Electrical Conductivity Structure of Southeastern North America: Implications for Lithospheric Architecture and Appalachian Topographic Rejuvenation

Benjamin S. Murphy, Gary D. Egbert

Keywords: Appalachians, Appalachian Orogen, Central Atlantic Magmatic Province, Topographic Rejuvenation, Magnetotellurics

Abstract

We present the first three-dimensional view of the lithospheric electrical conductivity structure beneath southeastern North America. By inverting EarthScope long-period magnetotelluric (MT) data, we obtain an electrical conductivity image that provides new insights into both the architecture of the Appalachian Orogen and the cryptic post-rifting geodynamic history of the southeastern United States. Our inverse solutions reveal several elongate electrically conductive features that we interpret as major terrane sutures within the Appalachian Orogen. Most significantly, we resolve a highly electrically resistive layer that extends to mantle depths beneath the modern Piedmont and Coastal Plain physiographic provinces. As high resistivity values in mantle minerals require cold mantle temperatures, the MT data indicate that the sub-Piedmont thermal lithosphere must extend to greater than 200 km depth. This firm bound conflicts with conclusions from seismic results. The boundary between the anomalously thick, resistive sub-Piedmont lithosphere and the relatively thin, moderately conductive sub-Appalachian lithosphere corresponds within resolution to the modern Appalachian topographic

escarpment. This newly recognized contrast in lithospheric properties likely has important implications for Appalachian topographic rejuvenation.

1. Introduction

Beneath the dense vegetation and the thick accumulations of saprolite, the crust and mantle lithosphere of the southeastern United States (Fig. 1) record a complicated history of accretionary and collisional orogenies, continental rifting, and passive-margin evolution. Although often scientifically overshadowed by the more active west, the eastern margin of North America nevertheless provides a natural laboratory for studying cryptic geodynamic and tectonic problems. The recent acquisition of EarthScope seismic and magnetotelluric (MT) data on the east coast of the United States now permits unprecedented three-dimensional views of the lithosphere beneath this enigmatic region.

The past and present evolution of the Appalachian Orogen dominates the geologic heritage of eastern North America. The ancestral Appalachian mountains were the product of a full Wilson cycle that spanned the late Mesoproterozoic to the late Paleozoic (Hatcher, 2010). The Grenville Orogeny at ~1.1 Ga marked the assembly of Rodinia, which persisted in various forms into the Neoproterozoic. Following Iapetan rifting of this supercontinent in the latest Neoproterozoic to early Cambrian, a series of Paleozoic terrane-suturing events in eastern Laurentia culminated in the Alleghenian Orogeny, which marked the assembly of Pangea and the closure of the Rheic Ocean. In the southern Appalachian Orogen, two pre-Pangean accretionary events are generally recognized: the mid-Ordovician Taconic Orogeny and the late-Ordovician to Silurian Cherokee Orogeny, in which the Carolina Superterrane (Carolina Zone) docked onto Laurentia (Hibbard et al., 2010; Fig. 1). In the mid-Mesozoic, Pangea was rifted apart with the opening of the Atlantic

Ocean. During this time, at ~200 Ma, the Central Atlantic Magmatic Province (CAMP; e.g., Whalen et al., 2015) formed as the largest continental large igneous province so far recognized in the geologic record. Geochemical evidence indicates that a mantle plume did not generate CAMP; rather, these flood basalts are likely due to passive continental rifting associated with orogenic collapse (Whalen et al., 2015; Frizon de Lamotte et al., 2015). With growth of the Atlantic Ocean, eastern Laurentia became a passive margin. The region has experienced no major tectonism since the mid Mesozoic.

Multiple lines of evidence suggest that the modern Appalachians Mountains are the result of topographic rejuvenation that occurred after the ancestral Alleghenian highlands had been eroded away. Geomorphic evidence indicates that the topography of the Southern and Central Appalachians is not in equilibrium (Gallen et al., 2013; Miller et al., 2013; Prince and Spotila, 2013). Apatite (U-Th)/He thermochronology suggests that topographic relief increased in the Southern Appalachians in the late Cretaceous (McKeon et al., 2014). Most importantly, the Cenozoic stratigraphic record on the Atlantic shelf shows major pulses of sedimentation in the Cretaceous and the Miocene that likely represent periods of topographic rejuvenation (Poag and Sevon, 1989). Multiple mantle-driven mechanisms for such low-magnitude topographic disequilibrium and rejuvenation have been proposed, including both dynamic subsidence and dynamic uplift due to large-scale mantle flow (Moucha et al., 2008; Spasojević et al., 2008; Liu, 2014) and hydration of the mantle beneath eastern Laurentia due to dewatering of the deep Farallon slab (van der Lee et al., 2008). Surficial processes, such as stream capture and basin reorganization (e.g., Willet et al., 2014), have also been suggested as an explanation for topographic disequilibrium. Despite much work on the history and development of modern Appalachian topography, no single explanation has yet to be widely accepted.

Here, we use recently collected EarthScope long-period MT data from the southeastern United States (Fig. 1) to provide a new geophysical perspective on the geologic architecture and geodynamic evolution of this region. Our work expands significantly on previous two-dimensional MT studies of the Appalachian Orogen (Ogawa et al., 1996; Wannamaker, 2005), which imaged several of the features we observe here but which could not thoroughly explore the implications of those features due to the limitations of their data. With the EarthScope MT dataset, we are now able to better constrain and interpret lithospheric electrical structures.

2. Data and Methods

Our dataset comprises full MT impedance tensors and vertical magnetic field transfer functions in the period range of ~ 10 s to $\sim 10,000$ s from 124 EarthScope Transportable Array (TA) long-period MT sites in the southeastern United States (Fig. 1). These data are available for community use through IRIS (<http://ds.iris.edu/spud/emtf>). We prescribed error floors of 5% for impedance tensor components (treating the two rows separately) and 0.03 for the real and imaginary parts of the vertical magnetic field transfer function components. We inverted the data with ModEM, a three-dimensional isotropic electromagnetic inversion code (Kelbert et al., 2014). Nominal horizontal grid-cell size for our model domain is 12 km. Vertical grid-cell size telescopes logarithmically to a maximum model depth of 900 km. Cell thickness is ~ 200 m at the surface; vertical grid-cell size is ~ 50 km at 300 km depth. Because the typical site spacing is ~ 70 km and the shortest period in our dataset is ~ 10 s, our model parameterization is sufficiently fine to model crust- and lithosphere-scale structures as well as the effects of distortion. We used a nested inversion approach to account for possible effects of large-scale electrical structures beyond our data footprint. The larger model within which our inversions were embedded was

derived from a coarse-scale inversion of all available EarthScope MT data in the eastern half of the United States. This large model included both the Atlantic Ocean and the Gulf of Mexico.

We assess gross model resolution through multiple inversion runs that utilized a range of prior resistivity models and that had various constraints imposed. Note that, in the ModEM regularization approach, deviations from a prior model are penalized (Kelbert et al., 2014); therefore, only features that appear for a range of prior models are considered required by the data. Results from an illustrative selection of inversion runs are shown in the Supplementary Materials. For the preferred solution shown here, a ModEM smoothing setting of 0.2 with two passes was utilized. In the inversion code, model smoothing is part of the inversion regularization. For our model discretization and covariance settings, features are smoothed over a length scale of ~30 km. This spreads bulk resistivity values into adjacent cells to the extent that regional-scale features are easily identified while also providing reasonable localization of those features. The preferred inversion began with a prior half-space resistivity of 180 Ωm that included ocean cells frozen to 0.3 Ωm . A normalized root-mean-square misfit of 1.75 was achieved after 350 iterations of the ModEM inversion. Further discussion of the data fit as well as resolution tests are presented in the Supplementary Materials.

