Photo courtesy of
Grant Clark

Body-wave constraints on lithospheric structure

Part 1: Introduction and methods

Introduction

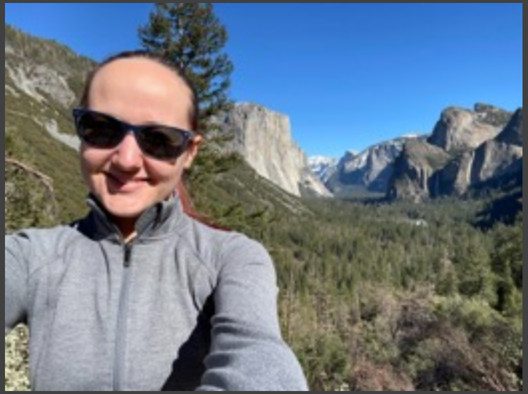
Heather Ford: Associate Professor of Geophysics, University of California Riverside
B.S. @ University of Michigan
MSc and PhD @ Brown University
Postdoc @ Yale University
Types of research: Interested in better understanding the tectonic evolution of continents using geophysics
Non-work stuff: First gen college student, single parent of two, enjoy rafting, camping, etc.

Introduction

Dr. Gillian Goldhagen
Graduated 2022
Now at EarthScope
Interested in education and outreach

Dr. Andrew Birkey
Graduated 2022
Postdoc at the Michigan State Univ.
Interested cratons; subduction; seismic anisotropy

Beth Shallon
Graduated 2022 (MSc)
3rd year PhD student
Interested in characterizing mantle properties with seismic imaging methods

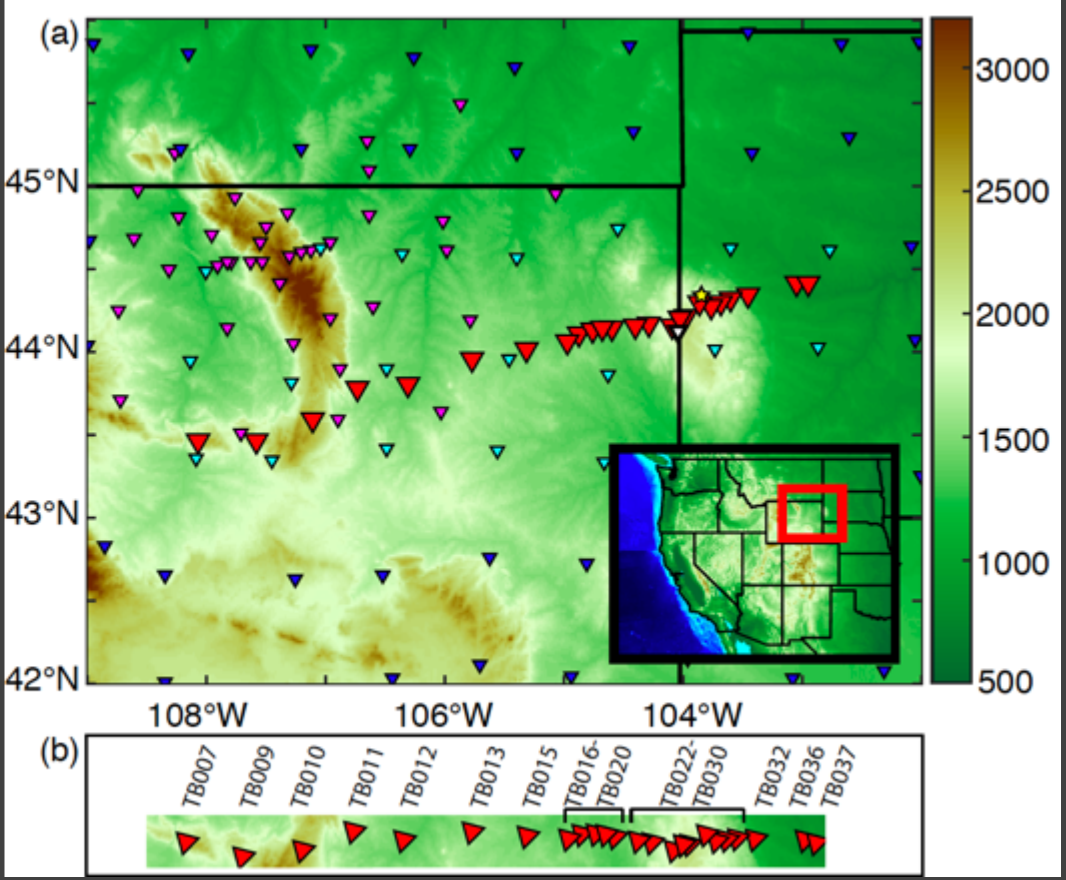


Ashley Stroup
2nd year PhD
Interested in crustal deformation and relating geology to geophysics

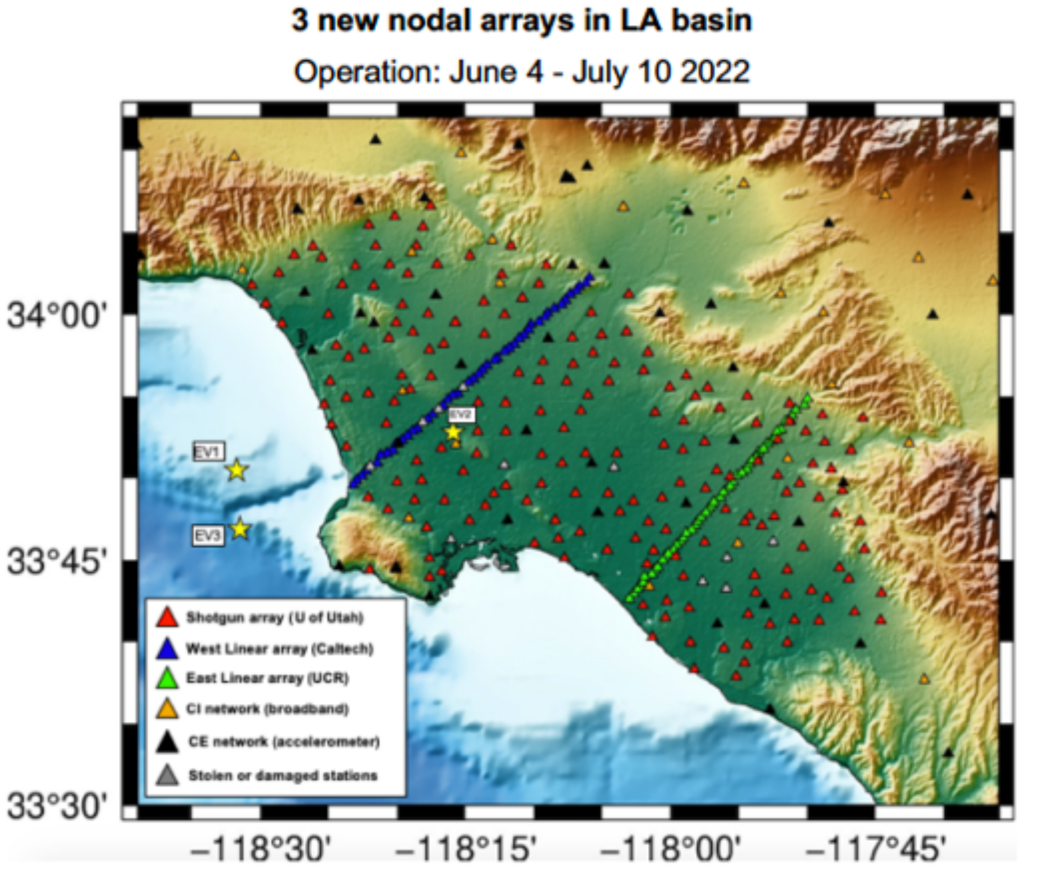
Delton Samuel
1st year PhD
Interested in crustal structure and planetary seismology

+ numerous (awesome!) undergraduate students and interns

Introduction



Ford et al. (2021)


3 new nodal arrays in LA basin

Operation: June 4 - July 10 2022

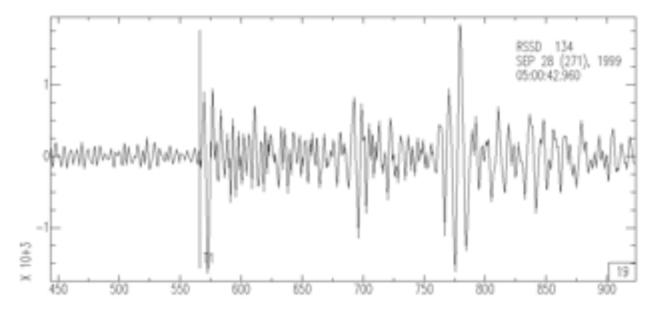
Lin et al. (in prep, SRL)

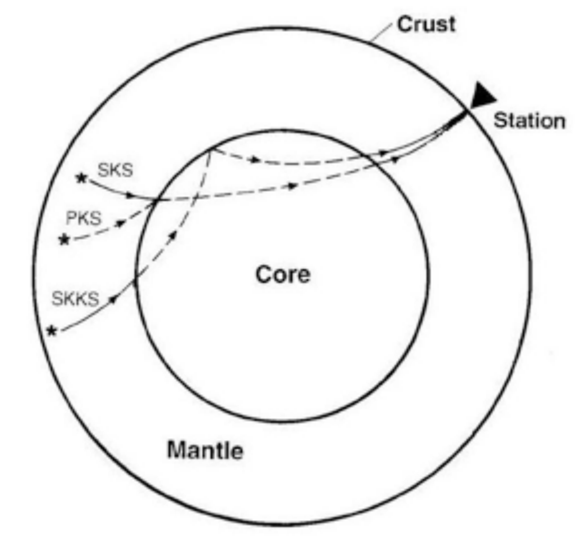
Introduction

Data: Seismograms of teleseismic earthquakes

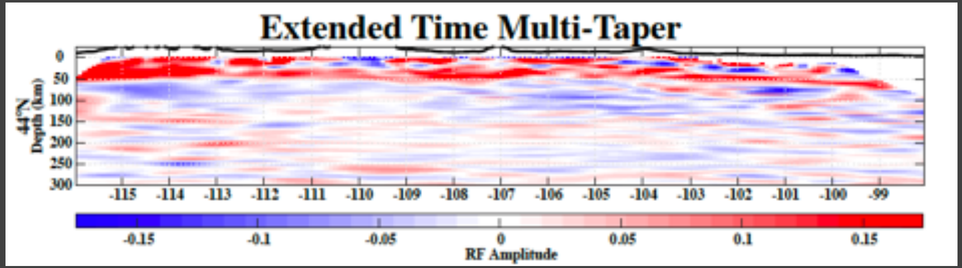
Methods: Variety of techniques

Results: "Images" of seismic structure



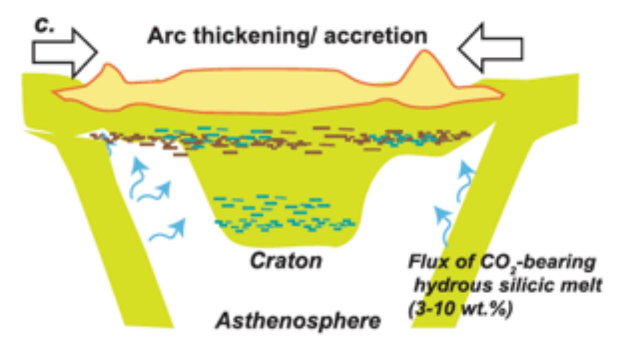


Methods	Targets
Ps receiver functions	Crustal Structure (Basins, Moho) Crust and Mantle anisotropy
Sp receiver functions	Lithosphere-Asthenosphere Boundary Mid-lithospheric discontinuities
Shear wave splitting	Upper mantle anisotropy Anisotropy of the lowermost mantle
Seismic Tomography	Upper mantle and crustal structure (volumes, not boundaries)
Seismic Attenuation	Upper mantle structure



Shallon et al. (in prep)

Interpretation: What do our results "mean"



Saha et al (2018)

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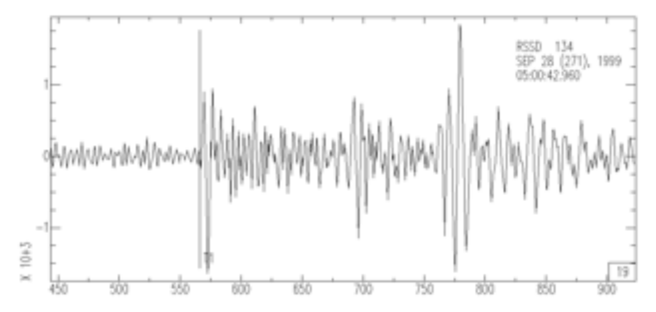

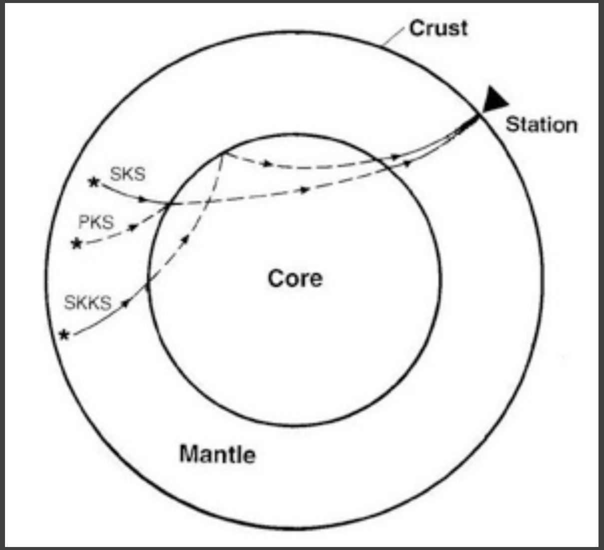

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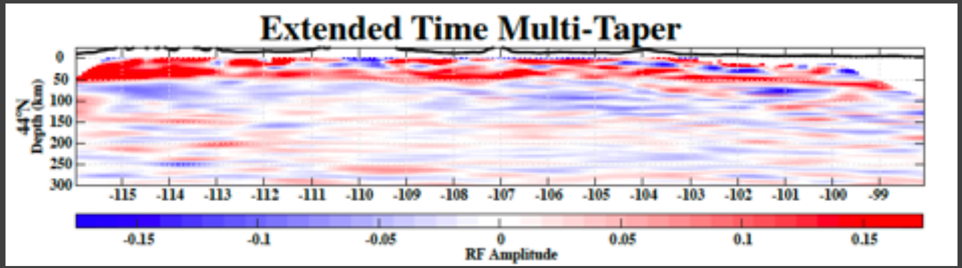

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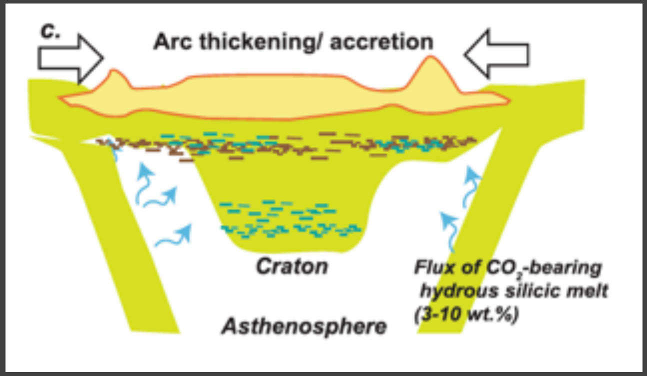
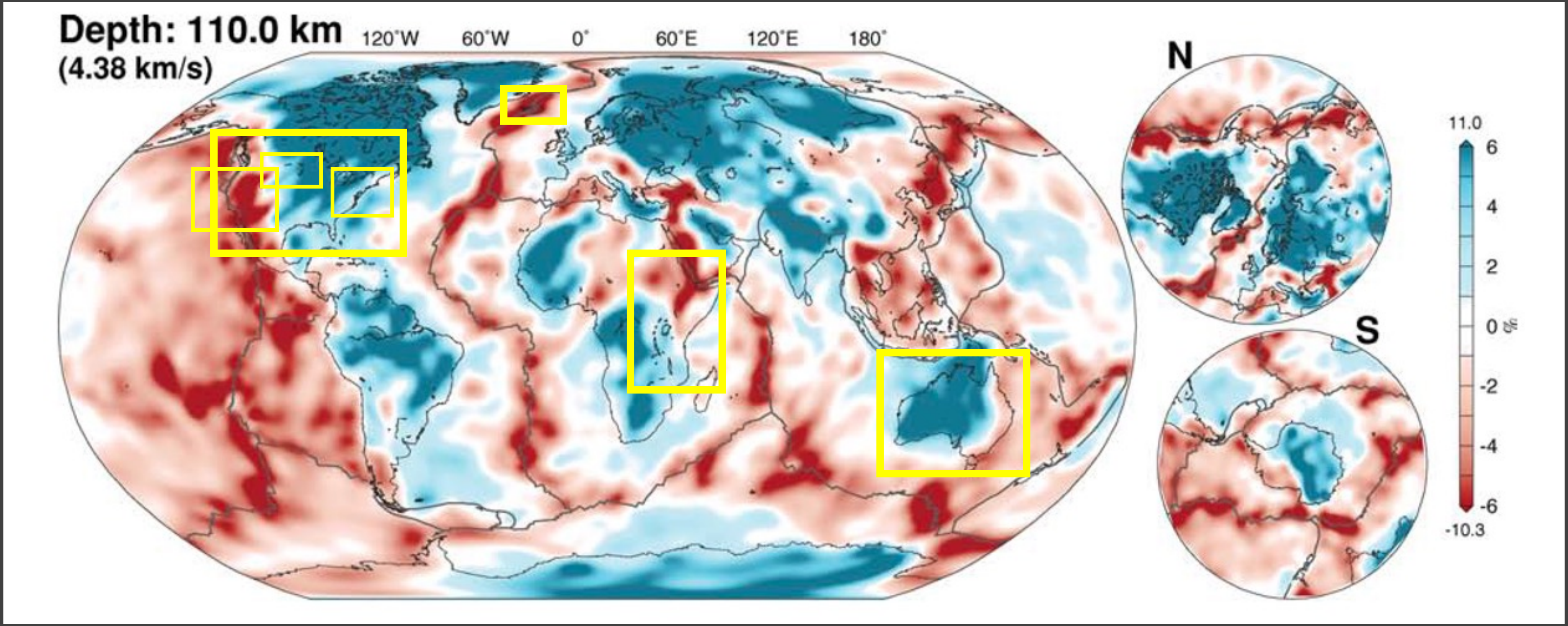


Saha et al (2018)

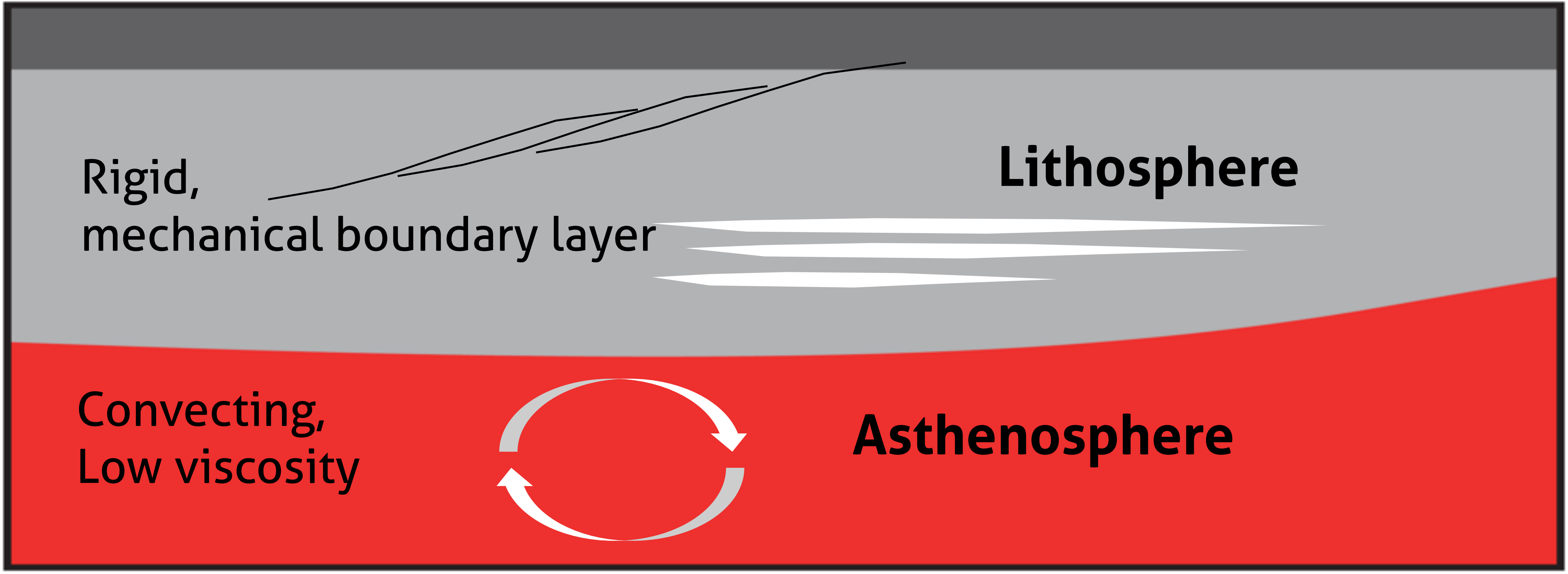
Focus of exercise

Introduction



Schaeffer and Lebedev (2013)

Introduction



Rigid,
mechanical boundary layer

Lithosphere

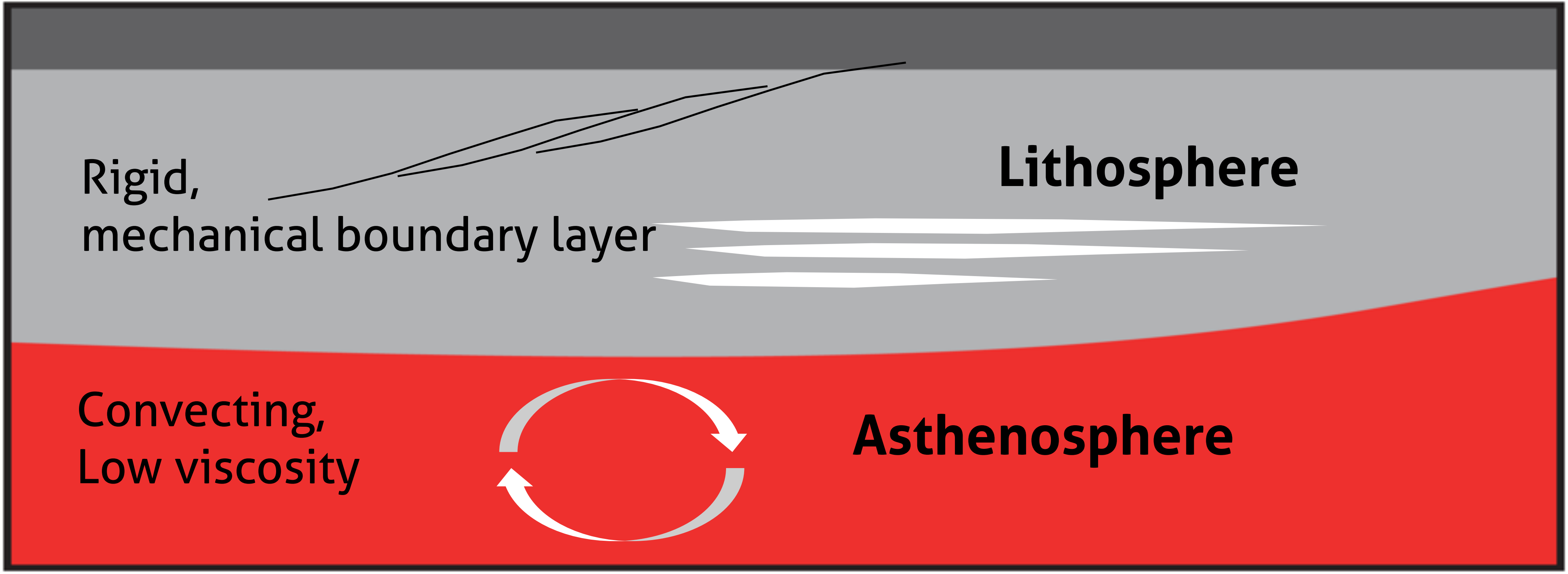
Convecting,
Low viscosity

Asthenosphere

"Barrell [1914] introduced the idea of a strong outer layer overlying a weak asthenosphere that could flow to maintain isostatic compensation."

