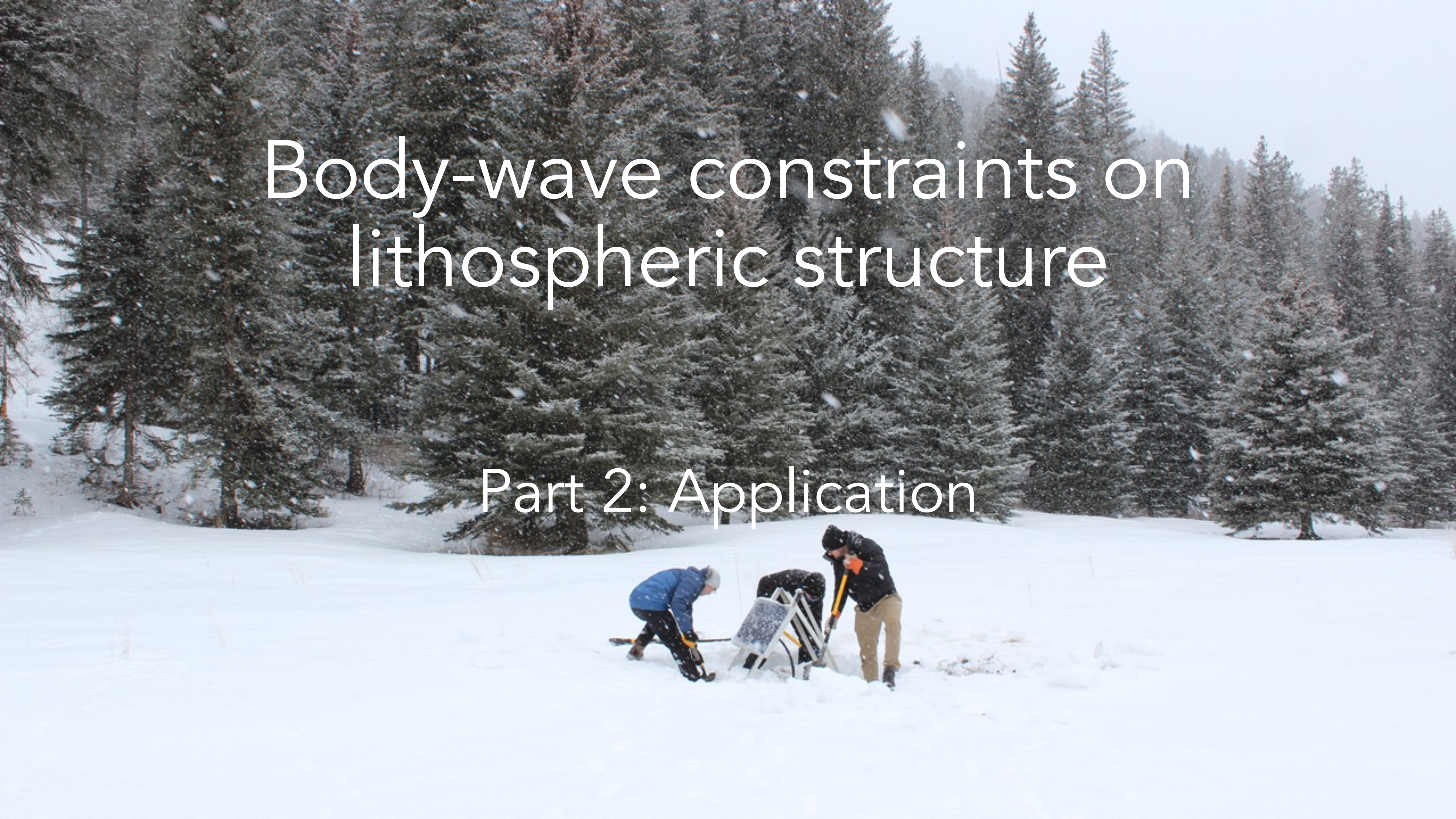
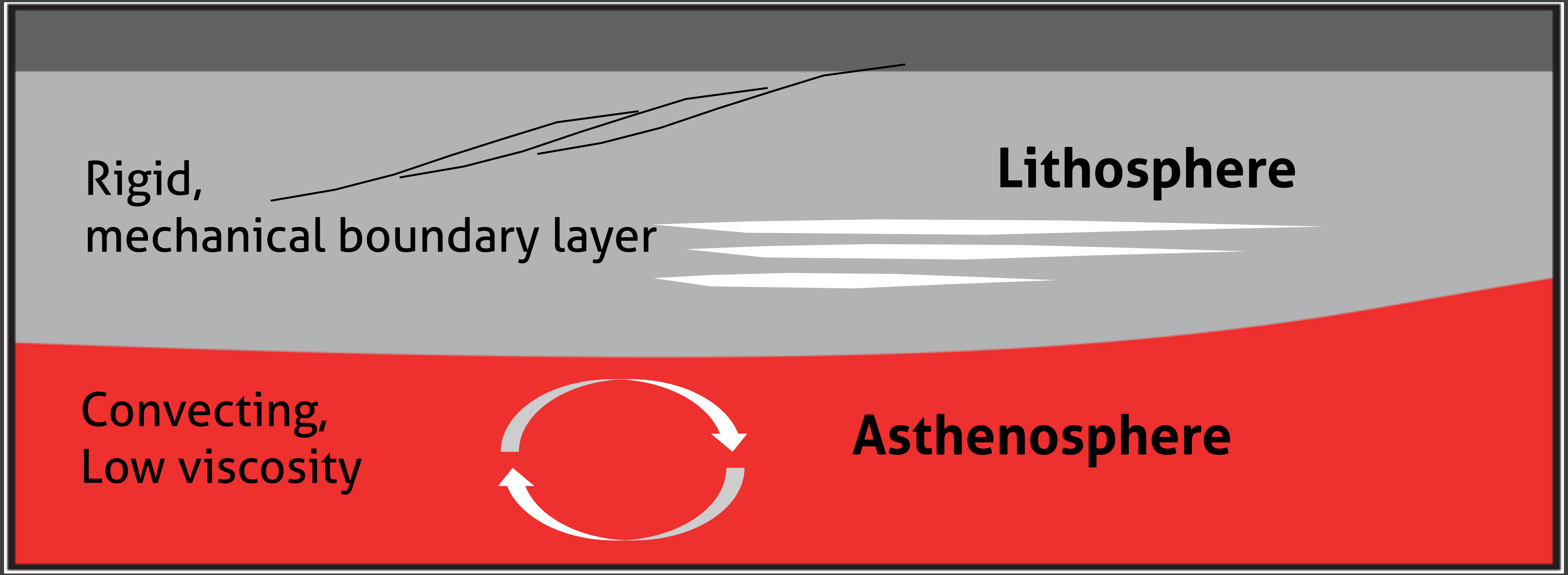

Body-wave constraints on lithospheric structure
Part 2: Application

# Introduction




What can seismology tell us about the properties of the lithosphere:

Temperature
Presence of melt
Hydration
Composition
Mineral alignment*

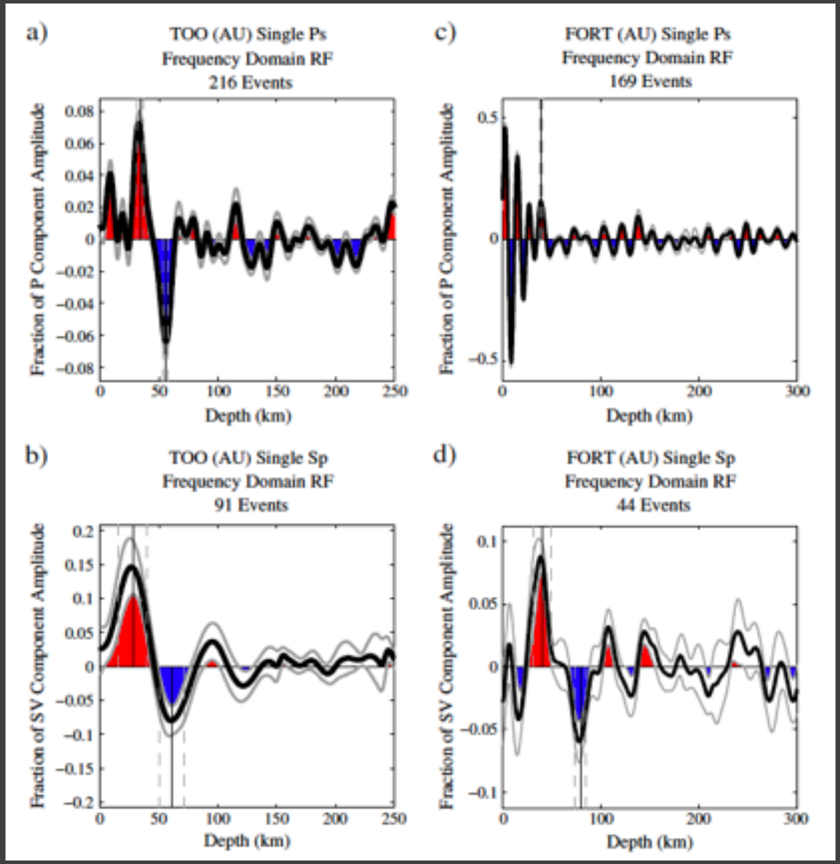
Tectonic & geodynamic processes can affect properties and structure, resulting in lateral and depth variations in seismic velocity

# Part 2 Overview

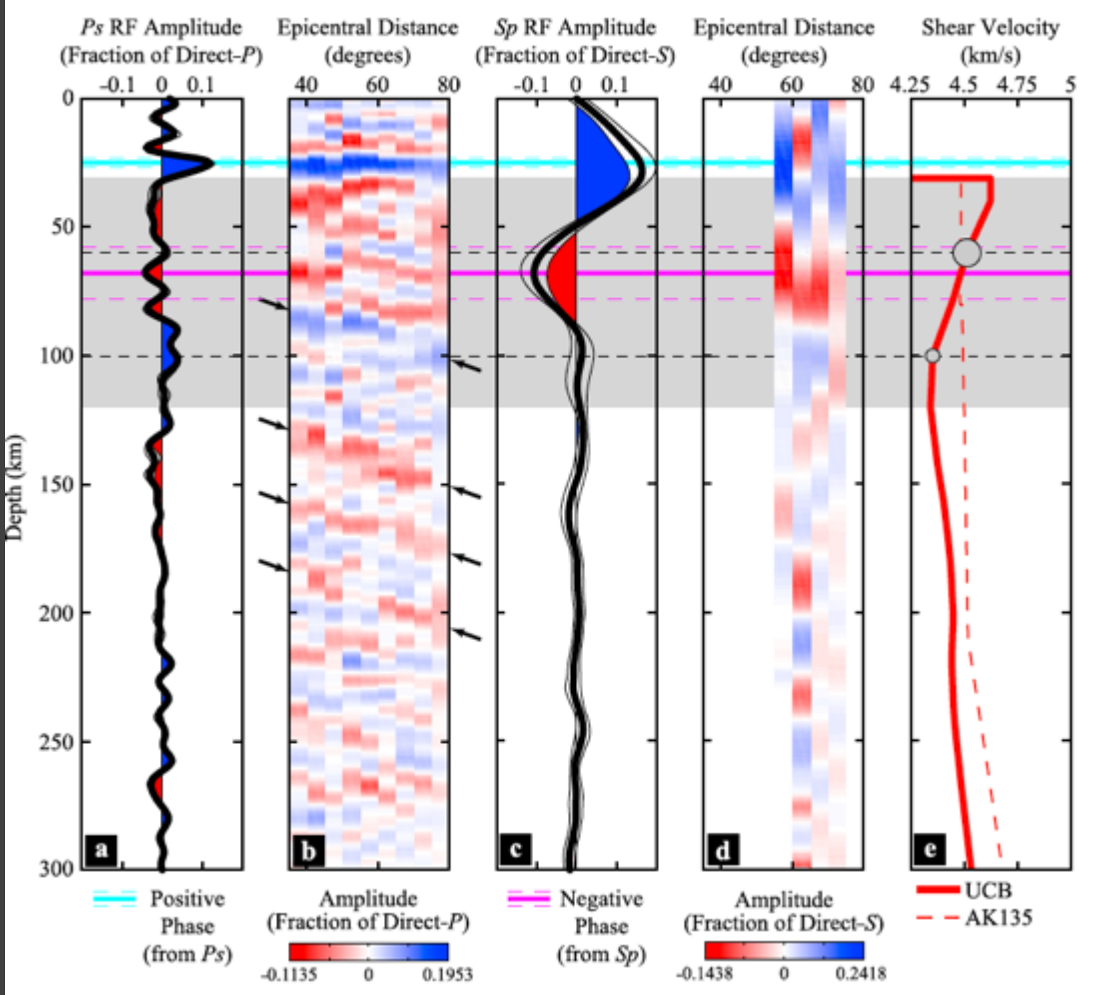
- Receiver functions and…
  - crustal structure
  - the lithosphere-asthenosphere boundary
  - mid-lithospheric discontinuities
- Receiver function sensitivity, finite frequencies, 2D structure
- Receiver functions and anisotropy
- Joint inversions including receiver functions

# Receiver functions and crustal structure

In general, Ps receiver functions are typically preferred over Sp receiver functions in the characterization of crustal structure. This is due to the higher frequencies present in P waves, allowing for increased resolution relative to S waves.



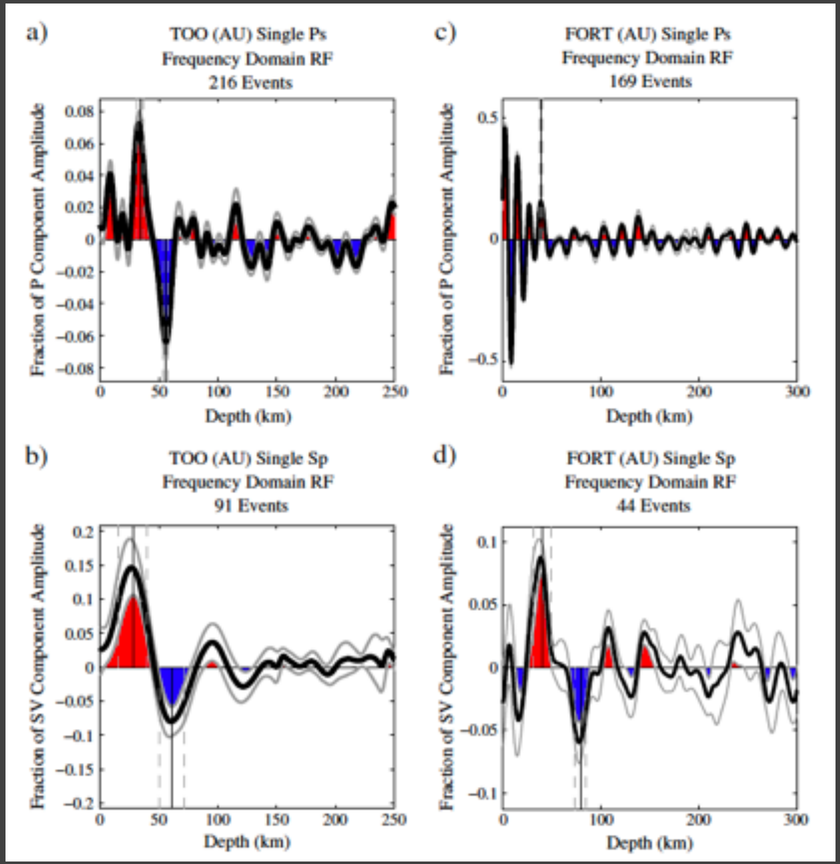

Ford et al. (2010)



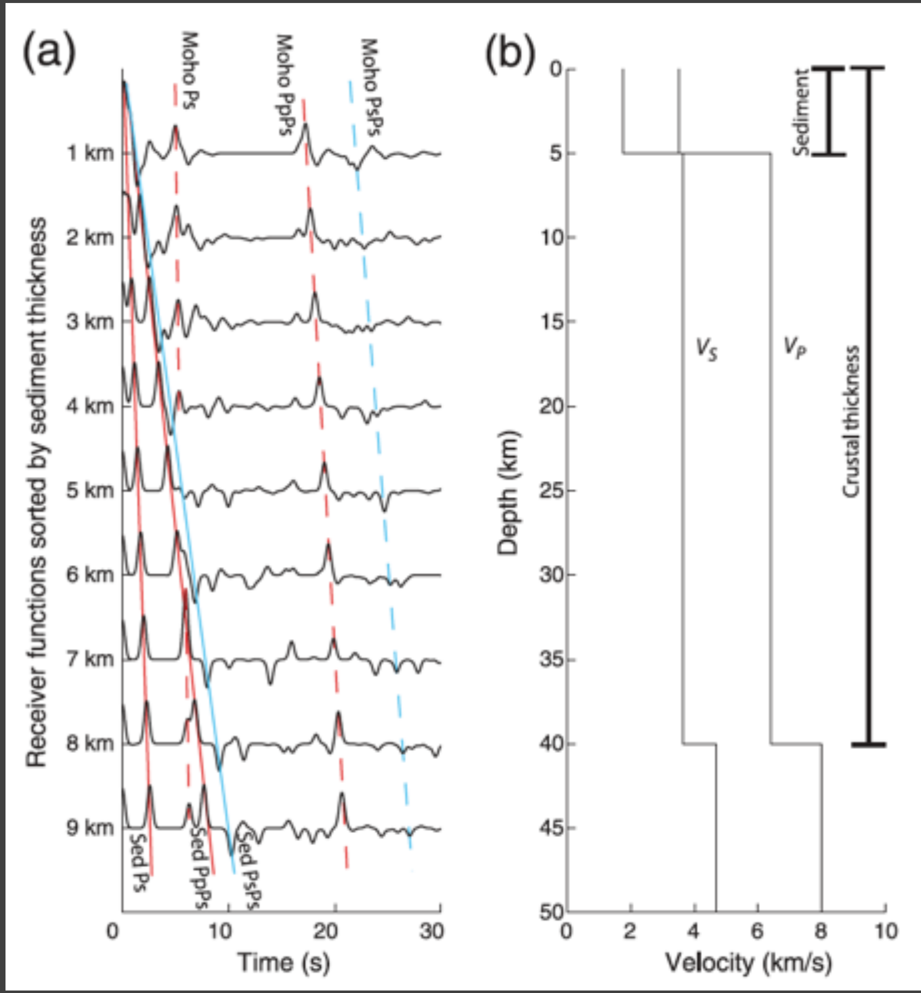

Abt et al. (2010)

# Receiver functions and crustal structure

However, the presence of basins, and associated basin multiples, can make analysis of crustal structure more complicated. Basin can lead to errors in migration and the multiples can interfere with other structure.



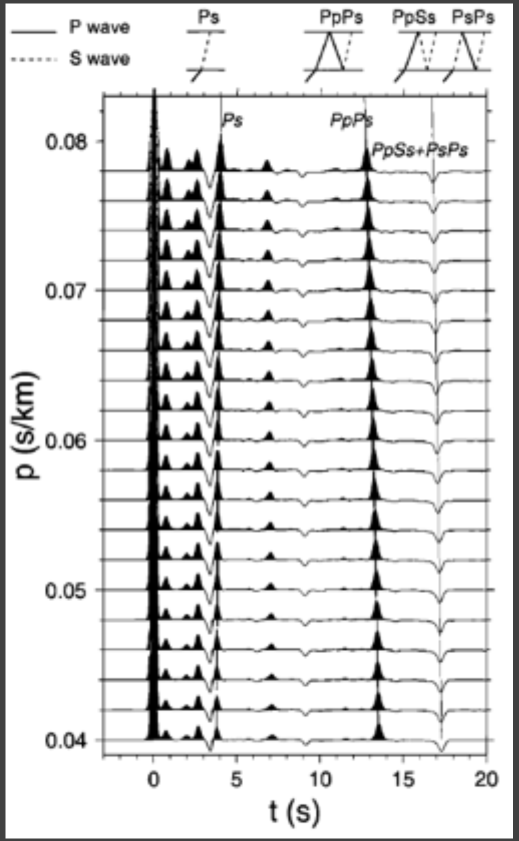

*Ford et al. (2010)*

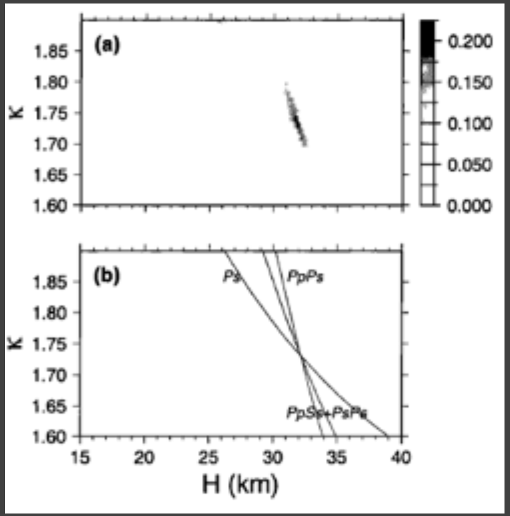



*Yeck et al. (2013)*

# Receiver functions and crustal structure

In cases where the Moho arrival and the subsequent crustal multiples arrivals are well constrained, they can be used to improve estimates of crustal thickness using H-k stacking (Zhu and Kanamori, 2000)




*Zhu and Kanamori (2000)*

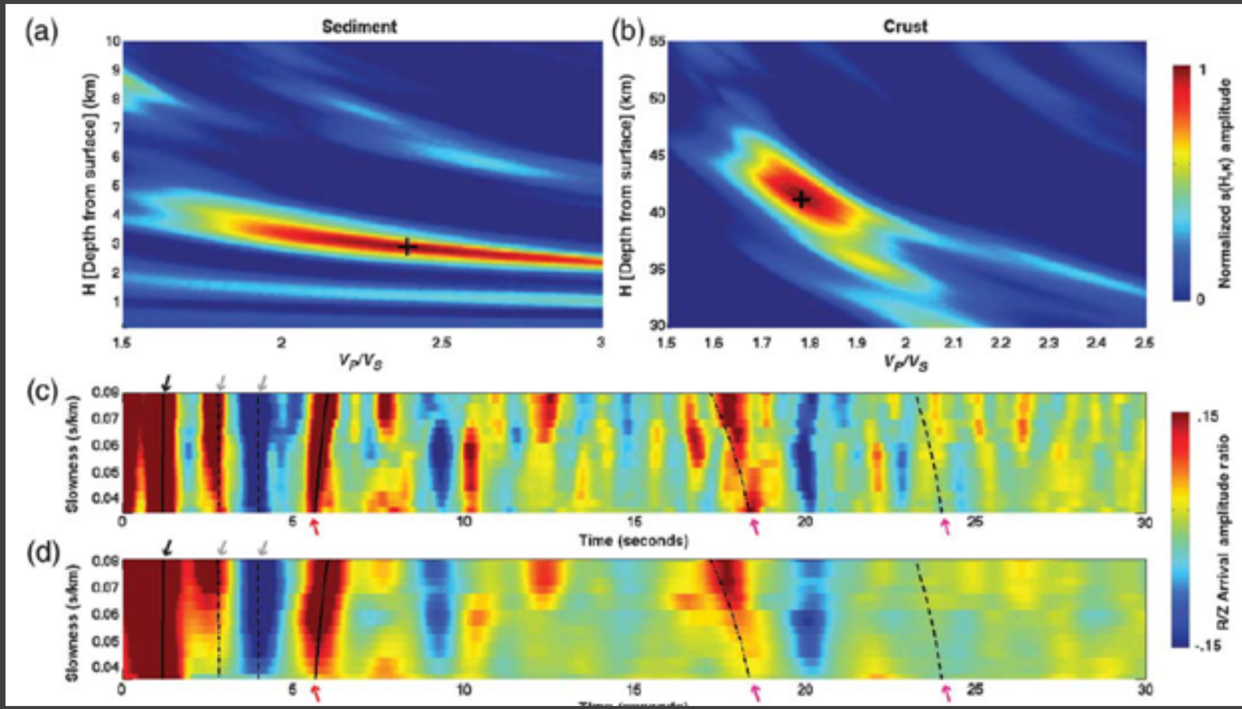



Table 2

Crustal Thickness Single and Two-Layer H-κ Stack Results for Transportable Array Stations

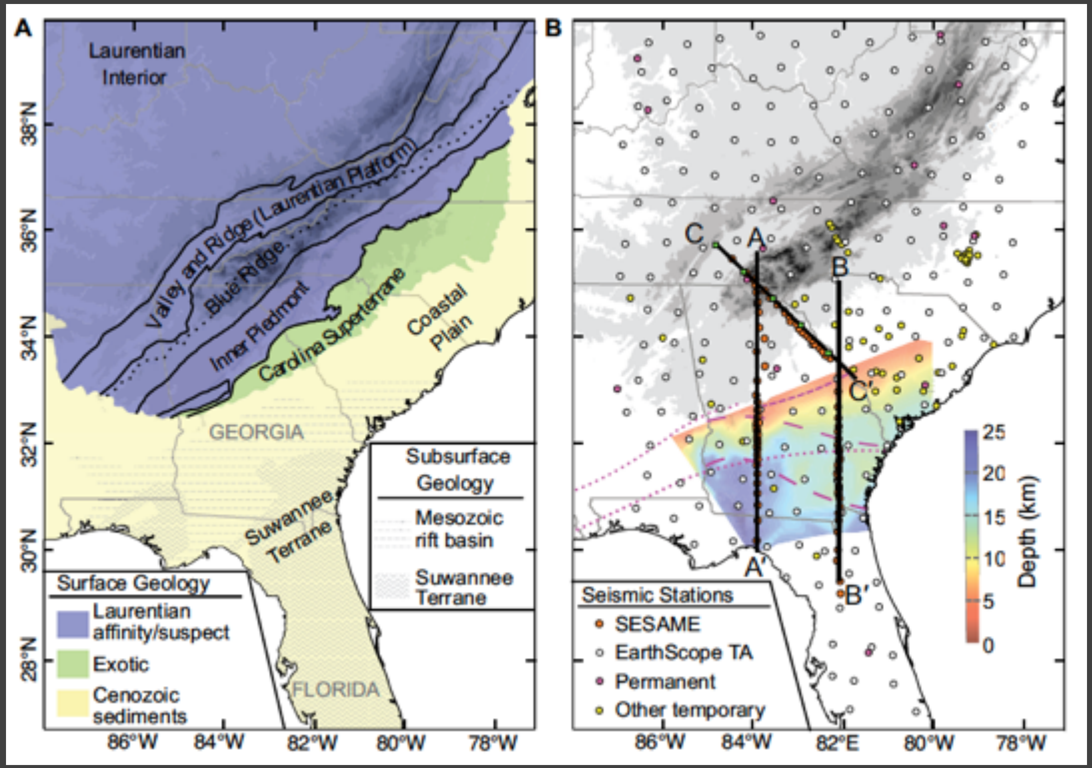
| Station | Assumed Sediment Velocity (km/s) | Assumed Basement Velocity (km/s) | Sediment Thickness (Two-Layer H-κ stack) | Sediment $V_P/V_S$ (Two-Layer H-κ stack) | Crustal Thickness (Two-Layer H-κ stack) | Basement $V_P/V_S$ (Two-Layer H-κ stack) | Crustal Thickness (One-Layer H-κ stack) | Crustal $V_P/V_S$ (One-Layer H-κ stack) |
|---|---|---|---|---|---|---|---|---|
| F22A | 3.6 | 6.7 | 2.1 ± 0.08 | 2.54 ± 0.07 | 40.5 ± 0.61 | 1.77 ± 0.02 | 42.6 ± 1.04 | 1.83 ± 0.03 |
| G22A | 3.6 | 6.7 | 2.9 ± 0.13 | 2.39 ± 0.13 | 41.2 ± 0.96 | 1.78 ± 0.02 | 44.4 ± 1.97 | 1.83 ± 0.06 |
| *H22A | 3.6 | 6.7 | 3.7 ± 0.11 | 2.22 ± 0.08 | 32.7 ± 4.38 | 2.17 ± 0.20 | 35.4 ± 5.99 | 2.21 ± 0.42 |
| *I22A | 3.6 | 6.7 | 4.7 ± 0.23 | 2.02 ± 0.17 | 32.7 ± 0.97 | 1.57 ± 0.03 | 37.3 ± 7.51 | 1.66 ± 0.07 |
| P24A | 3.0 | 6.4 | 4.2 ± 0.65 | 1.69 ± 0.35 | 37.0 ± 3.82 | 2.06 ± 0.11 | 42.0 ± 6.16 | 1.98 ± 0.31 |
| P25A | 3.0 | 6.4 | 3.7 ± 0.19 | 1.83 ± 0.06 | 41.0 ± 3.66 | 1.95 ± 0.13 | 45.6 ± 5.83 | 1.91 ± 0.17 |
| P26A | 3.0 | 6.4 | 2.7 ± 0.17 | 2.17 ± 0.13 | 40.3 ± 4.31 | 1.86 ± 0.12 | 43.8 ± 4.42 | 1.89 ± 0.11 |
| P27A | 3.0 | 6.4 | 2.1 ± 0.08 | 2.01 ± 0.07 | 45.5 ± 1.67 | 1.67 ± 0.03 | 48.1 ± 1.33 | 1.69 ± 0.003 |
| P24A | 4.0 | 6.4 | 5.7 ± 0.90 | 1.66 ± 0.36 | 38.4 ± 4.02 | 2.07 ± 0.11 | 42.0 ± 6.16 | 1.98 ± 0.31 |
| P25A | 4.0 | 6.4 | 4.9 ± 0.23 | 1.83 ± 0.05 | 42.5 ± 3.30 | 1.93 ± 0.12 | 45.6 ± 5.83 | 1.91 ± 0.17 |
| P26A | 4.0 | 6.4 | 3.4 ± 0.21 | 2.26 ± 0.12 | 41.4 ± 4.51 | 1.85 ± 0.13 | 43.8 ± 4.42 | 1.89 ± 0.11 |
| P27A | 4.0 | 6.4 | 2.8 ± 0.08 | 2.01 ± 0.07 | 46.0 ± 1.34 | 1.67 ± 0.03 | 48.1 ± 1.33 | 1.69 ± 0.003 |

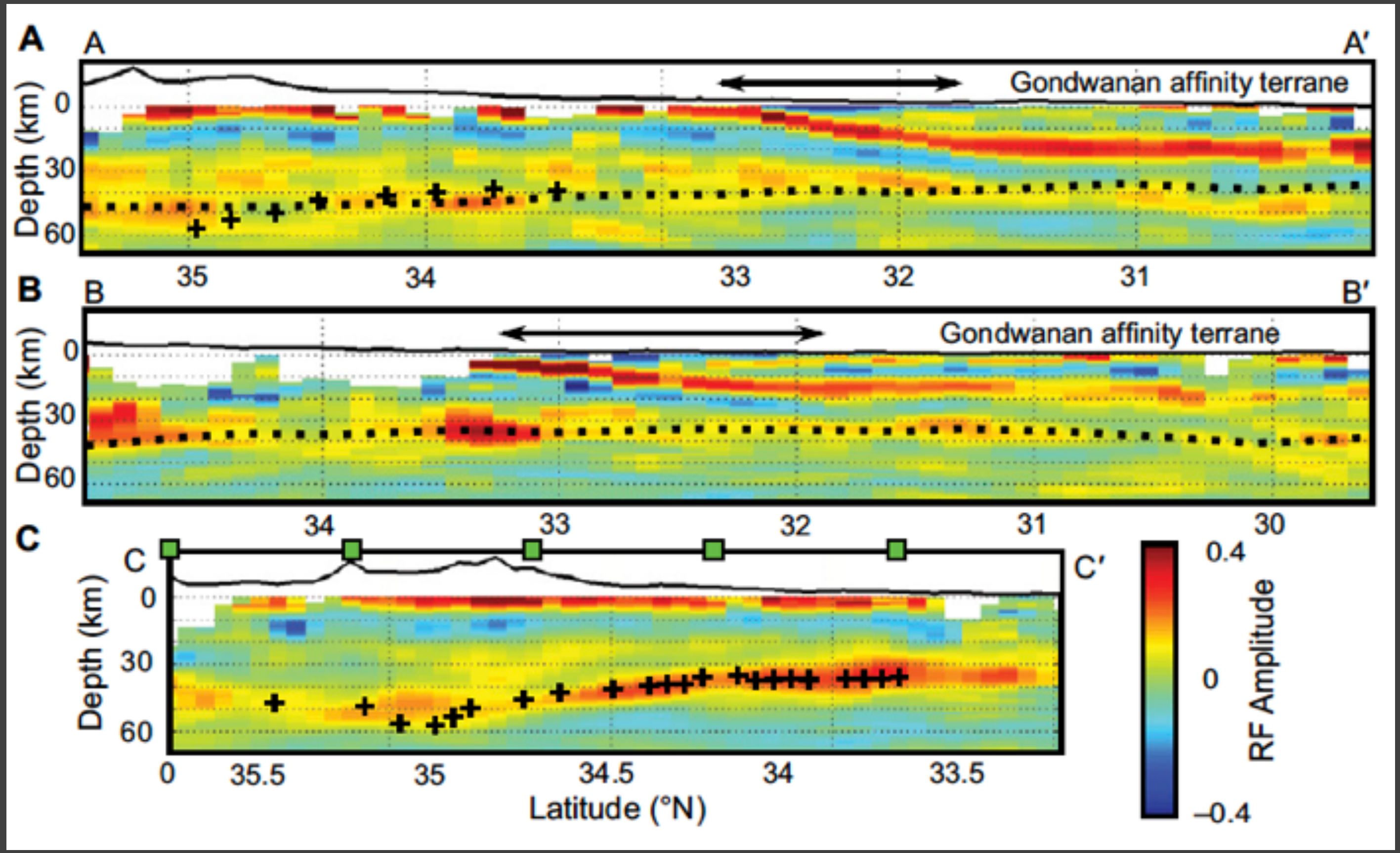
*Stations where Moho *Ps* phase is obfuscated by sediment multiples. Crustal thickness and $V_P/V_S$ values reported to demonstrate method results but do not accurately represent the Earth due to this obfuscation.