3. Results

Our preferred inverse solution is shown in Figure 2. We identify five well-resolved electrically conductive structures, denoted C1 through C5; three poorly resolved but significant electrically conductive features, identified EC1 through EC3; and two zones of high resistivity, denoted R1 and R2 (Fig. 2). The features presented here are those that we currently consider

robust in at least some capacity based upon multiple inversions and resolution tests (see Supplementary Materials).

Structures C1, C2, and C3 are major Appalachian-parallel, mid- to lower-crustal conductors. These three structures follow the northeast-southwest, slightly sinuous grain of the Appalachian Orogen. The average vertically integrated conductances (~25-50 km depth) are 3300 S for C1, 2800 S for C2, and 1500 S for C3. (Average conductances are calculated for the spatial footprint of each conductor as defined in Figure 2.) The signature of highly conductive structure C1 is apparent in the vertical magnetic field transfer functions. These data are plotted in Figure 3 as induction vectors (e.g., González-Castillo et al., 2015), which (with the Parkinson sign convention used here) point to anomalous conductors. C1 was observed in a previous two-dimensional MT study of the Appalachian Orogen (Wannamaker, 2005). C4 is a weak, east-west trending conductive feature in the mid to lower crust of central Georgia. Its average vertically integrated conductance (~25-50 km depth) is 210 S; this is marginally greater than a conductance of 190 S for the same region of the prior model. Although the conductivity contrast with the surrounding model domain is minimal, this structure appears in all inverse solutions and is therefore considered to represent a real feature. Structure C5 is a robust conductor in the mid to lower crust of central South Carolina that, at least at mid-crustal depths, weakly connects southwestward to C4 and the southernmost extent of C3.

Anomalies EC1, EC2, and EC3 appear consistently in inversions (Figs. S10-S12) beyond the footprint of our dataset. Although the exact positions and geometries of these structures are not resolved due to present limits on data coverage, their persistence in inversions suggests that they do represent real electrically conductive features outside of the current array. EC1 appears offshore of the study region, beneath the continental shelf; EC2 is imaged in southeastern

Alabama along the border with Georgia; and EC3 lies to the north of the array along the West Virginia-Virginia border. Induction vectors (Fig. 3) point to EC2 and EC3 and are therefore consistent with the high conductivities observed in the inverse solutions in these areas.

Perhaps the most enigmatic feature that appears in all inverse solutions is the large, thick block of resistive material beneath the Piedmont and Coastal Plain physiographic regions (Figs. 1, 2). We refer to this structure, which was observed in a previous two-dimensional MT study of the region (Wannamaker, 2005), as R1. In the preferred inverse solution (Fig. 2), high resistivity values associated with this structure extend to depths greater than 300 km. Resolution tests (see Supplementary Materials) indicate that this feature must maintain bulk resistivity values of at least 1000 Ωm to a depth of at least 200 km.

Strikingly, the northwestern limit of structure R1 coincides with the modern Appalachian topographic escarpment (Figs. 1, 2; see also Figs. S6-S7 for resolution tests). At ~200 km depth, the region to the northwest of the escarpment displays resistivity values on the order of 100 Ωm , whereas the region to the southeast displays resistivity values higher than 1000 Ωm in association with structure R1 (see Figs. S8-S9 for resolution tests). This sharp boundary in deep resistivity is clearly evident in plots of apparent resistivity and phase in an Appalachian-parallel coordinate system (Figs. S13, S14). Therefore, both multiple inversions and the data themselves indicate the presence of a major conductivity contrast between the mantle beneath the modern Appalachian highlands and the mantle beneath the Piedmont and Coastal Plain.

Finally, structure R2 is a small Appalachian-parallel resistive feature that appears in the lowermost crust and uppermost mantle beneath western North Carolina. This structure exhibits resistivity values up to 1000 Ωm and is separated from structure R1 by a zone of moderate electrical conductivity that extends downward from structure C3.

4. Discussion

4.1 Well-Resolved Shallow Structures

Structures C1, C2, C3, C4, and C5 are spatially coincident with terrane sutures inferred from studies of surface geology. As sutures have frequently been associated with elongate crustal conductors (e.g., Boerner et al., 1996; Jones et al., 2005; Wannamaker, 2005; Yang et al., 2015), we interpret these conductive structures as representing the major terrane sutures of the Southern Appalachian Orogen. The high conductivities associated with these structures are likely due to graphitic or authigenic-sulfide-rich sediments that became trapped in these zones of crustal convergence (e.g., Boerner et al., 1996; Wannamaker, 2005). We interpret C1 to represent the main Grenville suture; C2, the Taconic suture; and C3, the main Carolina Superterrane suture.

We interpret C4 and C5 to be associated with the Suwannee terrane.

Structure C1 coincides with the New York-Alabama (NY-AL) Lineament (Fig. 3), a continent-scale aeromagnetic anomaly (e.g., Steltenpohl et al., 2010) that, based upon regional contrasts in radiogenic isotope affinities, has been interpreted to represent the main Grenville suture (Fisher et al., 2010). Our electrical resistivity images therefore provide strong geophysical support for this geologically motivated interpretation. Both the induction vectors (Fig. 3) and inverse solutions indicate that structure C1 is highly conductive, more so than any other feature in the model. Repeated reactivation of the corresponding fault system to accommodate both orogen-perpendicular and orogen-parallel deformation throughout the latest Neoproterozoic and the Paleozoic (Steltenpohl et al., 2010) likely helped to concentrate and connect conductive phases and thereby increase bulk conductivity over time (e.g., Wannamaker, 2005).

Recent research indicates that the Suwannee suture lies to the north of its previously defined trend (Fig. 1; Boote and Knapp, 2016; Hopper et al., 2017; cf. Hatcher, 2010). Therefore, C5 may be part of the reinterpreted Suwannee suture and C4 may be a suture within the larger Suwannee terrane. (The downward continuation of C5 into the mantle shown in the preferred inverse solution is not robust; cf. Figs. S10-S12.) However, whereas seismic receiver function images indicate that the Suwannee suture dips shallowly through the crust, C5 appears at mid- to lower-crustal depths almost directly beneath the inferred surface trace of the redefined Suwannee suture. Resolution tests indicate that depth is poorly constrained for at least the weak southwestern extension of structure C5 (Figs. S10-S12), so this discrepancy may be due to the poor upper-crustal resolution of these long-period MT data. Curiously, the footprint of C5 is spatially coincident with an isolated relative isostatic gravity low (Figs. 2, 4). Structure C5 may therefore hold additional significance beyond representing a terrane suture. Further analysis is needed to explore the nature of this structure, especially as its relationship with C3 and C4 is complex. Incorporation of broadband MT data would greatly clarify these crustal-scale structures.

