the central and southern Appalachians makes a direct comparison of the Moho architecture with the New England Appalachians challenging. The gradual eastward decrease in crustal thickness shown in lines BB', DD', and WW' does not seem clearly correlated with terrane boundaries, relict subduction zones, or rifted continental margins, but instead it correlates with the present-day topography, especially when averaged within a 10 km radius (Figure 5 and Figure S3 in Supporting Information S1). The close resemblance of the Moho geometries and the 10 km-averaged topographies is consistent with regionally compensated topography (Hawman et al., 2012), and the smooth Moho geometry beneath the central and southern Appalachians likely reflects the regional topographic load.

Figure 5 also shows that the decreases in crustal thickness from the deepest points of Moho beneath lines BB', DD' and WW' are not accompanied by expected increases in the Bouguer gravity anomaly, which may signify strong lateral density variations either within the crust or uppermost mantle. Fischer (2002) proposed post-orogenic garnet growth in the lower crust as a potential mechanism to explain the preservation of crustal roots beneath orogens (Figure 6h). This mechanism is consistent with smaller density contrasts across the Moho beneath high elevation than beneath low elevation regions (Hopper et al., 2016). In the regions with thickest crust, the dense crustal root is also thicker, such that the crust is denser in an integrated sense. In this way, as the Moho depth decreases and the denser crustal root thins, the Bouguer anomaly increase due to shallower Moho is counteracted by the Bouguer anomaly decrease due to the crustal root thickness decrease, which effectively is the integrated crustal density decrease. As the crust further thins such that there is no longer a denser crustal root, the lateral density variation of the crust becomes smaller, and any further decrease in the Moho depth is manifested in the corresponding increase in Bouguer anomaly, as shown in the 100–200 km intervals in Figure 5 for lines BB', DD', and WW'. The fact that the BB' line shares the same topography-Moho depth-gravity correlation as the DD' and WW' line shows that this pattern is common for the central and southern Appalachians, perhaps reflecting the importance of the Alleghanian collision. In comparison, the abrupt Moho depth offset observed beneath AA' is accompanied by a drastic increase in the Bouguer anomaly (Figure 5), which indicates a less pronounced lateral variation in crustal density across the Moho depth offset beneath southern New England. This observation suggests that the crustal densities across the Moho offset do not differ significantly and supports the idea that the Moho offset in southern New England is internal to Grenville crust instead of representing the Grenville-Appalachian transition.

10.1029/2023JB027024

The crust of the southern Appalachians was greatly thickened before and during the Alleghanian thrusting (Ma et al., 2019; Stowell et al., 2019). The Alleghanian orogeny created an orogenic plateau in the southern Appalachians, with plateau collapse at the end of the orogeny greatly reducing the crustal thickness (Foster et al., 2023; Ma et al., 2019). Interestingly, the strong Alleghanian compression and the rise and collapse of an orogenic plateau following the Alleghanian orogeny did not result in a Moho offset in the central and southern Appalachians. This suggests that other conditions, such as the steepness of the subsurface boundary that accommodated the relative motion between crustal blocks during compression and plateau formation, must be favorable for an orogenic plateau to lead to an offset in depth to Moho like that observed in southern New England. The Alleghanian overthrust in the southern Appalachians took place on the Alleghanian suture, with a low-angle shallow interface transitioning into mostly flat-lying mid-crustal detachment (Hopper et al., 2017), so that the resulting relative displacement between the two crustal blocks was predominantly horizontal instead of vertical. The collapse of the orogenic plateau was along a low-angle extensional detachment, which separates the Suwannee terrane and previously accreted Carolina superterrane and likely does not penetrate the Grenville basement beneath (Ma et al., 2019). In this way, the resulting crustal thinning was more evenly distributed across a broader lateral distance (Foster et al., 2023) instead of creating a sharp contrast across a steep boundary cutting through the entire crust.

