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Evolution, Modification, and Deformation of Continental Lithosphere: Insights from the Eastern Margin of North America

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Abstract

Continental lithosphere is deformed, destroyed, or otherwise modified in several ways. Processes that modify the lithosphere include subduction, terrane accretion, orogenesis, rifting, volcanism/magmatism, lithospheric loss or delamination, small-scale or edge-driven convection, and plume-lithosphere interaction. The eastern North American margin (ENAM) provides an exceptional locale to study this broad suite of processes, having undergone multiple complete Wilson cycles of supercontinent formation and dispersal, along with ~200 Ma of postrift evolution. Moreover, recent data collection efforts associated with EarthScope, GeoPRISMS, and related projects have led to a wealth of new observations in eastern North America. Here I highlight recent advances in our understanding of the structure of the continental lithosphere beneath eastern North America and the processes that have modified it through geologic time, with a focus on recent geophysical imaging that has illuminated the lithosphere in unprecedented detail.

- Eastern North America experienced a range of processes that deform, destroy, or modify continental lithosphere, providing new insights into how lithosphere evolves through time.

- Subduction and terrane accretion, continental rifting, and postrift evolution have all played a role in shaping lithospheric structure beneath eastern North America.
- Relict structures from past tectonic events are well-preserved in ENAM lithosphere; however, lithospheric modification that postdates the breakup of Pangea has also been significant.

1. INTRODUCTION

Continental lithosphere is an essential component of Earth's plate tectonic system and plays a key role in stabilizing continental masses. While oceanic lithosphere forms, evolves, and is destroyed on timescales on the order of 100 Ma, continental lithosphere is generally significantly older (e.g., Pearson 1999, Carlson et al. 2005, Hawkesworth et al. 2017) and thicker (e.g., Artemieva & Mooney 2001, Poupinet & Shapiro 2009, Fischer et al. 2020), with a different thermal structure (Rudnick et al. 1998). In contrast to the negatively buoyant oceanic lithosphere, continental lithosphere may be close to neutrally buoyant overall (Jordan 1978), with the compositional contribution to buoyancy being positive (e.g., Lee 2003, Schutt & Lesher 2010). However, continental lithosphere can still be modified or destroyed via a suite of fundamental Earth processes. These potentially include subduction, terrane accretion, orogenesis, continental rifting, magmatic activity, lithospheric loss or delamination, small-scale or edge-driven convection, and plume-lithosphere interaction.

While we have a general sense of the processes that may modify, deform, or destroy continental lithosphere, we do not yet understand them in detail, and there are several fundamental unsolved problems related to lithospheric evolution. For example, how do lithospheric properties (e.g., rheology, composition, thermal history) affect how continents are modified, and to what extent does this vary from place to place? Why is some continental lithosphere seemingly unmodified over long stretches of geologic time, while some lithosphere has been modified relatively recently? To what extent do past tectonic processes imprint themselves on the lithosphere? How long does the imprint of past tectonic processes, where present, remain preserved? What are the relative roles of various processes that modify continental lithosphere? What controls the susceptibility of lithosphere to modification through various mechanisms? How, and at what depth ranges, does the lithosphere deform during tectonic episodes, and how does lithospheric rheology control this process? How well are the crust and the mantle lithosphere coupled during lithospheric deformation?

The eastern margin of the North American continent, often abbreviated as ENAM or the eastern North American margin (**Figure 1*a***), represents an ideal locale to study the modification of continental lithosphere in detail and to shed light on important unsolved problems related to lithospheric evolution. This region has undergone two complete Wilson cycles of supercontinent assembly and dispersal over the past ∼1.3 Ga, with the formation and subsequent breakup of the Rodinia and Pangea supercontinents. It is likely that the full suite of processes that can modify the structure of continental lithosphere has, in fact, affected eastern North America; it is therefore an exceptional locale to study these processes and how they may interact with or overprint each other. Importantly, this region has also recently undergone an explosion in the availability of geophysical (and other) data relevant to the structure and evolution of continental lithosphere, enabled by the EarthScope and GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins) initiatives. We now have geophysical images of ENAM lithosphere that are unprecedented, both in their spatial resolution and in their geographic extent. Importantly, this geophysical imaging

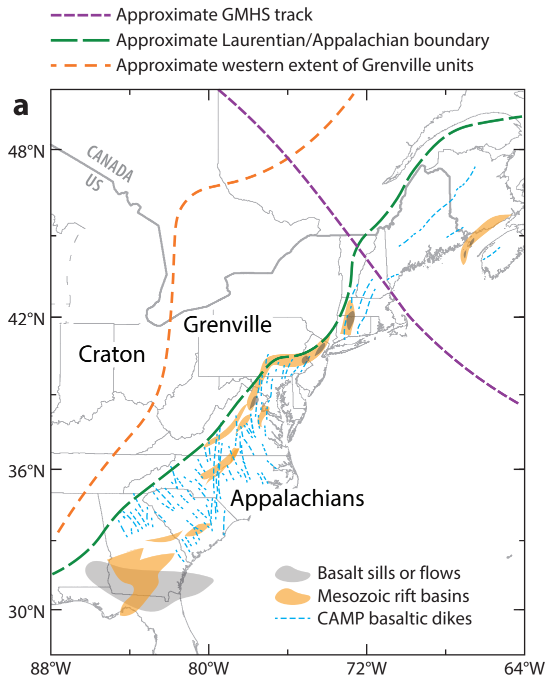

Figure 1

(*a*) Tectonic map of ENAM. The dashed orange line shows the approximate westward extent of the Grenville units; the dashed green line shows the approximate boundary between the Laurentian and accreted Appalachian terranes. The dashed purple line shows the approximate track of the GMHS (Kinney et al. 2021). Light orange patches indicate onshore Mesozoic rift basins (Jourdan et al. 2009, Withjack et al. 2012). Blue dashed lines indicate CAMP basaltic dikes, and gray patches indicate basalt sills or flows (Jourdan et al. 2009). Panel adapted from Gao et al. (2020), with major lithotectonic boundaries from Hibbard et al. (2006). (*b*) Map of USArray seismic TA stations (*gray triangles*) and magnetotelluric stations (*white circles*), along with broadband stations of the ENAM CSE (*light blue squares*). Lines indicate approximate locations of dense linear arrays deployed in ENAM. Abbreviations: CAMP, Central Atlantic Magmatic Province; CSE, Community Seismic Experiment; ENAM, eastern North American margin; GENESIS, GEology of New England via Seismic Imaging Studies; GMHS, Great Meteor Hotspot; MAGIC, Mid-Atlantic Geophysical Integrative Collaboration; NEST, New England Seismic Transects; SEISConn, Seismic Experiment for Imaging Structure beneath Connecticut; SESAME, Southeastern Suture of the Appalachian Margin Experiment; SUGAR, SUwanee Suture and GA Rift basin; TA, Transportable Array. Panel *a* adapted with permission from Gao et al. (2020).

can sometimes resolve features on the very short length scales that are relevant to understanding lithospheric architecture in relation to geologic structures. This cutting-edge geophysical imaging is complemented by new constraints from disciplines such as petrology, geochemistry, geomorphology, and geodynamics.

The goals of this review are to use eastern North America as a window into the processes that modify continental lithosphere and to highlight what we have learned about lithospheric evolution, modification, and deformation. I focus heavily on recent geophysical imaging results and how they have been combined with insights from adjacent disciplines to gain new insights into continental lithosphere evolution. A review of a topic this large cannot possibly hope to be comprehensive, and I do not provide a complete view of the vast literature on ENAM lithosphere. I refer the reader to general overviews of continental lithosphere (e.g., Artemieva 2011) and to other compilations of results from eastern North America. In particular, the Canadian Lithoprobe project has provided a wealth of important new knowledge about the continental lithosphere beneath the Canadian portion of ENAM (e.g., Clowes 2011, Cook et al. 2012).

2. MODES OF CONTINENTAL LITHOSPHERIC EVOLUTION, MODIFICATION, AND DEFORMATION

Many processes have been suggested to modify the structure of the continental lithosphere in different settings (**Figure 2**), most or all of which are relevant to ENAM. Subduction and related effects such as volcanism, orogenesis, terrane accretion, and metasomatic alteration are among the most important of these, and evidence for the effects of past subduction episodes on ENAM lithosphere is abundant. Subduction leaves its mark on continental lithosphere through arc volcanism and/or plutonism, typically well expressed in the geologic record (e.g., Michelfelder et al. 2013). Subduction can deliver oceanic volcanic arcs, oceanic plateaus, or continental slivers or ribbons onto the edges of existing continental lithosphere (e.g., Tetrault & Buiter 2012). This process of terrane accretion acts to graft pieces of crust onto existing continental cores and is well illustrated in the geologic record of many passive margins; modern examples also exist today [e.g., in the Sunda-Banda arc (Miller et al. 2021)]. While subduction can deliver material to existing continental lithosphere, it can also act to remove it through the process of erosive or ablative subduction (e.g., Clift & Vannucchi 2004), particularly in flat-slab subduction settings (Axen et al. 2018). Finally, subduction can act to cause metasomatism of overriding continental lithosphere, particularly through the mechanism of flat-slab or low-angle subduction, delivering volatiles (e.g., Hiett et al. 2021) or enriching the lithosphere in silica (e.g., Wagner et al. 2008).

Another process that plays a key role in shaping continental lithospheric structure is continental collision and its associated effects, such as the development of extensive orogenic plateaus. The classic and well-studied modern example is the Tibetan plateau (e.g., Schulte-Pelkum et al. 2005); in the geologic past, continental collision affected the ENAM lithosphere during the final stages of the Grenville and Appalachian orogenies. Orogenesis produces extensive thickening of the crust, as observed in modern settings (e.g., Zhang & Klemperer 2005); however, the corresponding evolution of the mantle lithosphere remains poorly understood (e.g., Gray & Pysklywec 2012). The deep lithosphere may be thickened (due to wholesale shortening or accommodation by a shear zone at the base of the overriding plate) or, alternatively, thinned via lithospheric foundering (e.g., Ducea & Saleeby 1996); some combination of these processes may operate in succession. In general, continental lithosphere is extensively deformed during collisional orogenesis; this deformation often expresses itself in seismic anisotropy (e.g., Silver 1996, Zhang et al. 2022). Despite extensive study, however, the details of how deformation is accommodated during continental collision, particularly in the deeper lithosphere, remain opaque. The amount of deformation accommodated at different depths depends strongly on the lithospheric rheology, which is imperfectly known (e.g., Warren & Hansen 2023).

Yet another fundamental tectonic process that modifies continental lithosphere is continental rifting and extension. As with continental orogenesis, this is a process that is studied in modern settings [such as the East African Rift (e.g., Ebinger 2005, Kogan et al. 2012)] but has also left a record in the structure of passive continental margins such as ENAM. Rifting can modify the lithosphere via wholesale extension and thinning (e.g., Withjack et al. 2020), but the competing roles of strain localization versus widespread extension as modes of deformation remain imperfectly understood (e.g., Davis & Kusznir 2004). Another major potential effect on lithospheric structure in a continental rift setting is that of upper mantle melting, volcanism, and emplacement of magmatic products at depth; these processes may in turn act to cause metasomatism of preexisting lithosphere (e.g., Dawson & Smith 1988). Continental breakup in the geologic past is often associated with widespread volcanism; one of the best-known examples is the Central Atlantic Magmatic Province (CAMP), which accompanied the breakup of Pangea (e.g., Blackburn et al. 2013).

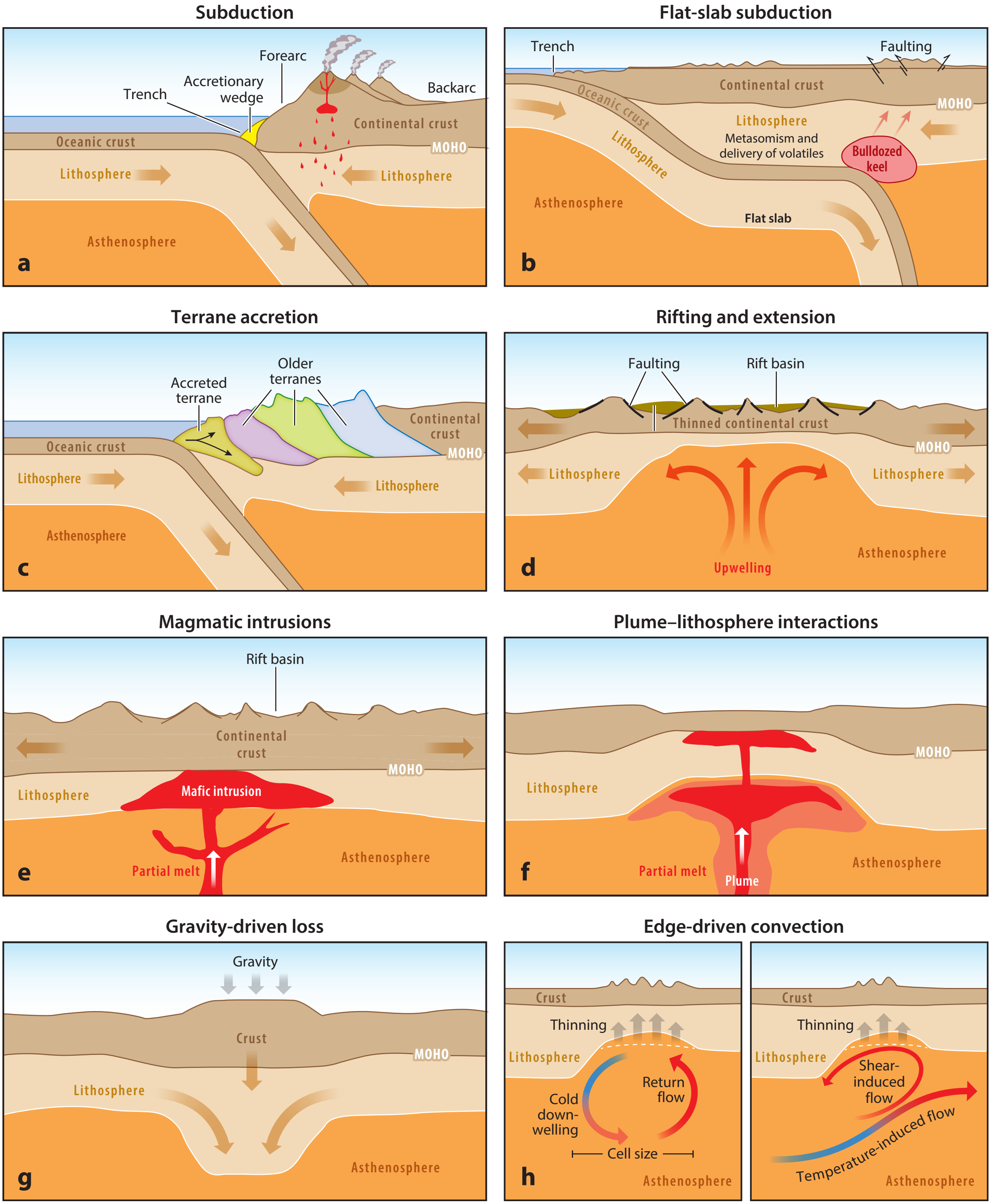

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Figure 2 (*Figure appears on preceding page*)

Schematic diagrams of various processes that can modify continental lithosphere. (*a*) Subduction, melt migration, volcanism, the emplacement of magmatic products at depth in the overriding plate, and/or the removal of continental lithosphere via ablative subduction. (*b*) A flat-slab subduction setting, in which lithosphere may be modified via metasomatism or lithospheric removal. (*c*) Terrane accretion, in which arcs or continental slivers are delivered to the side of an existing continent. (*d*) Continental extension during rifting. (*e*) The emplacement of mafic material at the base of the crust via the intrusion of magmatic material during extension (or from any process that delivers melt to the base of the plate). (*f*) Plume-lithosphere interaction. (*g*) Gravity-driven lithospheric loss via Rayleigh-Taylor instability. (*h*) Two possible modes of edge-driven convection. Panel *b* adapted from Gutscher (2018) with permission from Springer Nature. Panel *c* adapted with permission from Karabinos et al. (2017). Panel *e* adapted from Thybo & Artemieva (2013) (CC BY-NC-SA 3.0). Panel *g* adapted with permission from Long et al. (2021) (CC BY-NC-ND 4.0). Panel *h* adapted with permission from Kaislaniemi & van Hunen (2014) (CC BY-NC-ND 3.0).