These conductive features (at least C1, C2, and C3) define lateral limits on the extent of rocks of different terrane affinities in the mid to lower crust. In particular, our results indicate that Grenvillian rocks do not extend southeastward in the lower crust beneath the Piedmont and Coastal Plain, as has been suggested previously (e.g., Cook and Vasudevan, 2006). Furthermore, the interpreted mid- to lower-crustal electrical expressions of the Grenville, Taconic, and Carolina sutures lie almost directly beneath their surface expressions. Therefore, based on the MT images presented here, these sutures appear to extend essentially continuously through the entire crust in the Southern Appalachian Orogen. This structural model stands in contrast to that

from other work (e.g., Cook and Vasudevan, 2006; Hibbard et al., 2002) that has interpreted the upper-crustal expression of these sutures to be significantly offset (~400 km) to the northwest from their continuation at depth. Our conclusions here stand at least for the Appalachian Orogen north of the (redefined) Suwannee suture; because compelling seismic images indicate that the Suwannee suture is a low-angle detachment (Hopper et al., 2017), crustal architecture is likely far more complicated at the southernmost end of the orogen. Further detailed exploration of the geologic implications of these structures is left for future study.

Resistive structure R2 appears approximately coincident with a westward-dipping mid-lithospheric discontinuity that was detected by receiver-function imaging (Wagner et al., 2012). Previous studies have interpreted this seismic structure as a dangling remnant of either the Iapetan slab from accretion of the Carolina Superterrane (Wagner et al., 2012) or the Rheic slab after closure of the ocean between Laurentia and Gondwana (Whalen et al., 2015). However, because Carolinian subduction is believed to have been directed westward (Hibbard et al. 2010), neither of these previous explanations seems geometrically consistent with our resistivity images, which show structure R2 to the northwest of the downward continuation of what we interpret to be the Carolina Superterrane suture (C3). Alternatively, this feature could be a dangling remnant of the Iapetan slab that was trapped during the Taconic Orogeny. However, this interpretation is also geometrically problematic, as Taconic subduction is believed to have been directed to the east (e.g., Abbott and Greenwood, 2001) and structure R2 appears to the southeast of the conductive signature of the Taconic suture (C2). This structure therefore remains enigmatic.

4.2 Poorly Resolved Structures

The high bulk conductivity values associated with EC1 in the preferred inverse solution (Fig. 2) do not appear in all solutions (cf. Figs. S10-S12). This feature is likely an edge effect due to conductive shelf sediments or some other unresolved offshore, crustal-scale conductive structure. Such a conductor could correspond to the Alleghenian suture, which would mark the Laurentian boundary along which Pangea was assembled. However, EC1 appears in inversions southeast of the Suwannee suture, which is the Alleghenian suture in the southernmost Appalachian orogen (e.g., Boote and Knapp, 2016). This unresolved conductor could alternatively represent a structure within the Suwannee terrane.

The coherent, large amplitude, southwest-pointing induction vectors that cover most of Georgia and South Carolina (Fig. 3) require the presence of a major electrical conductivity contrast in the crust or upper mantle beneath southern Alabama or the northernmost Gulf of Mexico. Such a structure is represented in inverse solutions as EC2, although the characteristics of this feature are unresolved. Recent surface-wave tomography (Pollitz and Mooney, 2016) shows an isolated slow seismic anomaly in southern Alabama that may be due to lithospheric modification associated with passage of the Bermuda hotspot track underneath southern Laurentia at the end of the Cretaceous (Cox and Van Arsdale, 2002). Plume impingement could increase lithospheric conductivity by introducing water or even mantle sulfides into the constituent mantle rocks. However, slow shear-wave velocities in southern Georgia (Pollitz and Mooney, 2016) that may also be associated with this hot-spot track spatially coincide with resistive structure R1 in our inverse solutions, which possibly conflicts with what would be expected if hot-spot refertilization had significantly altered the lithosphere in this region. Alternatively, the thick sediment package in the Gulf of Mexico or the edge of resistive structure R1 could be responsible for the pattern in the induction vectors and for the appearance of EC2 in

inverse solutions. Forward-modeling tests suggest that either enhanced mantle conductivity or a sharp southwestern edge on R1 may explain the induction vectors (Fig. S15); however, further expansion of the EarthScope MT dataset into Alabama will be necessary to resolve the lithospheric electrical conductivity structure of this area.

Structure EC3 coincides with a region of Eocene volcanism that hosts the youngest volcanic rocks found on the eastern margin of the United States (e.g., Mazza et al., 2014). This volcanism has been ascribed to asthenospheric upwelling associated with a delamination event (Mazza et al., 2014), although hotspot activity is an equally compelling explanation (Chu et al., 2013). As EC3 lies at the edge of our current data footprint, at present our data cannot clearly distinguish between these two competing hypotheses.

4.3 Deep Lithospheric Conductivity Contrast and the Piedmont Resistor

We interpret resistive structure R1 as representing thick sub-Piedmont lithosphere. In the discussion that follows, we rely on the thermal definition of the lithosphere: the thickness of mantle and crustal material that lies above the $\sim 1300^{\circ}\text{C}$ isotherm.

4.3.1 Constraints from the Magnetotelluric Data: Thick Sub-Piedmont Lithosphere

In our preferred inverse solution, the lithosphere beneath the modern Appalachian highlands displays resistivity values of $\sim 100\text{--}300\ \Omega\text{m}$, which can be explained by moderate hydration ($\sim 10\text{--}100\ \text{ppm H}_2\text{O}$, Fig. 5; Selway, 2014; Gardés et al., 2014) at lower-lithosphere temperatures of $\sim 1000^{\circ}\text{--}1200^{\circ}\text{C}$. The moderately conductive lithosphere beneath the modern Appalachian highlands only extends to depths of $\sim 150\text{--}200\ \text{km}$, as typical asthenospheric conductivity values for moderately hydrated mantle minerals ($\sim 30\ \Omega\text{m}$, Fig. 5; Fullea et al., 2011; Jones et al., 2012)

appear in the inverse solution by a depth of 200 km in this region. Although mantle minerals could display resistivity values of $\sim 30 \Omega\text{m}$ at lithospheric temperatures with more than ~ 500 ppm incorporated H_2O (Gardés et al., 2014), such water contents would be at or above the solubility limit at pressures corresponding to 200 km depth (~ 6 GPa; Ardia et al., 2012). Additionally, if Appalachian lithosphere were to extend to ~ 250 - 300 km depth, temperatures at ~ 100 km would be $\sim 600^\circ\text{C}$ for a reasonable conductive geotherm and the uppermost mantle lithosphere would then need to be hydrated with >1000 ppm H_2O in order to produce resistivity values of $\sim 100 \Omega\text{m}$ (Fig. 5; Yoshino et al., 2009; Jones et al., 2012; Dai and Karato, 2014; Gardés et al., 2014). Such levels of hydration are unrealistic (Keppler and Bolfan-Casanova, 2006). Based on these considerations, the MT data suggest that the modern Appalachian thermal lithosphere is no more than ~ 150 - 200 km thick.

In contrast, the lithosphere beneath the Piedmont and Coastal Plain (R1) must extend to depths greater than 200 km and must be minimally hydrated. For all volumetrically significant mantle minerals (those that will dominantly control electrical conductivity), the maximum resistivity that could possibly be observed at 1300°C (the approximate temperature at the LAB) under dry conditions is $\sim 300 \Omega\text{m}$ (Fig. 5; Constable, 2006; Fullea et al., 2011; Jones et al., 2012; Selway, 2014). Even small amounts of incorporated water (~ 10 ppm H_2O) will lower the maximum possible temperature (Fig. 5). Therefore, the resistivity of dry mantle minerals provides an upper limit on temperature as well as a lower limit on sub-Piedmont thermal lithospheric thickness. As the data require resistivity values of $\sim 1000 \Omega\text{m}$ to a depth of at least 200 km, temperatures at that depth must be $\leq 1200^\circ\text{C}$ and the LAB beneath the Piedmont must therefore lie deeper than 200 km.