3.5. Mesozoic Rifting

The Mesozoic development of the eastern North America passive margin was complex and diachronous (Withjack & Schlische, 2005; Withjack et al., 2012). In the New England Appalachians, we observe relatively thin crust below the Mesozoic Hartford basin (AA' line in Figure 4). The Hartford basin is an abandoned Mesozoic rift basin (Hubert et al., 1992), and thus the crust beneath it may be thinner than surrounding regions due to concentrated extension (Bell et al., 1988; Gao et al., 2020; Luo et al., 2021, 2023). Nevertheless, the Hartford basin is located ~40 km to the east of the abrupt Moho offset and ~20 km to the east of the minimum Moho depth. Therefore, although Mesozoic rifting might have played a secondary role in shaping the smoothly varying and shallow Moho to the east of the abrupt Moho offset (Figure 4), it is unlikely to have played a dominant role in the formation of the Moho offset itself. Furthermore, the ~15 km contrast in crustal thickness that we see today is likely to have been set shortly after the plateau collapse at 330–310 Ma (Hillenbrand et al., 2021, 2022). The timing of the development of this ~15 km difference is unlikely to be much later, because the cooling histories of the rocks on the west and east sides of the Moho depth offset in southern New England converge between 300 and 280 Ma (Hillenbrand et al., 2021). This indicates that the Moho depth offset was substantially formed before this time.

The BB' line in the central Appalachians is about 10 km to the south of the Culpeper basin, whose deposits share the same Newark Supergroup characteristics as the Hartford basin (Luttrell, 1989). The common origin of these two basins suggests a potentially similar effect of concentrated extension of the crust during the Mesozoic. There is no abrupt Moho depth offset beneath the BB' line like the one beneath the western portion of AA'. The general trend of smooth west-to-east decrease in Moho depth is not interrupted by the proximity with the Culpeper basin. In the southern Appalachians, the South Georgia basin lies to the south of the DD' and WW' lines, so the Moho geometry beneath the South Georgia basin is not directly imaged in this study. A previous wide-angle seismic refraction/reflection experiment across the South Georgia basin reveals a ~4 km Moho depth decrease beneath the basin (Marzen et al., 2019, 2020), but this decrease is smooth and occurs over a distance of more than 40 km. We thus find it unlikely that Mesozoic rifting and concentrated extension beneath rift basins are a main cause of the abrupt Moho depth offset, though they may be responsible for some aspects of present-day Moho structure.

3.6. Summary: Controls on Moho Geometry in the Appalachian Orogen

We suggest that the abrupt 15 km change in crustal thickness and the overlap between the shallow and deep Moho boundaries observed in southern New England (western portion of line AA' in Figure 4) required two conditions: crustal-scale east-dipping faults and a driving force to thrust the rifted Grenville crust westward over unrifted Grenville crust. These faults may have started as a set of low-angle normal faults but gradually steepened during the later compressional events, and they must have been relatively steep during the offset-forming event, to facilitate large vertical displacement between the two crustal blocks (e.g., Li et al., 2018, 2020). Nevertheless, the scenario we favor is different from the steep suture fault that cuts all the way down to the lithospheric mantle, as proposed by Li et al. (2018); we propose instead that the observed doubled Moho beneath southern

New England would require the faults to be listric in geometry and flatten out in the lower crust of the western block (Figure 6g), as suggested by van Staal and Zagorevski (2023). These crustal-scale, east-dipping faults necessary for the Moho offset could have begun as a set of Neoproterozoic normal faults including the main detachment fault that were reactivated as reverse or thrust faults (with their upper portions steepened) during the Taconic and/or Acadian-Neoacadian orogenies. Substantial displacement would not have happened without a large compressional force, even if steep crustal-scale east-dipping faults were present. In particular, the extreme crustal shortening and thickening during the Acadian-Neoacadian orogeny could have displaced the rifted Grenville crust to the west over unrifted Grenville crust in southern New England (Figure 6e). Significant crustal thinning via ductile flow and orogen-parallel crustal escape (Massey et al., 2017) during the collapse of the Acadian orogenic plateau (Hillenbrand et al., 2021, 2022) could have further shaped the final configuration of the Moho depth offset (Figure 6g). The Silurian accretion of Ganderia during the Salinic orogeny and the Pennsylvanian-Permian collision of Gondwana with Laurentia during the Alleghanian orogeny were unlikely to have made major contributions, as evidence for the effects of these orogenies in western New England near the Moho offset is lacking (Hatcher, 2010; Hillenbrand et al., 2022; van Staal et al., 2009).

Segments of the orogen near lines BB', DD', and WW' in the central and southern Appalachians did not experience such dramatic crustal shortening during the Acadian-Neoacadian orogeny, and their crustal structures are more dominated by the effects of the Alleghanian orogeny (Hatcher, 2010). The Alleghanian overthrusting likely occurred on a low-angle interface that soles into a flat-lying detachment in the middle crust (Hopper et al., 2017), which displaced the Blue Ridge-Piedmont megathrust sheet hundreds of kilometers to the west over the Grenville crust (Hatcher, 2002). In this way, the significant crustal shortening during the Alleghanian overthrusting manifested as the horizontal relative displacement between the two crustal blocks, with little vertical displacement. The lack of large vertical displacement across the crustal boundary resulted in a smooth lateral change of the Moho depth; the Moho configuration was likely determined by the topographic load during the Paleozoic and preserved by the waning buoyancy of the denser crustal root (Fischer, 2002). The post-orogenic collapse of the southern Appalachian orogenic plateau likely resulted in smooth crustal thinning along a low-angle extensional detachment, without causing much vertical displacement on a crustal-scale fault, with no mechanism available to create a sharp contrast in the Moho depth (Foster et al., 2023; Ma et al., 2019).