*Yeck et al. (2013)*

# Receiver functions and crustal structure

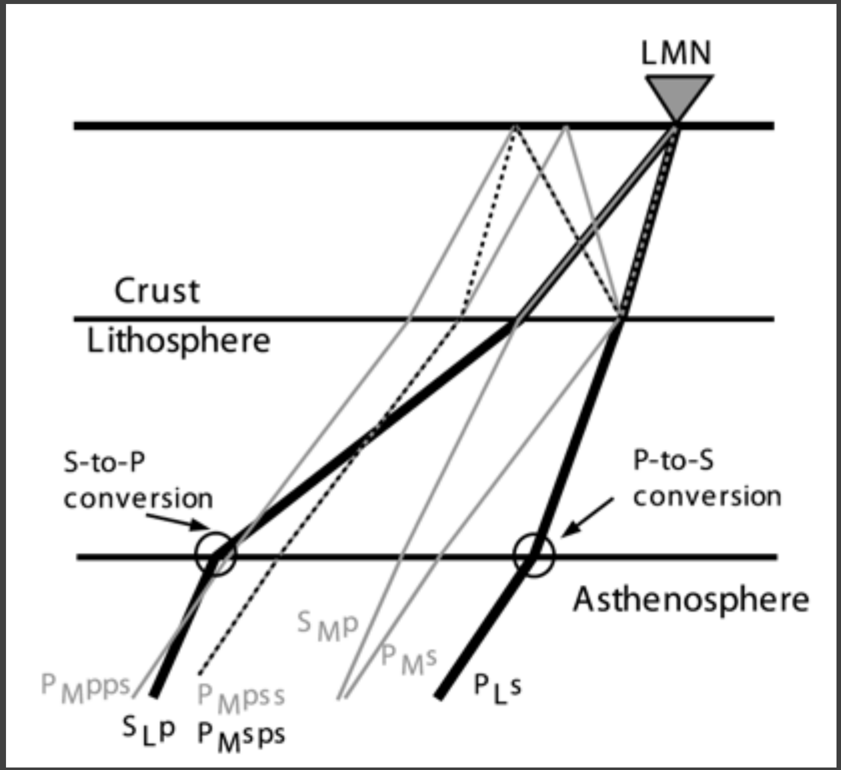
In some instances, Sp receiver functions have also proved capable of providing high resolution images of crustal structure



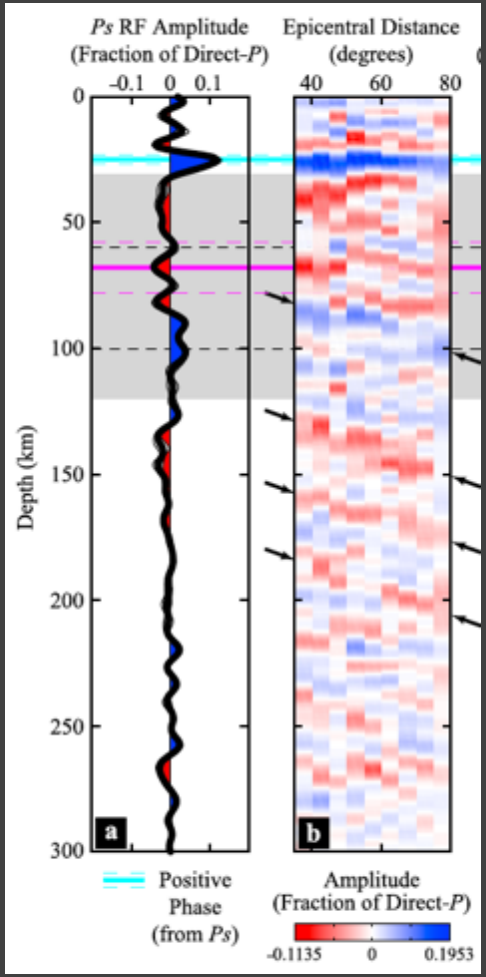

*Hooper et al.(2016)*

# Receiver functions and the LAB

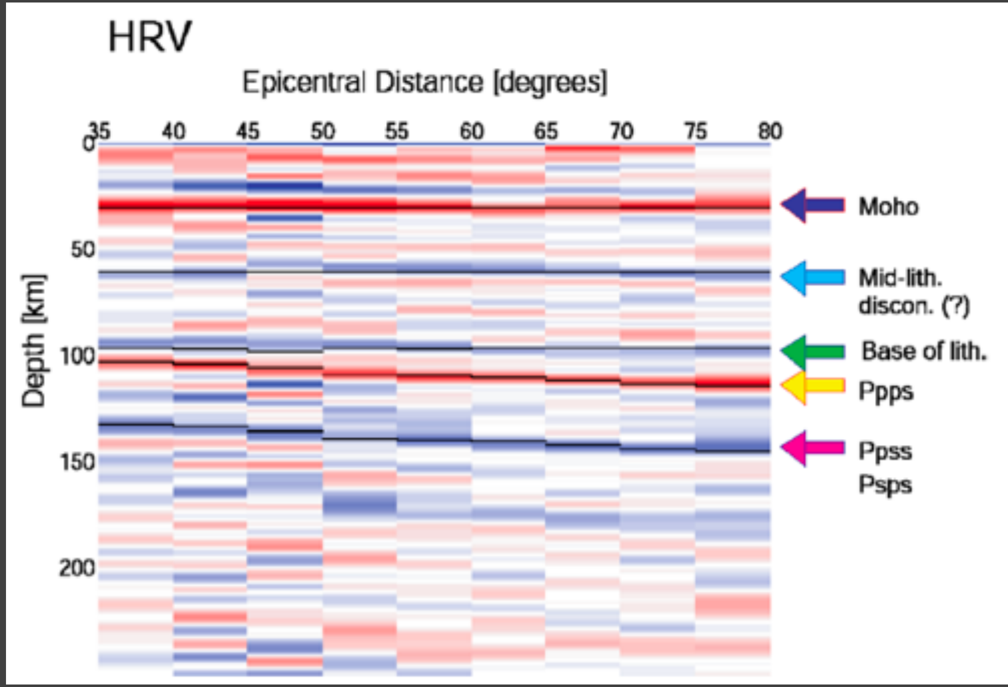



*Rychert et al., (2007)*

Numerous studies exist of receiver function imaging of the lithosphere-asthenosphere boundary. Early studies utilized Ps and Sp RFs, but most recent studies utilize Sp due to the lack of possible interference from crustal multiples.



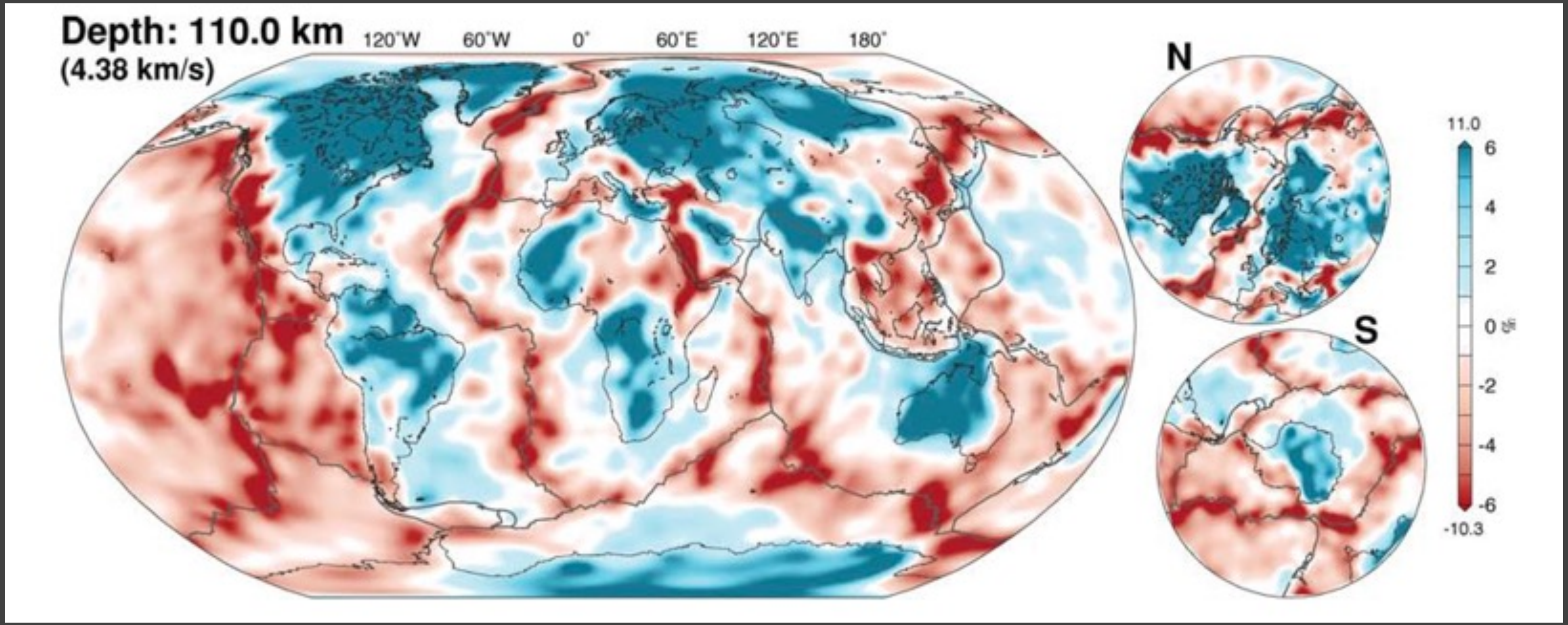

*Abt et al. (2010)*




*Rychert et al., (2007)*

# Receiver functions and the LAB

## What can receiver functions tell us about the lithosphere-asthenosphere boundary?

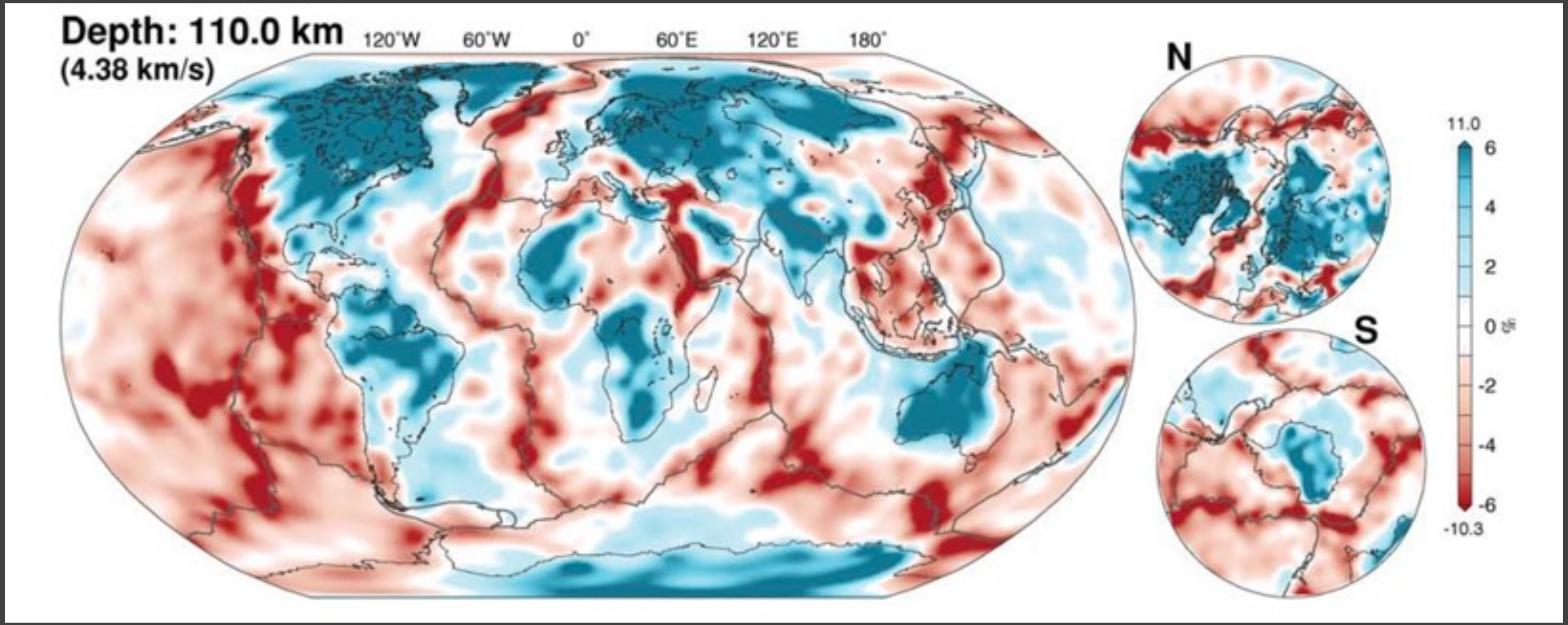



*Schaeffer and Lebedev (2013)*

- Global and regional tomography models provide constraints in lithospheric thickness.
- Global trends indicate that the lithosphere is seismically fast, and extends to greater depths beneath cratons/shields, and is thinner beneath tectonically active regions.
- See clear trends in lithospheric thickness and age beneath the oceans

# Receiver functions and the LAB

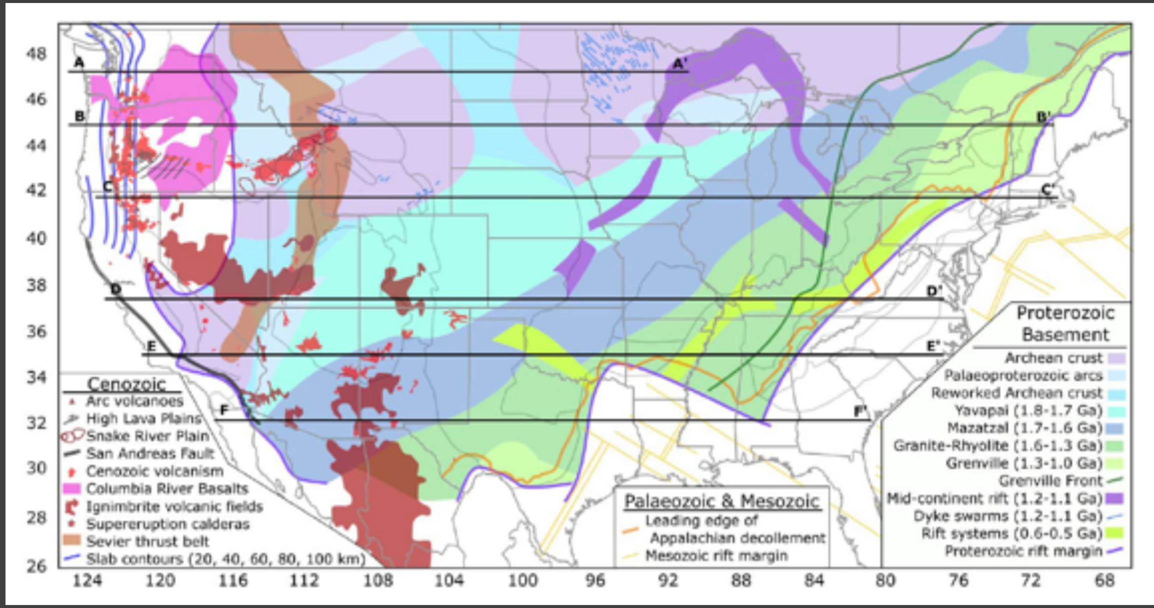
## What can receiver functions tell us about the lithosphere-asthenosphere boundary?

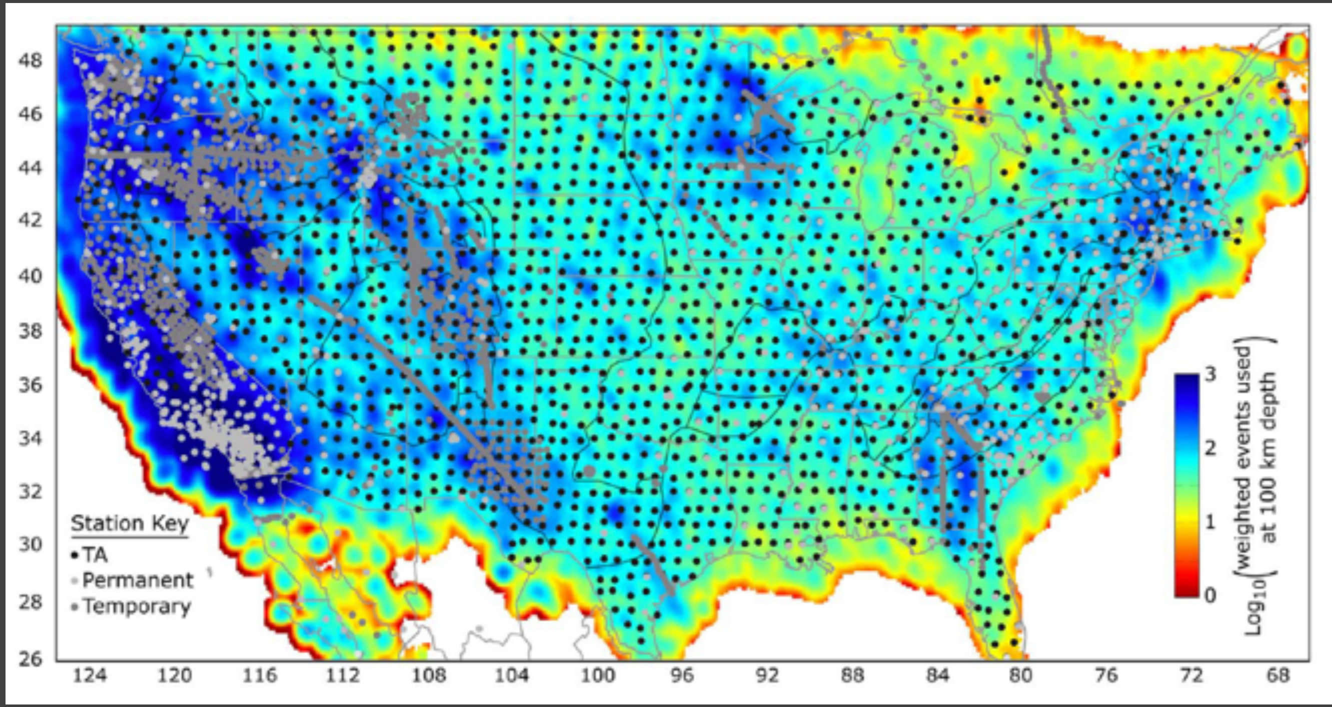



*Schaeffer and Lebedev (2013)*

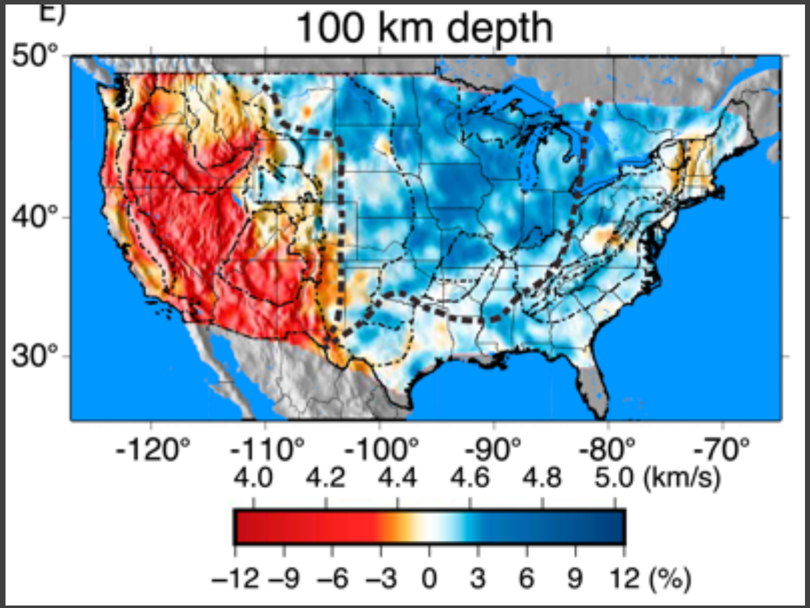
- BUT, tomographic estimates of lithospheric thickness tend to be lower resolution than receiver function estimates.
- Ps receiver function uncertainties may be as low as +-2 km, while Sp receiver functions have uncertainties on the order of +-10 km.
- This means that firmer constraints can be placed on the lithosphere-asthenosphere boundary, which has implications for our understanding of the physical properties responsible for the boundary.

# Receiver functions and the LAB



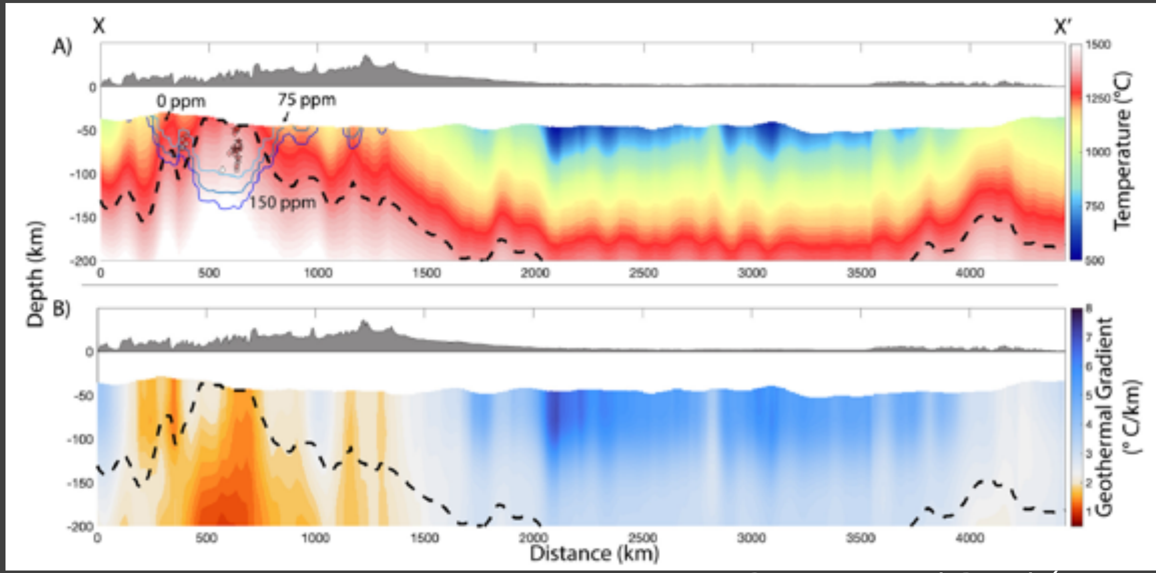

*Hopper and Fischer (2018)*



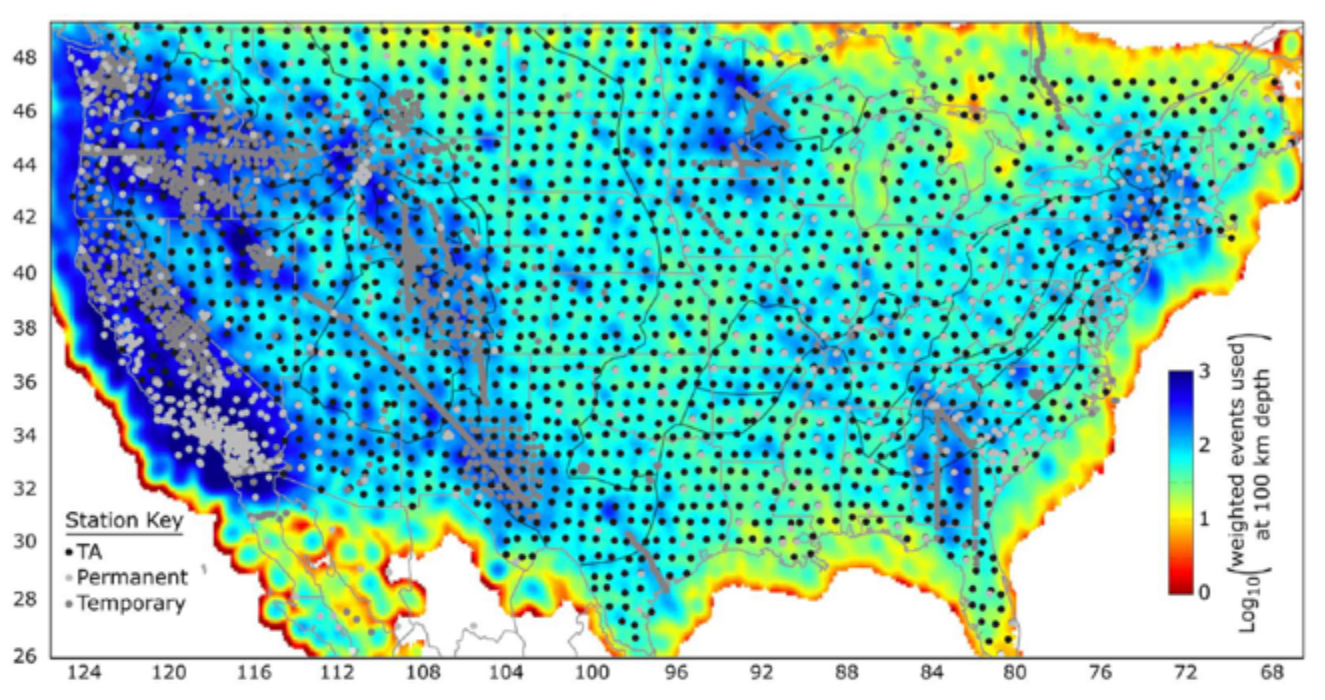

- Completion of the EarthScope Transportable Array allowed for a uniform sampling of the lithosphere of the United States
- Tomography models show a systematic east vs. west divide in seismic velocities, likely the result of tectonism in the western U.S.
- Low velocities are observed at shallow depths beneath the western U.S., while high velocities dominate the eastern half

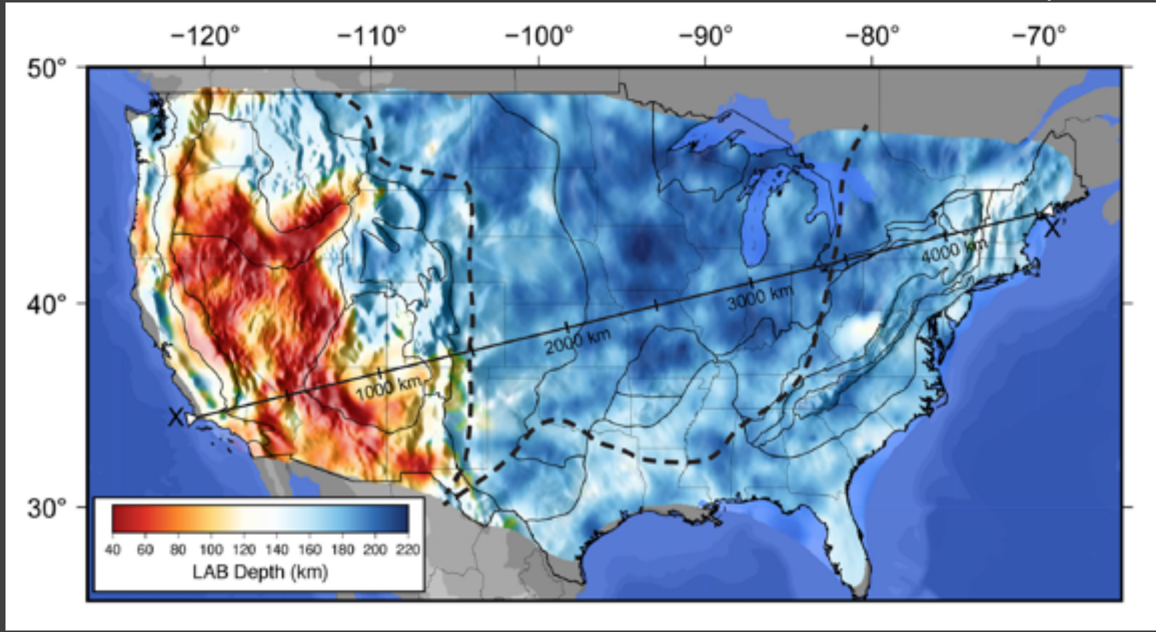
*Porter et al. (2015)*

# Receiver functions and the LAB




*Porter and Reid (2021)*

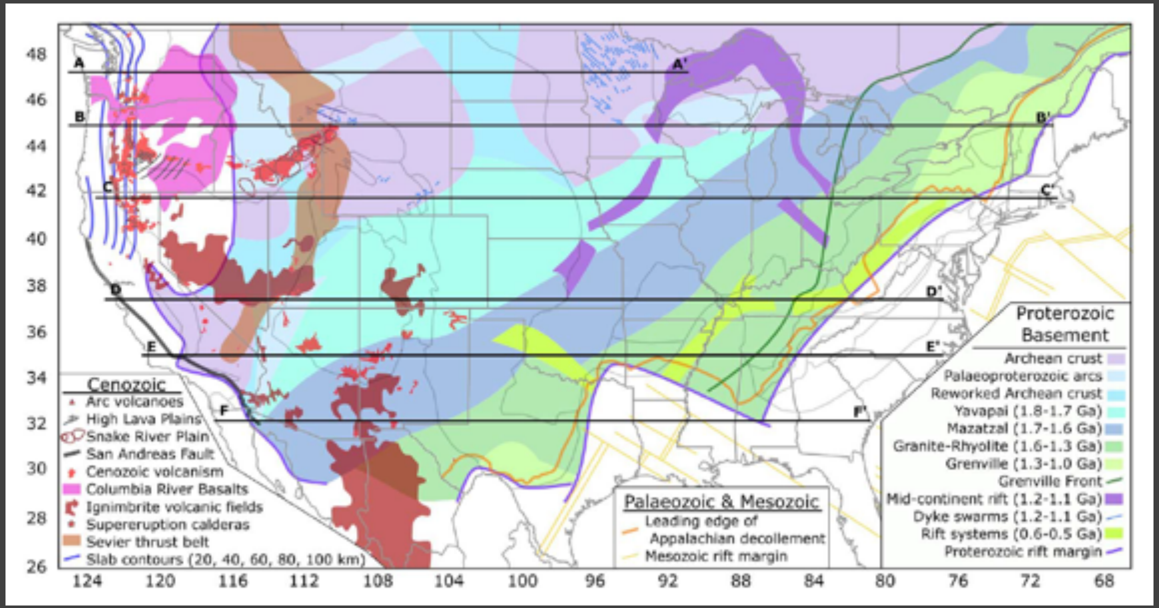


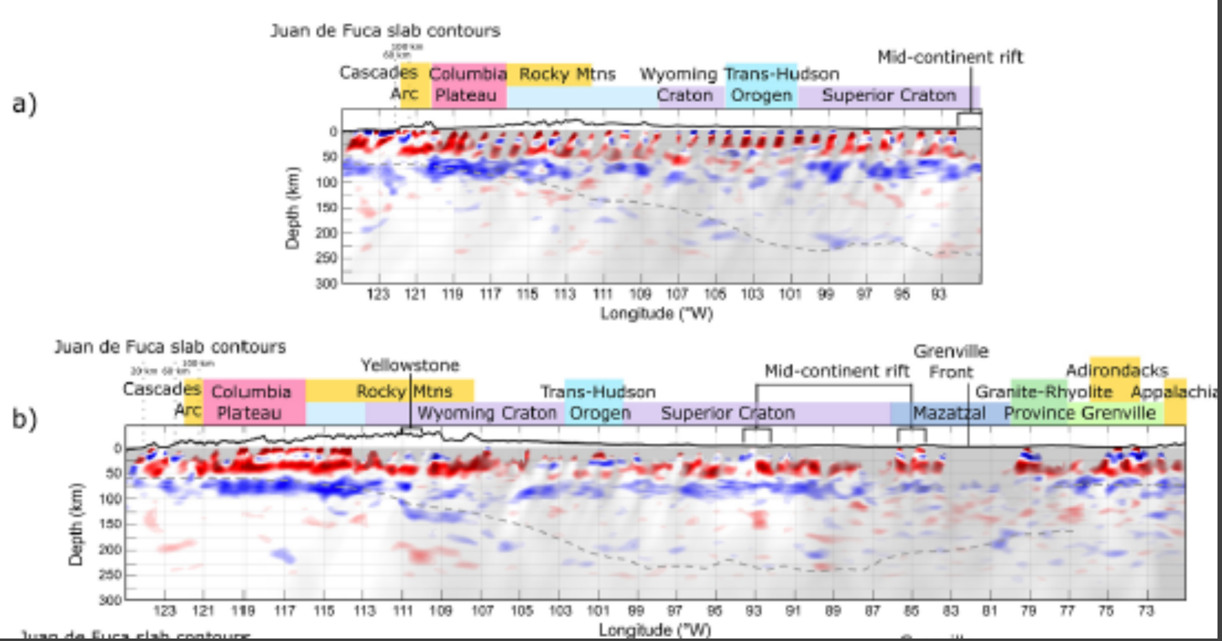




- Using tomography models and empirically derived relationships between velocity and temperature, an estimated lithospheric thickness can be determined but is based on the assumption that the lithosphere-asthenosphere boundary is thermal and occurs at 1300C.

