Orogenesis, rifting, and post-rift evolution: What have we learned from EarthScope in eastern North America?

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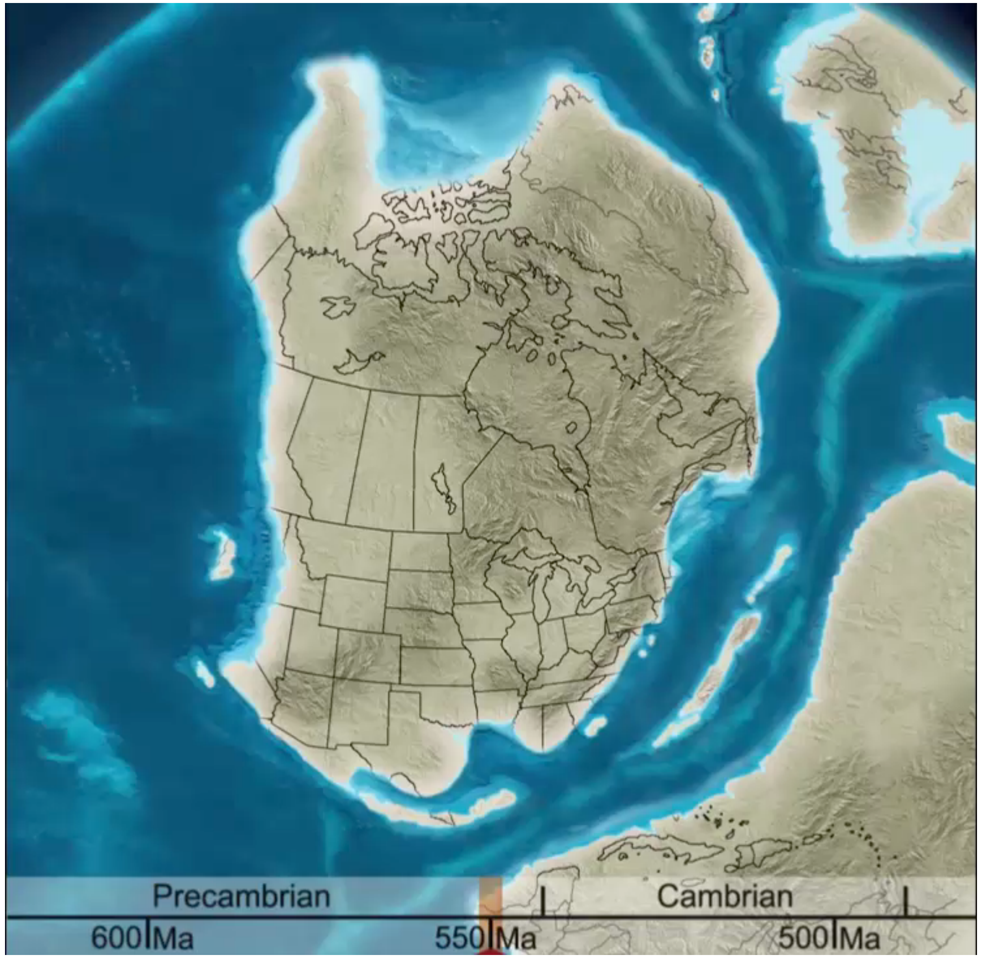
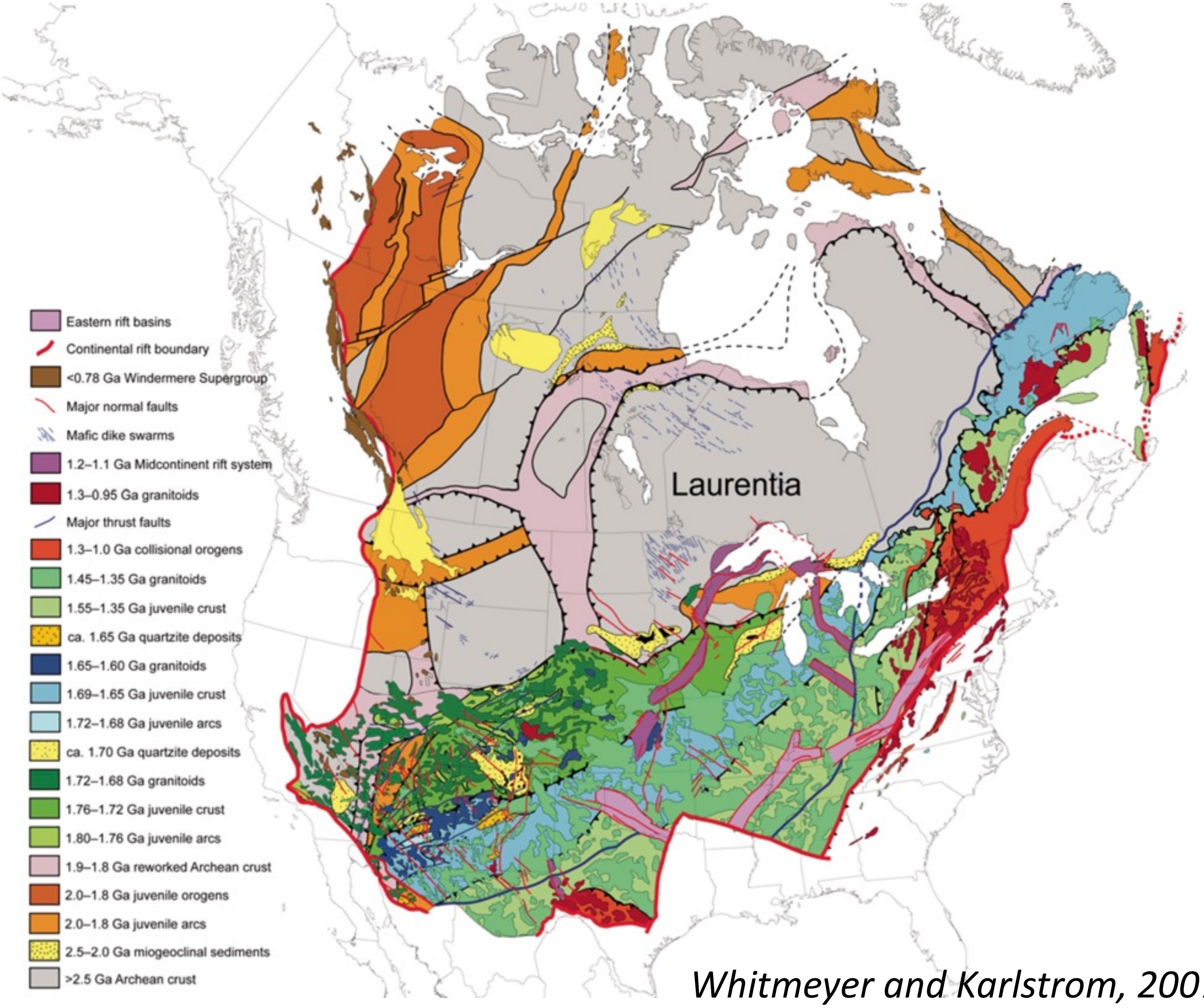
with contributions from: Margaret Benoit (now at NSF), Rob Evans (WHOI), Scott King (Va. Tech.), Eric Kirby (Oregon State), Heather Ford (UC-Riverside), Juan Aragon (Yale), Kenneth Jackson (Yale), John McNamara (Yale), Lauren Abrahams (U. Wisconsin), Erin Wirth (U. Washington)

Structure and evolution of the North American continent: a story of orogenesis and rifting

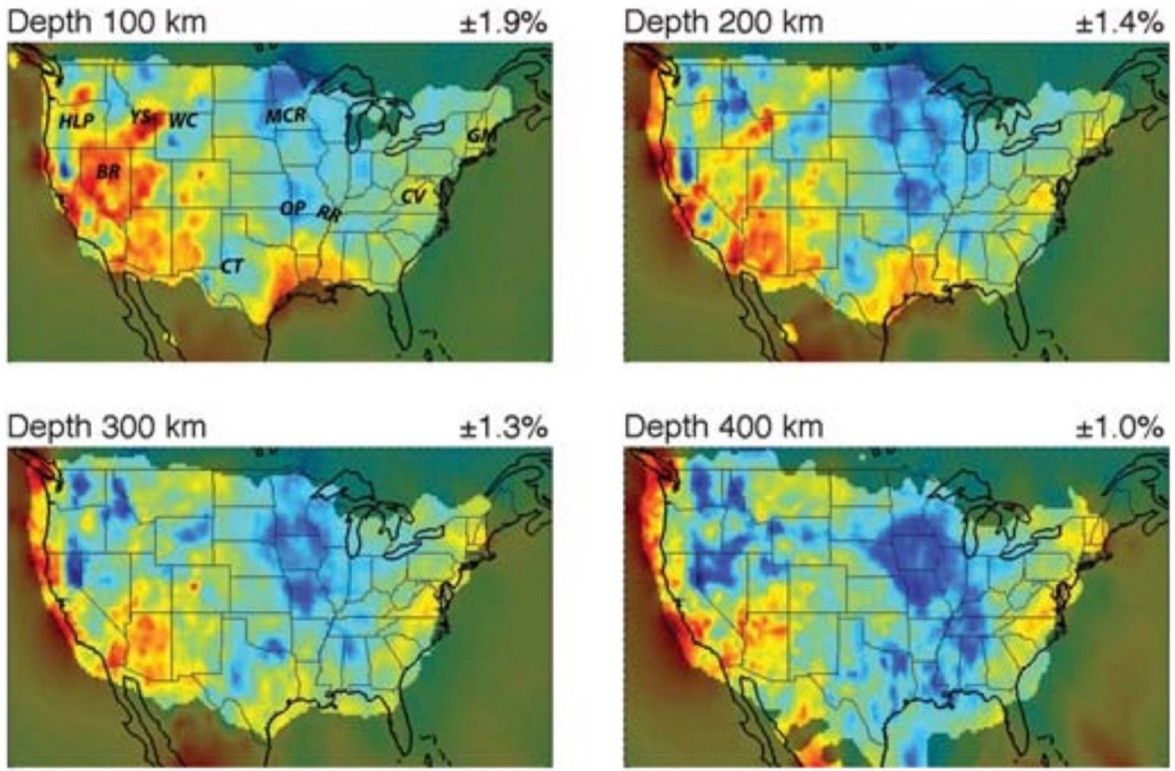


Interactive Geology Project, CU Boulder; R. Blakey et al.

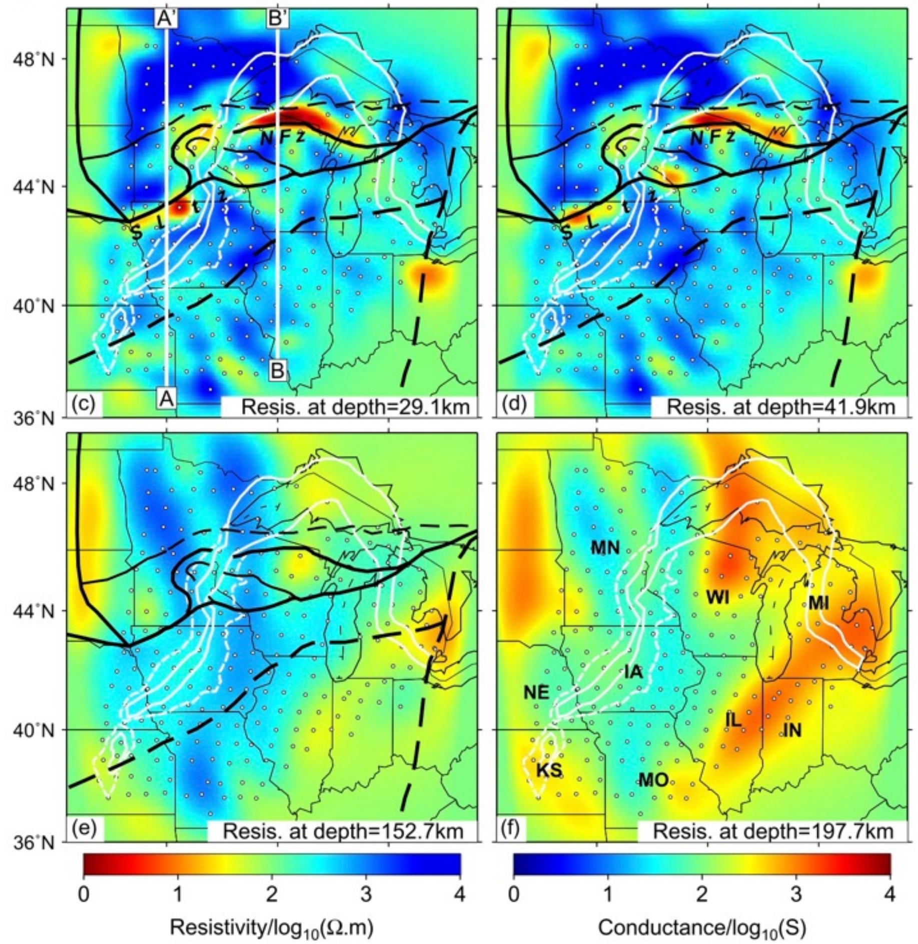


Whitmeyer and Karlstrom, 2007

Large-scale and regional views of the North American continent from EarthScope data