Dikes, sills, and lava flows associated with CAMP have been extensively documented throughout ENAM (e.g., Withjack et al. 2012), but it remains unclear to what extent the deep crust and mantle lithosphere have been modified by melt migration or by the emplacement of magmatic products.

In addition to the fundamental plate tectonic processes of subduction, orogenesis, and rifting, more exotic modes of lithospheric modification also exist. Examples include lithospheric delamination, in which a piece of mantle lithosphere peels away from the material above it (Bird 1979), or a more general category of gravity-driven lithospheric loss, in which cold and dense lithosphere detaches from the material above it and sinks into the less dense mantle beneath (e.g., Harig et al. 2010, Pysklywec et al. 2010, Lee et al. 2011, Wang & Currie 2015). This style of lithospheric foundering has been documented in many regions and tectonic settings, including within cratons (Menzies et al. 2007, Dave & Li 2016, Liu et al. 2018, Chen et al. 2023) and in orogenic or subduction zone settings (e.g., Ducea & Saleeby 1996, Wang et al. 2021). Such lithospheric loss events can be associated with upwelling return flow that generates melting and volcanism (e.g., Mazza et al. 2014), providing a secondary mechanism for altering lithospheric structure.

Another class of models invokes edge-driven or other small-scale convection, perhaps driven by a sharp lateral contrast between thick lithosphere beneath continental interiors and thinner lithosphere beneath the continental edge (e.g., King & Anderson 1998, Kaislaniemi & van Hunen 2014, Menke et al. 2016). These mechanisms can modify lithospheric structure either through the gravity-driven loss of lithospheric material as the downwelling limb of an edge-driven convection cell or through the effect of upwelling return flow, which can potentially thin the lithosphere above it and produce melting and volcanism (e.g., Menke et al. 2016, 2018; Long et al. 2021). A somewhat similar mechanism, known as shear-driven upwelling (Conrad et al. 2010), invokes asthenospheric shear in the presence of lateral viscosity variations, potentially including topography at the base of the continental lithosphere.

Finally, interactions between a mantle plume and an overlying continental plate can modify the lithosphere (e.g., Ribe & Christensen 1994, Burov & Guillou-Frottier 2005, Wang et al. 2015). Plumes can produce melt, and thus volcanism, in intraplate continental settings (sometimes in large volumes, as with continental flood basalts). Typically, plume-related volcanism produces a time-progressive track as the plate moves over the asthenosphere, although the spatiotemporal progression may be less clear in continental settings than in oceanic ones (e.g., Kinney et al. 2021). In addition to the eruption of volcanic products at the surface, plume-associated volcanism may also emplace magmatic products at depth, particularly in a flood basalt setting in which magmatic volumes are large (e.g., Mittal et al. 2021). Plumes interacting with the base of the continental lithosphere may also thin it via thermal ablation (e.g., Tao et al. 2021), and heating from beneath may enable the release of trapped volatiles (e.g., Burgess et al. 2017, Broadley et al. 2018).

3. NEW DATASETS FOR EASTERN NORTH AMERICA: EARTHSCOPE, GEOPRISMS, AND RELATED PROJECTS

3.1. Recent Geophysical Data Collection and Multidisciplinary Projects

ENAM is distinguished among other passive continental margins by its wealth of new, high-resolution geophysical datasets (**Figure 1*b***), including the multiple components of EarthScope's USArray (2004–2021). The seismic stations of the temporary Transportable Array (TA) were deployed for ∼24-month periods at ∼70-km station spacing, a station density that is particularly effective for imaging structure at upper mantle depths. The magnetotelluric array deployed temporary stations at roughly 70-km spacing, like the seismic TA, but deployed for periods of weeks instead of years. The USArray Flexible Array (FA) provided instruments for temporary, principal investigator–driven deployments to target specific regions of interest. Several FA experiments were carried out in ENAM (**Figure 1*b***), including SESAME (Southeastern Suture of the Appalachian Margin Experiment) [broadband seismic (Parker et al. 2013)] and SUGAR (SUwanee Suture and GA Rift basin) [active source seismic (Marzen et al. 2019)] in the southeastern United States, MAGIC (Mid-Atlantic Geophysical Integrative Collaboration) [broadband seismic and magnetotelluric (Long et al. 2020)] in the central Appalachians, and QMIII [broadband seismic (Levin et al. 2017)] in the northeastern United States and southeastern Canada. Additional temporary seismic experiments have also been carried out recently, including SEISConn (Seismic Experiment for Imaging Structure beneath Connecticut) in southern New England (Long & Aragon 2020) and the ongoing NEST (New England Seismic Transects) and GENESIS (GEology of New England via Seismic Imaging Studies) deployments in central New England (Long et al. 2022). Importantly, several of these experiments were part of multidisciplinary collaborations that explicitly sought to combine geophysical imaging with constraints from other disciplines.

Complementary to the data-gathering efforts of the USArray program, ENAM was selected as a focus site for the Rifting Initiation and Evolution (RIE) effort of GeoPRISMS, a National Science Foundation–funded decadal program (2010–2021). This included the major data-gathering effort of the ENAM Community Seismic Experiment (CSE) (Lynner et al. 2019), an onshore-offshore, multiscale seismic imaging project (**Figure 1*b***). The components included a 33-station array of broadband seismometers (mostly offshore), onshore and offshore wide-angle seismic profiles, and several marine multichannel seismic profiles. The ENAM CSE dataset represents one of the only shoreline-crossing, multiscale seismic datasets available in a passive continental margin setting (Lynner et al. 2019).

3.2. Regional Imaging of ENAM Lithosphere

Figure 3 shows four views of ENAM lithospheric structure based largely on USArray data. These are S-wave velocities at a depth of 150 km from the tomographic model of Porter et al. (2016), estimates of Moho depths derived from P-to-S receiver function (RF) analysis (Li et al. 2020, 2023), electrical conductivity values at a depth of 150 km from the model of Munch & Grayver (2023), and lithospheric thickness estimates from the WINTERC-G model of Fullea et al. (2021). Taken together, these reveal intriguing lateral variations in lithospheric properties, including marked contrasts between the continental interior and its edge and variability along the strike of the margin. Seismic tomography (Porter et al. 2016) (**Figure 3*a***) reveals high velocities in the continental interior to the west, suggesting thick lithosphere, with generally lower velocities to the east, implying thinner lithosphere. Two prominent low-velocity anomalies are visible in this image, one centered beneath New England [the Northern Appalachian Anomaly or NAA (e.g., Menke et al. 2016)] and the other beneath the central Appalachians [the Central Appalachian Anomaly or CAA (e.g., Wagner et al. 2018)]. Estimates of Moho depths derived from TA data

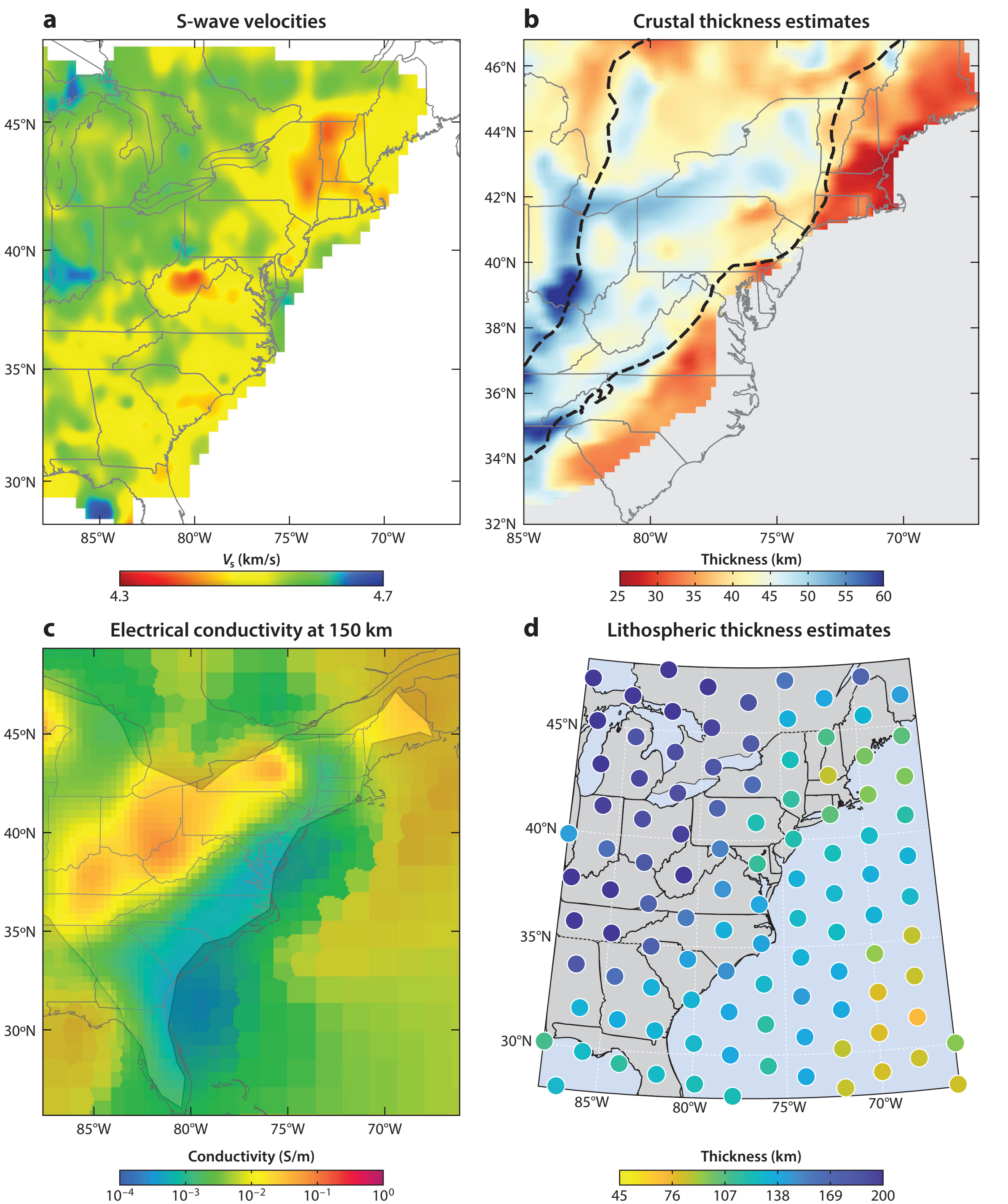

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Figure 3 (*Figure appears on preceding page*)

Regional-scale imaging of the eastern North American margin lithosphere. (*a*) Horizonal slice through an S-wave tomography model (Porter et al. 2016) at a depth of 150 km. (*b*) Map of depth to Moho from Ps receiver function analysis. Panel adapted with permission from Li et al. (2023). (*c*) Horizontal slice through an electrical conductivity model at a depth of 150 km. Panel adapted with permission from Munch & Grayver (2023) (CC BY 4.0). (*d*) Map of lithospheric thickness estimates from the model of Fullea et al. (2021).

(Li et al. 2020) (**Figure 3*b***) also reveal marked lateral variability, with significantly thicker crust (∼45–50 km) in the west and a generally sharp transition to thinner crust (∼25–35 km) to the east. The lateral transition in crustal thickness generally coincides with the transition from Laurentian units to Appalachian accreted terranes (Li et al. 2018).

Imaging of electrical conductivity structure (**Figure 3*c***) provides a view of lithospheric properties that contrasts somewhat with that provided by seismic tomography (**Figure 3*a***). At a depth of 150 km, the model of Munch & Grayver (2023) shows a region of relatively high conductivity values in the western portion, perhaps corresponding to thin or altered (e.g., Evans et al. 2019) continental lithosphere, with the eastern portion of the margin displaying significantly lower conductivity values, which taken at face value would suggest thicker lithosphere (Murphy & Egbert 2017). This difference between the electrical and seismic views of the eastern North American lithosphere represents an interesting puzzle (Murphy & Egbert 2019, Munch & Grayver 2023). Estimates of lithospheric thickness from the global WINTERC-G model (Fullea et al. 2021) (**Figure 3*d***), which include constraints from surface wave dispersion as well as from gravity, topography, and heat flow measurements, show a first-order difference between the thicker Laurentian lithosphere to the west and thinner Appalachian lithosphere to the east.

Several studies have provided a comprehensive view of upper mantle anisotropy, as expressed in SKS splitting measurements, beneath the ENAM margin (e.g., Long et al. 2016, Yang et al. 2017). SKS splitting beneath continents may reflect multiple contributions, including from the lithospheric mantle (corresponding to frozen-in structure from past deformation) and from the asthenosphere (due to present-day mantle flow). **Figure 4** shows SKS splitting from Long et al. (2016), who noted a first-order difference between the northern Appalachians, where measurements seem to reflect a primary contribution from plate motion parallel shearing in the asthenosphere, and the central and southern Appalachians, where fast directions often parallel local geological features, particularly the strike of Appalachian terranes. Long et al. (2016) and White-Gaynor & Nyblade (2017) both noted the striking rotation in fast splitting directions in Pennsylvania, following the bend in the Appalachian orogen around the Pennsylvania salient, and interpreted this observation as reflecting vertically coherent deformation of the mantle lithosphere during Appalachian orogenesis (Silver 1996), suggesting mechanical coupling between crust and mantle.

4. SUBDUCTION, TERRANE ACCRETION, AND OROGENESIS AS MODIFIERS OF ENAM LITHOSPHERE

4.1. History of Subduction and Terrane Accretion

ENAM has undergone two major subduction and orogenic cycles over the past ∼1.3 Ga, with the Mesoproterozoic Grenville orogeny culminating in the formation of the Rodinia supercontinent and the Paleozoic Appalachian orogeny culminating in the formation of Pangea. The western portion of ENAM (**Figure 1*a***) is made up of terranes of the Grenville orogenic belt (e.g., Whitmeyer & Karlstrom 2007, Swanson-Hysell et al. 2023). Here I use the term Laurentia to refer to the units that compose what is now North America, prior to Paleozoic terrane accretion during the Appalachian orogeny.