- Anderson, 1995

Introduction

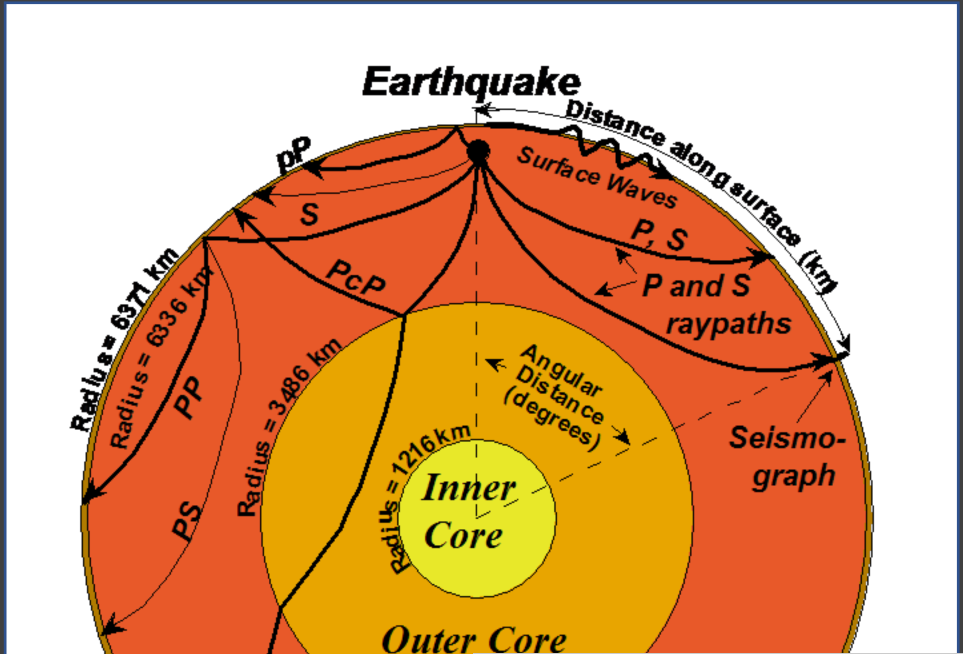


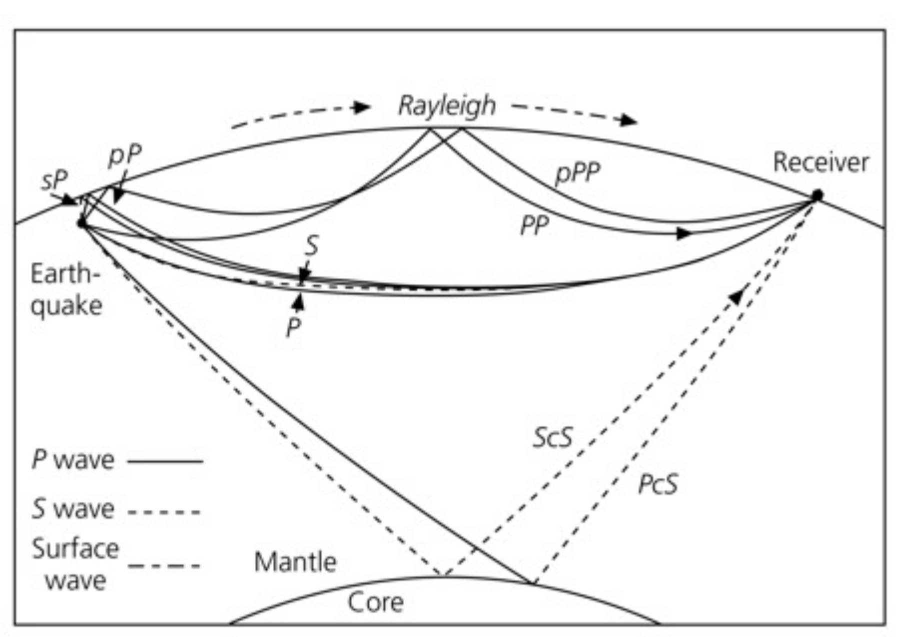
What can seismology tell us about the properties of the lithosphere:

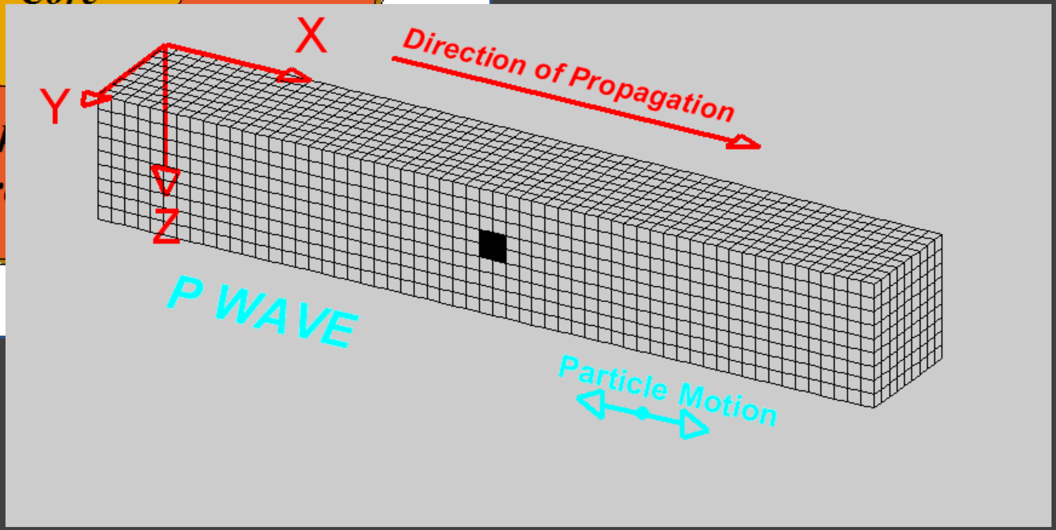
Temperature
Presence of melt
Hydration
Composition
Mineral alignment*

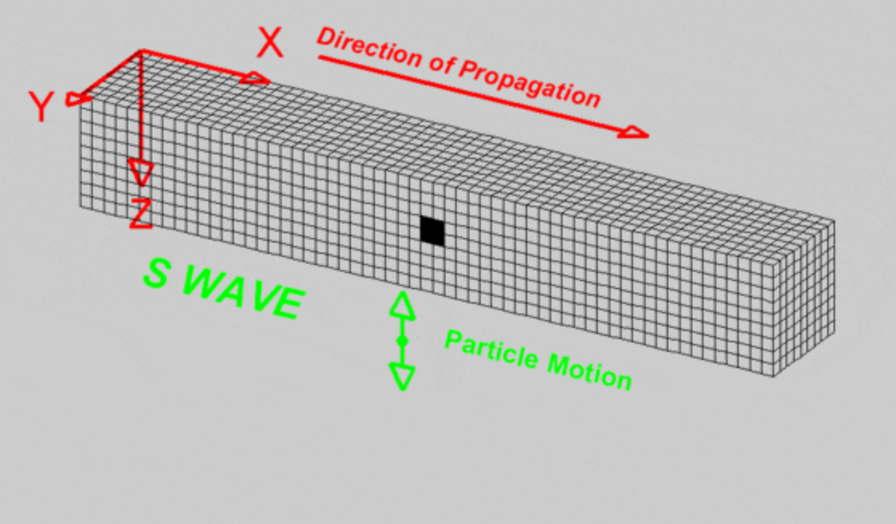
Tectonic & geodynamic processes can affect properties and structure, resulting in lateral and depth variations in seismic velocity

Introduction









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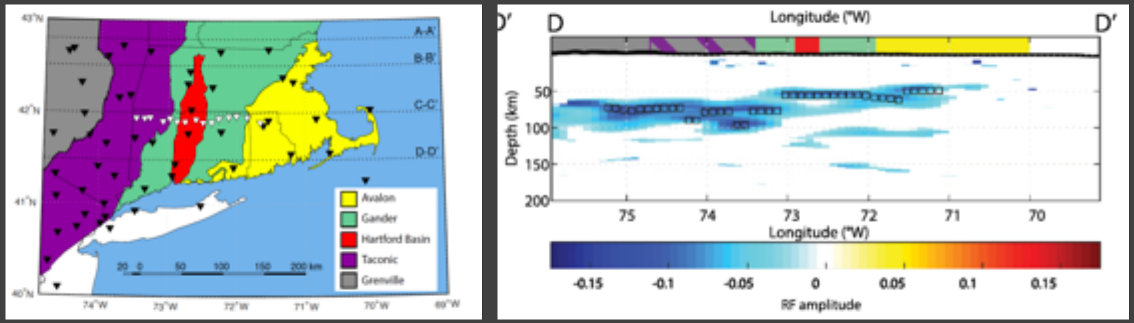
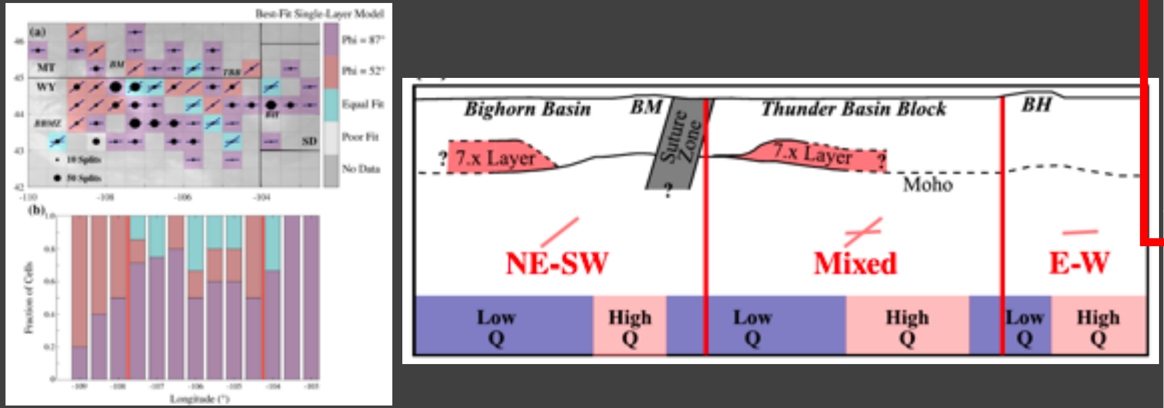
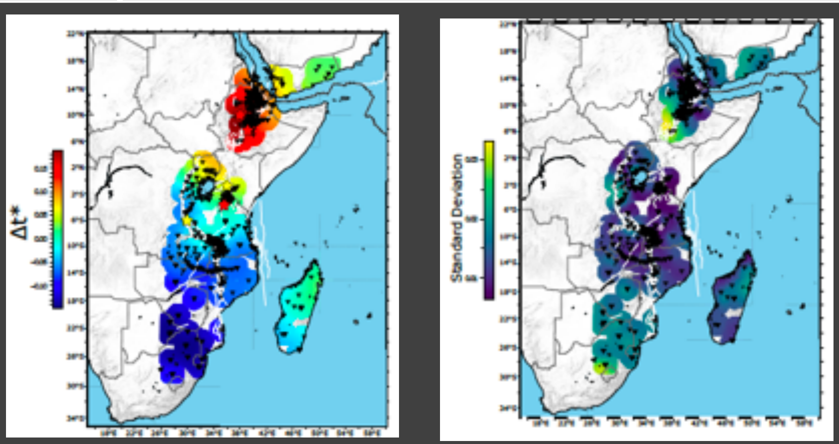


Goldhagen et al. (2022)



Birkey et al. (2024)



Ford et al. (in prep)

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  - My lab and research interests
  - The lithosphere and body waves
- Scattered waves and receiver functions
  - What are they and what can they tell us?
- Pre-processing: Requesting data and rotating waveforms
  - Event distribution
  - Coordinate systems
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  - Limitations
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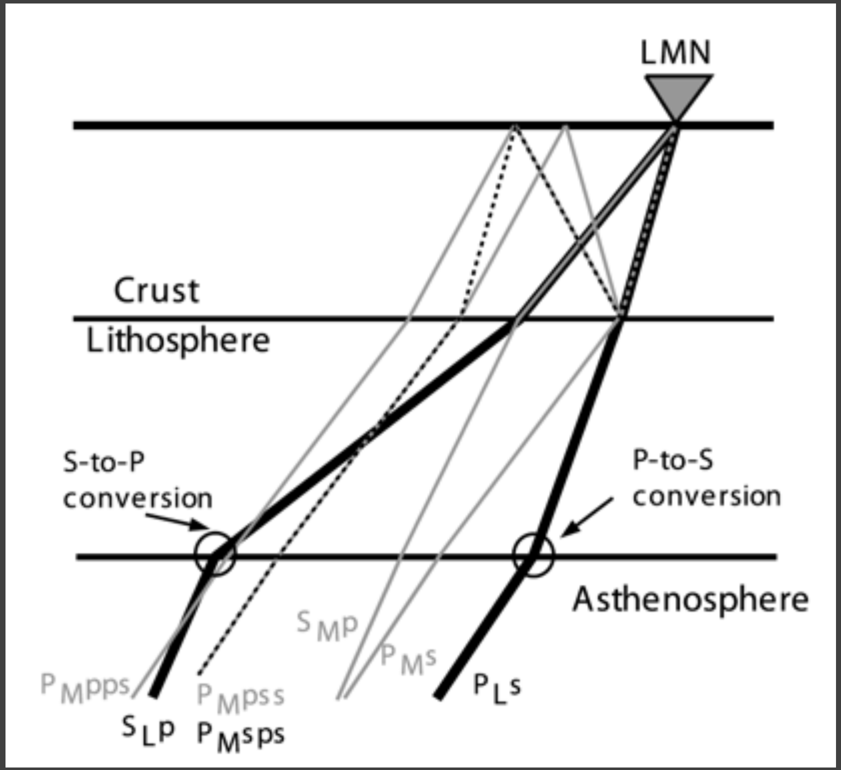
Part 2 Overview

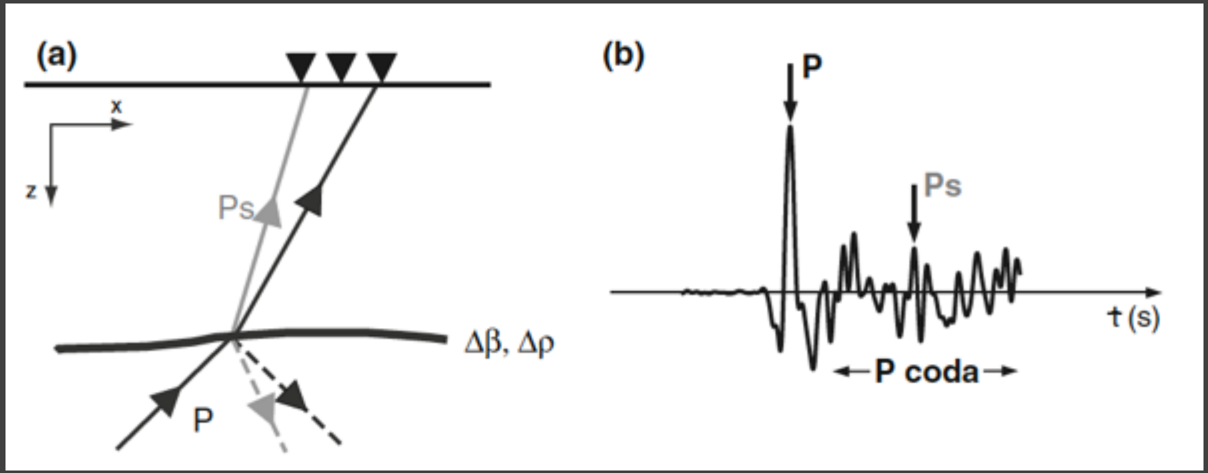
- Receiver functions and…
  - the crust, 410 and 660
  - the lithosphere-asthenosphere boundary
  - mid-lithospheric discontinuities
- Receiver function sensitivity, finite frequencies, 2D structure
- Receiver functions and anisotropy
- Joint inversions including receiver functions

Ps and Sp converted waves



Rychert et al. (2007)

By measuring the difference in arrival time (dt) between the converted phase and direct phase, and assuming a velocity structure (km/s) we can estimate the depth to the interface

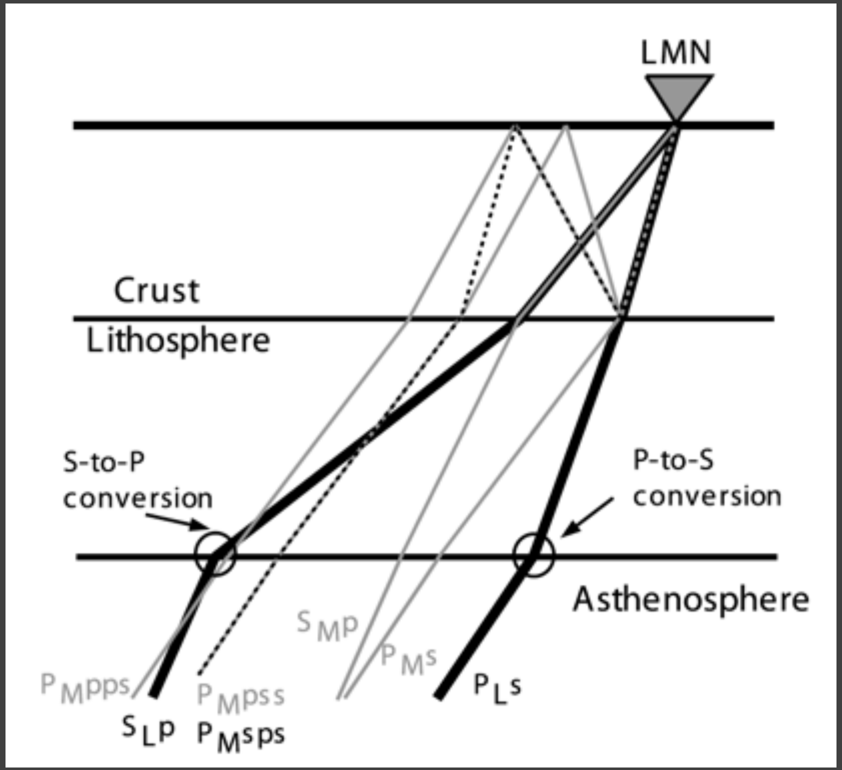


Rondenay (2009)

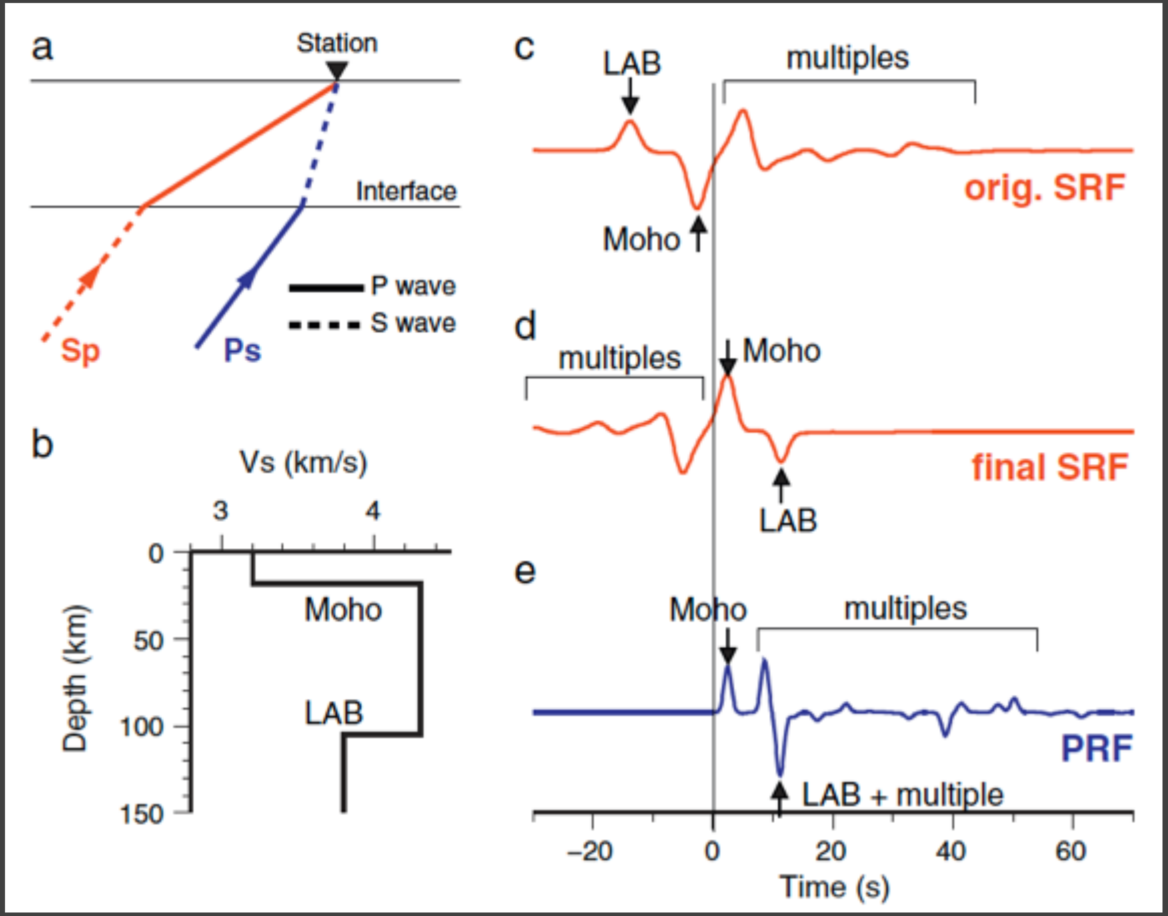
Ps: Direct wave arrives first (t=0 s), converted phases arrive after due to the slower speed of S waves; multiples may interfere with converted phases

Sp: Converted phases arrive first, followed by direct S and then multiples.

Ps and Sp converted waves



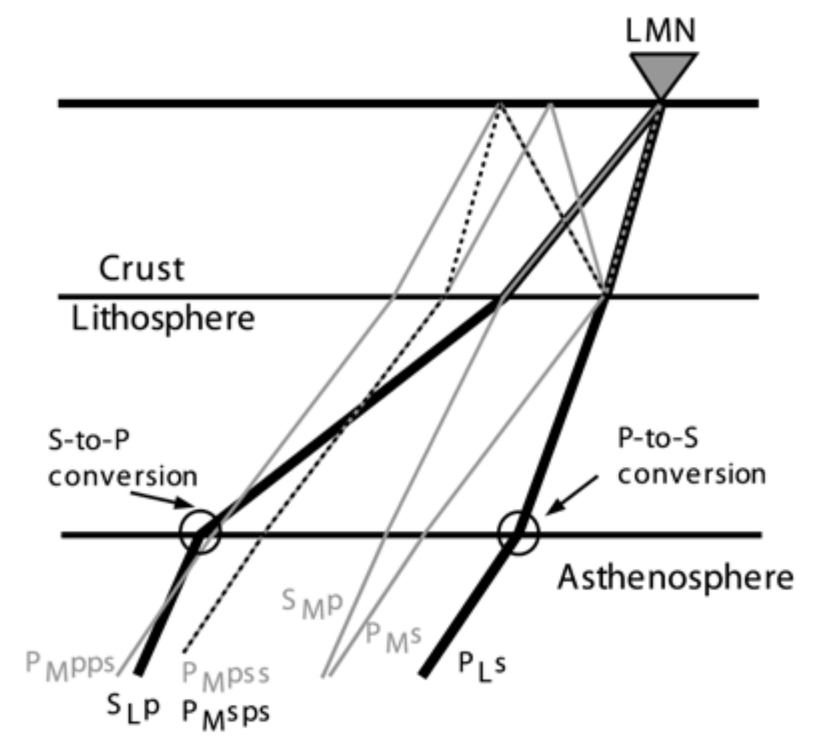
Rychert et al. (2007)



Kind et al. (2012)

By measuring the difference in arrival time (dt) between the converted phase and direct phase, and assuming a velocity structure (km/s) we can estimate the depth to the interface

Ps and Sp converted waves



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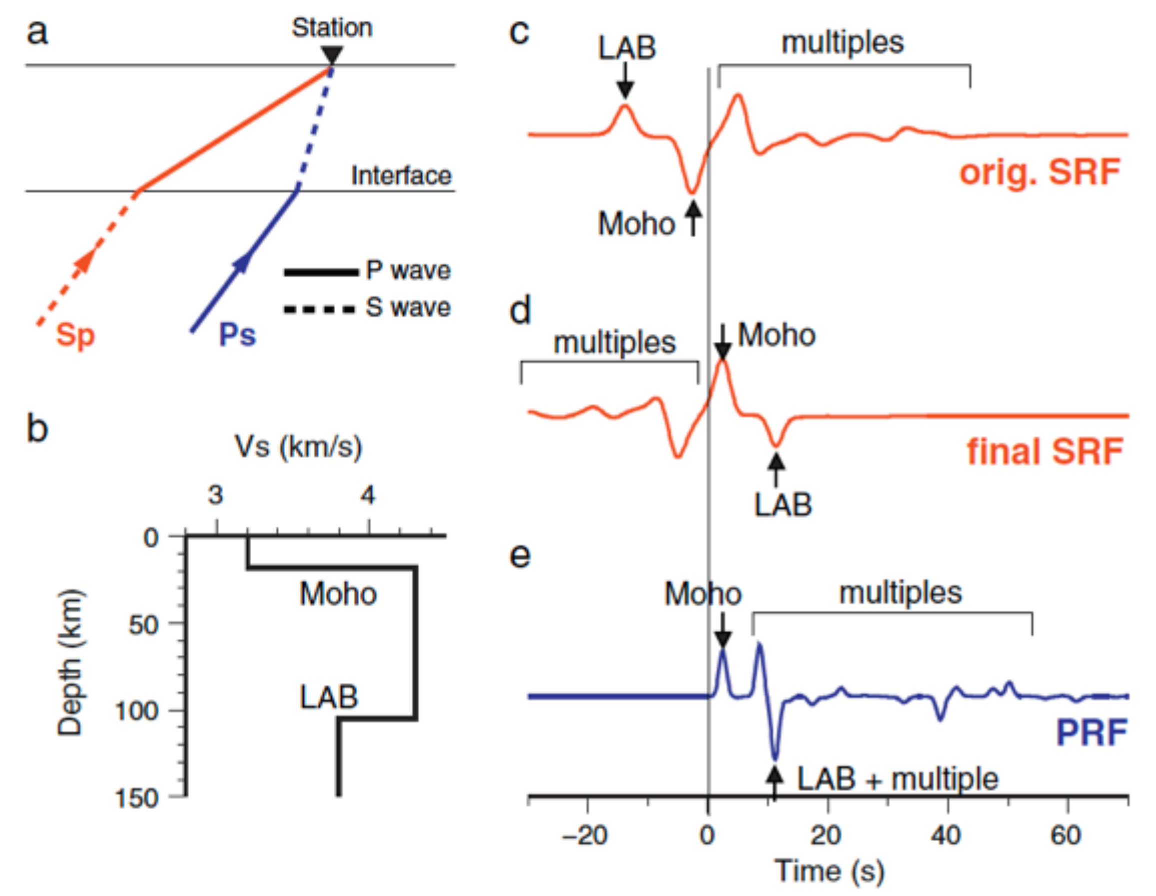
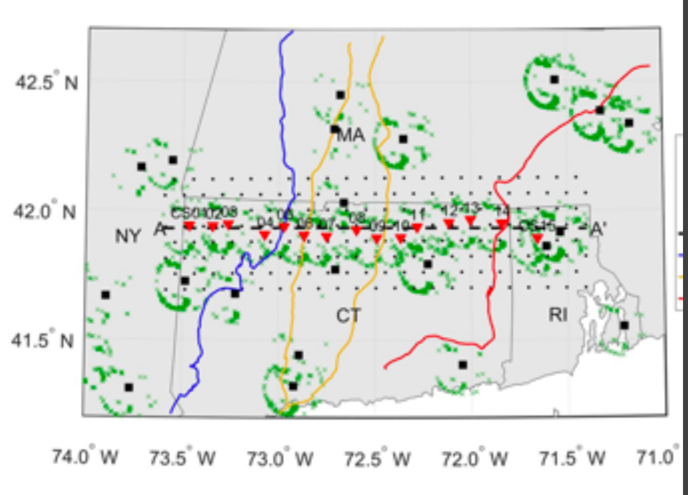
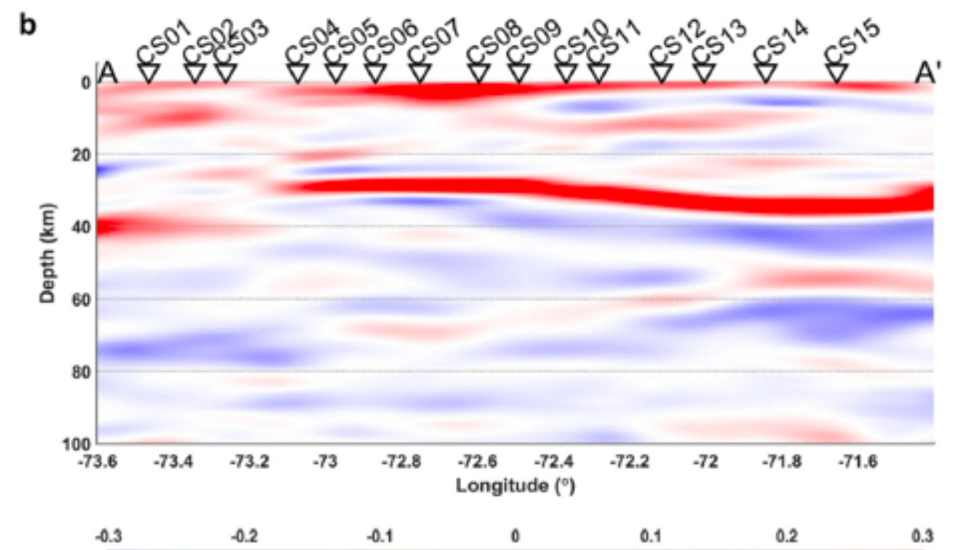


Kind et al. (2012)

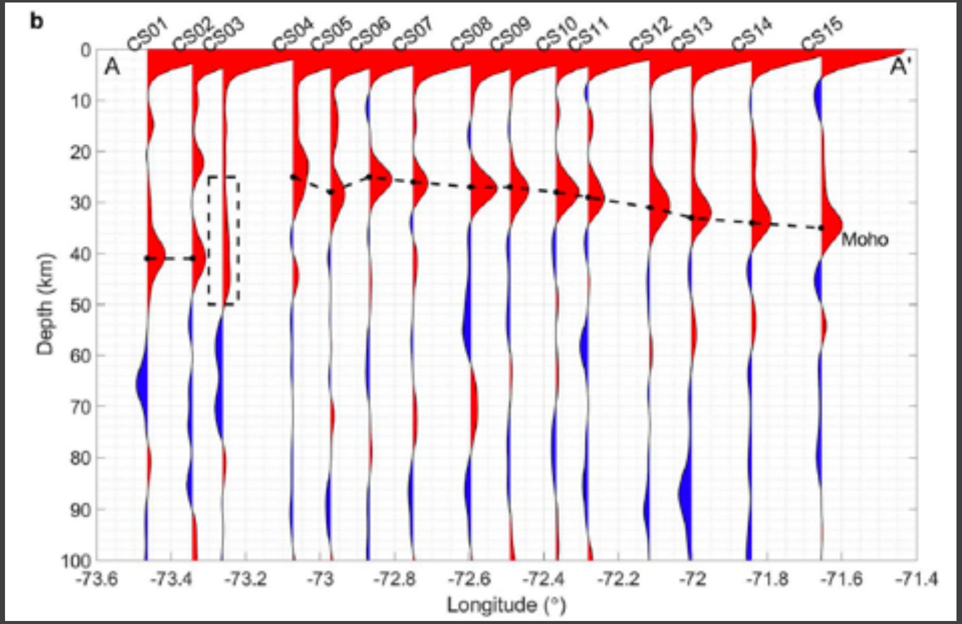
Practically, it is difficult to directly observe converted phases without a large number of events.