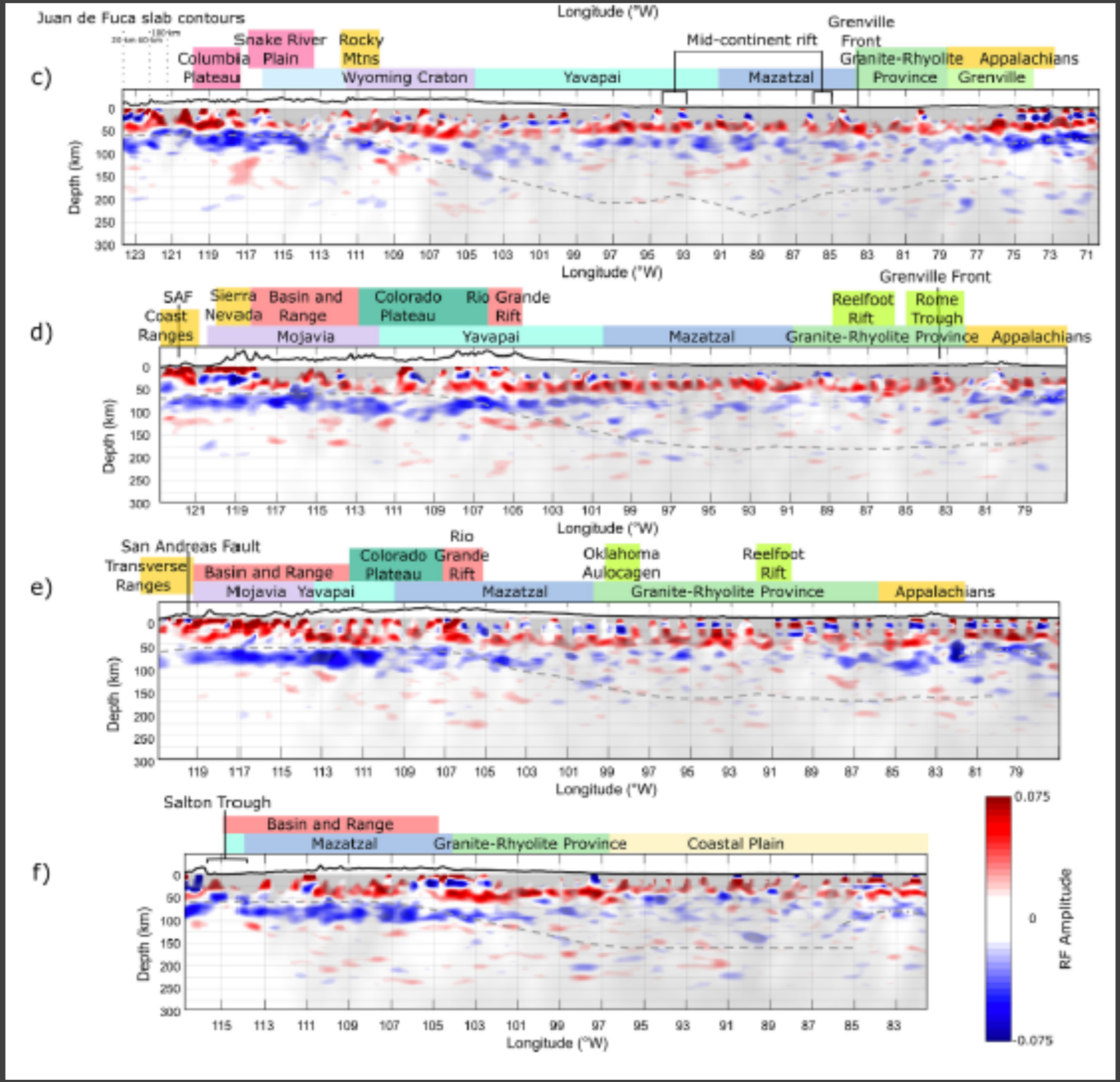
*Porter and Reid (2021)*

# Receiver functions and the LAB




*Hopper and Fischer (2018)*

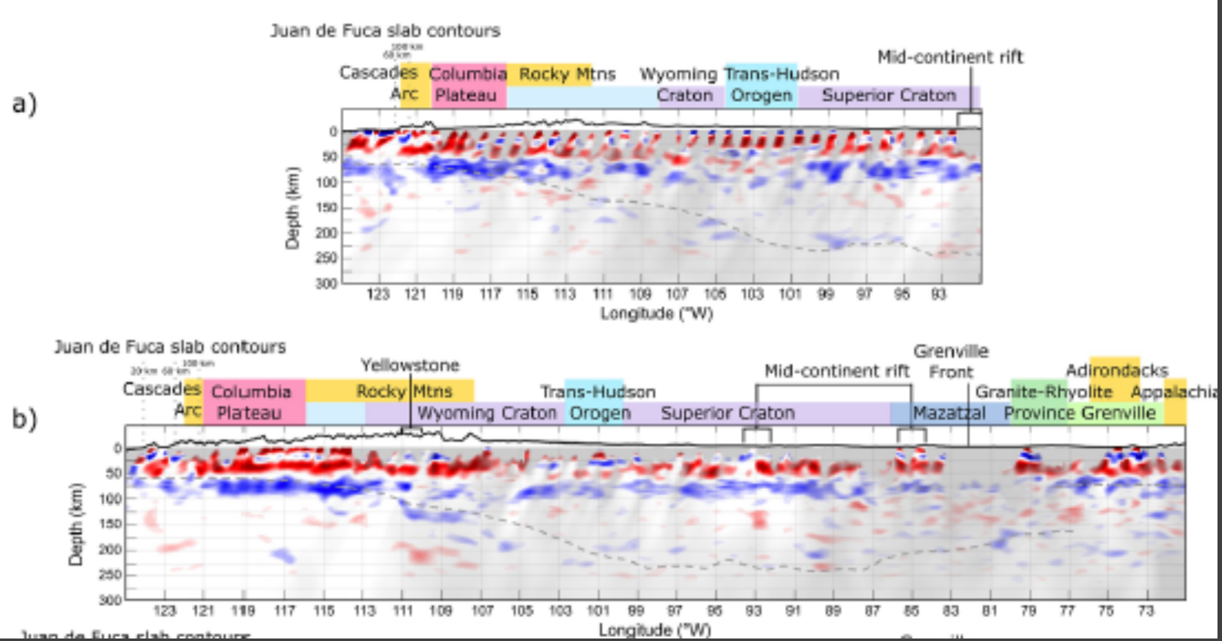


# Receiver functions and the LAB

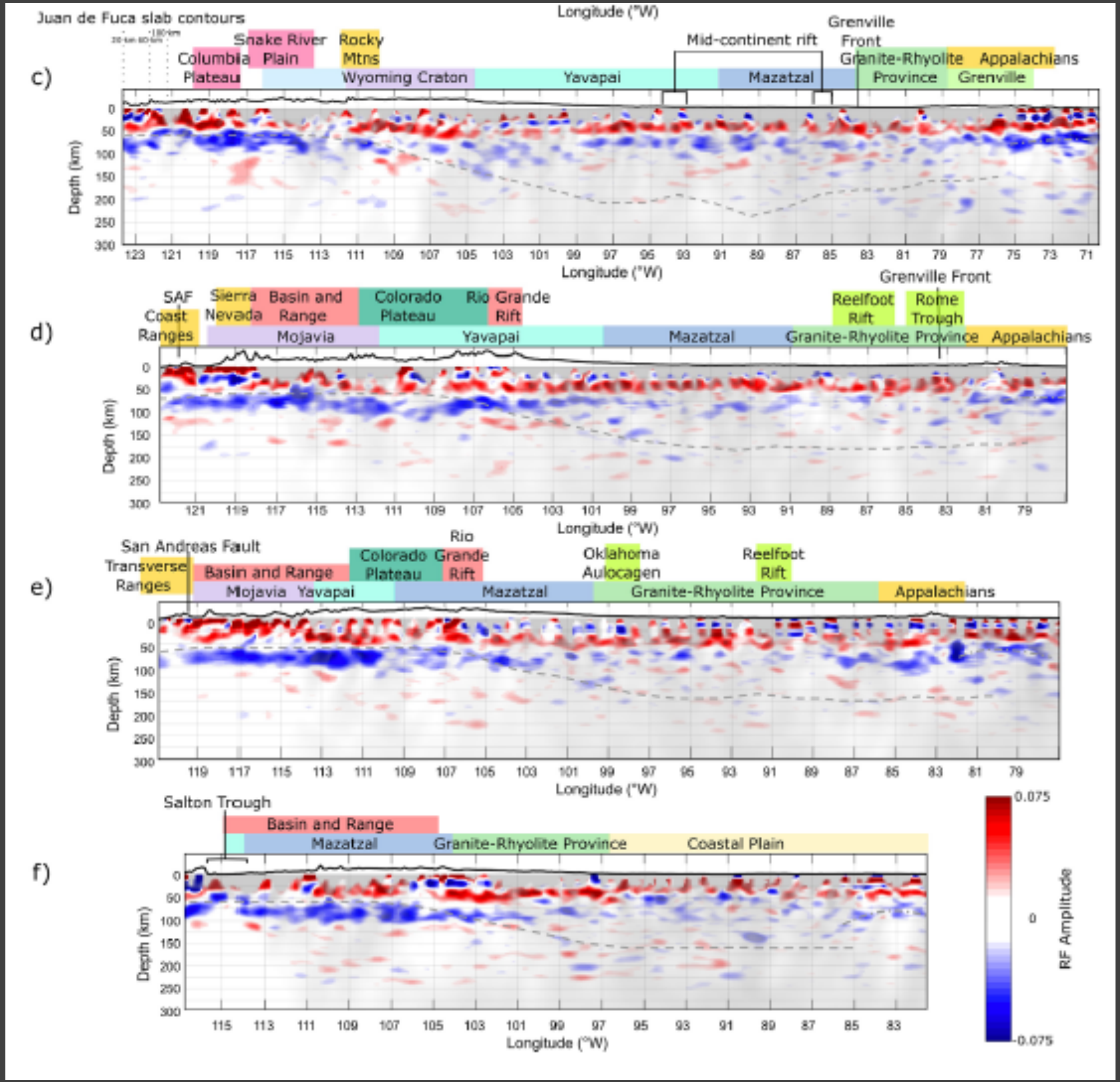
Three important observations:

**#1**. Large amplitude, relatively shallow (60-80 km) negative phase observed across the western U.S.

- Depth agrees well with estimates from seismic tomography models
- Large amplitudes thought to be indicative of significant gradients in velocity, and argued to be due to, in part, the presence of melt at the LAB (within the asthenosphere)




*Hopper and Fischer (2018)*



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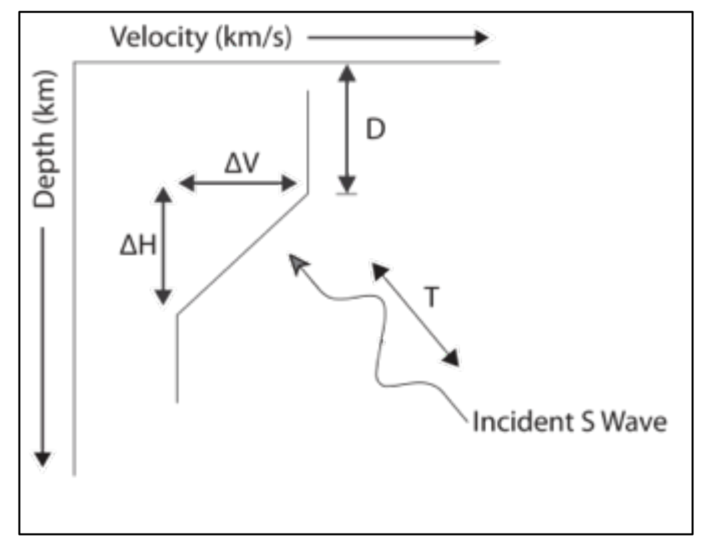
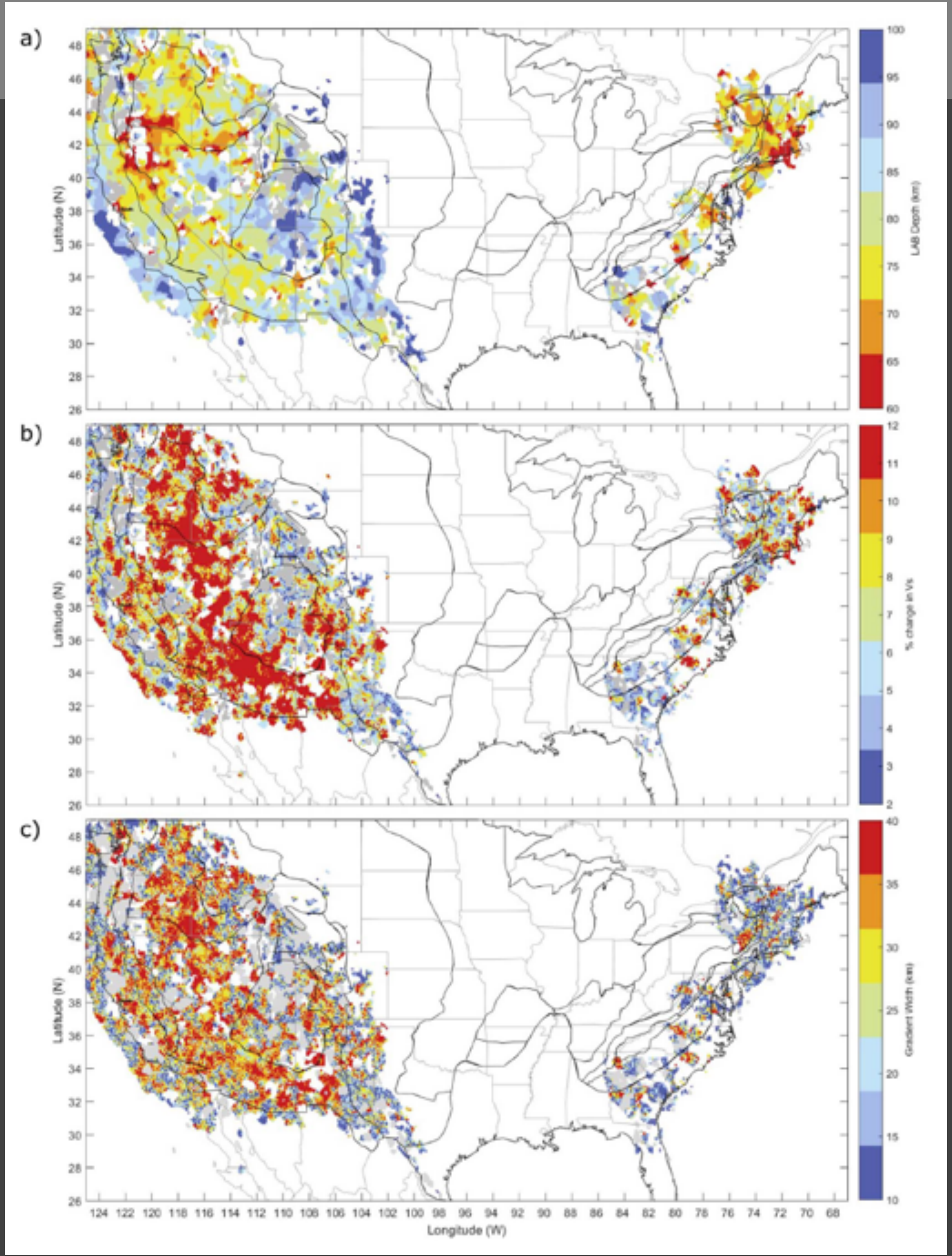
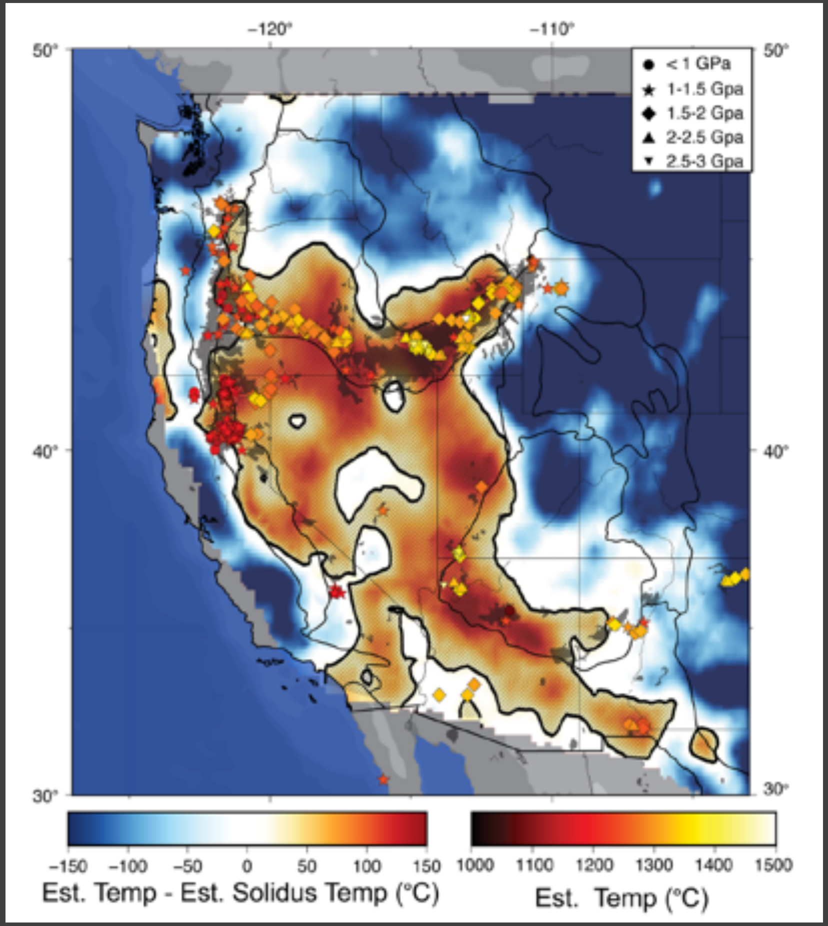
- Depth agrees well with estimates from seismic tomography models
- Large amplitudes thought to be indicative of significant gradients in velocity, and argued to be due to, in part, the presence of melt at the LAB (within the asthenosphere)
    - An average velocity decrease of 10+-4.5% and a gradient thickness of 30+-15 km was calculated

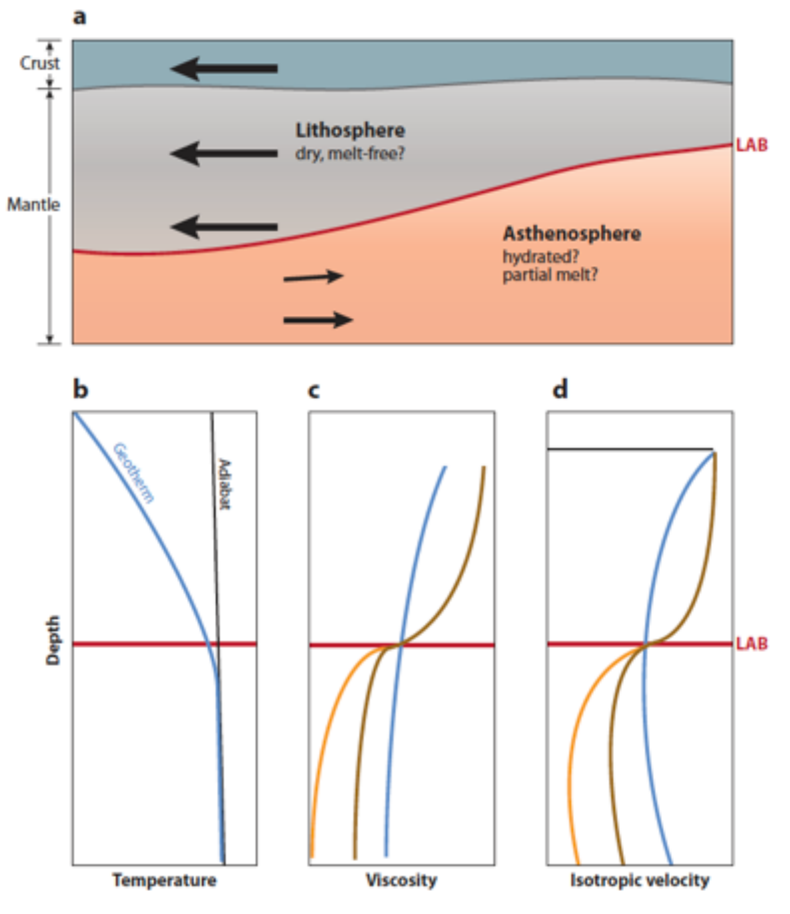


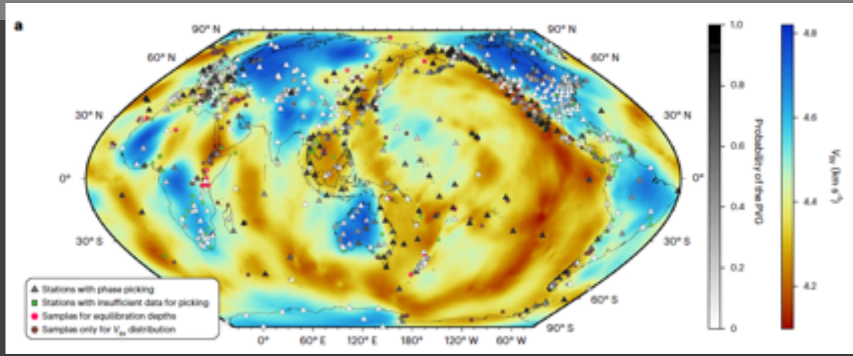
# Receiver functions and the LAB

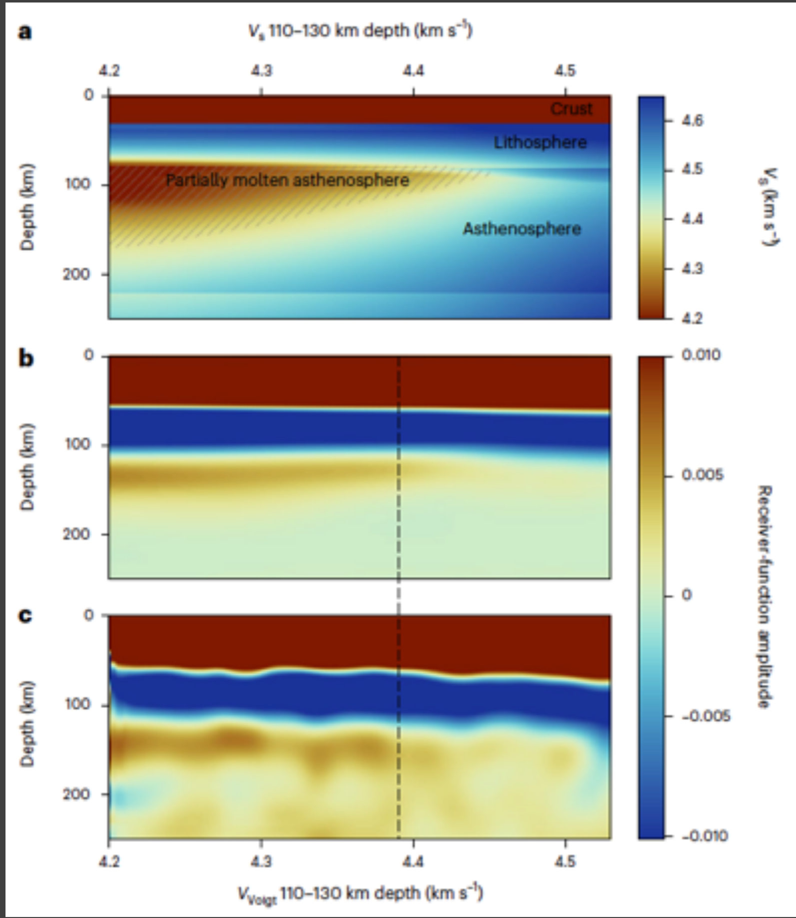



*Porter and Reid (2021)*




*Fischer et al. (2010)*






The argument for the presence of melt at the LAB (within the asthenosphere) is shared with some tomography models, and agrees well with global investigations using Sp receiver functions

*Hua et al. (2023)*

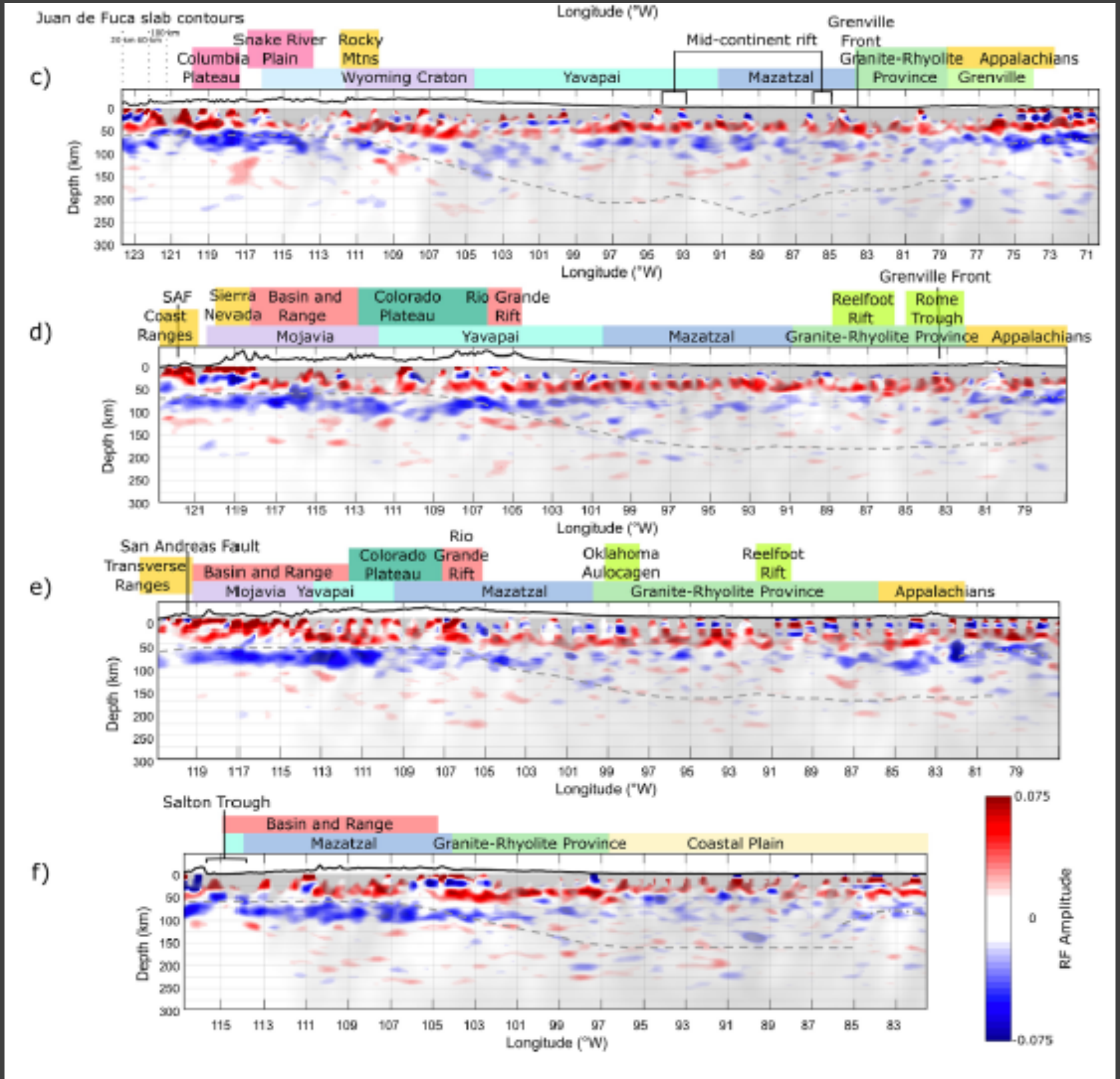
# Receiver functions and the LAB

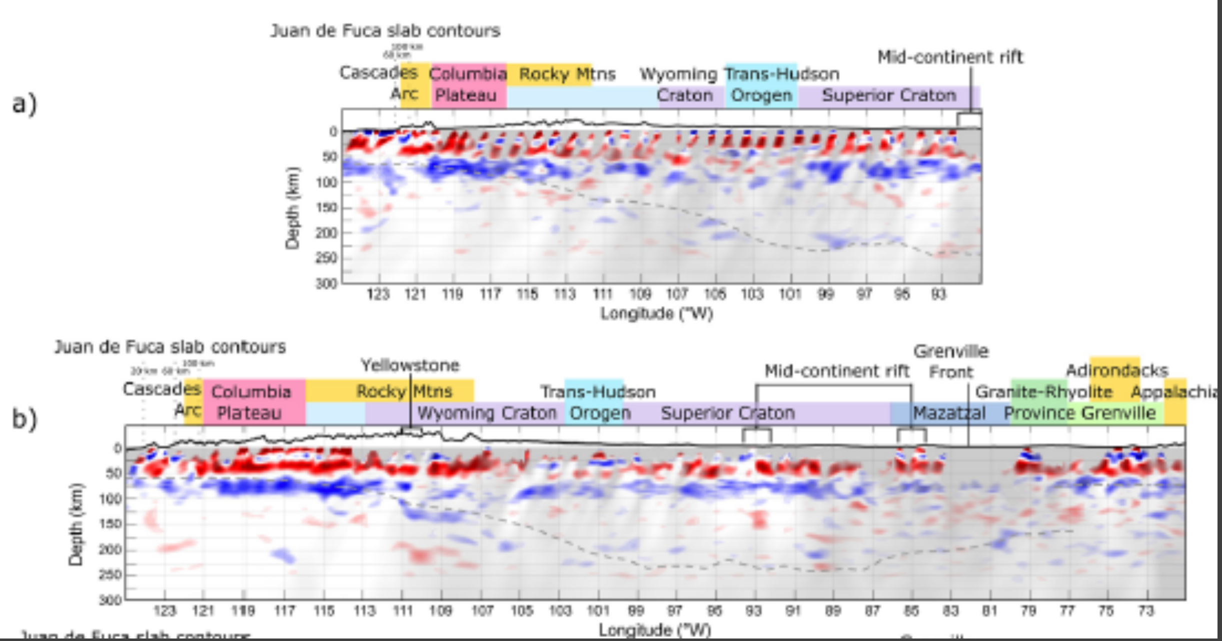
Three important observations:

**#2**. Negative phase energy consistent with the transition from lithosphere to asthenosphere is largely absent beneath the continental interior

- Dearth of energy at predicted LAB depths is thought to be the result of a gradual/small decrease in velocity, making the boundary difficult to image with receiver functions