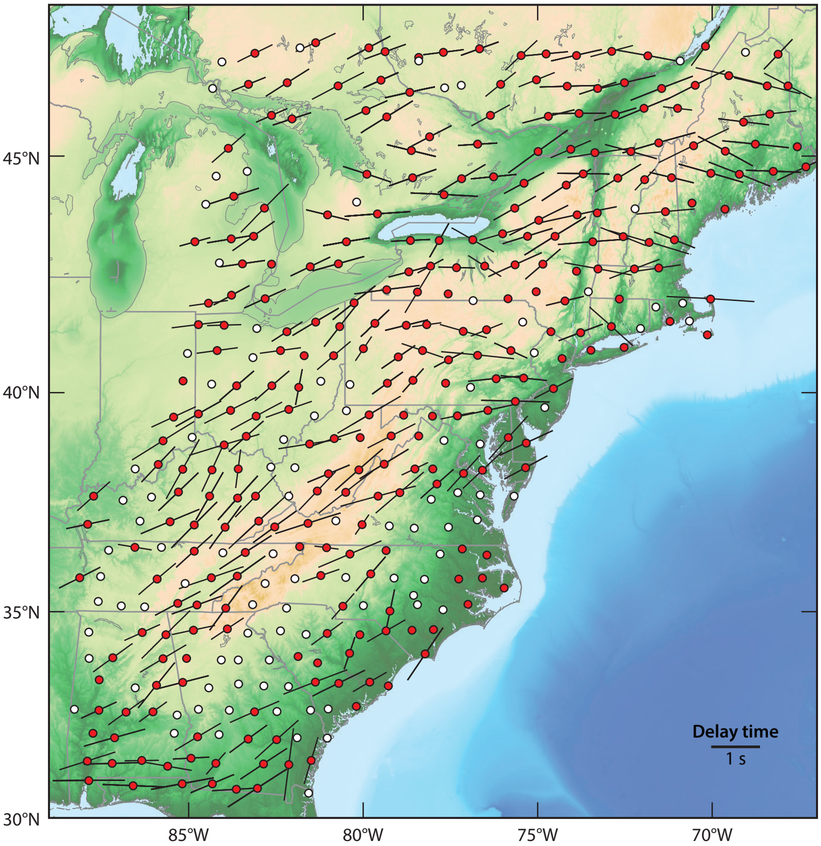

Figure 4

Map of single-station average SKS splitting parameters at Transportable Array stations in eastern North America. Parameters are plotted at station locations as a bar whose orientation is aligned with the fast direction and length is scaled to the delay time (see scale at *bottom right*). Stations for which Long et al. (2016) measured at least five null SKS arrivals, with no high-quality split arrivals, are shown with white circles; other stations are shown with red circles. Figure adapted with permission from Long et al. (2016).

Appalachian orogenesis encompassed multiple phases, each of which involved terrane accretion onto the edge of Laurentia but which varied significantly along the margin in terms of timing, subduction polarity, topographic expression, and the nature of accreted terranes. The main phases of Appalachian orogenesis were the Taconic (Ordovician), Acadian–Neoacadian (Late Devonian–Early Mississippian), and Alleghanian (Late Mississippian–Permian) orogenies (Hatcher 2010). The Taconic orogeny involved the accretion of peri-Gondwanan arc terranes, such as the Moretown terrane in New England (Macdonald et al. 2014), while the Acadian and Neoacadian orogenies involved the accretion of the Carolina and Ganderia terranes (in the southern and central Appalachians) and the Ganderia, Avalon, and Meguma terranes (in the northern Appalachians) (Hatcher 2010). During the Alleghanian orogeny, Gondwana collided with Laurentia to form Pangea, whose assembly was complete by ∼270 Ma. While this general outline of Appalachian tectonics is well understood, many of the details of these events remain obscure, including the polarity of some subduction episodes, the lateral extent of deformation, the controls on along-strike variability, and the configuration of various terranes at depth. Furthermore, it is unclear to what extent incoming continental masses such as the Carolinia, Ganderia, Avalon, and Meguma terranes were accreted with intact blocks of subcontinental lithospheric mantle. Did the lithospheric mantle that underlies the accreted Appalachian terranes today originate with the terranes themselves, or were the crustal portions of these terranes overthrust onto Laurentian lithosphere? New views of ENAM lithospheric structure have the potential to shed light on these unanswered questions.

4.2. Appalachian Versus Grenville Lithosphere: Distinct Lithospheric Histories?

Regional-scale seismic tomography (e.g., Porter et al. 2016, Boyce et al. 2019) suggests a first-order difference between relatively thick lithosphere beneath the Laurentian continental core, including beneath the Grenville Province, and relatively thin lithosphere beneath the Appalachian accreted terranes (**Figure 3**). This pattern is also borne out in global lithospheric models (e.g., Priestly et al. 2019, Fullea et al. 2021) and in RF studies; for example, Rychert et al. (2005) argued for thin (~90 km) lithosphere beneath Appalachian domains in the northeastern United States. A continent-scale RF imaging study by Hopper & Fischer (2018) also argued for a shallow (~60–70 km) lithosphere–asthenosphere boundary (LAB) beneath the northeastern United States, with a transition to thicker (~150 km) lithosphere beneath Laurentia. Some regional studies have also argued for a transition in lithospheric thickness from Laurentian to Appalachian domains; for example, Goldhagen et al. (2022) used Sp RF analysis to document a clear transition in lithospheric structure across the Laurentian suture in southern New England.

What are the implications of this observation? It is likely that this contrast reflects differences in the fundamental tectonic processes associated with the Grenville versus Appalachian orogenies, differences in lithospheric rheology, or a combination of these effects. One possibility is that the Appalachian lithosphere evolved differently during orogenesis than did its Grenville counterpart; perhaps Appalachian lithosphere never thickened to the extent that Grenville lithosphere did during continental collision. Another possibility is that the continental lithosphere that underlies Appalachian accreted terranes today might represent lithosphere that is, in fact, Laurentian in origin. One plausible scenario is that the lithosphere at the edge of Laurentia was thinned by extension and rifting during the breakup of Rodinia, and that Appalachian terrane accretion involved the emplacement of crustal blocks on top of this thinned, extended lithosphere. A third possible scenario is that Appalachian lithosphere was thinned either during Appalachian orogenesis or after the assembly of Pangea, perhaps via the gravity-driven detachment of the mantle lithospheric root (Levin et al. 2000, Whalen et al. 2015). Finally, Appalachian lithosphere may have been thinned during extension and rifting associated with the breakup of Pangea.

4.3. Geophysical Signatures of Subduction and Accretion in Continental Lithospheric Structure

An exciting development from recent geophysical imaging studies beneath ENAM has been the clear identification of lithospheric structures linked to past episodes of subduction and terrane accretion. These preserved structures allow us to study processes associated with past tectonic events in detail and can sometimes provide specific tests of predictions made by competing models of past tectonic episodes. Importantly, while many insights have come from regional-scale imaging studies (**Figure 3**), others have come from dense deployments (**Figure 1*b***) that have enabled imaging of both the crust and the lithospheric mantle on the length scales that are relevant for bedrock geological structures.

Evidence for wholesale modification of lithospheric structure via metasomatism during the Grenville orogeny was presented by Boyce et al. (2019), whose absolute P-wave velocity model of the eastern North American upper mantle features particularly good resolution in eastern Canada.

They note that despite the generally uniform thickness of Grenville lithosphere throughout the margin, the mantle lithosphere displays substantially faster than average P-wave velocities to the north beneath Canada, and slower than average to the south. However, S-wave models do not show a similar pattern (e.g., Priestly et al. 2019). Boyce et al. (2019) explained these observations with a model in which the composition of southern Grenville lithosphere was modified via metasomatism and orthopyroxene enrichment (e.g., Wagner et al. 2008) during the protracted subduction that accompanied the Grenville orogeny. They further hypothesized that the northern Grenville lithosphere was protected from metasomatic alteration by the old, thick, and stable Archean cratonic keel beneath this region. Metasomatic alteration of ENAM lithosphere was also explored by Gao & Li (2021), who identified intralithospheric low-velocity layers that they attributed to metasomatism.

While tomographic imaging beneath ENAM suggests wholesale, regional alteration of portions of the mantle lithosphere, high-resolution converted wave imaging has yielded evidence for localized lithospheric modification associated with terrane accretion or suturing. Hopper et al. (2017) applied Sp RF imaging to data from the SESAME array in the southern Appalachians (**Figure 1*b***) and found evidence for a dipping mid-crustal interface (**Figure 5**) that they interpreted as the Alleghanian suture associated with the final phase of the Appalachian orogeny. The style of continental collision during the final assembly of Pangea beneath the southern Appalachians had been debated; however, Hopper et al. (2017) showed that collision must have been nearly orthogonal to the margin, rather than oblique or transpressional. Another example of a relict lithospheric structure from a past collisional orogen comes from the MAGIC array in the central Appalachians; Long et al. (2019) used Ps RF imaging (**Figure 5**) to argue for a radially anisotropic shear zone in the mid-crust beneath Ohio and West Virginia, which they interpreted as corresponding to the crustal detachment of the Grenville deformation front.

Figure 5 compares images of crustal structures in the ENAM lithosphere due to Grenville (Long et al. 2019) and Appalachian (Hopper et al. 2017) collision with an image of the main Himalayan thrust (Schulte-Pelkum et al. 2005), the prime modern example of a continental collision. The notable similarity in structure, with gently dipping shear zones shallowing into nearly flat mid-crustal detachments, was noted in studies by Hopper et al. (2017) and Long et al. (2019). Both studies pointed out the apparent persistence of similar styles of crustal deformation (and, by inference, similar crustal rheologies) in continental collisional settings over ~1 Ga of Earth history. These images illuminate the processes through which crustal blocks are amalgamated during continental collision, highlighting the importance of mid-crustal structures in localizing shear as crustal blocks are juxtaposed and subjected to shortening. It is far less clear, however, how the underlying mantle lithosphere is affected during continental collisions and whether strain localization acts similarly at mantle depths; this represents a key outstanding question.

An exceptional example of structures preserved in continental lithosphere from past subduction episodes comes from southern New England, where the SEISConn experiment (**Figure 1*b***) was deployed with ~10-km station spacing, enabling high-resolution imaging of the crust and mantle lithosphere. **Figure 6** shows an image of the lithosphere beneath southern New England, based on common conversion point stacking of Ps RF traces (Luo et al. 2021). Of particular interest is how the structures imaged in the lithosphere at depth relate to the terrane boundaries at the surface, particularly the sutures between Laurentia and its adjacent terrane to the east (the Moretown terrane, accreted during the Taconic orogeny) and the Avalon terrane (accreted during the Acadian orogeny) and its adjacent terrane to the west (the Putnam-Nashoba terrane). A prominent, west-dipping negative velocity gradient (NVG) in the mid-crust (#3 in **Figure 6**), whose shallowest

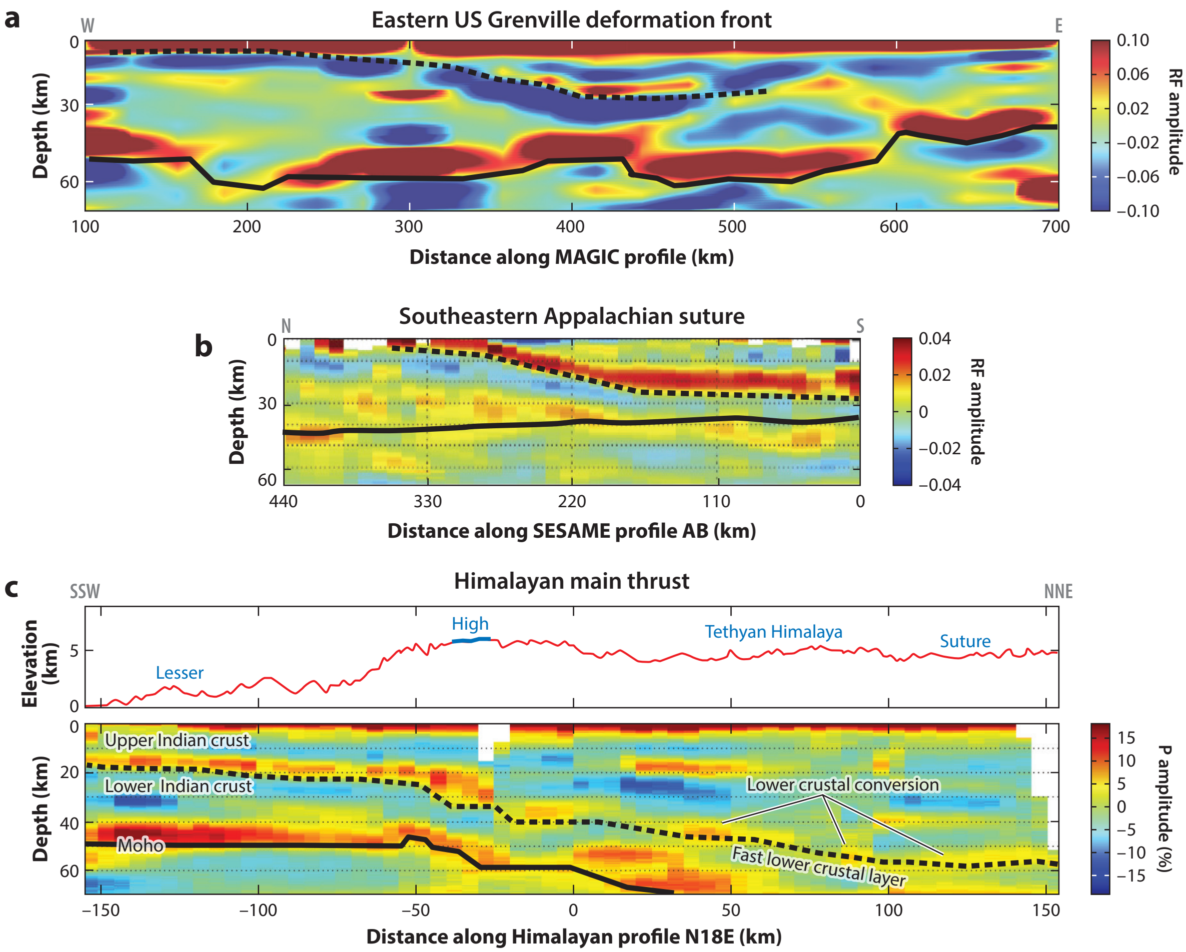

Figure 5

Comparison of geophysical images of continental sutures in the lithosphere from ancient and modern collisional settings. (*a*) Interpreted CCP Ps RF image of the inferred Grenville mid-crustal shear zone beneath Ohio from the MAGIC experiment (**Figure 1*b***). Panel adapted with permission from Long et al. (2019). (*b*) Interpreted CCP Sp RF image of the Alleghanian suture beneath the southeastern United States from the SESAME experiment (**Figure 1*b***). Panel adapted with permission from Hopper et al. (2017). (*c*) Ps CCP RF image of the main Himalayan crustal detachment, representing a comparison with a modern orogen. Seismic station names are at the top. Panel adapted from Schulte-Pelkum et al. (2005) with permission from Springer Nature. In each panel, the solid black line indicates the Moho interface and the dashed black line highlights the likely mid-crustal shear zone. Colors indicate the relative amplitude of the converted phases, as indicated by the color bars at right. Abbreviations: CCP, common conversion point; MAGIC, Mid-Atlantic Geophysical Integrative Collaboration; RF, receiver function; SESAME, Southeastern Suture of the Appalachian Margin Experiment. Figure by Scott King.

point corresponds approximately to the surface expression of the Avalon suture, was interpreted as a possible crustal shear zone associated with Avalon accretion. A deeper west-dipping NVG in the upper mantle (#5 in **Figure 6**), which is also evident in wavefield migration imaging (Luo et al. 2022), likely reflects a relict slab Moho interface from a past subduction episode lodged in the high-viscosity lithosphere (Luo et al. 2021). Luo et al. (2021) hypothesized that this subduction event may have been associated with the final stage of Pangea assembly during the Alleghanian orogeny, suggesting west-dipping subduction.