Ps receiver function example - SEISConn



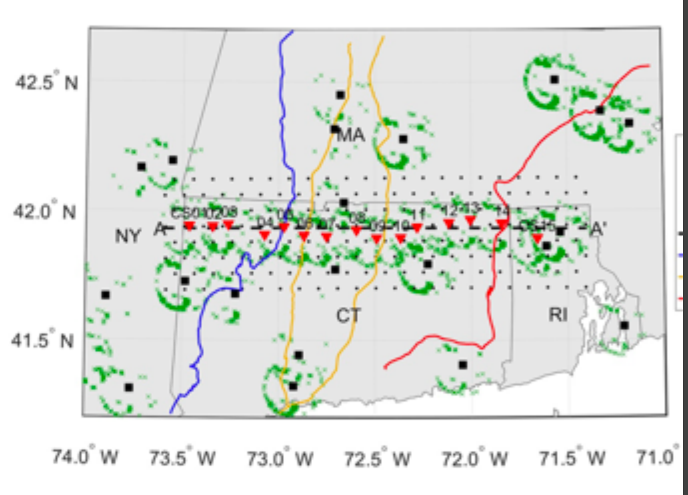


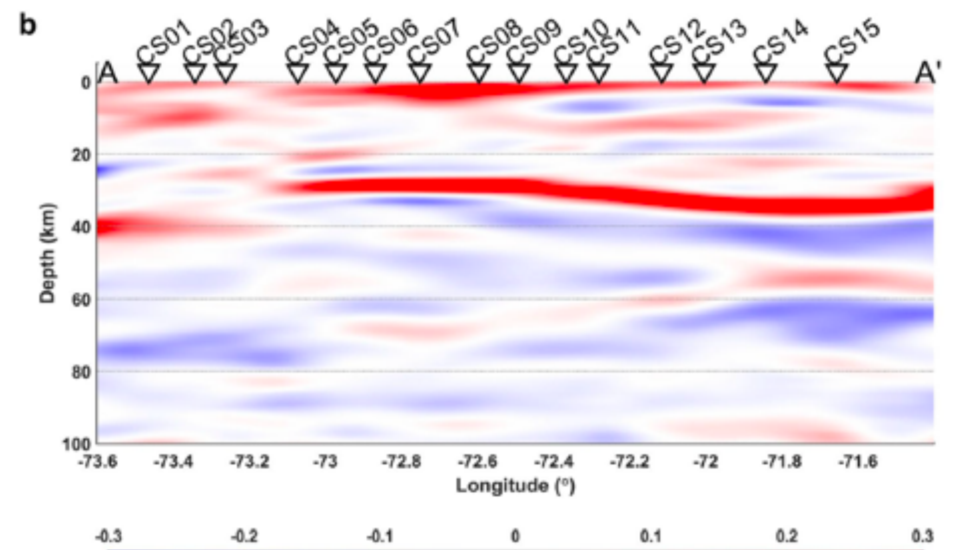
Luo et al. (2021)



Receiver function convention (for Ps and Sp) is that positive phases correspond to an increase of seismic wave speed with increasing depth; negative phases correspond to a decrease of seismic wave speed with increasing depth

Ps receiver function example - SEISConn





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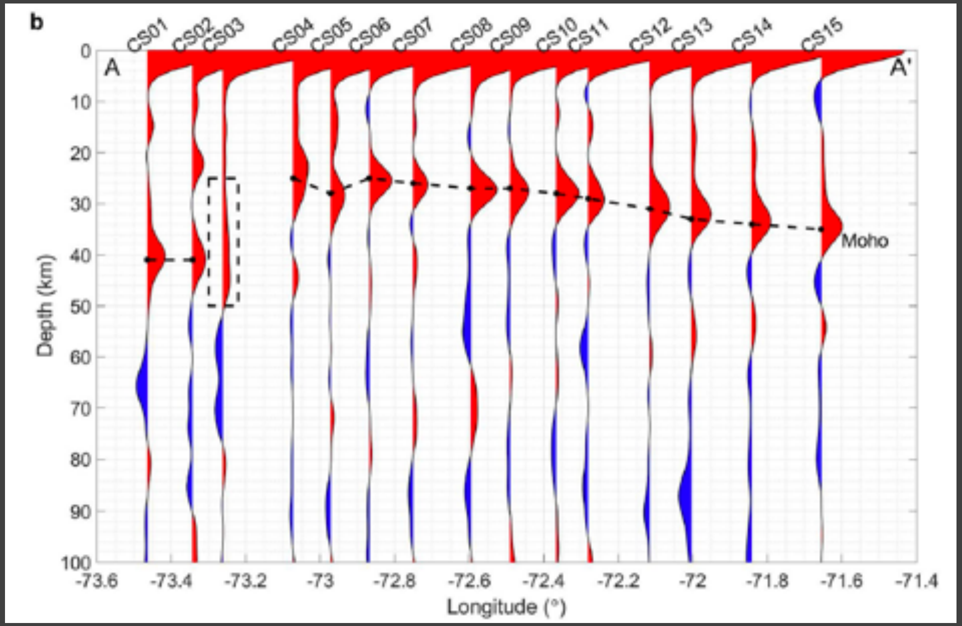
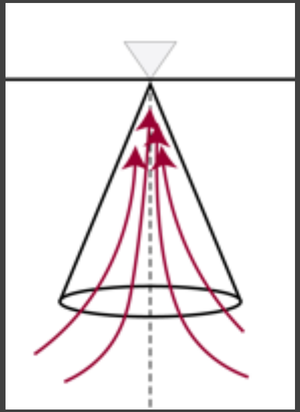
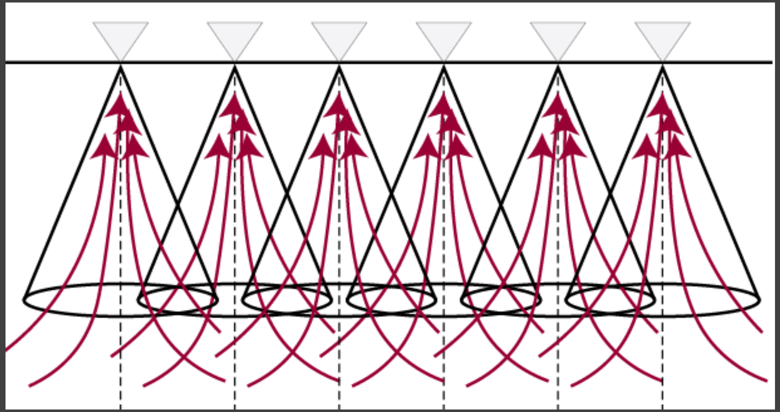


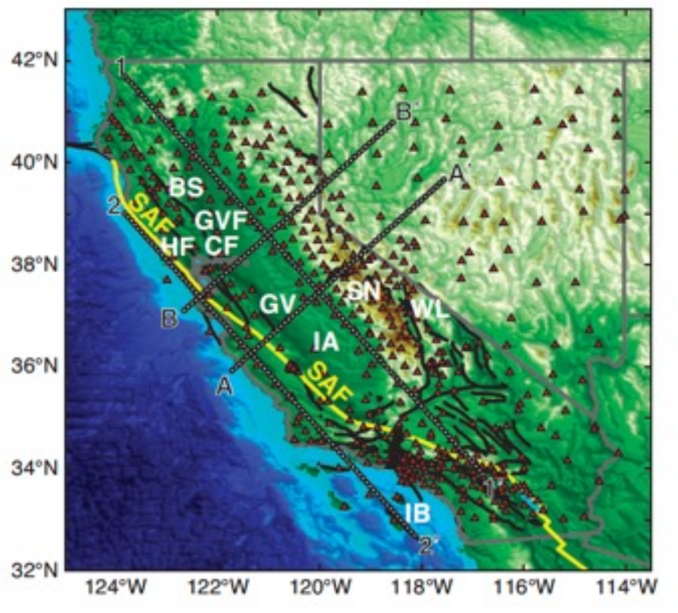


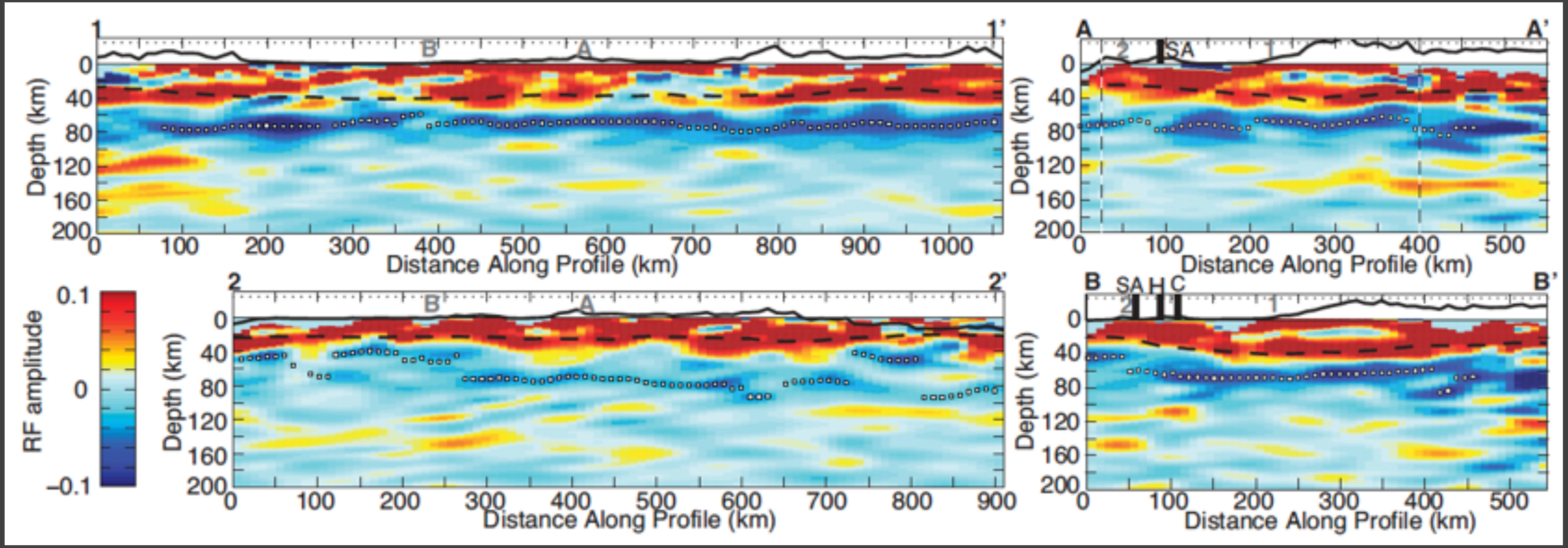
Single Station Stack

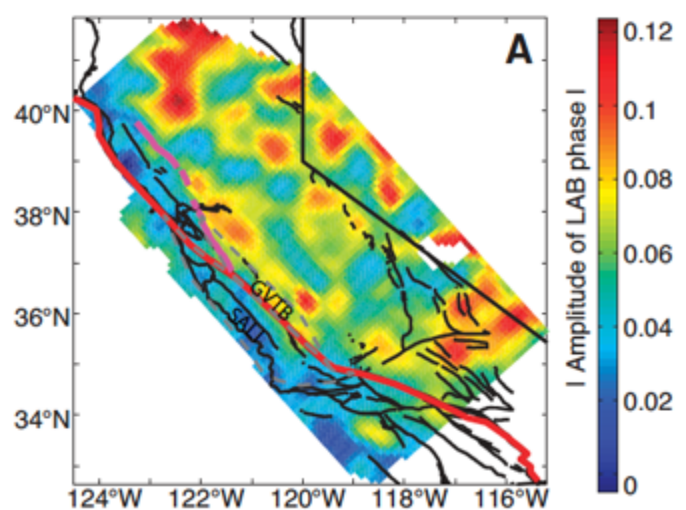


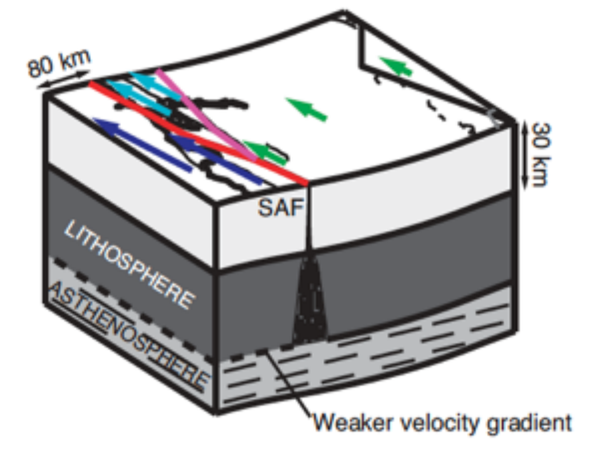
Common Conversion Point Stack

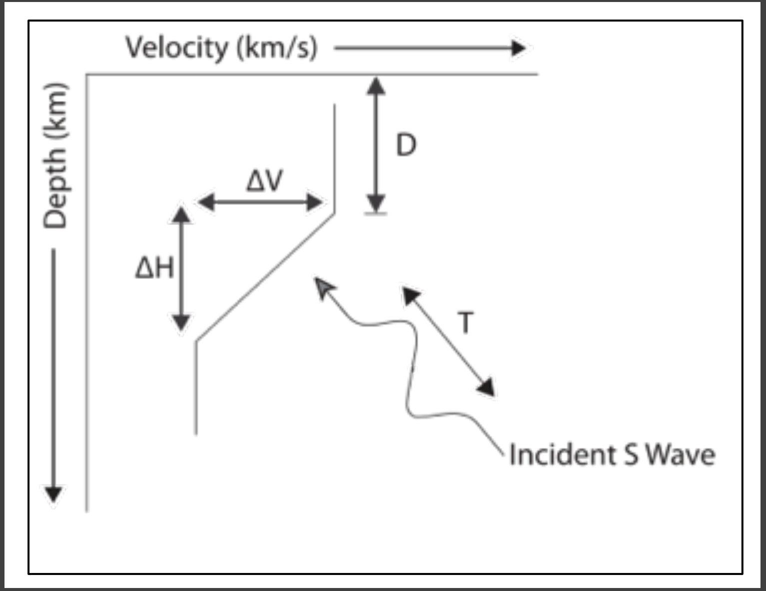
Sp receiver function example – San Andreas Fault











Ford et al. (2014)

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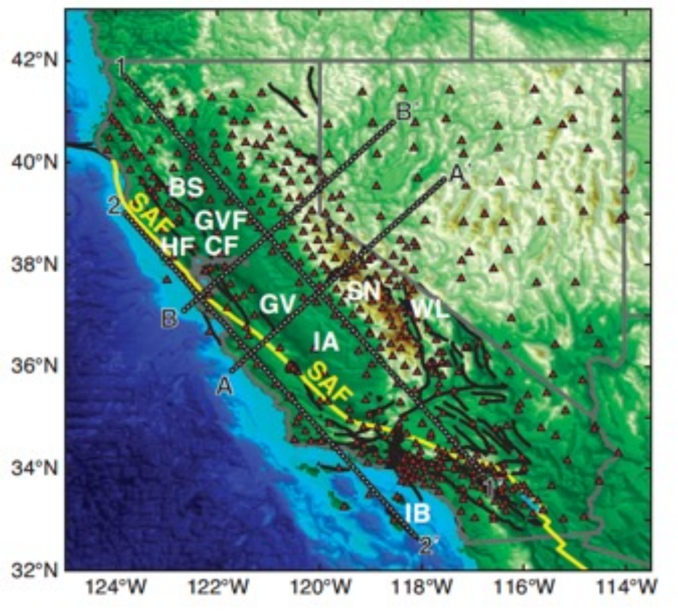
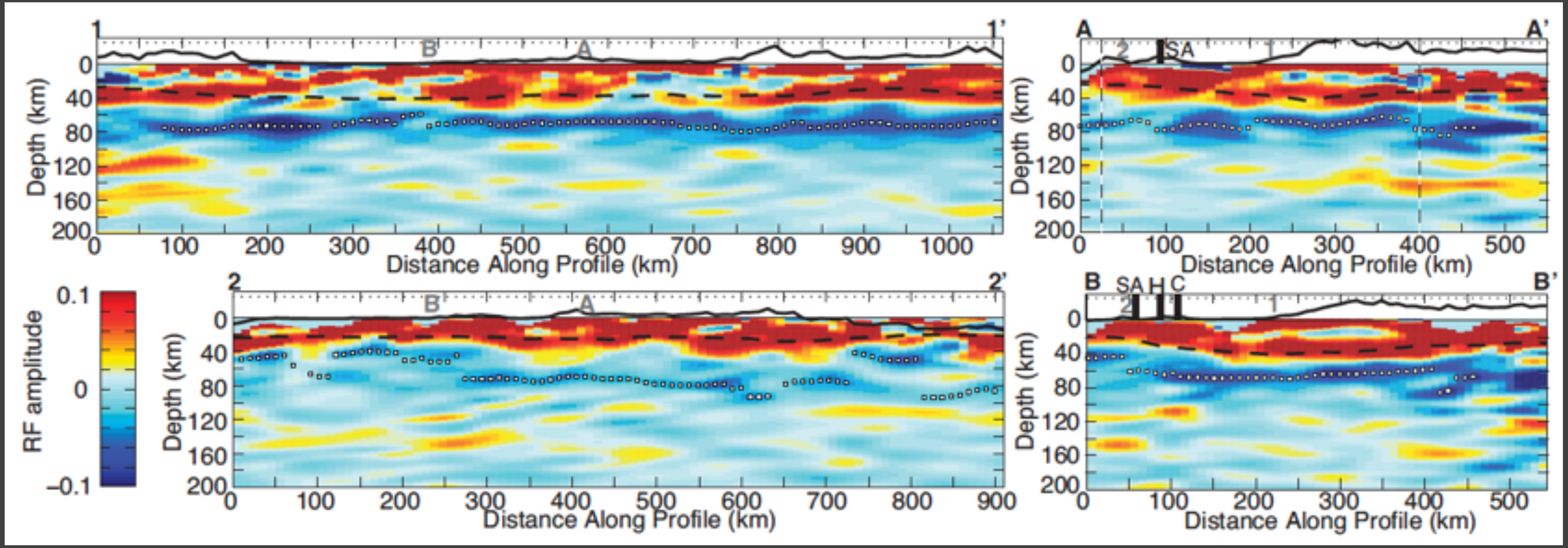
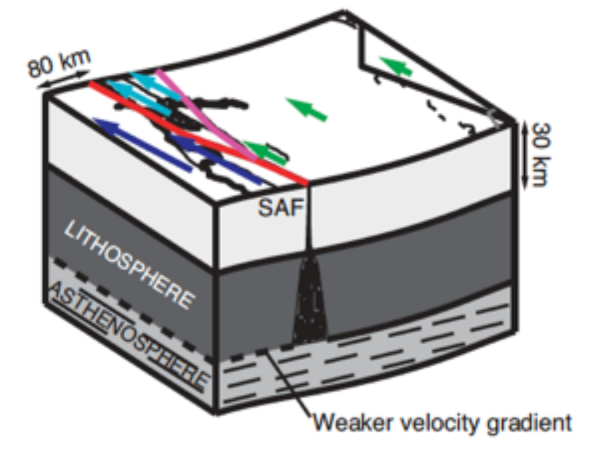
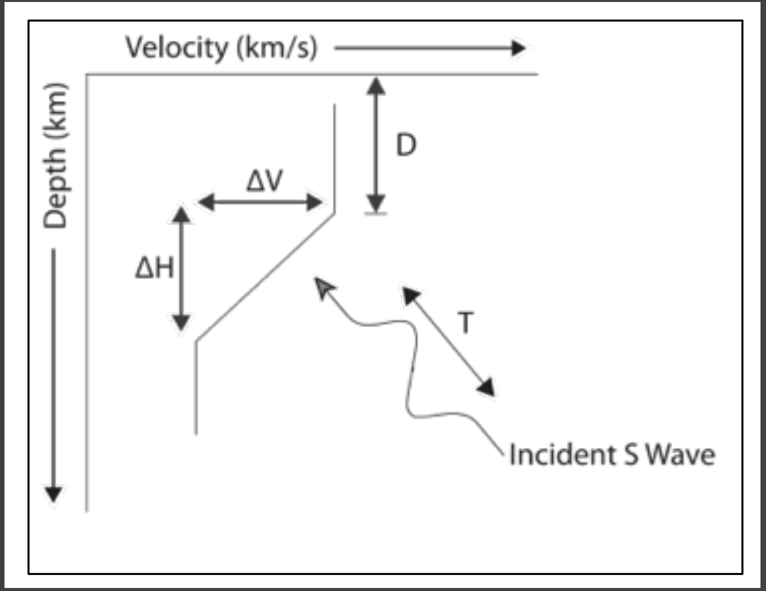




Receiver functions are most sensitive to boundaries in seismic wave speed, not volumetric heterogeneities. They are sensitive to changes in velocity gradient across a given boundary.





