EarthScope: Clearest Images of what's Beneath our Feet, from Sea to Shining Sea

Ved Lekic[1] & Andrew Schaeffer[2]

1. University of Maryland
2. University of Ottawa

With Thanks to: Scott Burdick, Erin Cunningham, Chao Gao

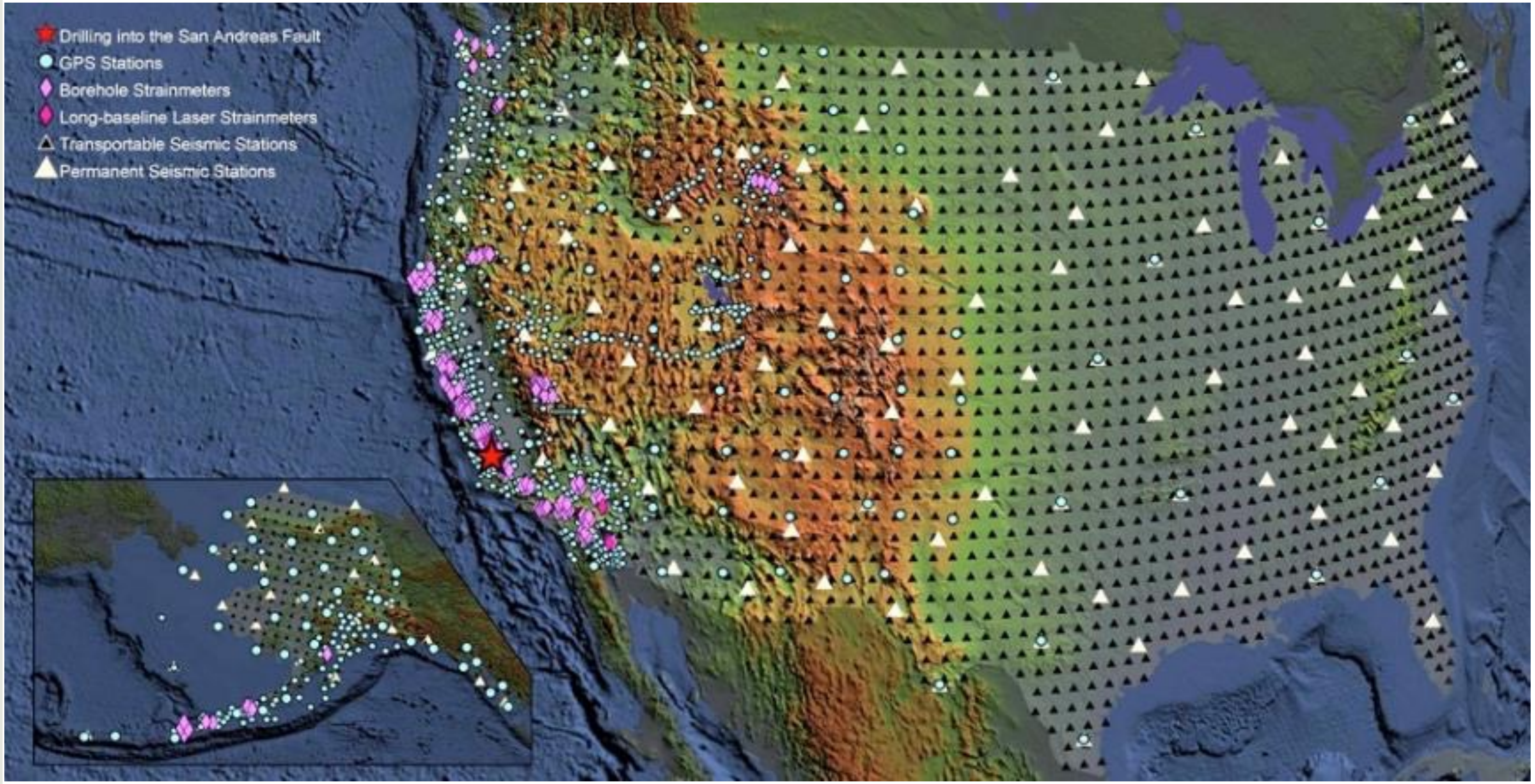
Earthscope National Meeting – Anchorage, Alaska – May 16, 2017

Talk outline

- Earthscope then & now: a technical, operational and scientific feat at the scale of an entire continent
- Instrumental and Installation Advances: a shining legacy for all future geophysical instrument deployments
- We contextualize the massive advances in seismological imaging techniques facilitated by EarthScope through highlighting results from across the continent and at a variety of scales:
  - Surface-wave based imaging approaches
  - Anisotropy Studies
  - Converted-waves and discontinuity structure
  - Body wave and probabilistic imaging approaches
- We conclude by quantifying the improvement in seismic images attributable to new data from the EarthScope project.

What Makes EarthScope Unique?

- >4000 Instruments
- >67 TB of Data
- Community Driven
- Free and Open datasets
- Named #1 "Epic Project" by Popular Science in 2011
- USArray (**TA, FA, Ref**, MT), PBO, SAFOD



Transportable Array & Flexible Array Deployments

Includes 400 Transportable Array (TA) Stations

Each Station occupies a site for 1.5 – 2 years

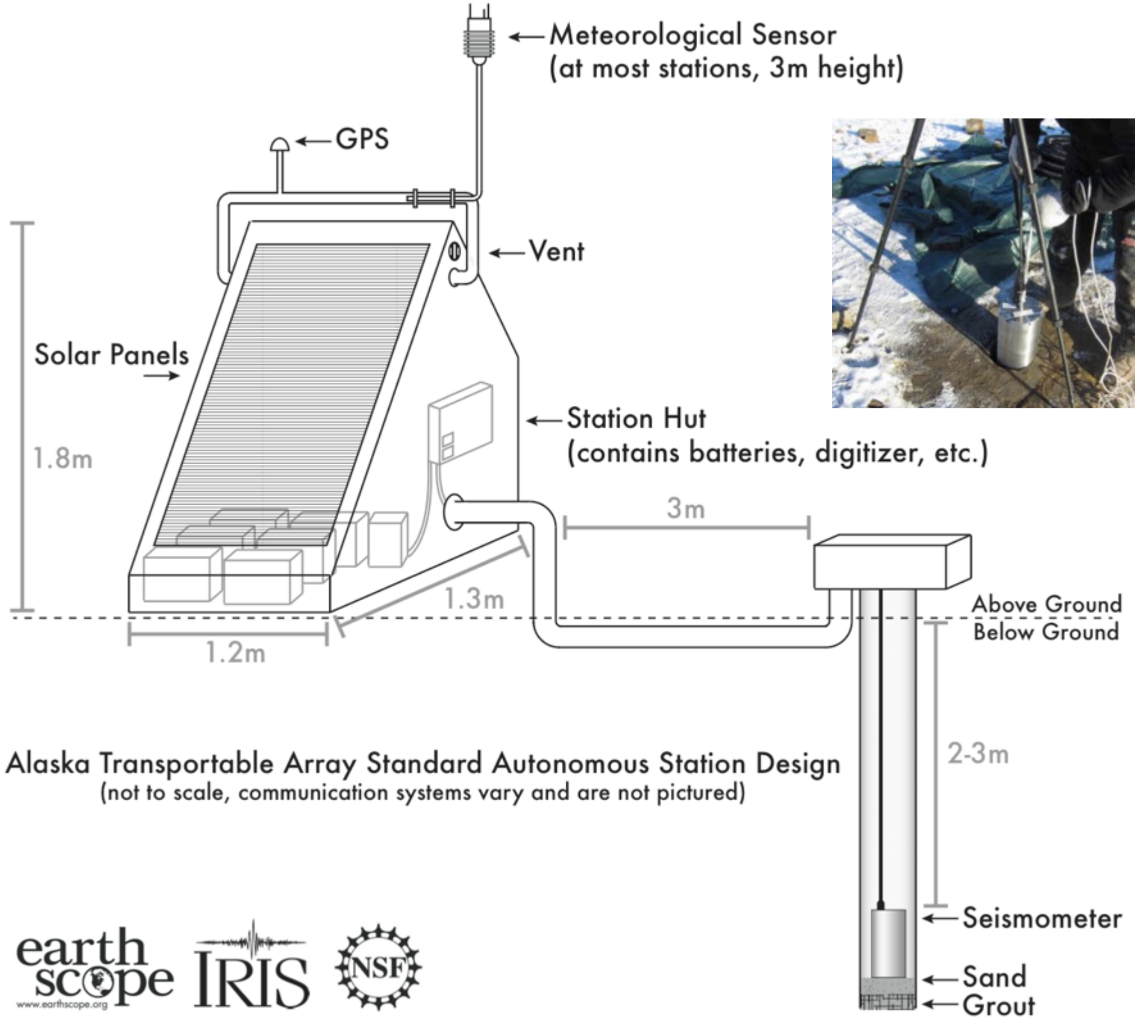
10 years to leap-frog across the country

Legacy: TA site adoption

380 NSF-EAR funded projects

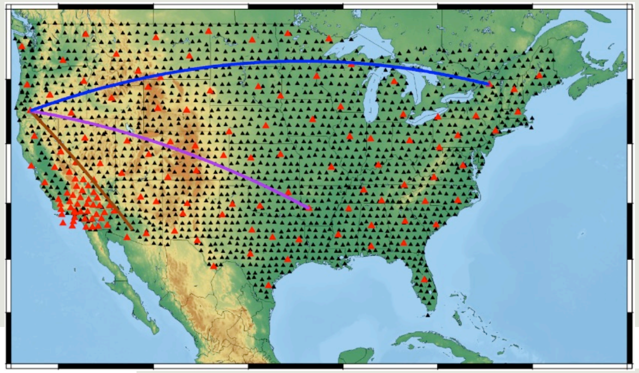
Alaska TA Stations: an evolution in site design

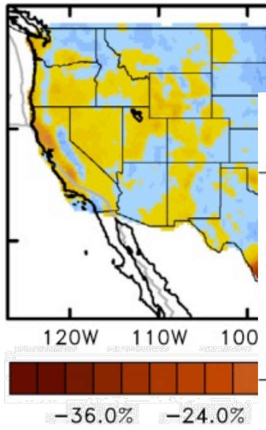
- The Transportable Array has made its way to Alaska, overcoming a new suite of logistical and technical challenges.

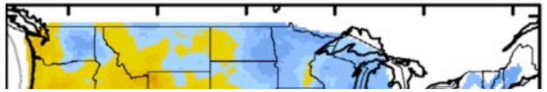


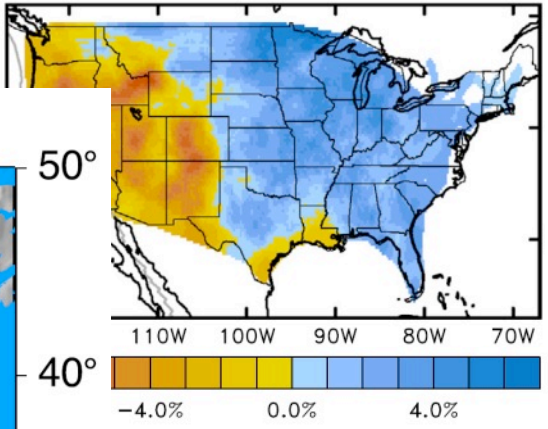
Detailed Images from Ambient Noise Records

Cross-correlations of seismic noise (days, weeks, months) at hundreds of simultaneously recording stations across a network are used to compute “empirical” Green’s functions, which provide short period surface wave dispersion measurements between pairs of stations

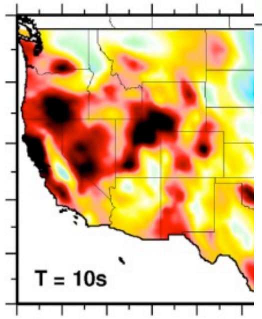


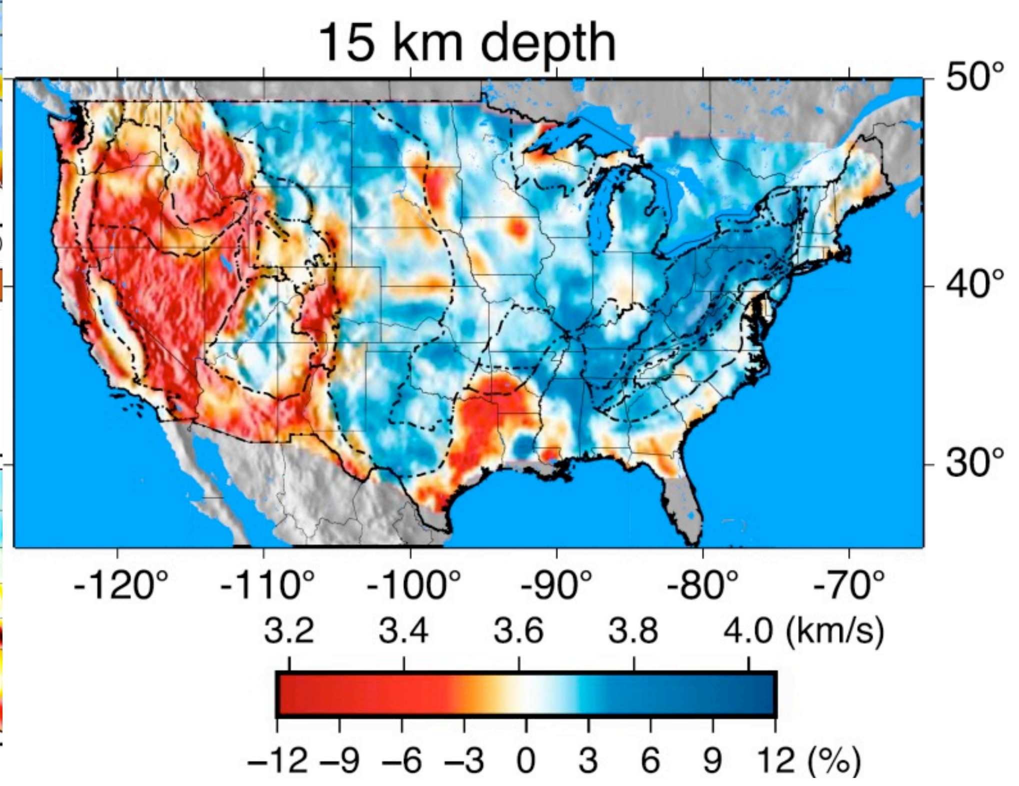




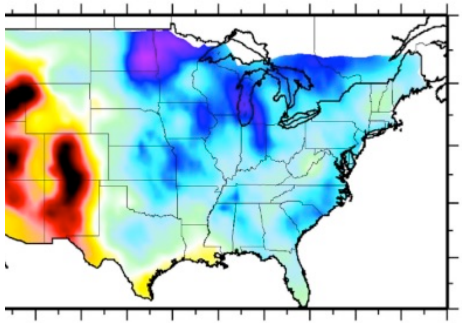


Ekstrom, EPSL (2014)





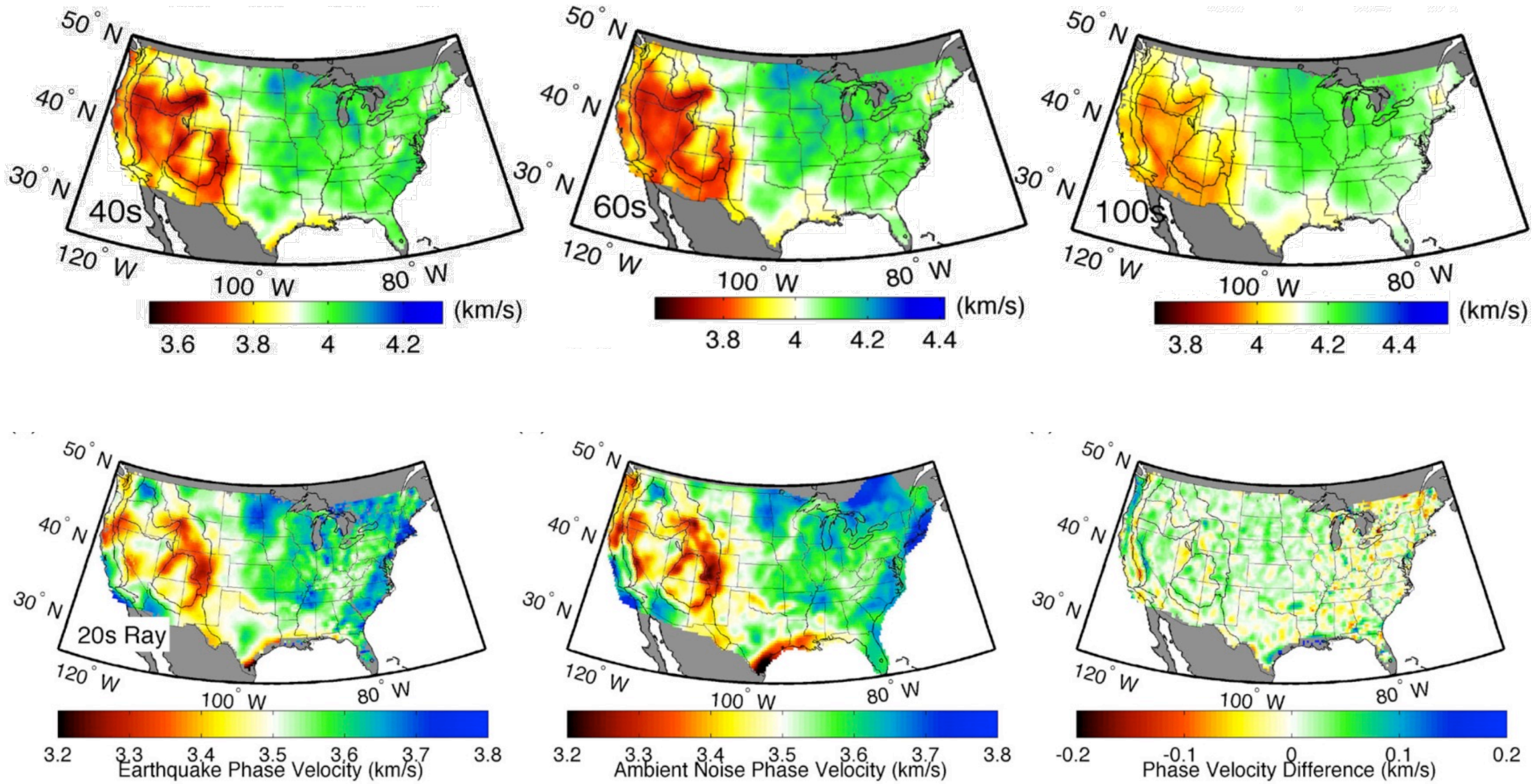
Porter et al, GRL (2016)



Zhao et al, GJI (2017)

Coherent phase tracking of Earthquakes across the USArray

- High density arrays facilitate coherent tracking of phase between neighbouring stations
- Array-based techniques enabling higher resolutions across broad period ranges through automated phase velocity retrieval via cross-correlation
- Improved correlation with Ambient Noise Tomography within common period band:
  - r = 0.95
  - μ = 7 m/s
  - σ = 30 m/s



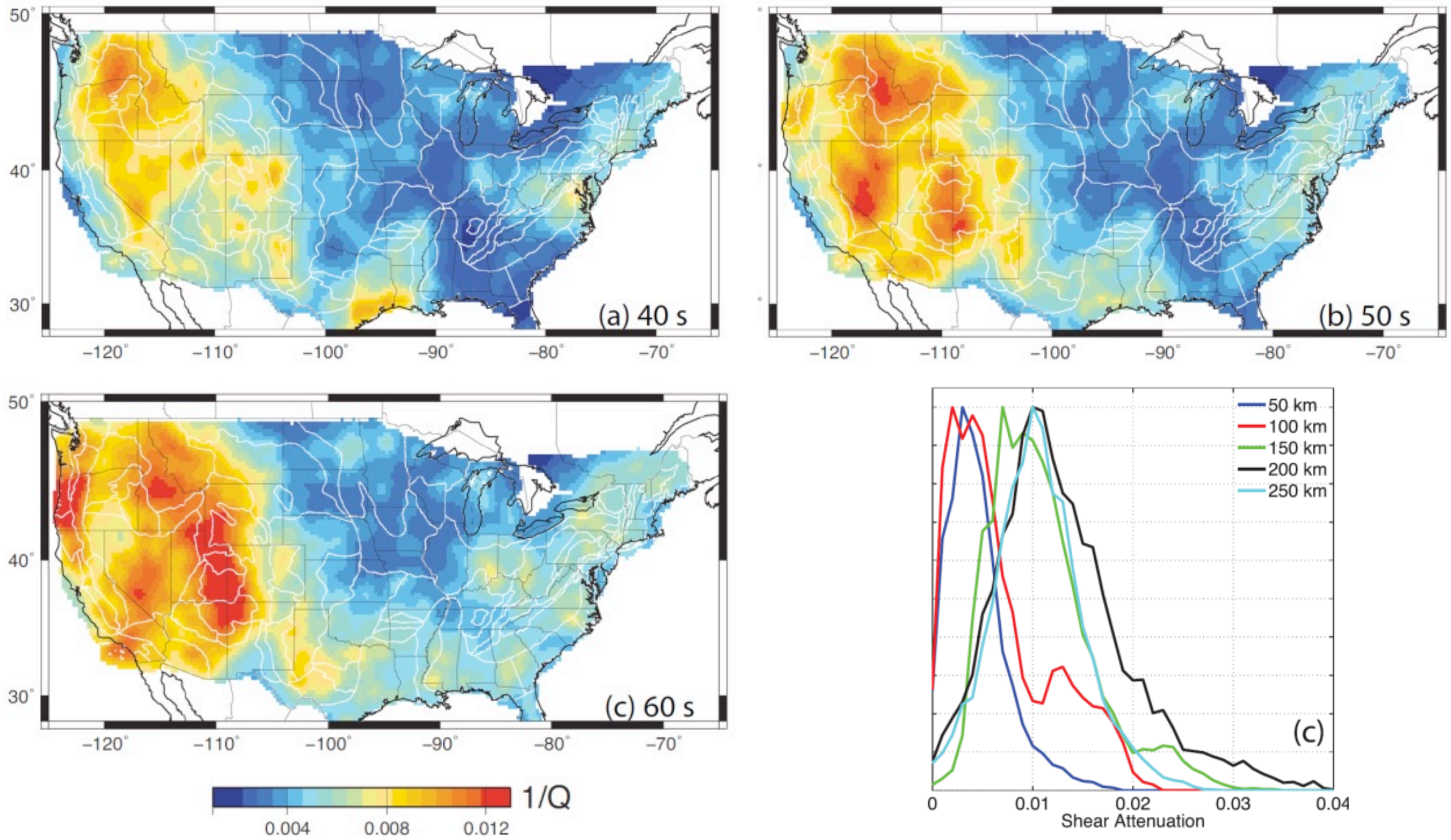
Jin & Gaherty, GJI (2015)

Rayleigh Wave Attenuation

Majority of models focus on seismic-wave speed variations

Joint interpretation with attenuation provides important constraints on temperature, composition, melt & volatile content of the mantle

Regionally averaged intrinsic shear attenuation maps constructed using interstation cross-correlation technique between 25-100 s



Bao et al, GJI (2016)