*Hopper and Fischer (2018)*



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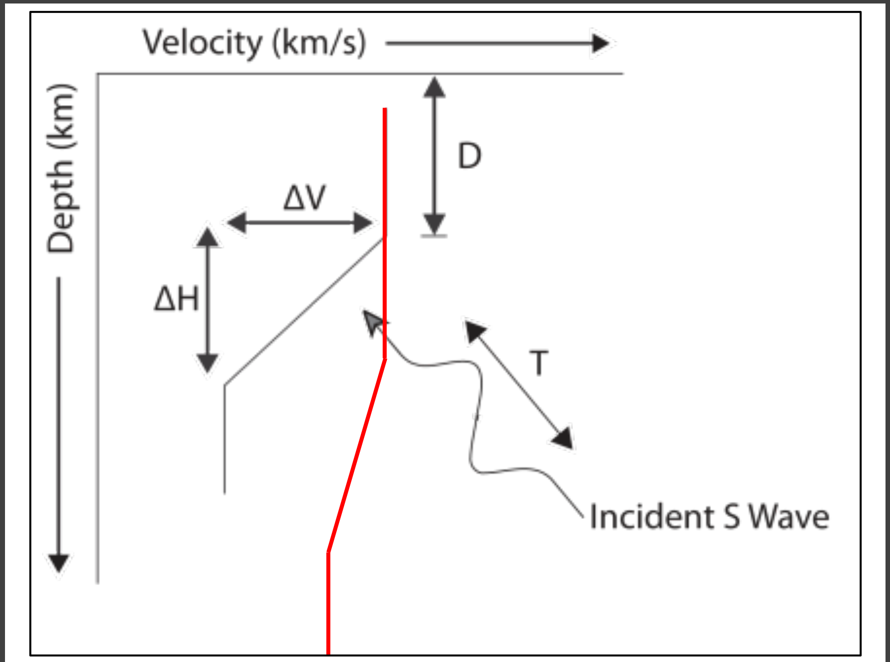
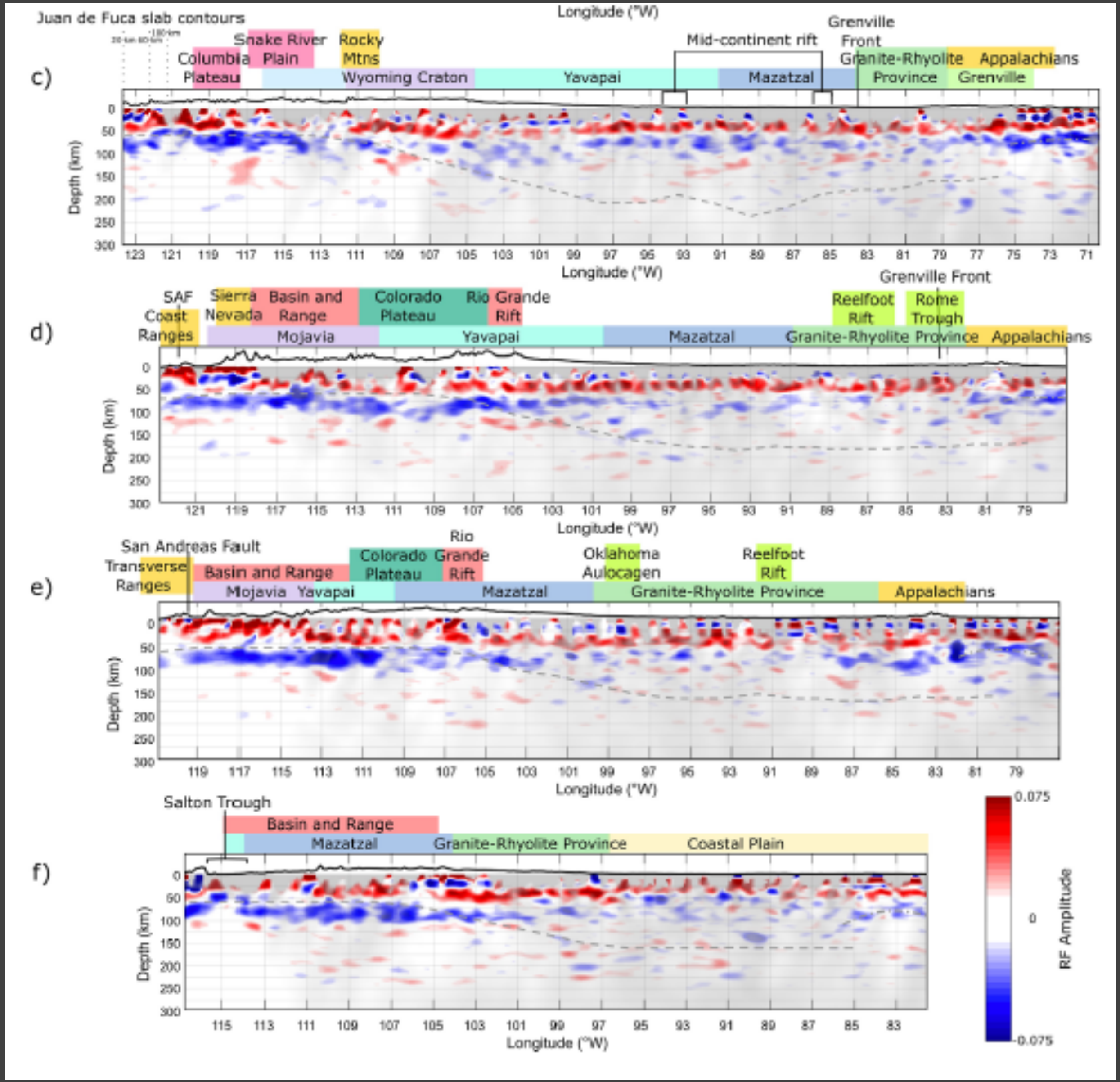
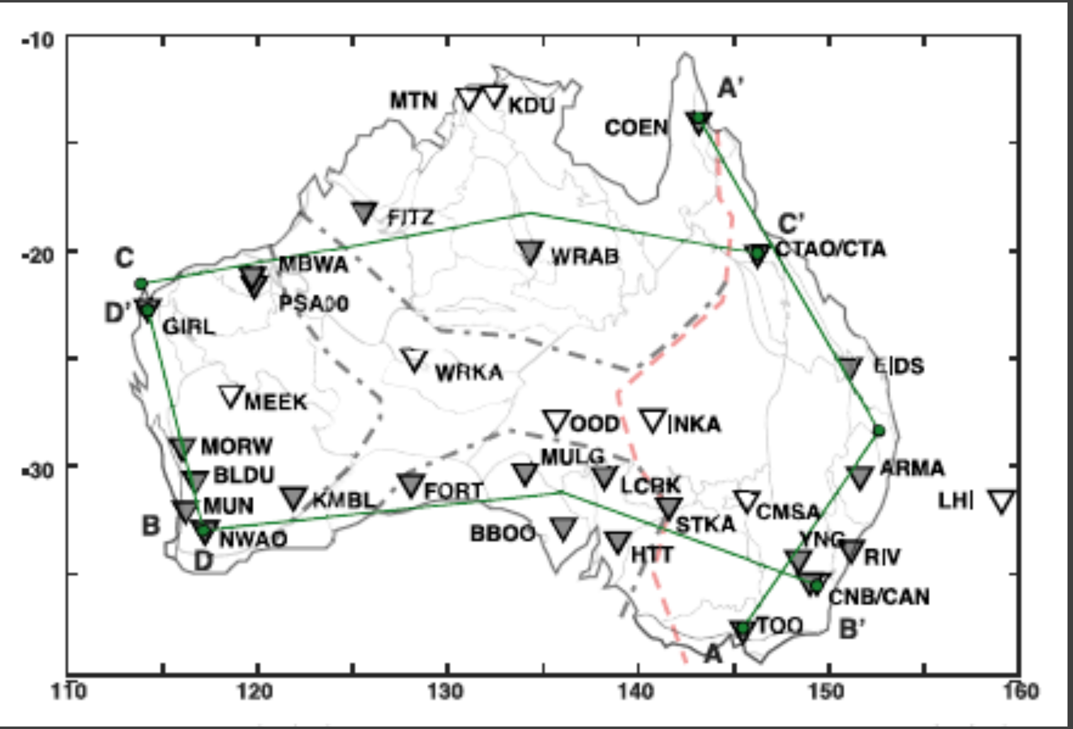


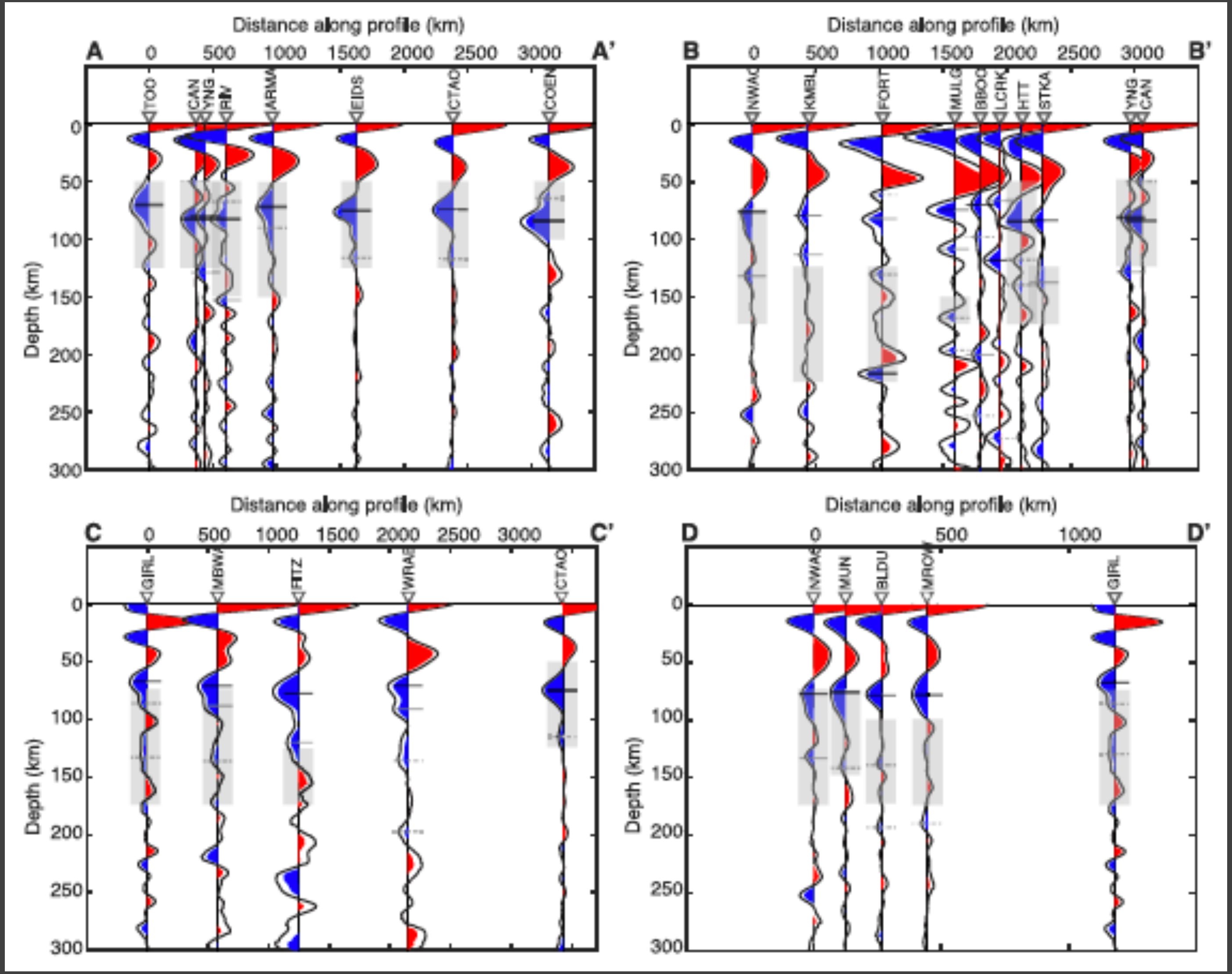

*Hopper and Fischer (2018)*



# Receiver functions and the LAB




*Berkey et al. (2021)*



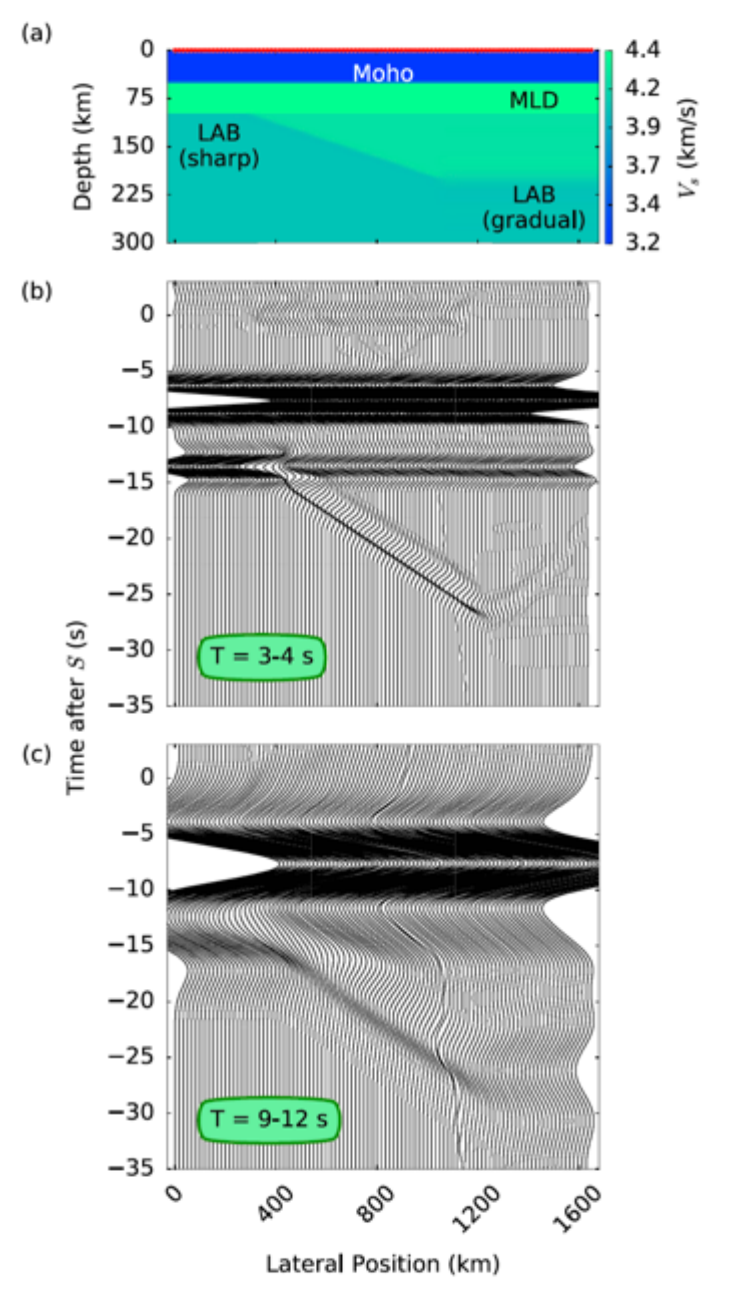
# Receiver functions and the LAB

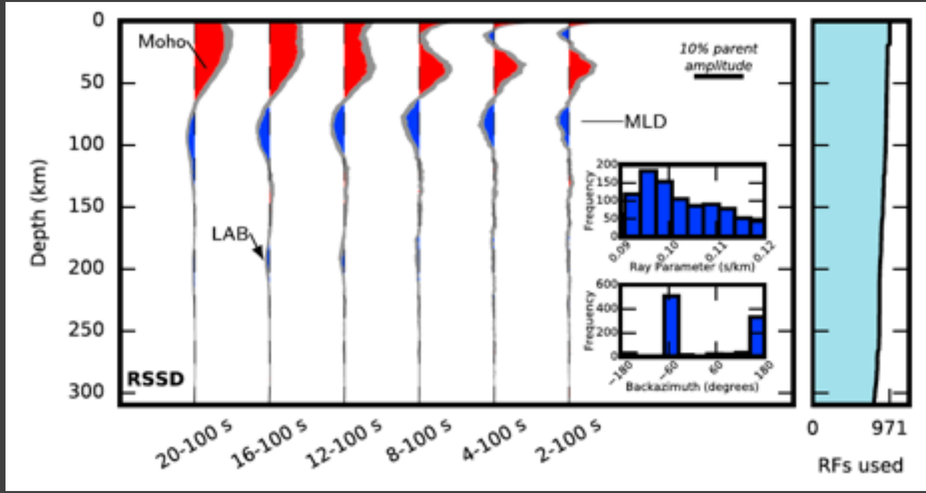
## How Sharp Is the Cratonic Lithosphere-Asthenosphere Transition?

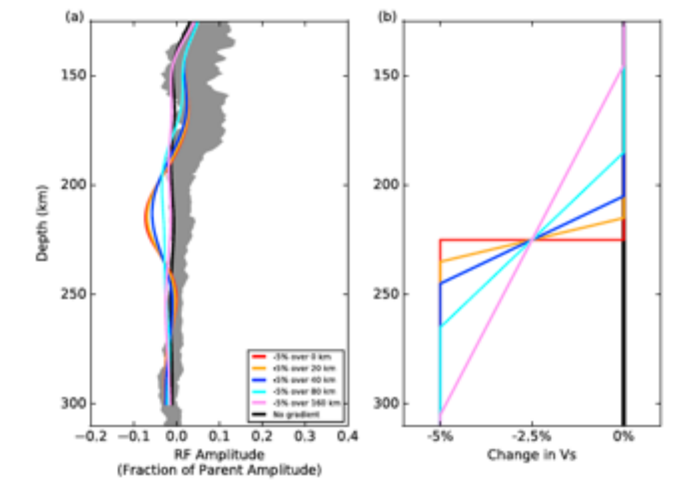
**Nicholas J. Mancinelli**[1], **Karen M. Fischer**[1], and **Colleen A. Dalton**[1]

[1]Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, RI, USA

**Abstract** Earth's cratonic mantle lithosphere is distinguished by high seismic wave velocities that extend to depths greater than 200 km, but recent studies disagree on the magnitude and depth extent of the velocity gradient at their lower boundary. Here we analyze and model the frequency dependence of *Sp* waves to constrain the lithosphere-asthenosphere velocity gradient at long-lived stations on cratons in North America, Africa, Australia, and Eurasia. Beneath 33 of 44 stations, negative velocity gradients at depths greater than 150 km are less than a 2–3% velocity drop distributed over more than 80 km. In these regions the base of the typical cratonic lithosphere is gradual enough to be explained by a thermal transition. Vertically sharper lithosphere-asthenosphere transitions are permitted beneath 11 stations, but these zones are spatially intermittent. These results demonstrate that lithosphere-asthenosphere viscosity contrasts and coupling fundamentally differ between cratons and younger continents.

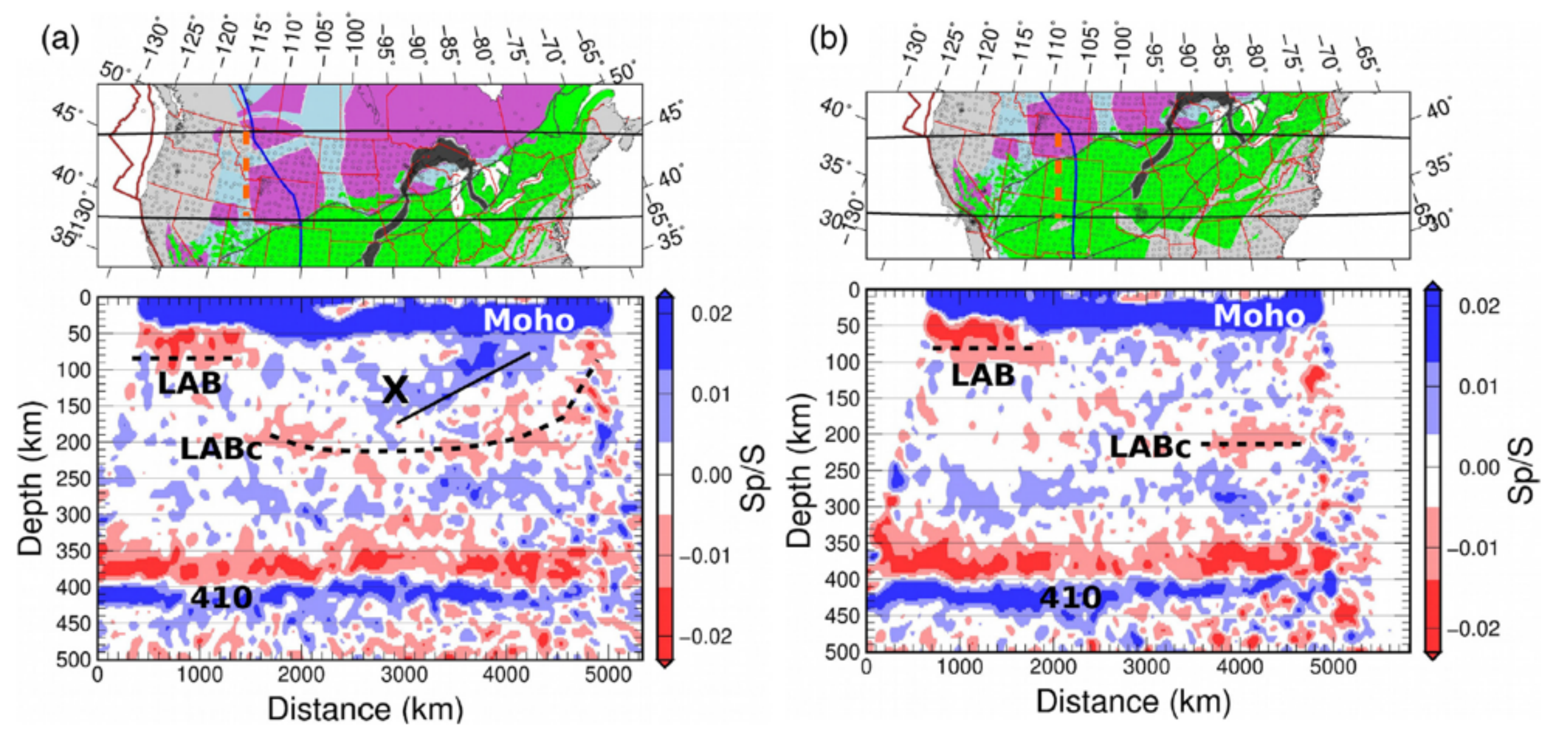



*Mancinelli et al. (2017)*

# Receiver functions and the LAB




*Kind et al. (2020)*

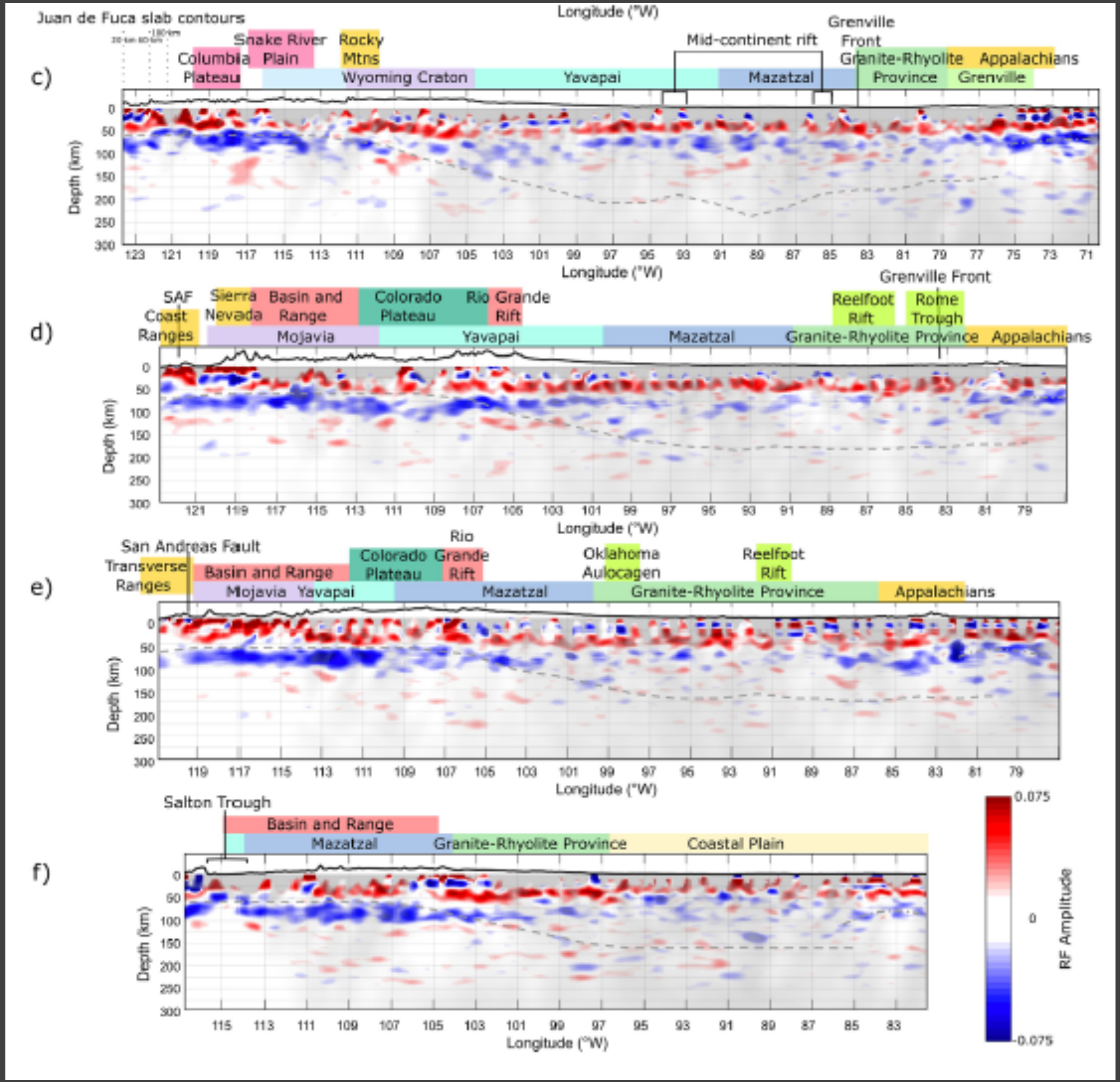
# Receiver functions and MLDs

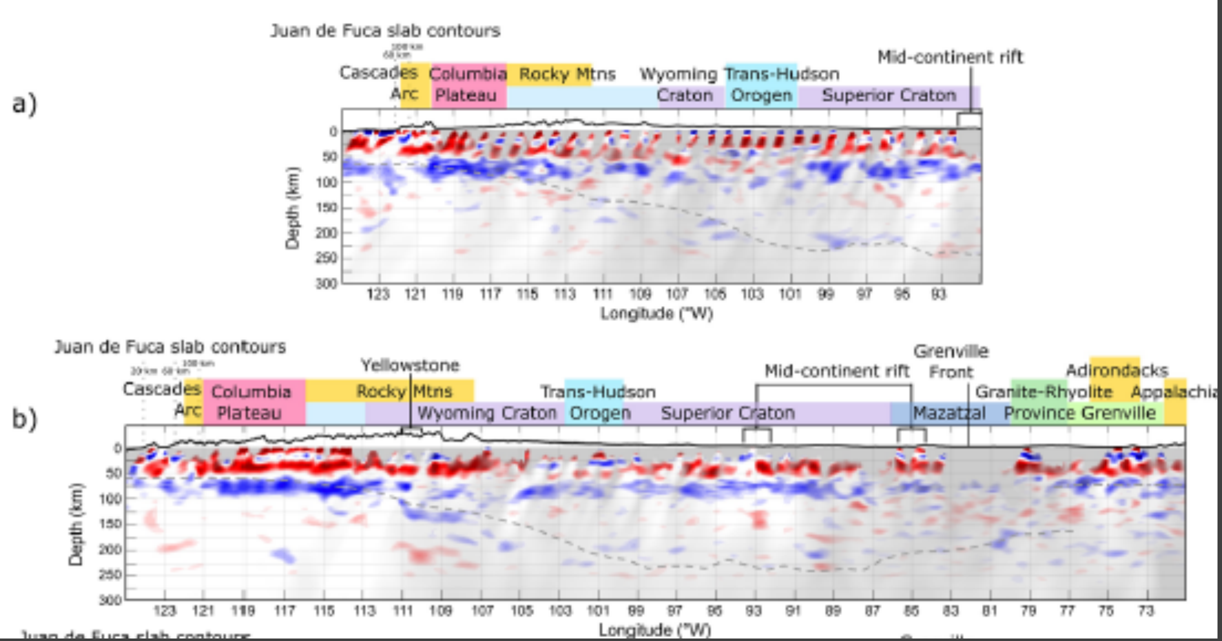
Three important observations:

**#3**. Coherent, negative phase energy observed across the continental interior at depths.

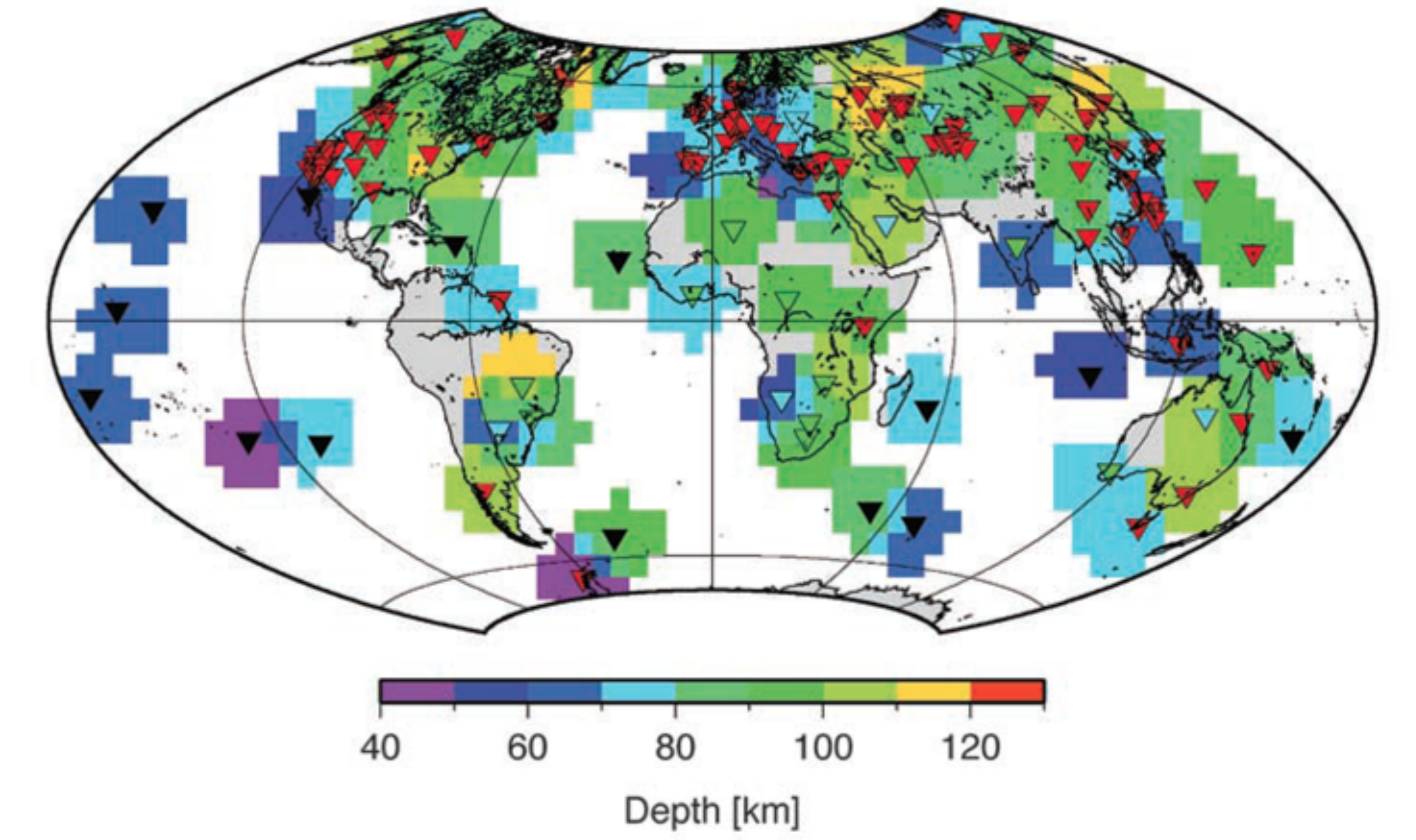
- Considered to be too shallow based on constraints from seismic tomography
- These negative phases have been observed in many regions globally and are commonly referred to as <u>mid-lithospheric discontinuities</u>