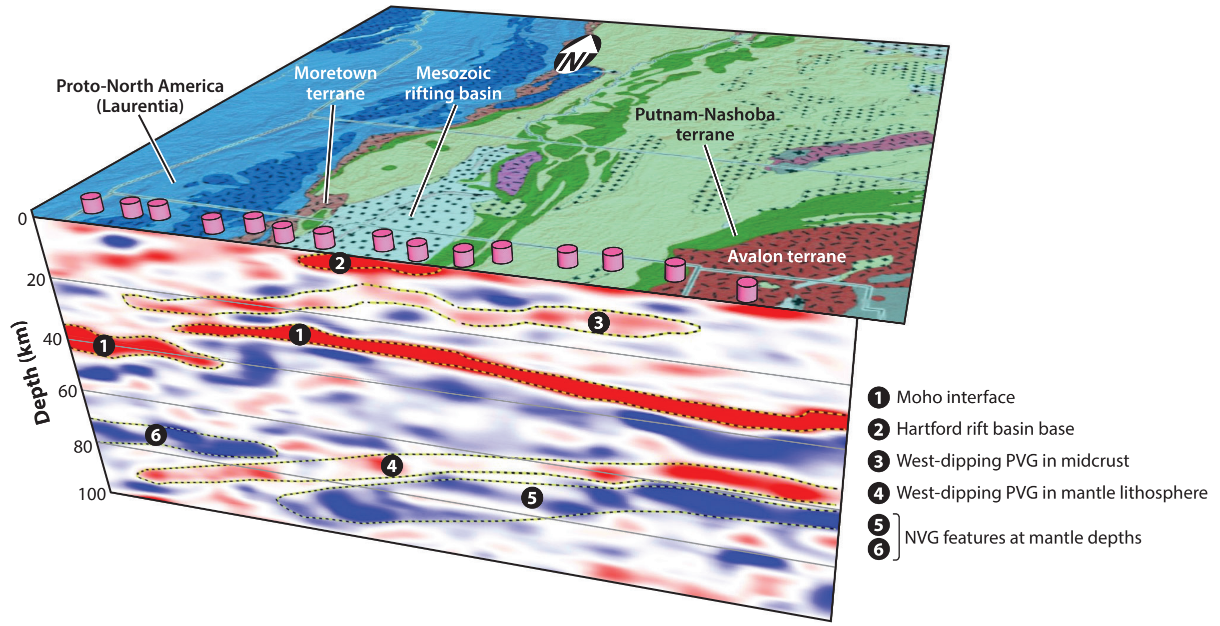

Figure 6

Image of the lithosphere beneath southern New England from the SEISConn project (**Figure 1*b***), derived from Ps receiver function analysis. The block diagram shows the Ps common conversion point image beneath bedrock geologic features (modified after Hibbard et al. 2006 and Karabinos et al. 2017). Red colors indicate positive impedance contrasts at depth, while blue colors indicate negative impedance contrasts. Key features are labeled, including the Moho interface (#1), the base of the Hartford sedimentary rift basin (#2), a west-dipping PVG in the mid-crust (#3), a west-dipping PVG in the mantle lithosphere (#4), and NVG features at mantle depths (#5 and #6) that may correspond to mid-lithospheric discontinuities, the base of the lithosphere, or other features. Abbreviations: NVG, negative velocity gradient; PVG, positive velocity gradient; SEISConn, Seismic Experiment for Imaging Structure beneath Connecticut. Figure adapted with permission from Luo et al. (2021).

Another prominent feature of the southern New England lithosphere is the transition from thick crust (~42 km) beneath Laurentia to thin crust (~28 km, gradually thickening to ~32 km to the east) beneath Appalachian terranes (**Figure 6**). This sharp transition from thick Laurentian to thin Appalachian crust was noted by Li et al. (2018, 2020), who posited the existence of a step in the Moho at the edge of Laurentia beneath southern New England and extending as far south as Pennsylvania. With the substantially denser station spacing of SEISConn (~10 km as opposed to ~70 km for the TA stations), Luo et al. (2021, 2022) were able to image this transition from Laurentian to Appalachian crust as an overthrust-type structure (**Figure 6**), with overlapping shallow and deep interfaces, rather than a true vertical step. Masis Arce & Long (2023) recently found evidence for a very similar Moho geometry beneath stations of the NEST array in northwestern Massachusetts. Hillenbrand et al. (2021) and Hillenbrand & Williams (2021) suggested that the Moho step beneath southern New England may have formed due to the rise and subsequent collapse of an orogenic plateau (the so-called Acadian Altiplano) associated with the Acadian orogeny. In this model, the Laurentian crust acted like a buttress during Acadian compression (Wintsch et al. 2014), with presumably weaker Appalachian crust undergoing shortening and thickening. Luo et al. (2023a) generally supported this interpretation, also invoking significant Acadian compression and shortening as a mechanism for forming the distinctive Moho offset. However, they pointed out that movement on reactivated thrust faults (Taconic or earlier) at depth in the crust may have been necessary to form the distinctive overthrust-like geometry (**Figure 6**). The models of Hillenbrand et al. (2021) and Luo et al. (2023a) highlight the importance of orogenic processes, rather than the simple juxtaposition of blocks with preexisting differences in crustal thickness, in shaping crustal structure beneath ENAM.

Luo et al. (2023a) compared the geometry of the Laurentian-Appalachian crustal transition beneath the SEISConn line to that beneath the MAGIC line in the central Appalachians and the SESAME lines in the southern Appalachians (**Figure 1*b***), using a scattered wave migration imaging approach. They found that while a lateral transition in crustal thickness is present throughout the margin, this transition is gradual beneath the central and southern Appalachians and is only sharp beneath southern New England. This finding mirrors the well-known along-strike differences in the timing and style of Appalachian orogenic and terrane accretion events (e.g., Hatcher 2010) and highlights the importance of past subduction and terrane accretion as processes that control the crustal structure of the ENAM passive margin. Importantly, Luo et al. (2023a) documented a lack of striking differences in depth to Moho beneath individual Appalachian terranes, despite their different formation and accretionary history. It is likely that multiple episodes of subduction and terrane accretion, and/or later extension during continental breakup, played a role in smoothing out any preexisting differences in crustal thickness across adjacent terranes that were juxtaposed during Appalachian orogenesis.

4.4. Crustal Deformation During Terrane Accretion and Orogenesis

Recently obtained constraints on crustal anisotropy from dense arrays have yielded exciting new insights into crustal deformation during terrane accretion and orogenesis. High-resolution imaging of crustal anisotropy using RF analysis, and its interpretation in terms of past or ongoing crustal deformation, is a frontier area (e.g., Schulte-Pelkum & Mahan 2014, Brownlee et al. 2017). Frothingham et al. (2022) used data from the SESAME array (**Figure 1*b***) to identify an anisotropic interface within the crust at ∼5–10 km depth beneath the southern Appalachians, corresponding to the Appalachian décollement. They noted a systematic offset between the inferred geometry of anisotropy at depth and the tectonic grain at the surface, evidence for crustal deformation oblique to the overlying structural fabric. This work demonstrates the power of crustal anisotropy observations as a tool for understanding the kinematics of past tectonic events in collisional orogens and, more generally, as a tool for gaining insights into the geometry and extent of deformation at different depth ranges in the crust. Luo et al. (2023b) carried out a similar study in the northern Appalachians using stations from SEISConn (**Figure 1*b***) and identified multiple robust intracrustal interfaces that involve contrasts in anisotropic structure. They argued for an anisotropic layer within the crust that reflects crustal deformation and shortening during Appalachian terrane accretion, and another, deeper crustal layer that may reflect orogen-parallel ductile flow of mid-crustal rocks during the collapse of the hypothesized Acadian altiplano (Hillenbrand et al. 2021).

5. EFFECTS OF RIFTING ON ENAM LITHOSPHERE: MAGMATISM AND LITHOSPHERIC THINNING

5.1. History of Rifting, Extension, and CAMP Emplacement

Roughly 30–40 Myr after the final assembly of Pangea at ∼270 Ma, a continental rift zone was established (e.g., Withjack et al. 2020), evidence of which is preserved today in ENAM as a series of rift basins. Rifting was accompanied by the emplacement of CAMP (e.g., Holbrook & Kelemen 1993, Blackburn et al. 2013), a large igneous province (LIP) that was emplaced over a period of less than one million years at 201 Ma. It is the most aerially extensive LIP on Earth and one of the largest in terms of the volume of magma produced (e.g., Marzoli et al. 1999, Blackburn et al. 2013). CAMP emplacement postdates the onset of rifting in ENAM but predates the breakup of Pangea and the rift-drift transition, which was complete by ∼180 Ma (e.g., Withjack et al. 2012, 2020; Frizon de Lamotte et al. 2015). CAMP expresses itself as a series of basalt dikes, sills, and flows; the flows are generally colocated with the onshore rift basins and are often interbedded with sedimentary rift strata (Jourdan et al. 2009) (**Figure 1*a***). Much of ENAM exhibits so-called seaward-dipping reflectors (SDRs) (e.g., Benson 2003) at the continent-ocean boundary; these features are thought to be volcanic in origin, formed during the transition from continental rifting to true seafloor spreading. In the northernmost part of ENAM, however, SDRs are absent, indicating magma-poor rifting (e.g., Withjack et al. 2020).

5.2. Modification of Continental Lithosphere from Rifting-Associated Magmatism

A key recent finding is evidence for the modification of lithospheric structure (particularly the mid-to-lower crust) via the emplacement of CAMP magmatic products and the spatial correlation between these modified areas and sedimentary rift basins. Marzen et al. (2019, 2020) processed data from the SUGAR wide-angle seismic reflection/refraction experiment in the South Georgia Basin (**Figure 1*b***), providing detailed images of its deep structure. Marzen et al. (2020) identified regions of particularly fast lower crust ($V_p > 7.0$ km/s) beneath the rift basin and interpreted them as evidence for magmatic addition of mafic material (e.g., Thybo & Artemieva 2013) during CAMP emplacement (**Figure 7*a***). Strikingly, the magmatic additions are relatively modest in volume and are localized to portions of the basin with the most crustal thinning and thickest syn-rift sediments. Marzen et al. (2020) noted the contrast between the widespread distribution of CAMP dikes throughout ENAM at the surface and the localized nature of lower crustal magmatic intrusions in the South Georgia Basin. They found the spatial correlation between the mafic intrusions and the rift basin itself somewhat surprising, given that CAMP magmas were emplaced after, and not during, the formation of the rift; this suggests a relationship between lithospheric thinning during rifting and extension and later magmatic emplacement.

Gao et al. (2020) applied a different type of data analysis to the Hartford Basin in southern New England to reach a similar conclusion to that of Marzen et al. (2020). They used data from the SEISConn experiment (**Figure 1*b***) to generate a tomographic model of crustal shear velocities based on ambient seismic noise (**Figure 7*b***). They identified a region of particularly fast velocities in the mid-to-lower crust beneath the Hartford Basin, corresponding spatially to the thinnest crust beneath the SEISConn transect. They concluded that, like the South Georgia Basin, the Hartford Basin experienced lower crustal modification via the emplacement of mafic intrusions during CAMP magmatism, with modification localized to the crust beneath the basin itself. A somewhat puzzling conundrum in southern New England, pointed out by van Staal & Zagorevski (2023), is the fact that while there is evidence for CAMP magmatism locally altering the structure of the lower crust beneath the Hartford Basin (Gao et al. 2020), there is no evidence that rifting-associated processes have overprinted the signature of Appalachian processes in the lithosphere (Luo et al. 2021). Strikingly, Appalachian structures such as crustal shear zones, relict slab interfaces, and the Moho overthrust beneath the edge of Laurentia remain preserved in the lithosphere today (Luo et al. 2021, 2022), despite the magmatic emplacement that accompanied rifting (Gao et al. 2020).

Taken together, these studies suggest that CAMP intrusions in the lower crust beneath ENAM are localized beneath sedimentary rift basins, implying that rifting, extension, and lithospheric thinning played an important role in focusing upwelling and melt generation during LIP emplacement (e.g., White & McKenzie 1995). A different view of the extent to which CAMP magmatism modified the lithosphere comes from the work of Murphy & Egbert (2017, 2019). They identified a highly electrically resistive feature in the upper mantle beneath the southeastern United States,

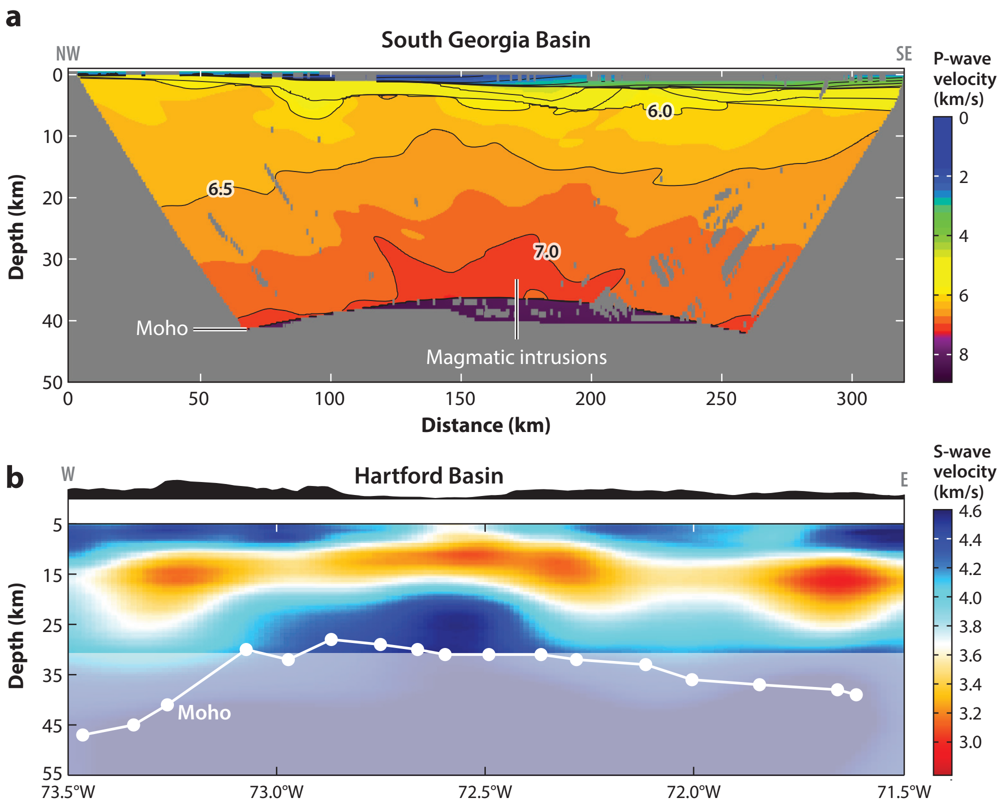

Figure 7

Examples of lithospheric modification via CAMP volcanism. (*a*) P-wave velocity model beneath the western SUGAR line (**Figure 1*b***). Colors and labeled contours indicate P velocity values, with the inferred magmatic intrusions indicated. Panel adapted with permission from Marzen et al. (2020) (CC BY 4.0). (*b*) S-wave velocity model beneath the SEISConn line (**Figure 1*b***). Colors indicate S velocity values; the white line indicates the location of the Moho as inferred from receiver function analysis (Luo et al. 2021). Panel adapted with permission from Gao et al. (2020). Abbreviations: CAMP, Central Atlantic Magmatic Province; SEISConn, Seismic Experiment for Imaging Structure beneath Connecticut; SUGAR, SUwanee Suture and GA Rift basin.

also visible in other models of mantle conductivity structure (**Figure 3*c***), corresponding to a region with extensive CAMP dikes (**Figure 1*a***). They interpreted this as evidence for thick (>200 km) lithosphere beneath this portion of the ENAM margin; as discussed above, this view contrasts with the prevailing interpretation of seismic tomography images (**Figure 3**). Murphy & Egbert (2017, 2019) proposed that this electrical feature represents a regrown lithospheric root that postdates a major lithospheric loss event across ENAM that prompted the generation of CAMP magmatism (Whalen et al. 2015). In this view of CAMP generation, melting was triggered not by a mantle plume but by widespread mantle upwelling that resulted from a pan-Appalachian lithospheric delamination event (Whalen et al. 2015; see also Biryol et al. 2016). In the model of Murphy & Egbert (2017, 2019), CAMP played a major role in the wholesale modification (via loss and regrowth) of mantle lithosphere beneath the southeastern United States, rather than playing a more minor and localized role (Gao et al. 2020, Marzen et al. 2020). Eilon et al. (2023) also postulated that CAMP may have modified lithospheric structure beneath the southeastern United States, noting the geographical coincidence between relatively slow average lithospheric velocities in their tomographic model and the distribution of CAMP dikes at the surface.