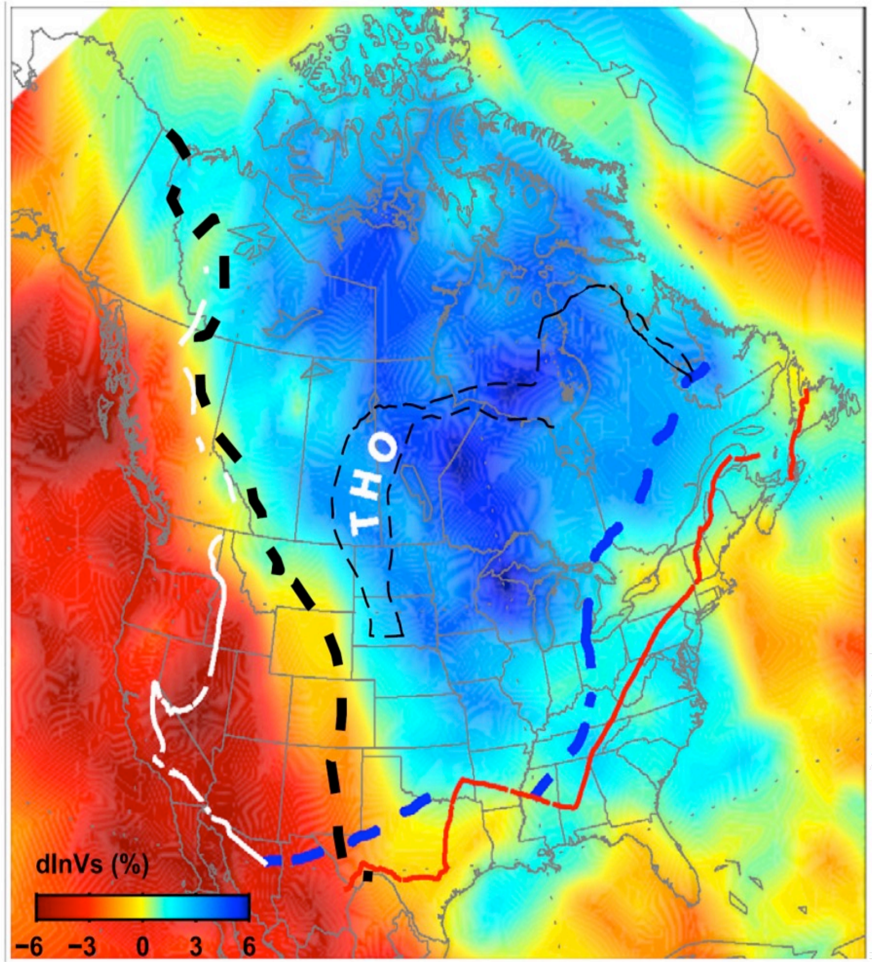
Viewing the Continent in its Entirety

Earthscope data has facilitated drastic improvements in resolving power outside the footprint of the Array

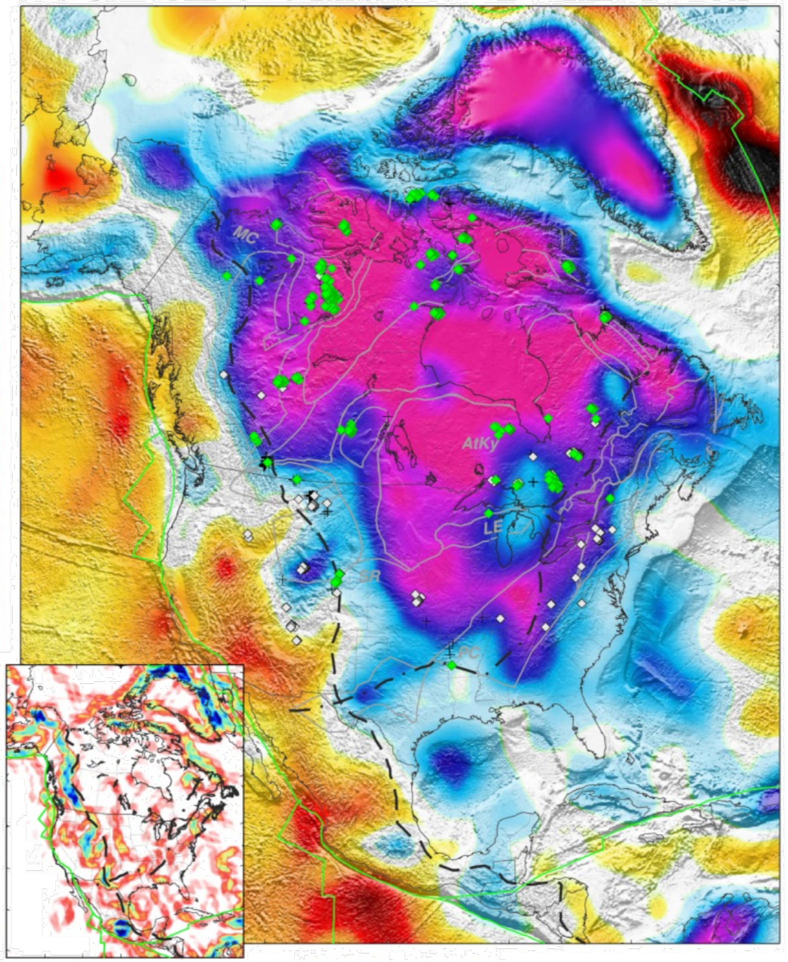
Higher resolution, more complete models of the entire continent, including the bounding Pacific and Atlantic Oceans, Gulf of Mexico

Provides greater context for the evolution of the continent as a whole

150 km Depth



Yuan et al, EPSL (2014)



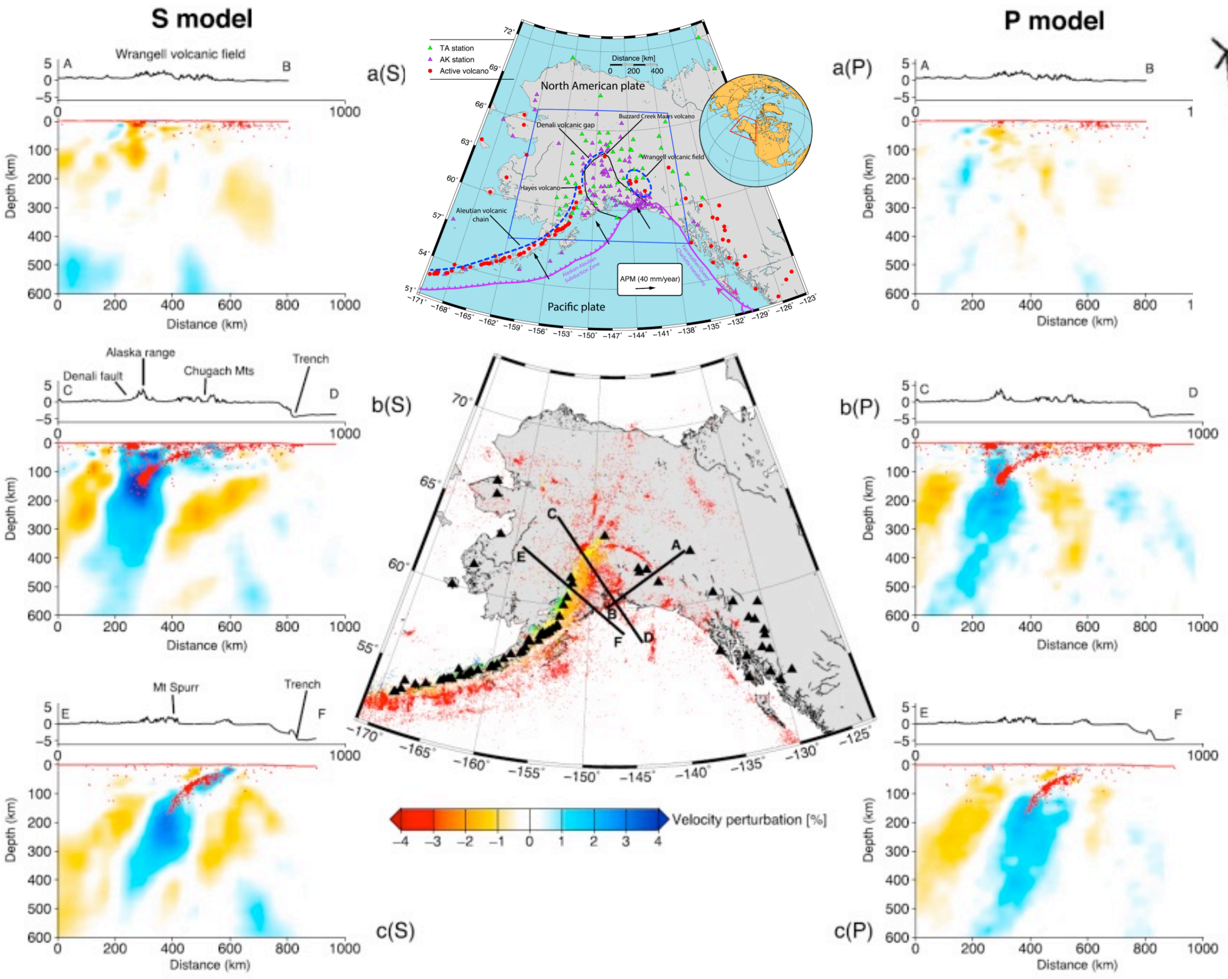
Schaeffer & Lebedev, EPSL (2014)

Complex Tectonics across Alaska and the Aleutians

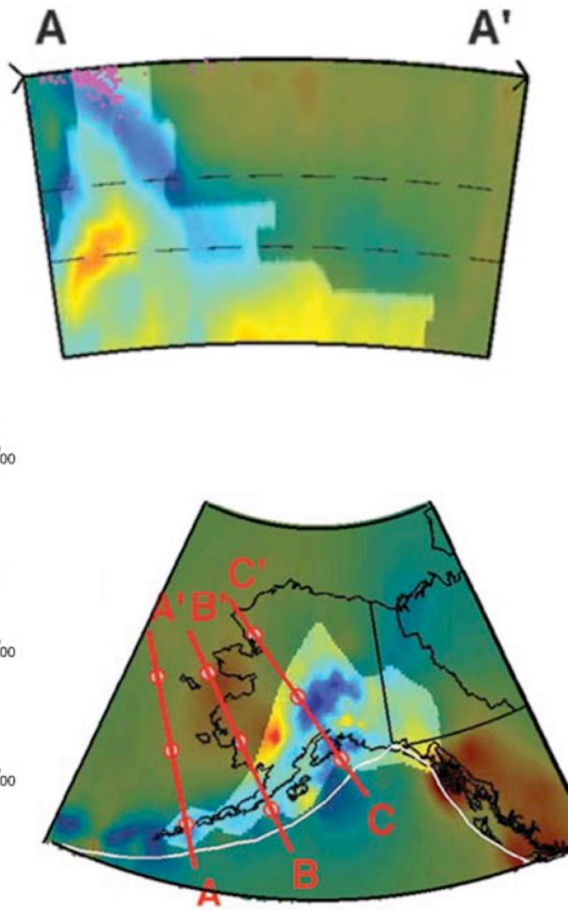
Complex tectonics including transition from compression to strike-slip deformation, terrane accretion, and termination of arc magmatism

Finite frequency P&S body wave tomography using newly installed TA stations plus numerous AK instruments

Continued deployment and completion of TA within Alaska and NW Canada will result in new high-resolution images and improved understanding of the complex 3D (4D) tectonics throughout the region



Martin-Short et al, GRL (2016)



Burdick et al., SRL (2016)

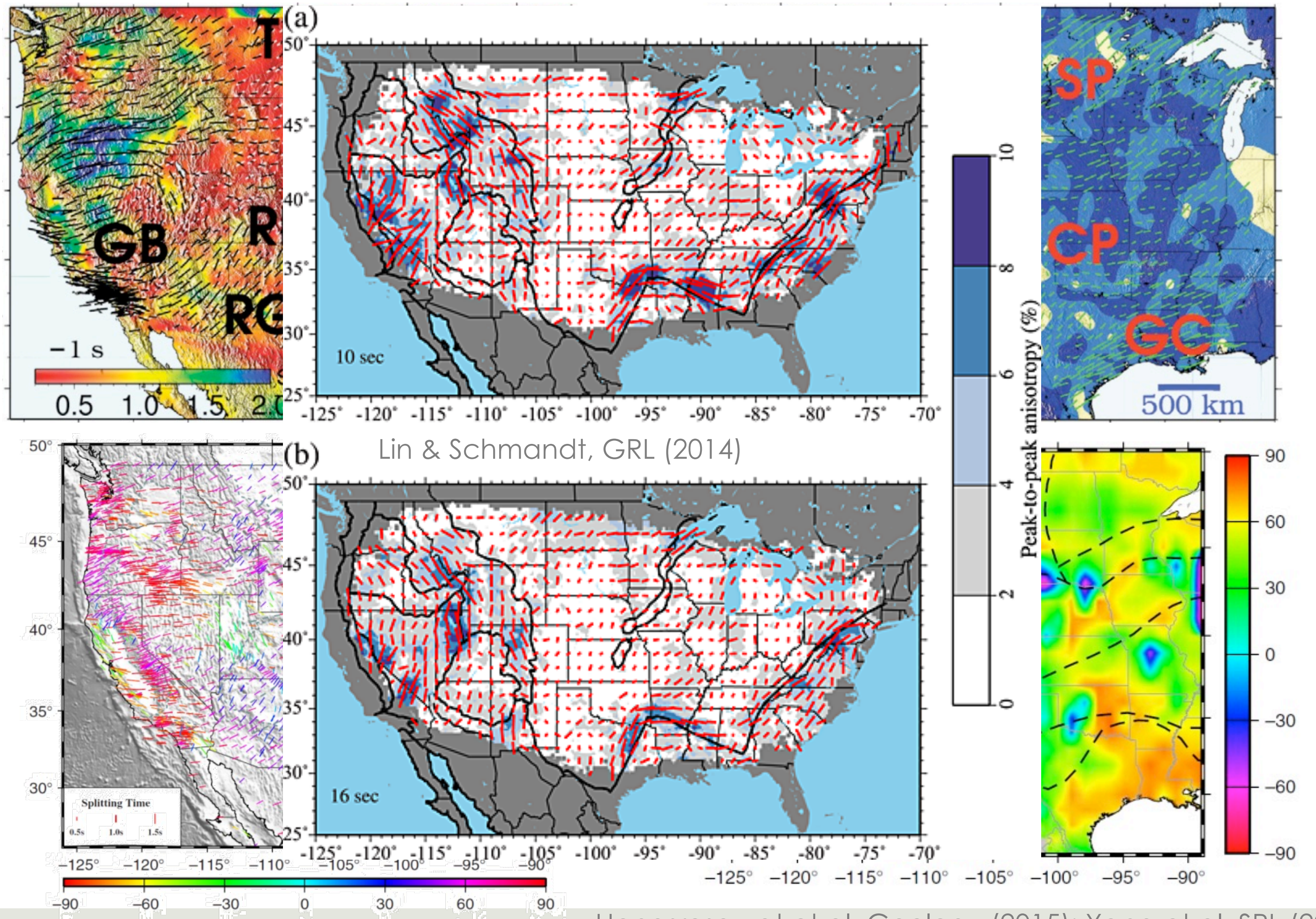
Seismic Anisotropy Across the Continent

Unprecedented spatial coverage of USArray provides unparalleled insights into complex patterns of deformation and flow within the lithosphere and sub-lithospheric mantle

Fast Direction WRT APM:

- $\mu = 2°$
- $\sigma = 27°$

Local deviations due to regional tectonics, with fabrics sourced in both asthenosphere and lithosphere



Lin & Schmandt, GRL (2014)

Hongsresawat et al, Geology (2015); Yang et al, SRL (2016)

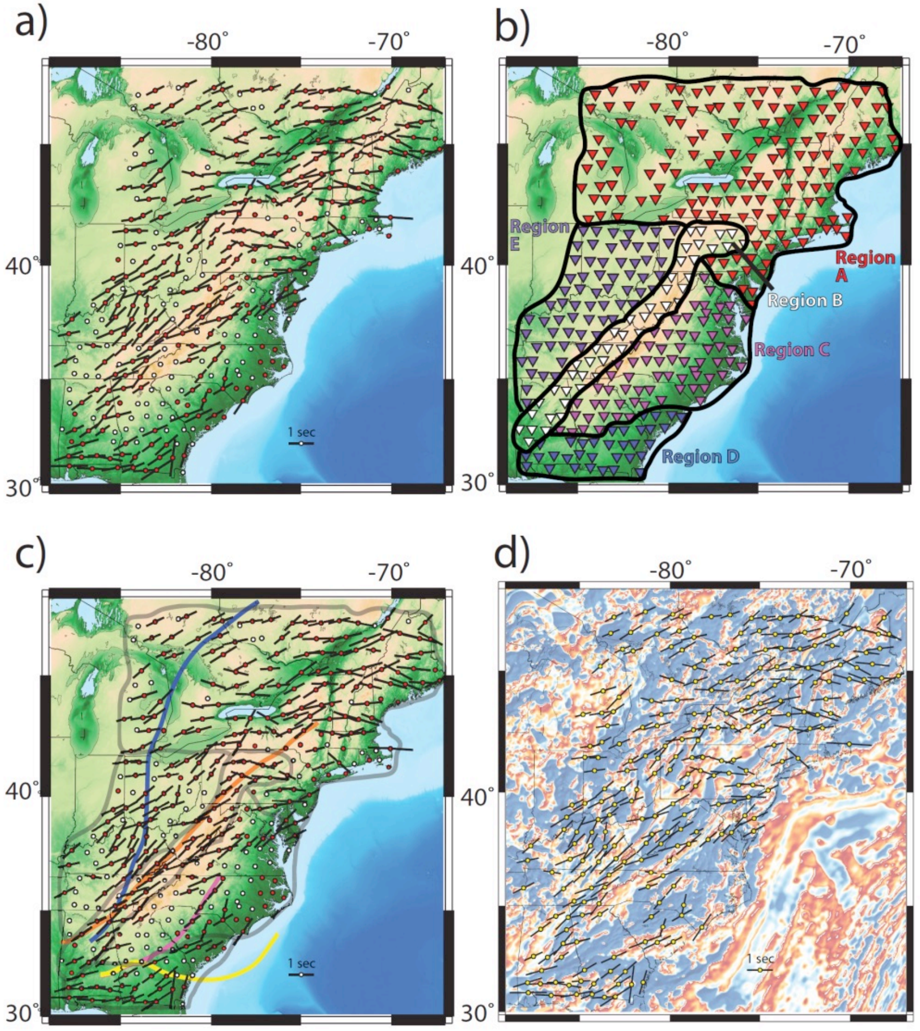
SKS Splitting Highlights Past Lithospheric Deformation

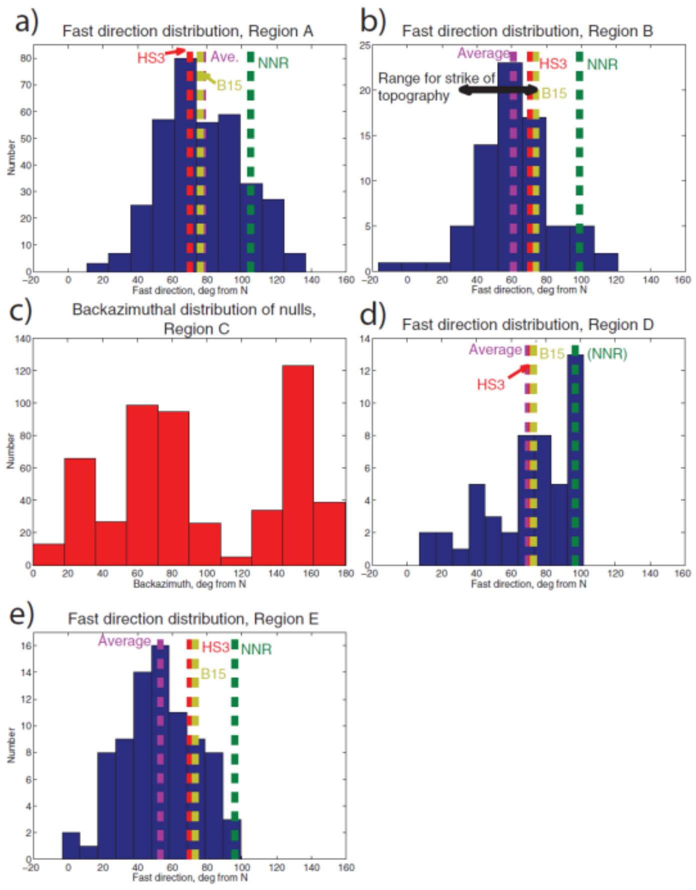
SKS splitting measurements (3902) from ~380 USArray TA stations

Asthenospheric and lithospheric contributions to anisotropic signal

Region B: Fast direction parallel to strike of Appalachian mountains

Region C: apparent increased lithospheric complexity or vertical present-day mantle flow

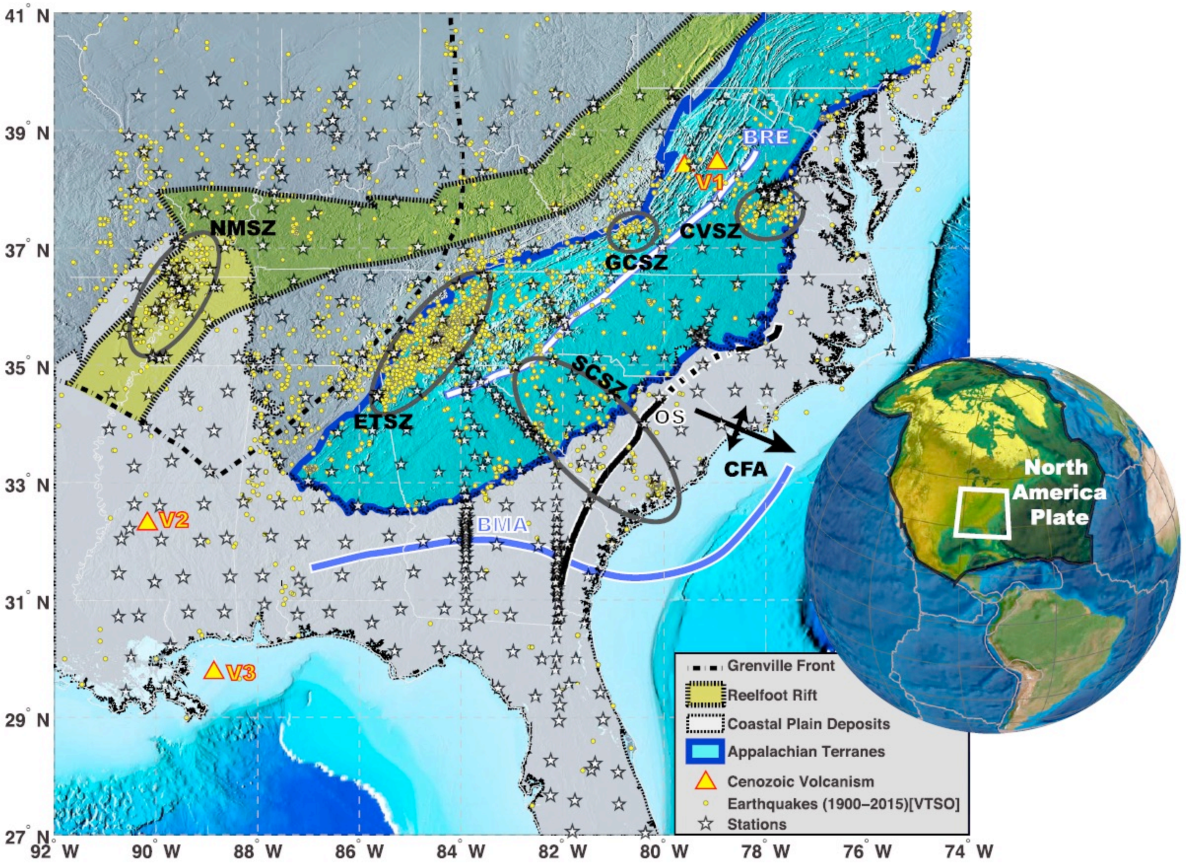


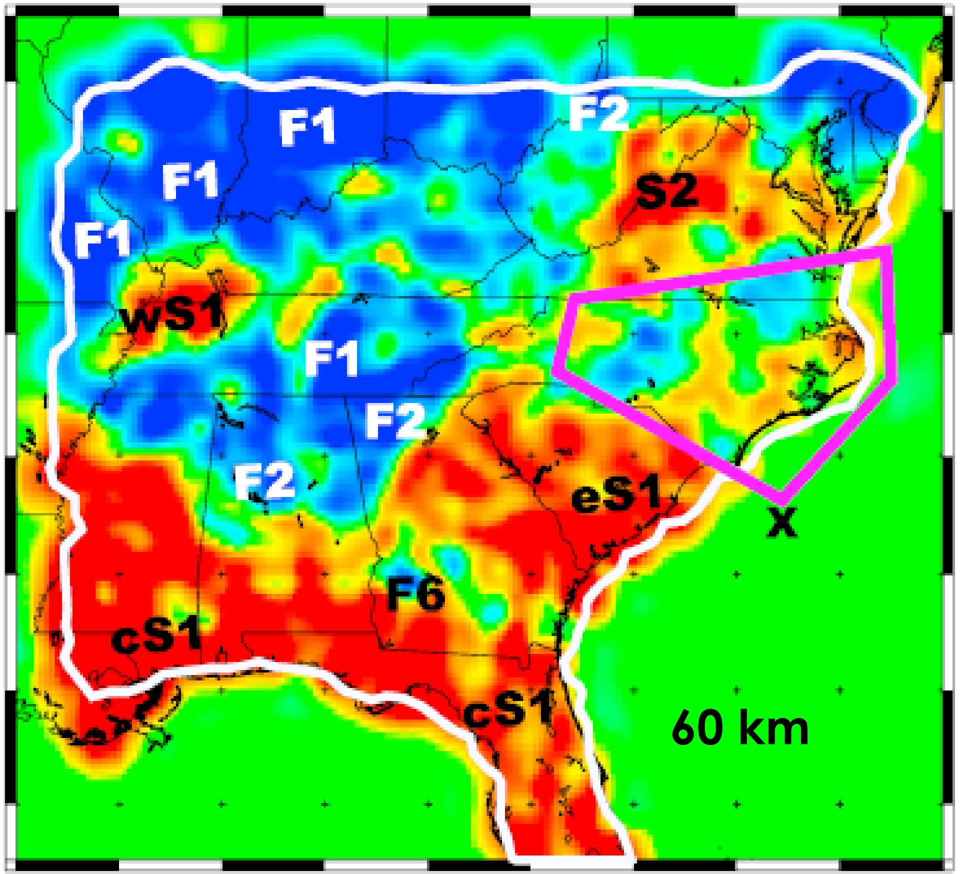


Long et al, GGG (2015)