*Hopper and Fischer (2018)*

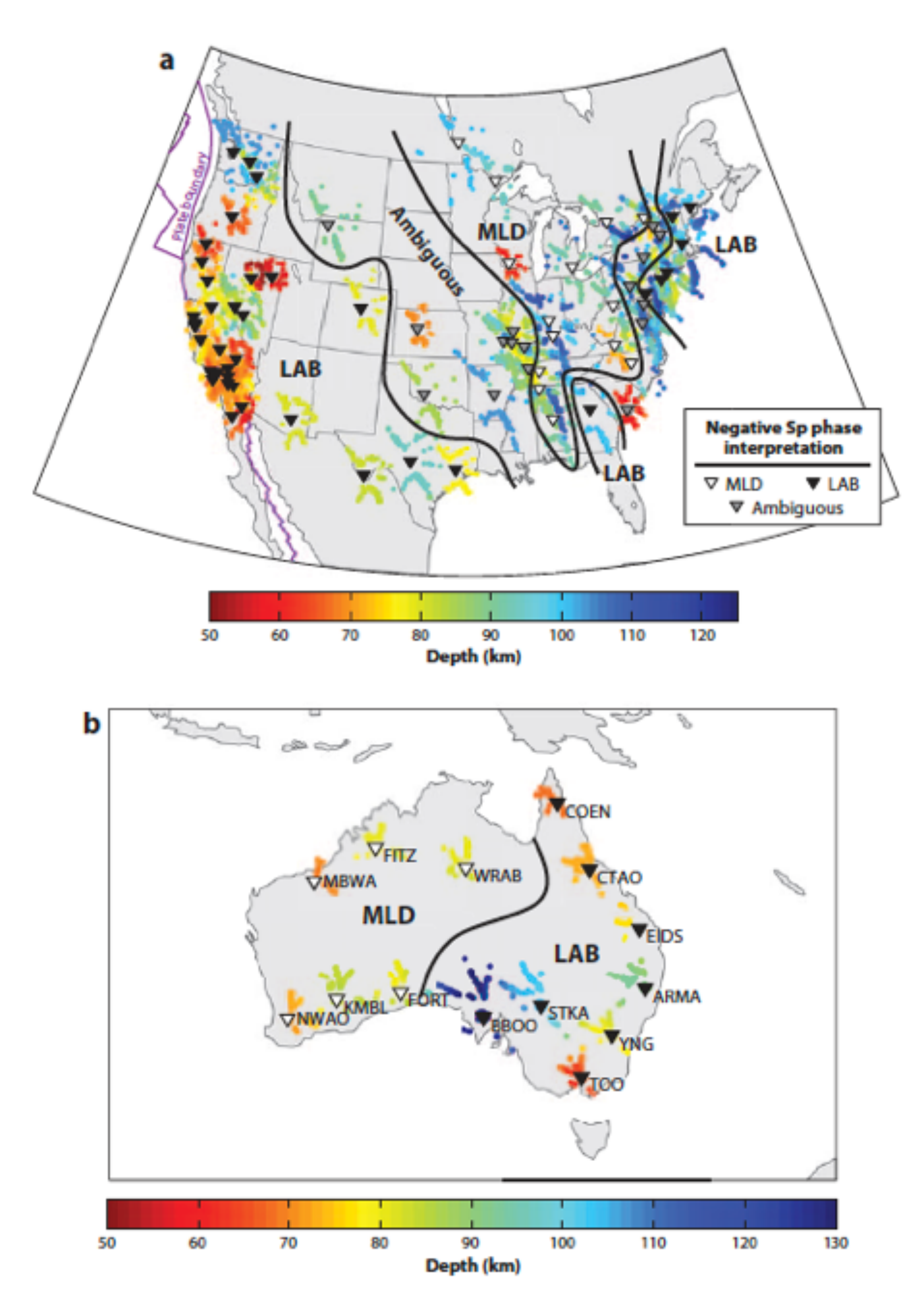


# Receiver functions and MLDs




*Rychert and Shearer (2009)*




*Fischer et al. (2010)*

# Receiver functions and MLDs

<u>Potential MLD mechanisms (Selway et al., 2015)</u>

**Thermal**

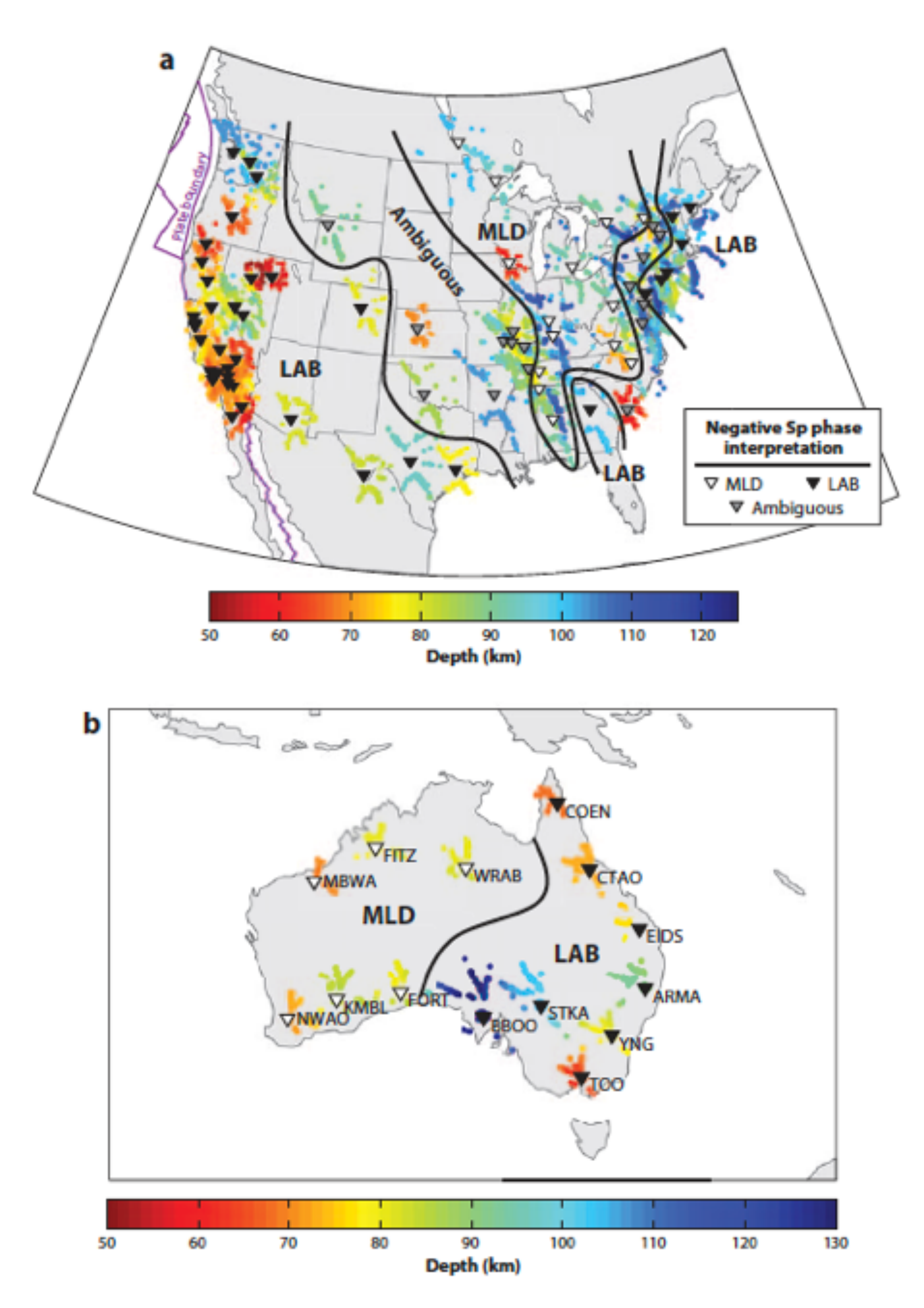
- **Partial melt** (Kumar et al., 2012; Thybo, 2006; Thybo and Perchuc, 1997)
  - Small amount could produce observable change in velocities
  - Requires water saturation, deeper than average MLD
  - Magnetotelluric data does not support melt layer hypothesis
- **Elastically accommodated GBS** (Karato et al., 2012)
  - Explains the "universal" presence of MLD
  - Key parameters still poorly constrained

**Composition** ( e.g., Foster et al., 2013; Sodoudi et al., 2013; Ford et al., 2010)

- **Change in Mg#**
- **Hydrous Minerals**
  - Evidence of minerals found in xenoliths
  - Capable of producing modeled velocity gradients

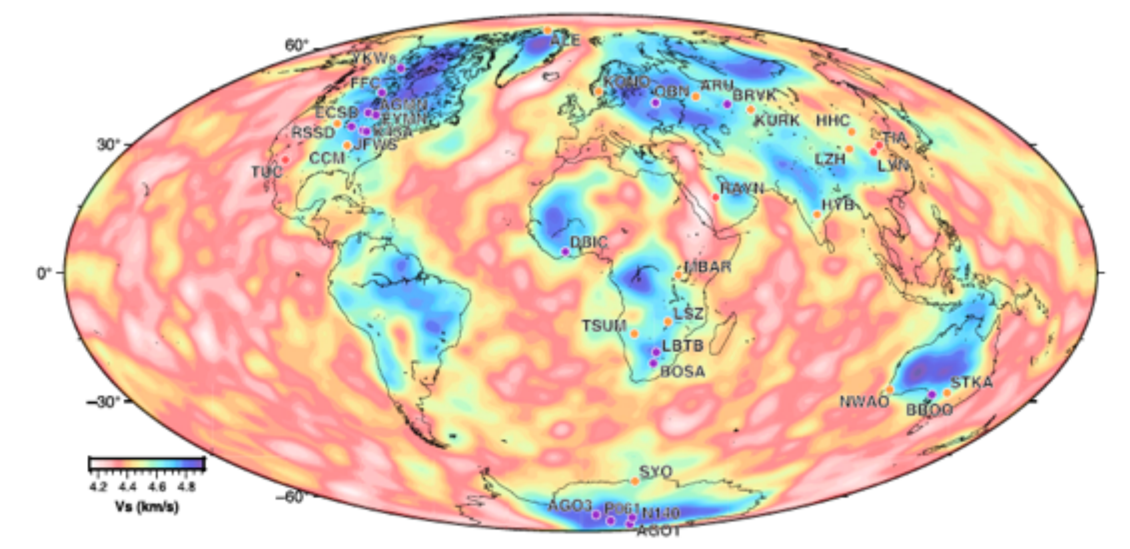
**Anisotropy** (Sodoudi et al., 2013; Wirth and Long, 2014; Ford et al., 2016)

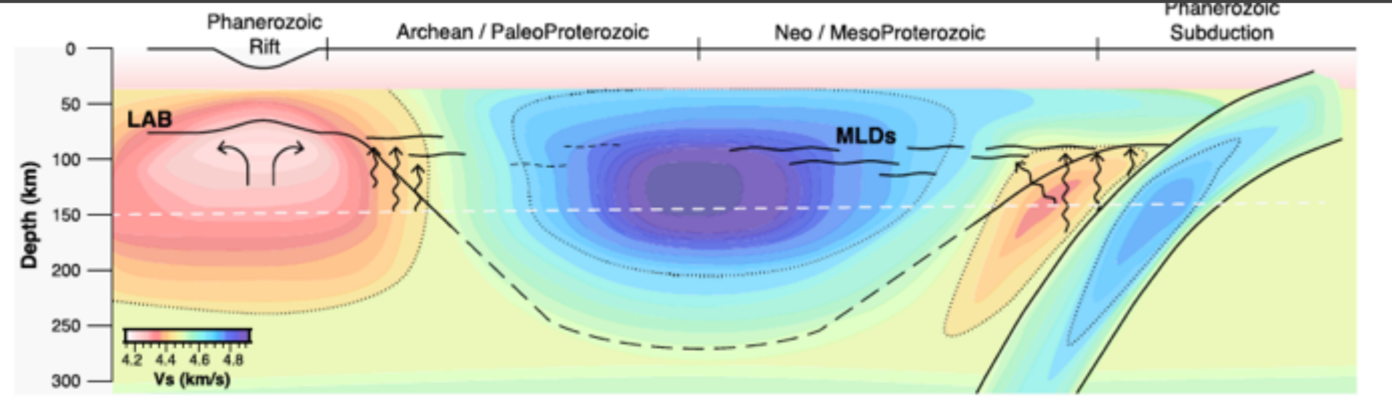
- Prior evidence for anisotropy at similar depths
- Difficult to explain as a universal feature



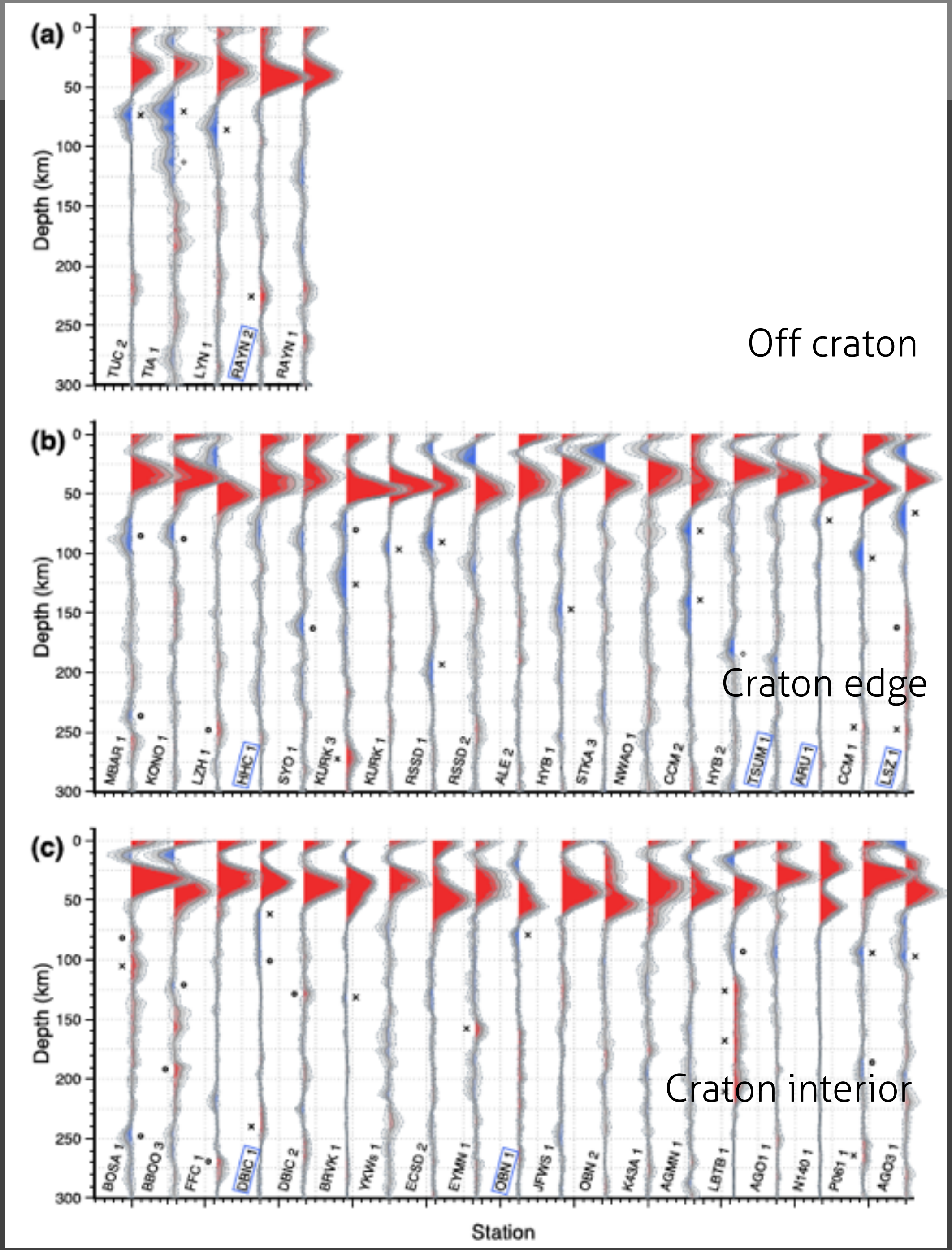

*Fischer et al. (2010)*

# Receiver functions and MLDs

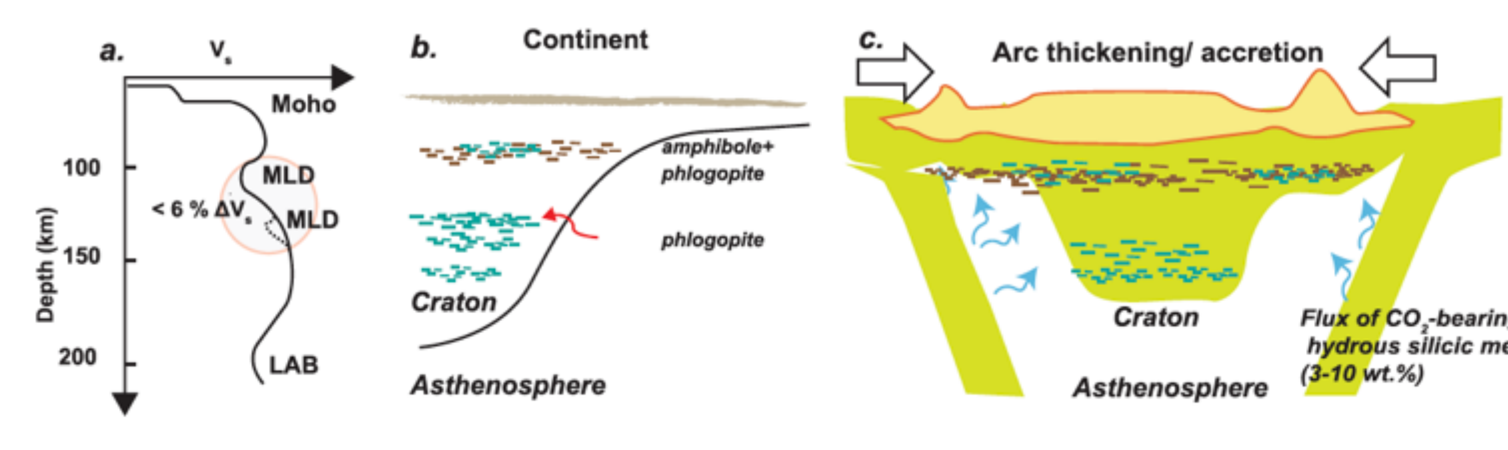


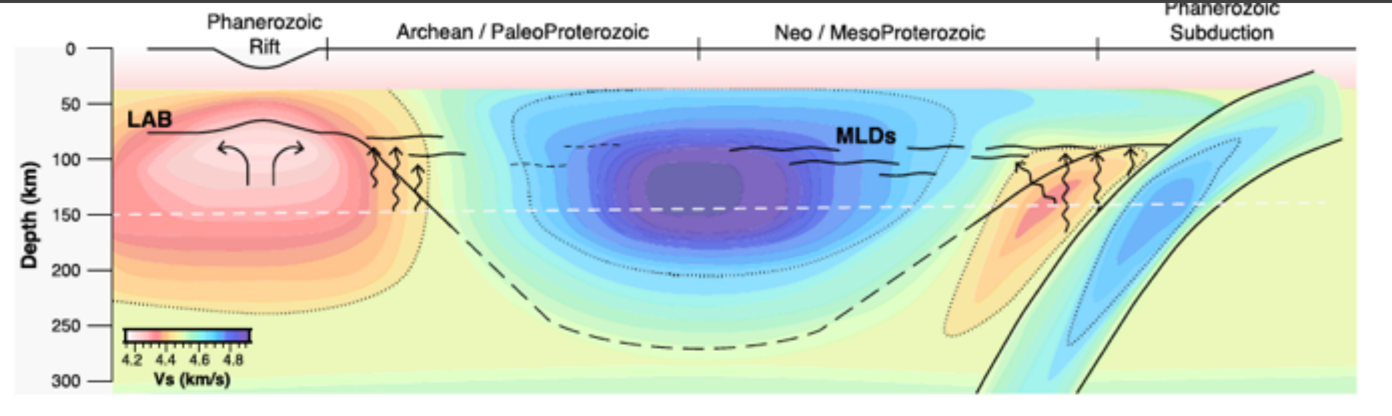

*Krueger et al (2021)*



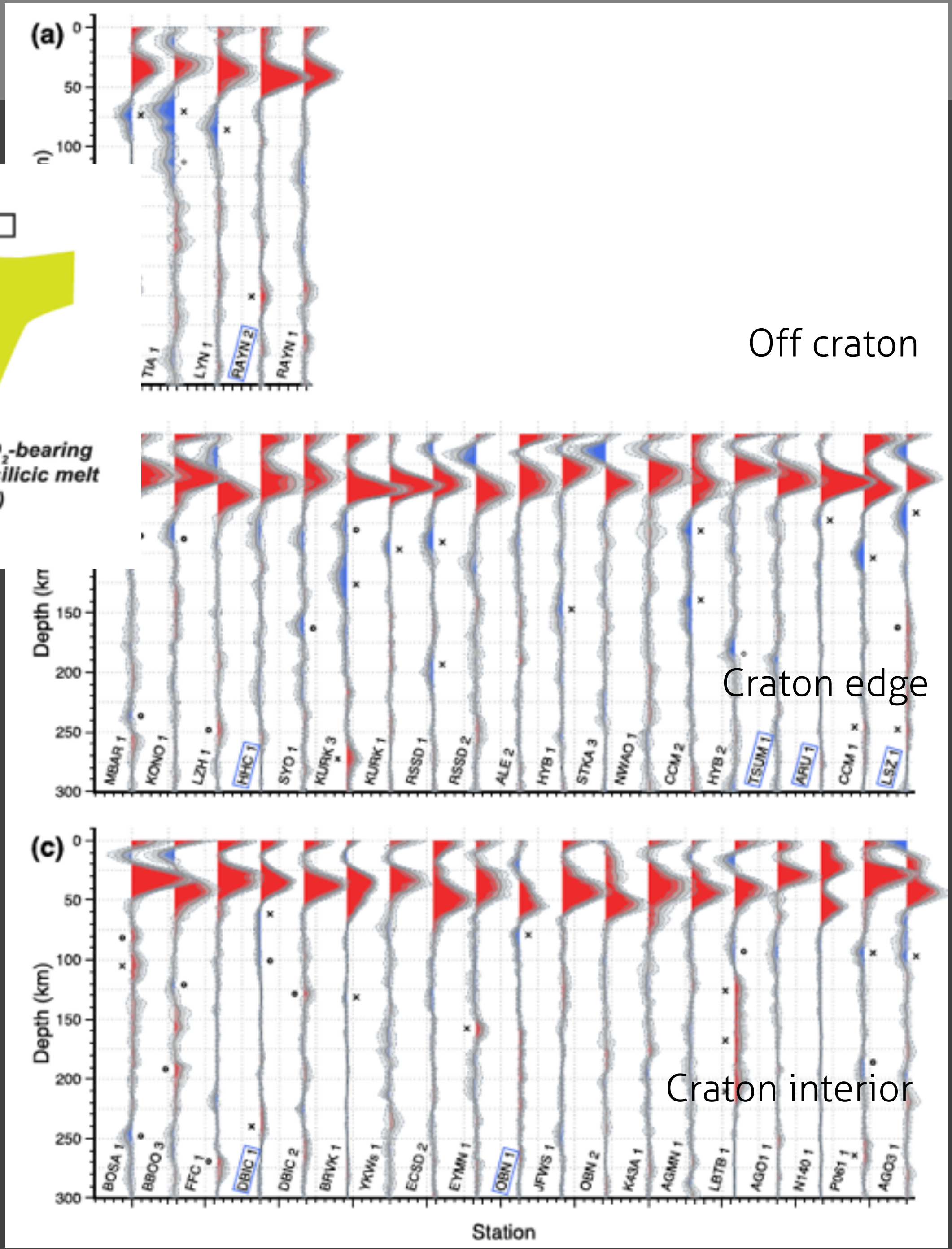
# Receiver functions and MLDs




*Saha et al. (2018)*




*Krueger et al (2021)*



# Receiver functions and other imaging constraints

**Points of emphasis:**

- Receiver function analysis is a complimentary method.
- The interpretability of receiver function results is predicated on a good first order understanding of lithospheric thicknesses provide by other methods such as, but not limited to, seismic tomography.
- Receiver functions excel at imaging seismically sharp/strong boundaries, such as the Moho, and the LAB in tectonically or magmatically active regions.
- Receiver functions can image boundaries to high precision, place constraints on the overall change in velocity (gradient)
- Receiver functions can also put constraints on complex structure internal to the lithosphere (mid-lithospheric discontinuities) that are largely absent in tomographic models.

# Part 2 Overview

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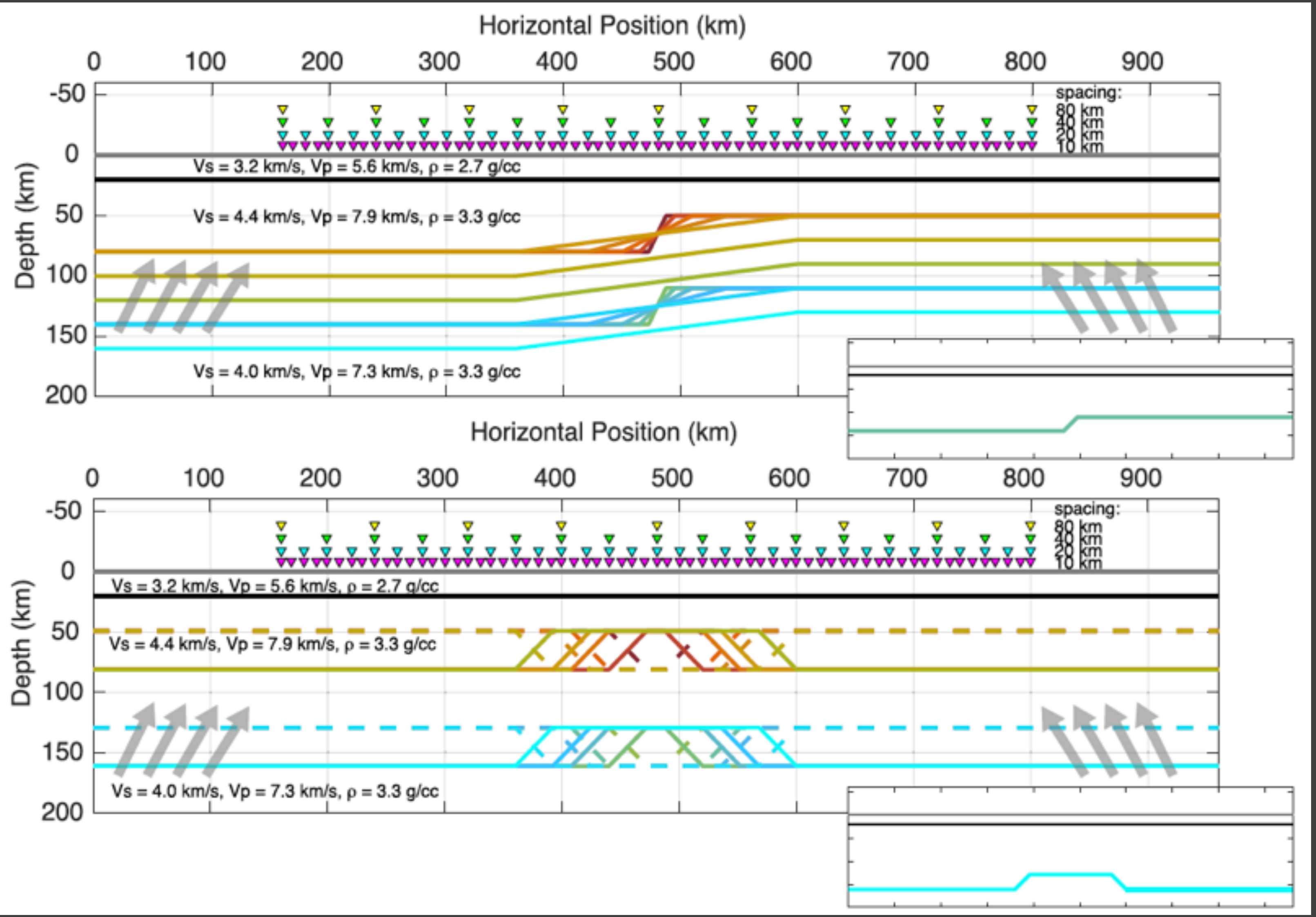
- Receiver functions and anisotropy
- Joint inversions including receiver functions

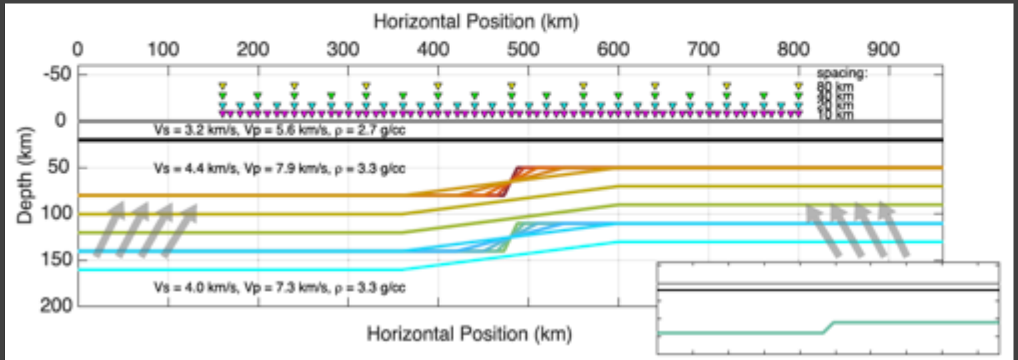
# Introducing complexity

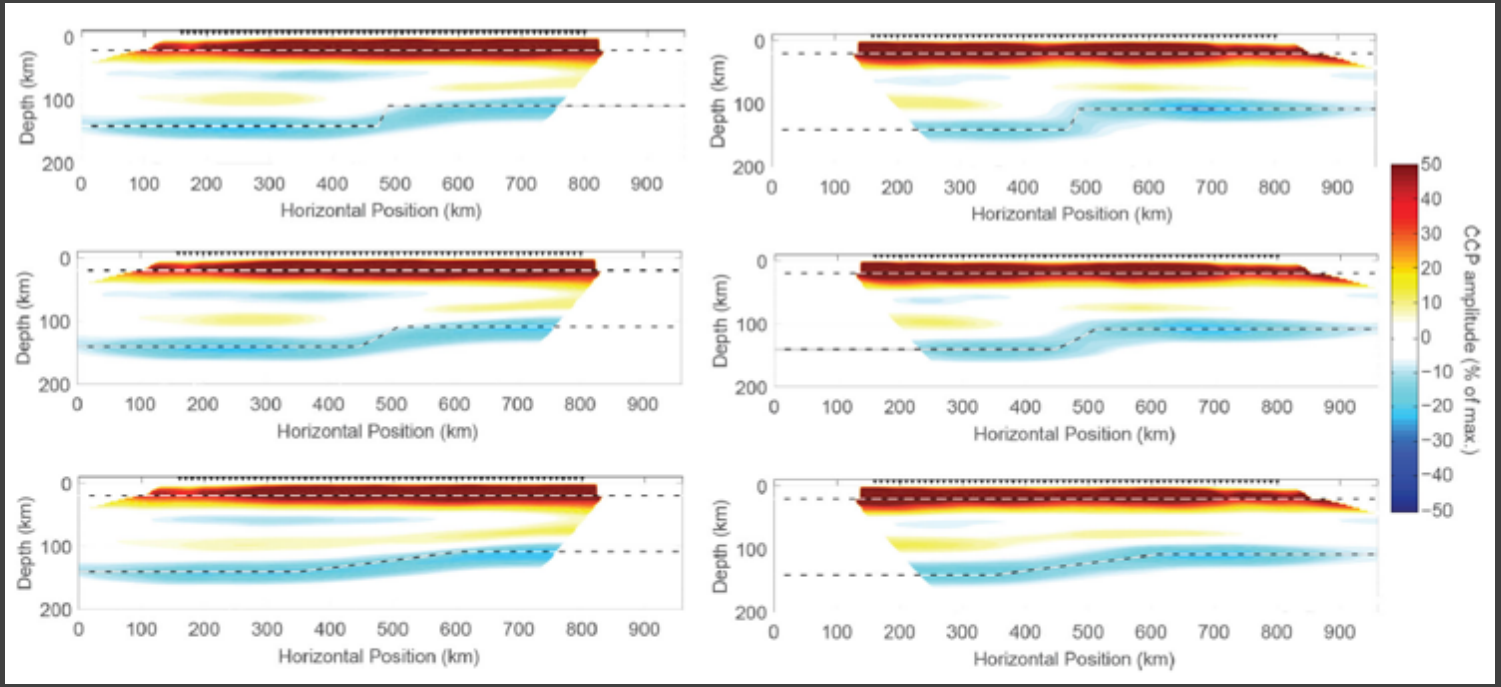


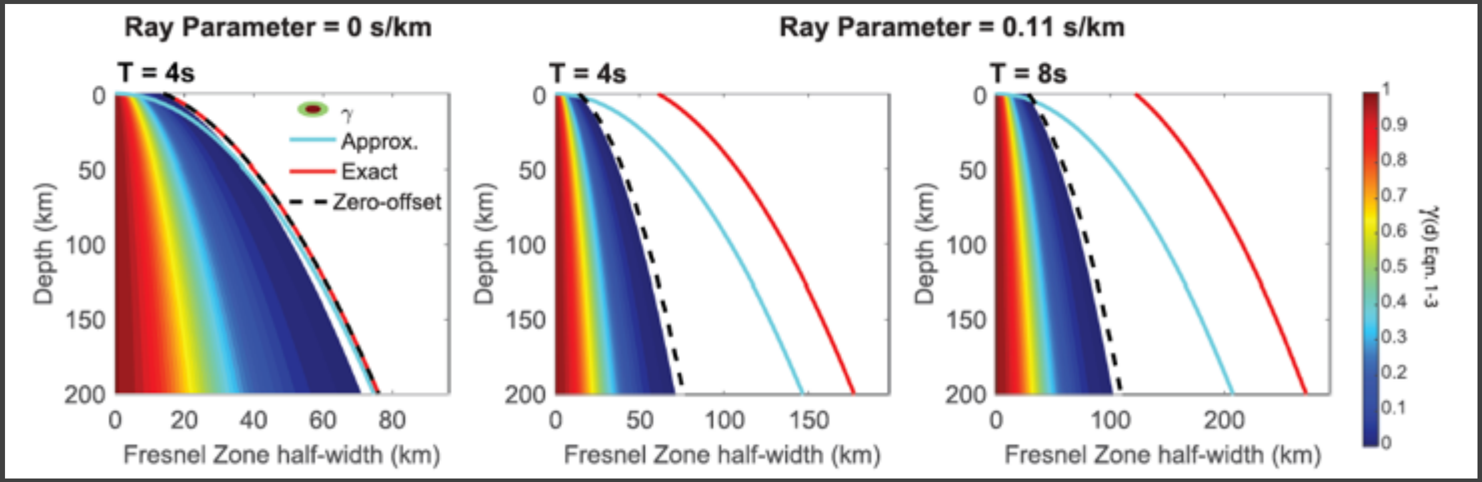

Lekic and Fischer (2017)