Burdick et al., 2017



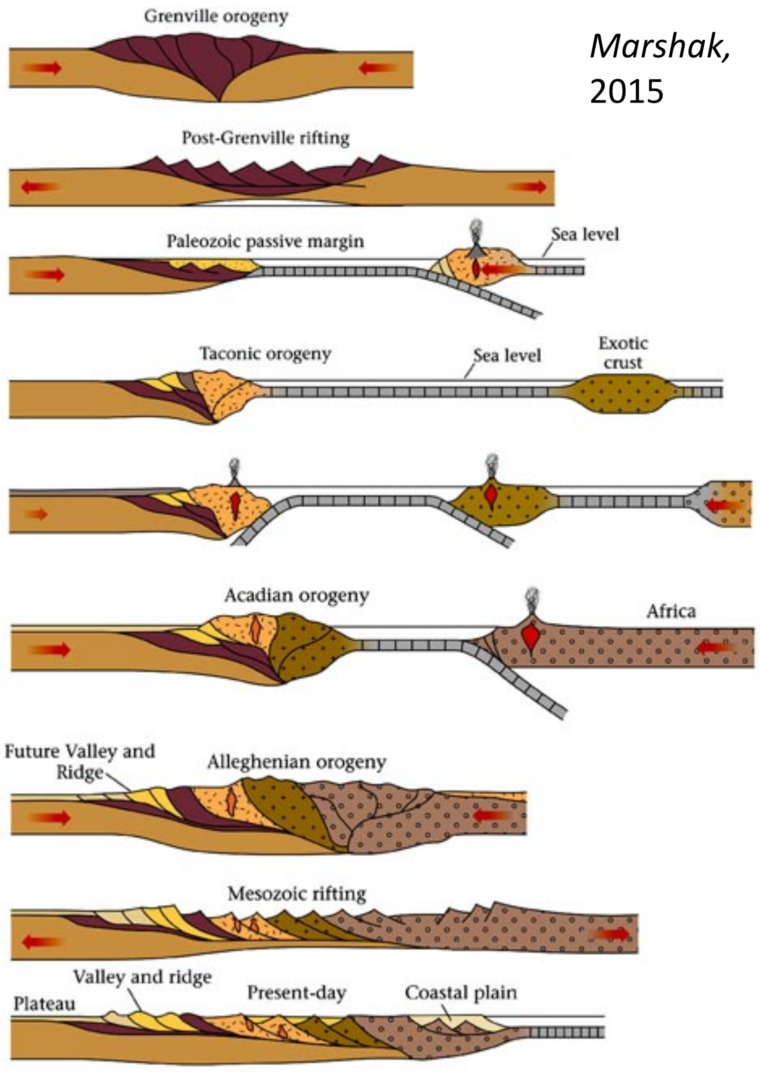
Yang et al., 2015

Spectacular images of lithospheric heterogeneity in seismic velocity (left) and electrical resistivity (right) in regions that have been affected by orogenesis and rifting in the past.

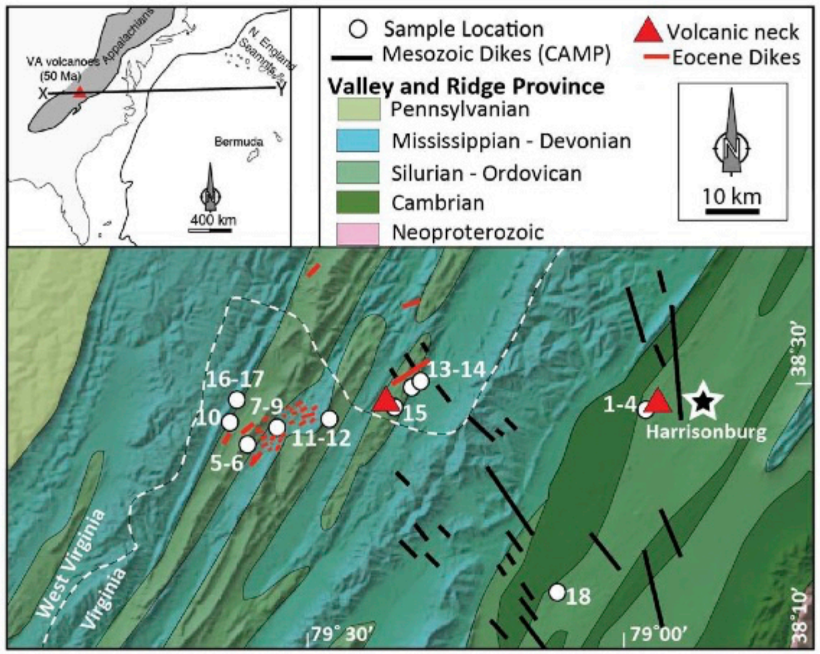
Insights into how orogenesis and rifting modify the continental lithosphere from EarthScope studies

- A focus on the eastern North America passive margin
  - New insights into lithospheric deformation from seismic anisotropy: how do orogenesis and rifting deform the lithosphere?
  - A detailed look at crustal structure beneath the central Appalachians: Crustal evolution in an ancient orogen
  - Post-rifting modification of ENAM via lithospheric removal and implications

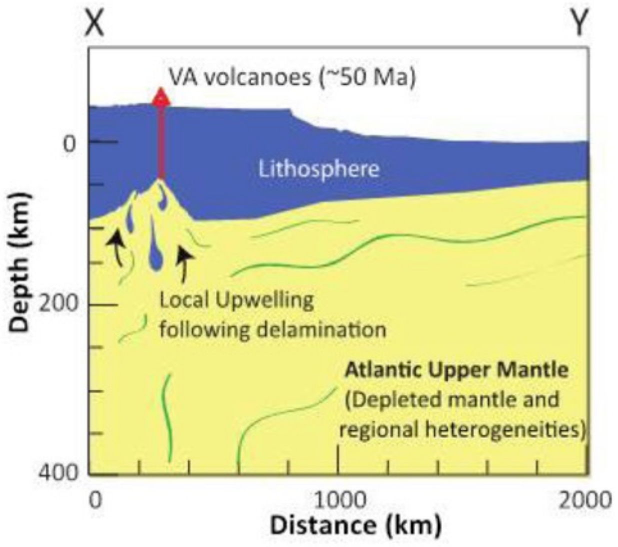
The Eastern North American Margin (ENAM): two complete Wilson cycles of orogenesis and rifting, and ~200 Ma of post-rift evolution



Marshak, 2015



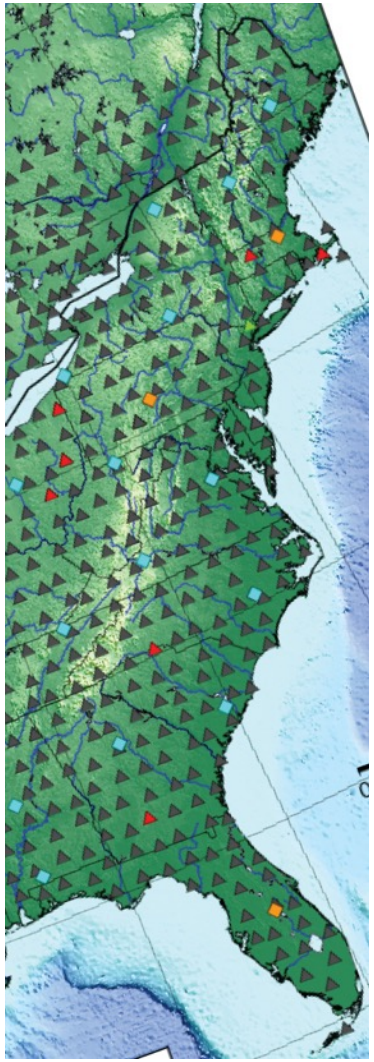
Mazza et al., 2014

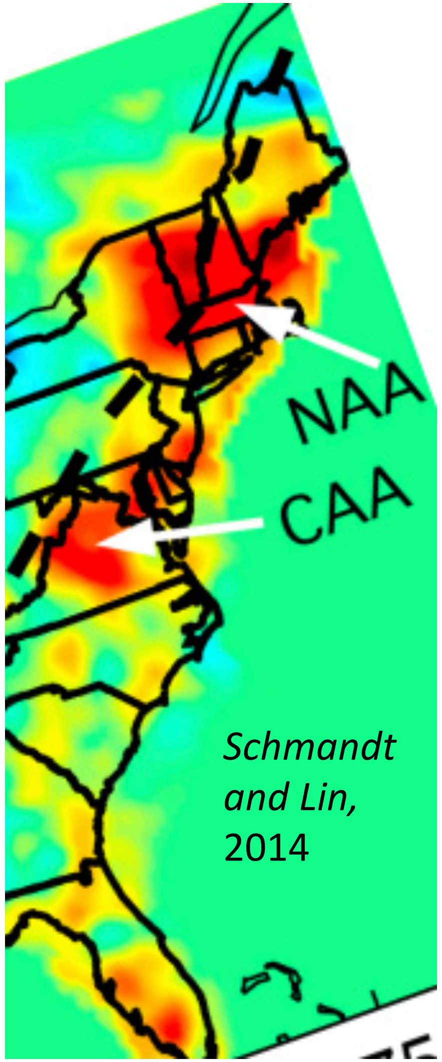


Eocene basalts near Harrisonburg, VA

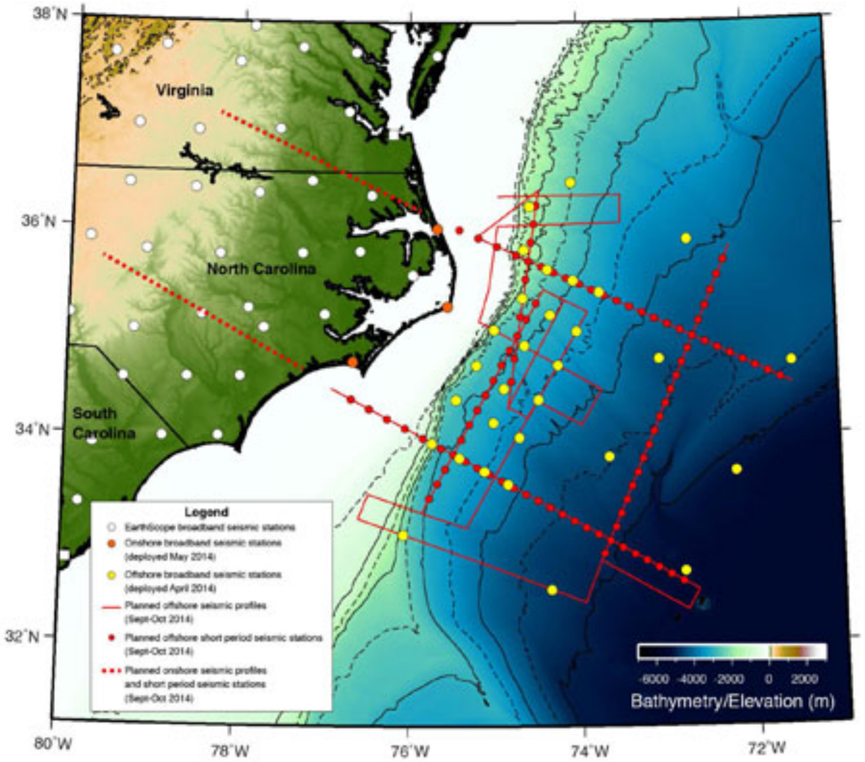
Is present-day lithospheric structure controlled by Appalachian orogenesis? By Mesozoic rifting? By earlier processes? Or has the lithosphere been modified post-rifting as the passive margin evolved?