Neither Passive nor Stable

- Thicker lithosphere beneath North Carolina, compared to Virginia and South Carolina, consistent with lower seismicity rates

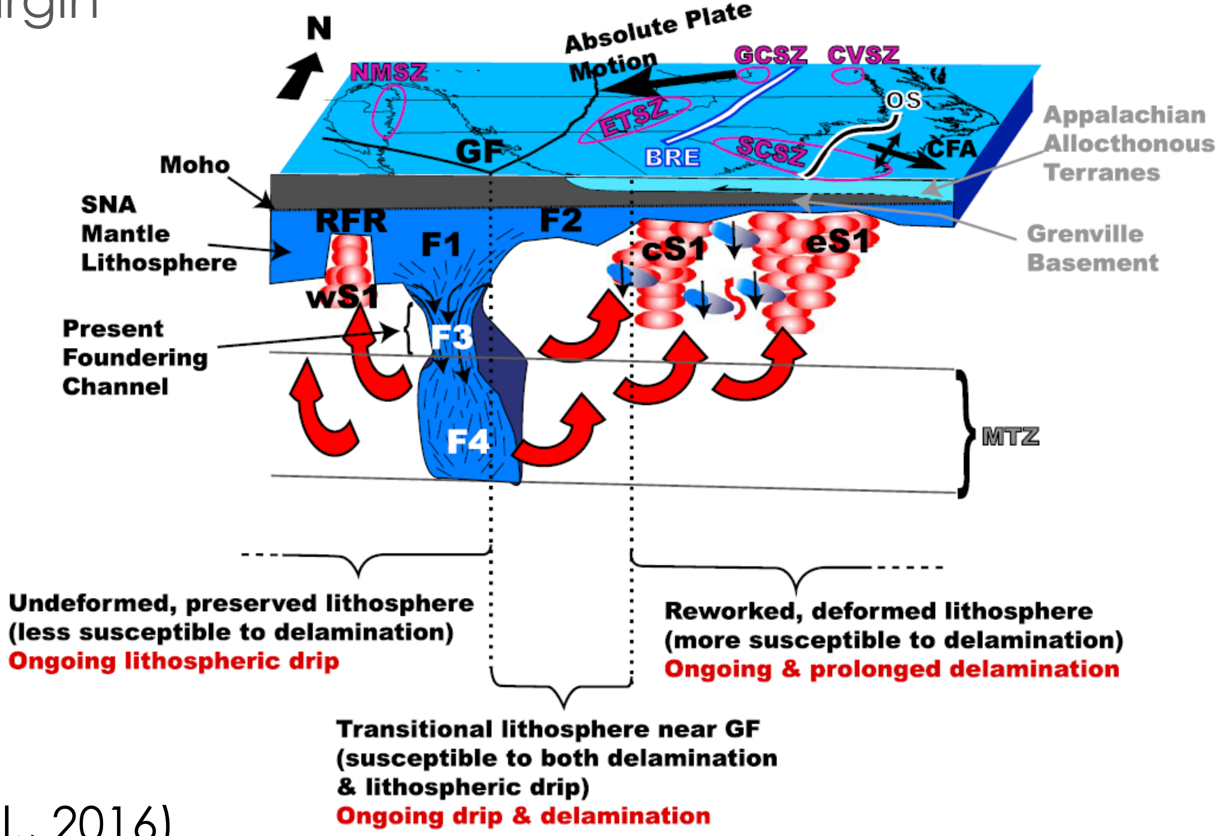


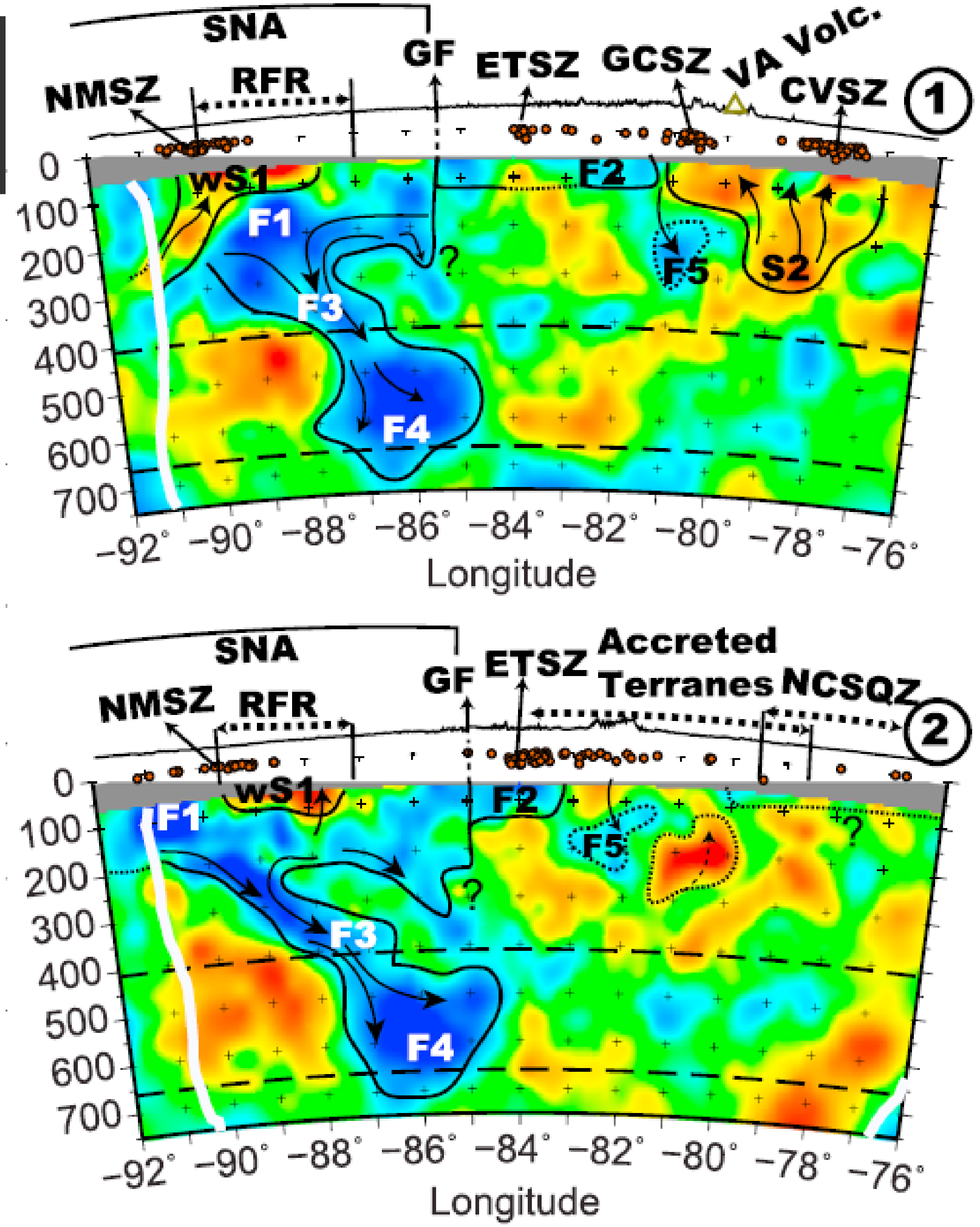


(Biryol et al., 2016)

Neither Passive nor Stable

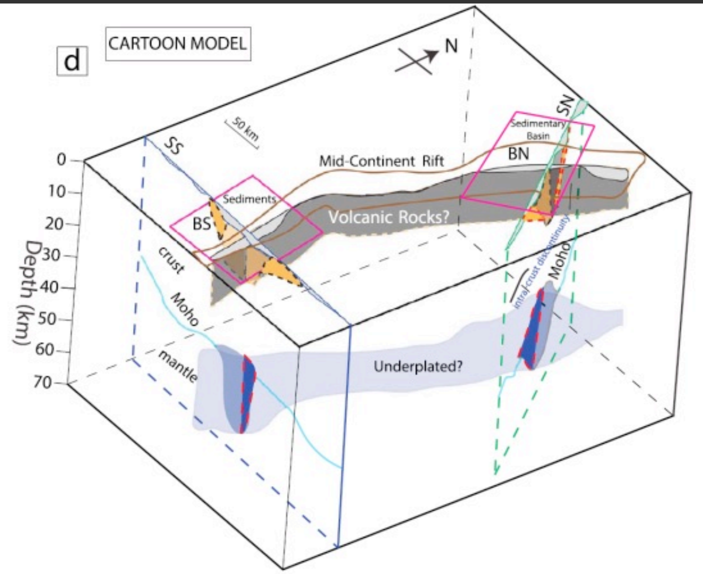
- Evidence of ongoing foundering beneath the Eastern US → Lithospheric structure is dynamically evolving even beneath passive margin

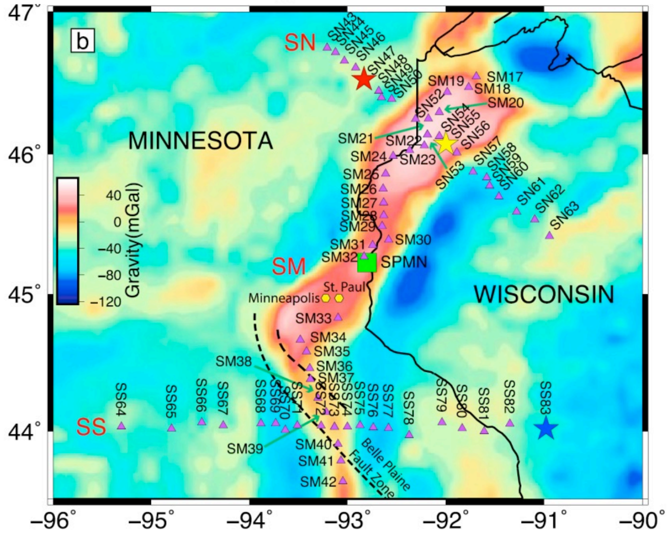




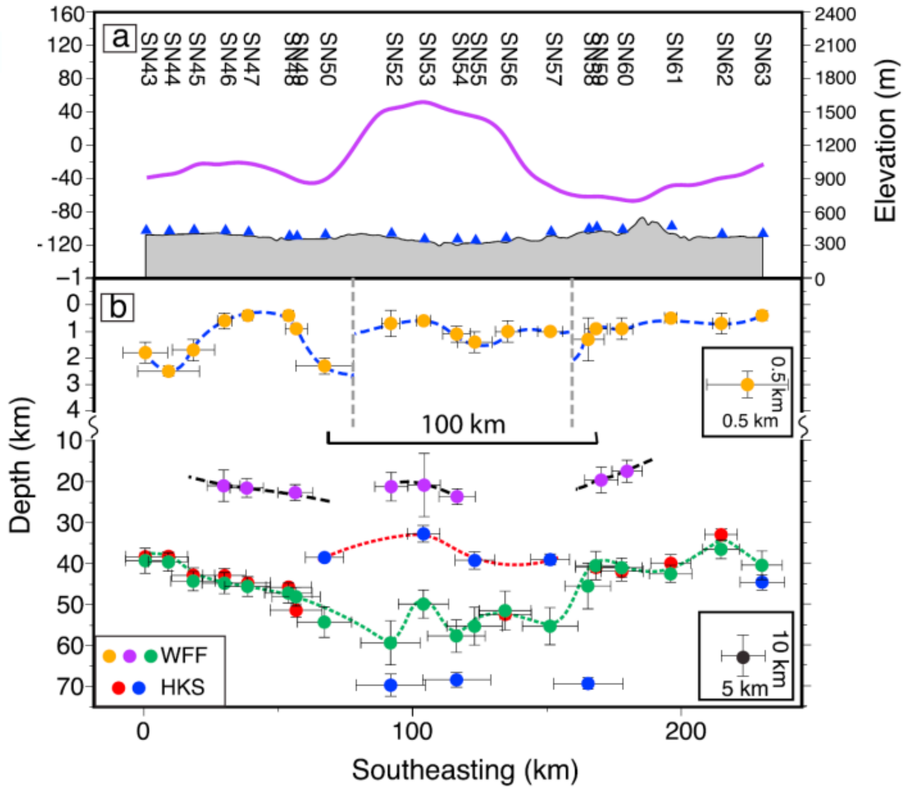
(Biryol et al., 2016)

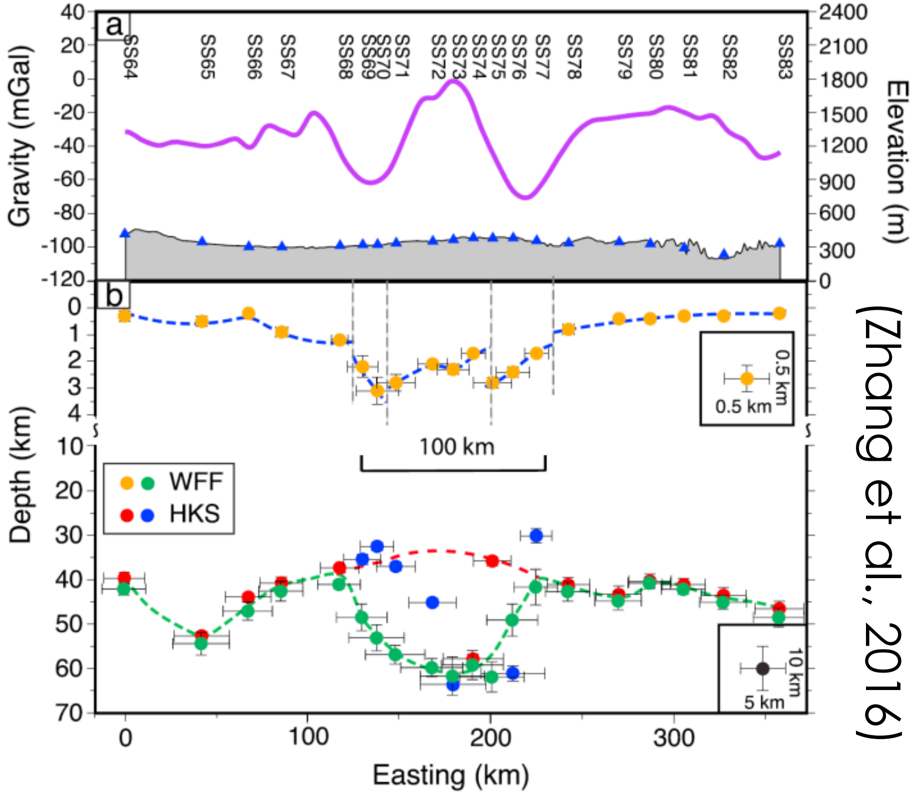
SPREE across the Mid-Continent Rift





- Intermittent mid-crustal P-to-S conversions from bottom of buried dense volcanic layers
- Signature of underplating found consistently along strike of the MCR

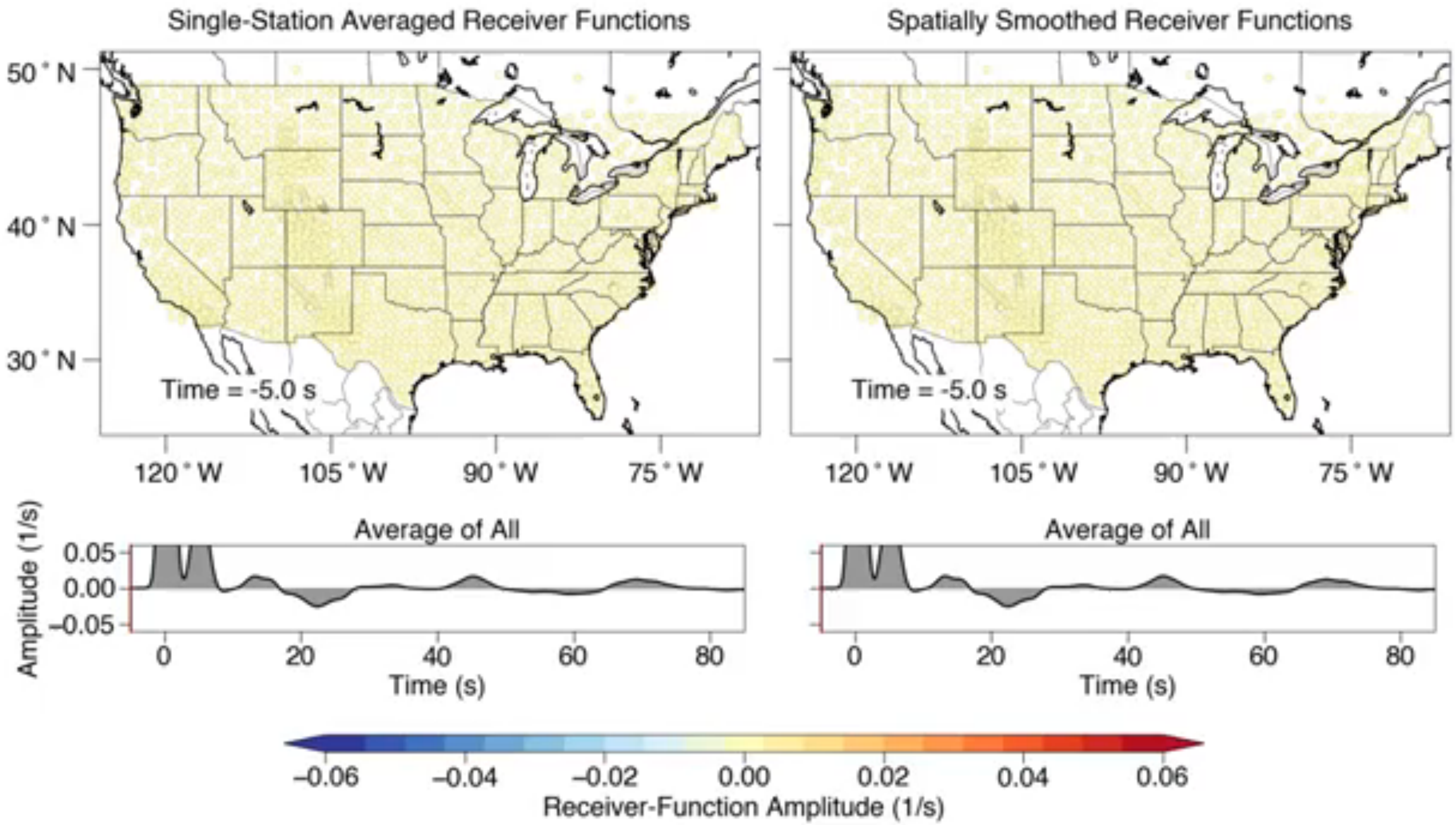




(Zhang et al., 2016)

Ps Receiver Functions

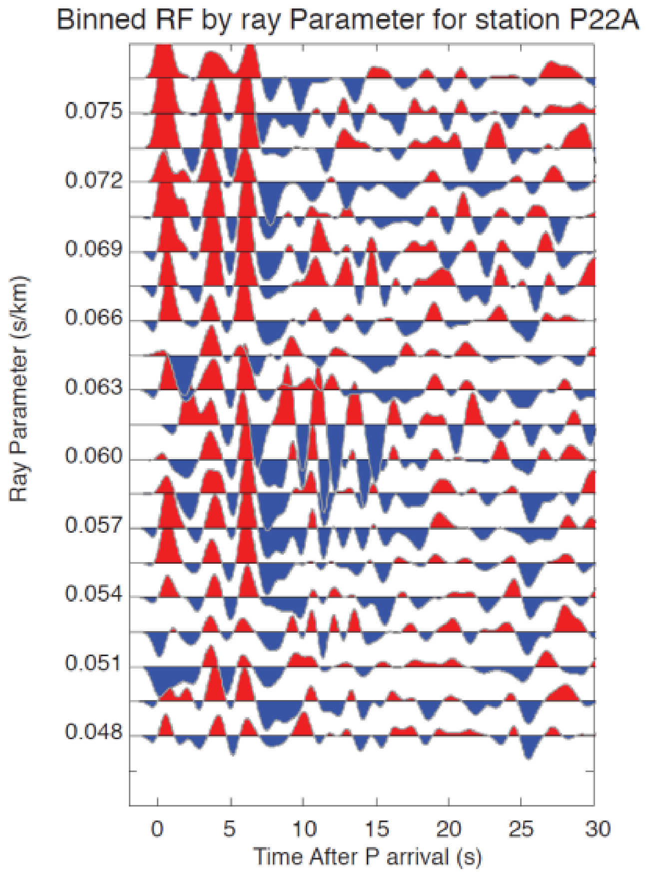
- Variations in conversions of P-wave energy to S waves across intra-lithospheric discontinuities have been mapped across the US.
- Large inter-station variability due to near-surface structure