- Computed 2D synthetics using a spectral element method (SPECFEM2D)
- Interrogated different geometries, station spacing, illumination geometry (ray path), frequency content, tapering and deconvolution methods

# Introducing complexity



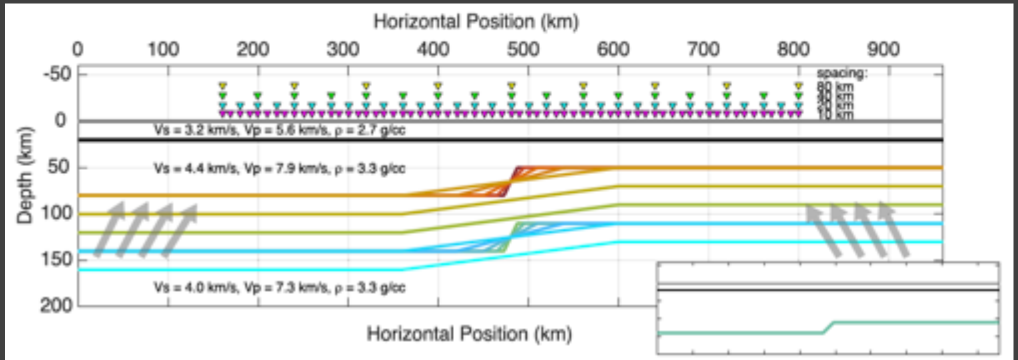



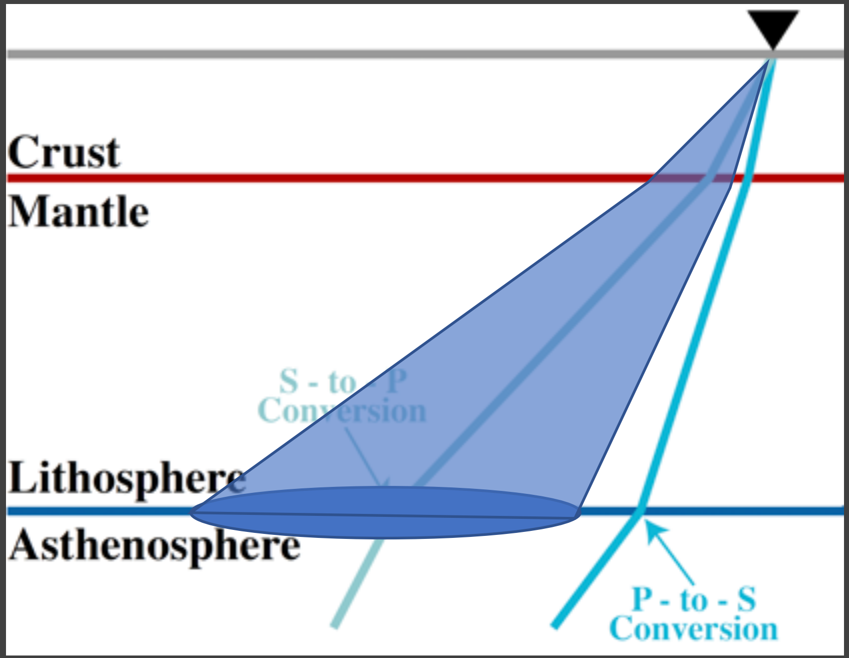




Lekic and Fischer (2017)

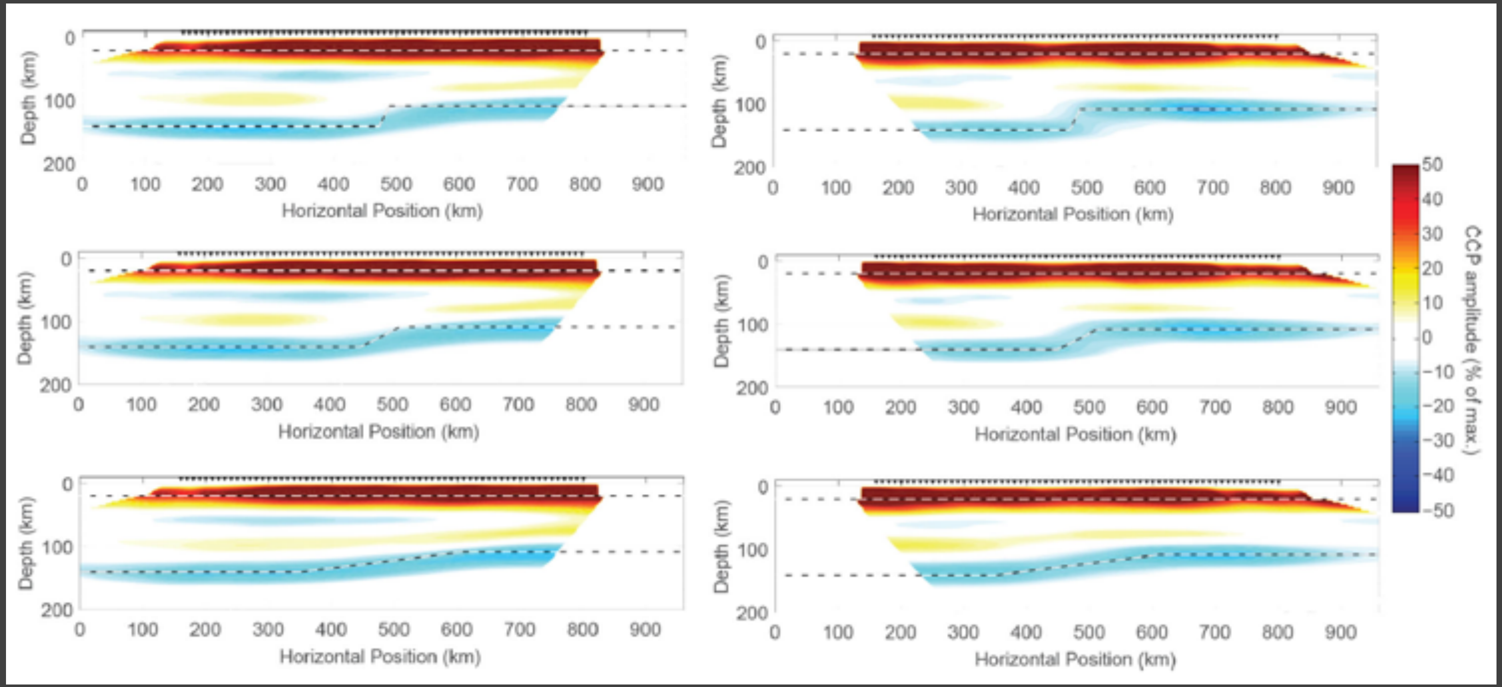
- CCP stacking in their example can resolve the steepness of the transition in some circumstances (illumination direction, however, amplitudes are reduced at the step in thickness for the steepest steps.
- Their CCP stacking takes into account finite frequency effects by binning according to an approximation of the Fresnel zone for each ray path.

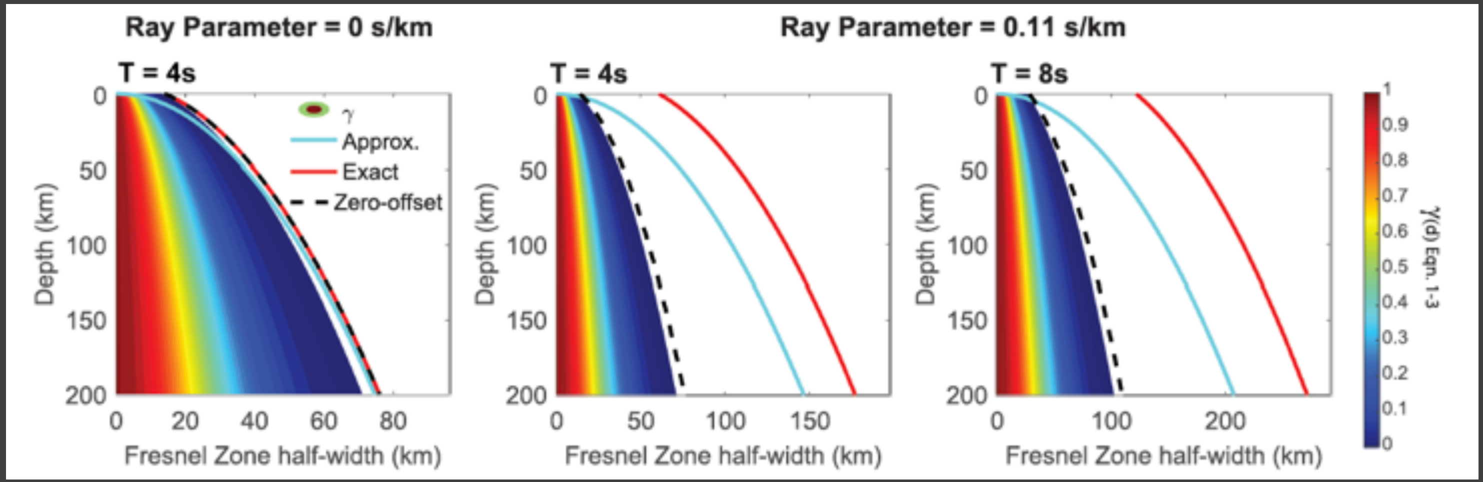
# Introducing complexity



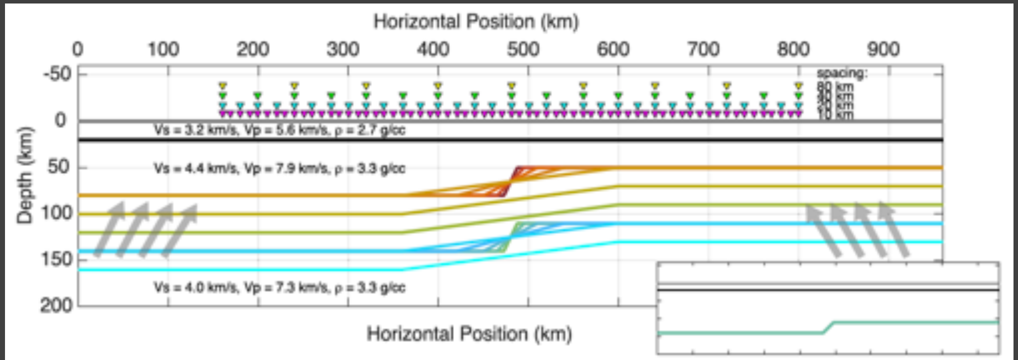



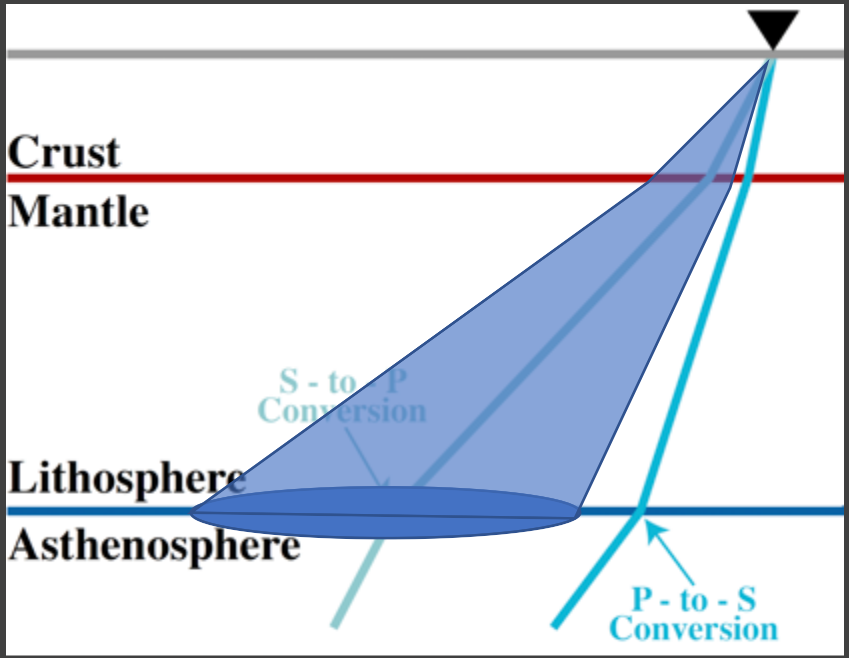

Sensitive to off ray path structure!!



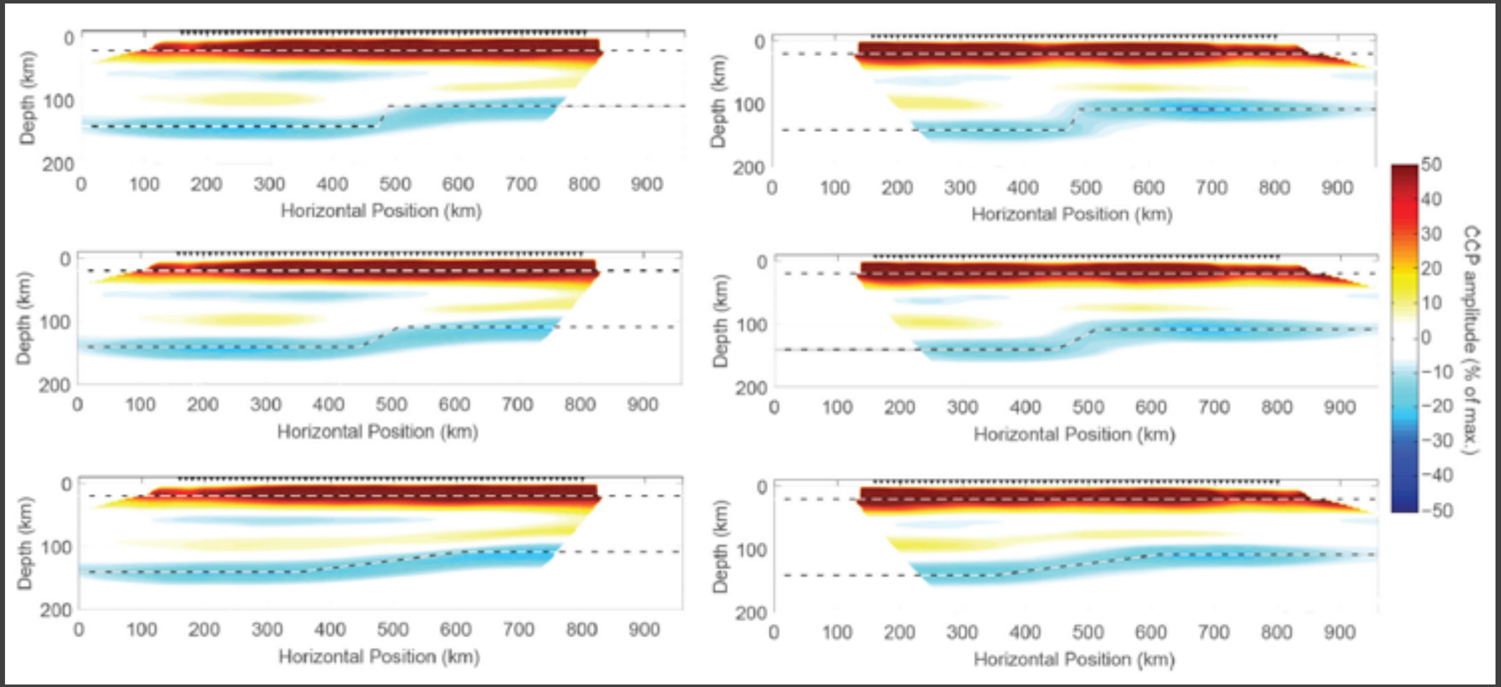



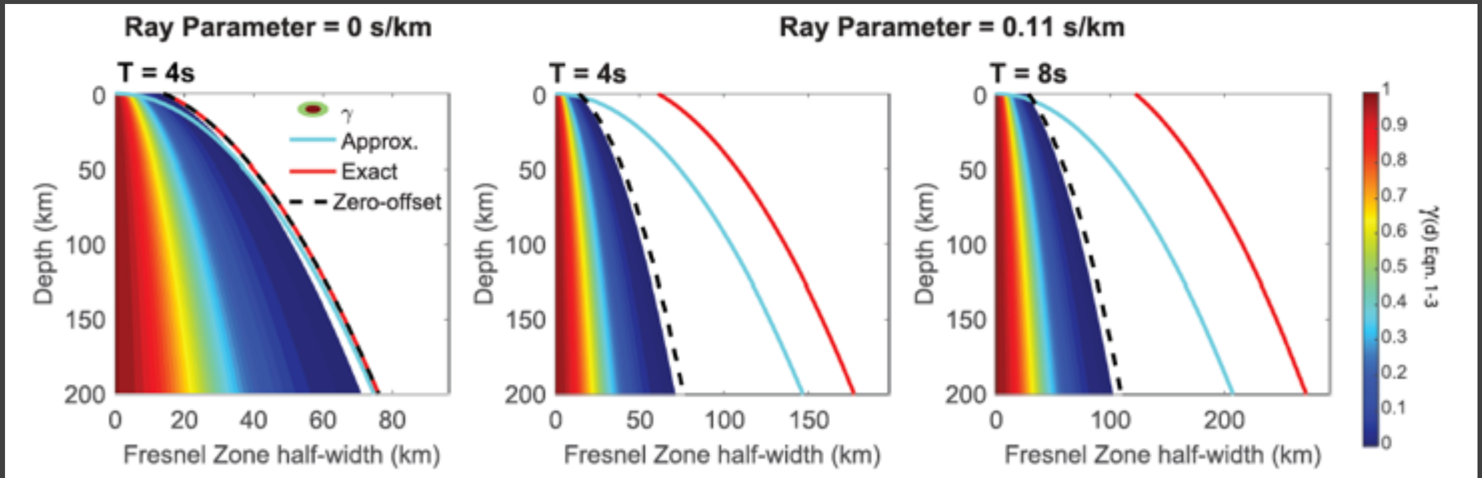
# Introducing complexity



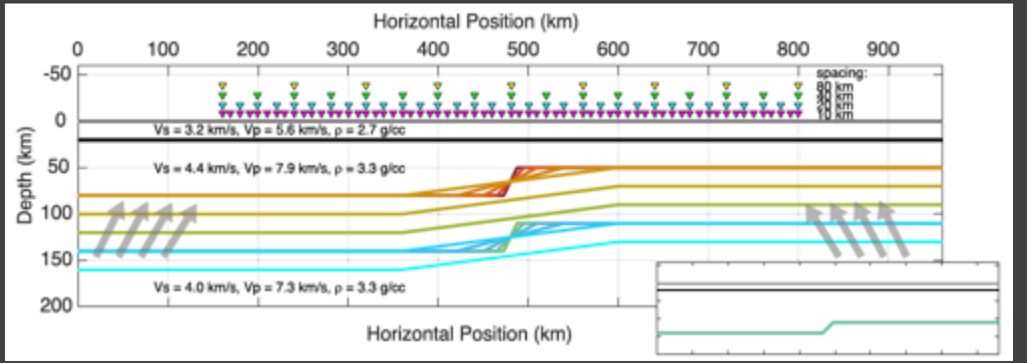



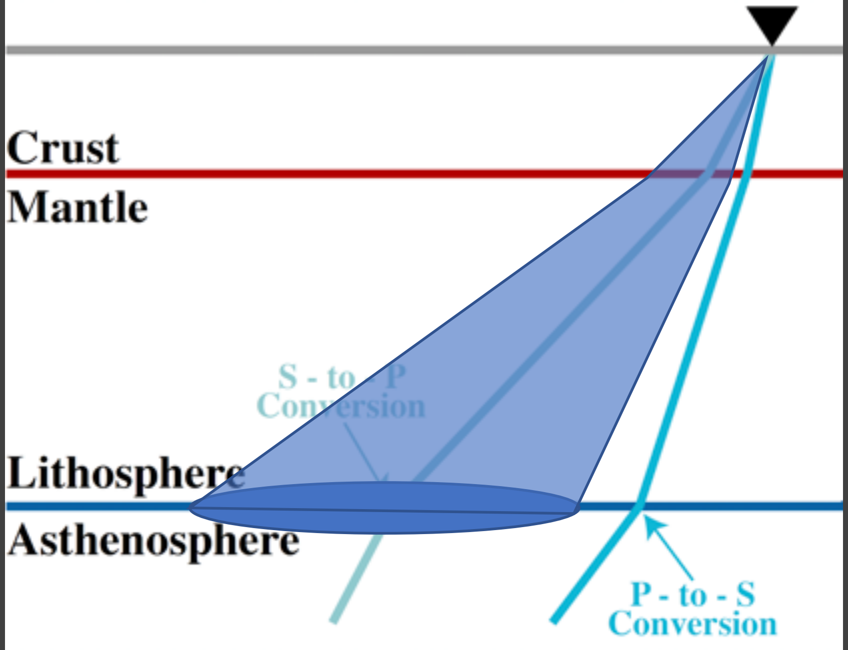

Sensitive to off ray path structure!!



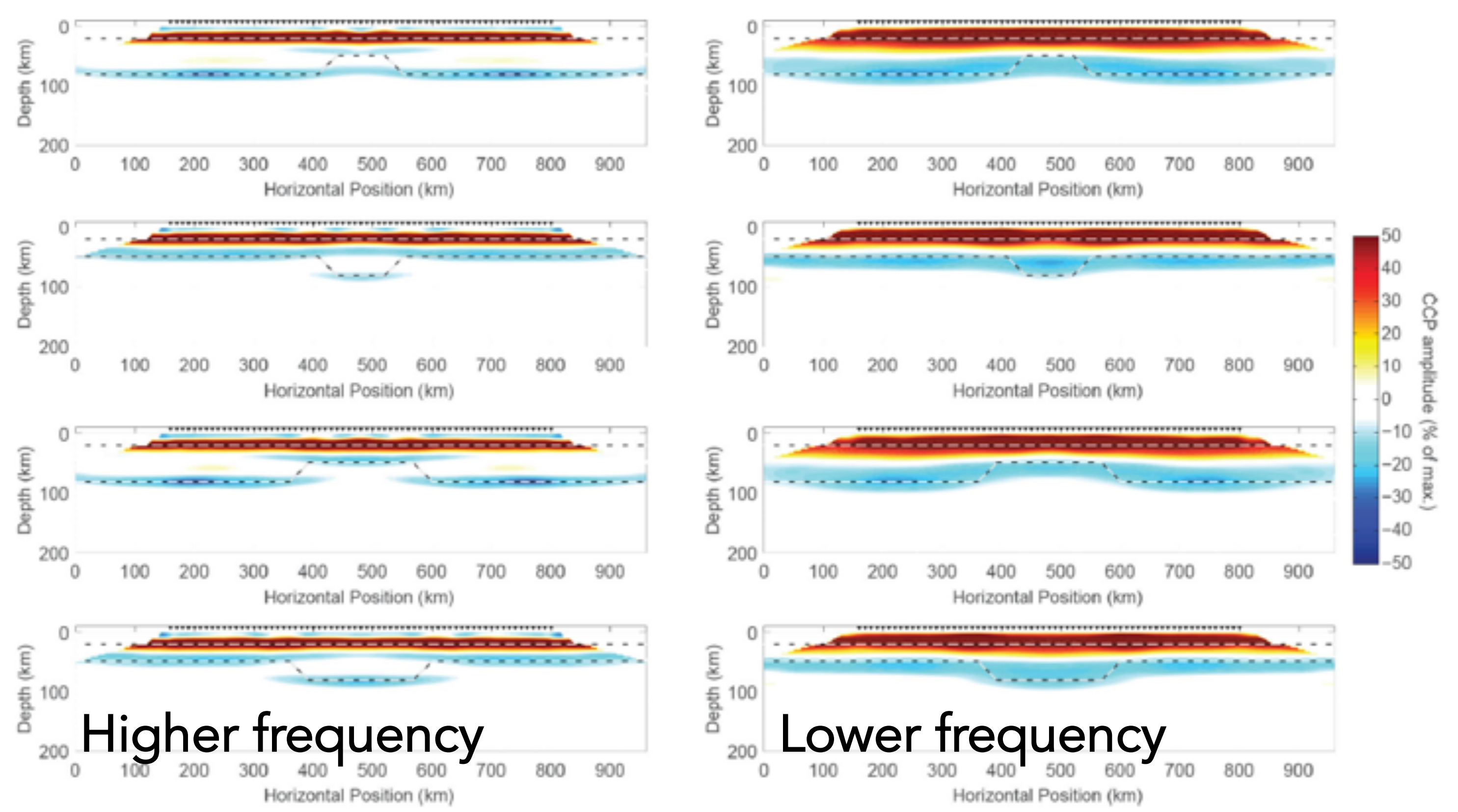



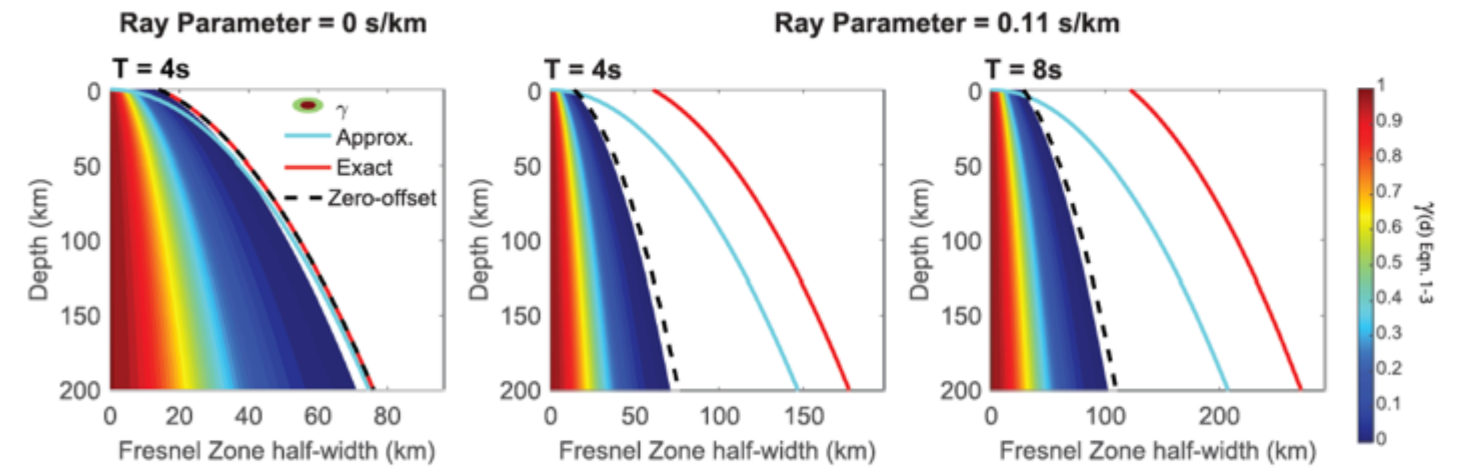
# Introducing complexity



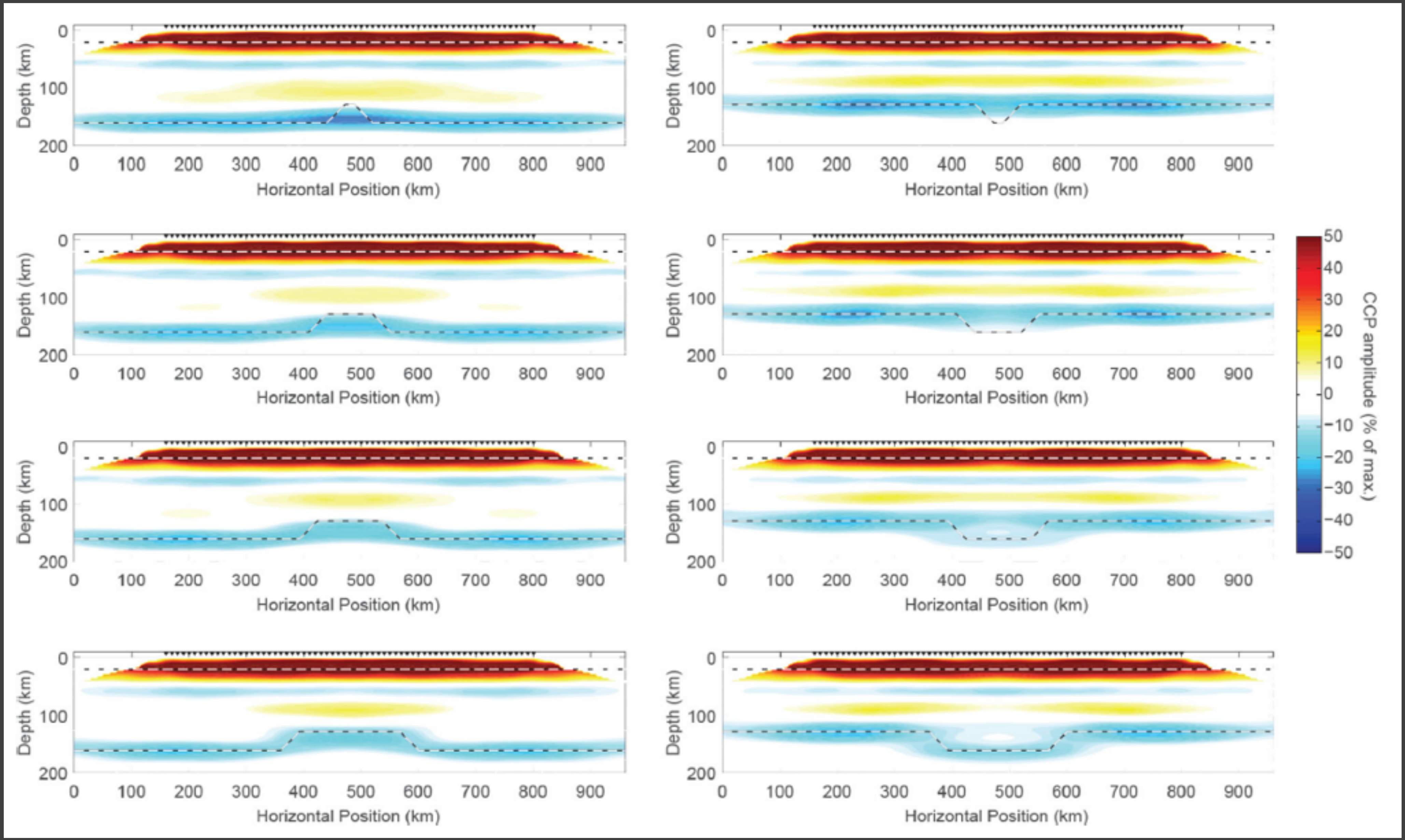




Longer periods unable to resolve fine scale structure



# Introducing complexity



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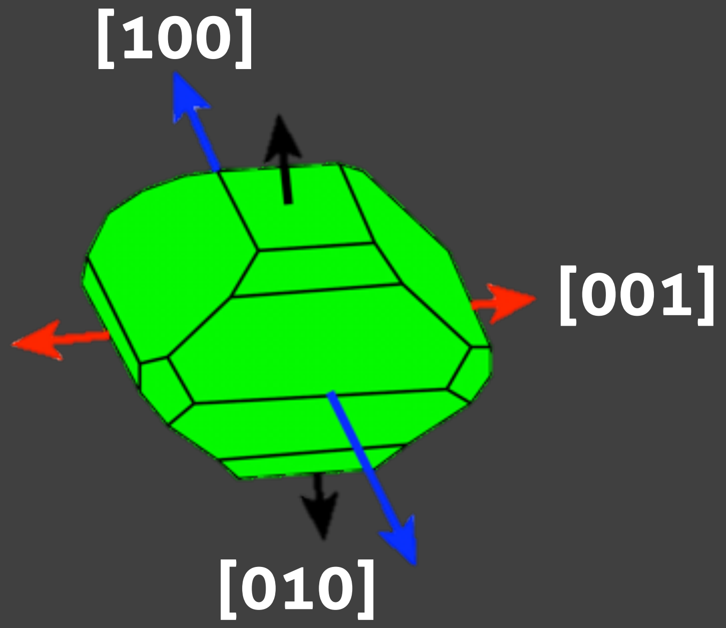
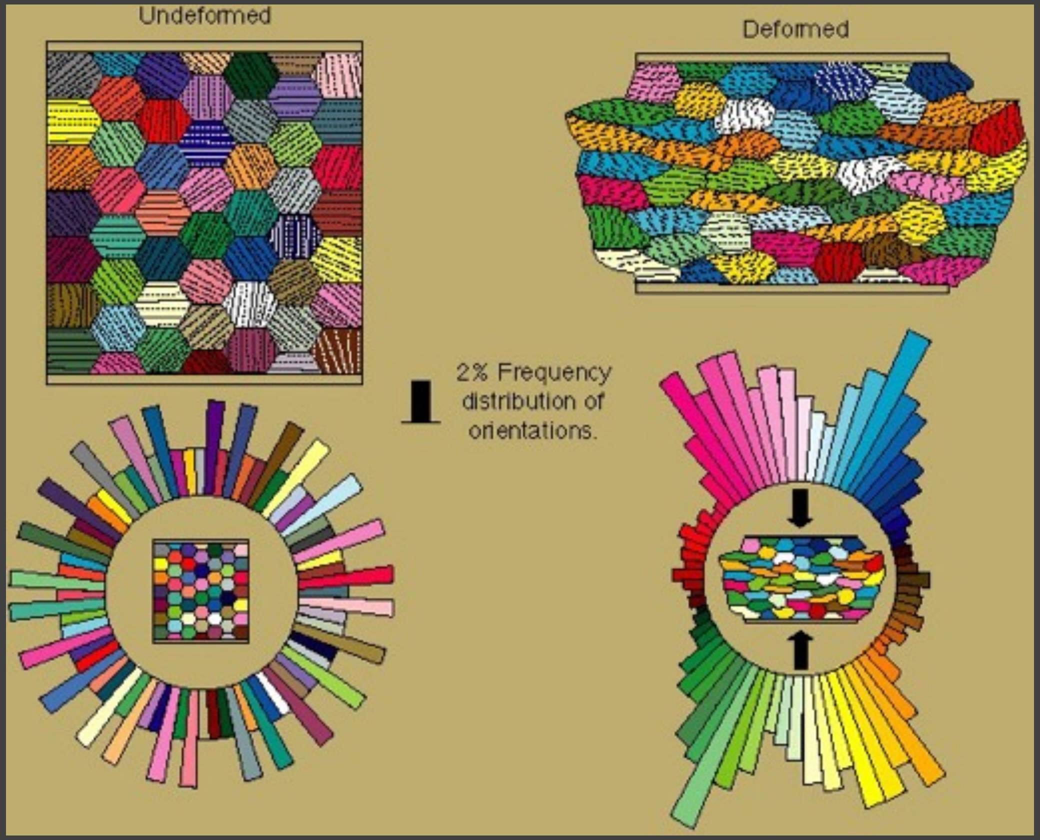
# Receiver functions and anisotropy