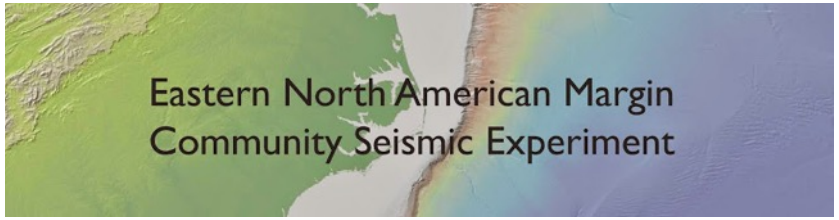
EarthScope and GeoPRISMS in ENAM: Truly transformative datasets



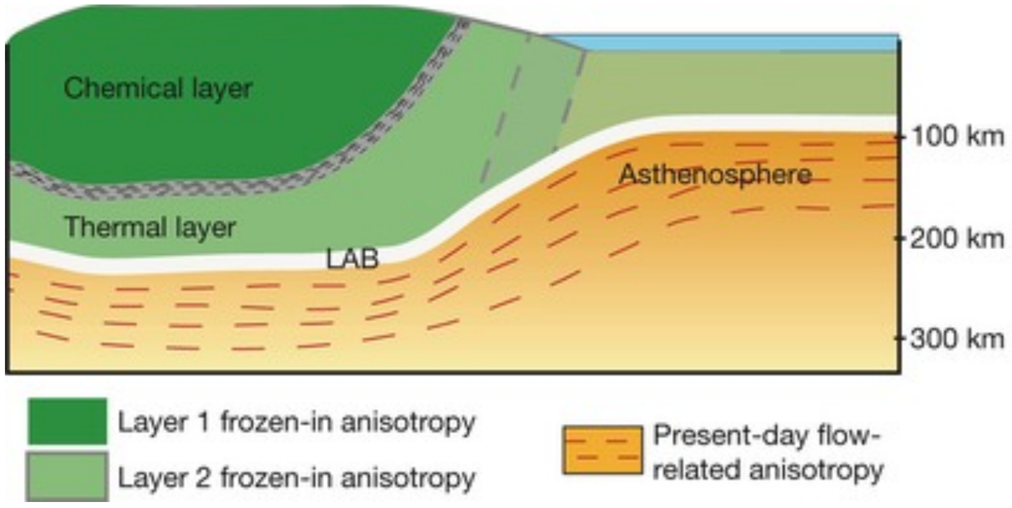


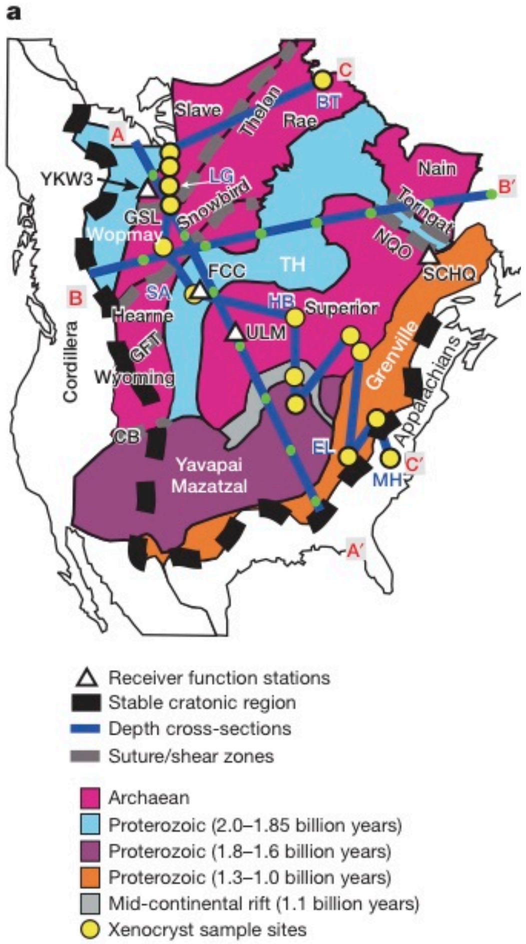
Schmandt and Lin, 2014

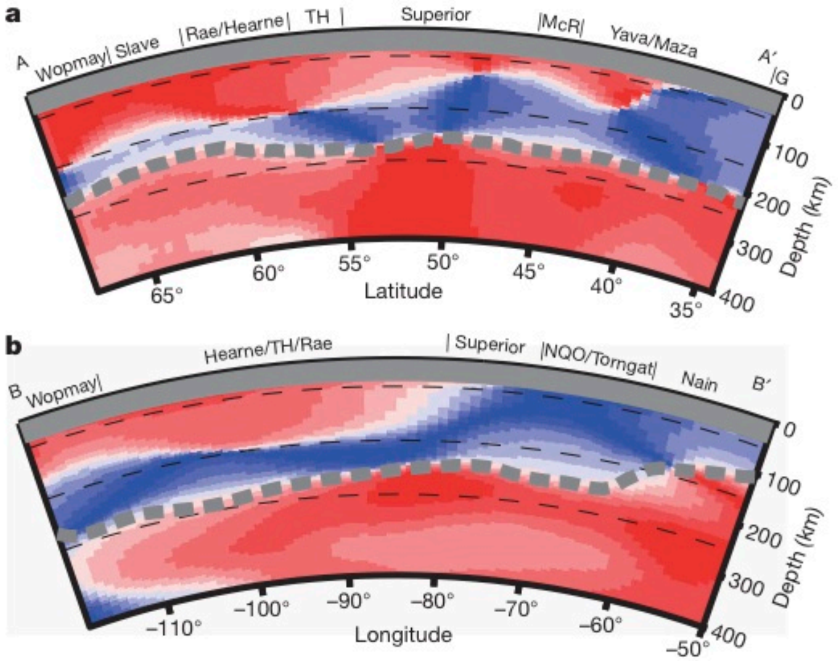




Seismic anisotropy beneath continental regions: multiple layers?



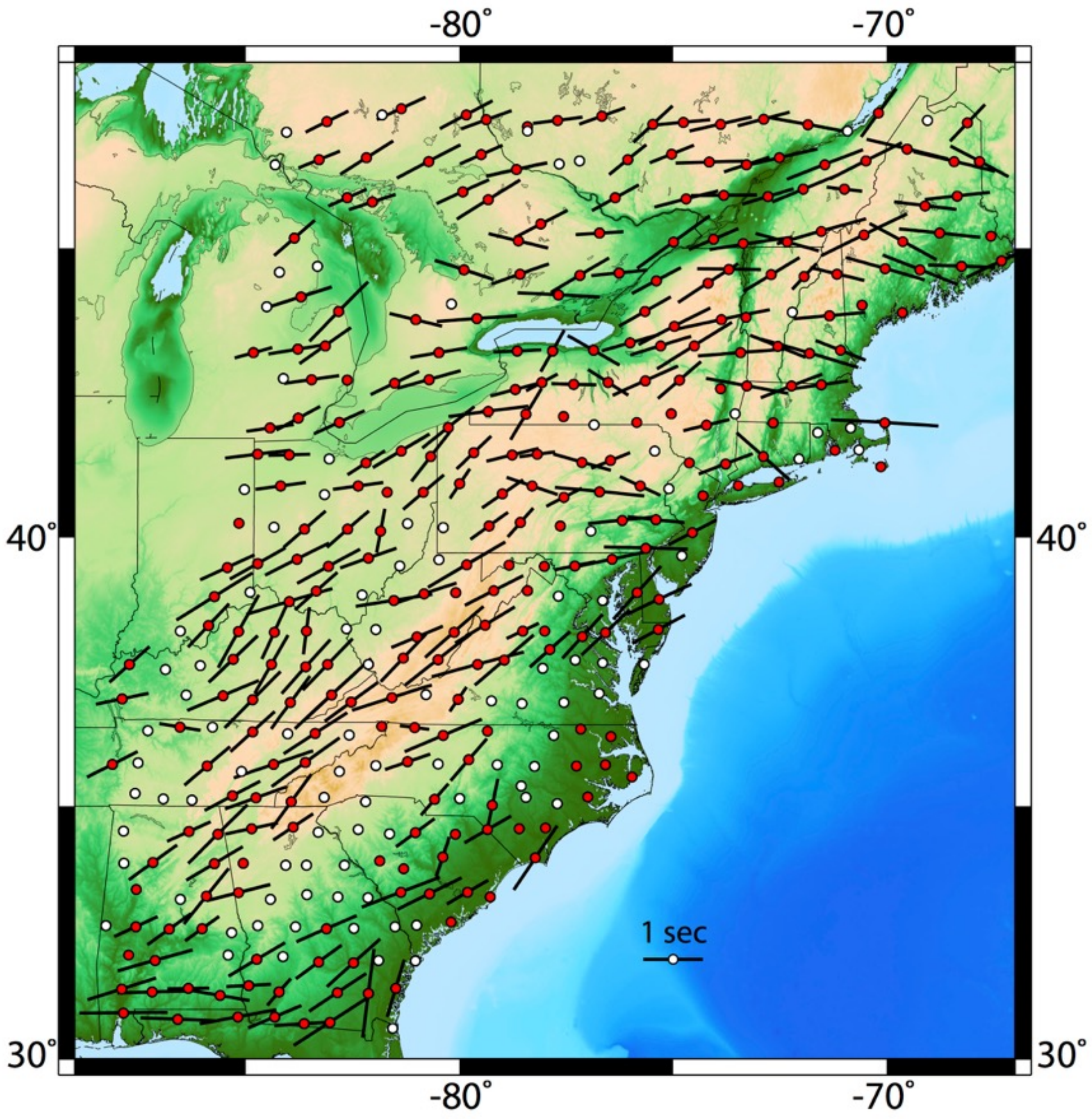




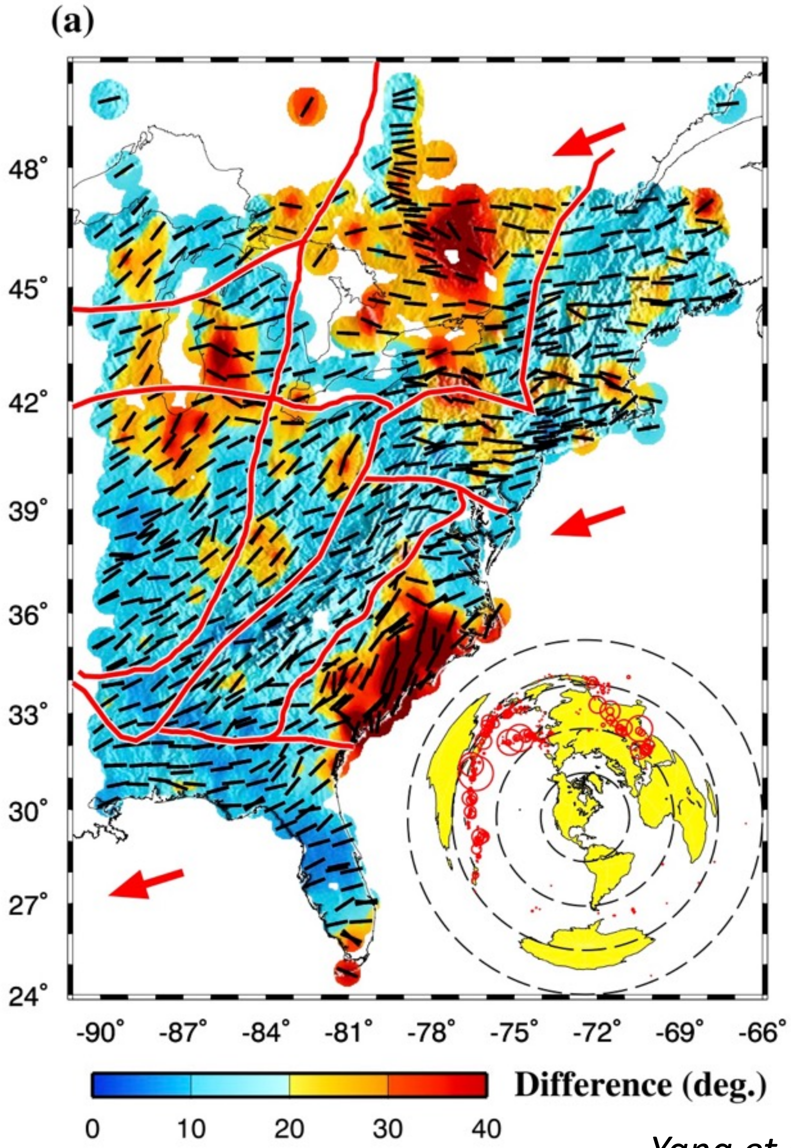
Beneath continents we expect (and often observe) multiple layers of anisotropy, with anisotropy in the mantle lithosphere reflecting ”frozen-in” structure from past deformation.