As electrical conductivity of dry mantle minerals is controlled primarily by temperature alone (Constable, 2006; Fullea et al., 2011), this conclusion is robust. At lithospheric temperatures and in the absence of interstitial water, thermally activated small-polaron hopping, which amounts to valence swapping between Fe^{2+} and Fe^{3+} within the crystal lattice (Elliot, 1998), is the dominant conduction mechanism in olivine, orthopyroxene, and clinopyroxene (e.g., Selway, 2014). Although this mechanism is dependent on iron content and oxygen fugacity to a limited extent (these control the number of charge carriers), temperature (which controls carrier mobility) is the overwhelmingly dominant factor that determines electrical conductivity (Fig. 5; Constable, 2006; Fullea et al., 2011). Since dry mantle minerals display minimal electrical anisotropy (e.g., Du Frane et al., 2005), this conclusion does not depend on mantle fabric. As electrical conduction in dry mantle silicates is well studied and understood in terms of both laboratory results (e.g., Constable 2006) and solid-state physics theory in general (e.g., Elliot, 1998), our bound on sub-Piedmont lithospheric temperature and, by extension, thermal lithospheric thickness rests on a solid foundation.

Our data thus strongly suggest the presence of a step in the LAB between the modern Appalachian highlands and the Piedmont. This coastward increase in LAB depth is geoelectrically characterized by a contrast between lithospheric resistivity values typical of Phanerozoic lithosphere and anomalously high lithospheric resistivity values.

4.3.2 Comparison to Seismic Images: Minor Agreement and Major Conflict

Our observation of a slightly hydrated lithosphere beneath the modern Southern Appalachian topographic highs is compatible with results from a study of local Pn travel times that indicate uppermost-mantle hydration in this region (MacDougall et al., 2015). Our depth range for the

LAB beneath the Appalachian highlands also agrees with estimates of local lithospheric thickness from body- and surface-wave tomography (Biryol et al., 2016; Pollitz and Mooney, 2016). However, the thick sub-Piedmont lithosphere that we observe with the MT data stands in conflict with images derived from body- and surface-wave tomography (Schmandt and Lin, 2014; Biryol et al., 2016; Pollitz and Mooney, 2016). Mantle lithosphere that extends beyond 200 km depth would follow an anomalously cold conductive geotherm and would therefore be expected to be clearly visible in body-wave travel times as a well-defined fast anomaly. However, no such anomaly is observed in seismic travel-time datasets or in body-wave tomography inversions (Schmandt and Lin, 2014; Biryol et al., 2016). Continent-scale body-wave tomography (Schmandt and Lin, 2014) shows that mantle velocities in this region deviate very little from the reference model. Local compressional body wave tomography (Biryol et al., 2016) shows heterogeneous mantle compressional velocities that generally exhibit small deviations ($<1\%$) from the reference model, although more significant slow-velocity anomalies (up to $\sim 3\%$) are also detected beneath the Piedmont and Coastal Plain. While local surface-wave inversions (Pollitz and Mooney, 2016) do not image an anomalous feature that could correspond to this large lithospheric resistor, more recent continent-scale surface-wave work (Shen and Ritzwoller, 2016) does appear to show relatively high shear-wave velocities beneath the Piedmont and Coastal Plain and lower shear-wave velocities beneath the adjacent Appalachians. Shear-wave splitting measurements show a contrast in behavior between the two lithospheric domains that we image here, although this pattern could be the result of overprinting by shallow lithosphere structures, such as sutures (Long et al., 2016). Measurements of local Pn travel times do indicate higher compressional-wave velocities beneath the Piedmont than beneath the modern

Appalachians (MacDougall et al., 2015), but this contrast could be characteristic of only the shallowest mantle (Biryol et al., 2016).

It is difficult, but not impossible, to reconcile the seismic and the MT results. While temperature is the first-order control on seismic velocity in the upper mantle, the effects of lithology or composition may be more important in defining anomalies than is widely appreciated. For example, an increase in the iron content of mantle rocks and a decrease in ambient temperature have opposite effects on seismic velocities (Cammarano et al., 2003; Lee, 2003). That is, a decrease in magnesium number by 4-5 units can offset effects of decreasing temperature by 100-200° C on seismic velocities so that the net deviation from a reference model is roughly zero. Changes in mineralogy can also affect seismic velocities. For example, a decrease in olivine content from 100% to 60% will decrease V_P by ~1% (Lee, 2003), and enrichment in orthopyroxene (up to ~50%) in particular can further lower V_P by up to 1% (Schutt and Lesher, 2010). Furthermore, mantle pyroxenite can be invisible to body-wave tomography, as under certain circumstances cold pyroxenite may exhibit similar seismic velocities to fertile asthenospheric (i.e., hot) peridotite (Erdman et al., 2016, their Fig. 3). As the MT data lead to the seemingly inescapable conclusion that sub-Piedmont mantle temperatures are colder than would be expected, careful consideration of possible compositional effects on seismic velocity is warranted.

4.3.3 Possible Explanation: A Metasomatized Lithospheric Root that Regrew after Delamination

A major orogen-parallel, post-Alleghenian delamination event has been invoked to explain the generation of CAMP lavas (Whalen et al., 2015). If the resulting void in the mantle lithosphere were filled by material that formed from asthenospheric consumption of the

363 delaminant or that trapped significant volumes of partial melt, then the regrown, now-cold
364 lithospheric root could plausibly be electrically resistive but not particularly seismically
365 anomalous.

366 The model that we propose here is shown graphically in Figure 6. Foundering of the
367 subducted Rheic slab may have led to the initiation of Pangean rifting in this region prior to 200
368 Ma, but a large, pan-Appalachian delamination at 200 Ma spurred CAMP magmatism and
369 accelerated the rifting of Pangea (Whalen et al., 2015). This delamination would have occurred
370 beneath the ancestral orogenic hinterland, which lies beneath the modern Piedmont and Coastal
371 Plain, and would have removed the lowermost, likely eclogitized crust. Fertile asthenospheric
372 peridotite would then upwell to fill the void left by this delamination.

373 If the regrown sub-Piedmont lithosphere were highly fertile, so that the constituent rocks
374 have very low magnesium numbers; rich in pyroxenes, so that any constituent lherzolites could
375 almost be classified as olivine websterites; and/or rich in mantle pyroxenite, then the structure
376 that we observe here could be seismically invisible (Cammarrano et al., 2003; Lee, 2003; Schutt
377 and Lesher, 2010; Erdman et al., 2016). If the step in the LAB between these two lithospheric
378 domains were ~50 km, then for reasonable conductive geotherms the temperature contrast would
379 be small enough for compositional differences to offset the temperature difference. Such unusual
380 mantle compositions could reconcile the MT and the seismic results as long as the regrown
381 lithosphere were minimally hydrated. Excess mantle water could have been removed during
382 CAMP magmatism. The heterogeneity observed in local body-wave tomography (Biryol et al.,
383 2016) may reflect compositional variations in this regrown lithosphere root.