5.3. Modification of Lithosphere via Extension and Thinning During Continental Breakup

Continent-scale imaging (e.g., Porter et al. 2016, Boyce et al. 2019, Fullea et al. 2021) suggests generally thicker lithosphere beneath Laurentia and generally thinner lithosphere beneath Appalachian terranes [although some aspects of electrical conductivity models are not obviously consistent with that view (e.g., Murphy & Egbert 2017)]. An important question is to what extent the apparently thinner Appalachian crust and mantle lithosphere (**Figure 3**) represent wholesale thinning via extension during continental breakup. This would provide a straightforward explanation for thinner lithosphere beneath easternmost North America; however, it is not obvious how extensional deformation might partition between the crust and mantle lithosphere. Some modeling studies suggest that while crust may undergo wholesale thinning during extension associated with continental breakup, extensional deformation in the mantle may be localized to shear zones (e.g., Harry & Sawyer 1992, Withjack et al. 2020). Of course, the distribution of extensional strain throughout the lithosphere depends strongly on the rheological structure, which is imperfectly known (e.g., Warren & Hansen 2023) and which may vary laterally.

Important new constraints on the extent of lithospheric alteration via extension and rifting, and the nature of lithospheric modification during the rift-to-drift transition, have come from imaging results based on the onshore-offshore ENAM CSE (**Figure 1*b***) using a range of analysis methods (Lynner & Porritt 2017, Shuck et al. 2019, Brunsvik et al. 2021, Li & Gao 2021, Russell & Gaherty 2021). Russell & Gaherty (2021) identified a low-velocity lid in the uppermost mantle beneath the offshore region and interpreted this feature as stretched, extended continental mantle lithosphere. Both Lynner & Porritt (2017) and Li & Gao (2021) imaged the transition from continental crust to oceanic crust across the passive margin, finding evidence for a region of modified, transitional crust that was likely underplated by dense magmatic material.

Observations of mantle lithospheric anisotropy beneath the eastern portion of ENAM may potentially record deformation due to extension and thinning, if the amount of strain was sufficient to overprint any existing fabric resulting from prior tectonic processes. Based on the inversion of SKS splitting observations (Lynner & Bodmer 2017), Brunsvik et al. (2021) argued that the continental mantle lithosphere in the ENAM CSE region exhibits azimuthal anisotropy with a margin-perpendicular fast direction that records the direction of extension during Pangea breakup; in contrast, the deeper asthenospheric mantle exhibits a margin-parallel signature. Russell & Gaherty (2021), however, argued for a margin-parallel fast anisotropy direction in the lithosphere and suggested that anisotropy is controlled not by paleoextension but by absolute plate motion at the time of plate formation. Aragon et al. (2017), who analyzed SKS splitting beneath the MAGIC array, hypothesized that the nearly E-W fast splitting directions observed at stations east of the Appalachian Mountains might reflect lithospheric anisotropy due to extension during Pangea breakup.

6. POSTRIFT MODIFICATION OF ENAM LITHOSPHERE: LITHOSPHERIC LOSS, SMALL-SCALE CONVECTION, AND PLUME INTERACTIONS

6.1. Postrift History of ENAM: Volcanism and Topographic Rejuvenation

ENAM exhibits abundant evidence for lithospheric modification that postdates its last major tectonic event, the breakup of Pangea. It therefore presents a fascinating case study for lithospheric modification that is unrelated to classical plate tectonic processes such as subduction and rifting. Several aspects of ENAM's behavior and evolution have led authors to jokingly refer to it as a passive-aggressive margin, including its relatively abundant seismicity (Wolin et al. 2012) and its rich history of intraplate volcanism (Mazza et al. 2017).

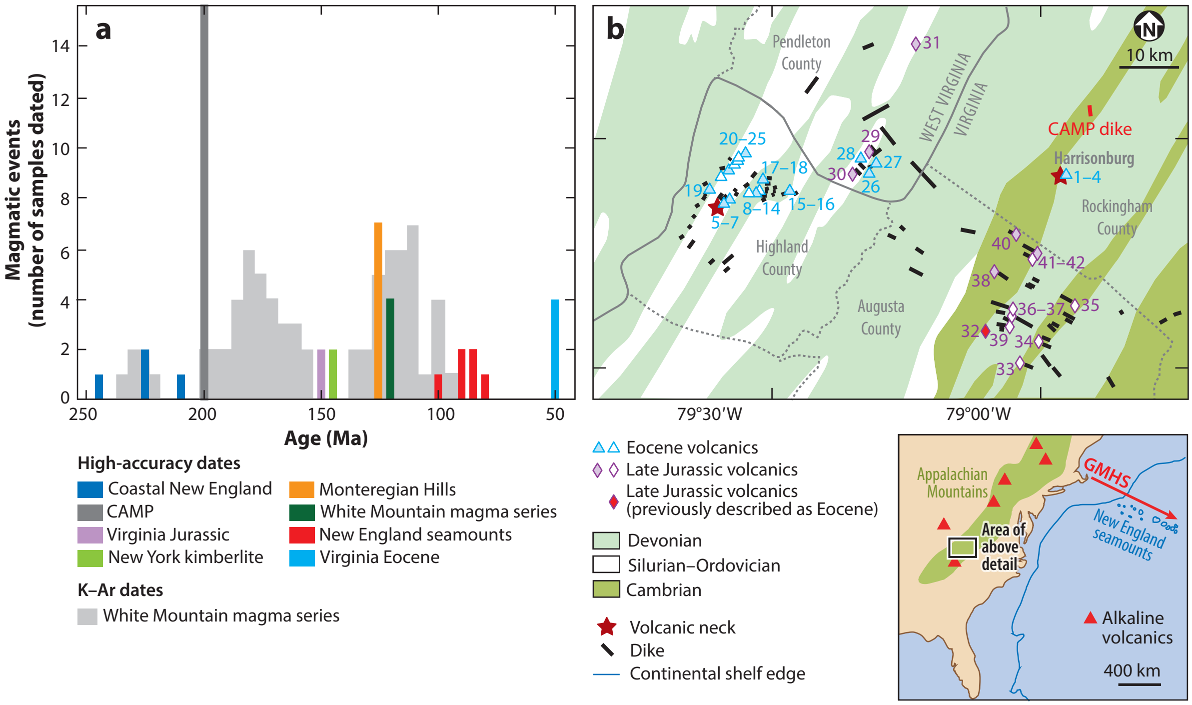

Figure 8

Summary of post-CAMP volcanism in ENAM. (*a*) Histogram showing dates of ENAM magmatic events; details of underlying data are given by Mazza et al. (2017). (*b*) Map of volcanic features in the central Appalachians, as indicated by the legend, which hosted pulses of intraplate magmatic activity during the Jurassic and Eocene. (*inset*) Map of distribution of intraplate volcanics throughout ENAM. The red arrow shows the path of the GMHS. Abbreviations: CAMP, Central Atlantic Magmatic Province; ENAM, eastern North American margin; GMHS, Great Meteor Hotspot. Figure adapted with permission from Mazza et al. (2017).

ENAM has exhibited widespread intraplate magmatic activity (Mazza et al. 2017) (**Figure 8**). This history encompasses the White Mountain magma series (WMMS) in central New England just after Pangea breakup, pulses of magmatism during the Jurassic and Eocene in the central Appalachians, kimberlite eruptions in New York around 145 Ma, and the New England-Québec Igneous Province around 125 Ma. Kinney et al. (2022) presented high-precision dates for WMMS plutons, showing that some magmatic activity in the White Mountains actually predates CAMP and that the main phase of WMMS magmatism was emplaced over a relatively short time frame of ∼20 Ma. Kinney et al. (2021) obtained high-precision dates for units of the New England-Québec Igneous Province, associated with the Great Meteor Hotspot (GMHS), and showed that the spatiotemporal progression on land is substantially less clear than for the New England Seamounts, thought to represent their offshore continuation. The anomalous Eocene volcanism (∼48 Ma) in the central Appalachians was studied in detail by Mazza et al. (2014). The expression of this volcanic swarm, consisting of dikes and volcanic necks (**Figure 8**), is colocated with the earlier pulse of magmatic activity during the Jurassic (∼150 Ma) (Mazza et al. 2017). There is little evidence for a time-progressive plume track associated with the central Appalachian intraplate volcanism, in contrast to the GMHS track in New England [although some have argued otherwise (Chu et al. 2013)].

ENAM also has a substantial history of topographic rejuvenation that may point to lithospheric modification at depth driving episodes of increased uplift. Pazzaglia & Brandon (1996) documented multiple postrifting episodes of increased sedimentation offshore of the central and northern Appalachians, implying temporarily faster erosion rates. Miller et al. (2013) estimated erosion rates in the central Appalachians through the application of stream profile analysis, applying a model calibrated with cosmogenic nuclide dates that explicitly accounts for lateral variability in rock erodibility. They argued for a period of recent (Neogene) rejuvenation of central Appalachian topography, perhaps linked to changes in mantle dynamics; any dynamic contribution to topography would be mediated by lithospheric structure (e.g., Moucha et al. 2008). Amidon et al. (2016) identified a period of accelerated erosion in the White Mountains of New England between ~65 and 85 Ma, noting its temporal coincidence with a pulse of increased offshore sedimentation in the Baltimore Canyon Trough.

This postrifting magmatic activity and episodes of topographic rejuvenation suggest modification of ENAM lithosphere over the past 200 Ma, with New England and the central Appalachians being particularly relevant. Intriguingly, both areas are associated with significant present-day geophysical anomalies in the upper mantle (the NAA and CAA, respectively). Both regions provide fascinating windows into lithospheric modification via nonplate tectonic processes such as gravity-driven lithospheric loss, edge-driven convection, and plume-lithosphere interaction.

6.2. The Central Appalachian Anomaly: Episodic Lithospheric Loss Beneath ENAM

Long et al. (2021) evaluated models for lithospheric loss by synthesizing a full suite of constraints from the CAA region, including seismic and electromagnetic imaging (much of it from the MAGIC experiment), petrologic and geochemical measurements, and geomorphologic analysis. These included thermobarometric estimates of the depths and temperatures at which the Eocene melts were produced (Mazza et al. 2014), which argue for relatively shallow (~75–80 km) melting at a temperature (~1,410°C) that is only slightly higher than is usual for decompression melting beneath a mid-ocean ridge. The geochemical signature of Eocene magmas was found to be typical of normal sub-Atlantic mantle, inconsistent with a mantle plume (Mazza et al. 2014). Long et al. (2021) also extended the channel steepness modeling of Miller et al. (2013) to understand spatial patterns in present-day erosion rates throughout the central and southern Appalachians, identifying a region of faster erosion that coincides spatially with the upper mantle anomaly.

The CAA is very well imaged by geophysical methods, including a combination of seismic tomography (e.g., Wagner et al. 2018), seismic attenuation measurements (Byrnes et al. 2019), and magnetotelluric observations combined with RF measurements (Evans et al. 2019). **Figure 9** shows a selection of geophysical images of the CAA from Long et al. (2021). There are multiple lines of evidence that the continental lithosphere in the CAA region is thin, with a total lithospheric thickness of ~70–90 km (of which ~50 km is crust) (Long et al. 2019). Long et al. (2021) tested the predictions of several models for lithospheric evolution in the CAA region, including a gravity-driven lithospheric loss model, against the full suite of observational constraints. Their preferred model invokes a lithospheric loss event during the Eocene (Mazza et al. 2014), resulting in upwelling return flow, melting, and volcanism (**Figure 9**). Ongoing processes in the upper mantle have allowed for the thin lithosphere to be maintained since the Eocene; small-scale convection and/or shear-driven upwellings likely play a role. Long et al. (2021) further hypothesized that gravity-driven lithospheric loss beneath the central Appalachians may be episodic, with an earlier occurrence during the Jurassic.