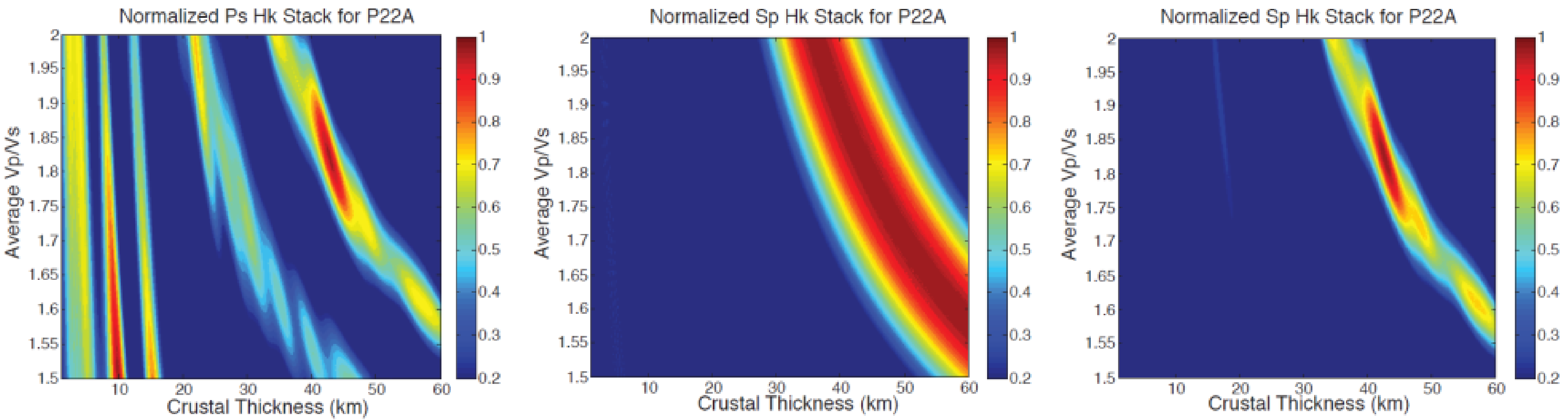


Courtesy of Chengping Chai

Sediment / shallow layer multiples

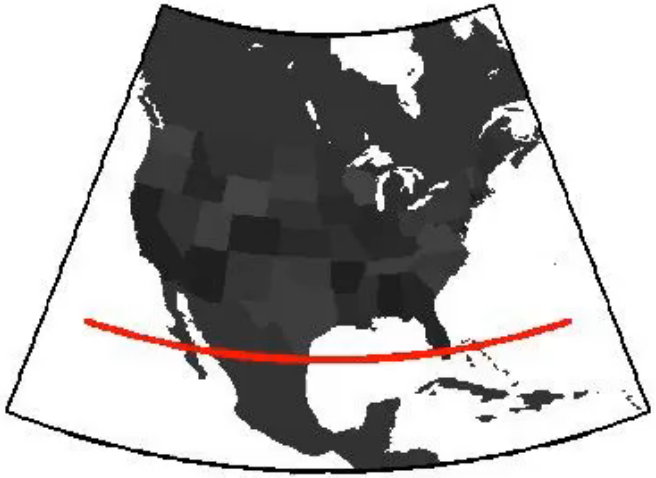
- Waves reverberating within sedimentary or other shallow layers can overprint the signal from Moho and deeper structures.
- H-k stacking obtains crustal thickness and average Vp/Vs ratio
- Combining Ps and Sp yields more easily interpretable H-k stacks



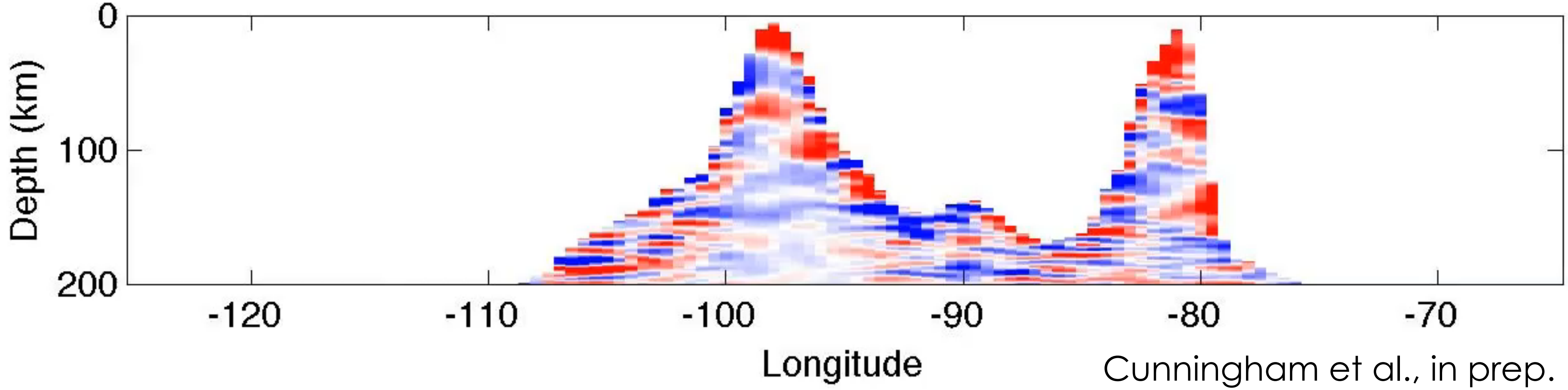


Courtesy of Erin Cunningham

Sp for crustal thickness



- Common conversion stacks of Sp receiver functions of Transportable Array stations reveal crustal thickness variations
- In places, thickness changes abruptly, amplitude disrupted, etc.
- Anomalous signals from lithospheric mantle, e.g. beneath Nebraska and Louisiana

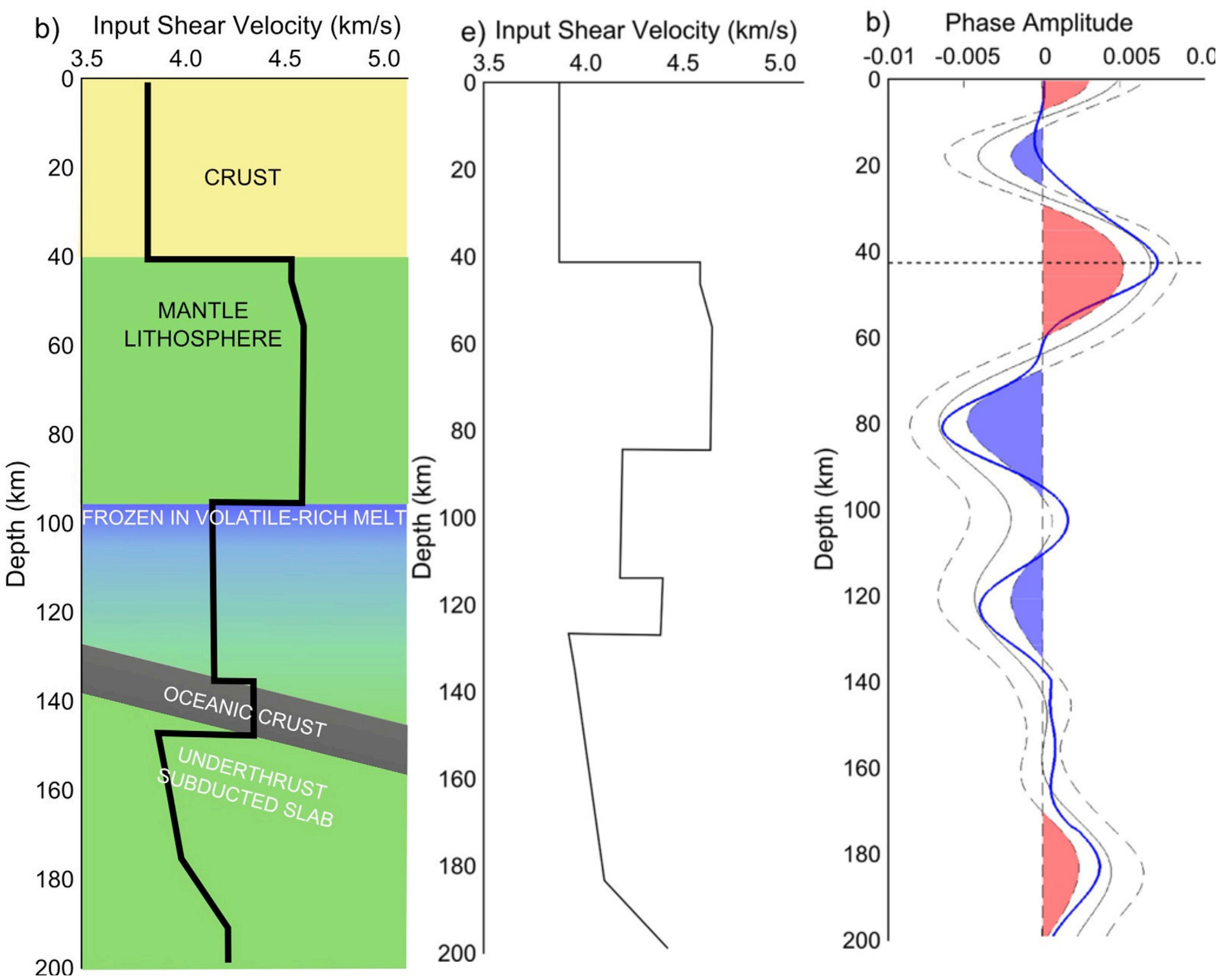


Cunningham et al., in prep.

Growth of cratonic mantle – Yavapai arc terranes

Near-flat negative velocity gradient beneath both Archean and Proterozoic cratons → frozen-in volatile-rich melt

Dipping negative velocity gradients are observed between 85 and 200 km depth → could represent remnant subducting slabs, and together with eclogite in xenoliths, indicate that subduction-related processes likely contributed to cratonic mantle growth.



Hopper & Fischer, G^3, 2015

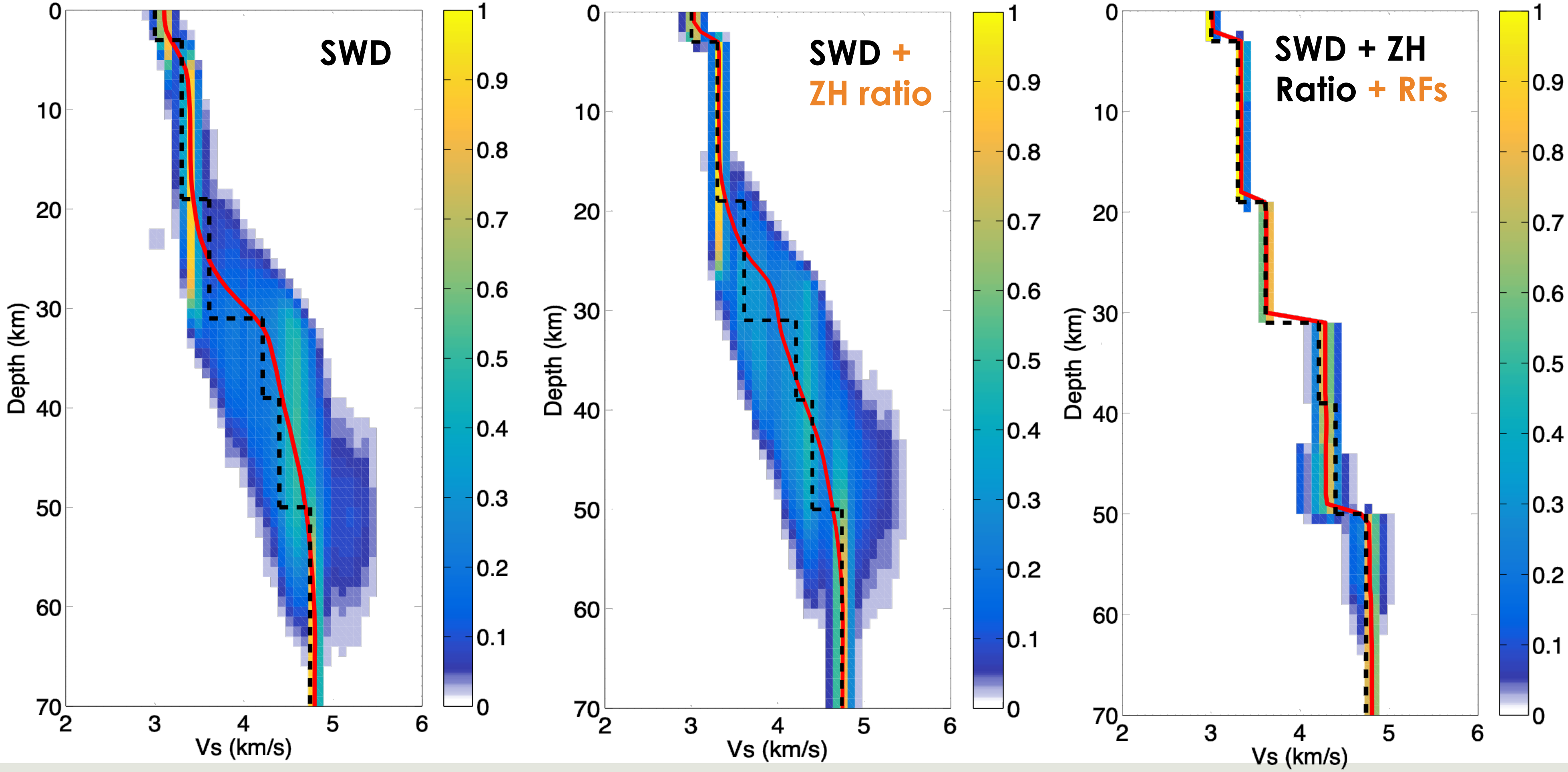
Leveraging complementary datasets

- The joint inversion of all three data types is able to constrain the Vs structure with a clear velocity jump.

Primary sensitivity: Absolute Vs

Shallow (<20km) Vp, Vs and density (Tanimoto and Alvizuri, 2006)

Velocity jumps (Langston, 1979)



Colormap: Probability distribution of ensemble results
: Target model
: Trimmed mean value of ensemble results

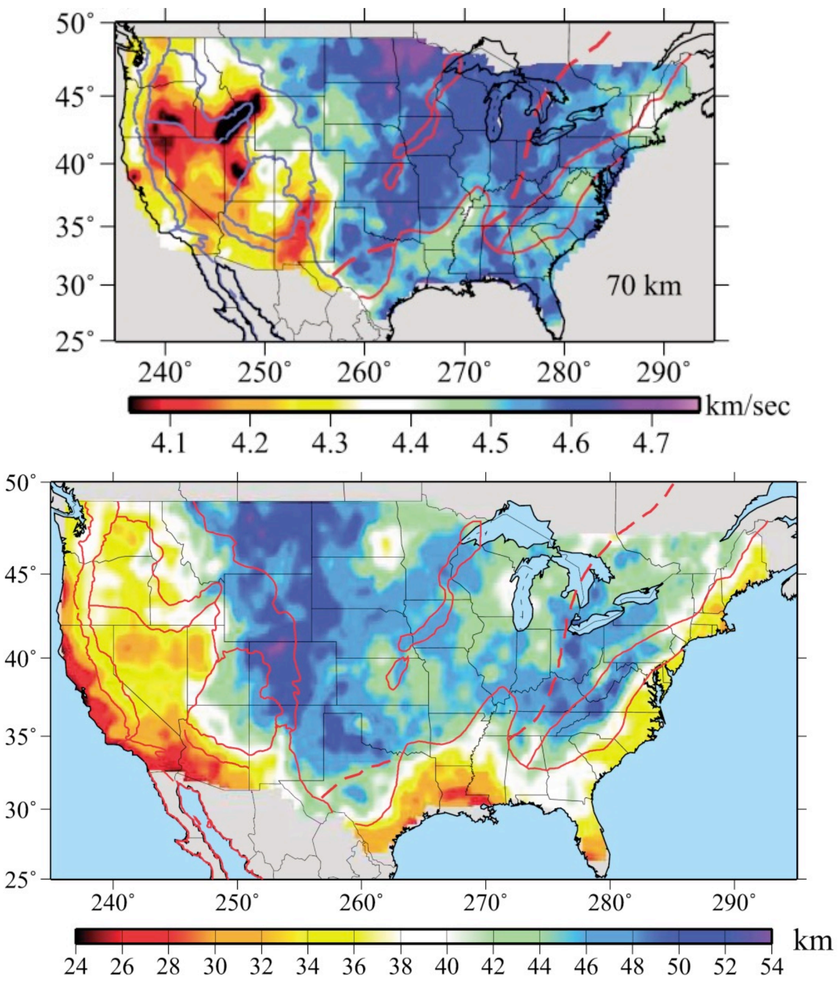
Gao et al., AGU 2015

Joint Inversion: Maximizing Sensitivity through Multiple Datasets

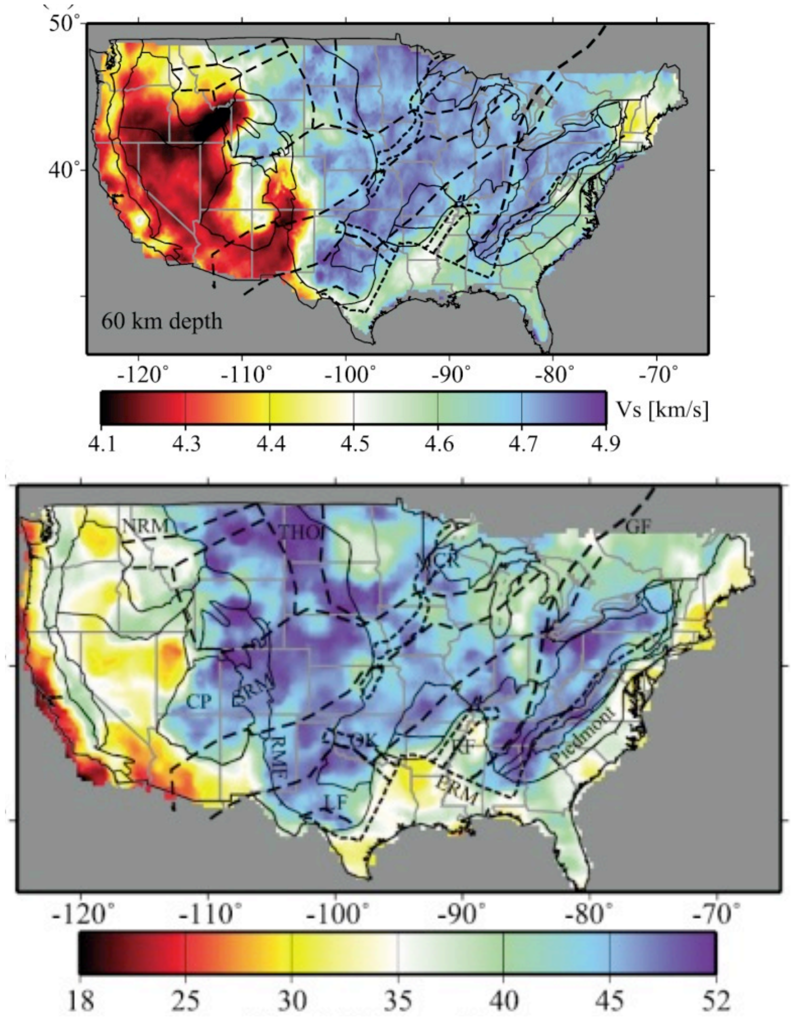
Joint Inversion: combining together Rayleigh Wave dispersion, Receiver Functions, and Rayleigh Wave Ellipticity (H/V) measurements

Left: Mean and σ from ~1800 TA stations across US provide error bounds on parameters defining uppermost mantle velocity & discontinuity structure

Right: RMF major E-W boundary in crustal thickness and elevation trend; primarily attributed to UM/LC density contrast (2x west than east)

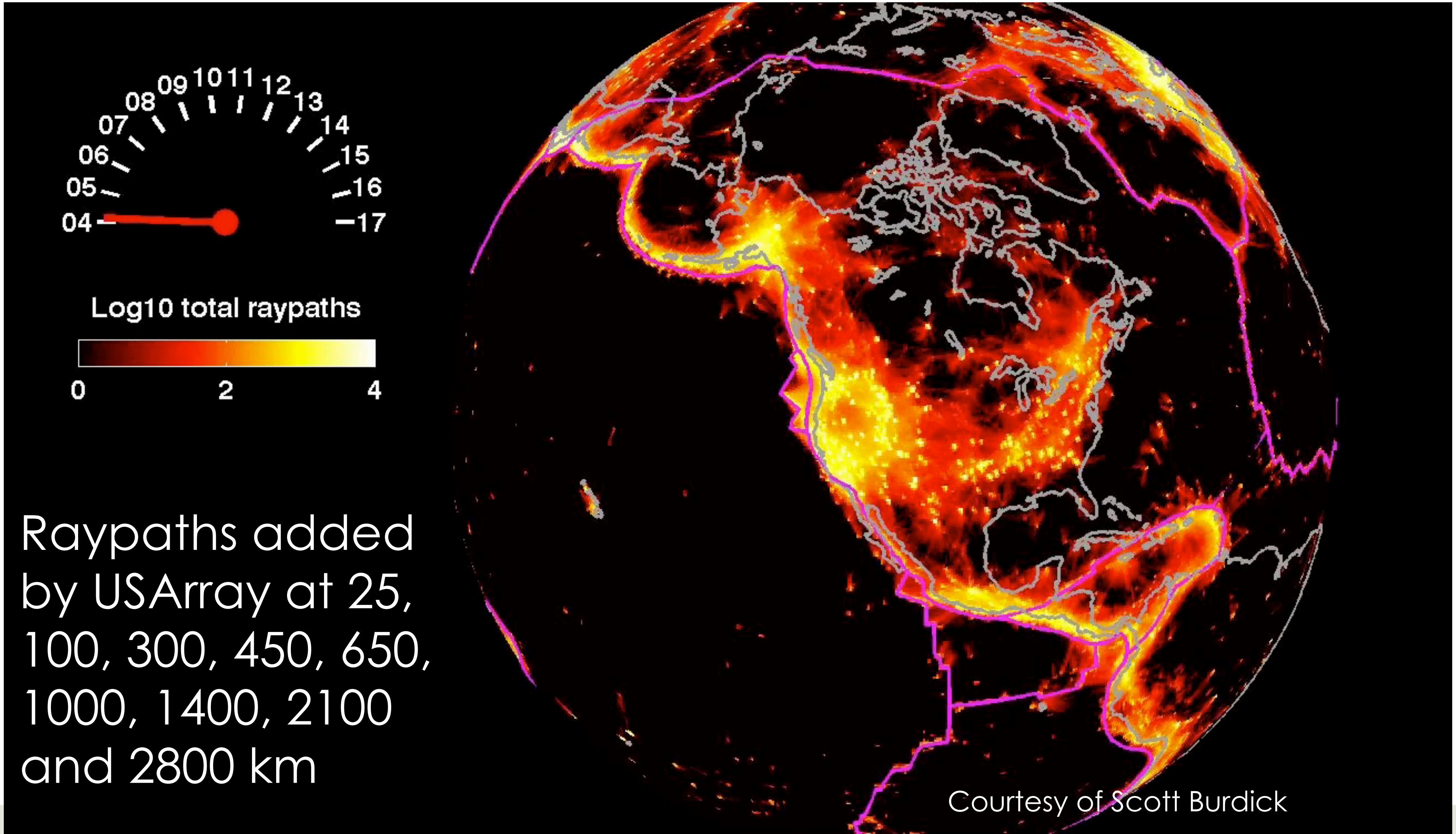


Shen & Ritzwoller, JGR (2016)