384 Such atypical mantle lithologies could form if the regrown lithosphere trapped abundant
385 asthenospheric melts or if the upwelling asthenosphere consumed significant amounts of the

386 delaminated lithosphere. The Alleghenian lithosphere was likely hydrated to some extent;
387 lithospheric absorption of asthenospheric melts that were generated during dehydration of the
388 delaminant (e.g., Elkins-Tanton, 2005) could result in fertilization of the regrown sub-Piedmont
389 lithosphere. If the Alleghenian lithosphere were already warm, as would be expected following
390 orogenesis, and if it detached slowly, then melting of the delamination itself would be expected
391 (Wang and Currie, 2015). Indeed, the geochemistry of CAMP lavas indicates a shallow-mantle
392 pyroxenite source (Whalen et al., 2015), so delaminated material must have melted to feed this
393 continental flood basalt. By assimilating this melt, the upwelling asthenosphere could have
394 become enriched in a pyroxene component or effectively metasomatized. Global geochemical
395 studies indicate that assimilation of eclogitic material can indeed produce abundant secondary
396 mantle pyroxenite (e.g., Sobolev et al., 2007).

397 With the transition from an active rift zone to a passive margin, the eastern margin of North
398 America would have cooled and subsided. Especially because particularly fertile lithosphere
399 would be relatively dense (Cammarano et al., 2003; Lee, 2003), subsidence of the regrown root
400 could have resulted in a depressed LAB that is still intact today (Fig. 6). Stability of this thick
401 root could be maintained if the constituent mantle rocks remain dry, as the MT data indicate they
402 are, and thereby strong. Further work will be necessary to rigorously test the geodynamic and
403 geochemical requirements and consequences of this possible model.

404 Seismic studies suggest that the crust beneath the modern Appalachian highlands is thicker
405 than the crust beneath the Piedmont lowlands (Hawman et al., 2012; Schmandt et al., 2015; Shen
406 and Ritzwoller, 2016). The model proposed here could provide an explanation for thinner crust in
407 the ancestral orogenic hinterland compared to the ancestral foreland, as the lower Piedmont crust
408 would have been removed during the delamination event.

409 An isostatic gravity high that spatially coincides with the highly resistive structure imaged
410 here (R1; Figs. 2, 4; Simpson et al., 1986) also supports the existence of exceptionally fertile,
411 dense lithosphere beneath the Piedmont. Although this Appalachian-parallel isostatic high has
412 been interpreted as due in part to mafic lithologies such as CAMP lavas, a single coherent
413 explanation for its origin has been lacking (Simpson et al., 1986). The model that we propose
414 here provides such an explanation for this gravity signal.

415 Thermal measurements from the southeastern United States show that heat flow is generally
416 higher in the Piedmont than in the adjacent Appalachians (Smith et al., 1981), seemingly in
417 contrast to what would be expected for the thick sub-Piedmont thermal lithosphere that we image
418 here. However, differences in heat production between the rocks of the Appalachian crust and the
419 rocks of the Piedmont crust could mask the deeper mantle heat-flow signature. Alternatively,
420 higher heat production within the thick, fertile sub-Piedmont lithosphere could yield a higher
421 heat flow than from the adjacent sub-Appalachian lithosphere. In this scenario, the temperature
422 difference between the sub-Piedmont mantle and the adjacent sub-Appalachian mantle could be
423 diminished by high internal heat production in the fertile sub-Piedmont lithospheric root. This
424 low thermal contrast would then certainly allow compositional effects to exert significant control
425 on seismic wave speeds.

426 Recent seismic body-wave tomography has been used to argue for continuing piecemeal
427 delamination of the lithosphere beneath the southeastern United States (Biryol et al., 2016).
428 Based on our results here, particularly our observation of the coherently resistive nature of the
429 sub-Piedmont lithosphere, we cannot support the interpretation that delamination events occurred
430 throughout the Cenozoic and are still occurring at present.

431

4.3.4 Implications for Appalachian Topographic Rejuvenation

Regardless of the exact nature and history of this anomalously thick sub-Piedmont lithosphere, its existence does indicate a major, previously unappreciated contrast in the upper mantle beneath the southeastern United States. The spatial correspondence between this lithospheric boundary and the modern Appalachian topographic scarp (Fig. 2) is likely not a coincidence; rather, this contrast in lithospheric properties may hold important consequences for Appalachian topographic rejuvenation.

Edge-driven, small-scale convection at the boundary between relatively thin Appalachian lithosphere and relatively thick Piedmont lithosphere could have driven the episodes of topographic rejuvenation that are suggested by the geomorphic, thermochronologic, and Atlantic sedimentary records (Fig. 6). Shear-induced flow associated with overall mantle motion beneath eastern North America could drive such a small convection cell (Fig. 6; Kaislaniemi and van Hunen, 2014). Vertical mantle flow associated with edge convection in this region may be responsible for elongating the edge of this resistive anomaly with depth (Kaislaniemi and van Hunen, 2014), so that it may in fact extend to depths significantly greater than 200 km. Hydration of the sub-Appalachian lithospheric mantle by dewatering of the Farallon slab (van der Lee et al., 2008) could have played an important role in enabling this small-scale convection.

5. Conclusions

Inversion of MT data from the southeastern United States provides new insights into the architecture of the Appalachian Orogen and also reveals the presence of an anomalous lithospheric block beneath the Piedmont and Coastal Plain. Based on these MT data, the lithosphere beneath the Piedmont must extend to >200 km depth. In contrast, the lithosphere

beneath the modern Appalachians only extends to 150-200 km depth. Although such relatively thick Piedmont lithosphere has not been observed by seismic studies, the MT data require low temperatures ($\sim 1100^{\circ}\text{C}$) to depths of ~ 200 km. This lithospheric step is therefore robust.

The origin of the thick sub-Piedmont lithosphere and the cause of its apparent long-term geodynamic stability are unclear at present. However, the contrast between highly resistive lithosphere and moderately conductive lithosphere corresponds to the topographic escarpment of the modern Appalachian Mountains. This structure therefore likely holds important implications for Appalachian topographic rejuvenation. We propose that it has enabled edge-driven convection that has provided dynamic support for topography in the eastern United States.

Further detailed study of this region is clearly warranted. Future collaboration with seismologists, geodynamicists, and geochemists is necessary in order to better characterize the composition and physical state of the Piedmont resistor and to explore the implications of this structure for the past and present geodynamics of the southeastern United States. The eastern boundary of this structure is poorly resolved at present due to the current limits of our dataset. A seafloor MT survey offshore of North Carolina, South Carolina, and Georgia would be tremendously beneficial in better understanding this region.

Acknowledgements

We thank Emily Hart, Kyle Jones, Allen Hooper, Kyle McDonald, Taryn Bye, Eleanor Kester, Lana Erofeeva, Brady Fry, Lu Pellerin, and Adam Schultz for their work in collecting and processing these data. Bo Yang and Naser Meqbel assisted greatly with use of ModEM in this project. Conversations with and input from Nikki Moore, Phil Wannamaker, Dave Graham, Gene Humphreys, Steve Constable, Paul Bedrosian, and Eric Kirby greatly benefited this work. We

thank Rob Harris and Brandon Schmandt for valuable feedback on a preliminary version of this paper. We also thank Kate Selway, Ian Ferguson, and Peter Shearer for very helpful reviews of the manuscript.

This research was supported by NSF Grant EAR1053628 and by the NSF Graduate Research Fellowship Program under Grant 1314109-DGE.

References

Abbott, R.N., Greenwood, J.P., 2001. Retrograde metamorphism of eclogite in the southern Appalachian Mountains, U.S.A.—A case involving seamount subduction? *Journal of Metamorphic Geology* 19, 433-443. <http://dx.doi.org/10.1046/j.0263-4929.2001.00321.x>.