Joint interpretation of P- and S-wave travel times, seismic attenuation measurements (Byrnes et al. 2019), and electrical conductivity values (Evans et al. 2019) in the CAA region by Mittal et al. (2023) yielded evidence for ~1–2% partial melt in the uppermost mantle; however, there is

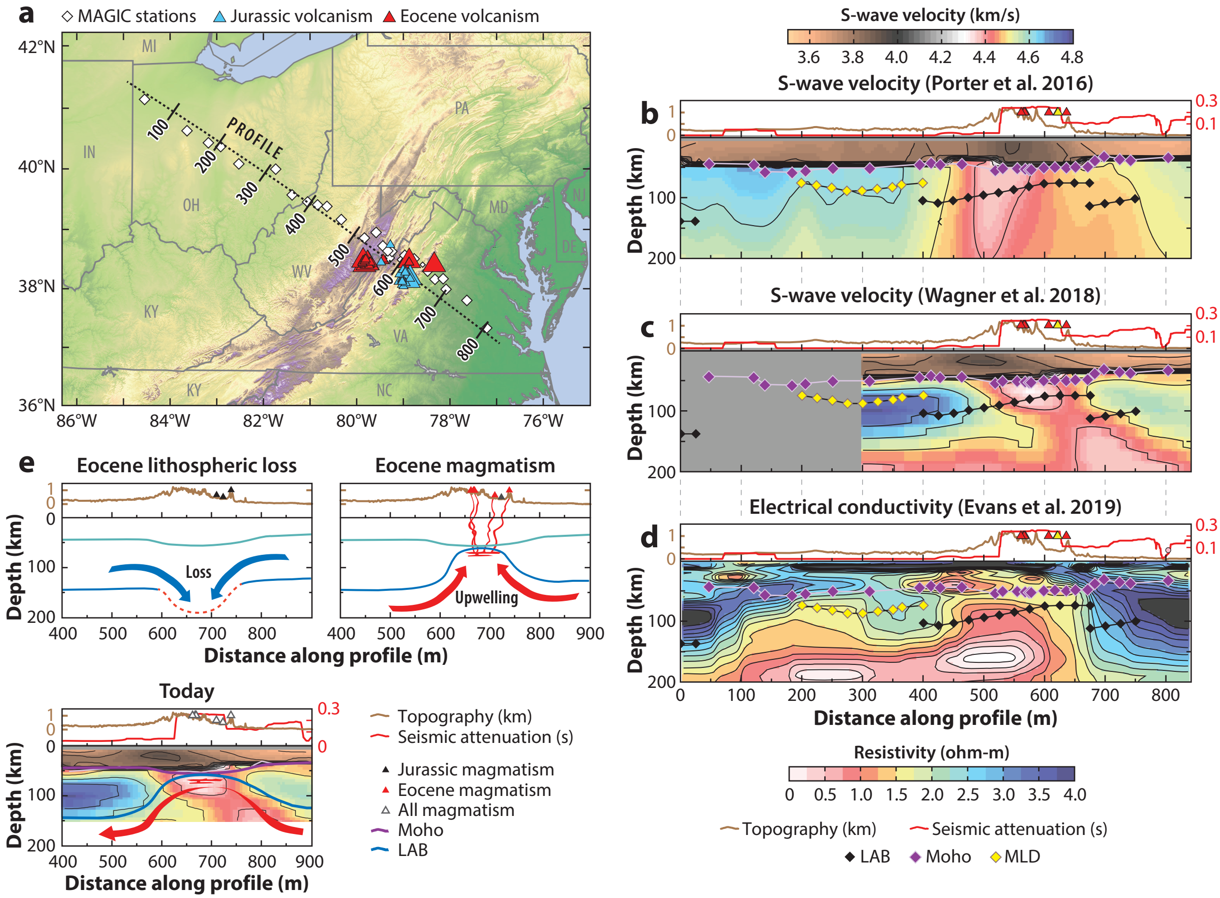

Figure 9

Imaging results, and corresponding interpretation, of the CAA. (*a*) Map of the MAGIC study area (**Figure 1*b***), with MAGIC station locations (*white diamonds*), locations of Jurassic (*blue triangles*) and Eocene (*red triangles*) volcanism, topography (*background colors*), and the profile location (*black dotted line*). (*b*) Cross section of the S-wave velocity model of Porter et al. (2016) along the profile, along with inferred LAB (*black diamonds*) from Sp RF analysis (Evans et al. 2019), Moho (*purple diamonds*) from Ps RF analysis (Long et al. 2019), MLD from Sp RF analysis (*yellow diamonds*), topography (*brown line at top*), seismic attenuation as expressed in t^* measurements (*red line at top*) from Byrnes et al. (2019), and locations of volcanics (as in panel *a*). (*c*) Same as panel *b* but with the velocity model of Wagner et al. (2018). (*d*) Same as panel *c* but with the electrical conductivity model of Evans et al. (2019); color scale is as shown in legend at bottom. (*e*) Schematic interpretation of the Eocene lithospheric loss event, subsequent upwelling and magmatism, and the present-day configuration of the CAA. Abbreviations: CAA, Central Appalachian Anomaly; LAB, lithosphere–asthenosphere boundary; MAGIC, Mid-Atlantic Geophysical Integrative Collaboration; MLD, mid–lithospheric discontinuity; RF, receiver function. Figure adapted with permission from Long et al. (2021) (CC BY-NC-ND 4.0).

no present-day volcanic activity. They hypothesized that the tectonic stress field may control the degree of melt accumulating beneath the continental LAB to migrate through the lithosphere, suggesting that the timescales and processes for lithospheric modification via melt migration may be controlled by the lithospheric stress state.

A key outstanding question is how general the processes of lithospheric loss and evolution that have operated in the central Appalachians might be. Do these processes operate broadly beneath passive continental margins and thus play a major role in the evolution of continental lithosphere in such settings? This represents an important unsolved problem, and understanding whether we can see evidence for similar lithospheric evolution in other passive margin settings is an important future direction.

6.3. The Northern Appalachian Anomaly: Plume Interactions and Small-Scale Convection

In most tomography models, the NAA manifests as a somewhat larger (radius of ∼100 km at a depth of 200 km) and stronger anomaly than the CAA (e.g., Schmandt & Lin 2014). The NAA is also associated with high attenuation in the upper mantle (e.g., Dong & Menke 2017, Yassminh et al. 2020). There are several indications that the continental lithosphere beneath the NAA is thin compared to elsewhere in ENAM, although estimates vary widely (ranging between 60 and 125 km in its central portion) (Rychert et al. 2005, Hopper & Fischer 2018, Levin et al. 2023). The model of Fullea et al. (2021) (**Figure 3*d***) suggests lithospheric thickness values as low as ∼85 km beneath central New England. Levin et al. (2023) jointly evaluated the Fullea et al. (2021) model and RF observations in New England and argued for a lithospheric thickness of ∼100–125 km in the NAA region. Estimates based on Sp RFs (Hopper & Fischer 2018, Menke et al. 2018) are considerably smaller (as thin as ∼60 km). Preliminary Ps RF results by Espinal et al. (2022) for the ongoing NEST deployment in New England identified a robust negative velocity gradient at ∼60–80 km throughout the NAA region, which may represent the base of the lithosphere.

Menke et al. (2016) used body wave travel time residuals to argue for a primarily thermal origin for the NAA, with neither compositional variations nor the presence of partial melt required. They proposed that the NAA corresponds to the upwelling limb of an edge-driven convection cell, with the downwelling limb presumably located to the west, at the eastern edge of the North American craton. Dong & Menke (2017) found evidence for strong attenuation beneath the NAA, which they argued could be explained via thermal effects, without needing to invoke the presence of partial melt (in contrast to arguments for the CAA) (Mittal et al. 2023). Menke et al. (2018) suggested that there has been localized thinning and alteration of the lithosphere in the NAA region, due to the upwelling associated with edge-driven convection; they noted the presence of warm springs in New England as evidence for lithospheric heating. Interestingly, Menke et al. (2018) attributed this lithospheric thinning to a bottom-up process (lithospheric ablation and heating from below), rather than the gravity-driven lithospheric loss that Mazza et al. (2014) and Long et al. (2021) invoked as an explanation for the CAA.

Levin et al. (2018) examined upper mantle anisotropy beneath the NAA and noted the presence of weak SKS splitting in the central portion of the anomaly (**Figure 10*a***). They suggested that the asthenospheric upper mantle beneath the central part of the NAA is dominated by vertical upwelling flow (resulting in vertical alignment of fast olivine a axes), consistent with the notion of edge-driven convection suggested by Menke et al. (2016). Later SKS splitting measurements by Li et al. (2019) and Lopes et al. (2020) showed that the zone of weak splitting identified by Levin et al. (2018) was more regionally extensive than initially thought, roughly colocated with the NAA itself at a depth of 200 km in the upper mantle.

Given the NAA region's extensive history of postrifting volcanic and magmatic activity (**Figure 8**), it is plausible that the NAA lithosphere was thinned and/or modified by the emplacement of magmatic products during hotspot passage at roughly 120–130 Ma (e.g., Tao et al. 2021). This early episode of lithospheric modification due to plume-lithosphere interaction may well have set the stage for later thinning, perhaps due to small-scale or edge-driven convection (Menke et al. 2016, 2018; Dong & Menke 2017) or shear-driven upwelling (Conrad et al. 2010). Ongoing upwelling of hot asthenosphere today may be continuing to thin the lithosphere via thermal ablation. Future detailed geophysical imaging of the NAA, along with cross-disciplinary

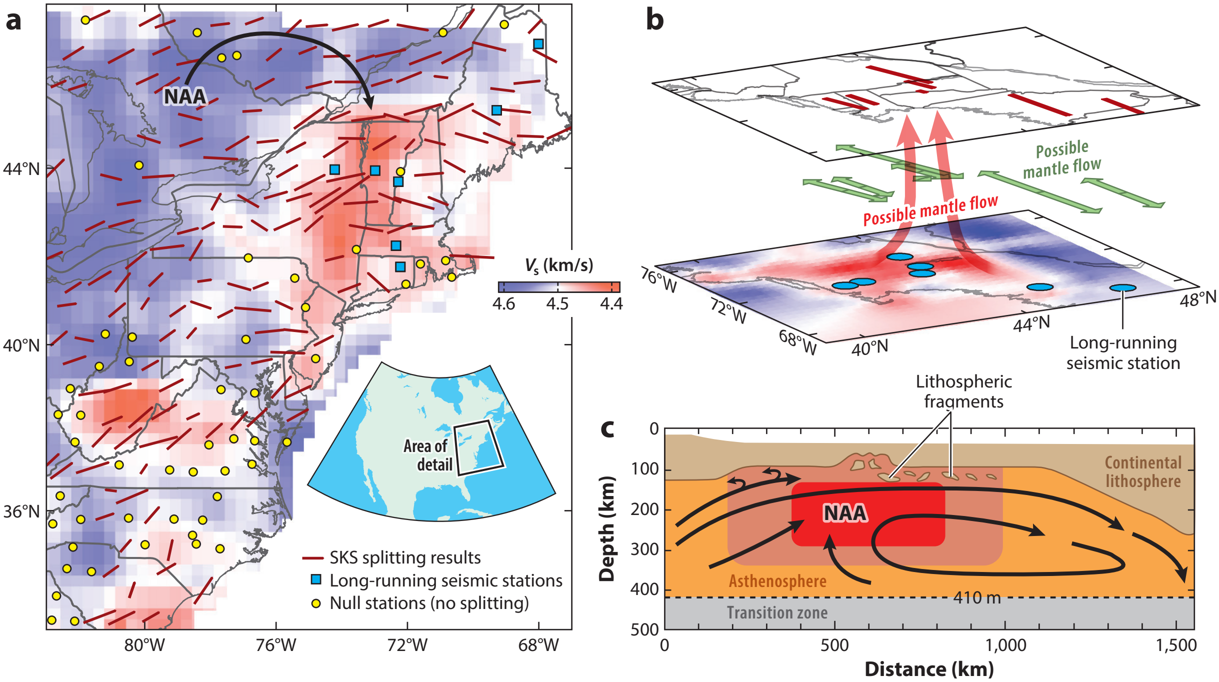

Figure 10

Summary of key observations and interpretations for the NAA. (*a*) Background colors show S-wave velocities from the model of Porter et al. (2016), with the NAA indicated; red bars show the SKS splitting results of Long et al. (2016). (*b*) SKS splitting results (*red sticks*) and interpretation (*green and red arrows* showing possible mantle flow) of Levin et al. (2018), who invoked present-day mantle upwelling in the NAA region. (*c*) Schematic interpretation of lithospheric alteration above the NAA. Panels *a* and *b* adapted with permission from Levin et al. (2018). Panel *c* adapted with permission from Menke et al. (2018). Abbreviation: NAA, Northern Appalachian Anomaly.

integration and synthesis, will be key to understanding modes of lithospheric alteration in the NAA region and their similarities and differences with other portions of ENAM, particularly the CAA. Ongoing data collection in New England associated with the NEST experiment (Long et al. 2022) will enable imaging of lithospheric structures with resolution comparable to that obtained with MAGIC data for the CAA.

SUMMARY POINTS

- Eastern North America represents a classic passive margin setting, with two Wilson cycles of supercontinent formation and breakup followed by 200 Ma of postrift evolution and episodic intraplate volcanism. It represents an exceptional locale to study the evolution of continental lithosphere.
- A range of processes have shaped lithospheric structure beneath the eastern North American margin (ENAM), including subduction, terrane accretion, orogenesis, rifting and extension, magmatism, lithospheric loss or delamination, small-scale or edge-driven convection, and plume-lithosphere interaction.

- There is a first-order difference in lithospheric structure (both crust and mantle) between Grenville and Appalachian terranes in ENAM, highlighting their different evolutionary trajectories and the likely role of lithospheric thinning due to extension and/or gravity-driven lithospheric loss.
- There is abundant evidence for the preservation of structures associated with past episodes of subduction and terrane accretion in the continental lithosphere associated with both Grenville and Appalachian orogenesis. These include widespread metasomatic alteration, shear zones associated with major terrane sutures, relict slab Moho interfaces from past subduction episodes, and anisotropic layers that preserve information about past deformation.
- ENAM lithosphere was modified by Pangea breakup and Central Atlantic Magmatic Province (CAMP) magmatism. The deep crust beneath Mesozoic rift basins has been modified via the emplacement of mafic magmatic products during extension. There is some evidence for widespread lithospheric thinning and alteration during rifting, but these effects remain imperfectly understood.
- Since the breakup of Pangea, ENAM continental lithosphere has been substantially modified in the central Appalachian and New England regions. The Central Appalachian Anomaly region has likely undergone multiple episodes of gravity-driven lithospheric loss, accompanied by upwelling return flow in the mantle, decompression melting, and magmatic activity.
- The continental lithosphere beneath New England likely underwent modification due to plume-lithosphere interaction during the passage of the Great Meteor Hotspot (GMHS) at ~125 Ma, with additional later episodes of alteration. The Northern Appalachian Anomaly (NAA) likely represents a region of present-day mantle upwelling that contributes to ongoing lithospheric thinning.

FUTURE ISSUES

- Is there a compositional and/or rheological difference between Grenville and Appalachian lithosphere? What combination of processes has led to the first-order difference in lithospheric properties between Grenville and Appalachian terranes?
- What controls the along-strike variability in Appalachian lithospheric structure, and in orogenic systems more generally? Why have some episodes of Appalachian subduction and terrane accretion been well preserved in the ENAM lithosphere while others have not?
- How extensive was the alteration of ENAM lithosphere during the breakup of Pangea and the contemporaneous emplacement of CAMP? If alteration was limited, then what controlled its localization? If it was widespread, then why have so many features associated with Appalachian orogenesis been preserved in ENAM lithosphere?
- How important has the process of gravity-driven lithospheric loss been beneath ENAM? Is it a relatively rare process whose effects are evident only in specific regions? Or has it been a common occurrence during eastern North American lithospheric evolution? Did

widespread lithospheric loss beneath the Appalachians play a role in driving the upwelling and melting that resulted in CAMP emplacement? To what extent is the gravity-driven loss of continental lithosphere a common process in other passive continental margin settings?

- What triggers gravity-driven lithospheric loss, and what are the controls on its spatiotemporal distribution? Is the lower crust involved in lithospheric loss events, or are they confined to the mantle lithosphere? Do time-progressive metamorphic reactions in the crustal roots of ancient mountain ranges (e.g., Fischer 2002, Williams et al. 2014) play a role? Why are some regions apparently prone to episodic lithospheric dripping?
- What have been the relative roles of plume-lithosphere interaction and mantle upwelling driven by small-scale or edge-driven convection in modifying the lithosphere beneath New England? Is the NAA geophysical anomaly a direct result of GMHS passage, or is it mostly a consequence of younger processes? Is the spatial correlation between the intraplate volcanism of the White Mountain magma series and the NAA coincidental or causative?
- To what extent is the deep continental mantle lithosphere deformed during major tectonic events such as collision, orogenesis, extension, and rifting? Does the deformation of the crust at depth that has been documented beneath ENAM extend to the mantle portion of the lithosphere? How is deformation partitioned among different depths, and how is this controlled by lithospheric rheology? Are the crust and mantle lithosphere mechanically coupled during deformation?
- What are the causative relationships among different processes that affect continental lithospheric structure? To what extent do structures inherited from past tectonic events act as nucleation points or triggers for later events? Are the conditions needed for processes such as lithospheric loss seeded by earlier events, such as orogenesis or rifting? Is lithosphere that has been thinned by delamination or other processes more likely to be affected by subsequent processes?