Yuan and Romanowicz, 2010

SKS splitting beneath ENAM from the TA: complex patterns

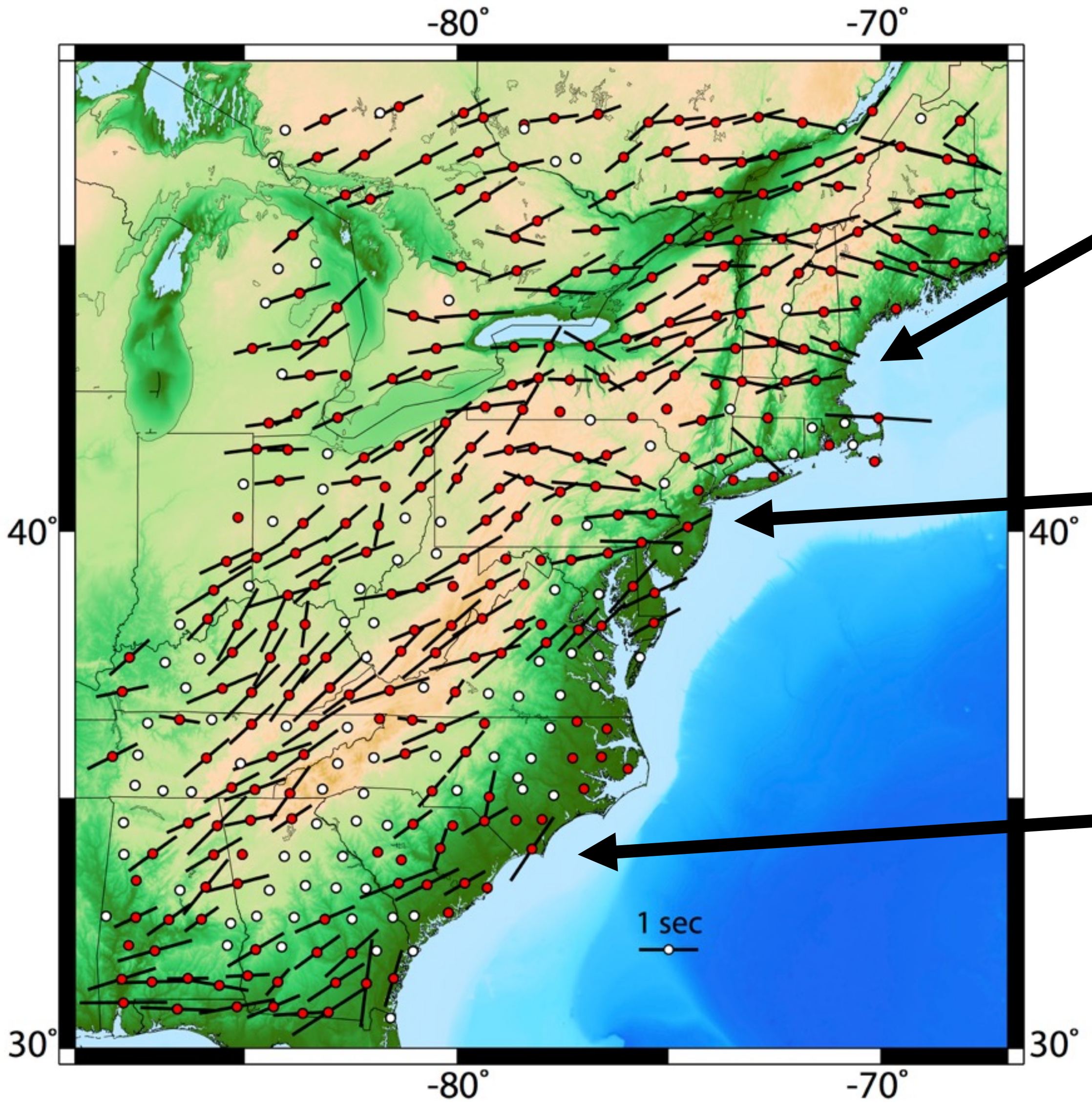


Long et al., 2016



Yang et al., 2017

SKS splitting beneath ENAM from the TA: interpretation?



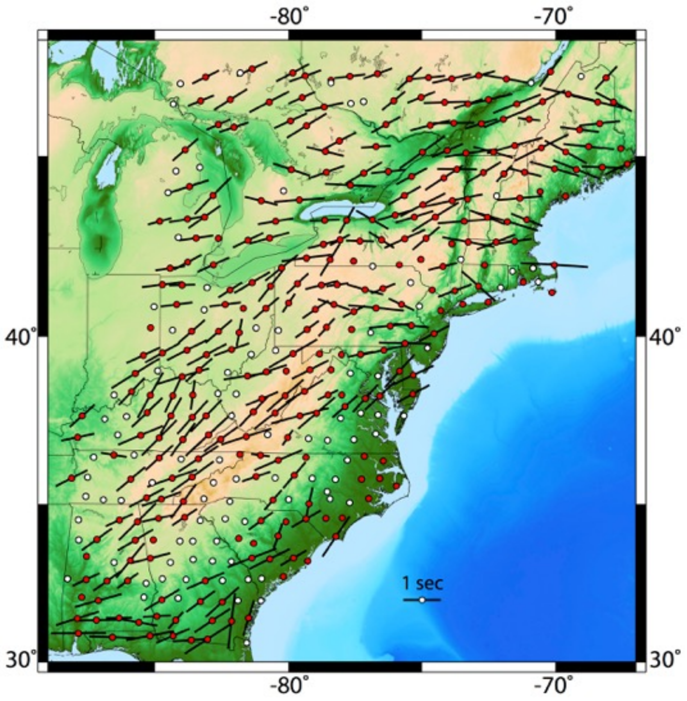
Long et al., 2016

In the north: fast directions generally parallel to absolute plate motion, with some complications (multiple layers)?

In the central/southern Appalachians: fast directions parallel to strike of topography, including orogenic bend in Pennsylvania

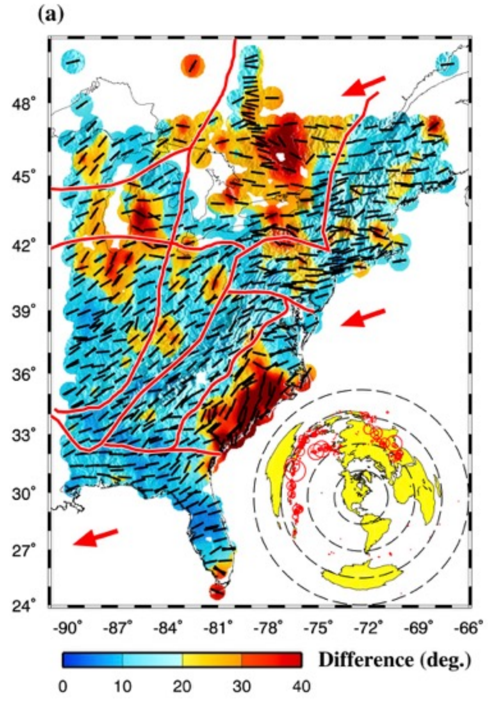
In the south: variable patterns, with null stations (little apparent SKS splitting) dominating in the Coastal Plain. Relationship to APM not clear – possible lithospheric control?

SKS splitting beneath ENAM: multiple interpretations…



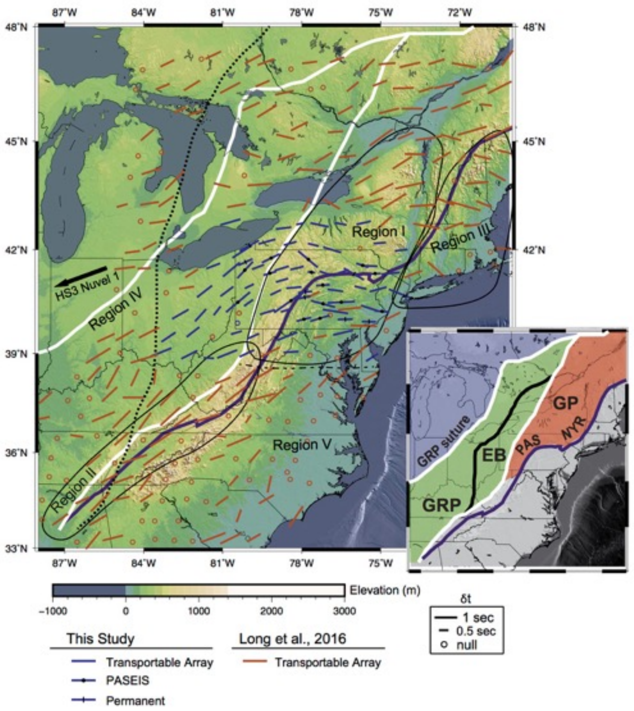
Long et al., 2016

Interpretation: mostly present-day mantle flow in north; mostly lithospheric anisotropy in south, with major contribution from Appalachian (orogenic) deformation.



Yang et al., 2017

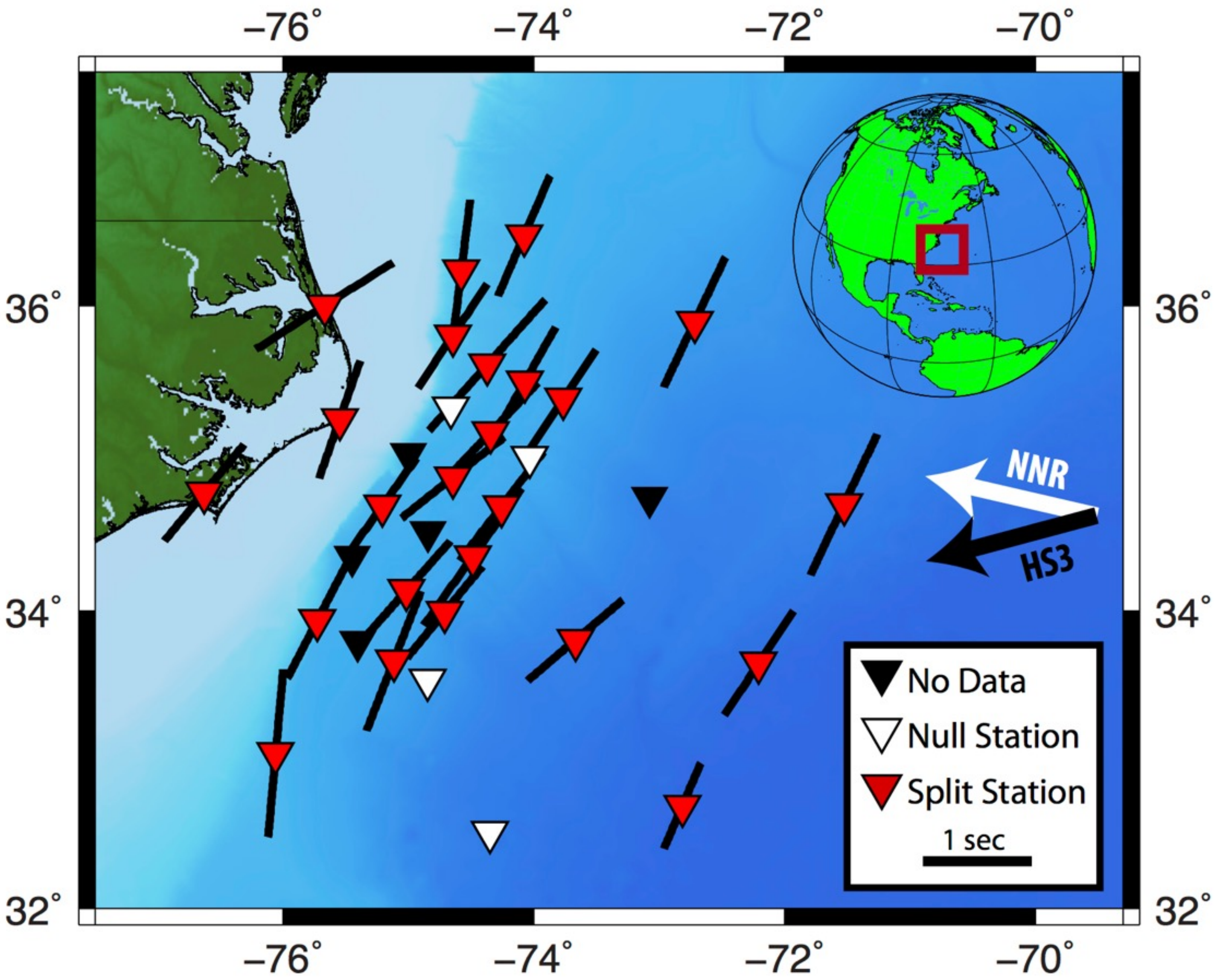
Interpretation: mostly reflects present-day mantle flow, including plate motion parallel shear and flow around continental keel. Little contribution from lithosphere.