Ardia, P., Hirschmann, M.M., Withers, A.C., Tenner, T.J., 2012. H₂O storage capacity of olivine at 5-8 GPa and consequences for dehydration partial melting of the upper mantle. *Earth and Planetary Science Letters* 345-348, 104-116. <http://dx.doi.org/10.1016/j.epsl.2012.05.038>.

Biryol, C.B., Wagner, L.S., Fischer, K.M., Hawman, R.B., 2016. Relationship between observed upper mantle structures and recent tectonic activity across the Southeastern United States. *Journal of Geophysical Research: Solid Earth* 121, 3393-3414. <http://dx.doi.org/10.1002/2015JB012698>.

Boerner, D.E., Kurtz, R.D., Craven, J.A., 1996. Electrical conductivity and Paleo-Proterozoic foredeeps. *Journal of Geophysical Research* 101, 13775-13791. <http://dx.doi.org/10.1029/96JB00171>.

Boote, S.K., Knapp, J.H., 2016. Offshore extent of Gondwanan Paleozoic strata in the southeastern United States: The Suwannee suture zone revisited. *Gondwana Research* 40, 199-210. <http://dx.doi.org/10.1016/j.gr.2016.08.011>.

Cammarano, F., Goes, S., Vacher, P., Giardini, D., 2003. Inferring upper-mantle temperatures from seismic velocities. *Physics of the Earth and Planetary Interiors* 138, 197-222. [http://dx.doi.org/10.1016/S0031-9201\(03\)00156-0](http://dx.doi.org/10.1016/S0031-9201(03)00156-0).

Chu, R., Leng, W., Helmberger, D.V., Gurnis, M., 2013. Hidden hotspot track beneath the eastern United States. *Nature Geoscience* 6, 963-966. <http://dx.doi.org/10.1038/ngeo1949>.

Constable, S., 2006. SEO3: A new model of olivine electrical conductivity. *Geophysical Journal International* 166, 435-437. <http://dx.doi.org/10.1111/j.1365-246X.2006.03041.x>.

Cook, F.A., Vasudevan, K., 2006. Reprocessing and enhanced interpretation of the initial COCORP Southern Appalachians traverse. *Tectonophysics* 420, 161-174. <http://dx.doi.org/10.1016/j.tecto.2006.01.022>.

Cox, R.T., Van Arsdale, R.B., 2002. The Mississippi Embayment, North America: a first order continental structure generated by the Cretaceous superplume mantle event. *Journal of Geodynamics* 34, 163-176. [http://dx.doi.org/10.1016/S0264-3707\(02\)00019-4](http://dx.doi.org/10.1016/S0264-3707(02)00019-4).

Dai, L., Karato, S., 2014. High and highly anisotropic electrical conductivity of the asthenosphere due to hydrogen diffusion in olivine. *Earth and Planetary Science Letters* 408, 79-86. <http://dx.doi.org/10.1016/j.epsl.2014.10.003>.

Du Frane, W.L., Roberts, J.J., Toffelmier, D.A., Tyburczy, J.A., 2005. Anisotropy of electrical conductivity in dry olivine. *Geophysical Research Letters* 32, L24315. <http://dx.doi.org/10.1029/2005GL023879>.

Elkins-Tanton, L.T., 2005. Continental magmatism caused by lithospheric delamination. *In* Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L., eds. *Plates, plumes, and paradigms*. Geological Society of America Special Paper 388, 449-461. <http://dx.doi.org/10.1130/0-8137-2388-4.449>.

Elliott, S., 1998. *The Physics and Chemistry of Solids*, Wiley, England.

Erdman, M.E., Lee, C.-T. A., Levander, A., Jiang, H., 2016. Role of arc magmatism and lower crustal foundering in controlling elevation history of the Nevadaplano and Colorado Plateau: A case study of pyroxenitic lower crust from central Arizona, USA. *Earth and Planetary Science Letters* 439, 48-57. <http://dx.doi.org/10.1016/j.epsl.2016.01.032>.

Fisher, C.M., Loewy, S.L., Miller, C.F., Berquist, P., Van Schmus, W.R., Hatcher, R.D., Jr., Wooden, J.L., Fullagar, P.D., 2010. Whole-rock Pb and Sm-Nd isotopic constraints on the growth

of southeastern Laurentia during Grenvillian orogenesis. Geological Society of America Bulletin
122, 1646-1659. <http://dx.doi.org/10.1130/B30116.1>.

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, 1009-1029.
<http://dx.doi.org/10.1002/2014TC003760>.

Fullea, J., Muller, M.R., Jones, A.G., 2011. Electrical conductivity of continental lithospheric
mantle from integrated geophysical and petrological modeling: Application to the Kaapvaal
Craton and Rehoboth Terrane, southern Africa. Journal of Geophysical Research 116, B10202.
<http://dx.doi.org/10.1029/2011JB008544>.

Gallen, S.F., Wegmann, K.W., Bohnenstiehl, D.R., 2013. Miocene rejuvenation of topographic
relief in the southern Appalachians. GSA Today 23, 4-10.
<http://dx.doi.org/10.1130/GSATG163A.1>.

Gardés, E., Gaillard, F., Tarits, P., 2014. Toward a unified hydrous olivine electrical conductivity
law. Geochemistry, Geophysics, Geosystems 15, 4984-5000.
<http://dx.doi.org/10.1002/2014GC005496>.

González-Castillo, L., Galindo-Zaldívar, J., Junge, A., Martínez-Moreno, F.J., Löwer, A., Sanz de
Galdeano, C., Pedrera, A., López-Garrido, A.C., Ruiz-Constán, A., Ruano, P., Martínez-Martos,
M., 2015. Evidence of a large deep conductive body within the basement of Guadalquivir

foreland Basin (Betic Cordillera, S-Spain) from tipper vector modelling: Tectonic implications.
Tectonophysics 663, 354-363. <http://dx.doi.org/10.1016/j.tecto.2015.08.013>.

Hatcher, R.D., Jr., 2010. The Appalachian orogen: A brief summary, *in* Tollo, R.P., Bartholomew, M.J., Hibbard J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region. Geological Society of America Memoir 206, 1-19.
[http://dx.doi.org/10.1130/2010.1206\(01\)](http://dx.doi.org/10.1130/2010.1206(01)).

Hawman, R.B., Khalifa, M.O., Baker, M.S., 2012. Isostatic compensation for a portion of the Southern Appalachians: Evidence from a reconnaissance study using wide-angle, three-component seismic soundings. Geological Society of America Bulletin 124, 291-317.
<http://dx.doi.org/10.1130/B30464.1>.

Hibbard, J.P., van Staal, C.R., Rankin, C.W., 2010. Comparative analysis of the geological evolution of the northern and southern Appalachian orogen: Late Ordovician-Permian. *In* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region. Geological Society of America Memoir 206, 51-69. [http://dx.doi.org/10.1130/2010.1206\(03\)](http://dx.doi.org/10.1130/2010.1206(03)).

Hopper, E., Fischer, K.M., Wagner, L.S., Hawman, R.B., 2017. Reconstructing the end of the Appalachian orogen. Geology 45, 15-18. <http://dx.doi.org/10.1130/G38453.1>.

Jones, A.G., Ledo, J., Ferguson, I.J., 2005. Electromagnetic images of the Trans-Hudson orogen: the North American Central Plains anomaly revealed. *Canadian Journal of Earth Sciences* 32, 457-478. <http://dx.doi.org/10.1139/e05-018>.