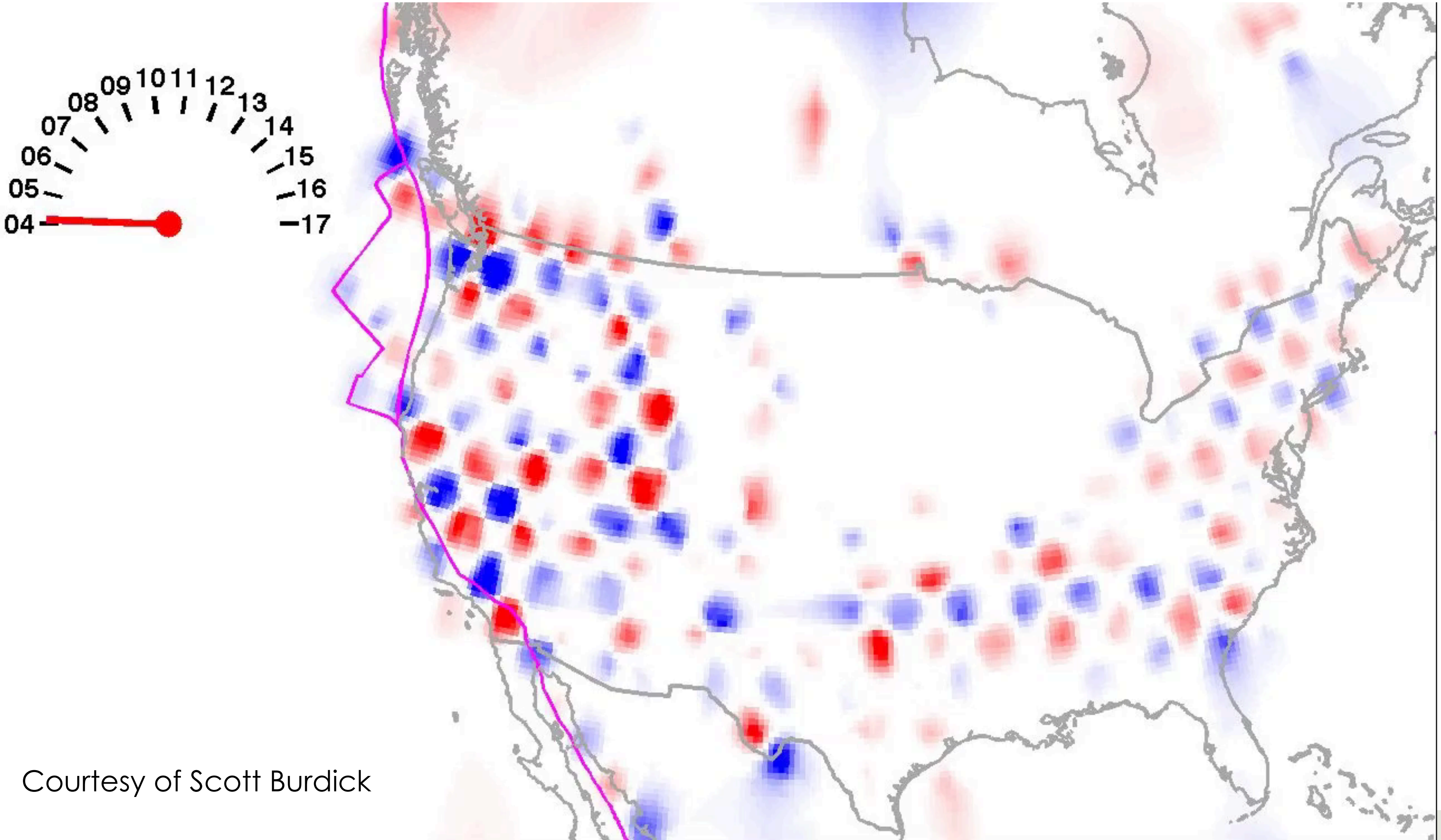
Schmandt et al, GRL (2015)

Improving P-wave Data Coverage



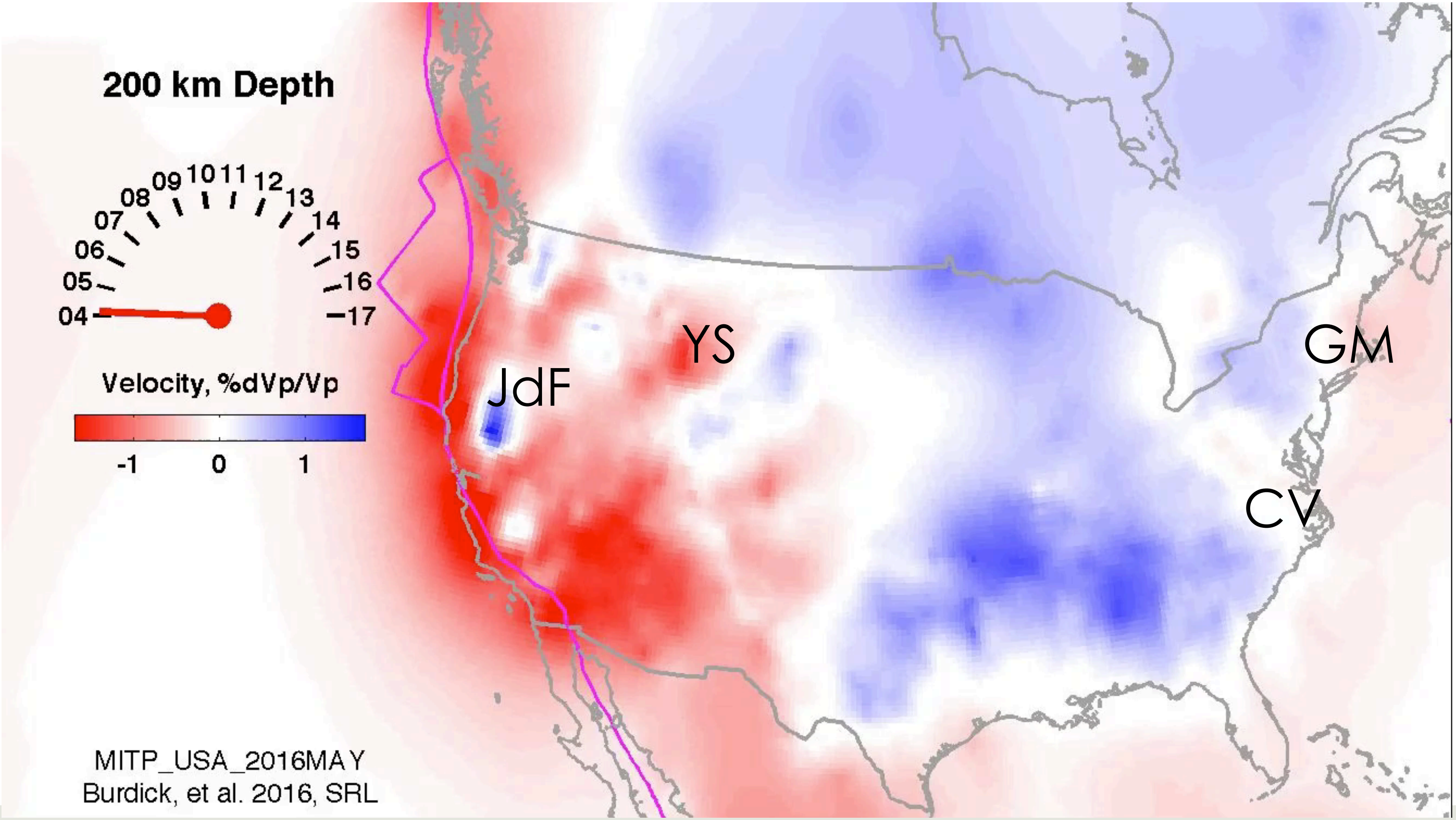
Raypaths added by USArray at 25, 100, 300, 450, 650, 1000, 1400, 2100 and 2800 km

Improving P-wave Tomography Resolution



Courtesy of Scott Burdick

Ever-Sharper Images (P-wave tomography)

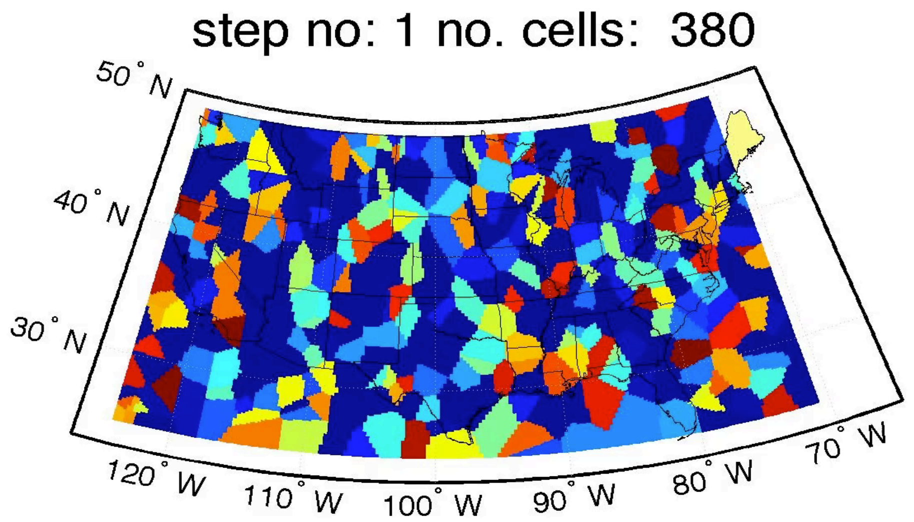


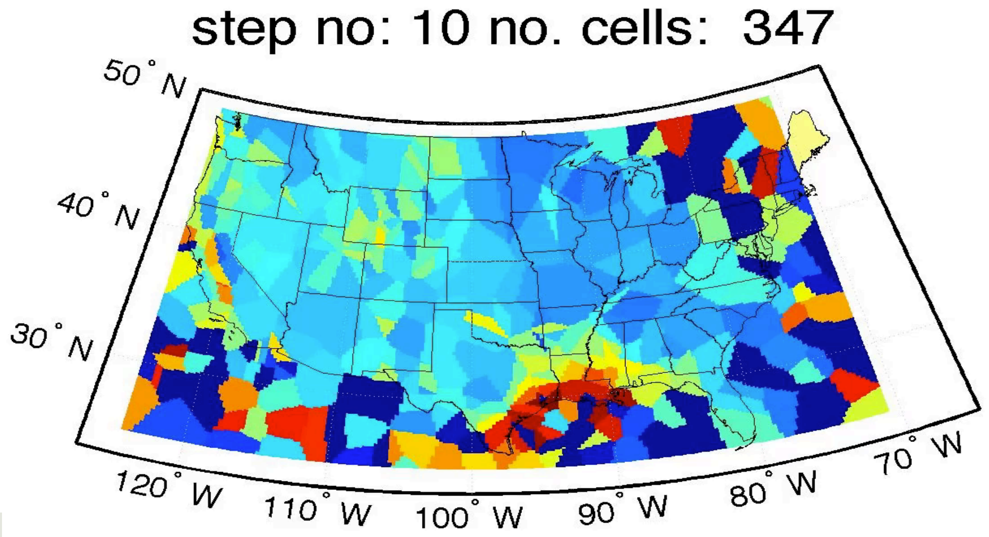
THB-Approach to *EarthScope* Data

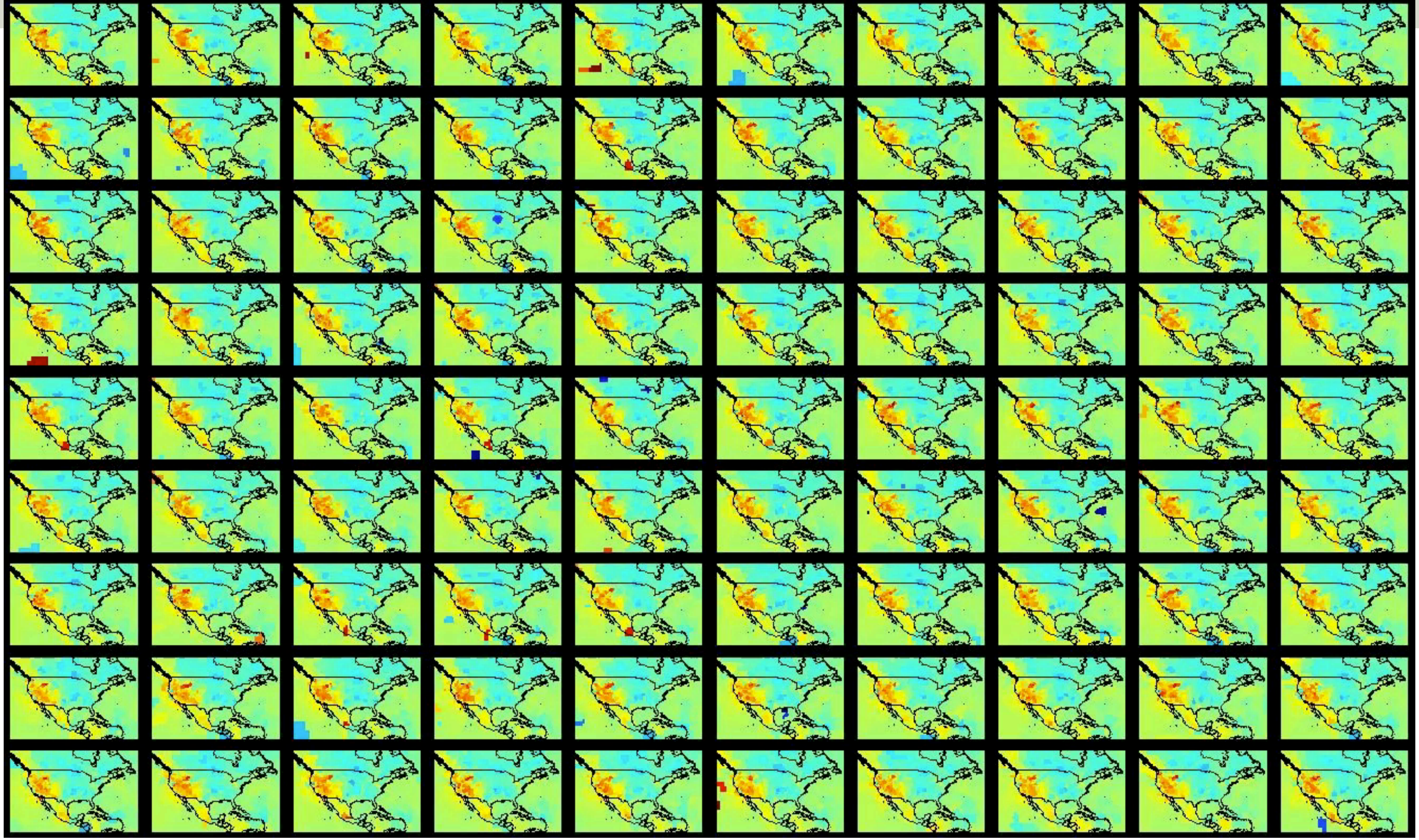
- **Transdimensional:** Infer **parameterization** from data, e.g.: unknown number of boxes / Voronoi cells of unknown location, shape, and phase velocity

- **Hierarchical:** Infer **noise** characteristics directly from data.

- **Bayesian:** Likelihood of each trial model is calculated, and a model space search is carried out to obtain an ensemble of solutions that can be analyzed to quantify **uncertainty** and compute **trade-offs** among parameters.



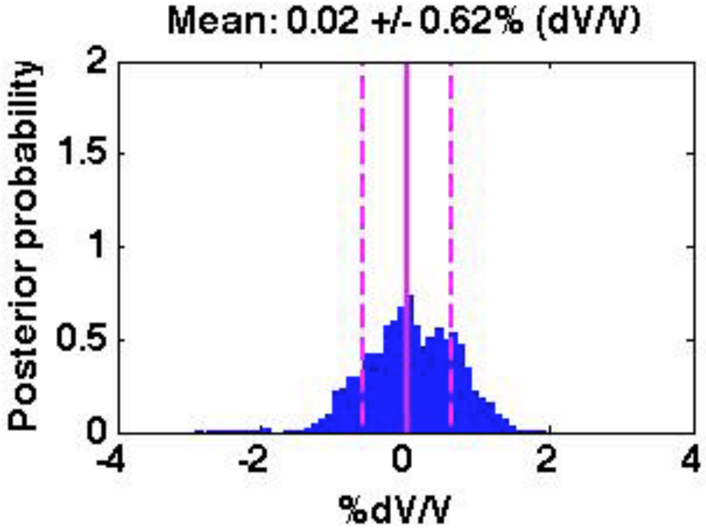




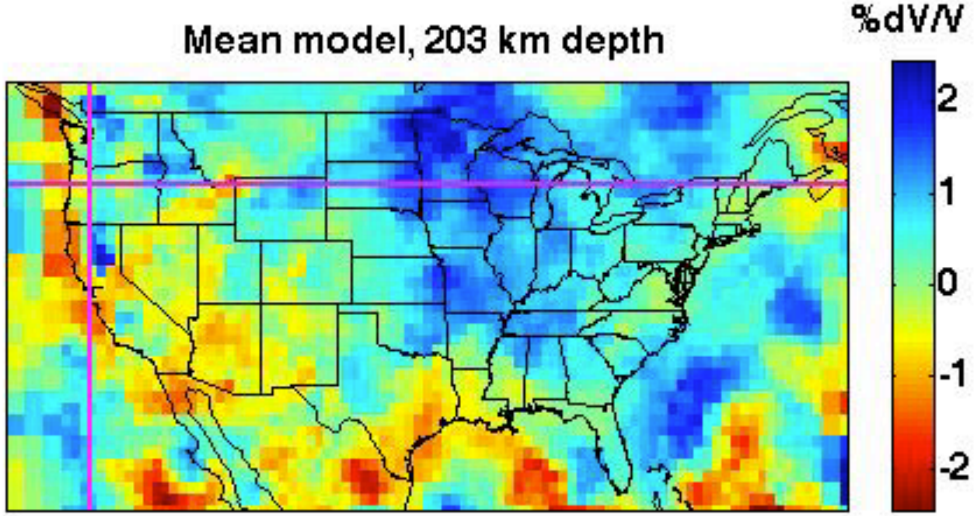
- Run 100s of millions of random model modifications (Markov chain Monte Carlo) to obtain a representative sample of possible models.
- **rjMcMC ➔ MOVE, BIRTH, DEATH, CHANGE Vp, CHANGE noise estimate**

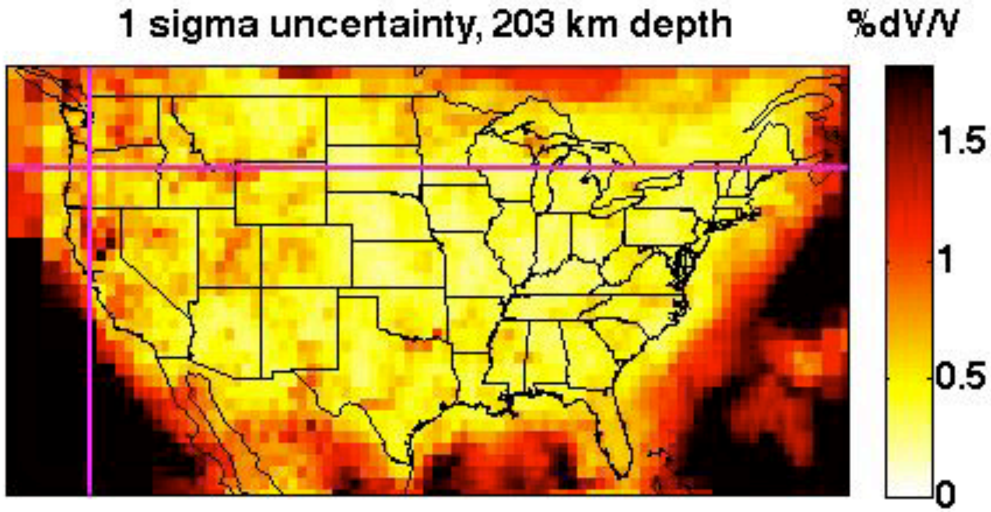
Investigating the model ensemble

- Posterior is not always normally distributed—multimodal in complex regions, uniform where no data is available



- Mean and standard deviation of the model don't (usually) tell the whole story

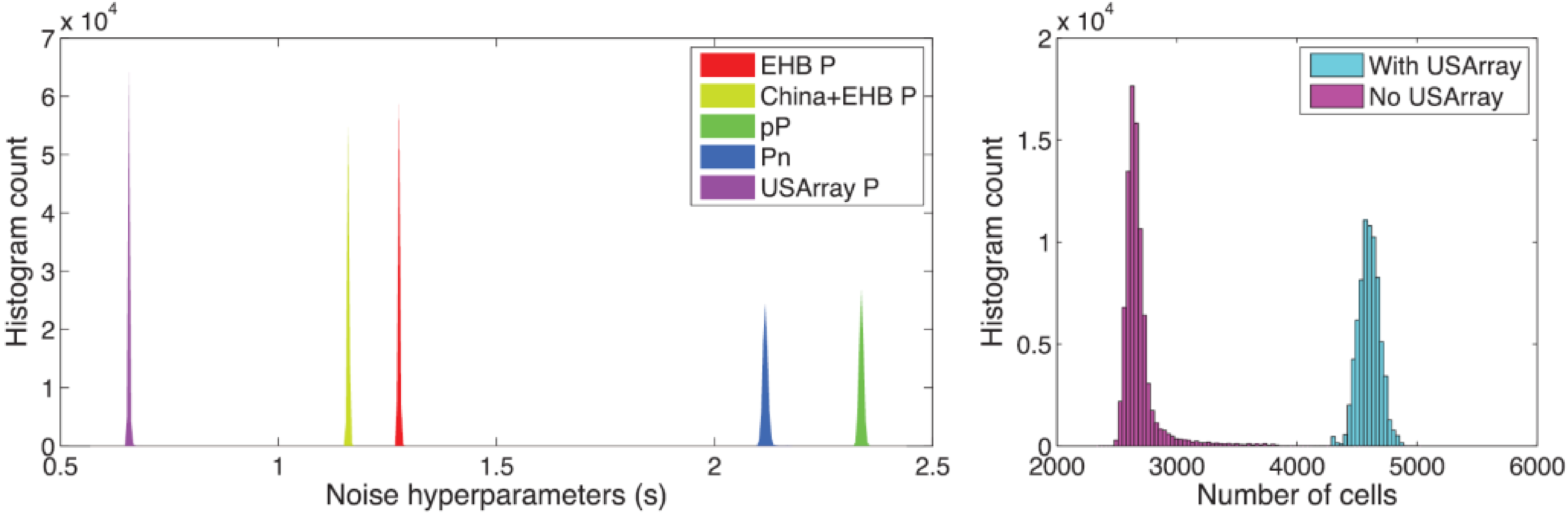




Burdick & Lekic GJI, 2017

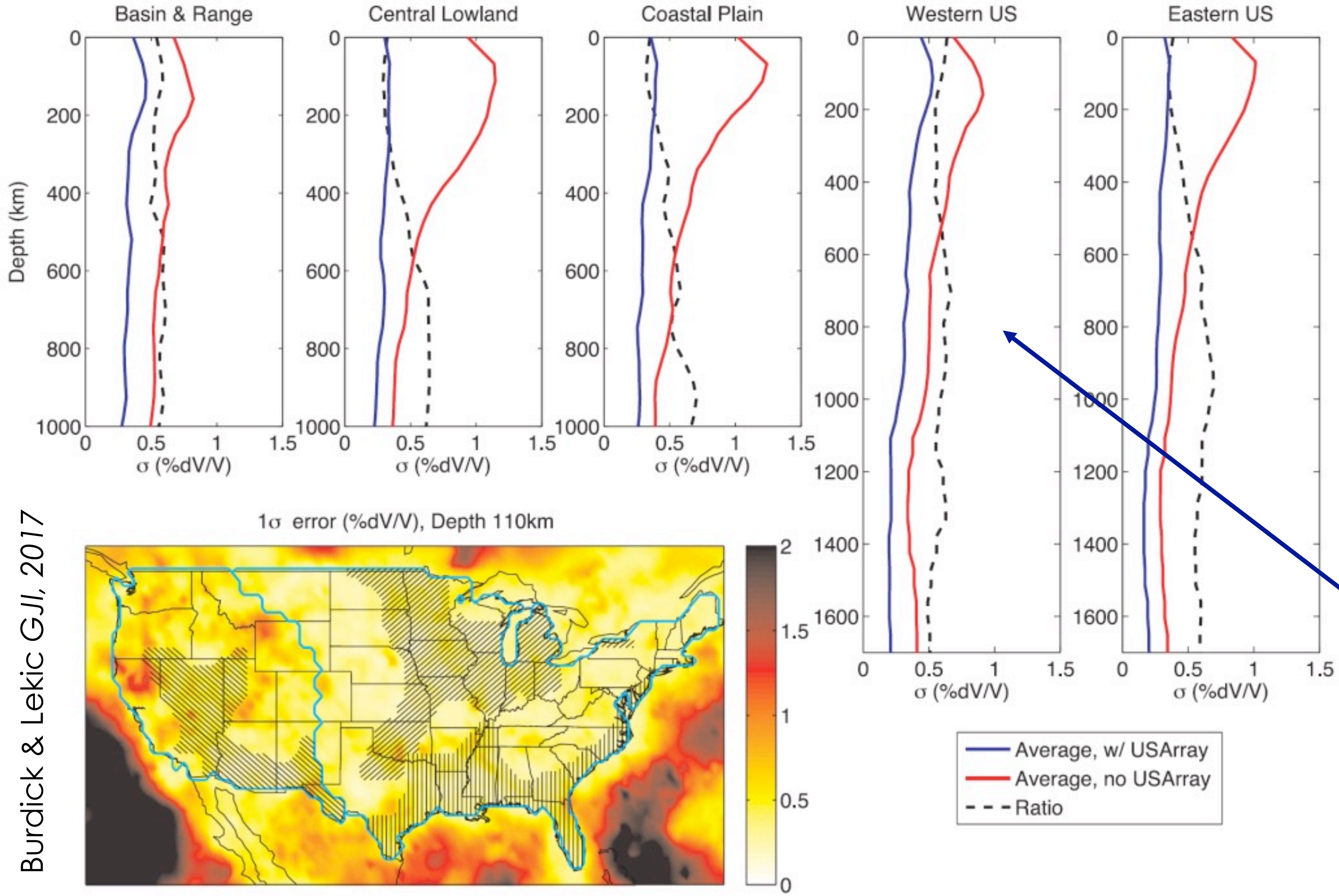
Unparalleled data consistency makes a difference!