White-Gaynor and Nyblade, 2017

Interpretation: mostly reflects lithospheric anisotropy, little contribution from asthenosphere. Major contributions from (Mesozoic) rifting (in north) and Appalachian orogenesis.

New results from the ENAM CSE broadband OBS deployment

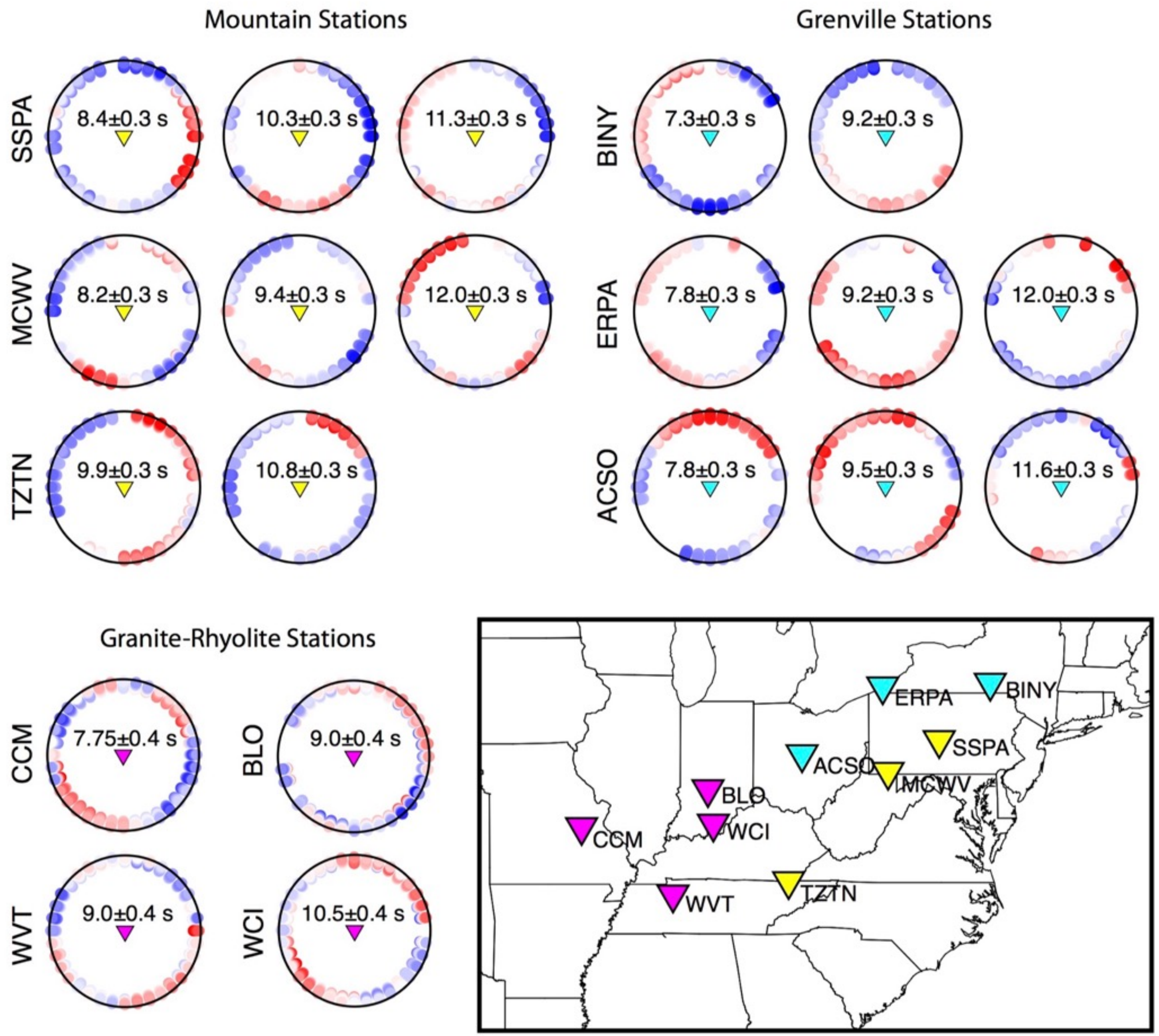


Offshore North Carolina, SKS fast directions are uniformly margin-parallel. Not parallel to present-day plate motion, and not parallel to fossil spreading direction.

Intriguing possibilities: complex, 3D asthenospheric flow field at the edge of the North American continent? Or, a lithospheric remnant of continental rifting?

Lynner and Bodmer, in press

Ongoing work: Anisotropic receiver function analysis in eastern US



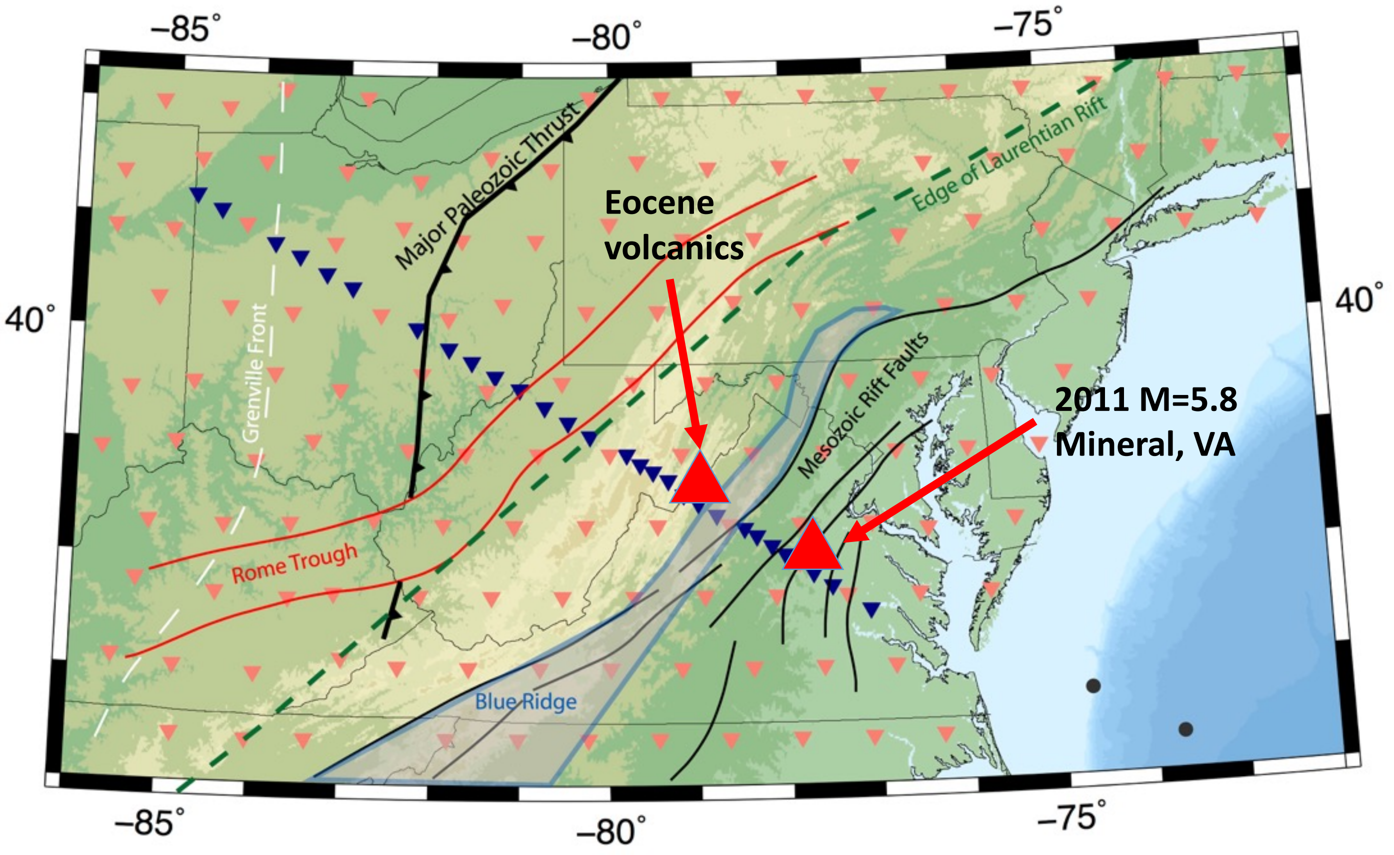
Long et al., in revision

Evidence for multiple layers of anisotropy within the mantle lithosphere throughout ENAM.

Comparison among stations suggests lithospheric deformation due to Grenvillian and Appalachian orogenesis.

Strong anisotropic layering in mid-to-lower crust beneath Appalachian stations – suggests complex pattern of crustal deformation during orogenesis, similar to findings in modern orogens (e.g., Taiwan).

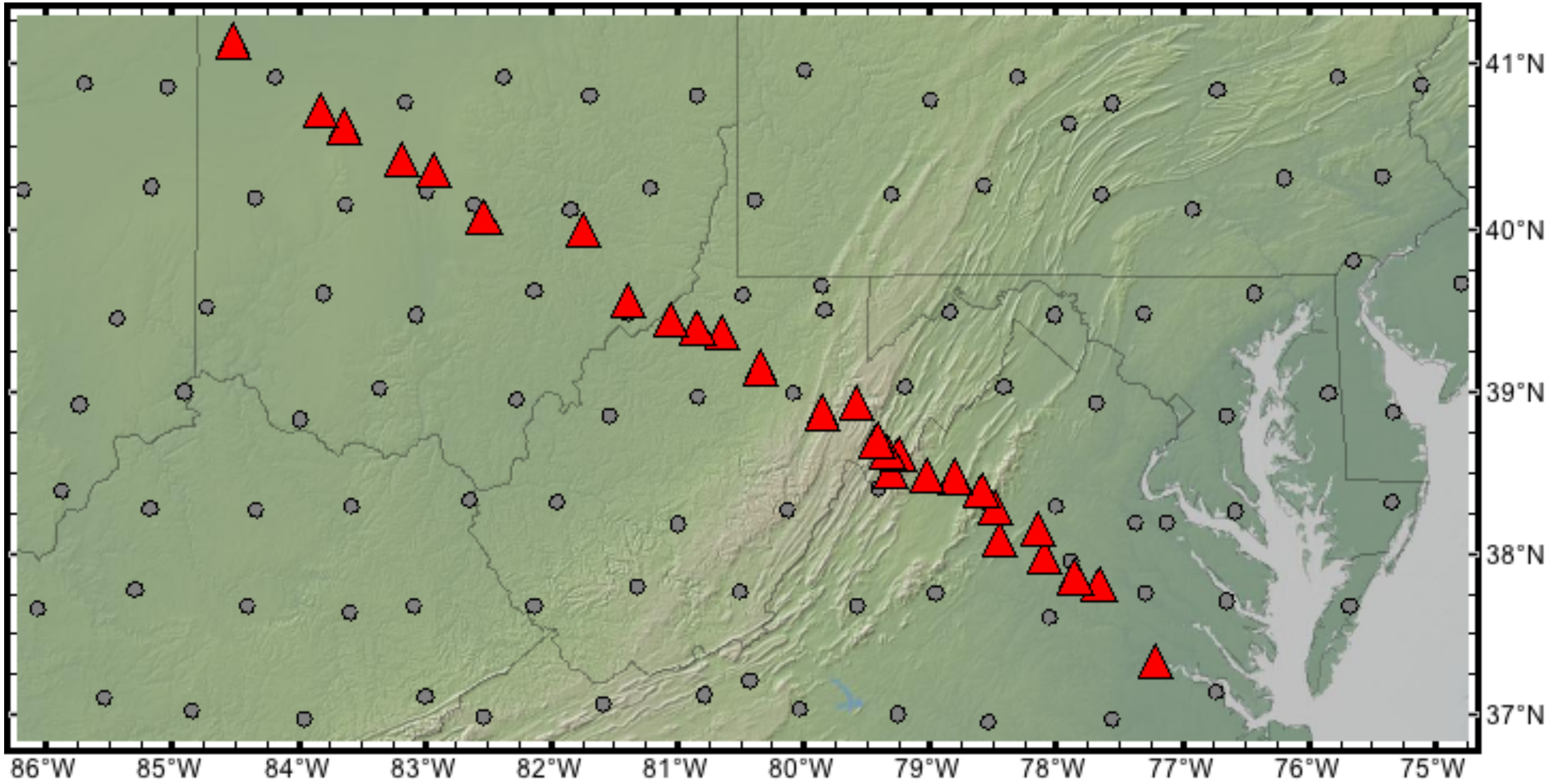
MAGIC (Mid-Atlantic Geophysical Integrative Collaboration)



Transect across the central Appalachians that crosses a number of physiographic provinces, inherited structures, Appalachian topography, Central VA seismic zone (CVSZ), and Eocene volcanics.