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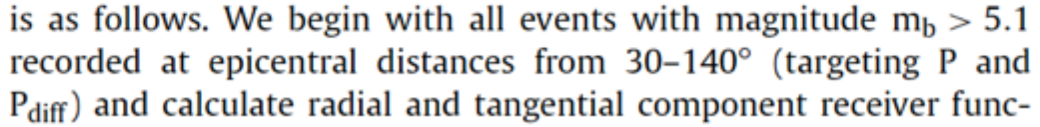
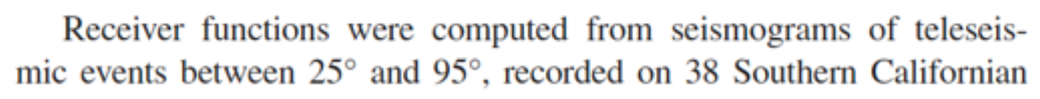
Event distribution – Ps Receiver Functions

- Magnitude threshold varies by study, commonly 5.8+, but some studies reduce threshold to 5.5+ or even lower. Largely depends on the data available, boundary being mapped, along with other considerations.
- Epicentral distances and phases used also varies from one study to another
    - P, Pdiff both used
    - Epicentral distances may be limited (30°-90°) or more generous (25°-140°)
- No limitations on depth



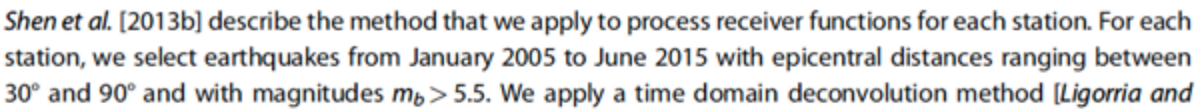
is as follows. We begin with all events with magnitude $m_b > 5.1$ recorded at epicentral distances from 30–140° (targeting P and P_{diff}) and calculate radial and tangential component receiver func-

Shulte-Pelkum and Mahan (2014)



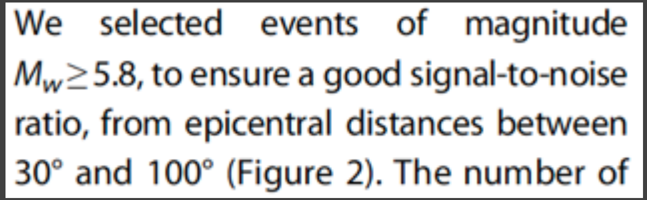
Receiver functions were computed from seismograms of teleseismic events between 25° and 95°, recorded on 38 Southern Californian

Porter et al. (2011)



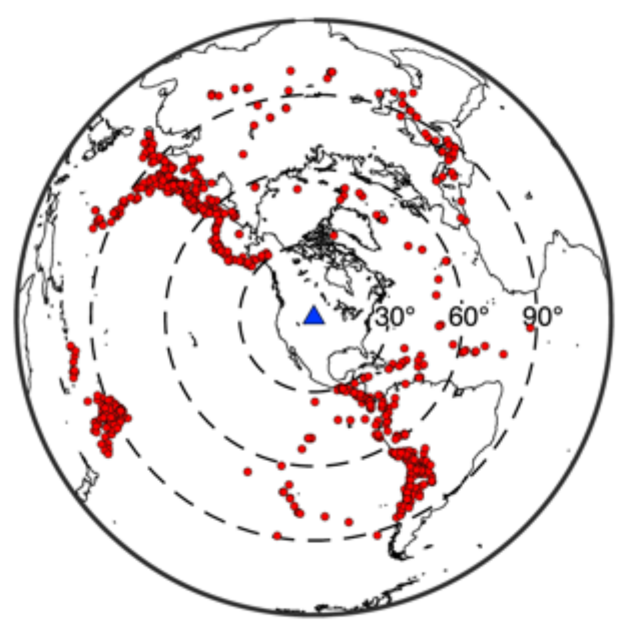
Shen et al. [2013b] describe the method that we apply to process receiver functions for each station. For each station, we select earthquakes from January 2005 to June 2015 with epicentral distances ranging between 30° and 90° and with magnitudes $m_b > 5.5$. We apply a time domain deconvolution method [*Ligorria and*

Shen and Ritzwoller (2016)

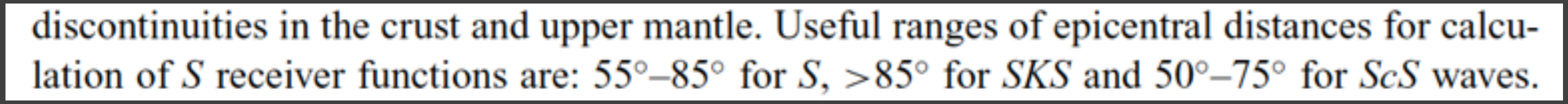


We selected events of magnitude $M_w \geq 5.8$, to ensure a good signal-to-noise ratio, from epicentral distances between 30° and 100° (Figure 2). The number of

Ford et al. (2016)

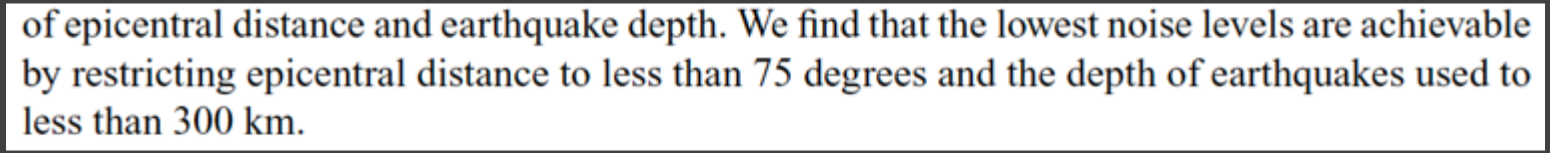


Event distribution – Sp Receiver Functions



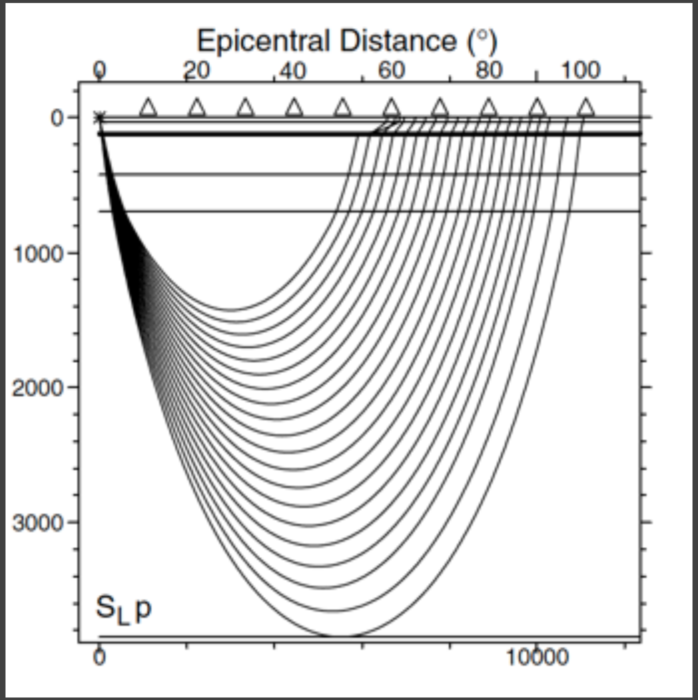
discontinuities in the crust and upper mantle. Useful ranges of epicentral distances for calculation of *S* receiver functions are: 55°–85° for *S*, >85° for *SKS* and 50°–75° for *ScS* waves.

Yuan et al. (2006)



of epicentral distance and earthquake depth. We find that the lowest noise levels are achievable by restricting epicentral distance to less than 75 degrees and the depth of earthquakes used to less than 300 km.

Wilson et al. (2006)



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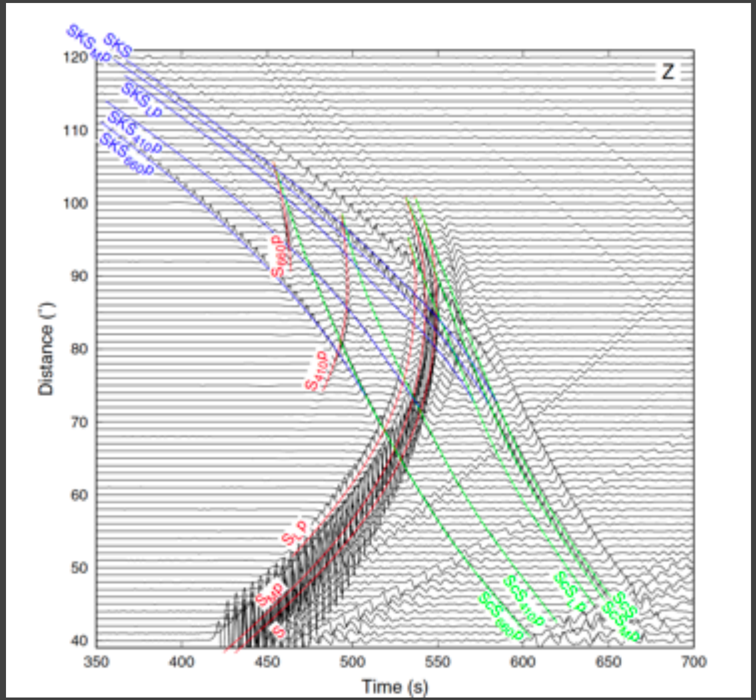

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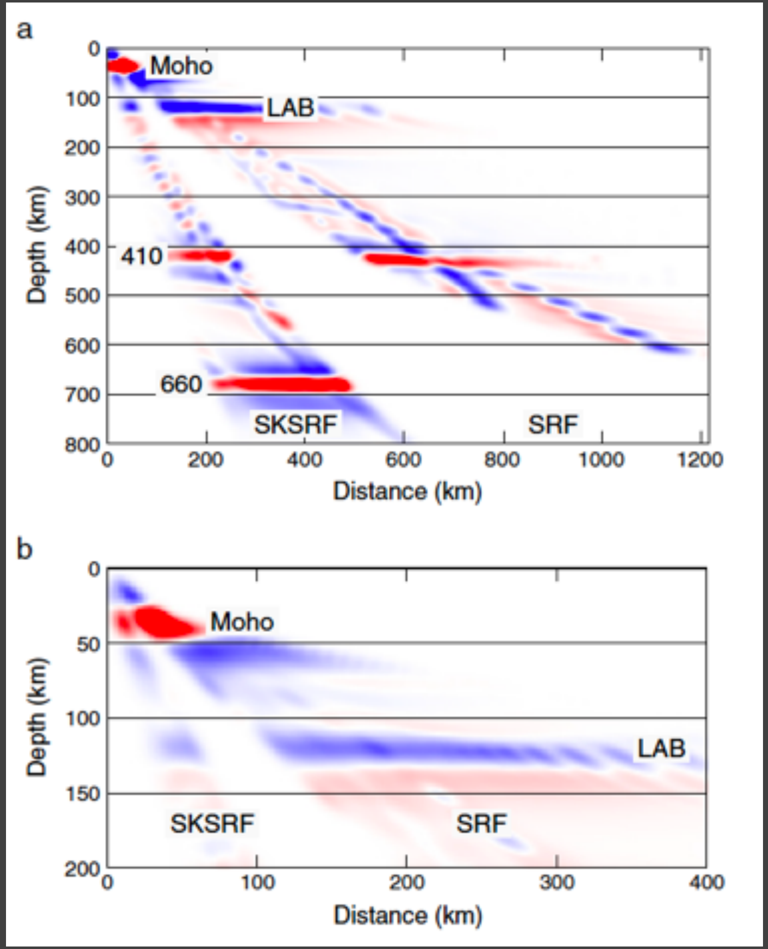
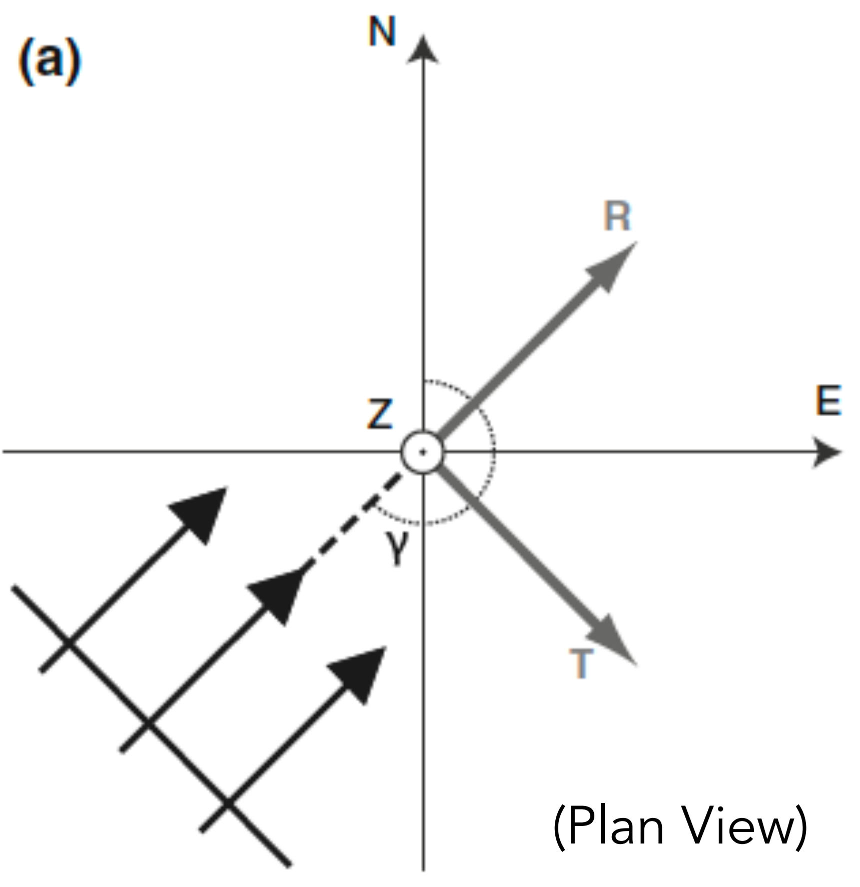


Kind et al. (2012)

Magnitude threshold varies by study, commonly 5.8+

Coordinate rotation (partitioning the signal)



Rondenay (2009)

Seismometers are typically installed in the North-East-Vertical direction*
(*Note: This is not always true – always refer to the metadata and consider using a quality control application to verify orientation)

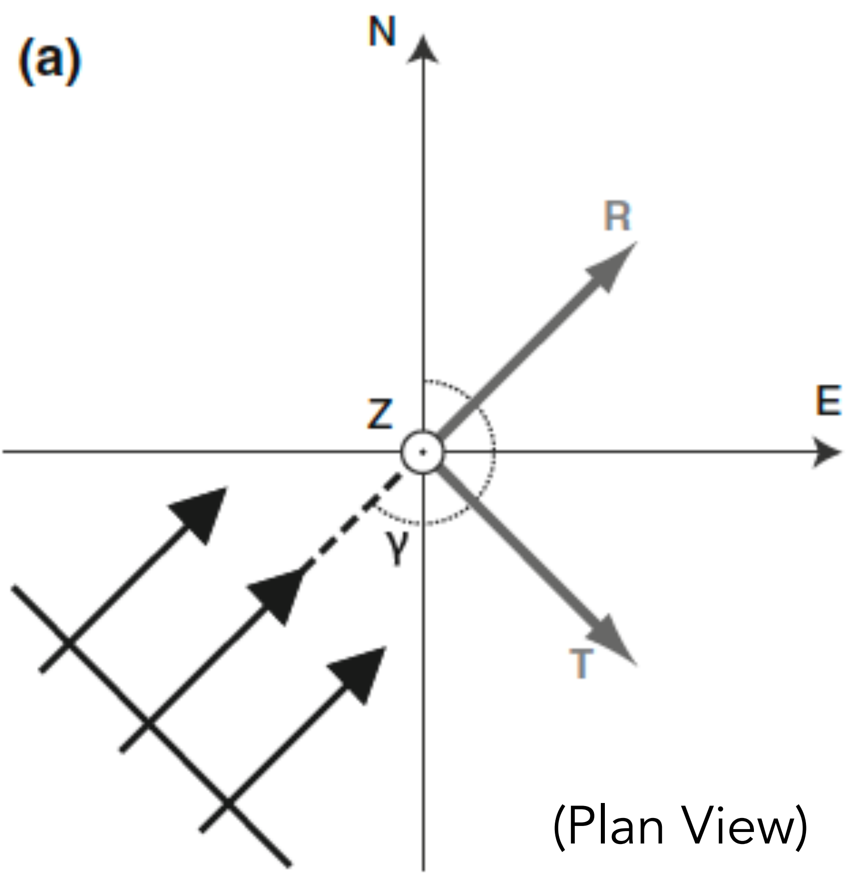
Seismograms are typically rotated to the Radial-Transverse-Vertical coordinate system prior to analysis

$$\begin{pmatrix} R \\ T \\ Z \end{pmatrix} = \begin{pmatrix} -\cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & -\cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} N \\ E \\ Z \end{pmatrix},$$

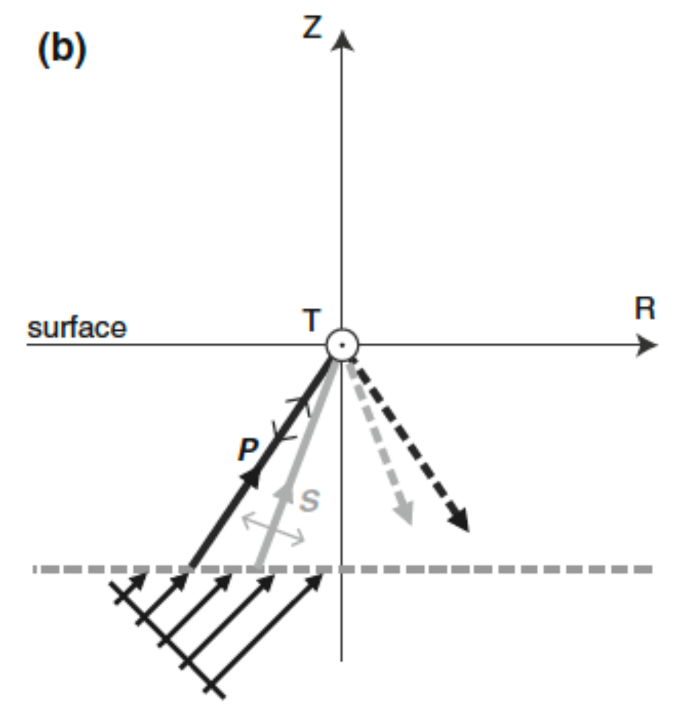
*gamma is the backazimuth of the incident wave

Coordinate rotation (partitioning the signal)

RF analysis goal: Isolate the direct phase and converted phase(s)



Rondenay (2009)



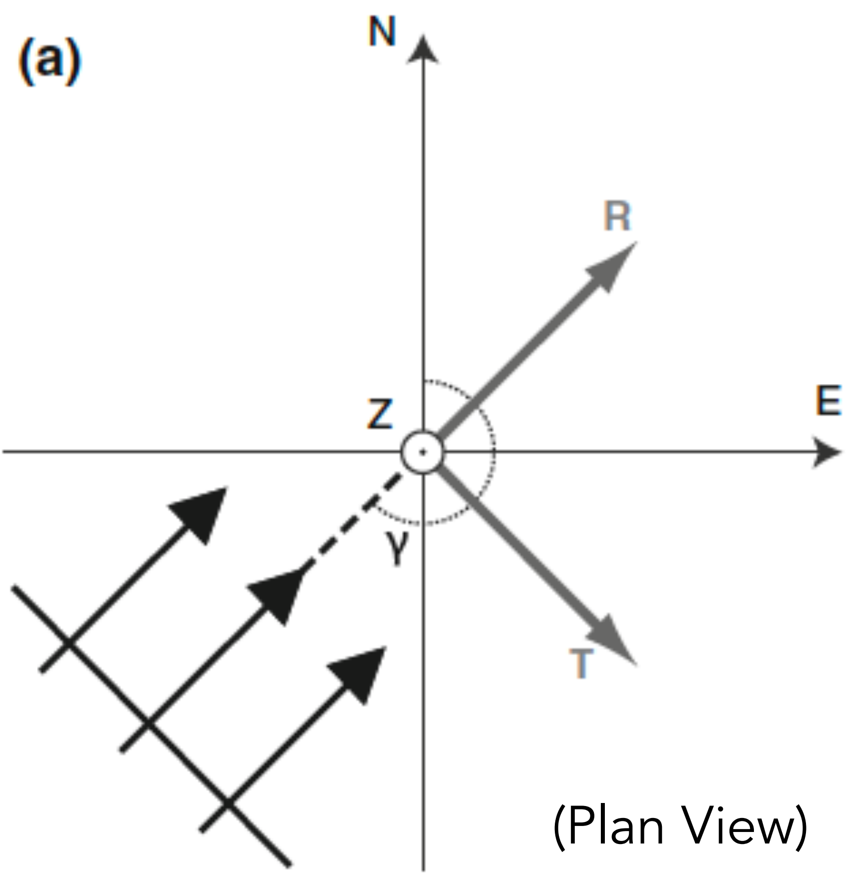
Rondenay (2009)

In one approach, it is assumed that the incident/direct P wave signal is confined to the vertical (Z) component, while the converted phase (Ps) signal is confined to the radial (R) component.

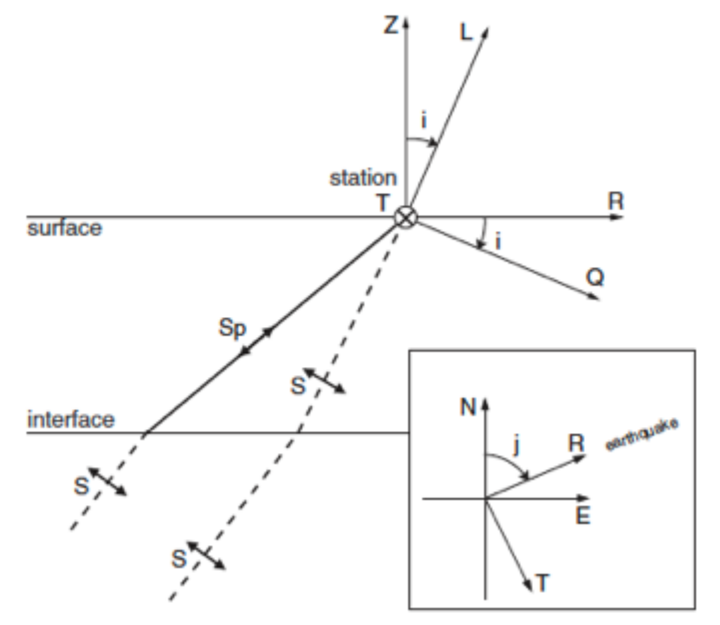
This approach has been used successfully in a number of applications and works well with P-waves as the incidence angle is close (10°-30°) to vertical

Coordinate rotation (partitioning the signal)

RF analysis goal: Isolate the direct phase and converted phase(s)



Rondenay (2009)



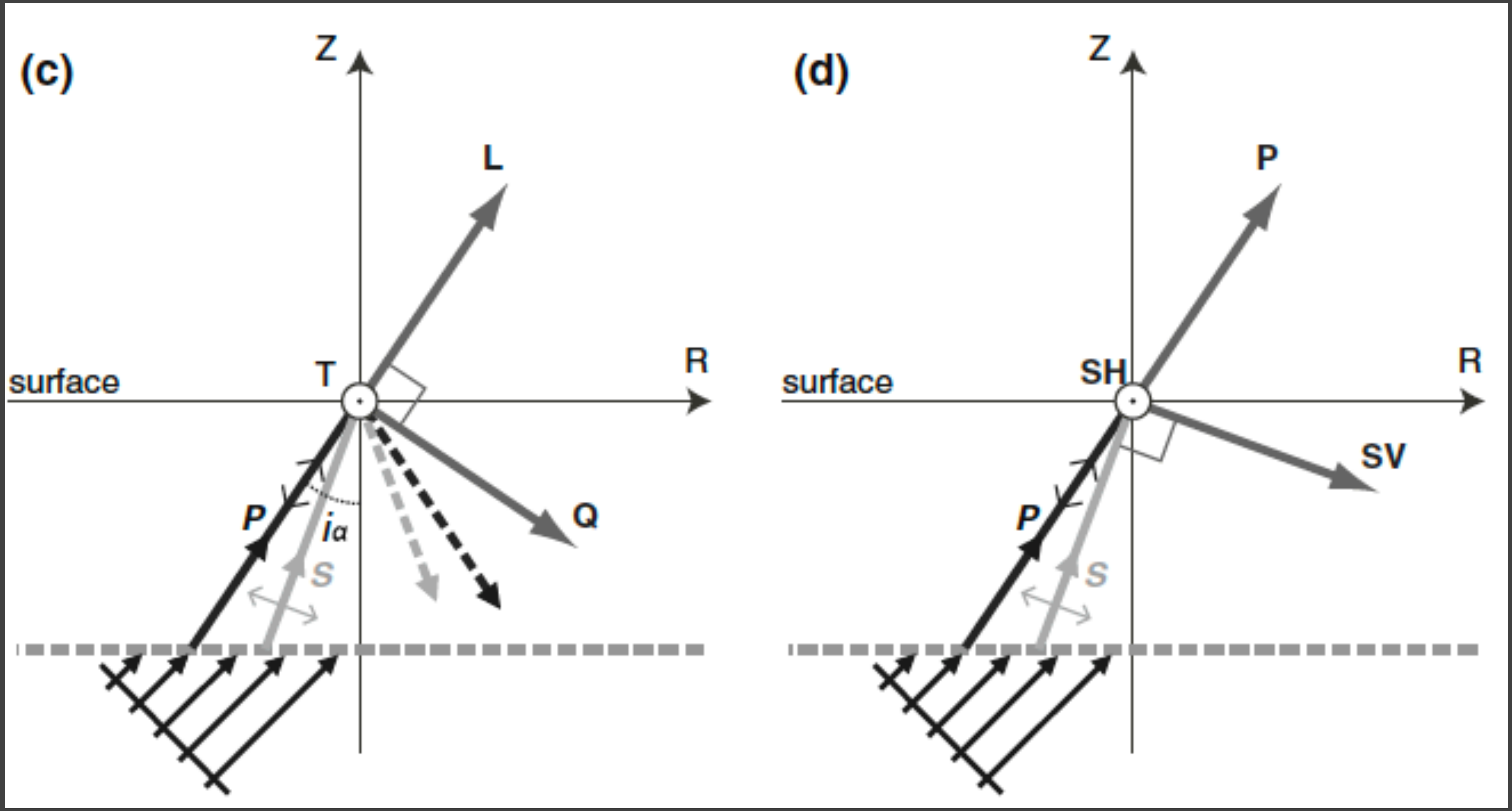
Kind et al. (2012)

In one approach, it is assumed that the incident/direct P wave signal is confined to the vertical (Z) component, while the converted phase (Ps) signal is confined to the radial (R) component.

This approach does NOT work as well in applications of Sp receiver function analysis due to the difference of incidence angle (less vertical).