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LITERATURE CITED

Amidon WH, Roden-Tice M, Anderson AJ, McKeon RE, Shuster DL. 2016. Late Cretaceous unroofing of the White Mountains, New Hampshire, USA: an episode of passive margin rejuvenation? *Geology* 44:415–18

Aragon JC, Long MD, Benoit MH. 2017. Lateral variations in SKS splitting across the MAGIC array, central Appalachians. *Geochem. Geophys. Geosyst.* 18:4136–55

Artemieva IM. 2011. *The Lithosphere: An Interdisciplinary Approach*. Cambridge, UK: Cambridge Univ. Press

Artemieva IM, Mooney WD. 2001. Thermal thickness and evolution of Precambrian lithosphere: a global study. *J. Geophys. Res.* 106(B8):16387–414

Axen GJ, van Wijk JW, Currie CA. 2018. Basal continental mantle lithosphere displaced by flat-slab subduction. *Nat. Geosci.* 11:961–64

Benson RN. 2003. Age estimates of the seaward-dipping volcanic wedge, earliest oceanic crust, and earliest drift-stage sediments along the North Atlantic continental margin. *Geophys. Monogr. Ser.* 136:61–75

Bird P. 1979. Continental delamination and the Colorado Plateau. *J. Geophys. Res.* 84(B13):7561–71

Biryol CB, Wagner LS, Fischer KM, Hawman RB. 2016. Relationship between observed upper mantle structures and recent tectonic activity across the Southeastern United States. *J. Geophys. Res. Solid Earth* 121:3393–414

Blackburn TJ, Olsen PE, Bowring SA, McLean NM, Kent DV, et al. 2013. Zircon U-Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province. *Science* 340:941–45

Boyce A, Bastow ID, Golos EM, Rondenay S, Burdick S, van der Hilst RD. 2019. Variable modification of continental lithosphere during the Proterozoic Grenville orogeny: evidence from teleseismic P-wave tomography. *Earth Planet. Sci. Lett.* 525:115763

Broadley MW, Barry PH, Ballentine CJ, Taylor LA, Burgess R. 2018. End-Permian extinction amplified by plume-induced volatile release of recycled lithospheric volatiles. *Nat. Geosci.* 11:682–87

Brownlee SJ, Schulte-Pelkum V, Raju A, Mahan K, Condit C, Orlandini OF. 2017. Characteristics of deep crustal seismic anisotropy from a compilation of rock elasticity tensors and their expression in receiver functions. *Tectonics* 36:1835–57

Brunsvik BR, Eilon ZC, Lynner C. 2021. Mantle structure and flow across the continent-ocean transition of the eastern North American margin: anisotropic *S*-wave tomography. *Geochem. Geophys. Geosyst.* 22:e2021GC010084

Burgess SD, Muirhead JD, Bowring SA. 2017. Initial pulse of Siberian Traps sills as the trigger of the end-Permian mass extinction. *Nat. Commun.* 8:164

Burov E, Guillou-Frottier L. 2005. The plume head–continental lithosphere interaction using a tectonically realistic formulation for the lithosphere. *Geophys. J. Int.* 161:469–90

Byrnes JS, Bezada M, Long MD, Benoit MH. 2019. Thin lithosphere beneath the central Appalachian Mountains: constraints from seismic attenuation beneath the MAGIC array. *Earth Planet. Sci. Lett.* 519:297–307

Carlson RW, Pearson DG, James DE. 2005. Physical, chemical, and chronological characteristics of continental mantle. *Rev. Geophys.* 43:RG1001

Chen H, Tang M, Song S. 2023. Catastrophic craton destruction via wholesale lithosphere delamination. *Geology* 51:460–64

Chu R, Leng W, Helmberger DV, Gurnis M. 2013. Hidden hotspot track beneath the eastern United States. *Nat. Geosci.* 6:936–66

Clift P, Vannucchi P. 2004. Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. *Rev. Geophys.* 42:RG2001

Clowes RM. 2011. Initiation, development, and benefits of Lithoprobe—shaping the direction of Earth science research in Canada and beyond. *Can. J. Earth Sci.* 47:291–314

Conrad CP, Wu B, Smith EI, Bianco TA, Tibbetts A. 2010. Shear-driven upwelling induced by lateral viscosity variations and asthenospheric shear: a mechanism for intraplate volcanism. *Phys. Earth Planet. Inter.* 178:162–75

Cook FA, Percival JA, Clowes RM. 2012. Tectonic styles in Canada: Lithoprobe perspective on evolution of the North American continent. *Geol. Assoc. Can. Spec. Pap.* 49:467–98

Dave R, Li A. 2016. Destruction of the Wyoming craton: seismic evidence and geodynamic processes. *Geology* 44:883–86

Davis M, Kusznir N. 2004. Depth-dependent lithospheric stretching at rifted continental margins. In *Rheology and Deformation of the Lithosphere at Continental Margins*, ed. GD Karner, B Taylor, NW Driscoll, DL Kohlstedt, pp. 92–137. New York: Columbia Univ. Press

Dawson JB, Smith JV. 1988. Metasomatized and veined upper-mantle xenoliths from Pello Hill, Tanzania: evidence for anomalously-light mantle beneath the Tanzanian sector of the East African Rift Valley. *Contrib. Mineral. Petrol.* 100:510–27

Dong MT, Menke WG. 2017. Seismic high attenuation region observed beneath southern New England from teleseismic body wave spectra: evidence for high asthenospheric temperature without melt. *Geophys. Res. Lett.* 44:10958–69

Ducea M, Saleeby J. 1996. Buoyancy sources for a large, uprooted mountain range, the Sierra Nevada, California: evidence from xenolith thermobarometry. *J. Geophys. Res.* 101(B4):8229–44

Ebinger C. 2005. Continental break-up: the East African perspective. *Astron. Geophys.* 26:2.16–21

Eilon Z, Brunsvik B, Lynner C. 2023. *Lithospheric structure across tectonic terranes of the eastern US*. Presented at AGU Fall Meet., Dec. 11–15, San Francisco, Abstr. T13B-07

Espinal K, Long MD, Levin VL, Karabinos P, Masis Arce R. 2022. *Lithospheric structure above the Northern Appalachian Anomaly*. Presented at AGU Fall Meet., Dec. 12–16, Chicago, Abstr. S55D-0140

Evans RL, Benoit MH, Long MD, Elsenbeck J, Ford HA, et al. 2019. Thin lithosphere beneath the central Appalachian Mountains: a combined seismic and magnetotelluric study. *Earth Planet. Sci. Lett.* 519:308–16

Fischer KM. 2002. Waning buoyancy in the crustal roots of old mountains. *Nature* 417:933–36

Fischer KM, Rychert CA, Dalton CA, Miller MS, Beghein C, Schutt DL. 2020. A comparison of oceanic and continental mantle lithosphere. *Phys. Earth Planet. Inter.* 309:106600

Fullea J, Lebedev S, Martinec Z, Celli NL. 2021. WINTERC-G: mapping the upper mantle thermochemical heterogeneity from coupled geophysical-petrological inversion of seismic waveforms, heat flow, surface elevation and gravity satellite data. *Geophys. J. Int.* 226:146–91

Frizon de Lamotte D, Fourdan B, Leleu S, Leparmentier F, de Clarens P. 2015. Style of rifting and the stages of Pangea breakup. *Tectonics* 34:1009–29

Frothingham MG, Schulte-Pelkum V, Mahan KH, Merschat AJ, Mather M, Cabrera Gomez Z. 2022. Don't judge an orogen by its cover: kinematics of the Appalachian décollement from seismic anisotropy. *Geology* 50:1306–11

Gao H, Li C. 2021. Lithospheric formation and evolution of eastern North American continent. *Geophys. Res. Lett.* 48:e2020GL091074

Gao H, Yang X, Long MD, Aragon JC. 2020. Seismic evidence for crustal modification beneath the Hartford rift basin in the northeastern United States. *Geophys. Res. Lett.* 47:e2020GL089316

Goldhagen GB, Ford HA, Long MD. 2022. Evidence for a lithospheric step and pervasive lithospheric thinning beneath southern New England, northeastern USA. *Geology* 50:1078–82

Gray R, Pysklywec RN. 2012. Geodynamic models of mature continental collision: evolution of an orogen from lithospheric subduction to continental retreat/delamination. *J. Geophys. Res.* 117(B3):B03408

Gutscher M-A. 2018. Scraped by flat-slab subduction. *Nat. Geosci.* 11:890–91

Harig C, Molnar P, Houseman GA. 2010. Lithospheric thinning and localization of deformation during Rayleigh-Taylor instability with nonlinear rheology and implications for intracontinental magmatism. *J. Geophys. Res.* 115(B2):B02205

Harry DL, Sawyer DS. 1992. A dynamic model of extension in the Baltimore Canyon Trough region. *Tectonics* 11:420–36

Hatcher RD Jr. 2010. The Appalachian orogeny: a brief summary. In *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*, ed. RP Tollo, MJ Hibbard, PM Karabinos, pp. 1–19. Boulder, CO: Geol. Soc. Am.

Hawkesworth CJ, Cawood PA, Dhuime B, Kemp TIS. 2017. Earth's continental lithosphere through time. *Annu. Rev. Earth Planet. Sci.* 45:169–98

Hibbard JP, van Staal CR, Rankin DW, Williams H. 2006. *Lithotectonic map of the Appalachian Orogen, Canada–United States*. Geol. Surv. Can., series map 2096A

Hiett CD, Newell DL, Jessup MJ. 2021. ^{3}He evidence for fluid transfer and continental hydration above a flat slab. *Earth Planet. Sci. Lett.* 556:116722

Hillenbrand IW, Williams ML. 2021. Paleozoic evolution of crustal thickness and elevation in the northern Appalachian orogen, USA. *Geology* 49:946–51

Hillenbrand IW, Williams ML, Li C, Gao H. 2021. Rise and fall of the Acadian altiplano: evidence for a Paleozoic orogenic plateau in New England. *Earth Planet. Sci. Lett.* 560:116797

Holbrook WS, Kelemen PB. 1993. Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup. *Nature* 364:433–36

Hopper E, Fischer KM. 2018. The changing face of the lithosphere-asthenosphere boundary: imaging continental scale patterns in upper mantle structure across the contiguous U.S. with Sp converted waves. *Geochem. Geophys. Geosyst.* 19:2593–614

Hopper E, Fischer KM, Wagner LS, Hawman RB. 2017. Reconstructing the end of the Appalachian orogeny. *Geology* 45:15–18

Jordan TH. 1978. Composition and development of the continental tectosphere. *Nature* 247:544–48

Jourdan F, Marzoli A, Bertrand G, Cirilli S, Tanner LH, et al. 2009. ^{40}Ar/^{39}Ar ages of CAMP in North America: implications for the Triassic–Jurassic boundary and the ^{40}K decay constant bias. *Lithos* 110:167–80

Kaislaniemi L, van Hunen J. 2014. Dynamics of lithospheric thinning and mantle melting by edge-driven convection: application to Moroccan Atlas mountains. *Geochem. Geophys. Geosyst.* 15:3175–89

Karabinos P, Macdonald FA, Crowley JL. 2017. Bridging the gap between the foreland and hinterland I: geochronology and plate tectonic geometry of Ordovician magmatism and terrane accretion on the Laurentian margin of New England. *Am. J. Sci.* 317:515–54

King SD, Anderson DL. 1998. Edge-driven convection. *Earth Planet. Sci. Lett.* 160:289–96

Kinney ST, MacLennan SA, Keller CB, Schoene B, Setera JB, et al. 2021. Zircon U-Pb geochronology constraints continental expression of Great Meteor Hotspot magmatism. *Geophys. Res. Lett.* 48:e2020GL091390

Kinney ST, MacLennan SA, Szymanowski D, Keller CB, VanTongeren JA, et al. 2022. Onset of long-lived silicic and alkaline magmatism in eastern North America preceded Central Atlantic Magmatic Province emplacement. *Geology* 50:1301–5

Kogan LS, Fisseha S, Bendick R, Reilinger R, McClusky S, et al. 2012. Lithospheric strength and strain localization in continental extension from observations of the East African Rift. *J. Geophys. Res.* 117(B3):B03402

Lee C-TA. 2003. Compositional variation of density and seismic velocities in natural peridotites at STP conditions: implications for seismic imaging of compositional heterogeneities in the upper mantle. *J. Geophys. Res.* 108(B9):2441

Lee C-TA, Luffi P, Chin EJ. 2011. Building and destroying continental mantle. *Annu. Rev. Earth Planet. Sci.* 39:59–90

Levin V, Lebedev S, Fullea J, Li Y, Chen X. 2023. Defining continental lithosphere as a layer with abundant frozen-in structures that scatter seismic waves. *J. Geophys. Res. Solid Earth* 128:e2022JB026309

Levin V, Long MD, Skryzalin P, Li Y, López I. 2018. Seismic evidence for a recently formed mantle upwelling beneath New England. *Geology* 46:87–90

Levin V, Park J, Brandon MT, Menke W. 2000. Thinning of the upper mantle during late Paleozoic Appalachian orogenesis. *Geology* 28:239–42

Levin V, Servali A, VanTongeren J, Menke W, Darbyshire F. 2017. Crust-mantle boundary in eastern North America, from the (oldest) craton to the (youngest) rift. *Geol. Soc. Am. Spec. Pap.* 526:107–31

Li C, Gao H. 2021. Modification of crust and mantle lithosphere beneath the southern part of the eastern North American passive margin. *Geophys. Res. Lett.* 48:e2020GL090555

Li C, Gao H, Williams ML. 2020. Seismic characteristics of the eastern North American crust with Ps converted waves: terrane accretion and modification of continental crust. *J. Geophys. Res. Solid Earth* 125:e2019JB018727

Li C, Gao H, Williams ML, Levin V. 2018. Crustal thickness variation in the northern Appalachian Mountains: implications for the geometry of 3-D tectonic boundaries within the crust. *Geophys. Res. Lett.* 45:6061–70

Li C, Hibbard L, Gao H, Williams ML. 2023. Seismic evidence for metamorphic densification of the lower continental crust in eastern North America. *J. Geophys. Res. Solid Earth* 128:e2023JB026602

Li Y, Levin V, Elkington S, Hlavaty J. 2019. Localized anisotropic domains beneath eastern North America. *Geochem. Geophys. Geosyst.* 20:5499–521

Liu L, Morgan JP, Xu Y, Menzies M. 2018. Craton destruction 1: cratonic keel delamination along a weak midlithospheric discontinuity layer. *J. Geophys. Res. Solid Earth* 123:10040–68

Long MD, Aragon JC. 2020. Probing the structure of the crust and mantle lithosphere beneath the southern New England Appalachians via the SEISConn deployment. *Seismol. Res. Lett.* 91:2976–86

Long MD, Benoit MH, Aragon JC, King SD. 2019. Seismic imaging of mid-crustal structure beneath central and eastern North America: possibly the elusive Grenville deformation? *Geology* 47:371–74