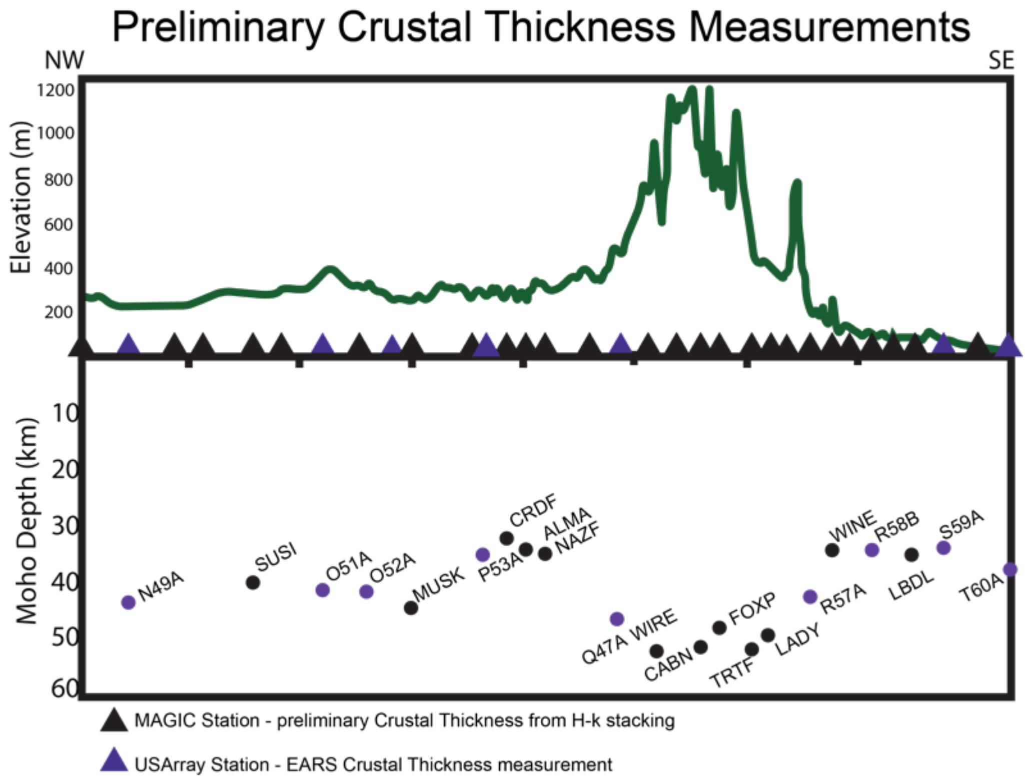
Multi-disciplinary collaboration funded by EarthScope/GeoPRISMS including seismology (M. Long, Yale; M. Benoit, TCNJ), geodynamics (S. King, Virginia Tech), and geomorphology (E. Kirby, Oregon State). Companion magnetotelluric array (MT) by R. Evans, WHOI.

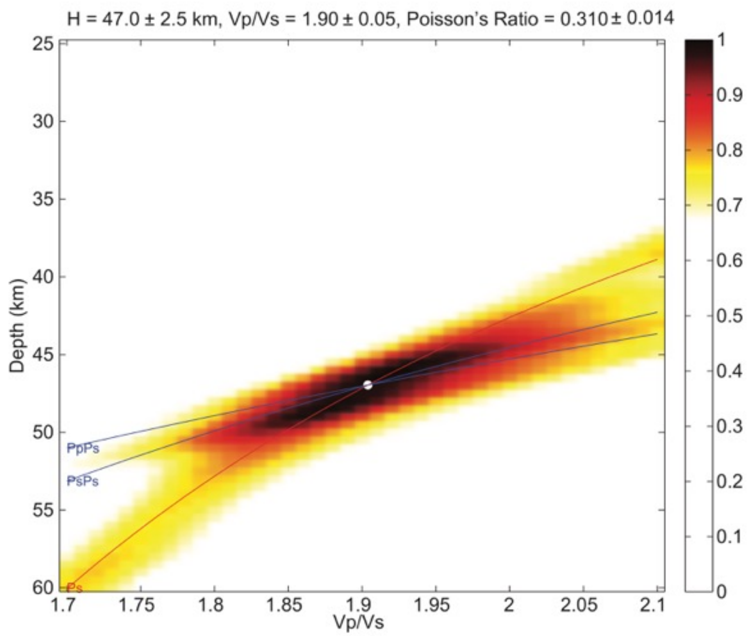
The MAGIC seismic deployment



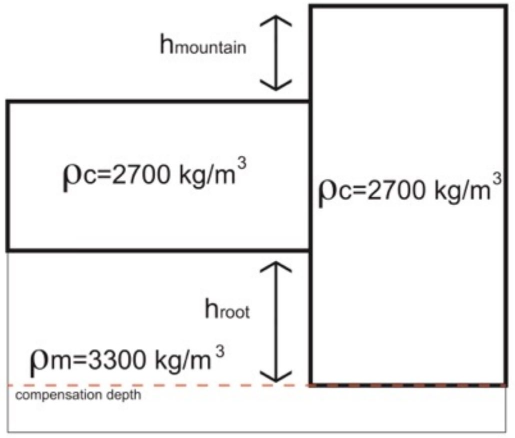
Deployment of 28 broadband stations. Some (~7) deployed in late 2013, most deployed in late 2014, for 2-3 years of data collection. Stations demobilized October 2016.

Results from MAGIC: Crustal structure from Ps receiver functions





Benoit and Long, in prep.



$h_{mountain} = h_{root} (\rho m - \rho c)/\rho c$

We identify a VERY sharp step (~15 km) in the Moho beneath central VA – near location of Eocene basalts. We also find that the eastern Appalachians are overcompensated (that is, Moho is deeper than expected given topography). Suggests lower crust beneath Appalachians is denser than typical continental crust. Also notable: crustal thinning beneath Rome Trough (early Cambrian rifting).

Results from MAGIC: Lithospheric structure from Sp RFs

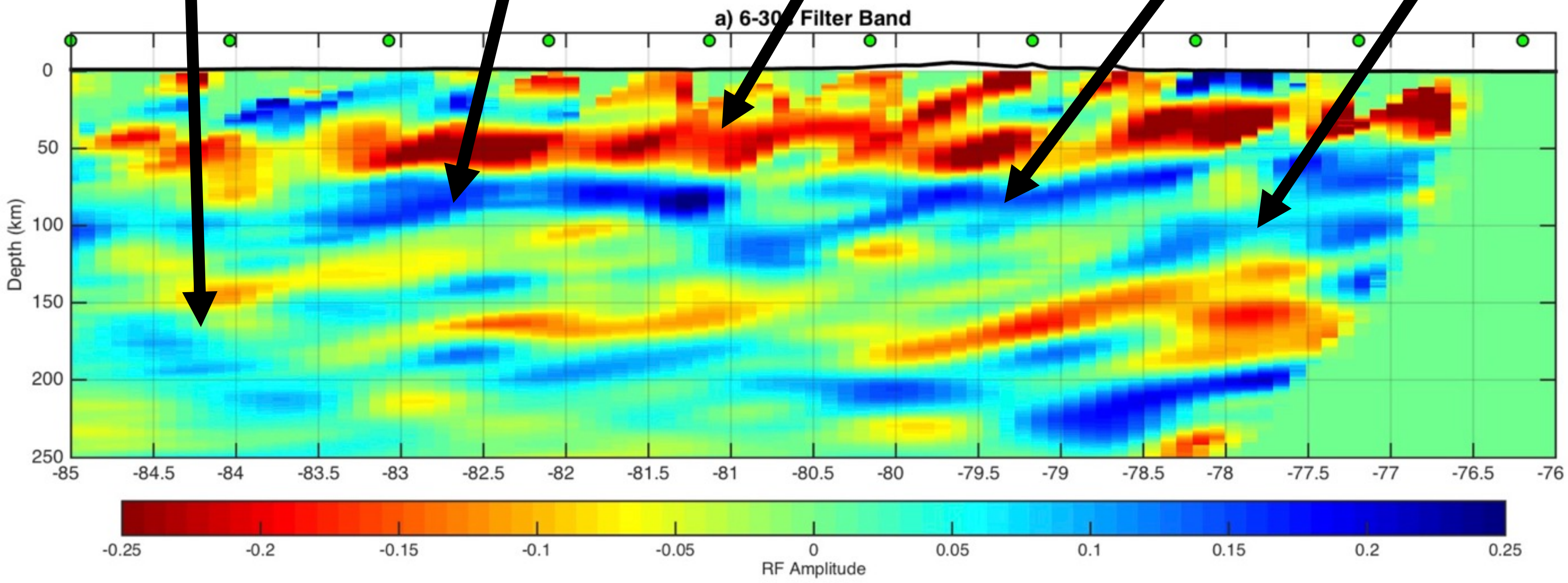
Perhaps hint of deep LAB here?

Mid-lithosphere discontinuity (MLD)

Moho

Lithosphere-asthenosphere boundary (LAB); shallow (~80 km) and dips to west

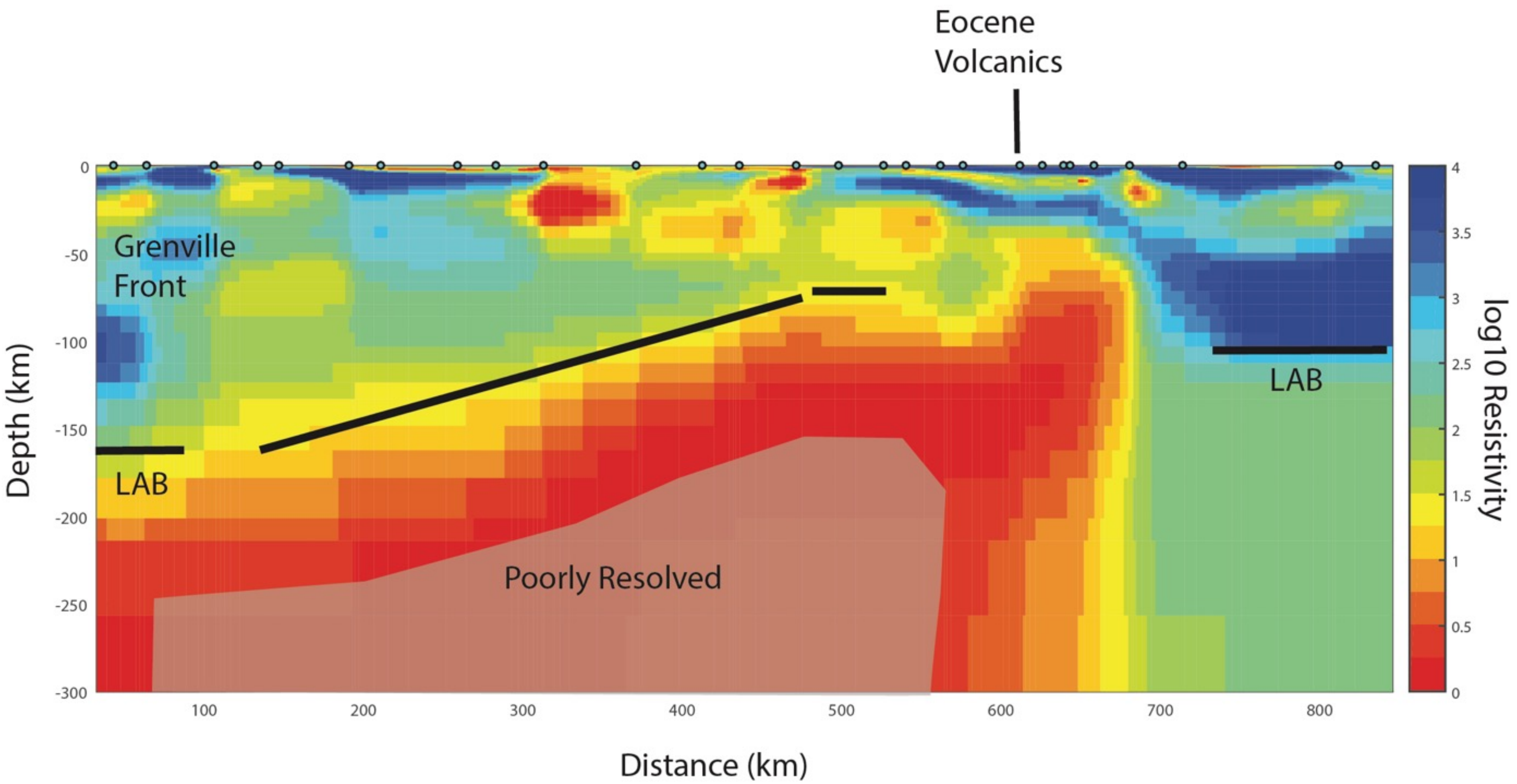
LAB?