Coordinate rotation (partitioning the signal)

RF analysis goal: Isolate the direct phase and converted phase(s)



Rondenay (2009)

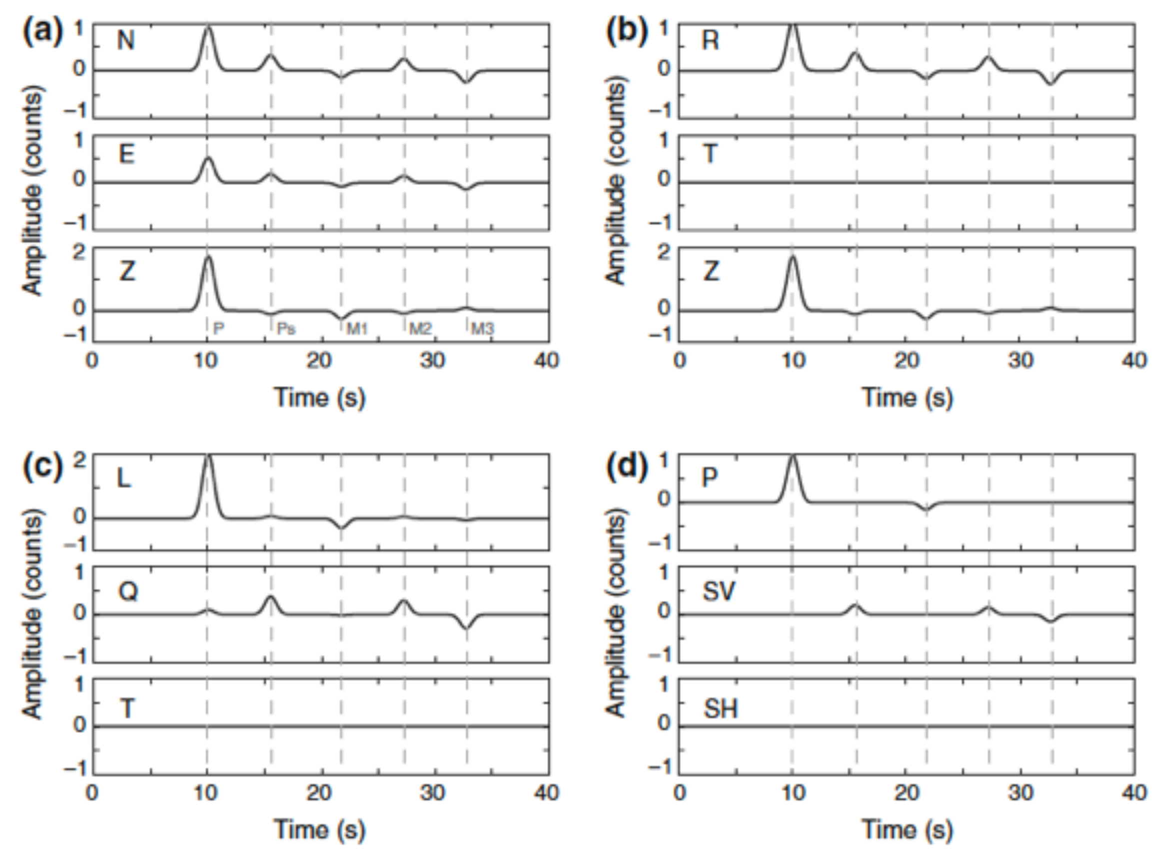
In two additional approaches, an additional rotation into either the L-Q-T or P-SV-SH reference frame is made by estimating near surface velocities and ray parameter. In the P-SV-SH rotation, the effects of reflection at the free surface are suppressed.

$$\begin{pmatrix} P \\ \mathrm{SV} \\ \mathrm{SH} \end{pmatrix} = \begin{pmatrix} \frac{\beta^2p^2-1/2}{\alpha q_\alpha} & \frac{p\beta^2}{\alpha} & 0 \\ p\beta & \frac{1/2-\beta^2p^2}{\beta q_\beta} & 0 \\ 0 & 0 & 1/2 \end{pmatrix} \begin{pmatrix} \mathrm{Z} \\ \mathrm{R} \\ \mathrm{T} \end{pmatrix},$$

Bostock and Rondenay (1999)

Coordinate rotation (partitioning the signal)

RF analysis goal: Isolate the direct phase and converted phase(s)



Rondenay (2009)

While this is theoretically straightforward, practically the uncertainties in near surface structure, as well as assumptions about ray path, make these rotations difficult. See Abt et al. (2010) for a discussion of one method to determine best-fitting P-SV-SH.

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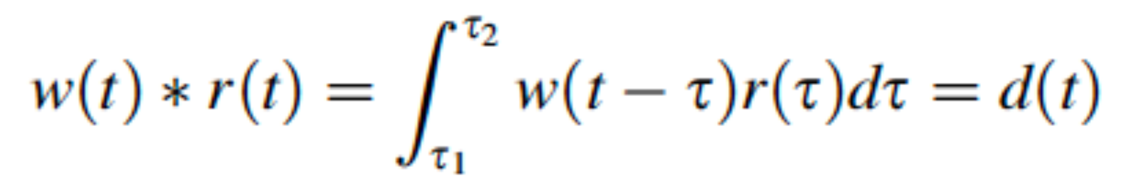
  - Source normalization
  - Frequency and time domain approaches
  - Limitations
- Stacking, moveout correction and migration
  - Improving signal and stacking methods
  - Moveout correction
  - Migration

Deconvolution - Source normalization

RF analysis goal: Source normalization

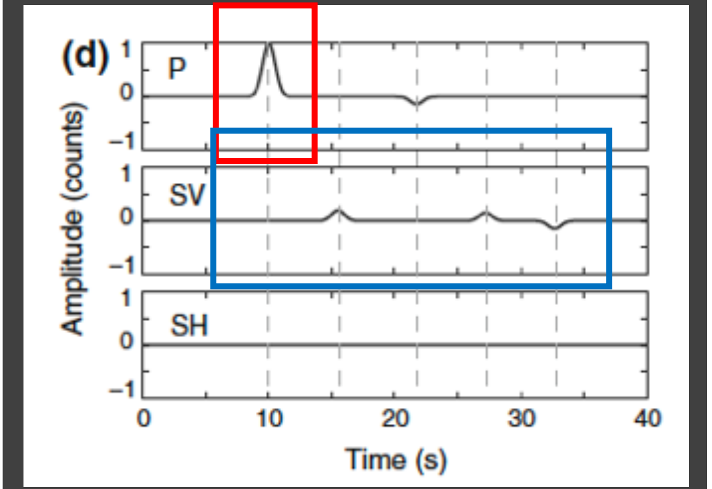


$$w(t) * r(t) = \int_{\tau_1}^{\tau_2} w(t-\tau) r(\tau) d\tau = d(t)$$

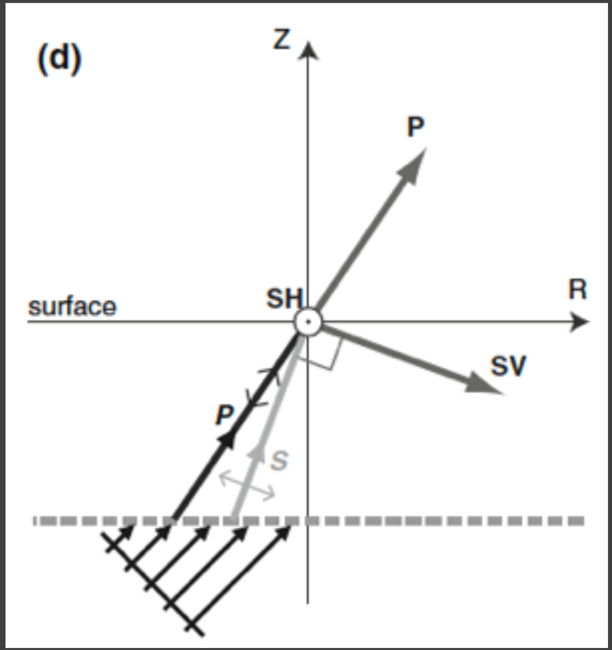
"…the recorded signal (dt) is expressed as the convolution of the Earth's impulse response r(t) with the combined source time function and instrument response w(t)."

Rondenay (2009)

Earthquake source $*$ Structure $*$ Instrument response $=$ Seismogram



Rondenay (2009)



For Ps receiver functions:
w(t) = P, while d(t) = SV (or SH)

Through deconvolution, we can remove source and instrument response, leaving the Earth's impulse response (structure). Note: This almost removes source side path effects, meaning this method isolates <u>receiver</u> side structure.

Deconvolution - Source normaliz

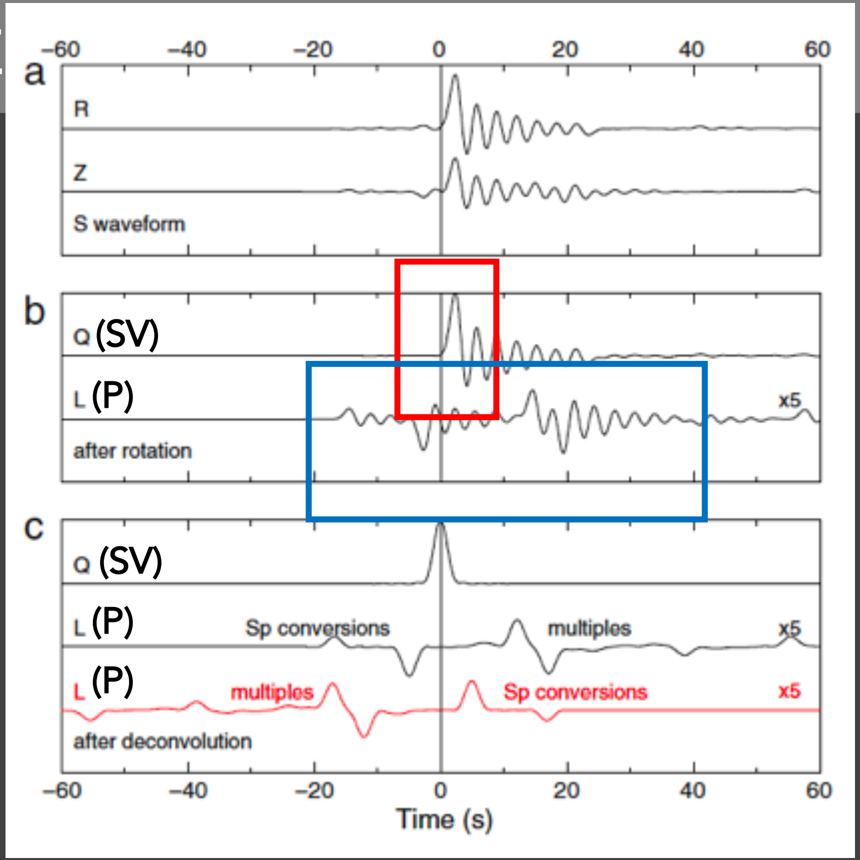
RF analysis goal: Source normalization

$$w(t) * r(t) = \int_{\tau_1}^{\tau_2} w(t-\tau)r(\tau)d\tau = d(t)$$

"…the recorded signal (dt) is expressed as the convolution of the Earth's impulse response r(t) with the combined source time function and instrument response w(t)."

Rondenay (2009)

Earthquake source * Structure * Instrument response = Seismogram



Kind et al. (2012)

For Sp receiver functions:
w(t) = SV (or SH), while d(t) = P

Through deconvolution, we can remove source and instrument response, leaving the Earth's impulse response (structure). Note: This also removes source side path effects, meaning this method isolates <u>receiver</u> side structure.

Deconvolution – Approaches and limitations

Deconvolution in the frequency domain (Ps)

$$w(t) * r(t) = \int_{\tau_1}^{\tau_2} w(t-\tau) r(\tau) d\tau = d(t)$$

"…the recorded signal (dt) is expressed as the convolution of the Earth's impulse response r(t) with the combined source time function and instrument response w(t)."

Rondenay (2009)

In theory, if we are hoping to solve for r(t) and have both w(t) (which is P) and d(t) (which is SV), we can perform a division of w(t) from d(t)

This is, however, practically difficult due to noise in the deta and inaccuracies in determining w(t) and additional steps must be taken.

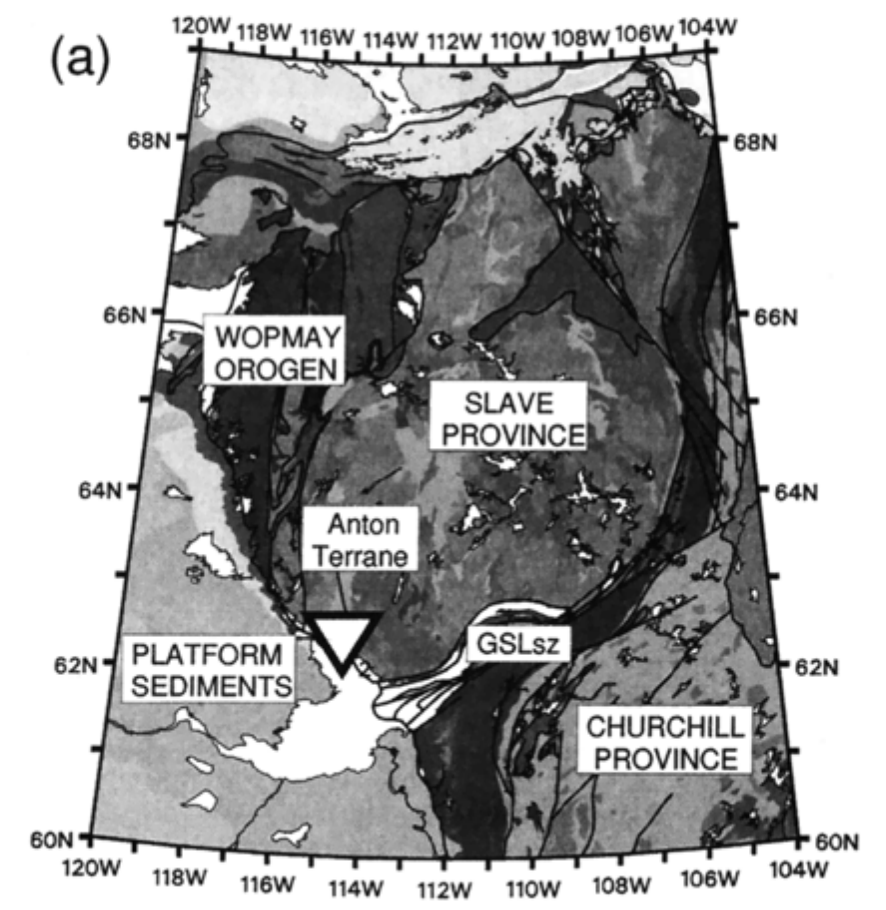
$$g(t) = \mathcal{F}^{-1}\left[G(\omega)\right] = \mathcal{F}^{-1}\left[\frac{\sum_n^N S_n(\omega) P_n^*(\omega)}{\sum_n^N P_n(\omega) P_n^*(\omega) + \delta}\right],$$

Bostock (1998)

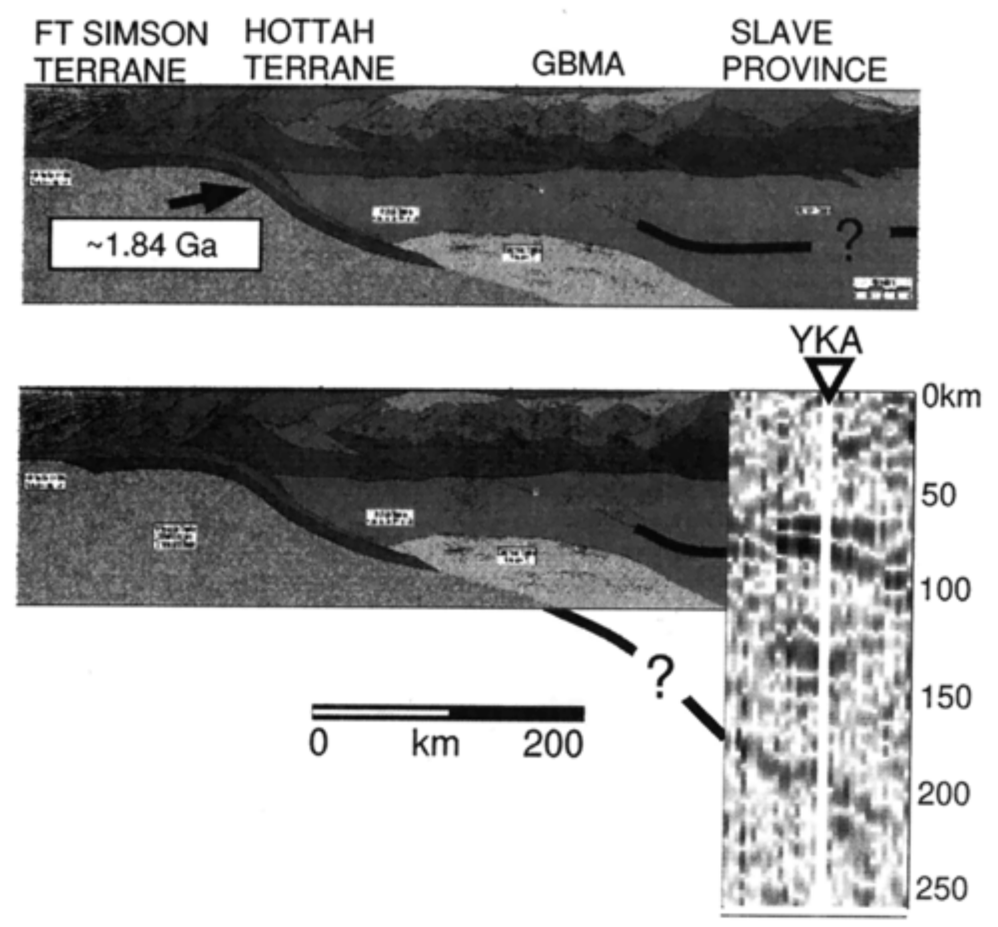
g(t) = impulse response
S(w) corresponds to the S wave component (SV or SH) in the frequency domain
P(w) corresponds to the source-instrument wavelet (direct P from the P component)
P*(w) is the complex conjugate of P

Deconvolution – Approaches and limitations

Example of Ps frequency domain deconvolution



Bostock (1998)



Bostock (1998)

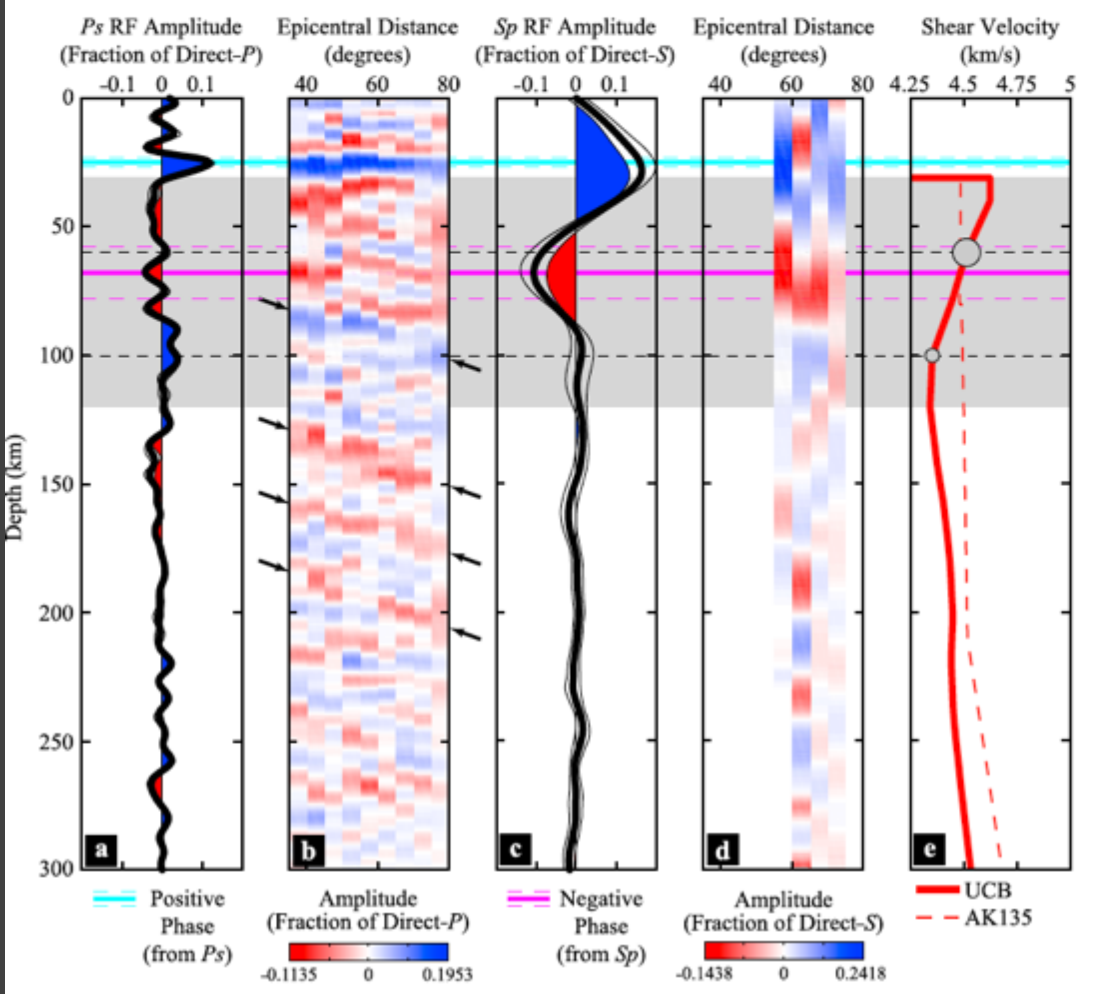
Deconvolution – Approaches and limitations

Deconvolution in the frequency domain (Sp)

$$RF_{time}(z_c) = F^{-1}\left(\frac{\sum_{i=1}^{N} DC_i(\omega) PC_i^{*}(\omega) e^{i\omega\tau_{p_i z_c}}}{\sum_{i}^{N} PC_i(\omega) PC_i^{*}(\omega) + \delta} \right)$$

Abt et al. (2010)

More generalized form:
DC = "daughter component"
= P in Sp RFs
= SV or SH in Ps RFs
PC = "parent component"
= SV of SH in Sp RFs
= P in Ps RFs

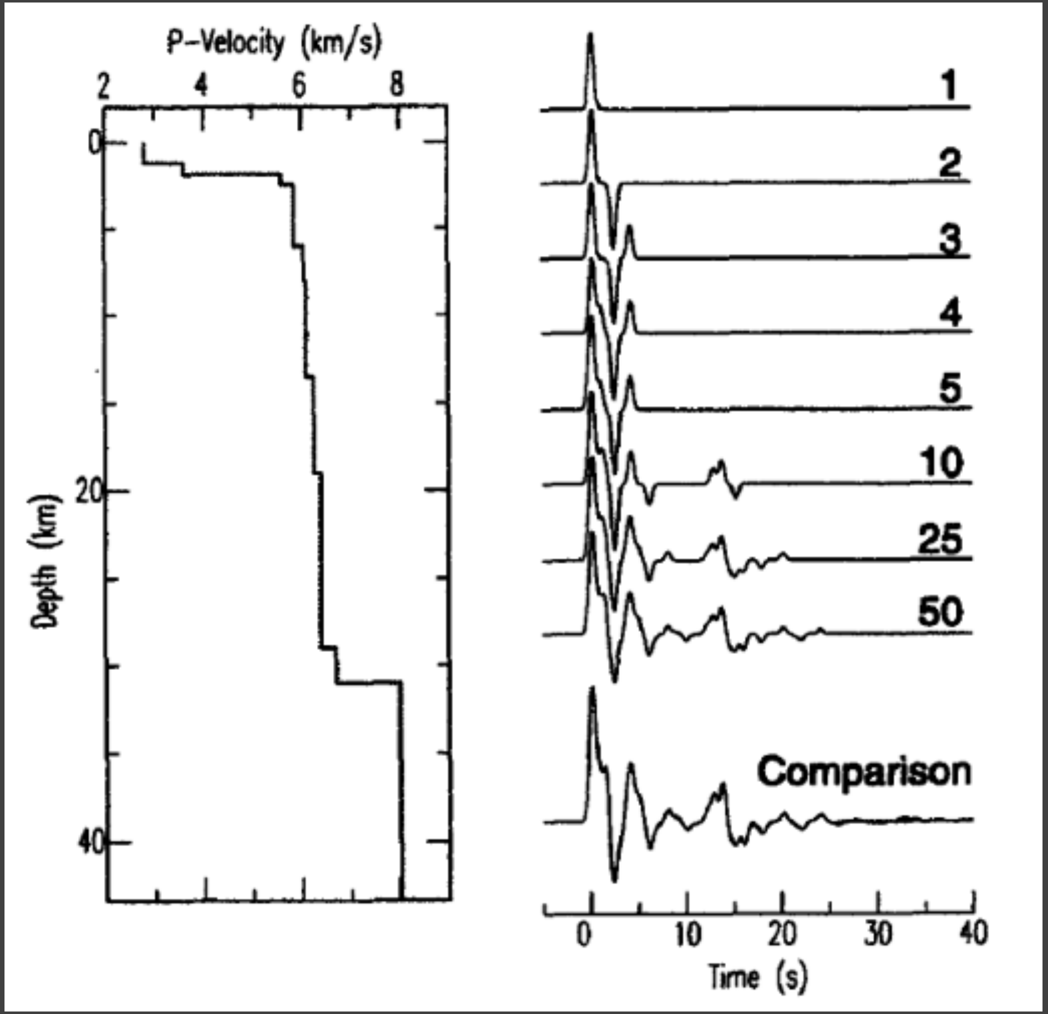


Abt et al. (2010)

Deconvolution – Approaches and limitations

Deconvolution in the time domain (Ps and Sp)