- Statistical properties of the ensemble solution can be used to quantify the uncertainties of the inferred velocities, and to quantify **noise** characteristics inferred directly from data.
- USArray data make a difference in complexity of inferred model.



Burdick & Lekic GJI, 2017

Quantifying EarthScope Improvement



Burdick & Lekic GJI, 2017

55-70% lower uncertainty

Only 35-50% lower uncertainty

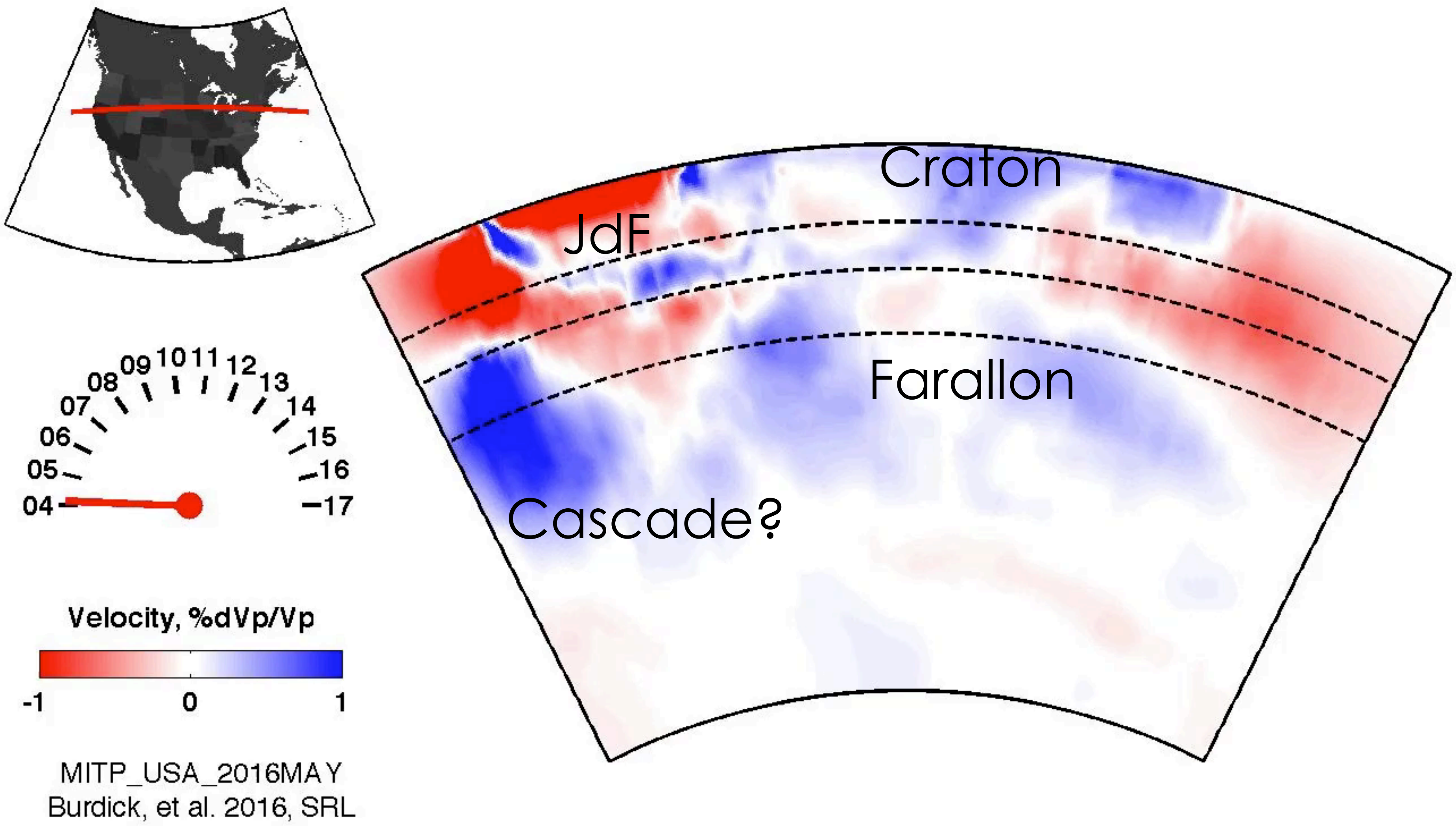
40-50% improvement in West over all depths

Summary & Conclusions

- Recordings from USArray, the seismological component of *EarthScope*, have revealed the crust and mantle beneath North America at unprecedented resolution.
- A variety of body wave, surface wave, and receiver function, and combinations thereof, studies have yielded images that have motivated the formulation of hypotheses that mapped rifts, basins, and that relate intraplate deformation and volcanic activity to newly-imaged crustal and lithospheric structures:
- As the USArray moved into the eastern half of the United States where data had been even more sparse, new models illuminated connections between rift structure and deeper processes at the Midcontinent Rift (e.g. Zhan et al., 2016) and the Reelfoot Rift (Chen et al., 2014) and the origins of seismicity and volcanism in the southeastern US (e.g. Schmandt and Lin, 2014; Biryol et al., 2016).

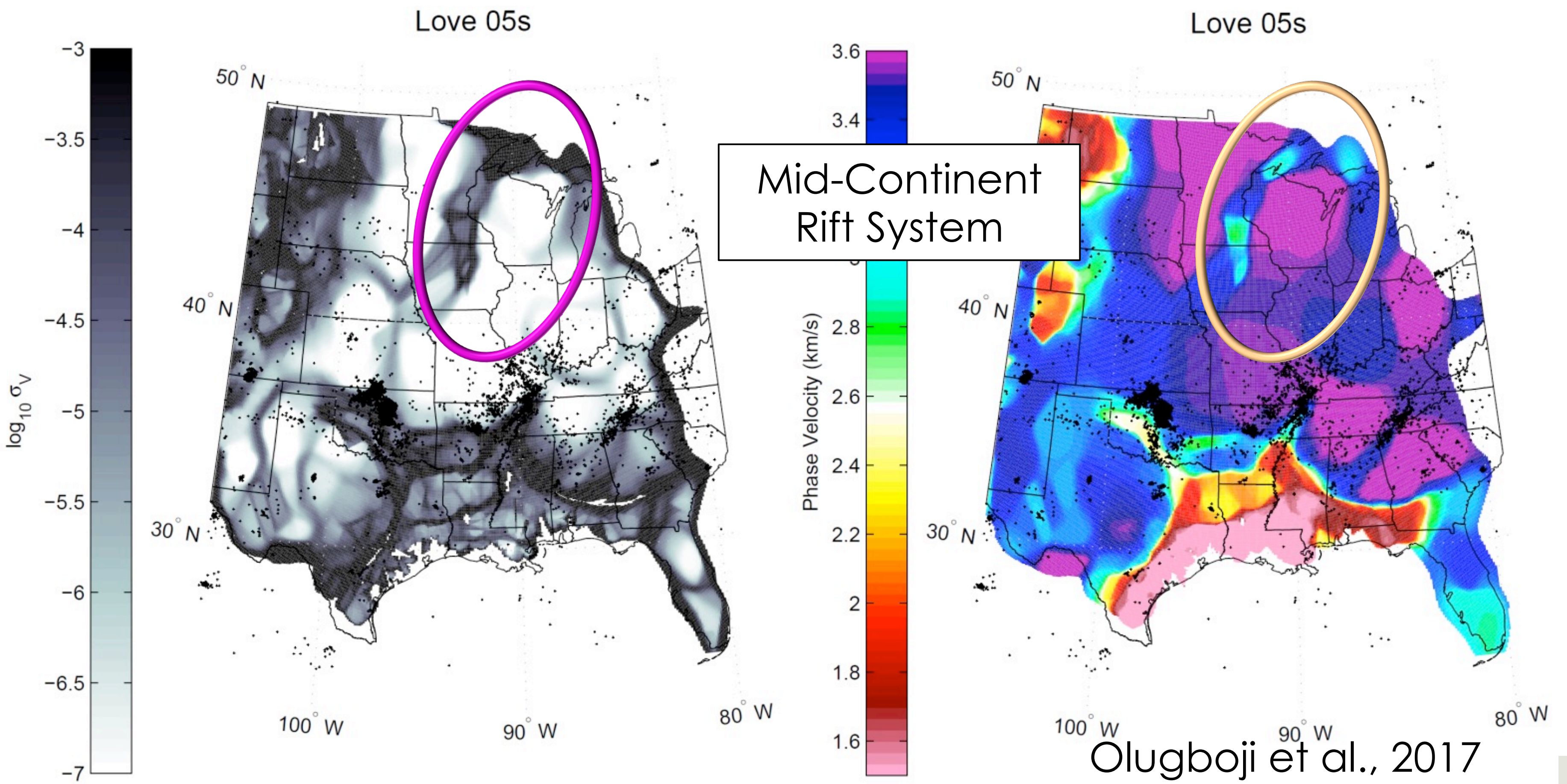
Extra Slides

P-wave Community Model



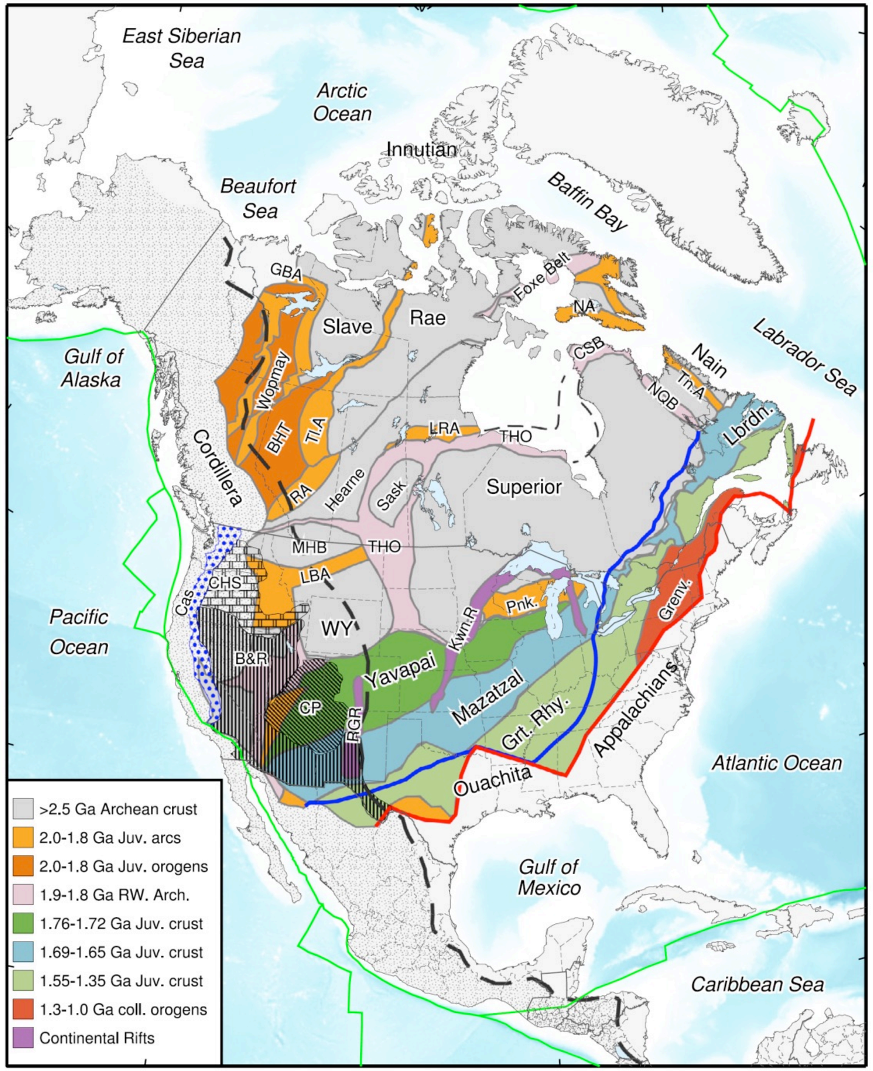
Phase Velocity Maps

- Upper crust shows laterally abrupt structural variations associated with past tectonic events

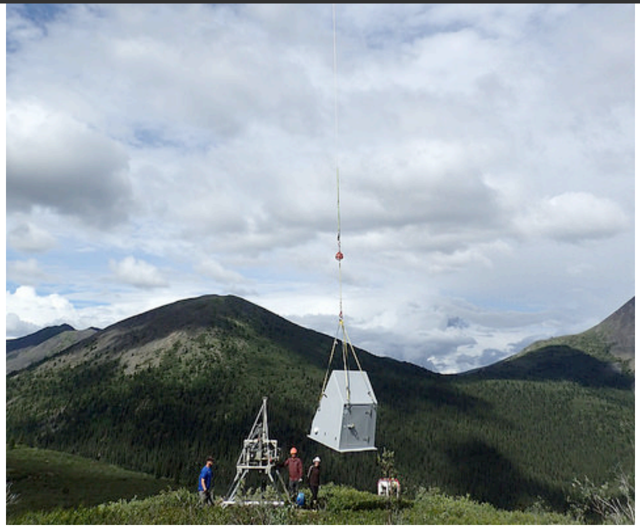


Olugboji et al., 2017

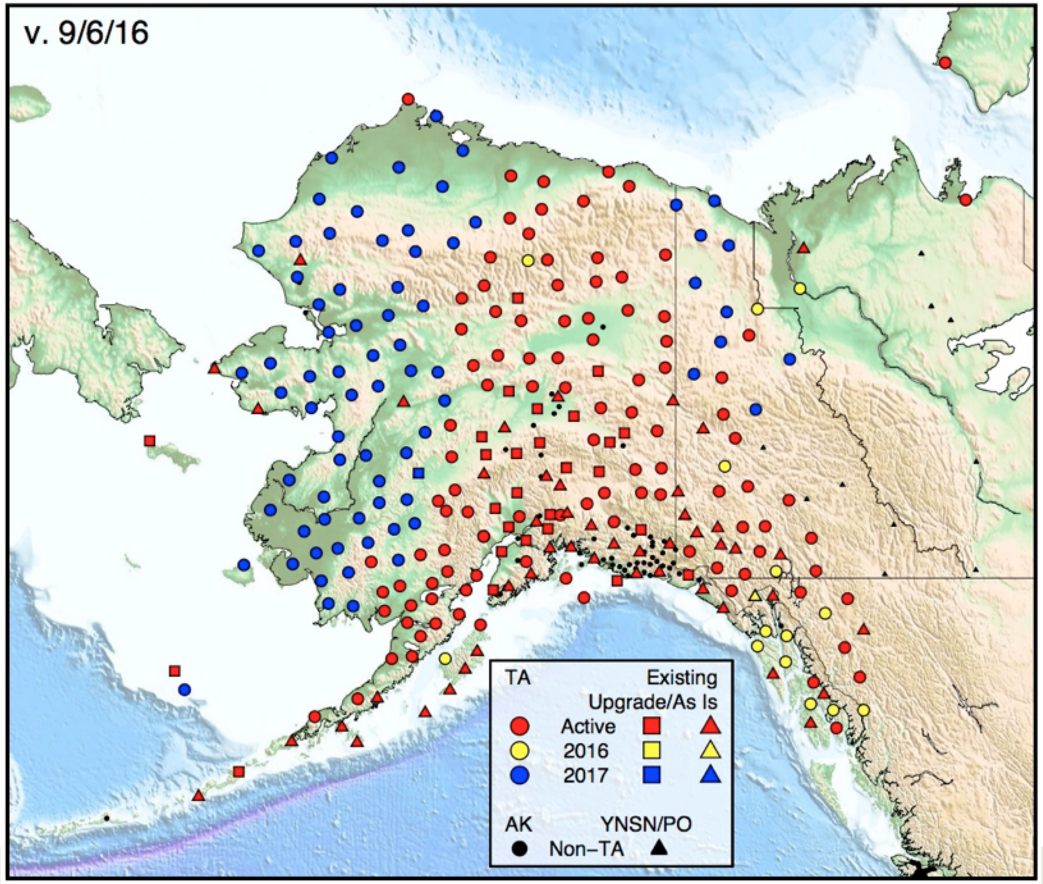
A 4 Billion Year Old Natural Laboratory



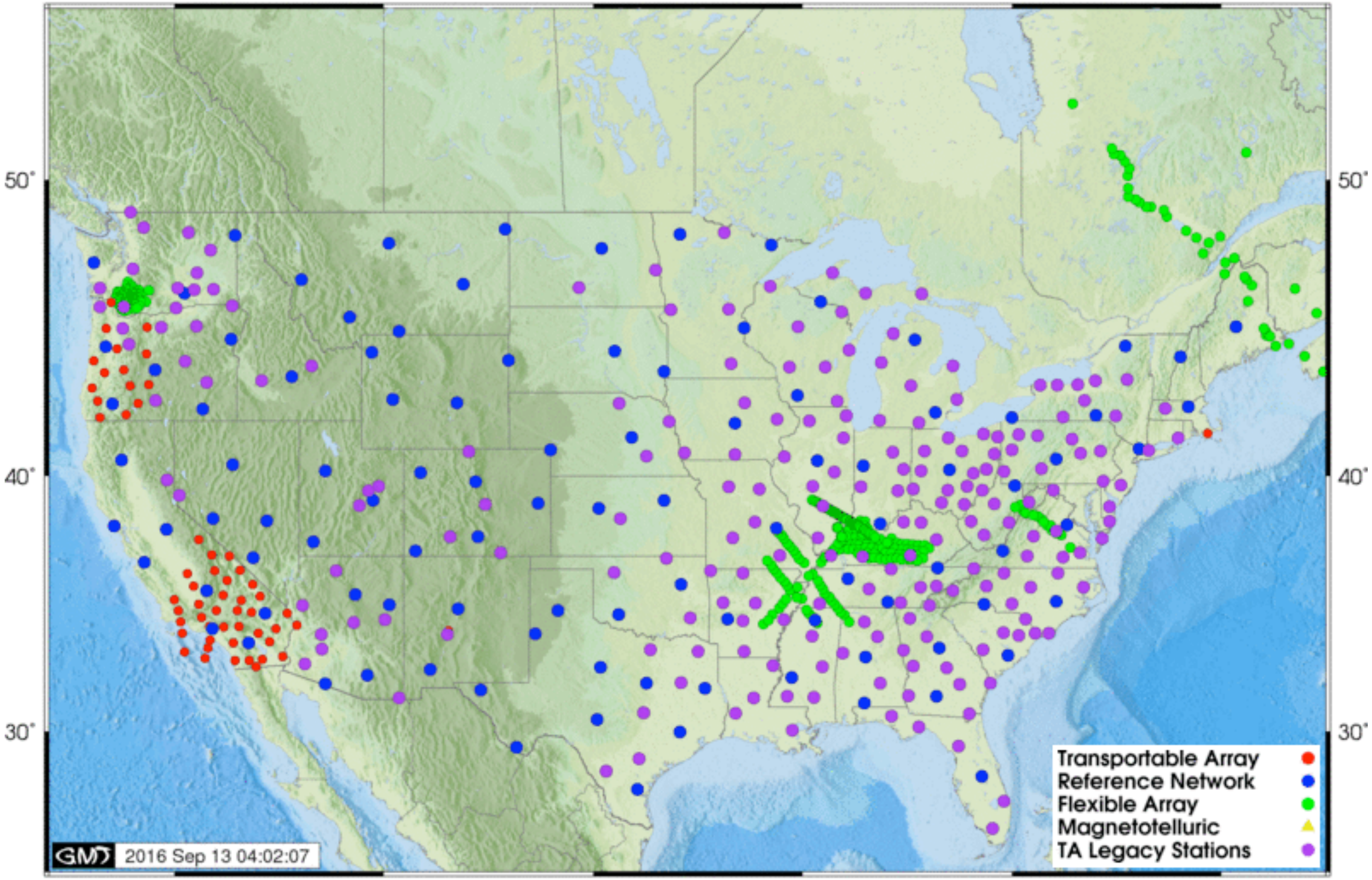
EarthScope in Alaska



- The Transportable Array has made its way to Alaska, overcoming a new suite of logistical and technical challenges.