Evans, Benoit, Long, et al., in prep.

Common conversion point (CCP) stack of S-to-P RFs reveals dramatic lithospheric thinning to the east – consistent with lithospheric removal beneath Eocene basalts.

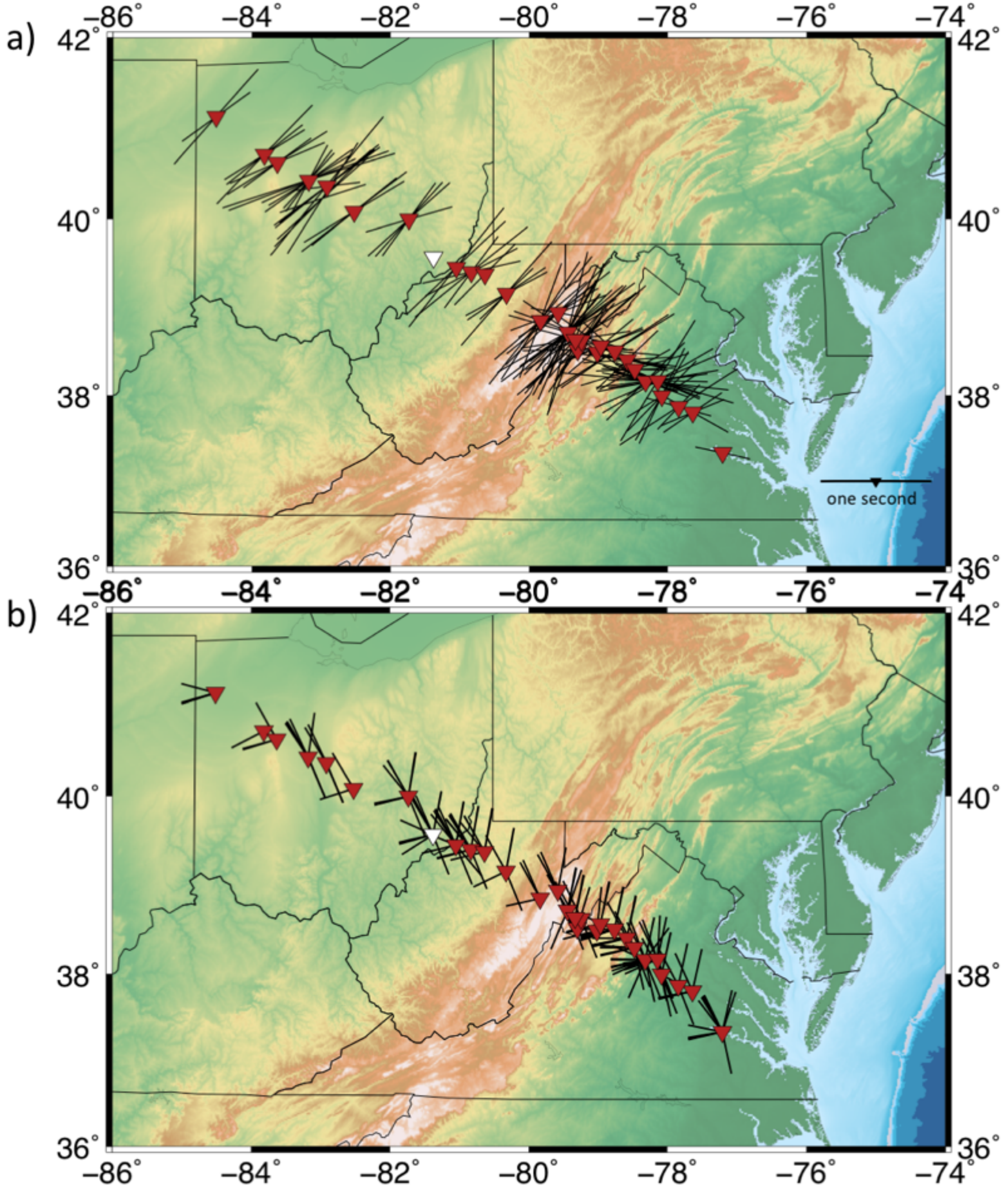
Results from MAGIC: Magnetotelluric imaging

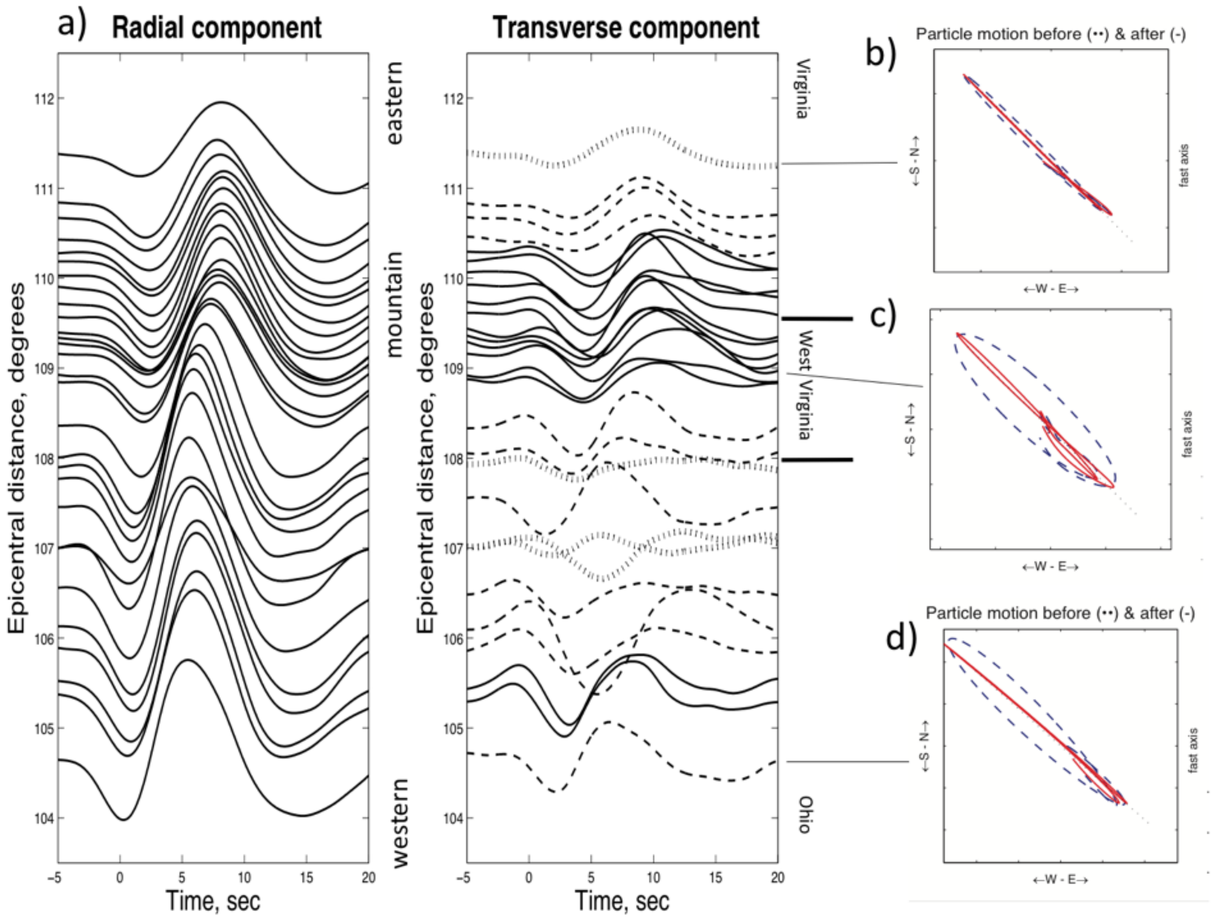


Evans et al., in prep.

Resistivity model from MT measurements by Rob Evans along the MAGIC line also yields evidence for lithospheric thinning to the east, with thin lithosphere under Eocene volcanics.

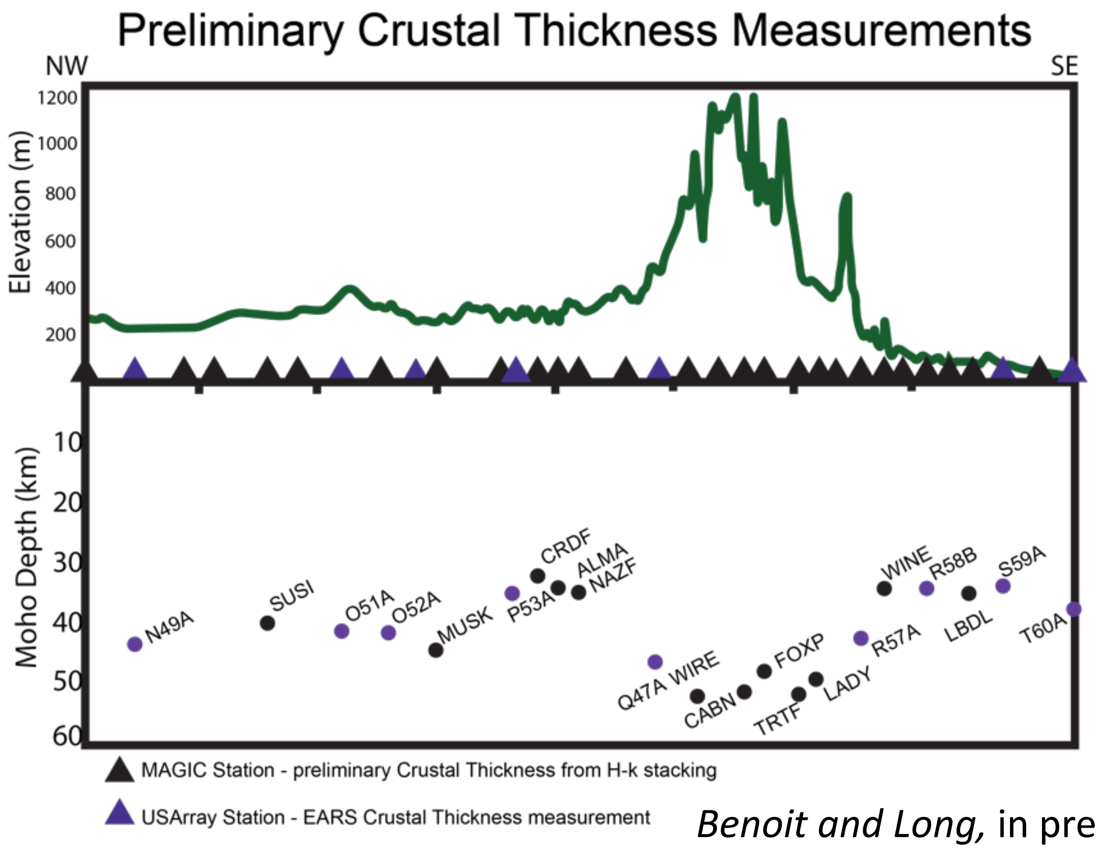
Results from MAGIC: SKS splitting



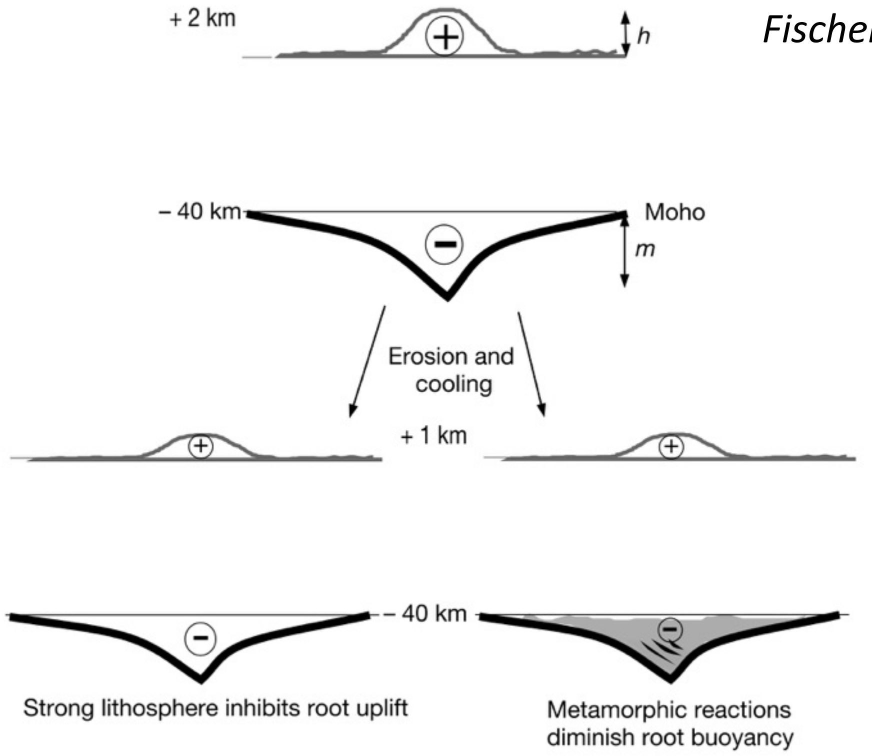


Aragon, Long, Benoit, in prep.