Long MD, Benoit MH, Evans RL, Aragon JC, Elsenbeck J. 2020. The MAGIC experiment: a combined seismic and magnetotelluric deployment to investigate the structure, dynamics, and evolution of the Central Appalachians. *Seismol. Res. Lett.* 91:2960–75

Long MD, Jackson KG, McNamara JF. 2016. SKS splitting beneath Transportable Array stations in eastern North America and the signature of past lithospheric deformation. *Geochem. Geophys. Geosyst.* 17:2–15

Long MD, Levin V, Karabinos P, Kuiper YD, Webb LE, et al. 2022. *New insights into crustal and mantle structure beneath the New England Appalachians from temporary broadband seismic deployments and integration with geological constraints*. Presented at AGU Fall Meet., Dec. 12–16, Chicago, Abstr. S45C-05

Long MD, Wagner LS, King SD, Evans RL, Mazza SE, et al. 2021. Evaluating models for lithospheric loss and intraplate volcanism beneath the Central Appalachian Mountains. *J. Geophys. Res. Solid Earth* 126:e2021JB022571

Lopes E, Long MD, Karabinos P, Aragon JC. 2020. SKS splitting and upper mantle anisotropy beneath the southern New England Appalachians: constraints from the dense SEISConn array. *Geochem. Geophys. Geosyst.* 21:e2020GC009401

Luo Y, Long MD, Karabinos P, Kuiper YD, Rondenay S, et al. 2021. High-resolution Ps receiver function imaging of the crust and mantle lithosphere beneath southern New England and tectonic implications. *J. Geophys. Res. Solid Earth* 126:e2021JB022170

Luo Y, Long MD, Karabinos P, Rondenay S, Masis Arce R. 2023a. First-order transition in Appalachian orogenic processes revealed by along-strike variation of the Moho geometry. *J. Geophys. Res. Solid Earth.* 128:e2023JB027024

Luo Y, Long MD, Link F, Karabinos P, Kuiper YD. 2023b. Insights from layered anisotropy beneath southern New England: from ancient tectonism to present-day mantle flow. *Geochem. Geophys. Geosyst.* 24:e2023GC011118

Luo Y, Long MD, Rondenay S, Karabinos P, Kuiper YD. 2022. Wavefield migration imaging of Moho geometry and upper mantle structure beneath southern New England. *Geophys. Res. Lett.* 49:e2022GL099013

Lynner C, Bodmer M. 2017. Mantle flow along the eastern North American margin inferred from shear wave splitting. *Geology* 45:867–70

Lynner C, Porritt RW. 2017. Crustal structure across the eastern North American margin from ambient noise tomography. *Geophys. Res. Lett.* 44:6651–57

Lynner C, Van Avendonk HJA, Bécel A, Christeson GL, Dugan B, et al. 2019. The eastern North American margin community seismic experiment: an amphibious active- and passive-source dataset. *Seismol. Res. Lett.* 91:533–40

Macdonald FA, Ryan-Davis J, Coish RA, Crowley JL, Karabinos P. 2014. A newly identified Gondwanan terrane in the northern Appalachian Mountains: implications for the Taconic orogeny and closure of the Iapetus Ocean. *Geology* 42:539–42

Marzen RE, Shillington DJ, Lizarralde D, Harder SH. 2019. Constraints on Appalachian orogenesis and continental rifting in the southeastern United States from wide-angle seismic data. *J. Geophys. Res. Solid Earth* 124:6625–52

Marzen RE, Shillington DJ, Lizarralde D, Knapp JH, Heffner DM, et al. 2020. Limited and localized magmatism in the Central Atlantic Magmatic Province. *Nat. Commun.* 11:3397

Marzoli A, Renne PR, Piccirillo EM, Ernesto M, Bellieni G, De Min A. 1999. Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. *Science* 284:616–18

Masis Arce R, Long MD. 2023. *Seismic analysis of lithospheric structure of Laurentia and peri-Gondwanan terranes: a comparative study between North America, Ireland, and Great Britain*. Presented at AGU Fall Meet., Dec. 11–15, San Francisco, Abstr. S23F-0438

Mazza SE, Gazel EA, Johnson EA, Bizimis M, McAleer R, Biryol CB. 2017. Post-rift magmatic evolution of the eastern North American "passive-aggressive" margin. *Geochem. Geophys. Geosyst.* 18:3–22

Mazza SE, Gazel EA, Johnson EA, Kunk MJ, McAller R, et al. 2014. Volcanoes of the passive margin: the youngest magmatic event in eastern North America. *Geology* 42:483–86

Menke W, Lamoureaux J, Abbott D, Hopper E, Hutson D, Marrero A. 2018. Crustal heating and lithospheric alternation and erosion associated with asthenospheric upwelling beneath southern New England (USA). *J. Geophys. Res. Solid Earth* 123:8995–9008

Menke W, Skryzalin P, Levin V, Harper T, Darbyshire F, Dong T. 2016. The Northern Appalachian Anomaly: a modern asthenospheric upwelling. *Geophys. Res. Lett.* 43:10173–79

Menzies M, Xu Y, Zhang H, Fan W. 2007. Integration of geology, geophysics and geochemistry: a key to understanding the North China Craton. *Lithos* 96:1–21

Michelfelder GS, Feeley TC, Wilder AD, Klemetti EW. 2013. Modification of the continental crust by subduction zone magmatism and *vice-versa*: across-strike geochemical variations of silicic lavas from individual eruptive centers in the Andean Central Volcanic Zone. *Geosciences* 3:633–67

Miller MS, Zhang P, Dahlquist MP, West AJ, Becker TW, Harris CW. 2021. Inherited lithospheric structures control arc-continent collisional heterogeneity. *Geology* 49:652–56

Miller SR, Sak PB, Kirby E, Bierman PR. 2013. Neogene rejuvenation of central Appalachian topography: evidence for differential rock uplift from stream profiles and erosion rates. *Earth Planet. Sci. Lett.* 369–370:1–12

Mittal T, Richards MA, Fendley IM. 2021. The magmatic architecture of continental flood basalts I: observations from the Deccan traps. *J. Geophys. Res. Solid Earth* 126:e2021GB021808

Mittal V, Long MD, Evans RL, Byrnes JS, Bezada M. 2023. Joint analysis of seismic and electrical observables beneath the Central Appalachians requires partial melt in the upper mantle. *Geochem. Geophys. Geosyst.* 24:e2022GC010690

Moucha R, Forte AM, Mitrovica JX, Rowley DB, Quéré S, et al. 2008. Dynamic topography and long-term sea-level variations: There is no such thing as a stable continental platform. *Earth Planet. Sci. Lett.* 271:101–8

Munch FD, Grayver A. 2023. Multi-scale imaging of 3-D electrical conductivity structure under the contiguous US constraints lateral variations in the upper mantle water content. *Earth Planet. Sci. Lett.* 602:117939

Murphy BS, Egbert GD. 2017. Electrical conductivity structure of southeastern North America: implications for lithospheric architecture and Appalachian topographic rejuvenation. *Earth Planet. Sci. Lett.* 462:66–75

Murphy BS, Egbert GD. 2019. Synthesizing seemingly contradictory seismic and magnetotelluric observations in the southeastern United States to image physical properties of the lithosphere. *Geochem. Geophys. Geosyst.* 20:2606–25

Parker EH Jr., Hawman RB, Fischer KM, Wagner LS. 2013. Crustal evolution across the southern Appalachians: initial results from the SESAME broadband array. *Geophys. Res. Lett.* 40:3853–57

Pazzaglia FJ, Brandon MT. 1996. Macrogeomorphic evolution of the post-Triassic Appalachian mountains determined by deconvolution of the offshore basin sedimentary record. *Basin Res.* 8:255–78

Pearson DG. 1999. The age of continental roots. *Lithos* 48:171–94

Porter R, Liu Y, Holt WE. 2016. Lithospheric records of orogeny within the continental US. *Geophys. Res. Lett.* 43:144–53

Poupinet G, Shapiro NM. 2009. Worldwide distribution of ages of the continental lithosphere derived from a global seismic tomographic model. *Lithos* 109:125–30

Priestly K, McKenzie D, Ho T. 2019. A lithosphere–asthenosphere boundary—a global model derived from multimode surface-wave tomography and petrology. In *Lithospheric Discontinuities*, Vol. 239, ed. H Yuan, B Romanowicz, pp. 111–23. Hoboken, NJ: Wiley & Sons

Pysklywec RN, Gogus O, Percival J, Cruden AR, Beaumont C. 2010. Insights from geodynamical modeling on possible fates of continental mantle lithosphere: collision, removal, and overturn. *Can. J. Earth Sci.* 47:541–63

Ribe NM, Christensen UR. 1994. Three-dimensional modeling of plume-lithosphere interaction. *J. Geophys. Res.* 99(B1):669–82

Rudnick RL, McDonough WF, O'Connell RJ. 1998. Thermal structure, thickness and composition of continental lithosphere. *Chem. Geol.* 145:395–411

Russell JB, Gaherty JB. 2021. Lithosphere structure and seismic anisotropy offshore eastern North America: implications for continental breakup and ultra-slow spreading dynamics. *J. Geophys. Res. Solid Earth* 126:e2021JB022955

Rychert CA, Fischer KM, Rondenay S. 2005. A sharp lithosphere–asthenosphere boundary imaged beneath eastern North America. *Nature* 436:542–45

Schmandt B, Lin F-C. 2014. *P* and *S* wave tomography of the mantle beneath the United States. *Geophys. Res. Lett.* 41:6342–49

Schulte-Pelkum V, Mahan KH. 2014. A method for mapping crustal deformation and anisotropy with receiver function and first results from USArray. *Earth Planet. Sci. Lett.* 402:221–33

Schulte-Pelkum V, Monsalve PG, Sheehan A, Pandey MR, Sapkota S, et al. 2005. Imaging the Indian subcontinent beneath the Himalaya. *Nature* 435:1222–25

Schutt DL, Lesher CE. 2010. Compositional trends among Kaapvaal Craton garnet peridotite xenoliths and their effects on seismic velocity and density. *Earth Planet. Sci. Lett.* 300:367–73

Shuck BD, Van Avendonk HJA, Bécel A. 2019. The role of mantle melts in the transition from rifting to seafloor spreading offshore eastern North America. *Earth Planet. Sci. Lett.* 525:115756

Silver PG. 1996. Seismic anisotropy beneath the continents: probing the depths of geology. *Annu. Rev. Earth Planet. Sci.* 24:385–432

Swanson-Hysell NL, Rivers T, van der Lee S. 2023. The late Mesoproterozoic to early Neoproterozoic Grenvillian orogeny and the assembly of Rodinia: turning point in the tectonic evolution of Laurentia. In *Laurentia: Turning Points in the Evolution of a Continent*, ed. SJ Whitmeyer, ML Williams, DA Kellett, B Tikoff, pp. 221–50. Boulder, CO: Geol. Soc. Am.

Tao Z, Li A, Fischer KM. 2021. Hotspot signatures at the North American passive margin. *Geology* 49:525–30

Tetrault JL, Buiter SJH. 2012. Geodynamic models of terrane accretion: testing the fate of island arcs, oceanic plateaus, and continental fragments in subduction zones. *J. Geophys. Res.* 117(B8):B08403

Thybo H, Artemieva IM. 2013. Moho and magmatic underplating in continental lithosphere. *Tectonophysics* 609:605–19

van Staal CR, Zagorevski A. 2023. A note on the timing and nature of the Moho geometry and upper mantle structure beneath southern New England. *Geophys. Res. Lett.* 50:e2022GL102057

Wagner LS, Anderson ML, Jackson JM, Beck SL, Zandt G. 2008. Seismic evidence for orthopyroxene enrichment in the continental lithosphere. *Geology* 36:935–38

Wagner LS, Fisher KM, Hawman R, Hopper E, Howell D. 2018. The relative roles of inheritance and long-term passive margin lithospheric evolution on the modern structure and tectonic activity in the southeastern United States. *Geosphere* 14:1385–410

Wang H, Currie CA. 2015. Magmatic expressions of continental lithosphere removal. *J. Geophys. Res. Solid Earth* 120(10):7239–60

Wang H, Currie CA, DeCelles PG. 2021. Coupling between lithosphere removal and mantle flow in the Central Andes. *Geophys. Res. Lett.* 48:e2021GL095075

Wang H, van Hunen J, Pearson DG. 2015. The thinning of subcontinental lithosphere: the roles of plume impact and metasomatic weakening. *Geochem. Geophys. Geosyst.* 16:1156–71

Warren JM, Hansen LN. 2023. Ductile deformation of the lithospheric mantle. *Annu. Rev. Earth Planet. Sci.* 51:581–609

Whalen L, Gazel E, Vidito C, Puffer J, Bizimis M, et al. 2015. Supercontinental inheritance and its influence on supercontinental breakup: the Central Atlantic Magmatic Province and the breakup of Pangea. *Geochem. Geophys. Geosyst.* 16:3532–54

White RS, McKenzie D. 1995. Mantle plumes and flood basalts. *J. Geophys. Res.* 100(B9):17543–85

White-Gaynor AL, Nyblade AA. 2017. Shear wave splitting across the mid-Atlantic region of North America: a fossil anisotropy interpretation. *Geology* 45:555–58

Whitmeyer WJ, Karlstrom KE. 2007. Tectonic model for the Proterozoic grown of North America. *Geosphere* 3:220–59

Williams ML, Dumond G, Mahan K, Regan S, Holland M. 2014. Garnet-forming reactions in felsic orthogneiss: implications for densification and strengthening of lower continental crust. *Earth Planet. Sci. Lett.* 405:207–19

Wintsch RP, Yi K, Dorais MJ. 2014. Crustal thickening by tectonic wedging of the Ganderian rocks, southern New England, USA: evidence from cataclastic zircon microstructures and U-Pb ages. *J. Struct. Geol.* 69:428–48

Withjack M, Malinconico M, Durcanin M. 2020. The "passive" margin of eastern North America: rifting and the influence of prerift orogenic activity on postrift development. *Lithosphere* 2020:8876280

Withjack MO, Schlische RW, Olsen PE. 2012. Development of the passive margin of Eastern North America: Mesozoic rifting, igneous activity, and breakup. In *Phanerozoic Rift Systems and Sedimentary Basins*, ed. DG Roberts, AW Bally, pp. 300–35. Amsterdam: Elsevier

Wolin E, Stein S, Pazzaglia F, Meltzer A, Kafka A, Berti C. 2012. Mineral, Virginia, earthquake illustrates seismicity of a passive-aggressive margin. *Geophys. Res. Lett.* 39:L02305

Yang BB, Liu Y, Dahm H, Liu KH, Gao SS. 2017. Seismic azimuthal anisotropy beneath the eastern United States and its geodynamic implications. *Geophys. Res. Lett.* 44:2670–78

Yassminh R, Laphim P, Sandvol E. 2020. Seismic attenuation and velocity measurements of the uppermost mantle beneath the Central and Eastern United States and implications for the temperature of the North American lithosphere. *J. Geophys. Res. Solid Earth* 125:e2019JB017728

Zhang B, Bao X, Xu Y. 2022. Seismic anisotropy in the central Tien Shan unveils rheology-controlled deformation during intracontinental orogenesis. *Geology* 50:812–16

Zhang Z, Klemperer SL. 2005. West-east variation in crustal thickness in northern Lhasa block, central Tibet, from deep seismic sounding data. *J. Geophys. Res.* 110(B9):B09403