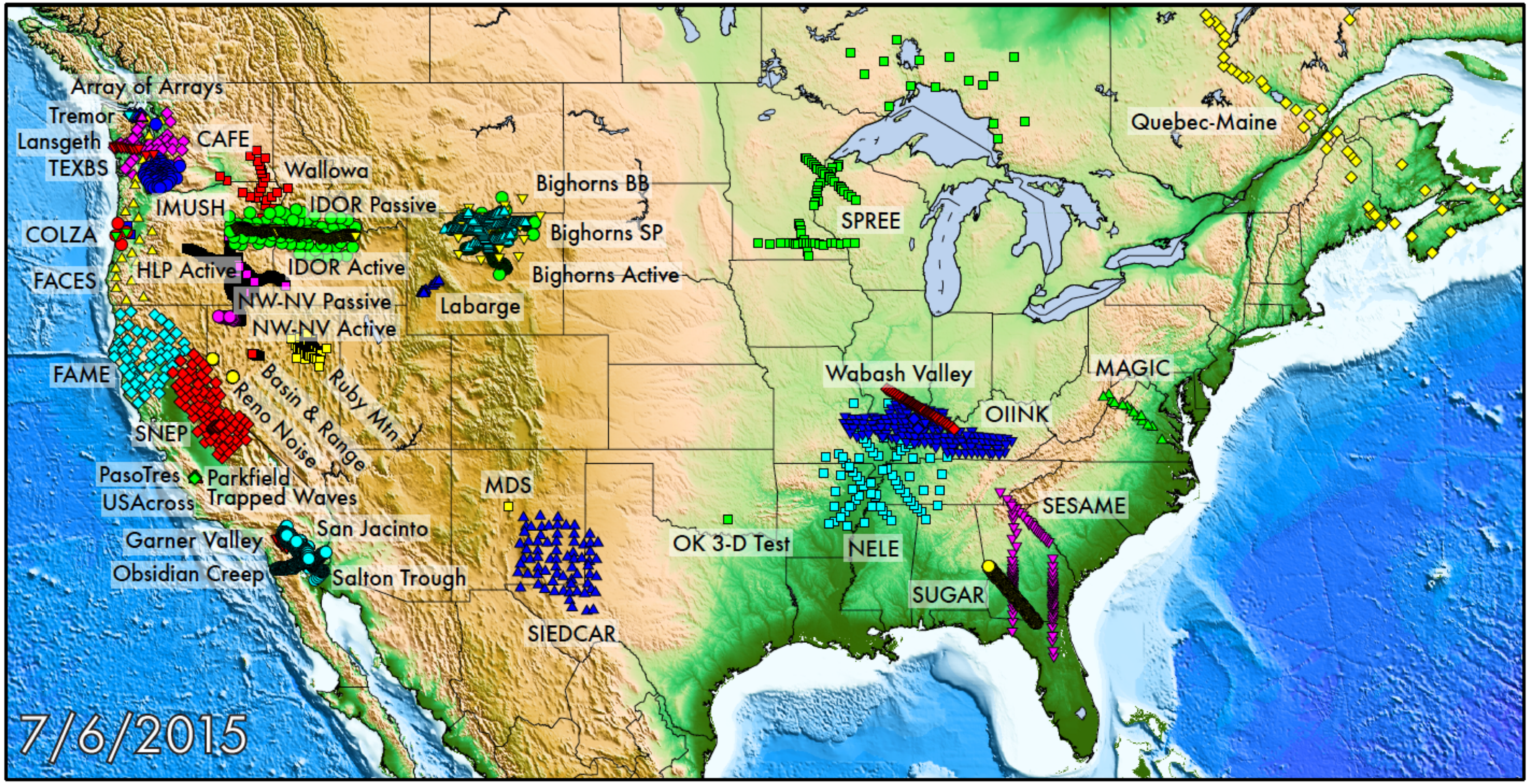
The Lower 48: EarthScope's Legacy



- TA Site Adoption
- Includes 400 Transportable Array (TA) Stations
- Each Station occupies a site for 1.5 – 2 years
- 10 years to leap-frog across the country

The Lower 48: Flexible Array deployments

- >20 temporary deployment experiments "zoom-in" on specific structures

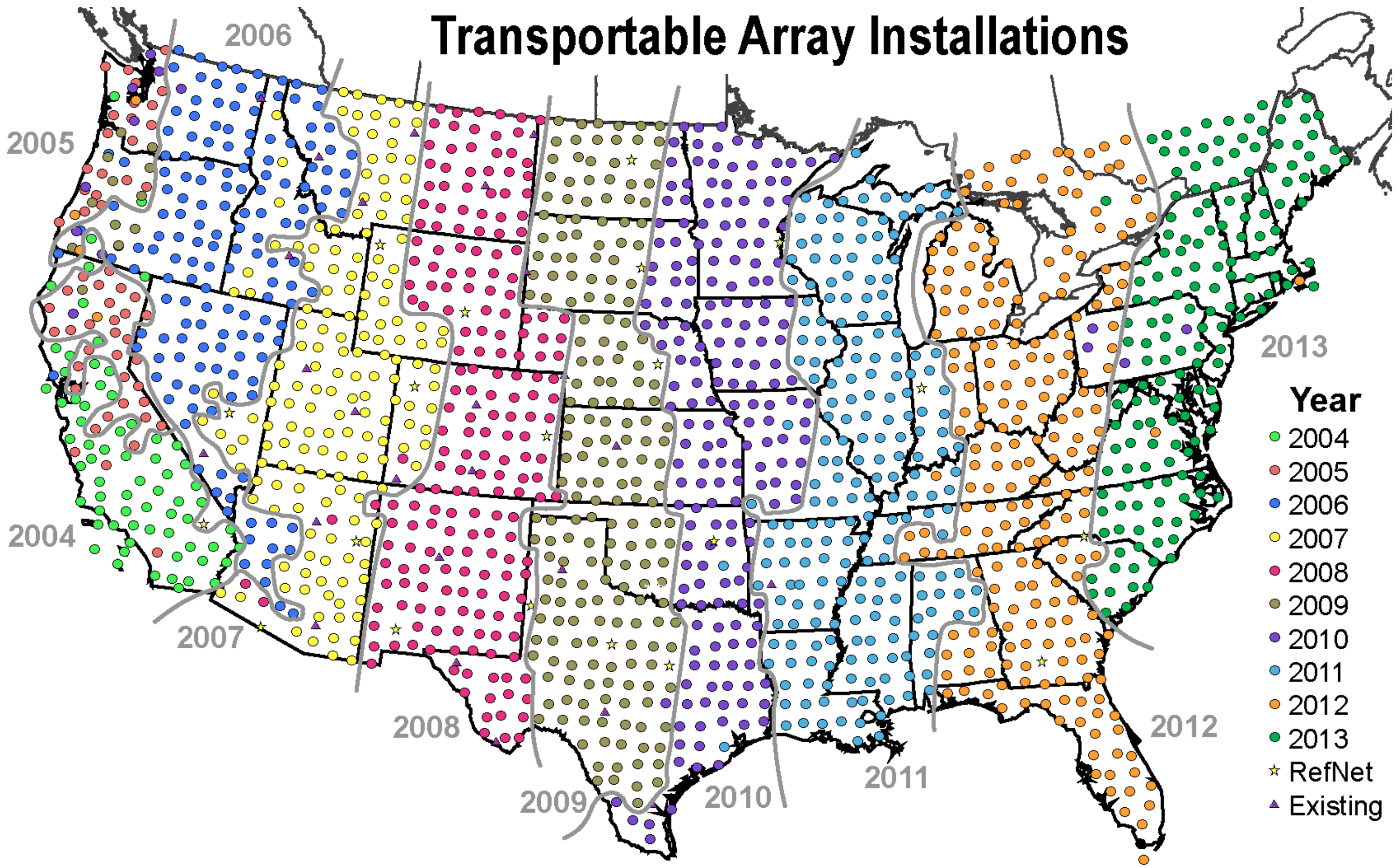


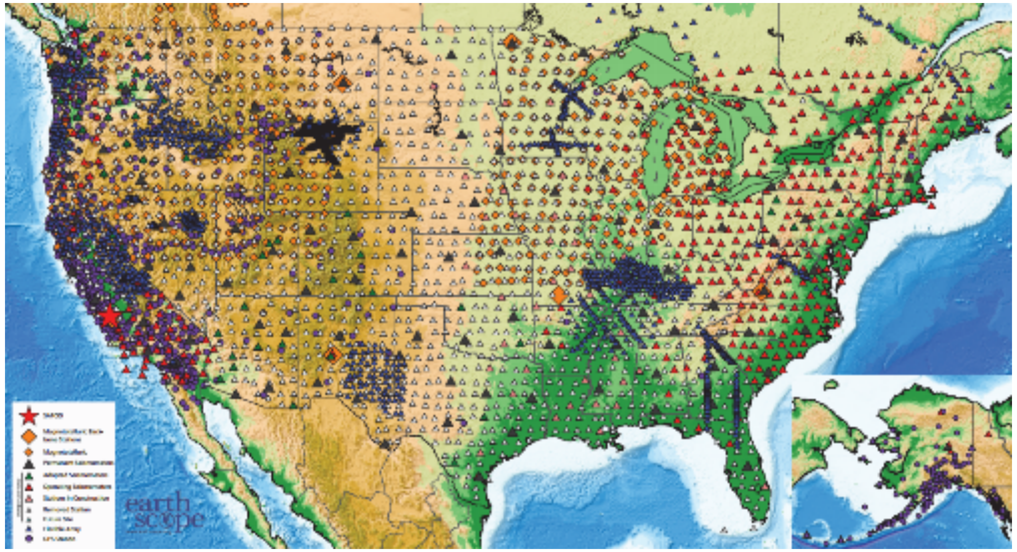
Transportable Array in the lower 48

Includes 400 Transportable Array (TA) Stations

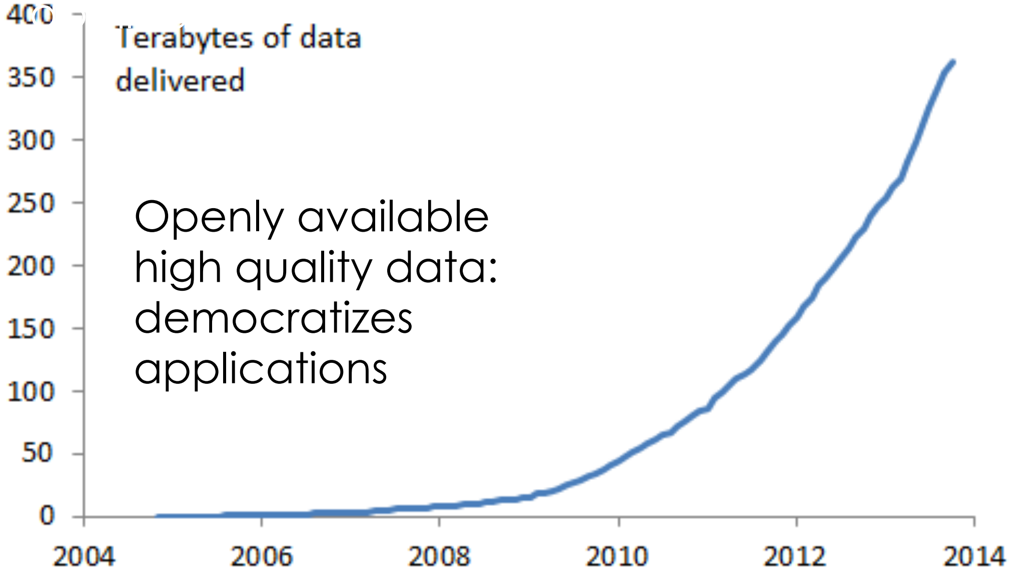
Each Station occupies a site for 1.5 – 2 years

10 years to leap-frog across the country



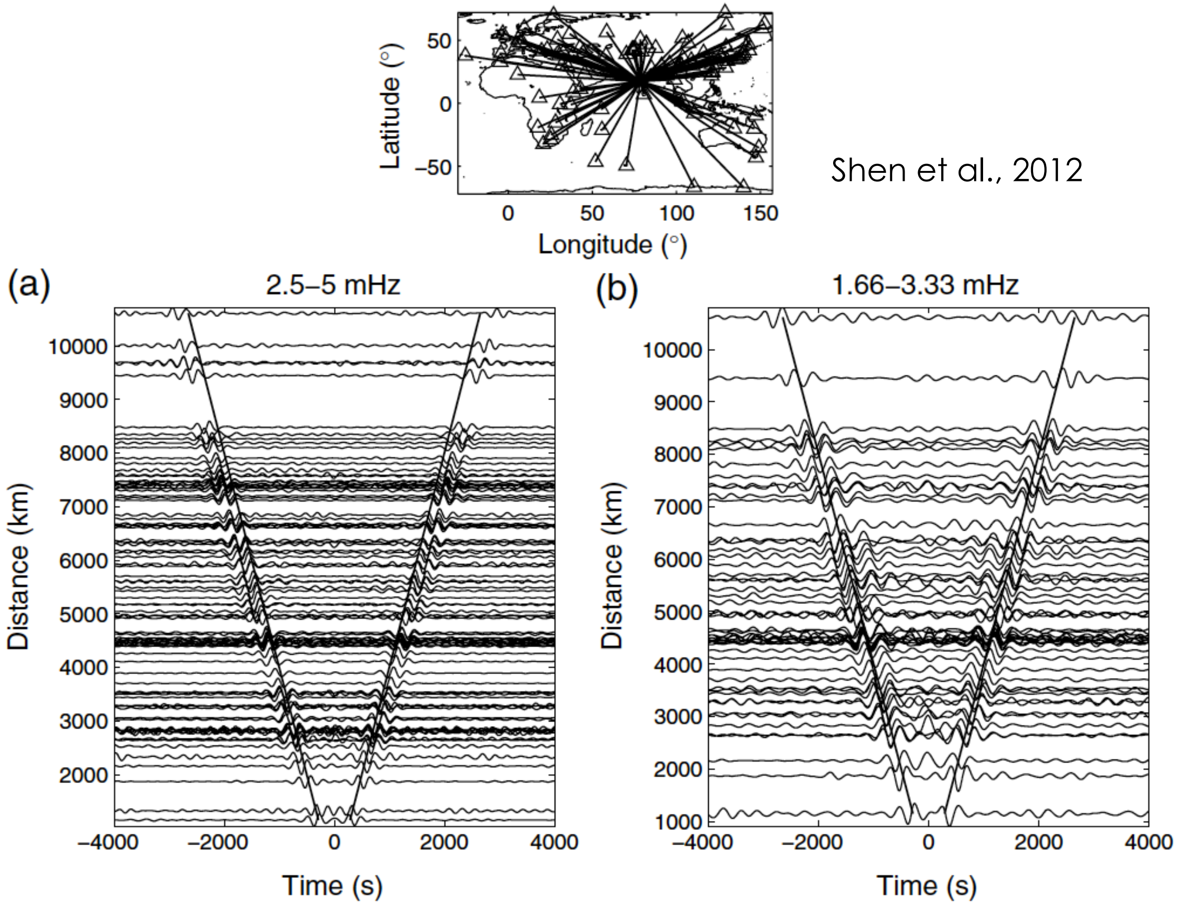



Dedicated, talented professional sta


400
350
300
250
200
150
100
50
0
Terabytes of data delivered
Openly available high quality data: democratizes applications
2004
2006
2008
2010
2012
2014

Green’s Functions from Noise

Cross-correlations of (days, weeks, months of) seismic noise recorded at different stations within a network can be used to compute an “empirical” Green’s function that tells us how quickly different frequency waves propagate between those two locations.



Shen et al., 2012

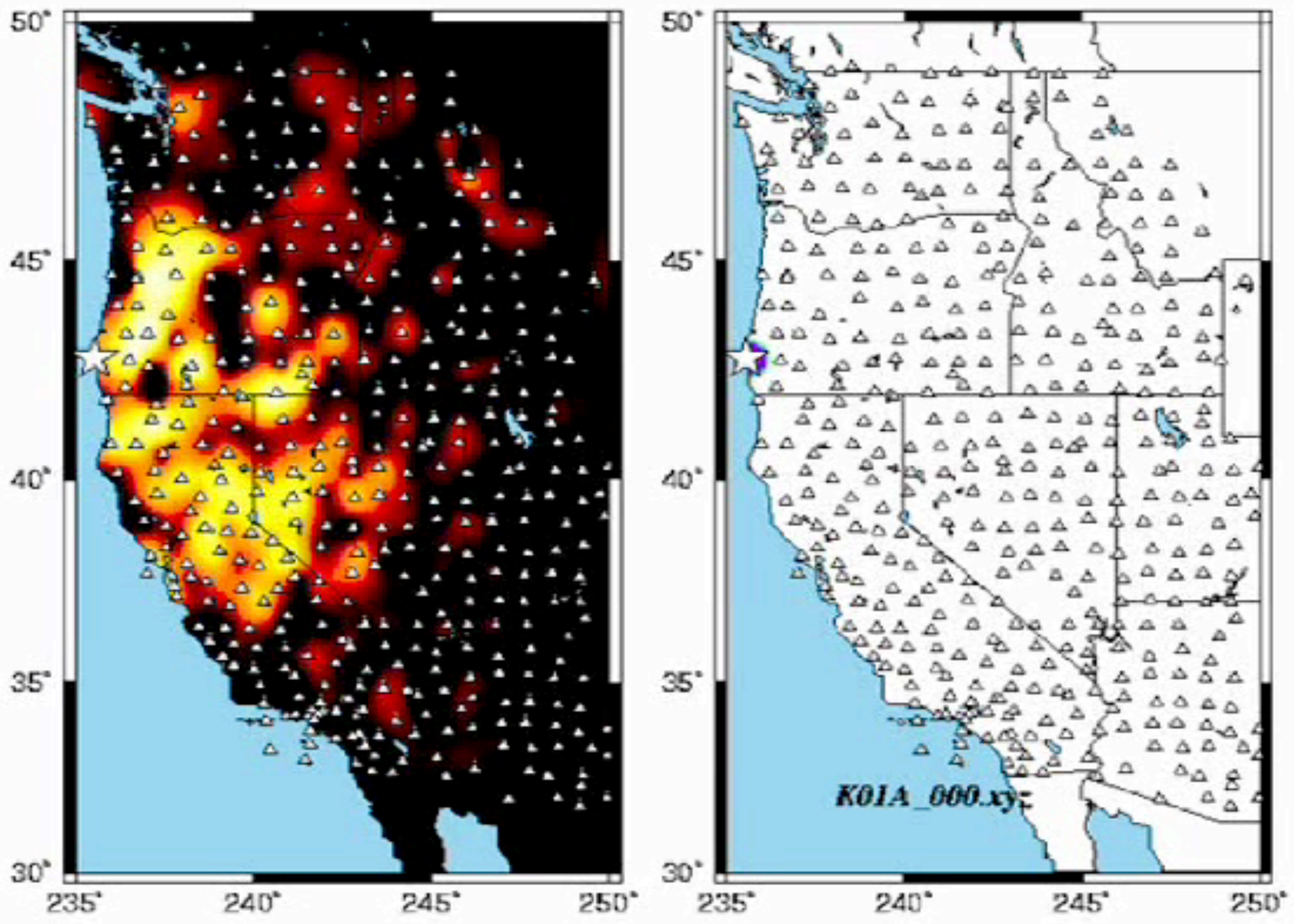
Using Noise to Obtain Seismic Velocity

Correlate correlation of noise between one common station and all other stations.

Filter in 10-20 sec pass-band

Compute envelope of this correlation and assign to station

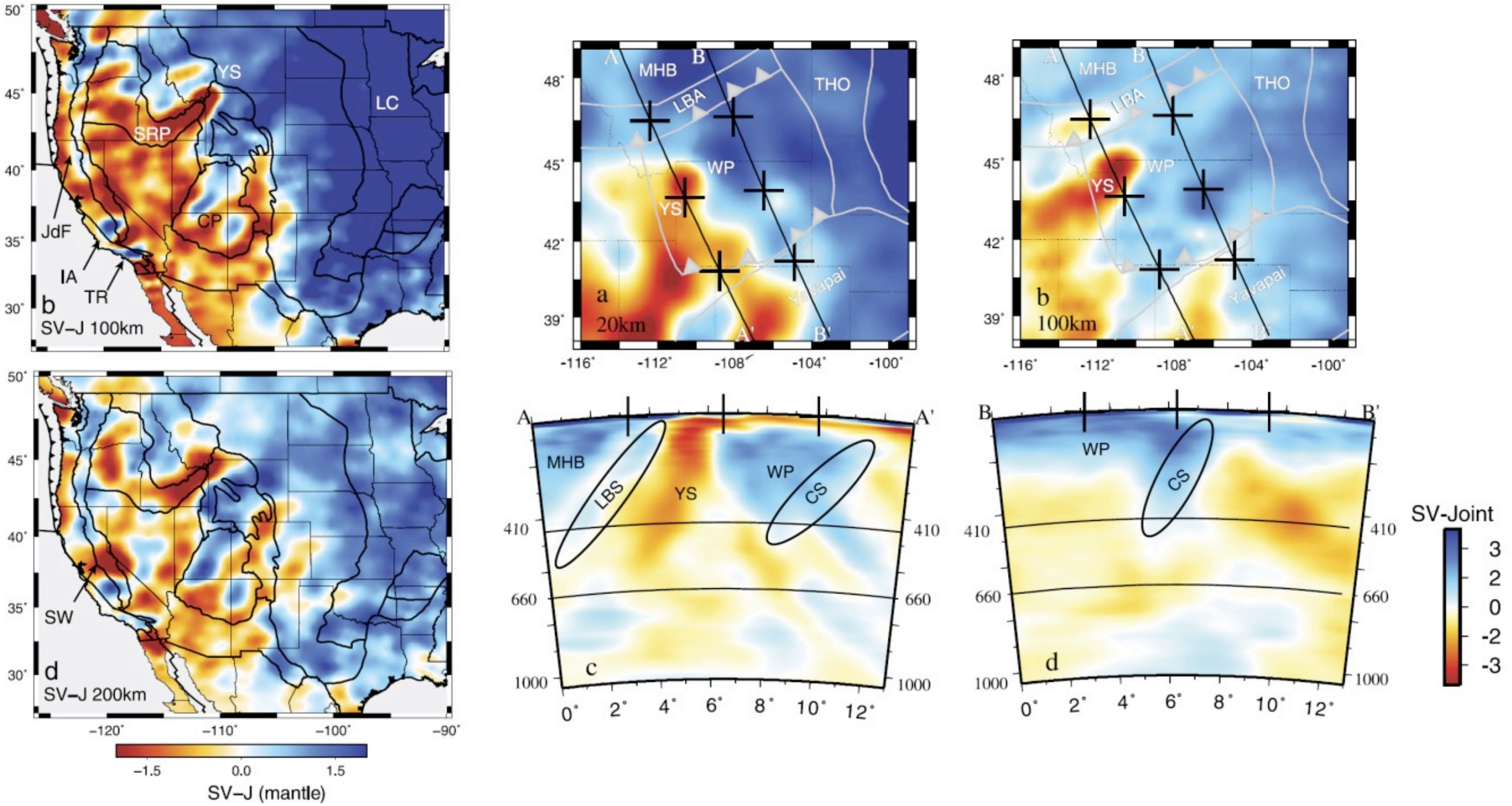
Interpolate with smooth surface



Courtesy of Fan-Chi Lin

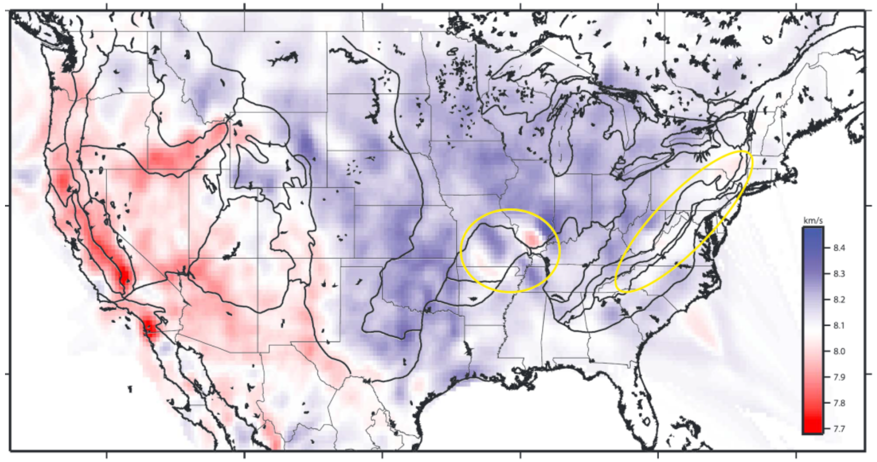
Joint Inversion: Maximizing Sensitivity through Multiple Datasets

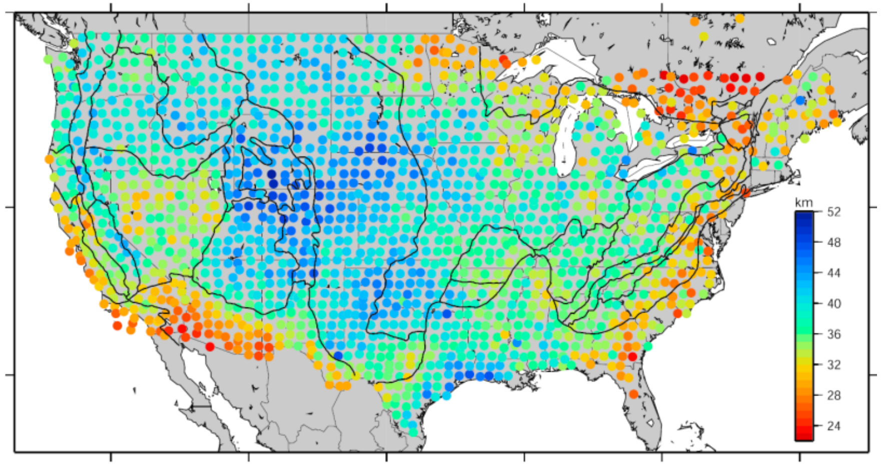
DNA13: Joint inversion of 3-component body wave travel times (P, SV, SH) and Rayleigh Wave Dispersion from Earthquake and Ambient Noise Data