Thick crust and overcompensated topography beneath central Appalachians: Implications?



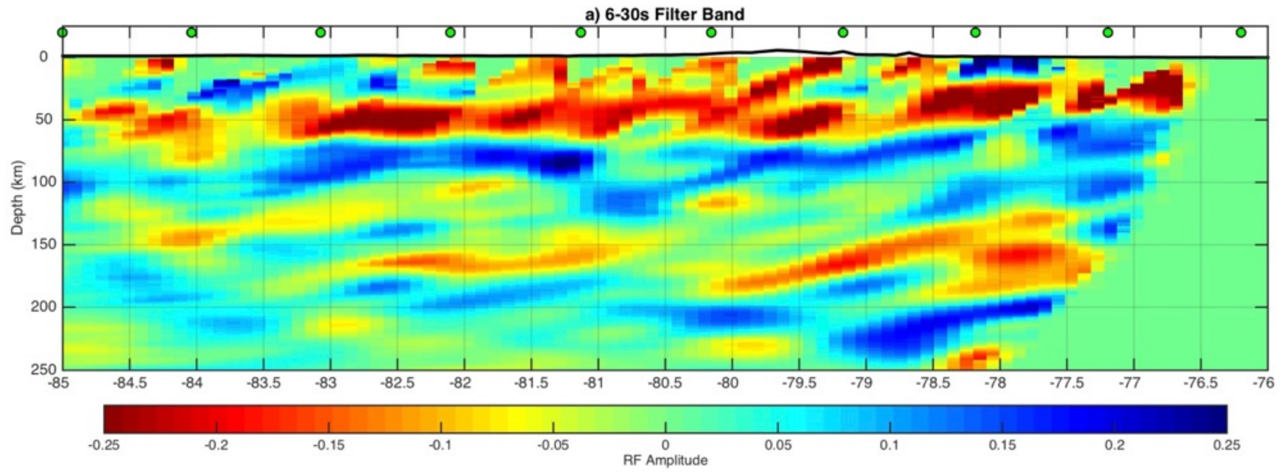
Benoit and Long, in prep.



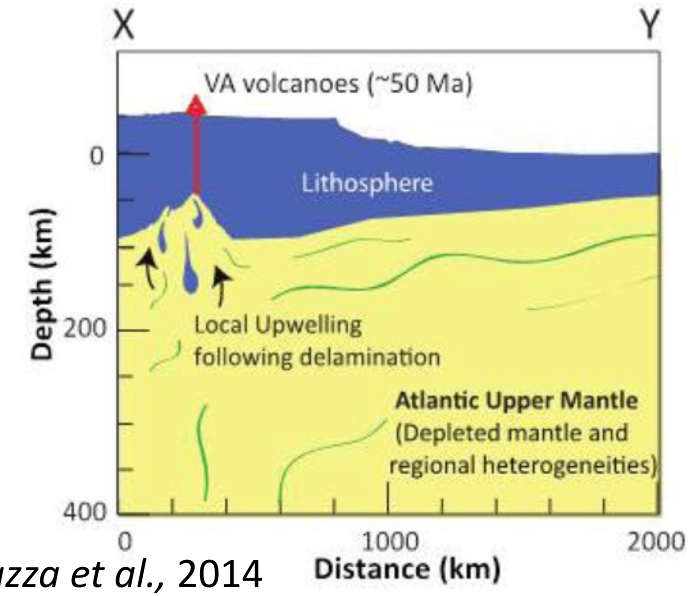
Fischer, 2002

VERY sharp jump in crustal thickness across the eastern boundary of Appalachian topography. Moho is deeper than expected if topography was isostatically compensated. Suggests either 1) lithosphere is extremely rigid, or 2) lower crustal density has increased over time (metamorphic reactions; e.g. Williams et al., 2014), leading to diminished root buoyancy.

Lithospheric removal beneath Eocene basalts: evidence for significant post-rift modification of lithospheric structure

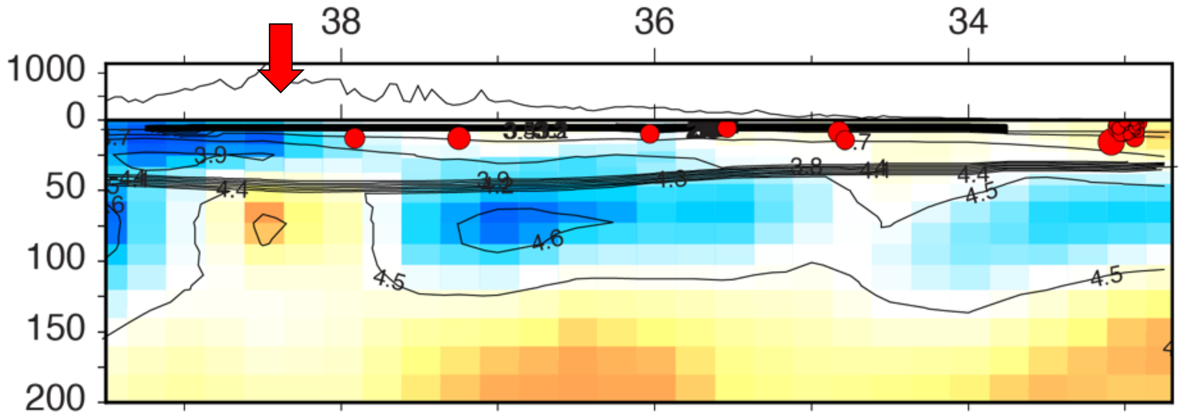


Evans et al., in prep.



Mazza et al., 2014

Eocene Volcanism

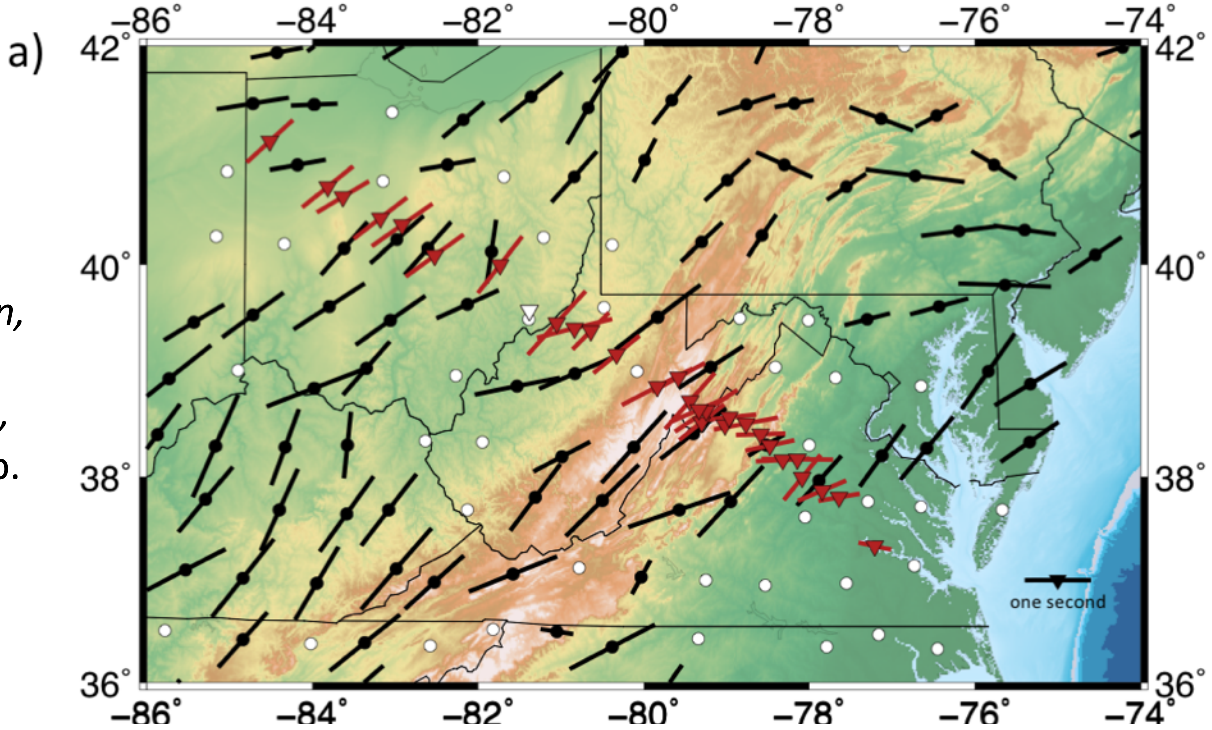


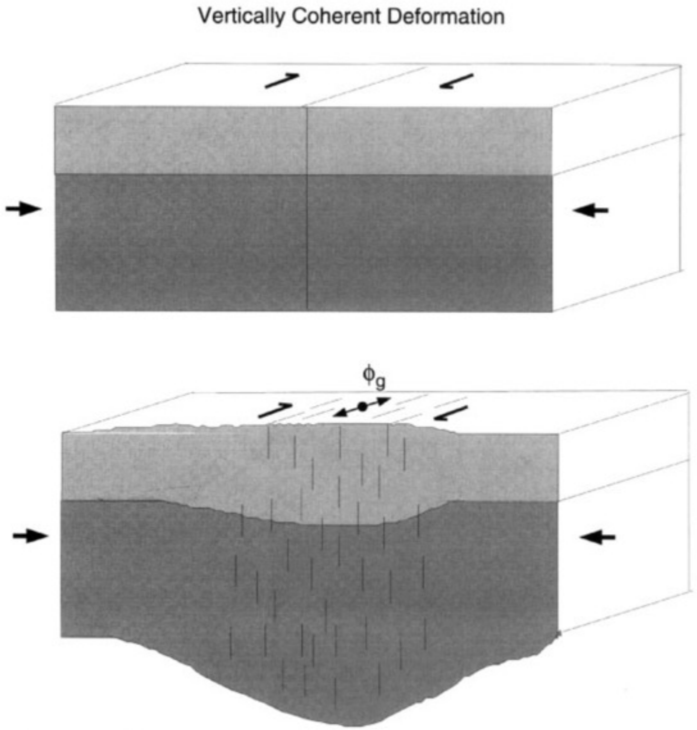
Wagner et al., in prep.

Evidence from tomography (work by Lara Wagner and others) and receiver functions consistent with lithospheric delamination. Outstanding questions? Why? What controlled location/timing?

Seismic anisotropy beneath the central Appalachians: Orogen-parallel deformation of the mantle lithosphere?

Aragon, Long, Benoit, in prep.





Silver, 1996

Sharp change in anisotropy at eastern edge of present-day high topography suggests transition in lithospheric anisotropy, from NE-SW fast directions to E-W. Thin lithosphere cannot account for entire delay time (~1 sec), but lithospheric contribution seems to be required. A speculative idea: could E-W directions to the east of mountains associated with Mesozoic rifting?

Summary: What have we learned about orogenesis, rifting, and post-rift evolution beneath ENAM?

- Present-day Appalachian topography associated with thick crustal root; may reflect time-progressive metamorphic reactions and increased lower crustal density.
- Evidence for deformation of mantle lithosphere due to Appalachian orogenesis, with sharp lateral transition in anisotropy geometry.
- Signature of late Cambrian continental rifting evidence in thinned crust beneath Rome Trough in western WV. E-W anisotropy fast directions in central VA associated with Mesozoic rifting? Do offshore SKS splits reflect present-day flow or lithospheric deformation in early stages of rift-to-drift transition?
- Post-rift modification of central Appalachian lithosphere has been extensive, with lithospheric removal resulting in Eocene volcanism. How universal a process is this in old orogens?