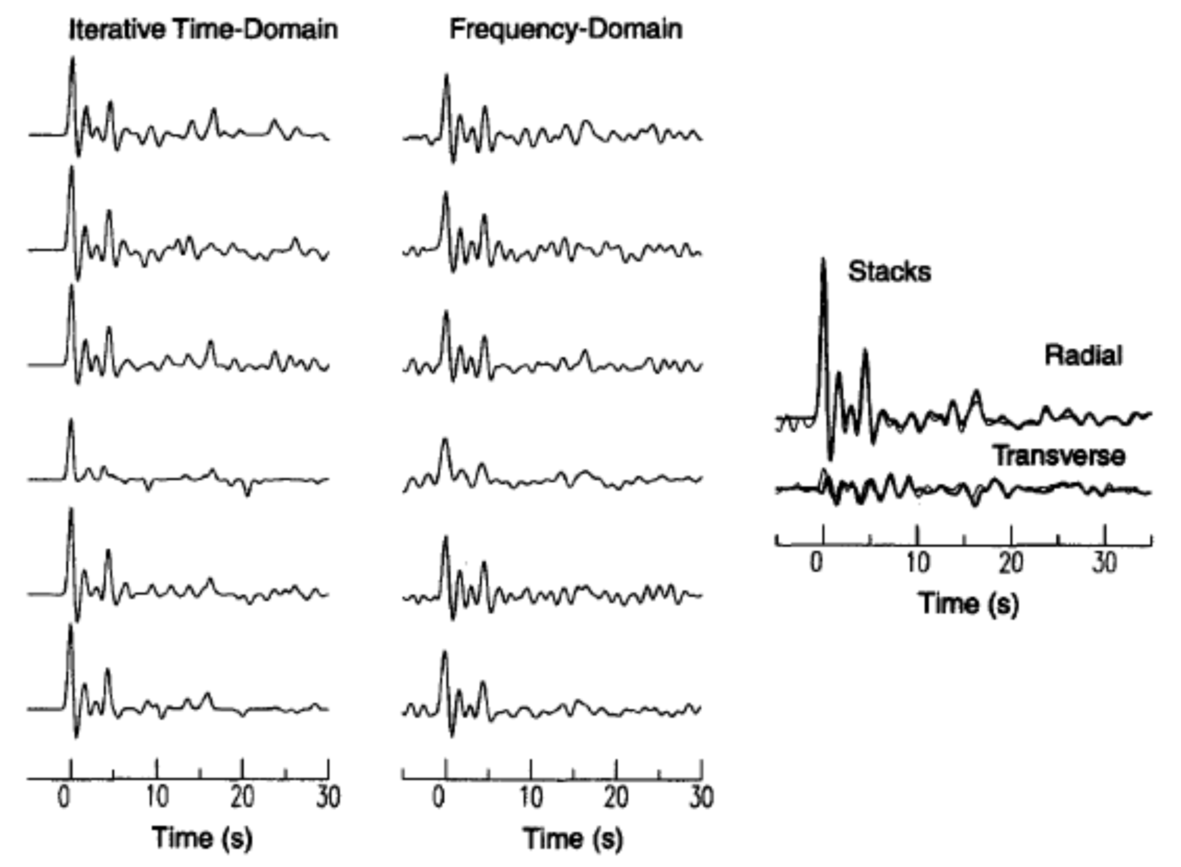
- First described in Ligorría and Ammon (1999)
- General workflow of iterative time domain deconvolution (assuming Ps receiver function analysis):
  - Vertical component (P) is cross-correlated with the radial (SV) component to estimate lag of the first and largest spike in the RF.
  - Current RF is then convolved with the vertical component seismogram (P) is subtracted from the radial (SV) component.
  - Procedure repeats until misfit is sufficiently reduced



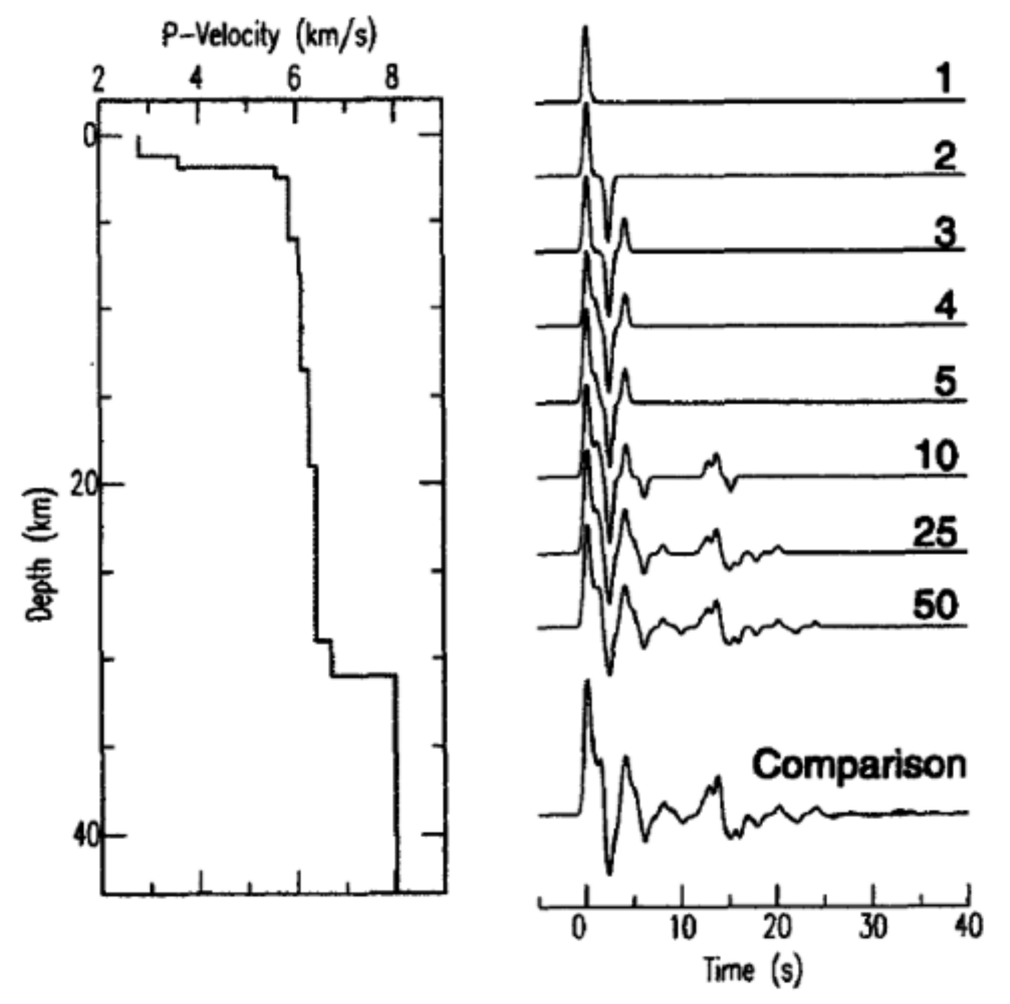
Liggoría and Ammon (1999)

Deconvolution – Approaches and limitations

Deconvolution in the time domain (Ps and Sp)

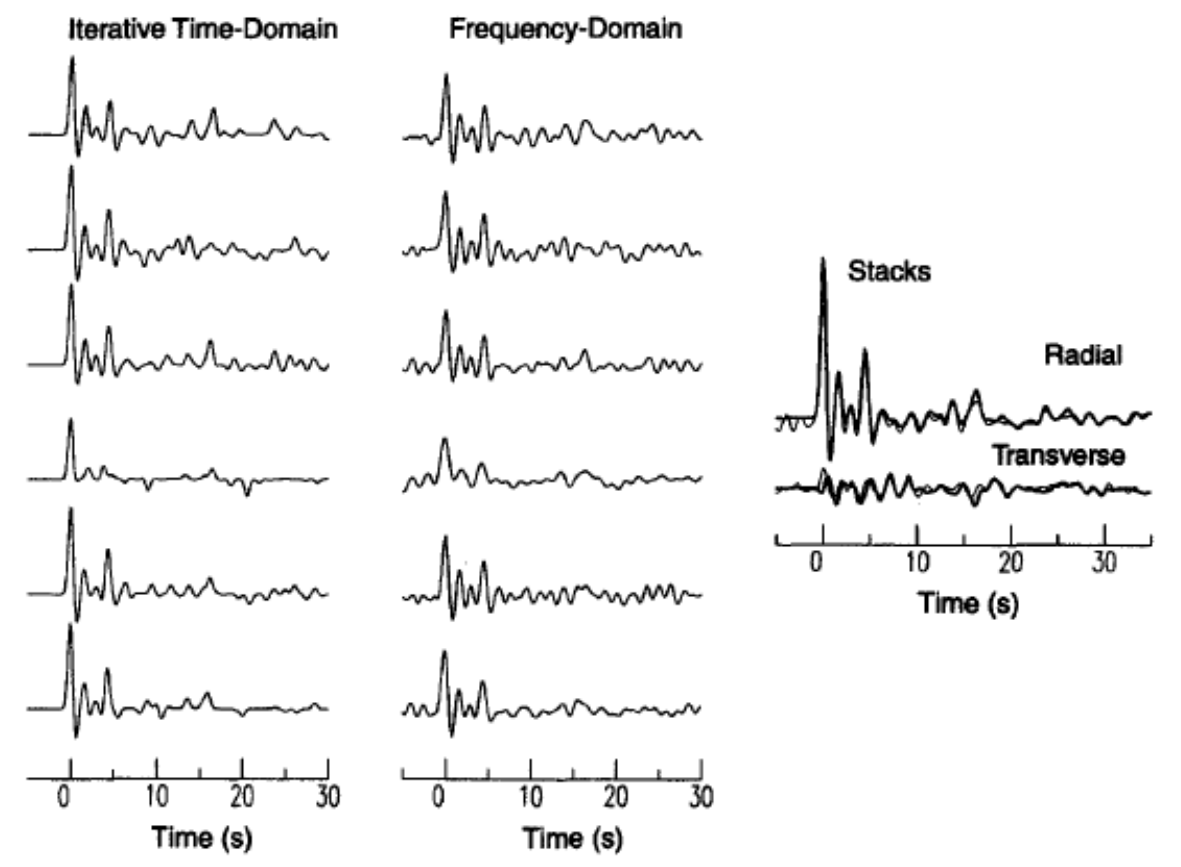


Liggoría and Ammon (1999)



Liggoría and Ammon (1999)

Deconvolution – Approaches and limitations

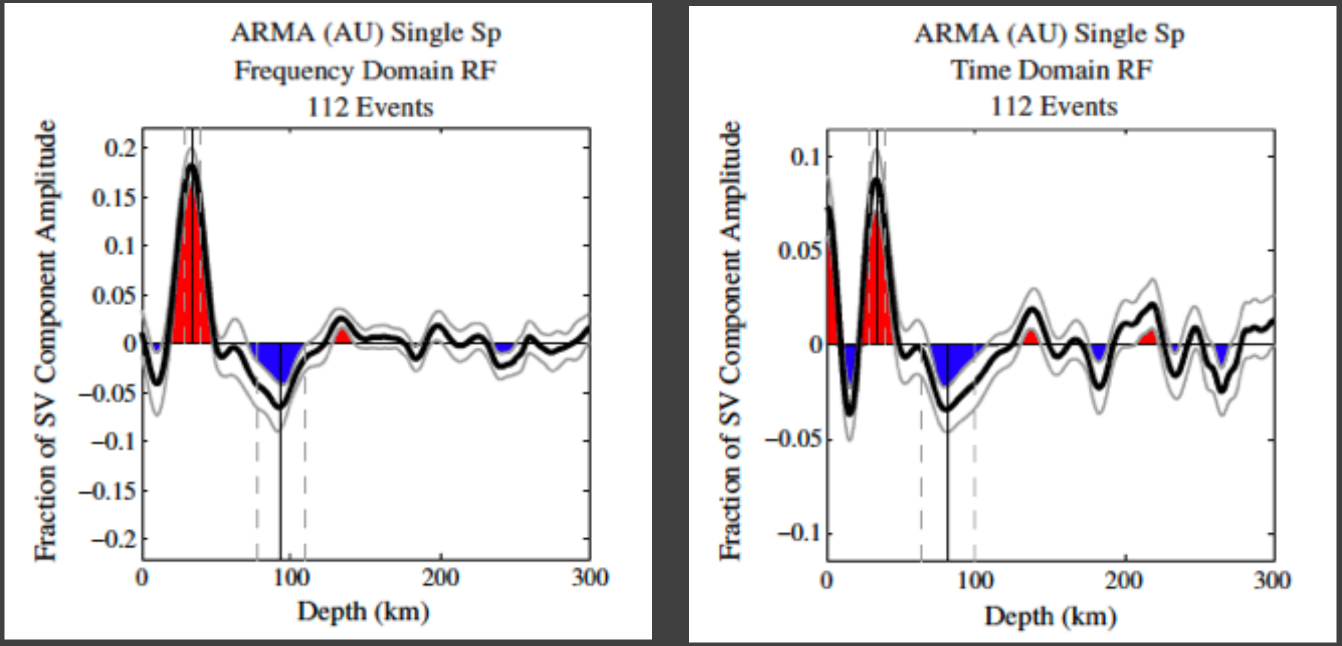


Liggoría and Ammon (1999)

Frequency vs. time domain approach

- Time domain considered to be less computationally efficient
- Time domain does not require a water level or damping parameter required in frequency domain methods
- Time domain does not have the same issues of acausal troughs (side lobes) that frequency domain methods can struggle with

Deconvolution – Approaches and limitations



Ford et al. (2010)

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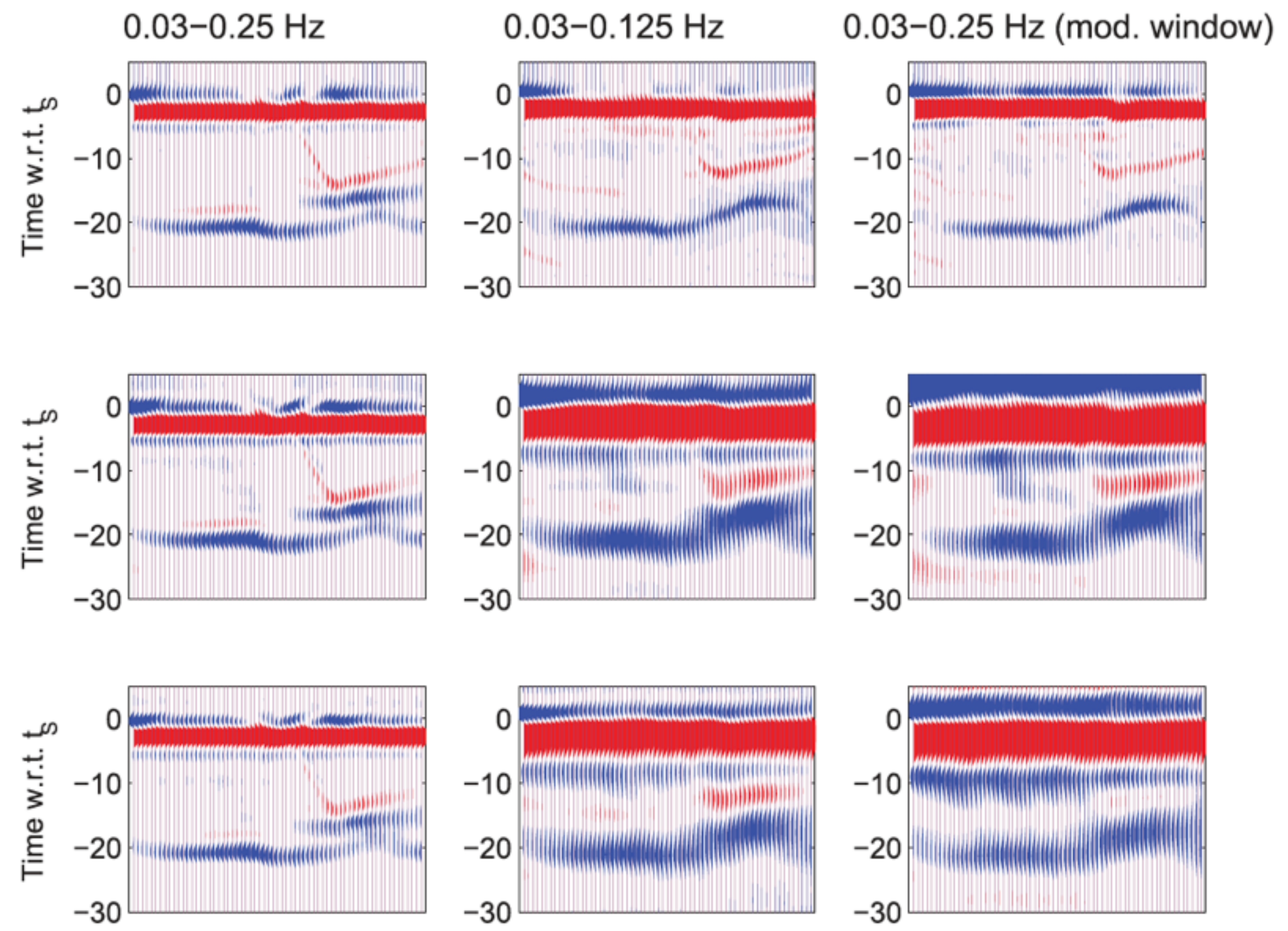
Deconvolution – Approaches and limitations

Time domain

Freq. domain

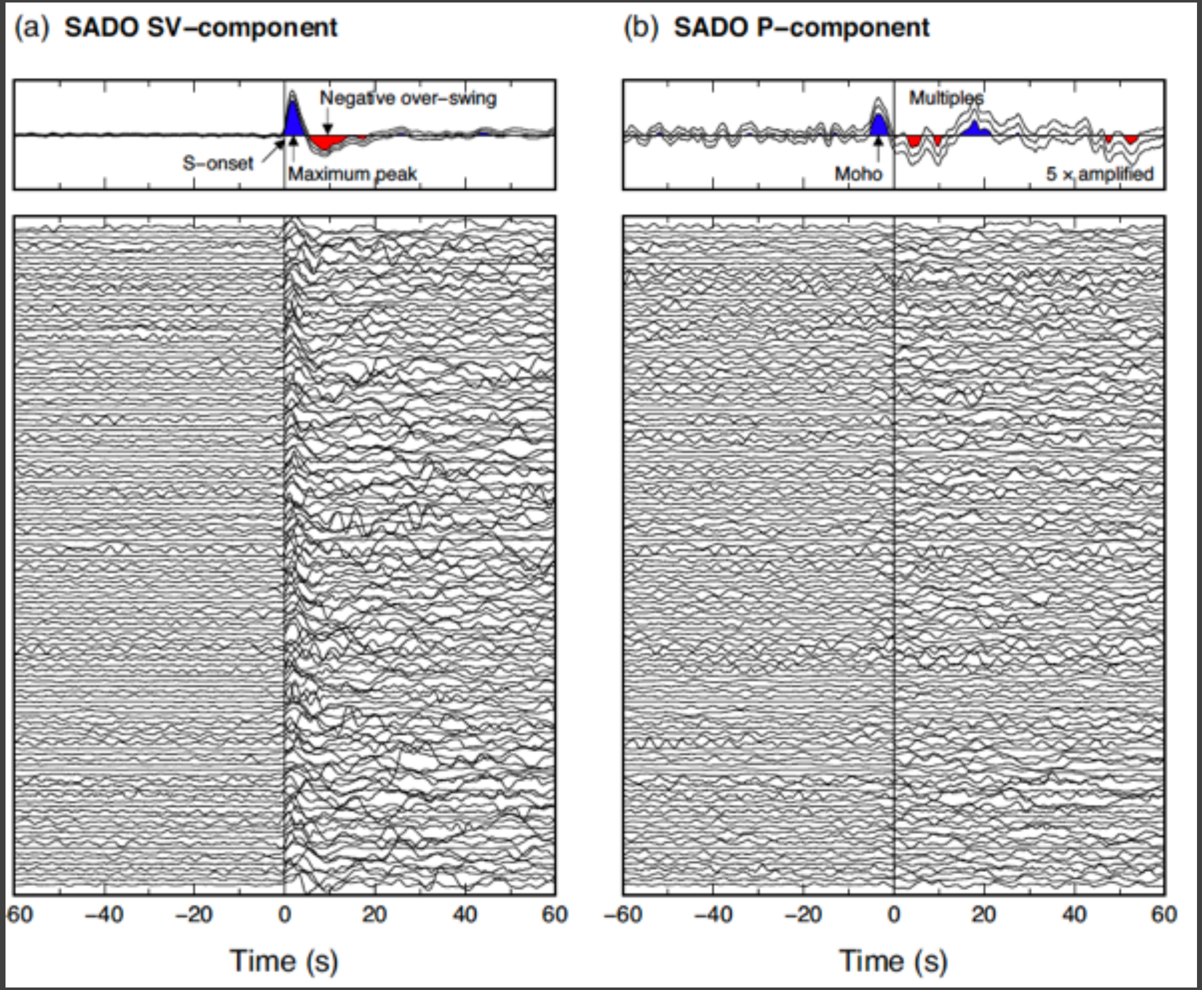
Extended time multitaper method



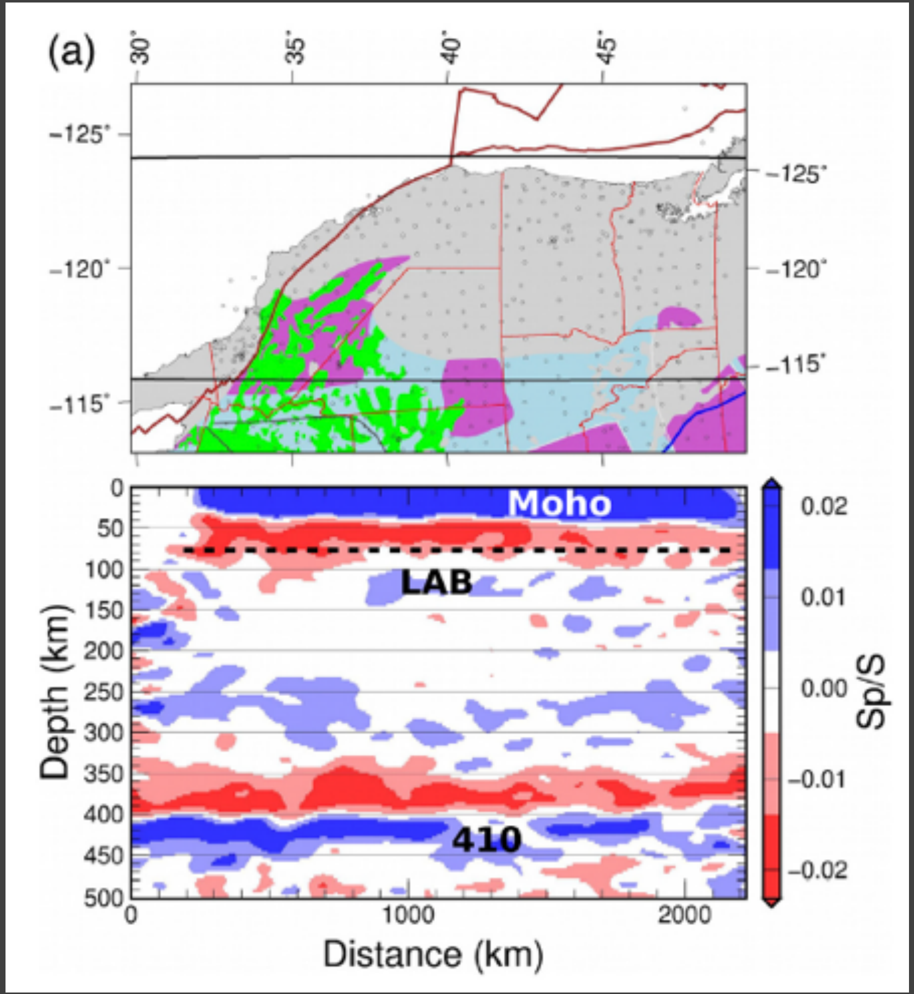
Lekic and Fischer (2017)

Deconvolution – Approaches and limitations

"causal" SRF method



Kind et al. (2020)



Kind et al. (2020)

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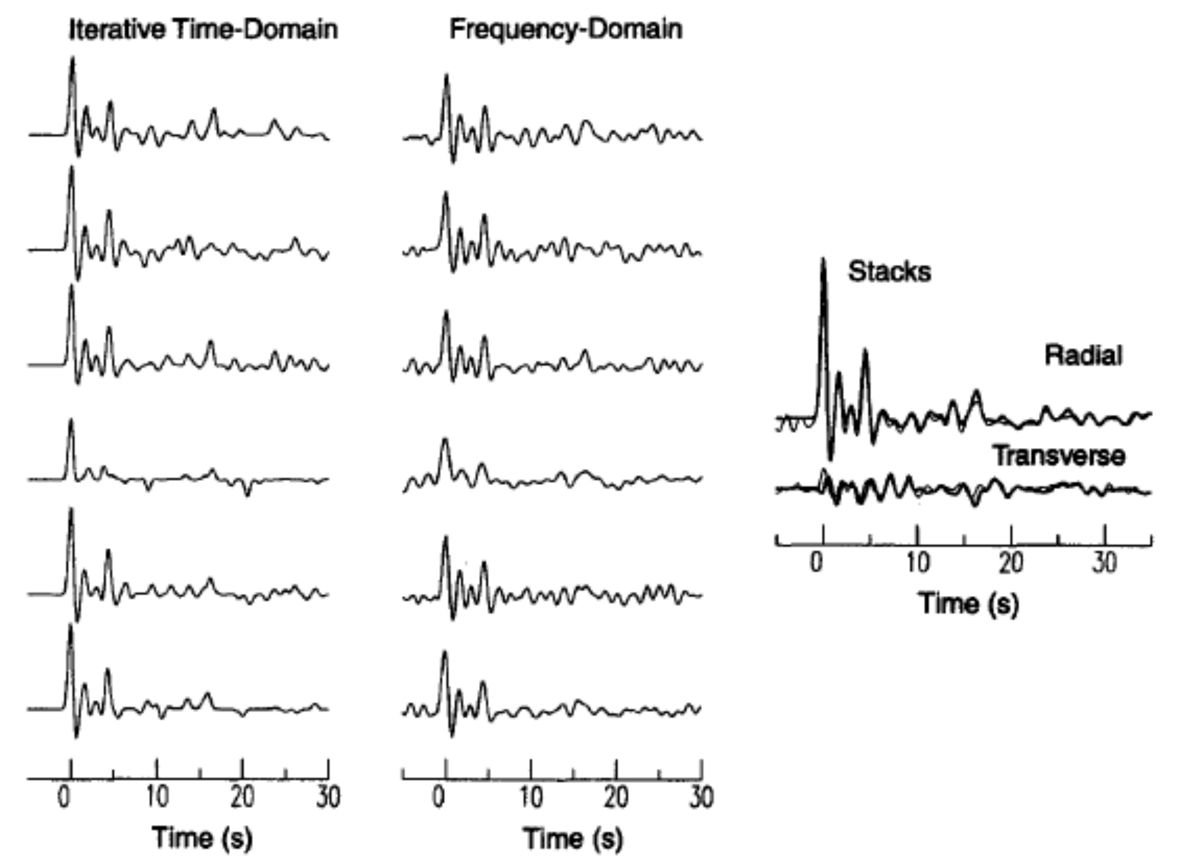
Stacking and moveout correction