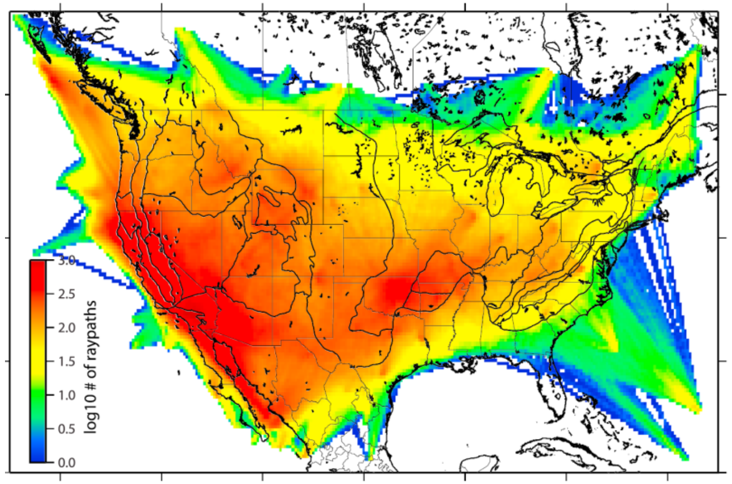


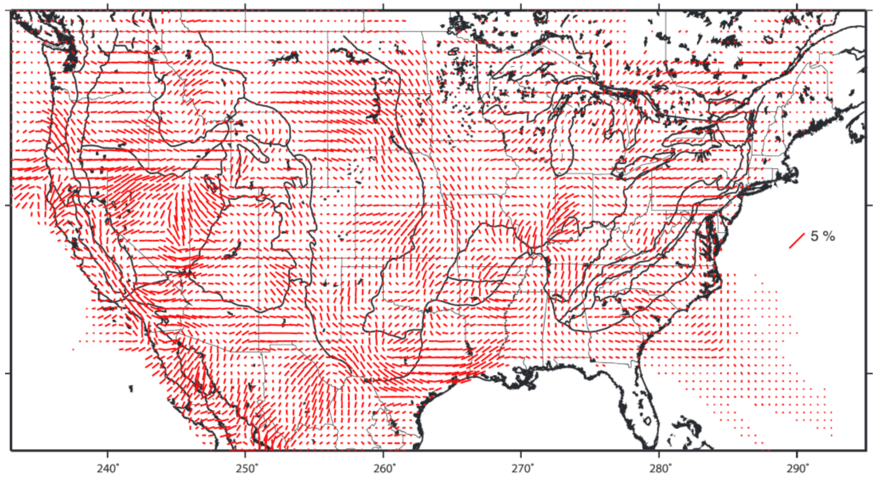
Porritt et al, EPSL (2014)

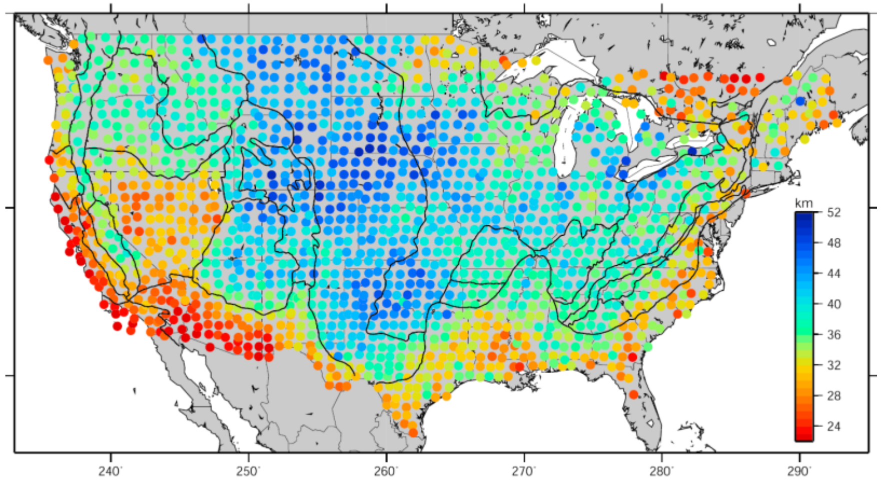
Pn Isotropic and Anisotropic Velocities





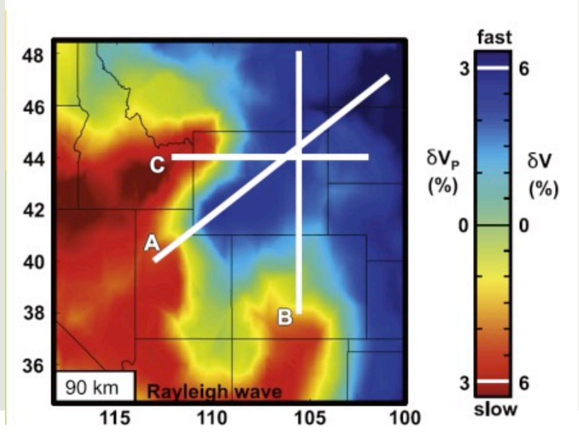


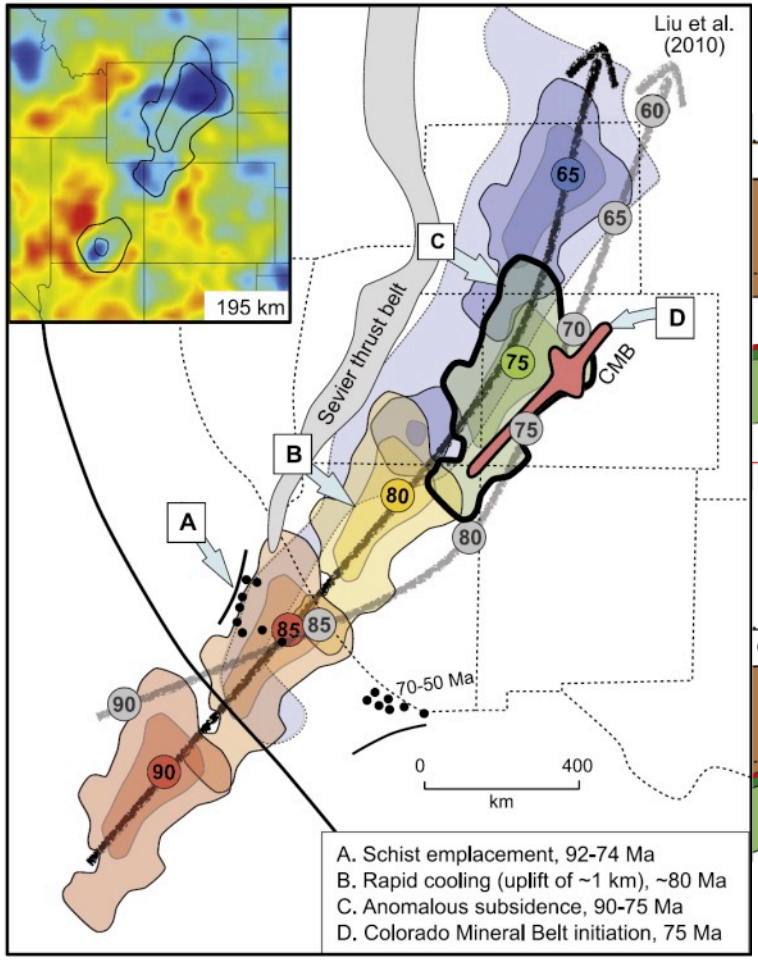


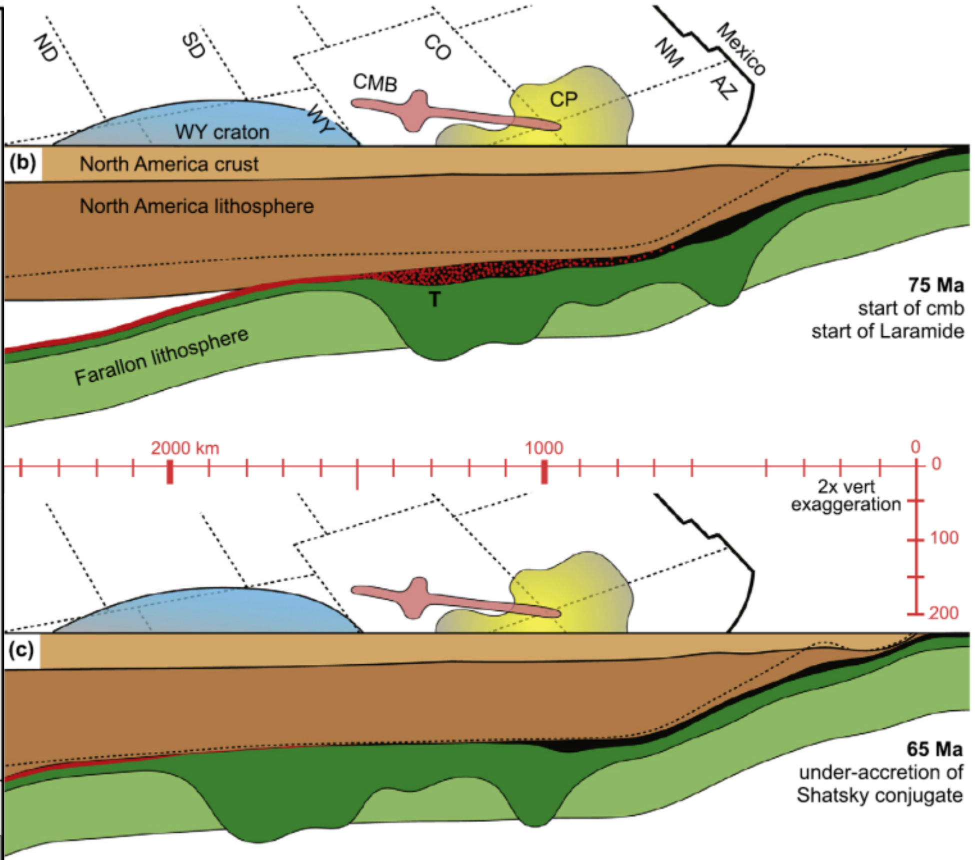


Buehler & Shearer, JGR (2017)

Slab Stacking Beneath the Wyoming craton





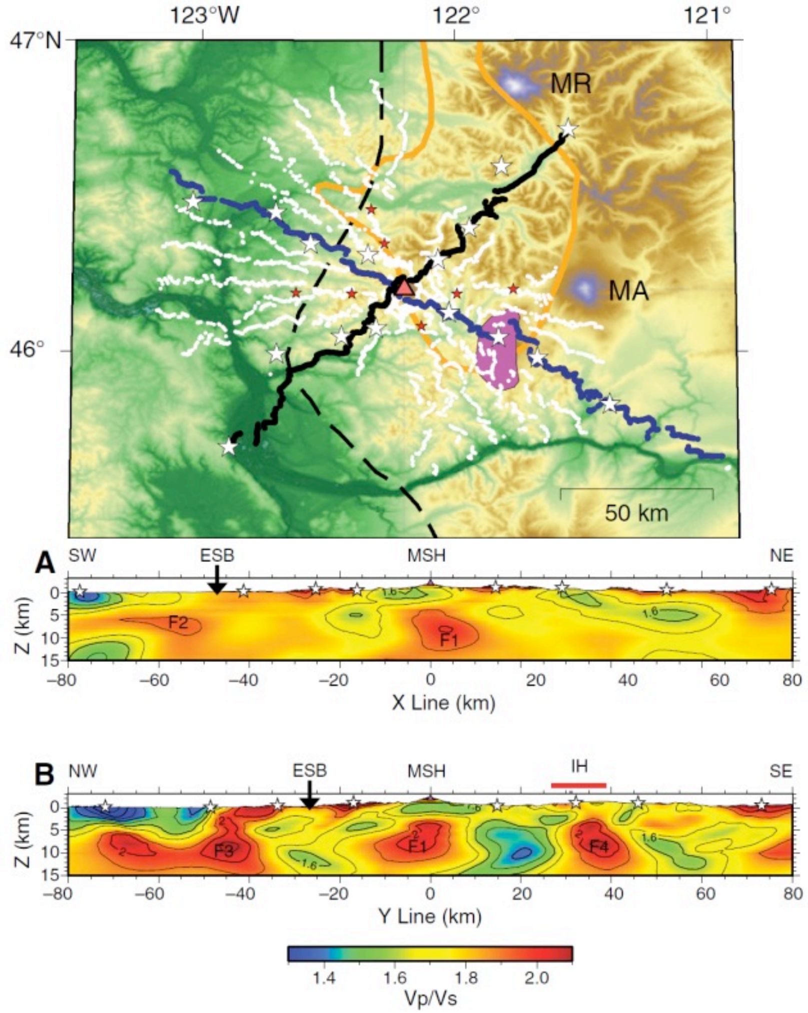


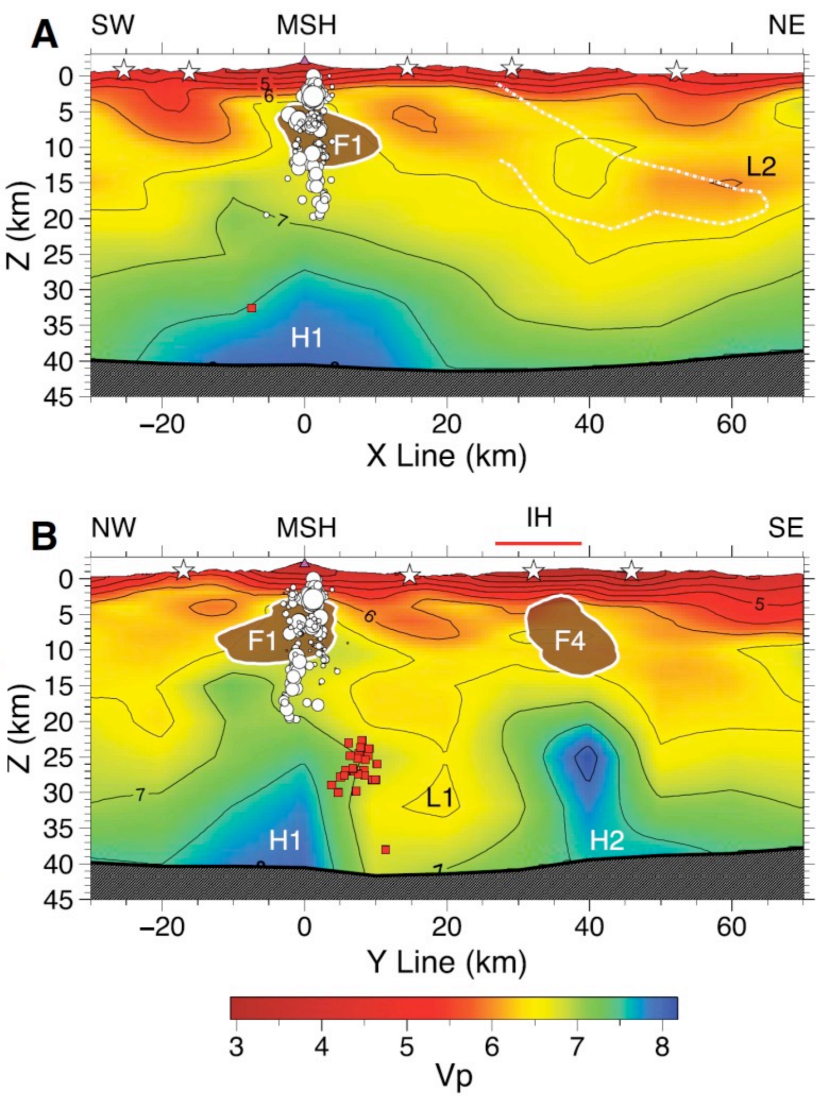
Humphreys et al, EPSL (2015)

Mapping Magma within Mt. St. Helens

Previous studies limited in depth to ~7 km, missing base of primary magma chamber and connection to deeper magma accumulation

Dense instrumentation from iMUSH reveals primary upper-middle crust magma chamber between 4-13 km depth





Kiser et al, Geology (2015)

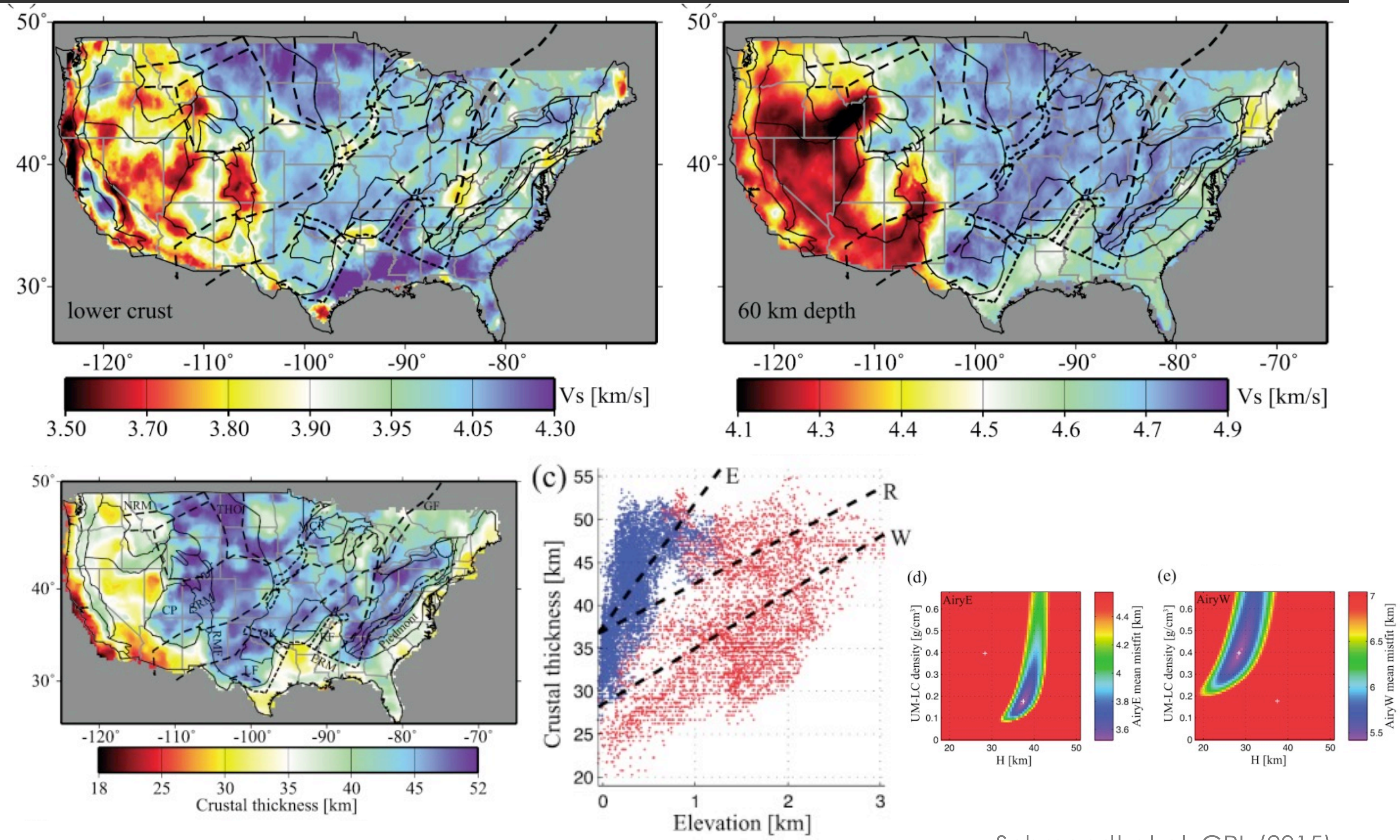
uOttawa

Rocky Mountain Front Great E-W Divide in Crustal Trends

Joint Inversion: RFs, Rayleigh wave dispersion, Ellipticity (H/V)

RMF: boundary between east-west contrast in crustal thickness and elevation trend

Attributed primarily to lower crustal density: UM/LC density contrast 2x higher west of RMF than east



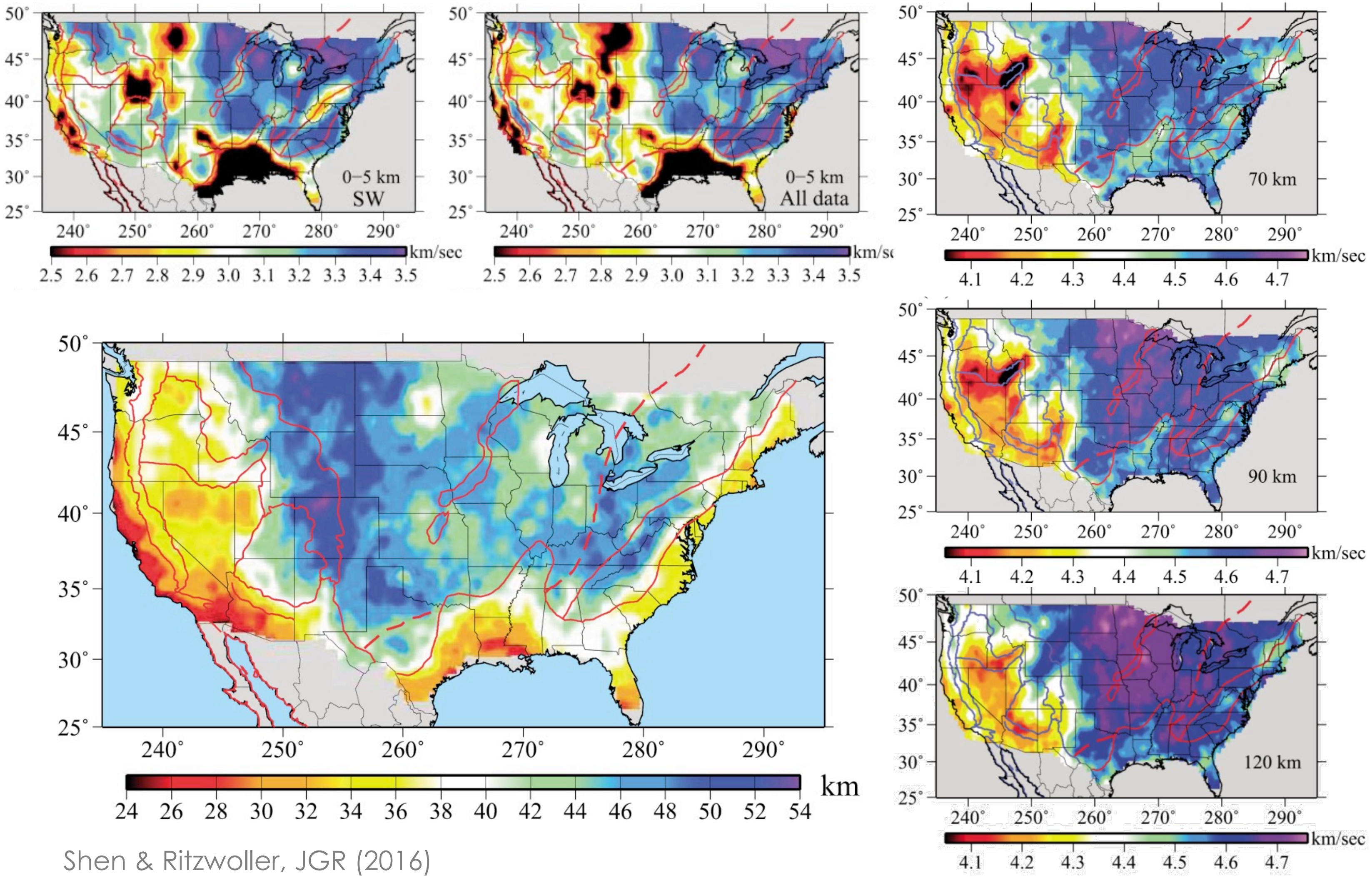
Schmandt et al, GRL (2015)

Joint Inversion: Maximizing Sensitivity through Multiple Datasets

Bayesian Monte Carlo inversion of Rayleigh Wave group and phase speeds derived from Ambient Noise and Earthquake data, Receiver Functions, and Rayleigh Wave ellipticity (H/V) measurements

Mean and σ from ~1800 TA stations across US interpolated onto 0.25° grid 3D model

Uppermost mantle velocity & discontinuity structure; error bounds on the parameters



Shen & Ritzwoller, JGR (2016)