## What causes seismic anisotropy? (Polycrystalline)




Lattice Preferred Orientation (LPO) is one possibility




*B. Hacker, UCSB*

Commonly invoked in upper mantle
Proxy for mantle flow

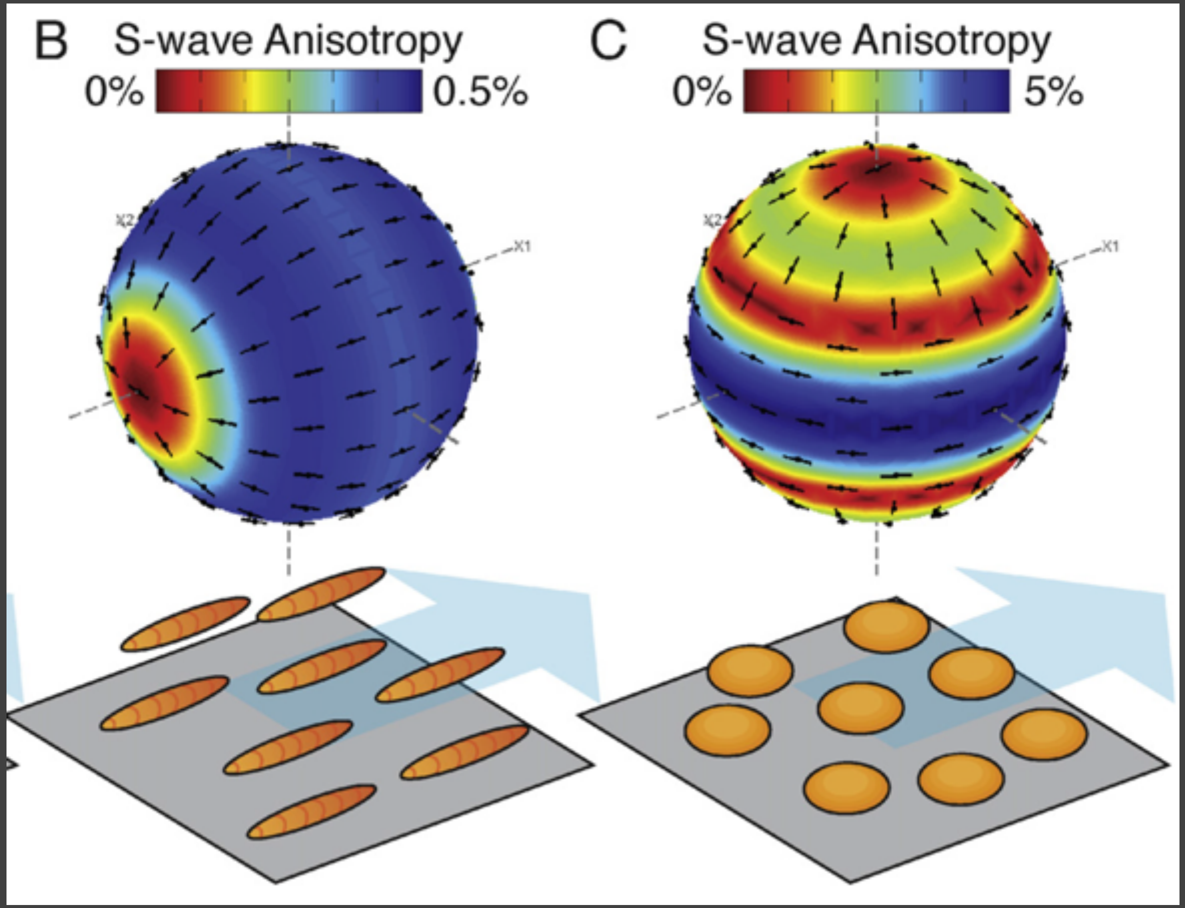
# Receiver functions and anisotropy

## What causes seismic anisotropy? (Polycrystalline)

Shape Preferred Orientation (SPO) is another possibility

Sub-wavelength layering or ordering of materials with varying seismic velocities

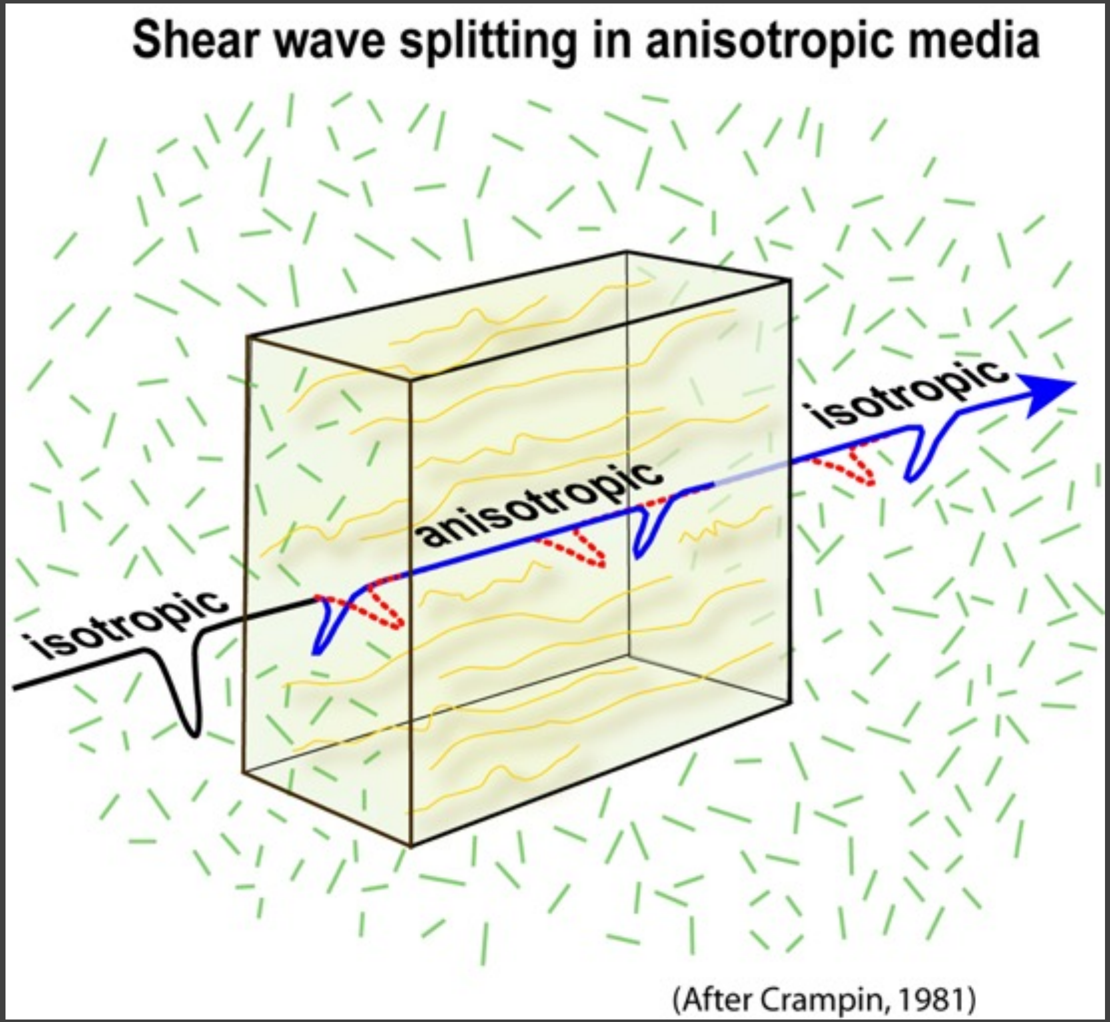
Possibilities:
Layering of distinct materials, cracks, alignment of melt



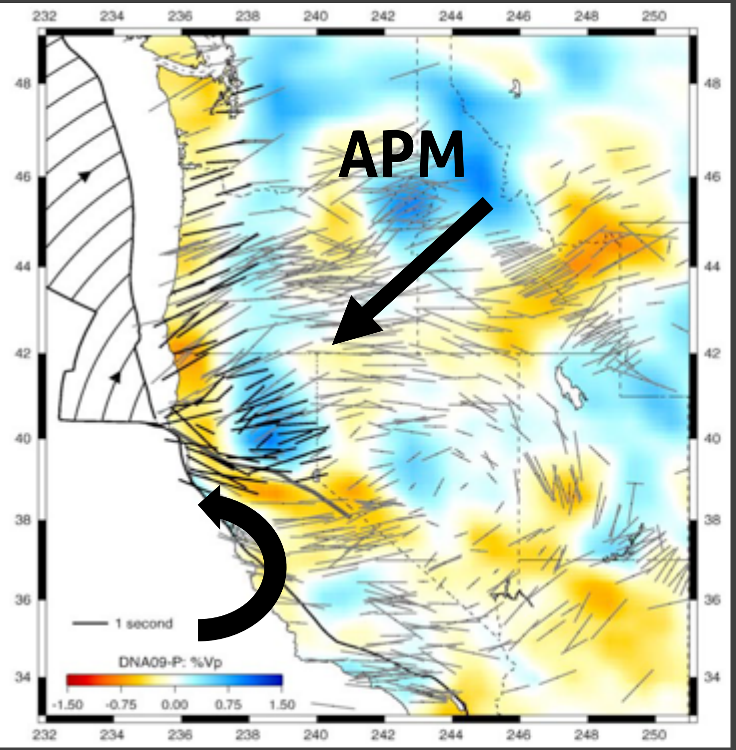

*Nowacki et al. (2011)*

# Receiver functions and anisotropy

Measuring Anisotropy: Shear wave splitting



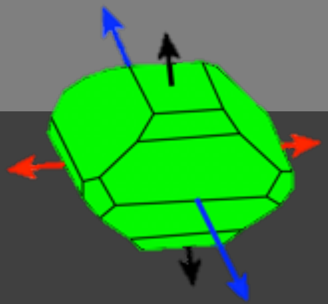

Used to assess "seismic birefringence"
Incident shear wave splits into two
Offset in arrival time and polarization direction are measured



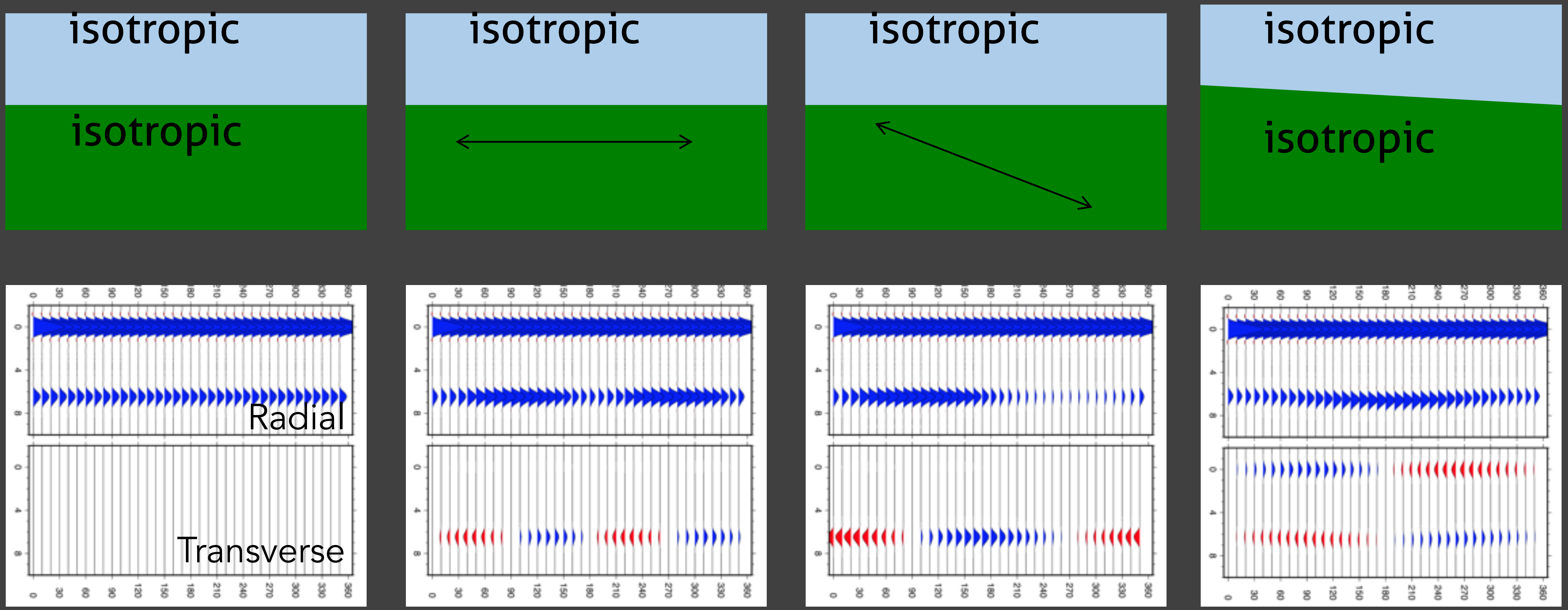

*Eakin et al., 2010*

Key observation: Splitting direction often aligned with direction of plate motion
…but not always

# Receiver functions and anisotropy



Measuring Anisotropy: Ps Receiver functions



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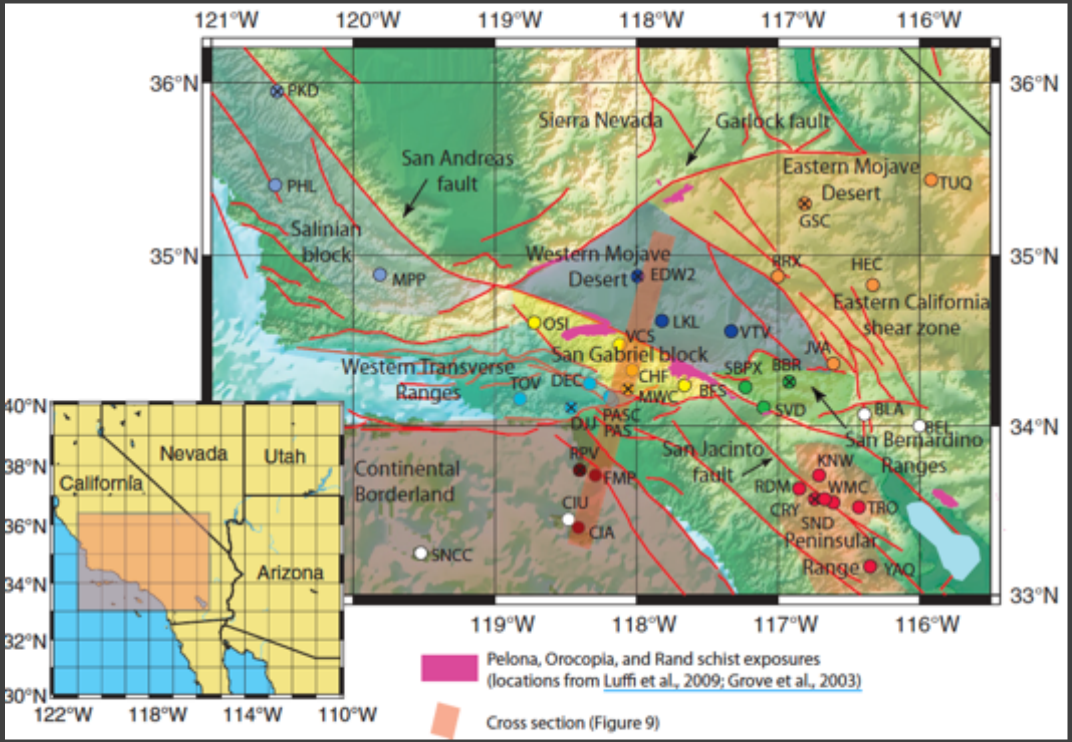
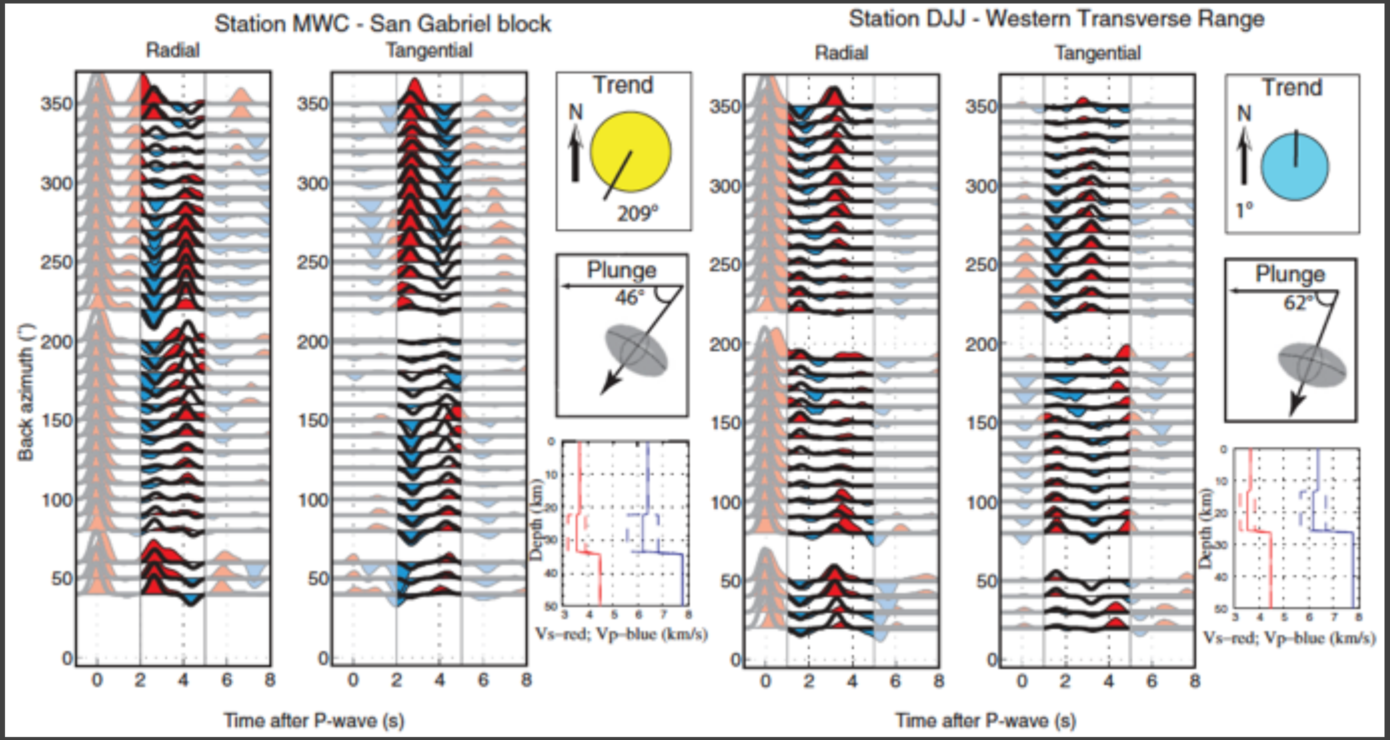
Measuring Anisotropy: Ps Receiver functions

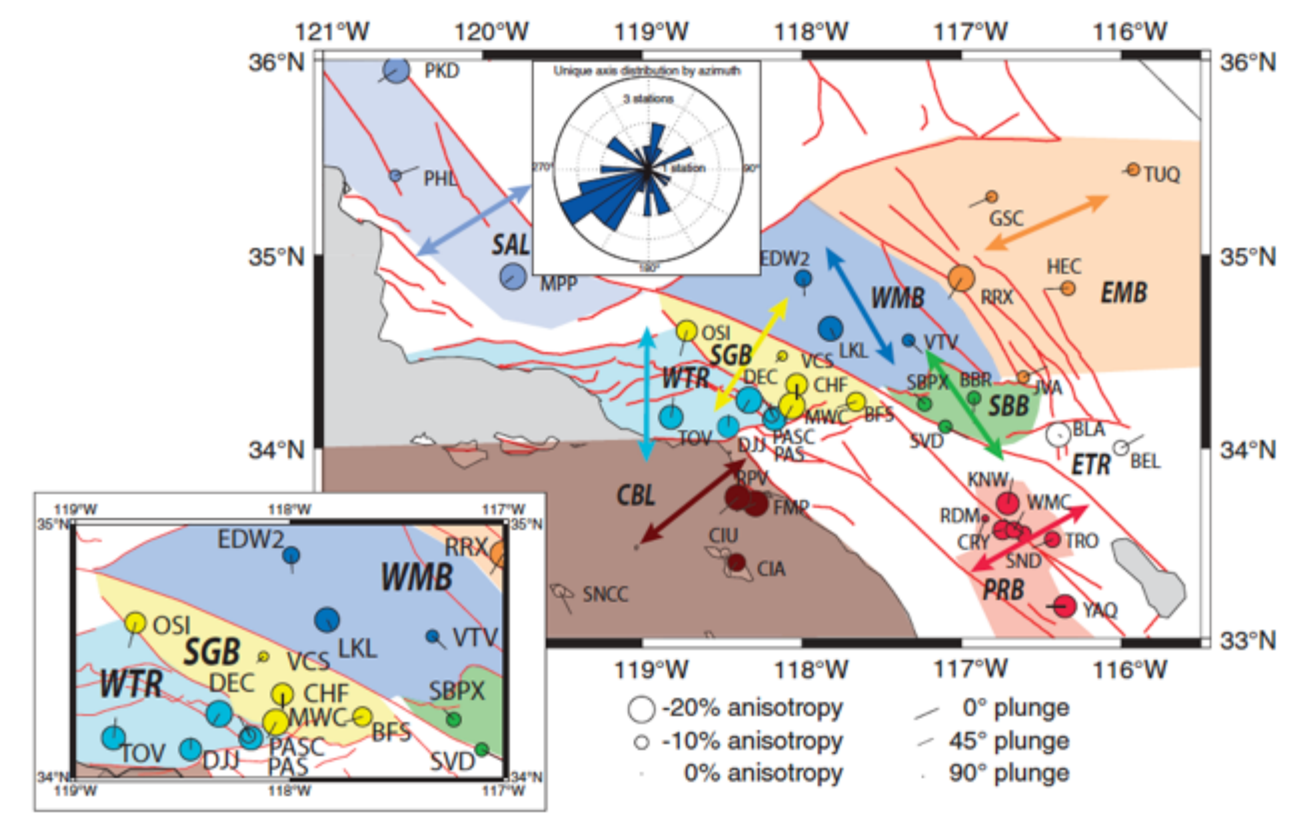


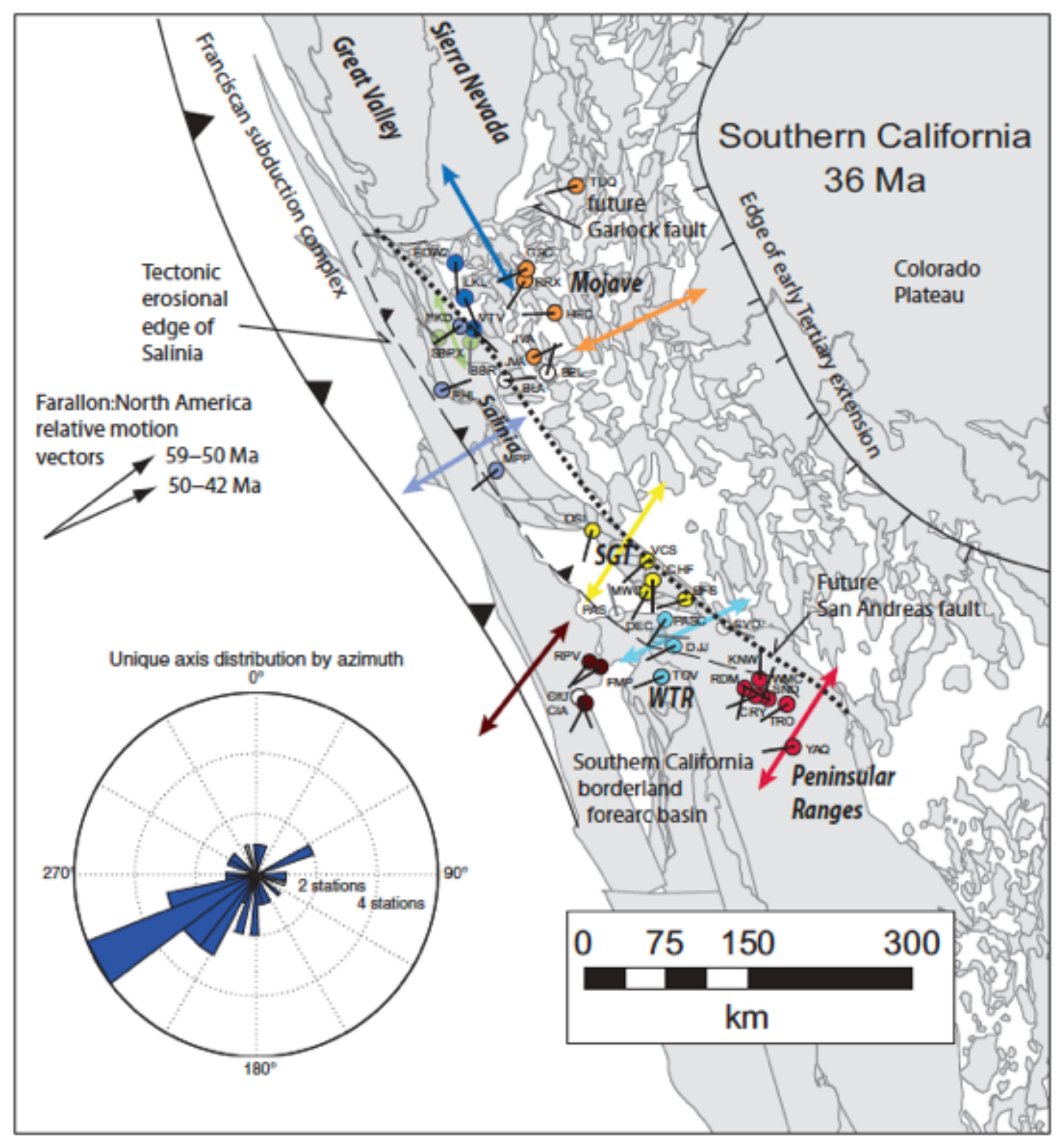

*Porter et al. (2011)*

# Receiver functions and anisotropy

## Measuring Anisotropy: Ps Receiver functions




*Porter et al. (2011)*



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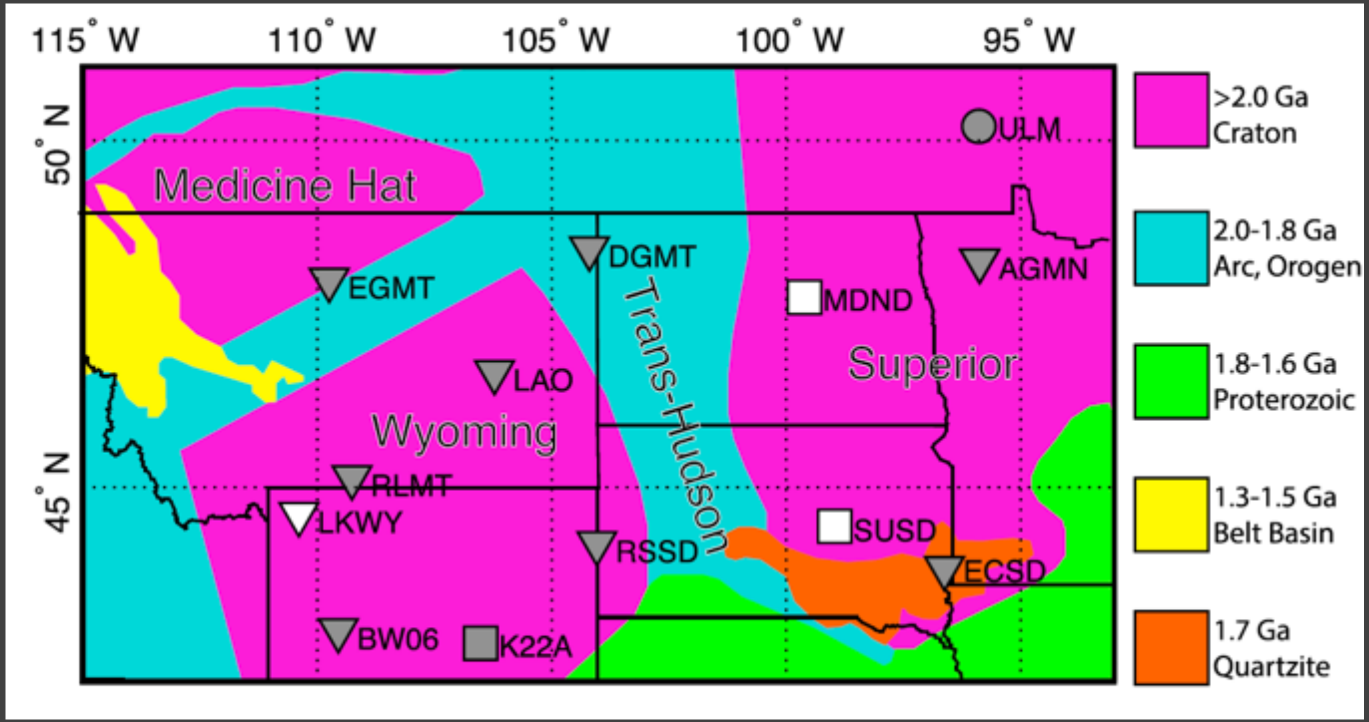
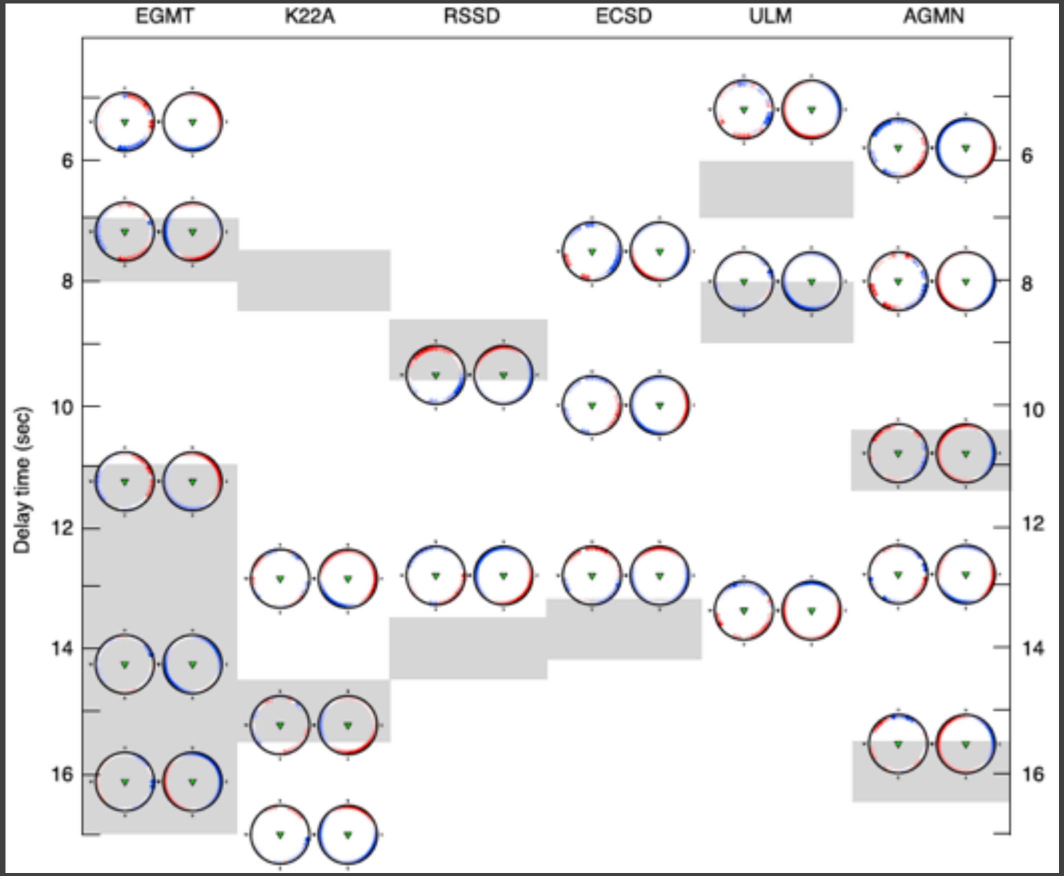
Measuring Anisotropy: Ps Receiver functions