4. Conclusion and Implications

Uniformly processed wavefield migration imaging using data from dense seismic arrays deployed across the Appalachians reveals similar, smooth Moho geometries beneath the central and southern Appalachians and a distinct, abrupt Moho depth offset beneath New England. The location of this transition in the Moho geometry is consistent with the presence of a major boundary near the New York Promontory, as suggested by geologic observations, that divides the Appalachian orogen into the southern and northern segments in a general sense (e.g., Hibbard et al., 2007; Hibbard & Karabinos, 2013). Our observation suggests that this boundary marks not only a change in bedrock geological features but also a fundamental transition in deeper crustal structure, separating regions with different tectonic settings which either did or did not favor the development of an abrupt Moho depth offset. Major factors affecting the evolution of the present-day Moho geometry likely include tectonic inheritance from the Neoproterozoic rifting of Rodinia (e.g., Thomas, 1993) along with extreme crustal shortening during the Acadian-Neoacadian orogeny in southern New England (e.g., Hillenbrand et al., 2022; Karabinos et al., 2010) and the Alleghanian orogeny in the central and southern Appalachians (Foster et al., 2023; Thomas & Hatcher, 2021). For the unique abrupt Moho depth offset in southern New England, we suggest that the extreme crustal shortening during the Acadian/Neoacadian orogeny and the resulting large vertical displacement occurring on steep crustal-scale faults may be the most convincing explanation, based on the strong spatial correlation among the narrow Taconic-Acadian orogenic belt (Hibbard et al., 2006), the along-strike extent of a thick orogenic plateau in southern New England (Hillenbrand et al., 2022; Hillenbrand & Williams, 2021), and the extent of the Moho offset (Levin et al., 2017; Li et al., 2020; this study). Future deployments of additional dense arrays across the Appalachians may enable detailed imaging of Moho geometry at different latitudes, allowing for a fuller picture of the controls on along-strike variability.

Insights from this study about the origin of varied Moho geometries beneath the Appalachians can shed light on how along-strike variations of orogenic processes can affect crustal development at different segments of the orogen more generally. The Paleozoic Appalachian orogenesis is not unique in having different preexisting

10.1029/2023JB027024

structures, tectonic regimes, and degrees of crustal shortening along its strike. The ongoing orogenies in Himalayan-Tibetan and Andean regions also exhibit substantial along-strike variations. For example, there is a systematic change of Himalayan topography, possibly associated with a westward decrease of total crustal shortening along the Himalayan orogen (Yin, 2006), that likely also manifests in the deep crustal structure. Similarly, the Andean orogen also exhibits significant along-strike variability. The recorded orogenic crustal shortening is the largest in the Bolivian Altiplano in the central Andes and much smaller to the north and south, as a result of varied absolute motions of the upper plate and other factors (Ramos, 2010). Basement thrusts that affect the entire crust are widely reported along the orogen, and the overthrusting of Andean crust over the Brazilian shield has been proposed as a potential explanation for the thick lithosphere beneath the central Andean Altiplano (Kley et al., 1999; Whitman et al., 1996). Our study of Appalachian crustal evolution, and the along-strike variability in the processes that control that evolution, also reinforces the idea that the details of present-day crustal structure in ancient orogens can shed light on the fundamental tectonic processes that have operated in orogenic settings in the past, and continue to operate on Earth today.

Data Availability Statement

Waveform data used in this study, including those from temporary deployment MAGIC, SEISConn, and SESAME, are archived by IRIS DMC and can be openly accessed at https://ds.iris.edu. In particular, the MAGIC array (Long & Wiita, 2013; network code: 7A) can be found at https://doi.org/10.7914/SN/7A_2013; the SEISConn array (Long, 2015; network code: XP) can be found at https://doi.org/10.7914/SN/XP_2015; the SESAME array (Fischer et al., 2010; network code: Z9) can be found at https://doi.org/10.7914/SN/Z9_2010.

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