Jones, A.G., Fullea, J., Evans, R.L., Muller, M.R., 2012. Water in cratonic lithosphere: Calibrating laboratory-determined models of electrical conductivity of mantle minerals using geophysical and petrological observations. *Geochemistry, Geophysics, Geosystems* 13, 27. <http://dx.doi.org/10.1029/2012GC004055>.

Kaislaniemi, L., van Hunen, J., 2014. Dynamics of lithospheric thinning and mantle melting by edge-driven convection: Application to Moroccan Atlas mountains. *Geochemistry, Geophysics, Geosystems* 15, 3175-3189. <http://dx.doi.org/10.1002/2014GC005414>.

Kelbert, A., Meqbel, N., Egbert, G.D., Tandon, K., 2014. ModEM: A modular system for inversion of electromagnetic geophysical data. *Computers & Geosciences* 66, 40-53. <http://dx.doi.org/10.1016/j.cageo.2014.01.010>.

Keppler, H., Bolfan-Casanova, N., 2006. Thermodynamics of Water Solubility and Partitioning. *In* Keppler, H., Smyth, J.R., eds. *Water in Nominally Anhydrous Minerals*. *Reviews in Mineralogy and Geochemistry* 62, 193-230. <http://dx.doi.org/10.2138/rmg.2006.62.9>.

Lee, C.-T. A., 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. *Journal of Geophysical Research* 108, B92441.

<http://dx.doi.org/10.1029/2003JB002413>.

Liu, L., 2014. Rejuvenation of Appalachian topography caused by subsidence-induced differential erosion. *Nature Geoscience* 7, 518-523. <http://dx.doi.org/10.1038/ngeo2187>.

Long, M.D., Jackson, K.G., McNamara, J.F., 2016. *SKS* splitting beneath Transportable Array stations in eastern North America and the signature of past lithospheric deformation. *Geochemistry, Geophysics, Geosystems* 17, 2-15. <http://dx.doi.org/10.1002/2015GC006088>.

MacDougall, J.G., Fischer, K.M., Forsyth, D.W., Hawman, R.B., Wagner, L.S., 2015. Shallow mantle velocities beneath the southern Appalachians from *P_n* phases. *Geophysical Research Letters* 42, 339-345. <http://dx.doi.org/10.1002/2014GL062714>.

Mazza, S.E., Gazel, E., Johnson, E.A., Kunk, M.J., McAleer, R., Spotila, J.A., Bizimis, M., Coleman, D.S., 2014. Volcanoes of the passive margin: The youngest magmatic event in eastern North America. *Geology* 42, 483-486. <http://dx.doi.org/10.1130/G35407.1>.

McKeon, R.E., Zeitler, P.K., Pazzaglia, F.J., Idleman, B.D., Enkelmann, E., 2014. Decay of an old orogen: Inferences about Appalachian landscape evolution from low-temperature thermochronology. *Geological Society of America Bulletin* 126, 31-46.

<http://dx.doi.org/10.1130/B30808.1>.

Miller, S.R., Sak, P.B., Kirby, E., Bierman, P.R., 2013. Neogene rejuvenation of central Appalachian topography: Evidence for differential rock uplift from stream profiles and erosion rates. *Earth and Planetary Science Letters* 369-370, 1-12.

<http://dx.doi.org/10.1016/j.epsl.2013.04.007>.

Moucha, R., Forte, A.M., Mitrovica, J.X., Rowley, D.B., Quéré, S., Simmons, N.A., Grand, S.P., 2008. Dynamic topography and long-term sea-level variations: There is no such thing as a stable continental platform. *Earth and Planetary Science Letters* 271, 101-108.

<http://dx.doi.org/10.1016/j.epsl.2008.03.056>.

Ogawa, Y., Jones, A.G., Unsworth, M.J., Booker, J.R., Lu, X., Craven, J., Roberts, B., Parmelee, J., Farquharson, C., 1996. Deep electrical conductivity structures of the Appalachian Orogen in the southeastern U.S. *Geophysical Research Letters* 23, 1597-1600.

<http://dx.doi.org/10.1029/95GL03601>.

Phillips, J.D., Duval, J.S., Ambroziak, R.A., 1993. National geophysical data grids: gamma-ray, gravity, magnetic, and topographic data for the conterminous United States. United States Geological Survey Digital Data Series 9. <http://mrdata.usgs.gov/geophysics/gravity.html> (accessed Oct. 1, 2016).

Poag, C.W., Sevon, W.D., 1989. A record of Appalachian denudation in postrift Mesozoic and Cenozoic sedimentary deposits of the U.S. Middle Atlantic continental margin. *Geomorphology* 2, 119-157. [http://dx.doi.org/10.1016/0169-555X\(89\)90009-3](http://dx.doi.org/10.1016/0169-555X(89)90009-3).

Pollitz, F.F., Mooney, W.D., 2016. Seismic velocity structure of the crust and shallow mantle of the Central and Eastern United States by seismic surface wave imaging. *Geophysical Research Letters* 43, 118-126. <http://dx.doi.org/10.1002/2015GL066637>.

Prince, P.S., Spotila, J.A., 2013. Evidence of transient topographic disequilibrium in the landward passive margin river system: knickpoints and paleo-landscapes of the New River basin, southern Appalachians. *Earth Surface Processes and Landforms* 38, 1685-1699. <http://dx.doi.org/10.1002/esp.3406>.

Schmandt, B., Lin, F.-C., 2014. *P* and *S* wave tomography of the mantle beneath the United States. *Geophysical Research Letters* 41, 6342-6349. <http://dx.doi.org/10.1002/2014GL061231>.

Schmandt, B., Lin, F.-C., Karlstrom, K.E., 2015. Distinct crustal isostasy trends east and west of the Rocky Mountain Front. *Geophysical Research Letters* 42, 10290-10298. <http://dx.doi.org/10.1002/2015GL066593>.

Schutt, D.L., Leshner, C.E., 2010. Compositional trends among Kaapvaal Craton garnet peridotite xenoliths and their effects on seismic velocity and density. *Earth and Planetary Science Letters* 300, 367-373. <http://dx.doi.org/10.1016/j.epsl.2010.10.018>.

Selway, K., 2014. On the Causes of Electrical Conductivity Anomalies in Tectonically Stable Lithosphere. *Surveys in Geophysics* 35, 219-257. <http://dx.doi.org/10.1007/s10712-013-9235-1>.

Shen, W., Ritzwoller, M.H., 2016. Crustal and uppermost mantle structure beneath the United States. *Journal of Geophysical Research: Solid Earth* 121, 37.

<http://dx.doi.org/10.1002/2016JB012887>.

Simpson, R.W., Jachens, R.C., Blakely, R.J., Saltus, R.W., 1986. A New Isostatic Residual Gravity Map of the Conterminous United States With a Discussion on the Significance of Isostatic Residual Anomalies. *Journal of Geophysical Research* 91, 8348-8372.

<http://dx.doi.org/10.1029/JB091iB08p08348>.

Smith, D.L., Gregory, R.G., Emhof, J.W., 1981. Geothermal Measurements in the Southern Appalachian Mountains and Southeastern Coastal Plains. *American Journal of Science* 281, 282-298. <http://dx.doi.org/10.2475/ajs.281.3.282>.