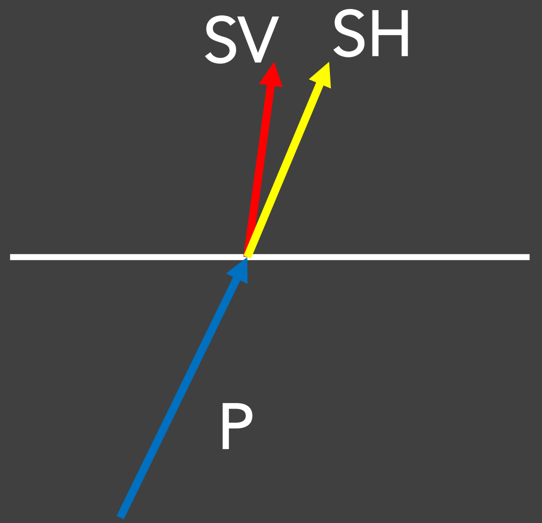




*Ford et al (2016)*

Receiver functions generally do not support the notion that MLDs are through going boundaries in anisotropy. Anisotropy is complex and local.

# Receiver functions and anisotropy

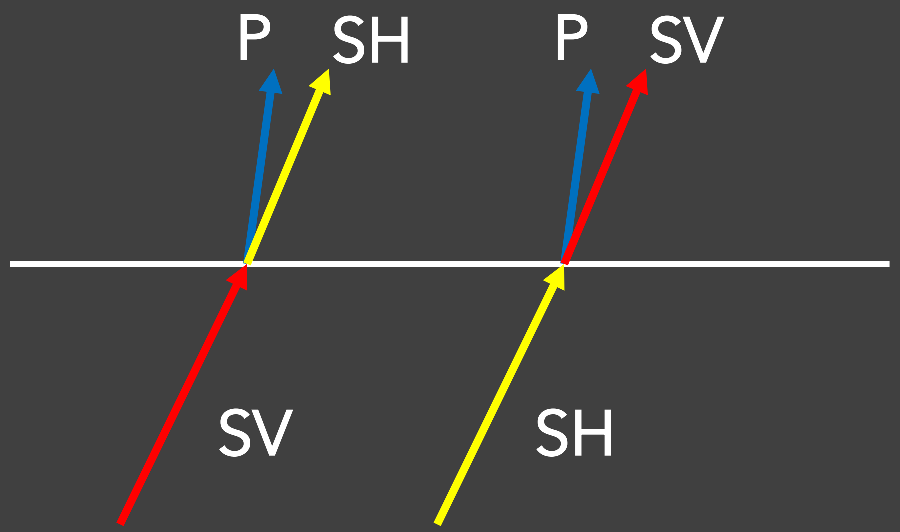
Measuring Anisotropy: Sp Receiver functions




Significantly less straight forward:

- Sp RFs tend to be noisier, and data is more limited, making it difficult to observe small variations in amplitude across a sufficient range of backazimuths. Analysis can only be employed at long running stations.
- Must consider the effects of both SV → P and SH → P both in the transmission of energy and an anisotropic boundary, and in the deconvolution itself
- Different events have varying amounts of SV:SH energy. A ratio that must be accounted for.
- One solution is to consider using SKSp receiver functions

Deconvolution choices:
SV/P or SH/P



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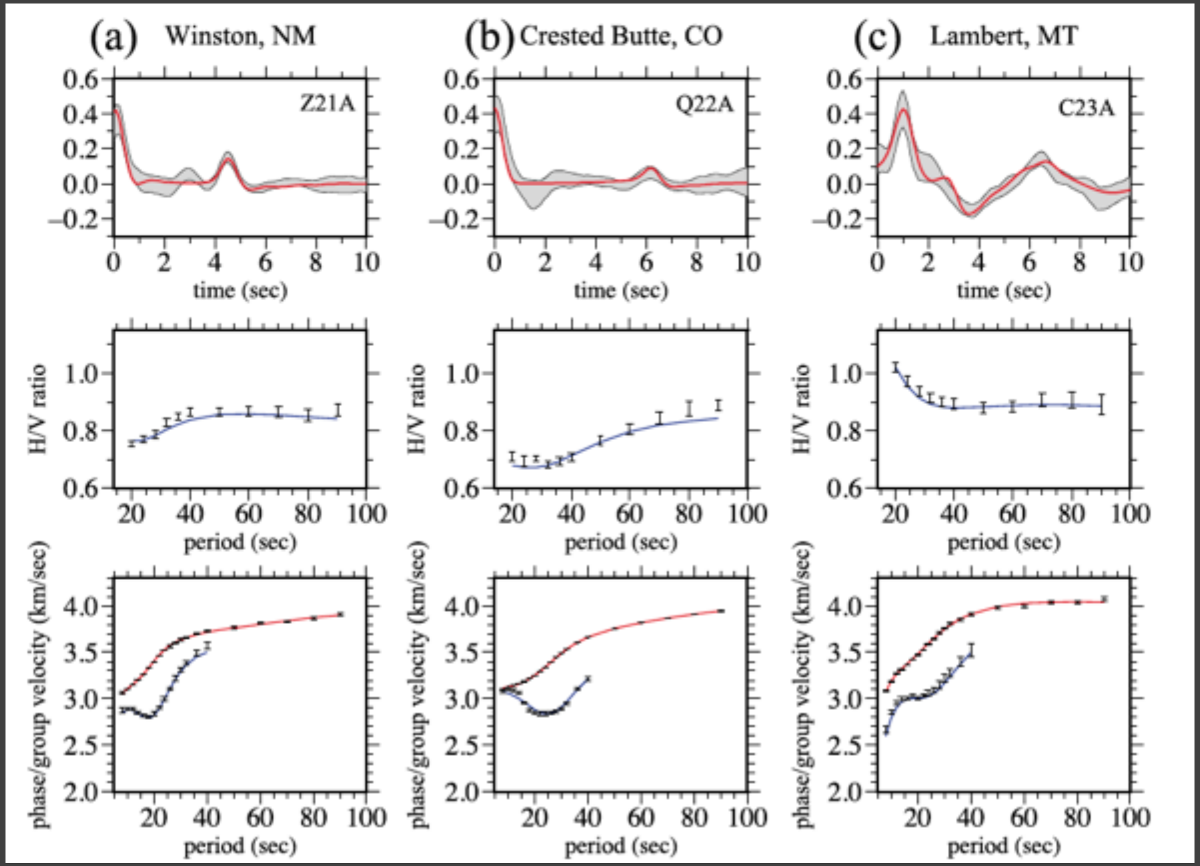
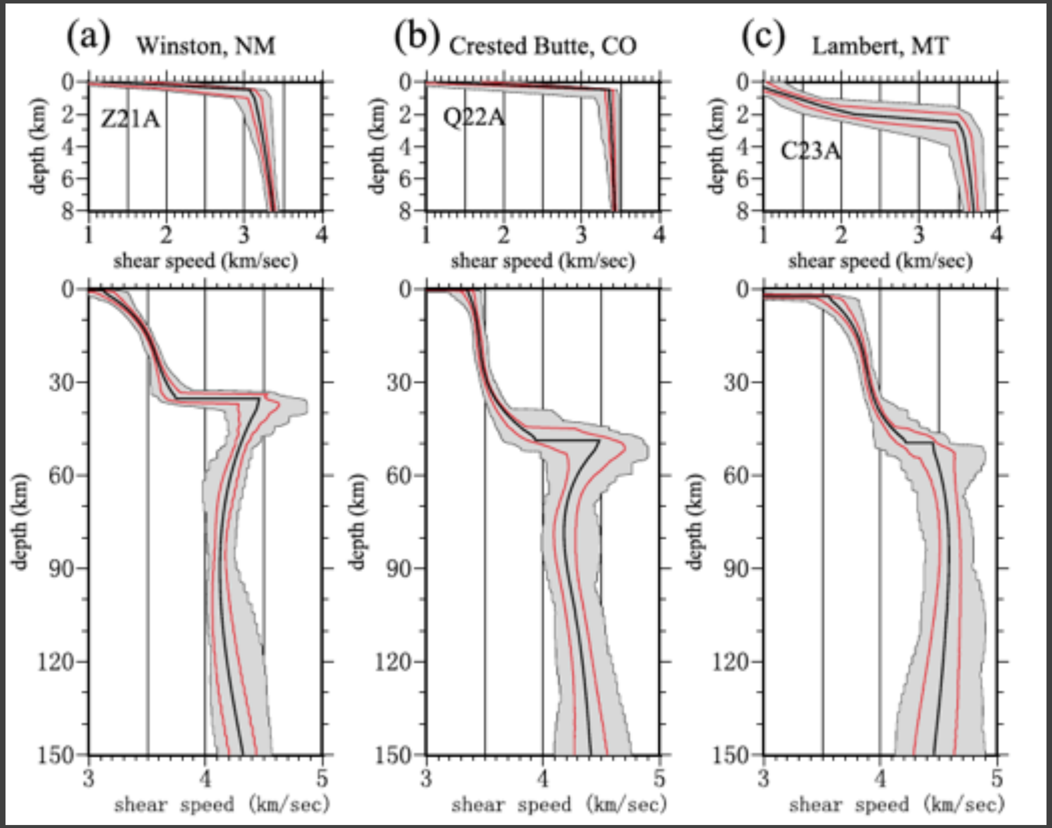
# Joint inversions

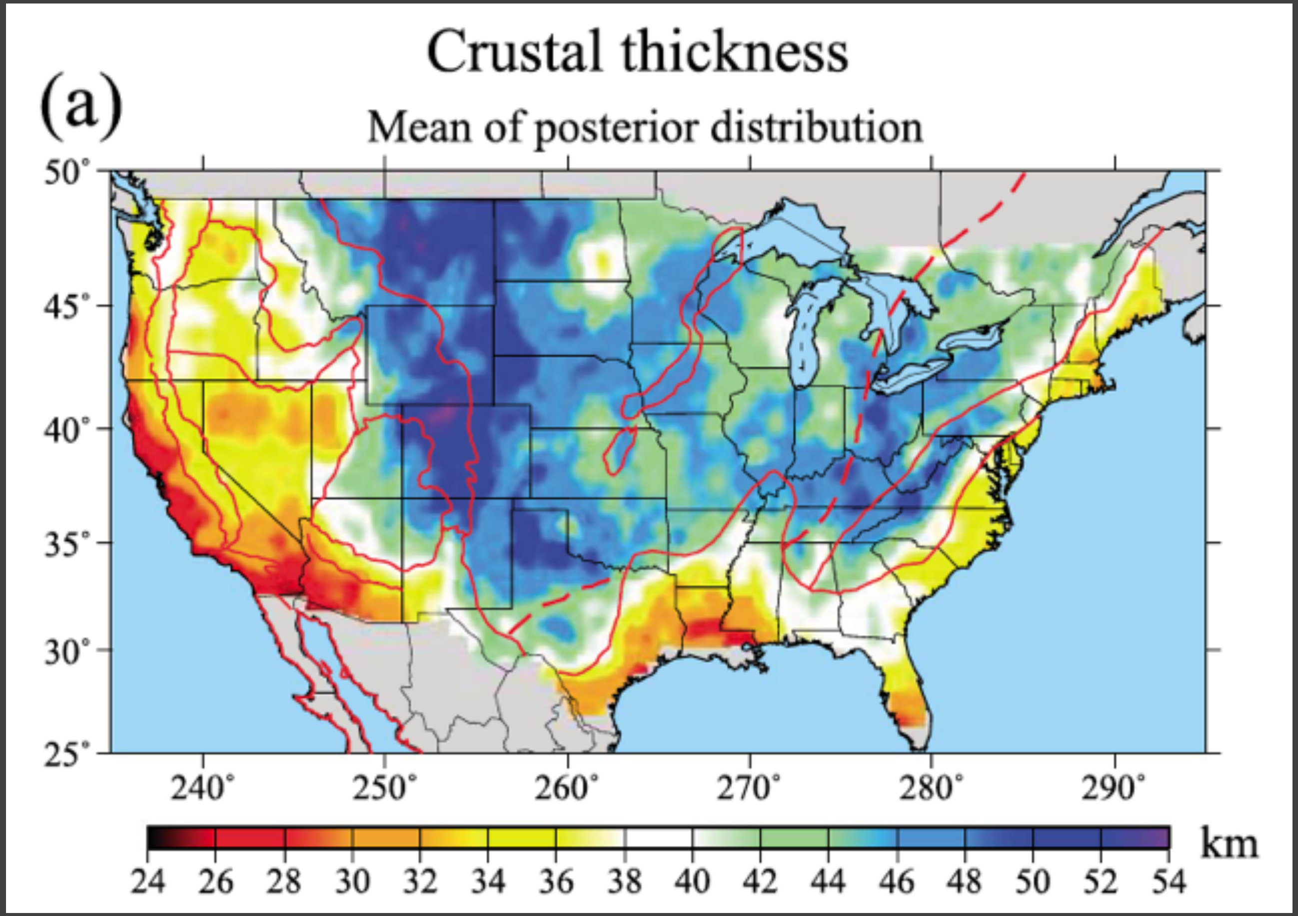



*Shen and Ritzwoller (2016)*

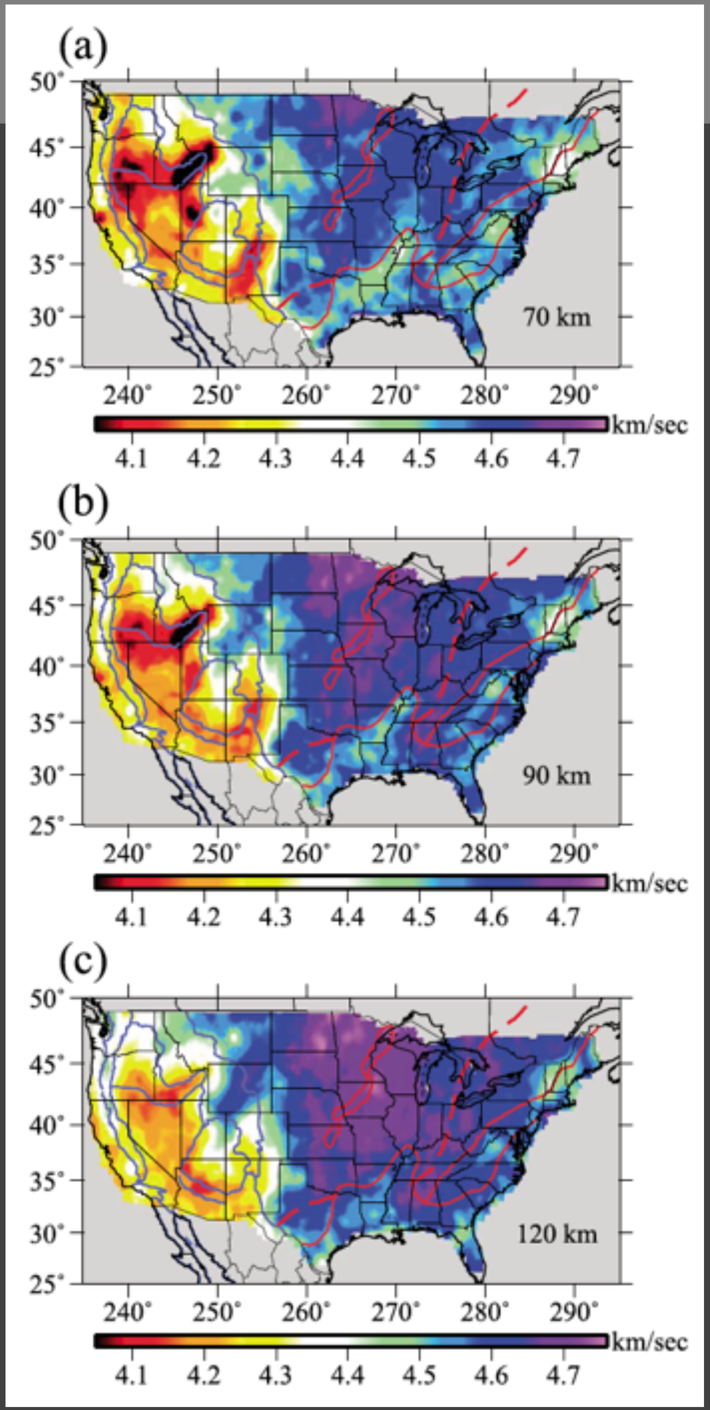



Including Ps receiver functions in seismic tomography models can help improve estimates in crustal thickness, prevent velocities from being mapped to incorrect depths

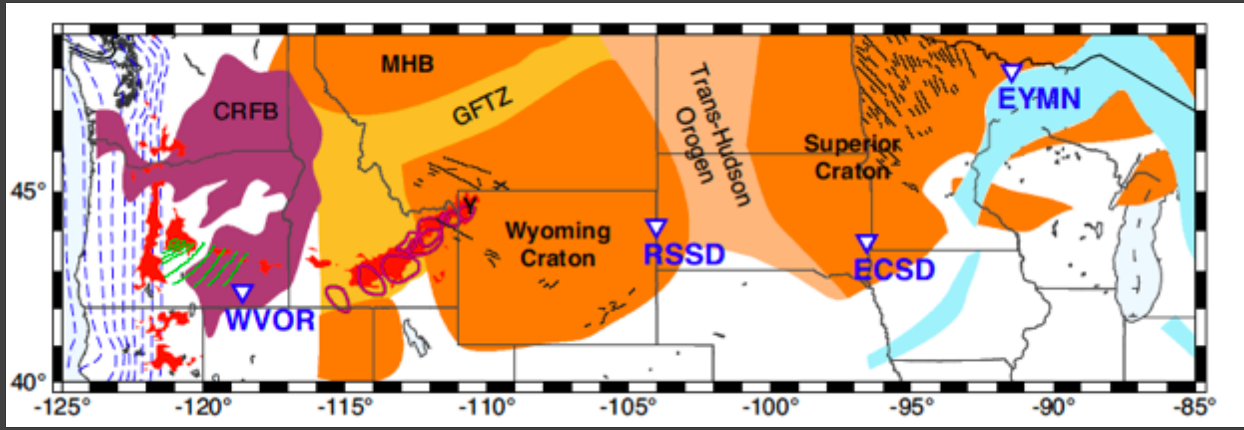
# Joint inversions

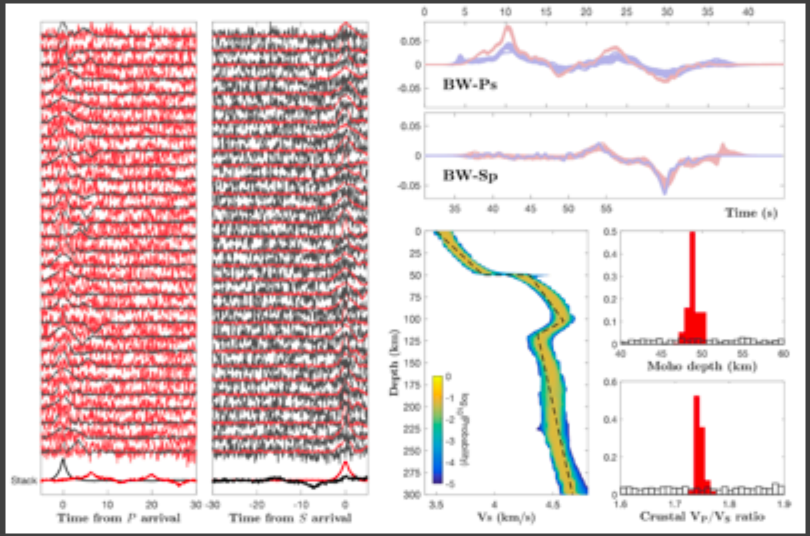


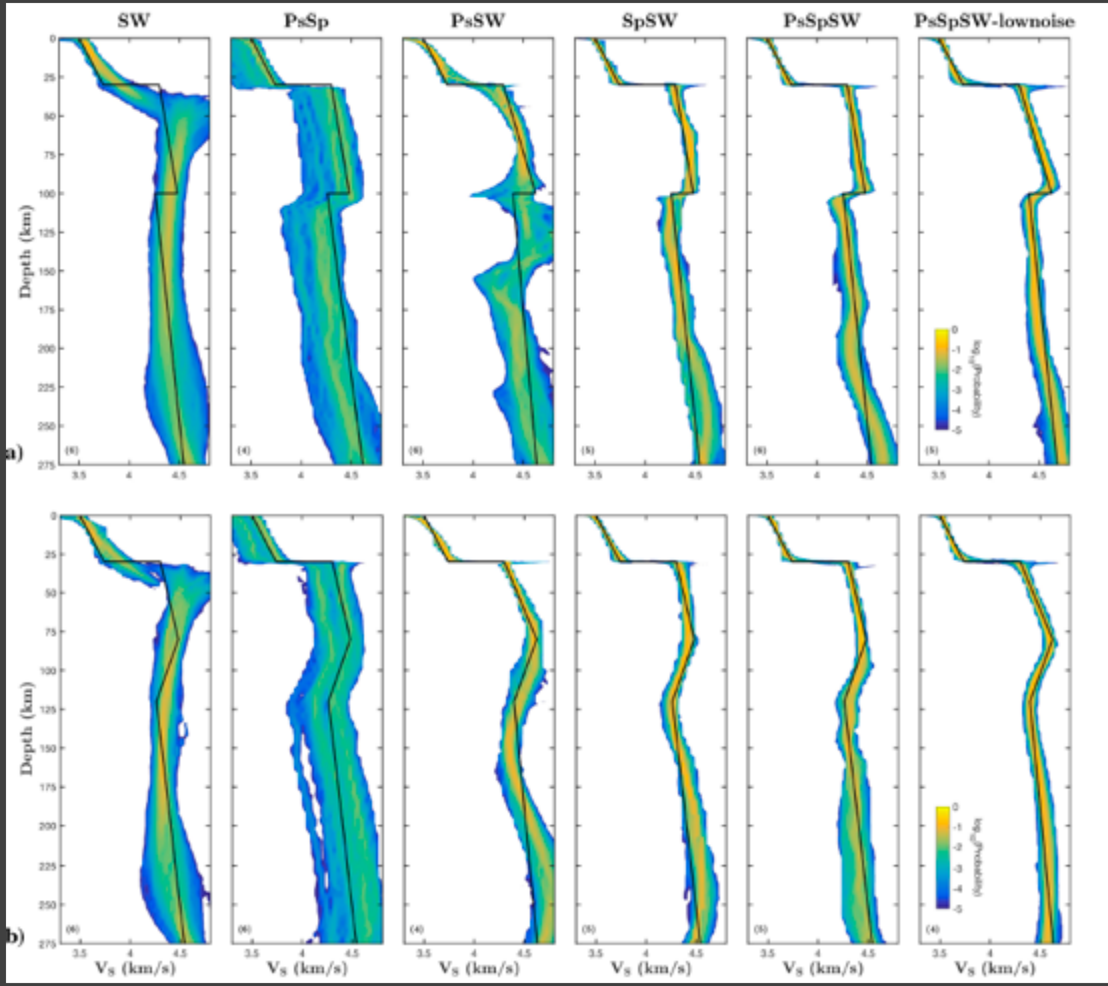

*Shen and Ritzwoller (2016)*



# Joint inversions



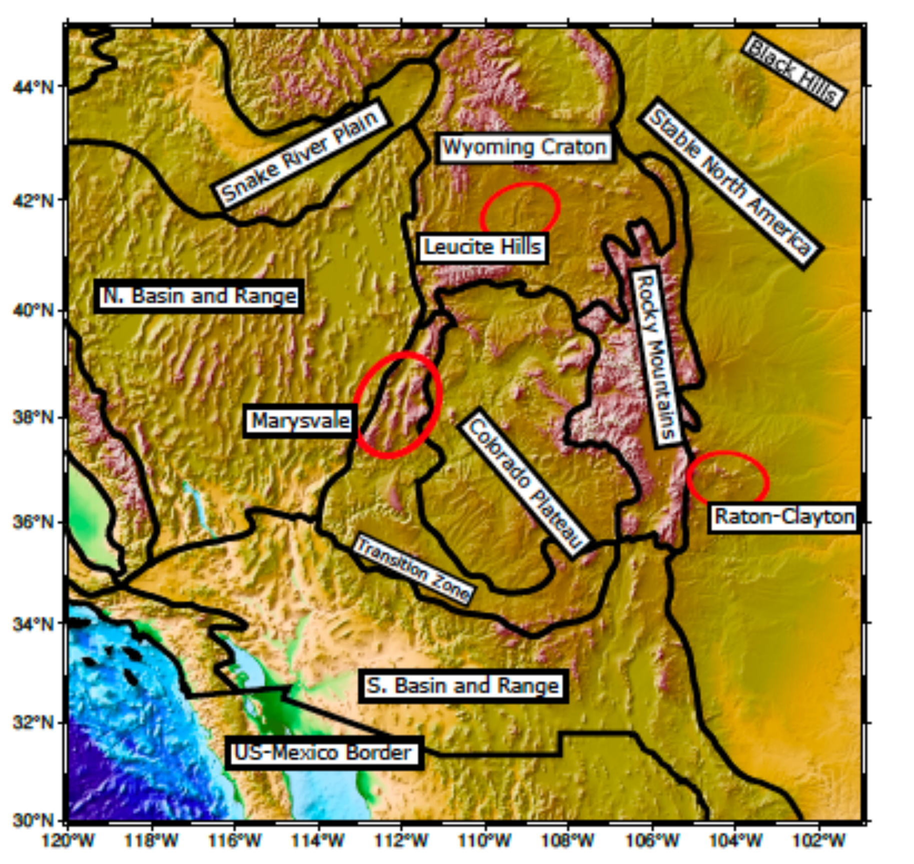



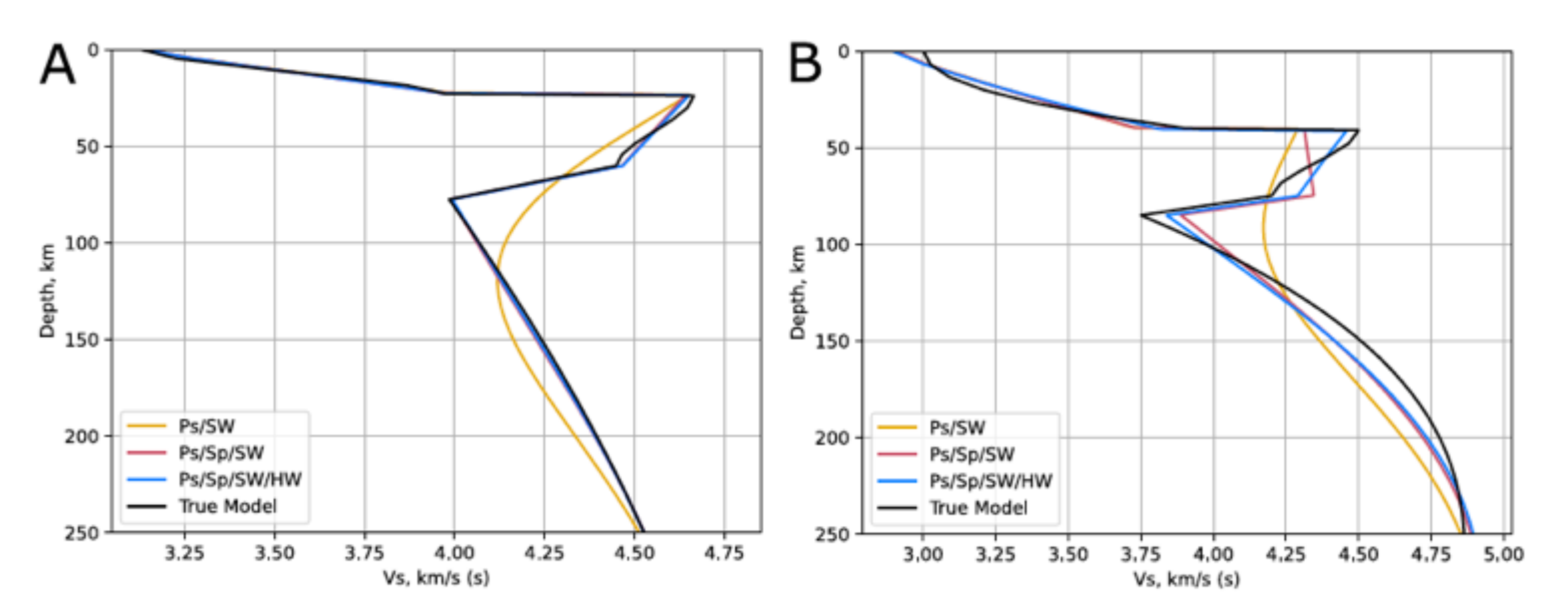




*Eilon et al. (2018)*

Ps and Sp converted phases are also being included in models designed to improve resolution of seismic structure in the upper mantle

# Joint inversions




*Byrnes et al. (2023)*

Ps and Sp converted phases are also being included in models designed to improve resolution of seismic structure in the upper mantle

# Body-wave constraints on lithospheric structure

Questions?