RF analysis goal: Enhance the signal



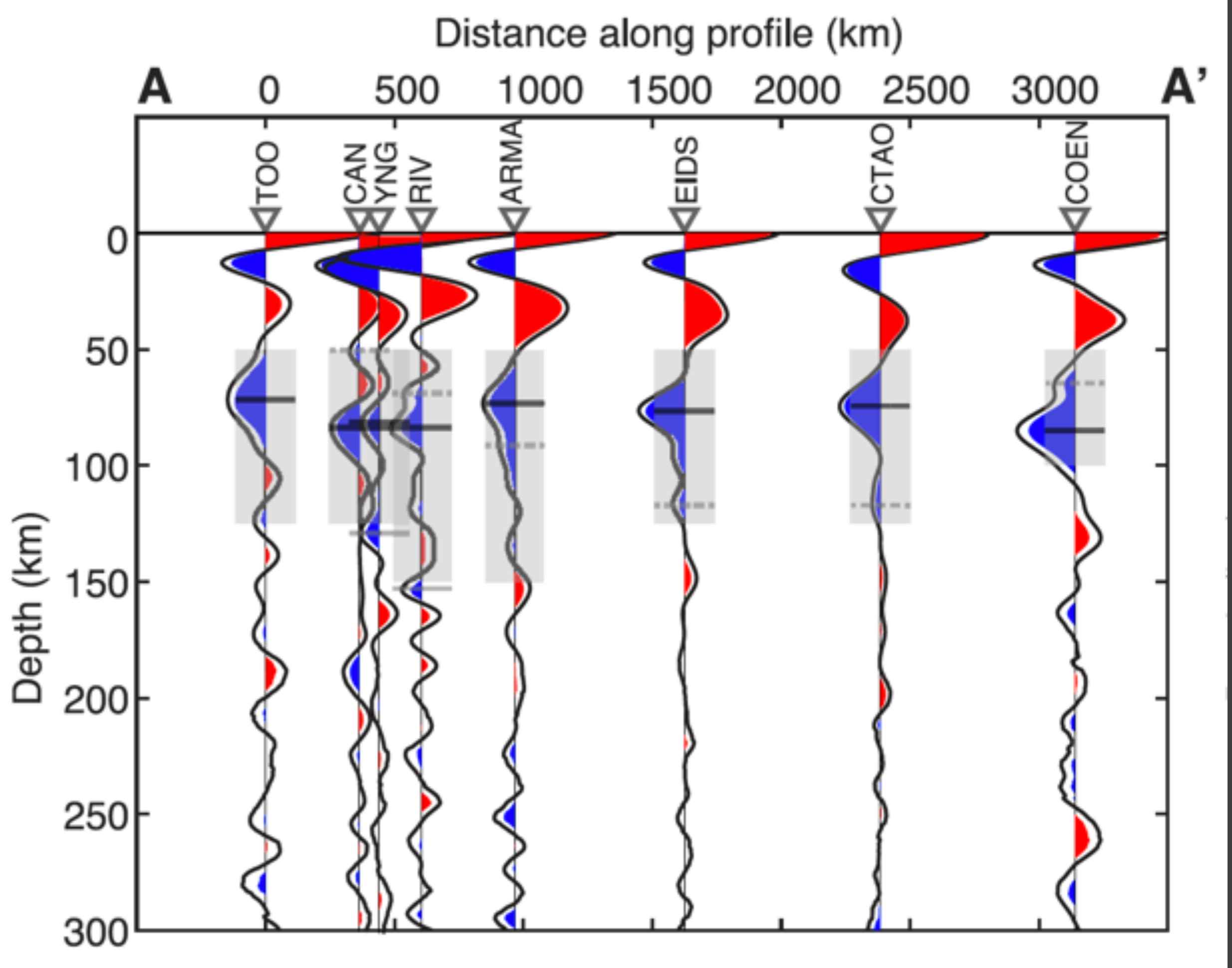
Liggoría and Ammon (1999)

Commonly used stacks:

- Single station stack
- Epicentral distance stack
- Backazimuthal stack
- Common Conversion Point

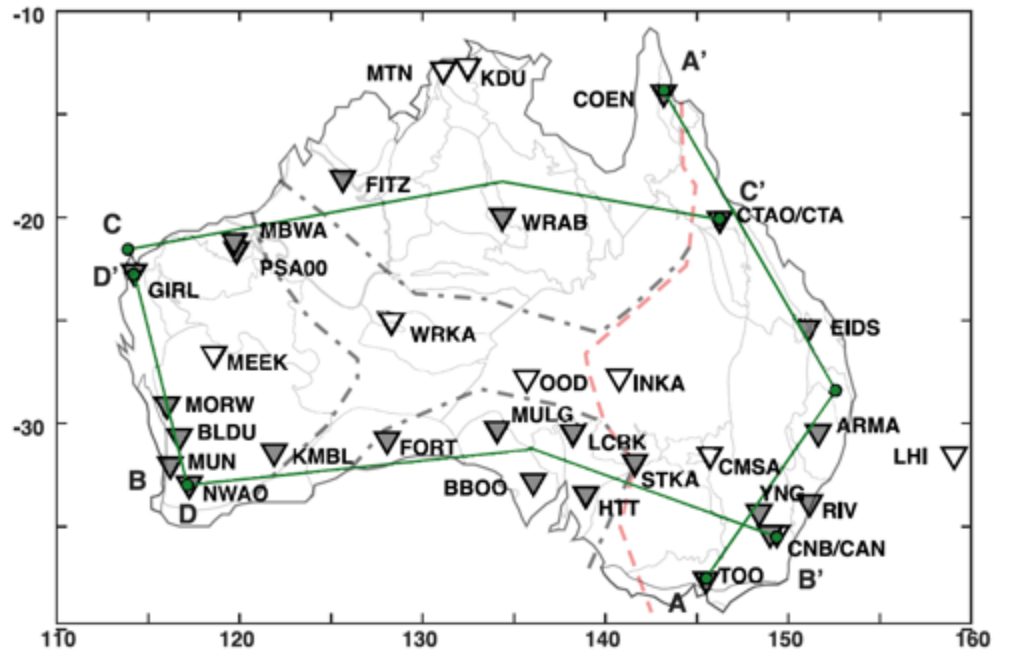
Stacking and moveout correction

RF analysis goal: Enhance the signal



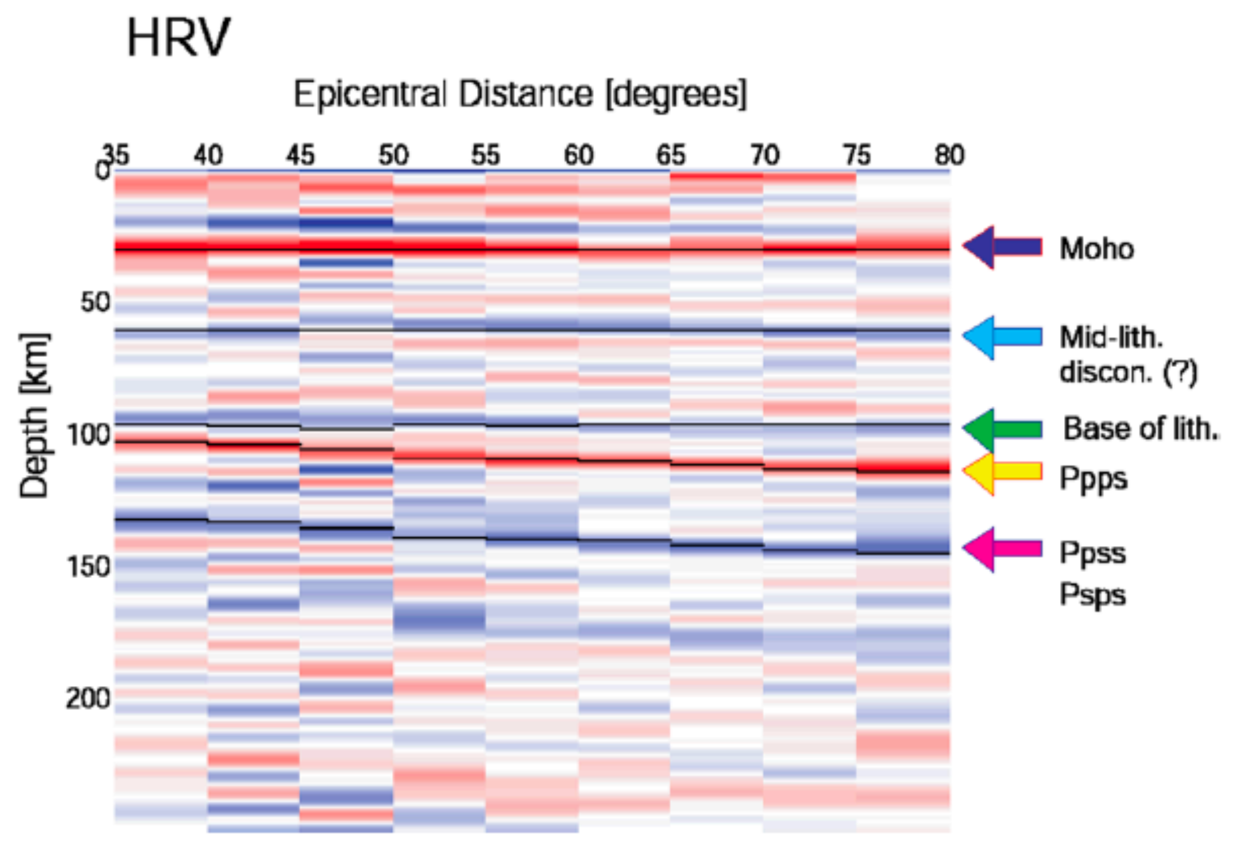
Berkey et al. (2021)

Single station stacks are useful for covering large geographic regions and/or regions when station spacing is not dense enough to permit other techniques



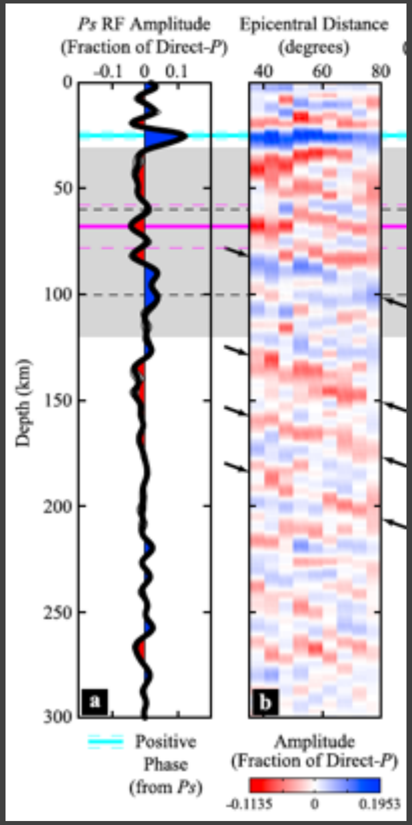
Stacking and moveout correction

RF analysis goal: Enhance the signal



Rychert et al., (2007)

Epicentral distance stacks are useful for discriminating between converted phases and crustal multiples, which can be an issue for Ps receiver functions

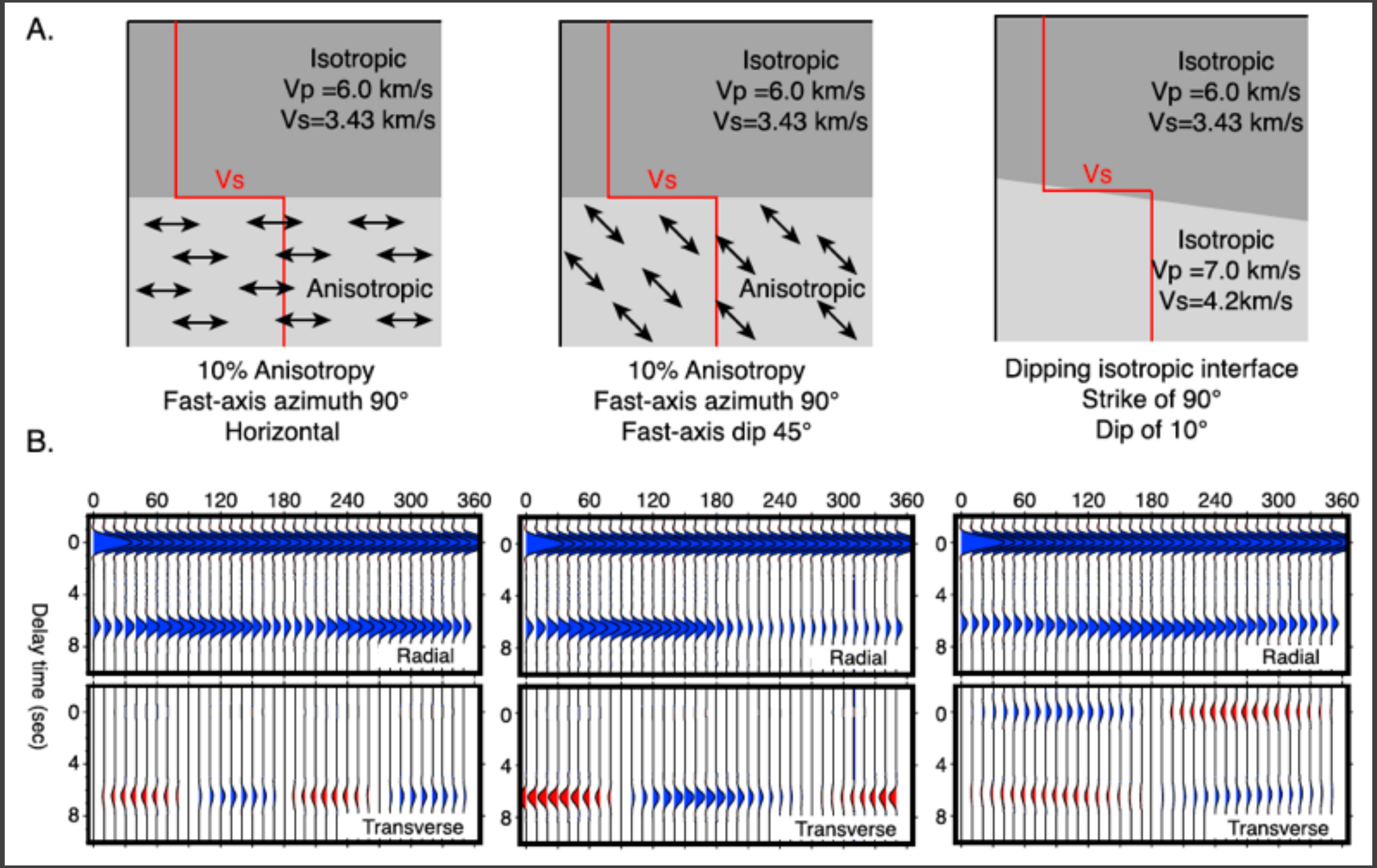


Abt et al. (2010)

Stacking and moveout correction

RF analysis goal: Enhance the signal

Backazimuthal stacks are useful for characterizing dipping layers as well as anisotropy

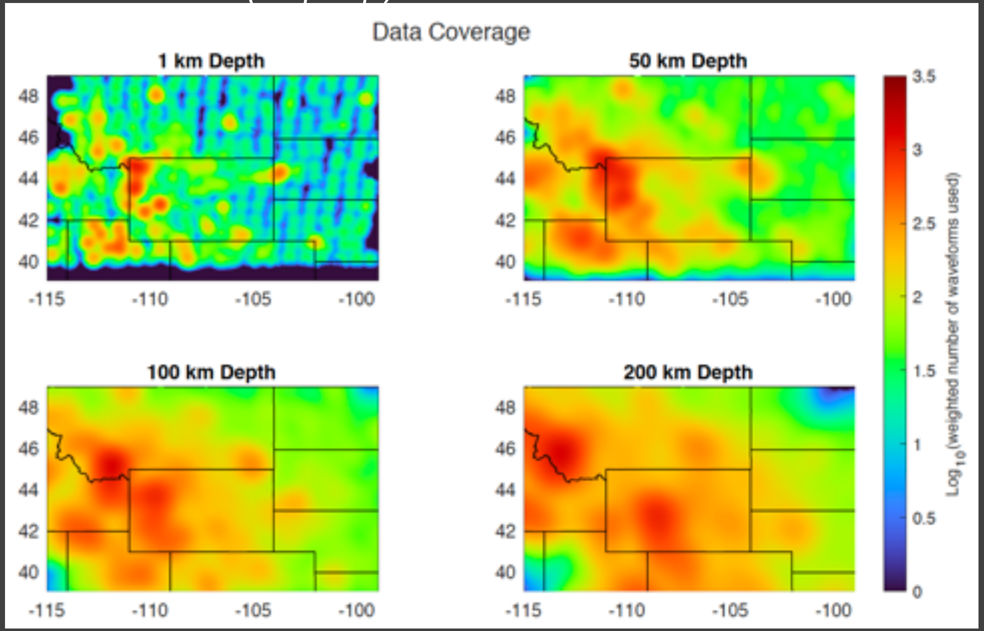


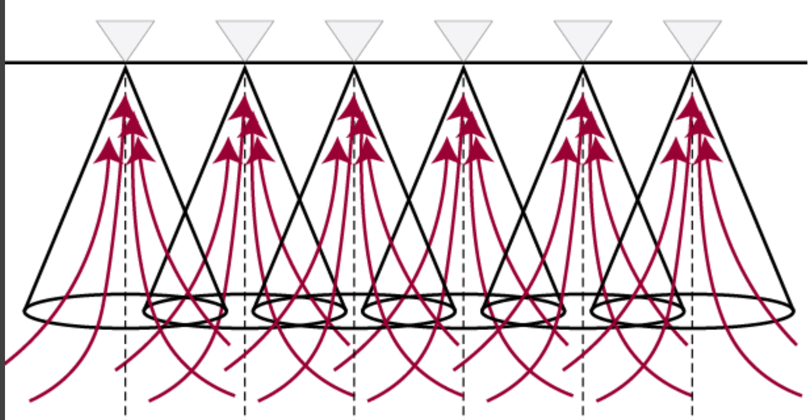
Ford et al. (2016)

Stacking and moveout correction

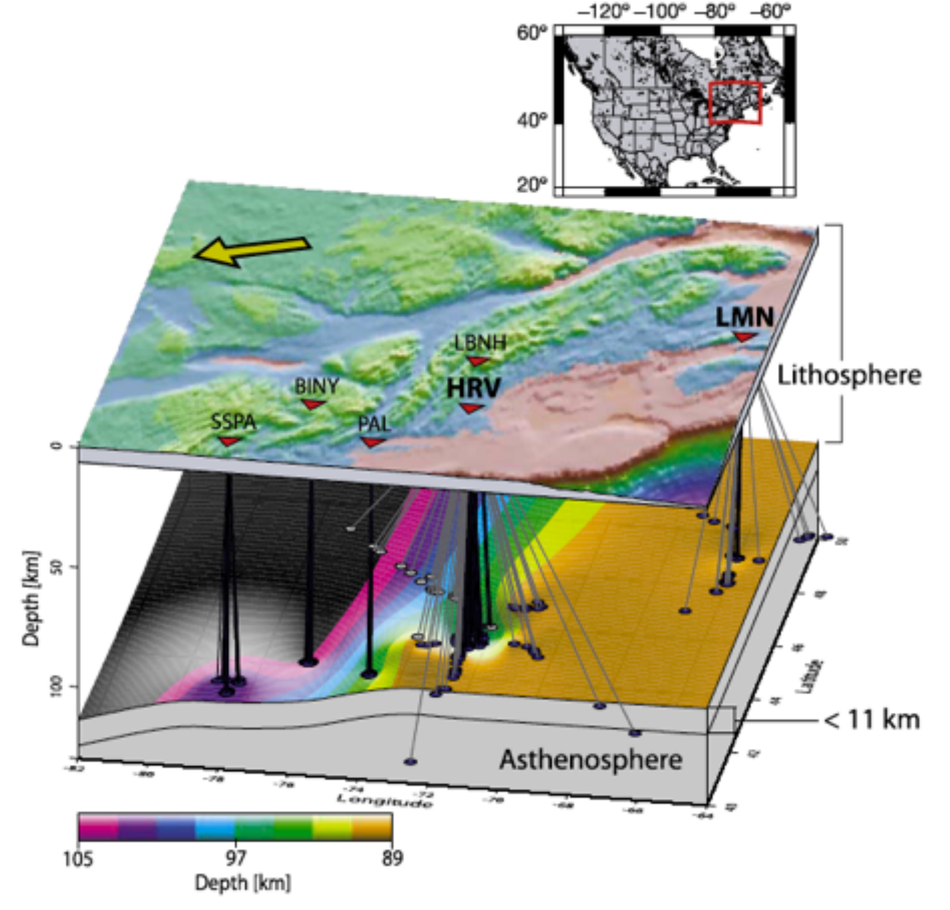
RF analysis goal: Enhance the signal

Shallon et al. (in prep)





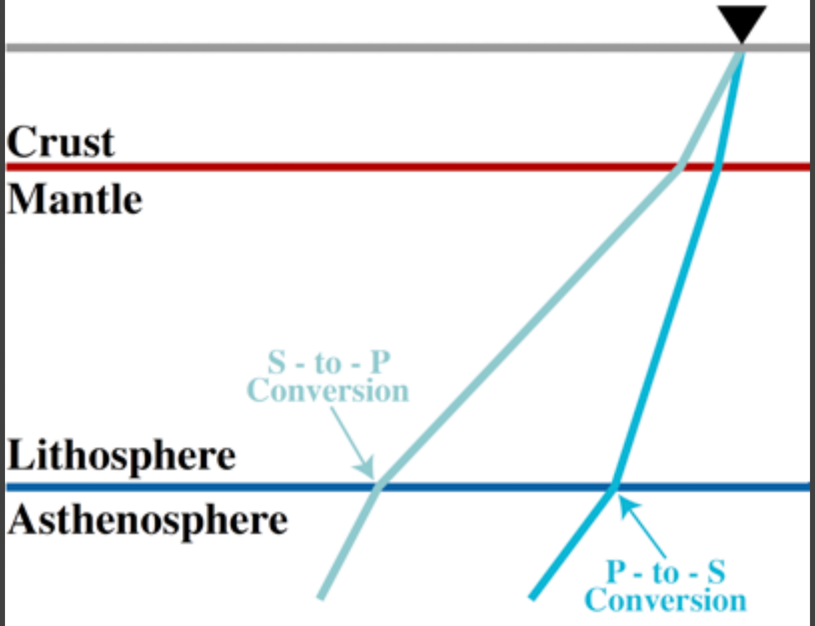
Common conversion point stacks are useful for generating 3D images of structure, if the station density is great enough

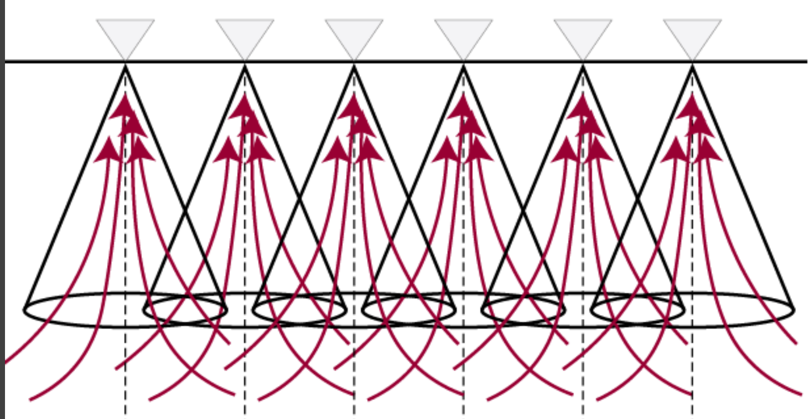


Rychert et al. (2005)

Stacking and moveout correction

RF analysis goal: Enhance the signal





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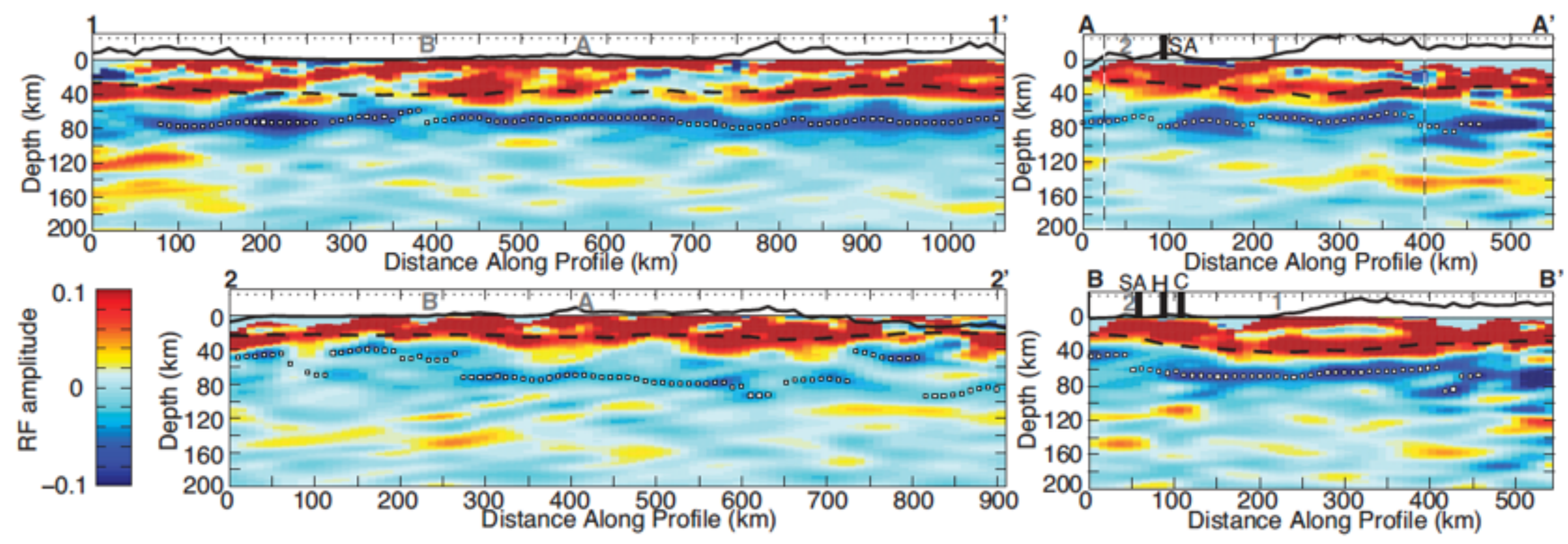
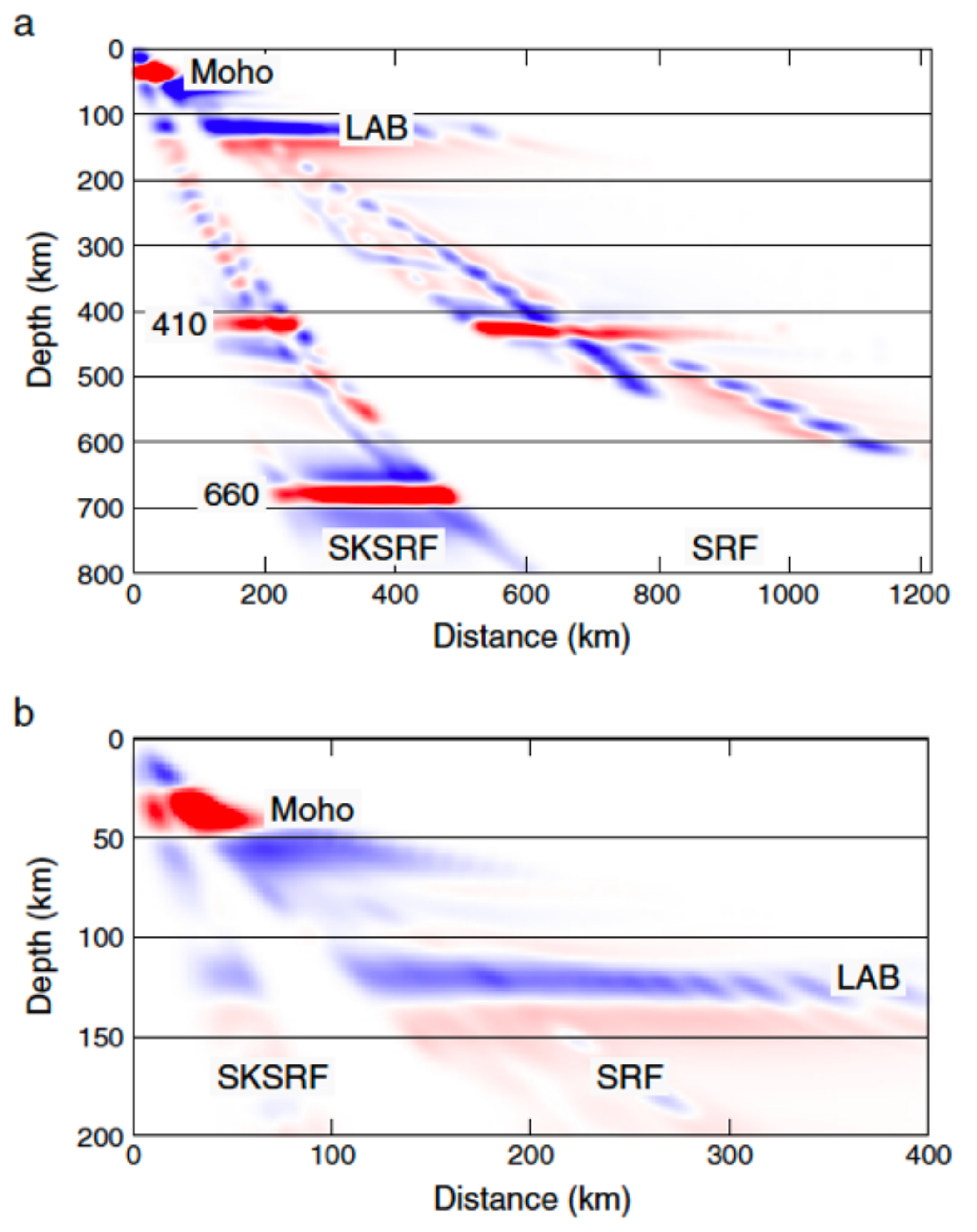