Sobolev, A.V., Hofmann, A.W., Kuzmin, D.V., Yaxley, G.M., Arndt, N.T., Chung, S.-L., Danyushevsky, L.V., Elliott, T., Frey, F.A., Garcia, M.O., Gurenko, A.A., Kamenetsky, V.S., Kerr, A.C., Krivolutsкая, N.A., Matvienkov, V.V., Nikogosian, I.K., Rocholl, A., Sigurdsson, I.A., Sushchevskaya, N.M., Teklay, M., 2007. The Amount of Recycled Crust in Sources of Mantle-Derived Melts. *Science* 316, 412-417. <http://dx.doi.org/10.1126/science.1138113>.

Spasojević, S., Liu, L., Gurnis, M., Müller, R.D., 2008. The case for dynamic subsidence of the U.S. east coast since the Eocene. *Geophysical Research Letters* 35, L08305.

<http://dx.doi.org/10.1029/2008GL033511>.

Steltenpohl, M.G., Zietz, I., Horton, J.W., Jr., Daniels, D.L., 2010. New York-Alabama lineament: A buried right-slip fault bordering the Appalachians and mid-continent North America. *Geology* 38, 571-574. <http://dx.doi.org/10.1130/G30978.1>.

van der Lee, S., Regenauer-Lieb, K., Yuen, D.A., 2008. The role of water in connecting past and future episodes of subduction. *Earth and Planetary Science Letters* 273, 15-27. <http://dx.doi.org/10.1016/j.epsl.2008.04.041>.

Wagner, L.S., Stewart, K., Metcalf, K., 2012. Crustal-scale shortening structures beneath the Blue Ridge Mountains, North Carolina, USA. *Lithosphere* 4, 242-256. <http://dx.doi.org/10.1130/L184.1>.

Wang, H., Currie, C.A., 2015. Magmatic expressions of continental lithosphere removal. *Journal of Geophysical Research: Solid Earth* 120, 7239-7260. <http://dx.doi.org/10.1002/2015JB012112>.

Wannamaker, P.E., 2005. Anisotropy versus Heterogeneity in Continental Solid Earth Electromagnetic Studies: Fundamental Response Characteristics and Implications for Physicochemical State. *Surveys in Geophysics* 26, 733-765. <http://dx.doi.org/10.1007/s10712-005-1832-1>.

Whalen, L., Gazel, E., Vidito, C., Puffer, J., Bizimis, M., Henika, W., Caddick, M.J., 2015. Supercontinental inheritance and its influence on supercontinental breakup: The Central Atlantic

Magmatic Province and the breakup of Pangea. *Geochemistry, Geophysics, Geosystems* 16, 3532-3554. <http://dx.doi.org/10.1002/2015GC005885>.

Willett, S.D., McCoy, S.W., Perron, J.T., Goren, L., Chen, C.-Y., 2014. Dynamic Reorganization of River Basins. *Science* 343, 9. <http://dx.doi.org/10.1126/science.1248765>.

Yang, B., Egbert, G.D., Kelbert, A., Meqbel, N.M., 2015. Three-dimensional electrical resistivity of the north-central USA from EarthScope long period magnetotelluric data. *Earth and Planetary Science Letters* 422, 87-93. <http://dx.doi.org/10.1016/j.epsl.2015.04.006>.

Yoshino, T., Matsuzaki, T., Shatskiy, A., Katsura, T., 2009. The effect of water on the electrical conductivity of olivine aggregates and its implications for the electrical structure of the upper mantle. *Earth and Planetary Science Letters* 288, 291-300. <http://dx.doi.org/10.1016/j.epsl.2009.09.032>.

Figure Captions

Figure 1: Overview map of the study region. Orange inverted triangles indicate EarthScope MT sites that constitute our dataset. Black solid lines delineate major terrane boundaries as determined from geologic datasets (adapted from Hatcher, 2010). Black dotted line indicates the recently reinterpreted surface trace of the Suwannee suture (Boote and Knapp, 2016; Hopper et al., 2017). White dashed lines divide the major physiographic provinces referenced in the text (adapted from USGS physiographic province dataset). Basemap shows modern Southern Appalachian topography. Abbreviations for US states that are shown on the map are as follows:

VA, Virginia; WV, West Virginia; KY, Kentucky; TN, Tennessee; NC, North Carolina; SC, South Carolina; GA, Georgia; AL, Alabama.

Figure 2: Depth slices and cross sections through the preferred inverse solution. Each cross section is paired with the corresponding topographic profile. Labels that begin with *C* denote well-resolved conductive structures that are described in the text; labels that begin with *EC* denote poorly resolved conductive features mentioned in the text; and labels that begin with *R* denote resistive structures discussed in the text. The off-shore southeastern limit of R1 is poorly resolved at present; see Figure S7 and the accompanying text in the Supplementary Materials for a discussion of resolution.

Figure 3: Vertical magnetic field transfer function data (tippers) at 1092 s plotted as induction vectors with the Parkinson sign convention. When plotted in this manner, these arrows point towards anomalous conductivity contrasts. These data delineate a feature along which the induction vectors change direction by 180° in the northwestern portion of our data coverage. This linear feature corresponds to the trace of the New York-Alabama (NY-AL) Lineament. The induction vectors from the vast majority of the southern sites in our dataset point towards a major conductivity contrast beyond our spatial footprint to the southwest, in southern Alabama or the northern Gulf of Mexico.

Figure 4: Isostatic gravity map for the southeastern United States (from Phillips et al., 1993; data available at <http://mrdata.usgs.gov/geophysics/gravity.html>). Note the relative isostatic gravity

low that spatially corresponds to electrically conductive structure C5. The major Appalachian-parallel isostatic gravity high coincides with electrically resistive structure R1.

Figure 5: Resistivity as a function of temperature for olivine (ol), orthopyroxene (opx), and clinopyroxene (cpx). As these three minerals are the dominant phases in the upper mantle, they will control mantle resistivity values (Fullea et al. 2011, Selway 2014). Black lines are for dry olivine and demonstrate the minimal effect that compositional variations have on electrical conductivity (compositional effects are similarly small for pyroxenes). Red and green lines are representative of dry orthopyroxene and clinopyroxene resistivity, respectively. Blue lines demonstrate the effects of adding small amounts of water to mantle minerals. The blue-shaded region denotes the resistivity values that are observed for structure R1. The green-shaded region denotes resistivity values that are observed for the region beneath the modern Appalachian highlands. The curves plotted here are representative of mantle mineral resistivities as a function of temperature. Other calibrations differ slightly but are generally in agreement with those shown here. These calibrations are from Fullea et al. (2011), Jones et al. (2012), and Gardés et al. (2014).

Figure 6: Possible model for the formation of the sub-Piedmont lithospheric resistor. Delamination of pyroxenite-rich mantle and eclogitized lower crust from the Alleghenian Orogen leads to CAMP magmatism as well as development of a void in the Appalachian lithosphere that is filled by upwelling asthenosphere. This asthenospheric mantle assimilates material from the delaminant and thereby becomes highly fertilized or metasomatized. As the eastern Laurentian margin cools after opening of the Atlantic, this region subsides. Lithospheric cooling and the

797 high density of the fertile regrown root allow for development of a step in the LAB, which now
798 supports edge convection that can drive topographic disequilibrium.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

~230 Ma: Assembly of Pangea

~200 Ma: Delamination & CAMP Magmatism

~190 Ma: Rifting

~150 Ma: Cooling & Subsidence

~100 Ma - Present: Edge Convection