Ford et al. (2014)

Stacking and moveout correction

RF analysis goal: Enhance the signal

In order to stack events however, we have to consider where the event comes from (epicentral distance, backazimuth) and make any necessary adjustments with steps including a move-out



Kind et al. (2012)

Stacking and moveout correction

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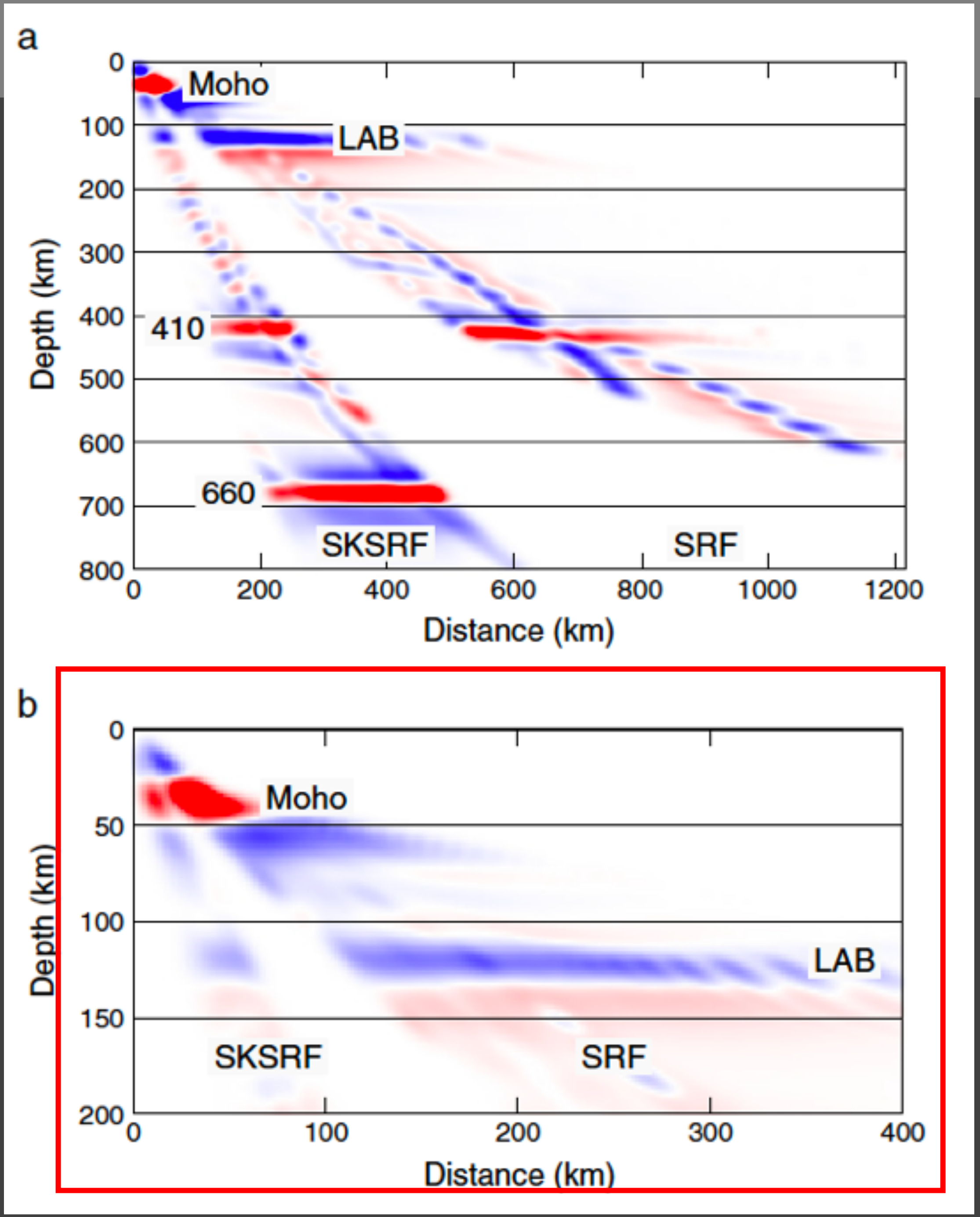
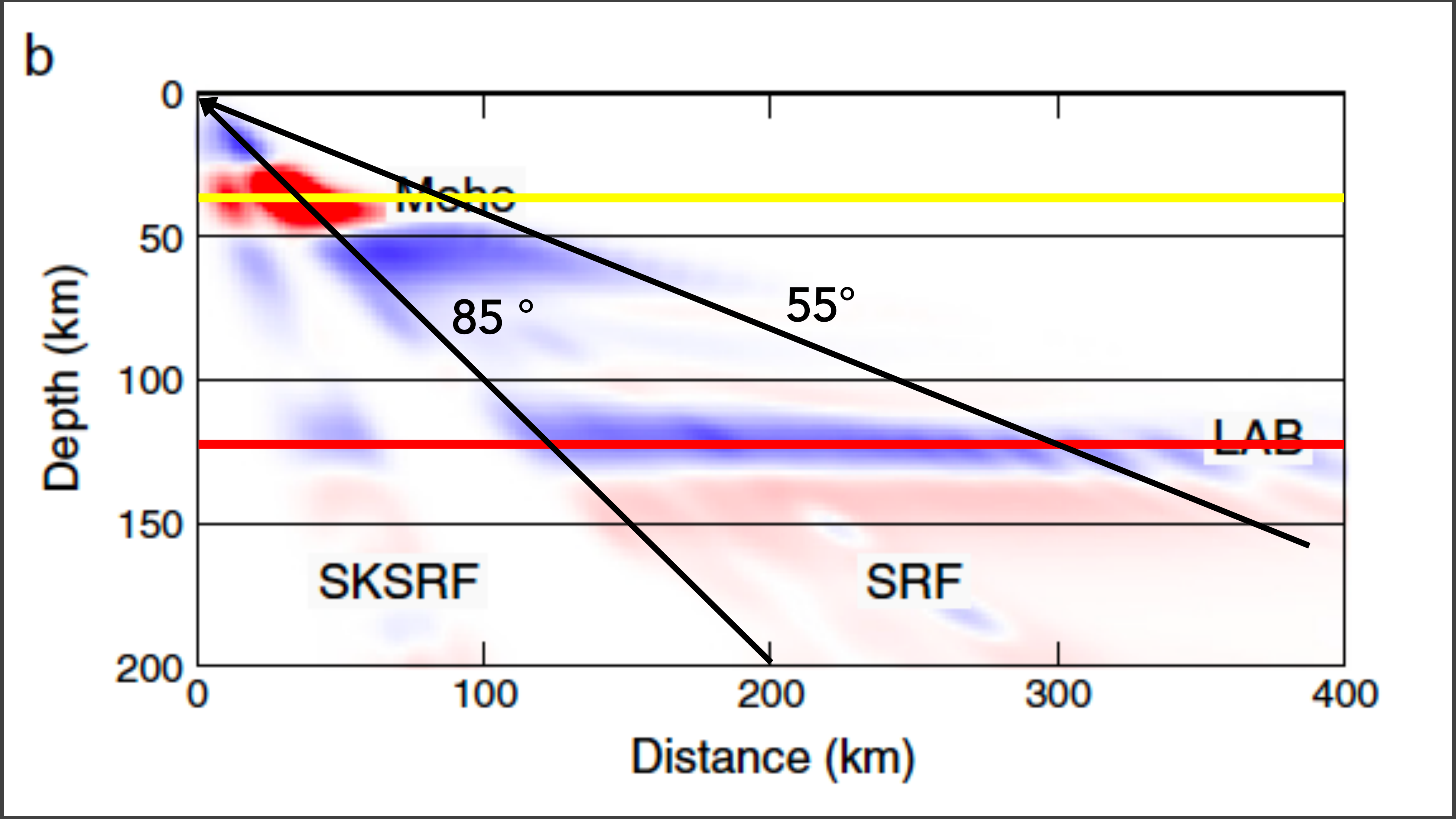


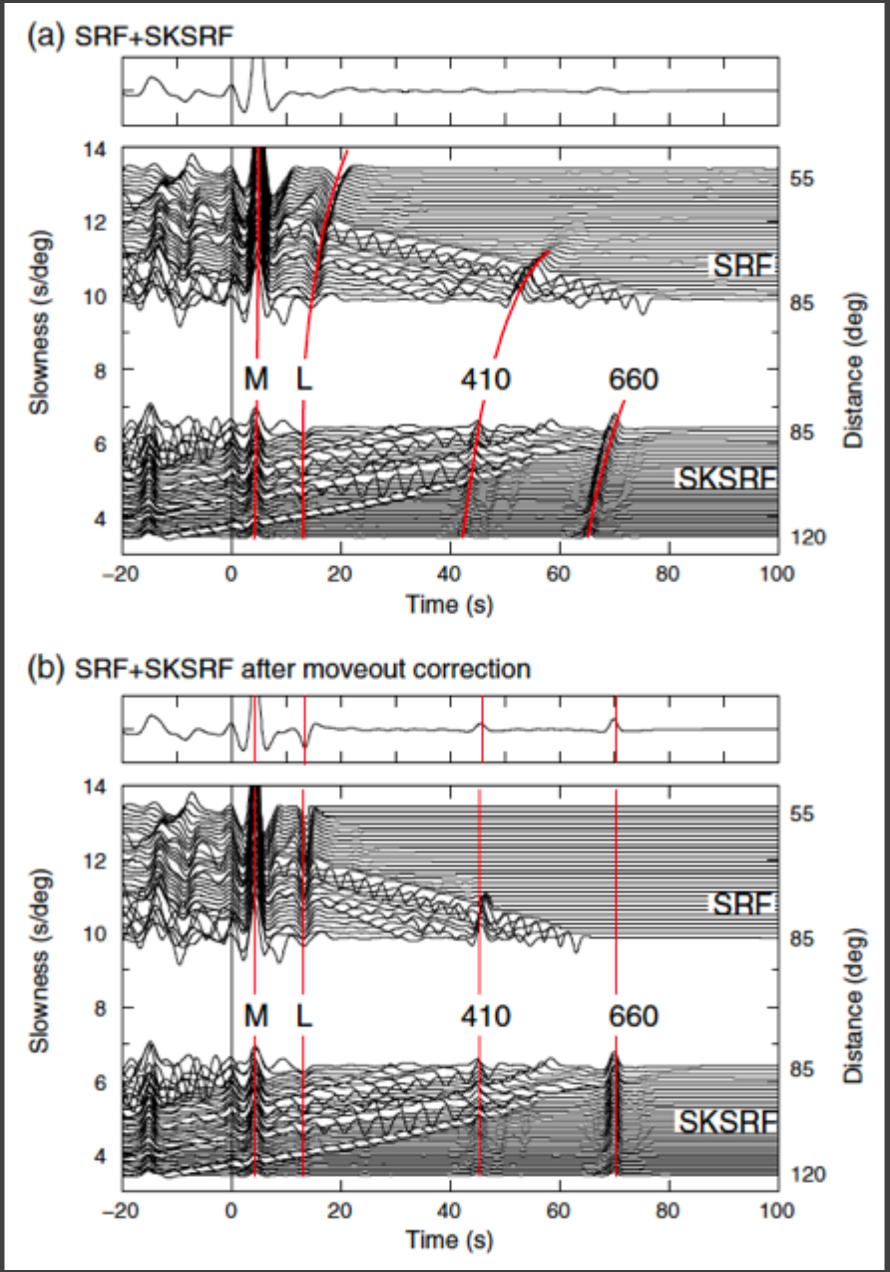
Kind et al. (2012)

Stacking and moveout correction



Kind et al. (2012)

Stacking and moveout correction

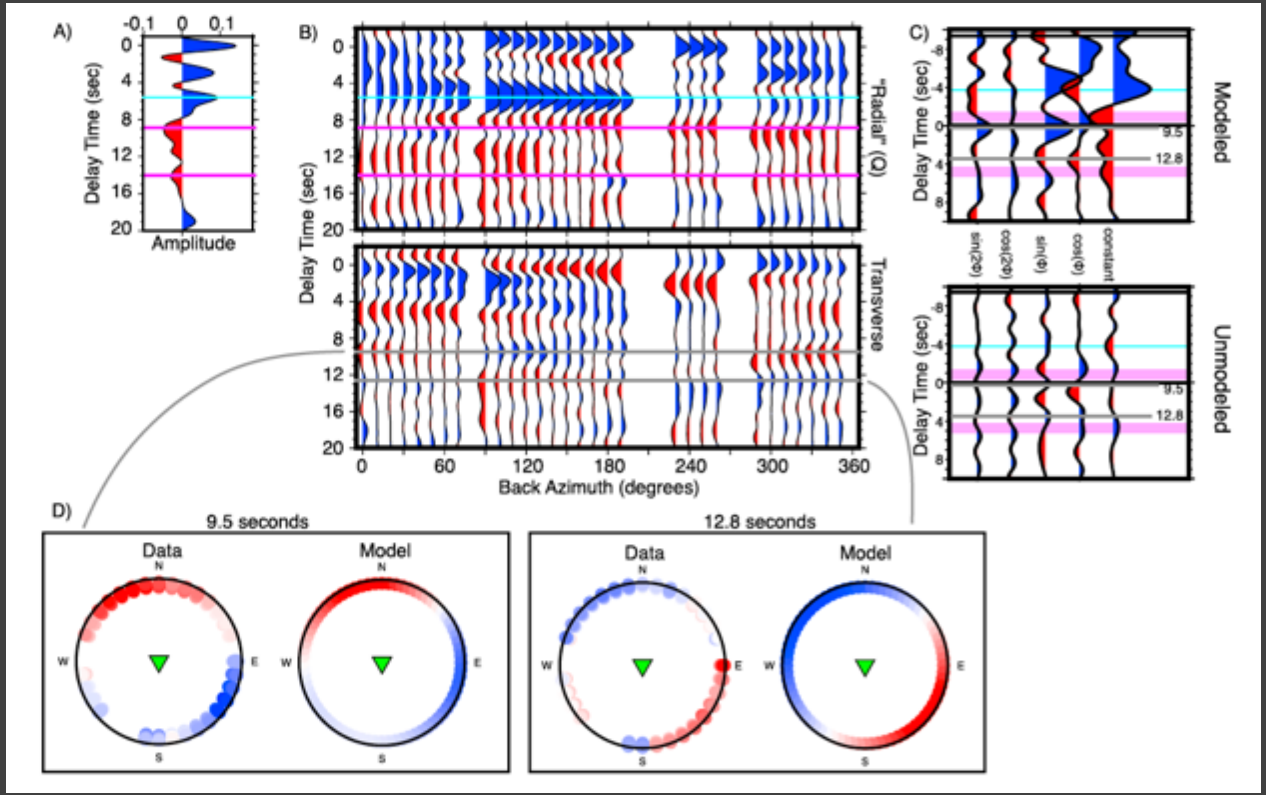


Moveout correction

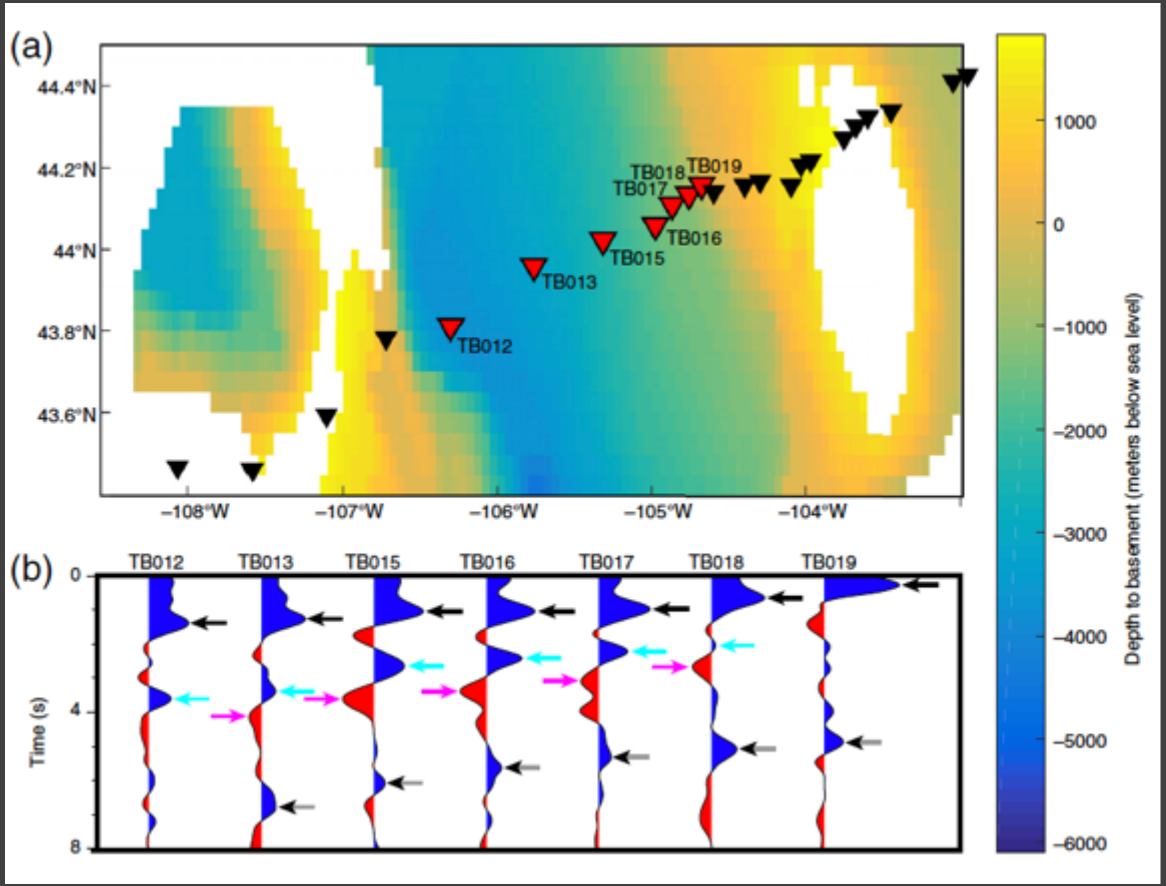
- When the moveout correction is applied varies amongst studies.
- A reference velocity model is required in order to complete a moveout correction
- A reference distance is selected, and the time scale of the other distances/events are stretched or compressed in order to match the reference distance.
- Times are compressed at shorter distances (larger slownesses) and stretched at longer distances (smaller slownesses)

Kind et al. (2012)

Migration



Ford et al. (2016)

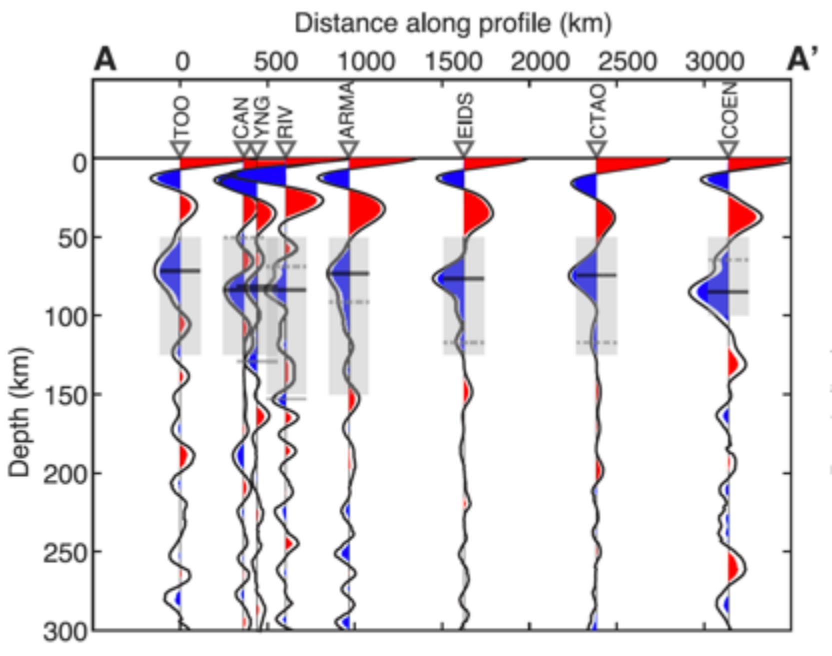


Ford et al. (2021)

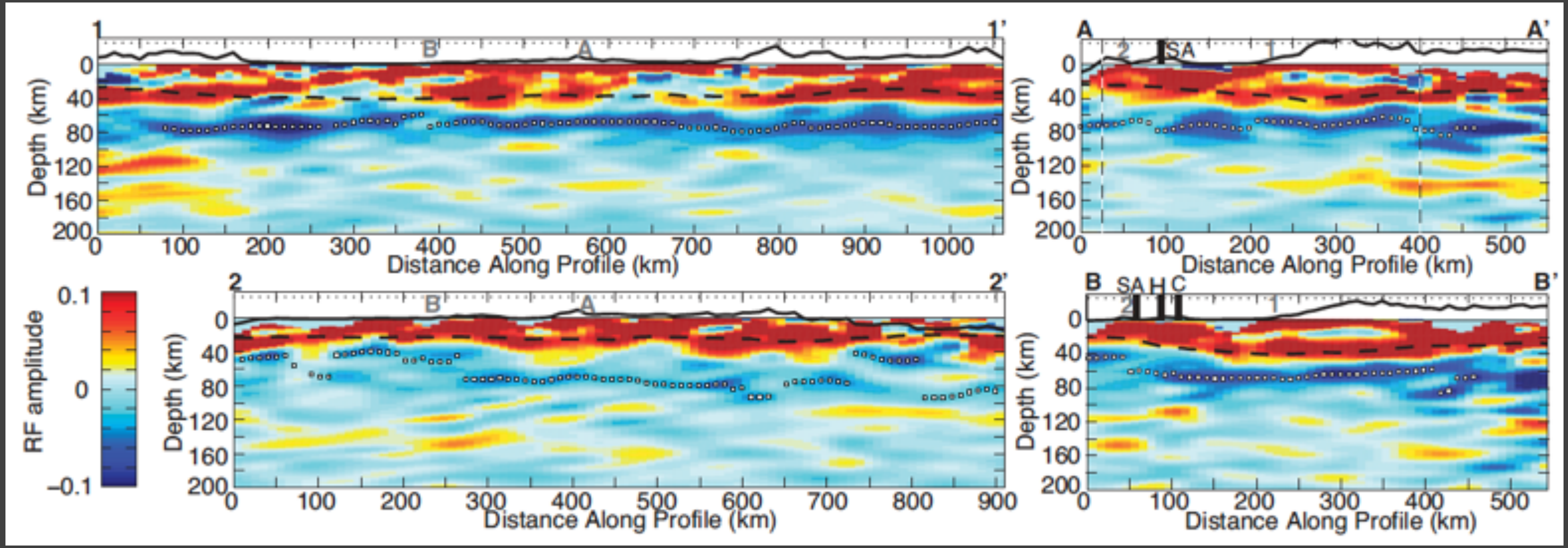
Migration

Receiver function are fundamentally a time series, however, many authors choose to assume a velocity structure and convert the time series to an approximate depth. This is referred to as migration.

Migration



Birkey et al. (2021)



Ford et al. (2014)

Migration
Migration to depth requires the assumption of a velocity model, which may not be accurate. But provides the readers with a better sense of depths that boundaries or other features may be located at.

Photo courtesy of
Grant Clark

Body-wave constraints on lithospheric structure

Questions?