Constraints on radial anisotropy in the central Pacific upper mantle from the NoMelt OBS array

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Lamont-Doherty Earth Observatory
Columbia University | Earth Institute
OCEAN BOTTOM SEISMOGRAPH INSTRUMENT POOL

Outline

- **Background & Motivation**
- **High frequency ambient noise (4-10 s)**
  - Characterizing NoMelt ambient noise signals
  - Phase velocity measurements and inversion
  - Anisotropy results
- **Love wave earthquake data (20-100 s)**
  - Challenges due to Love wave overtone interference
  - Forward modeling multimode Love waves to constrain radial anisotropy
- **Interpretation & Conclusions**

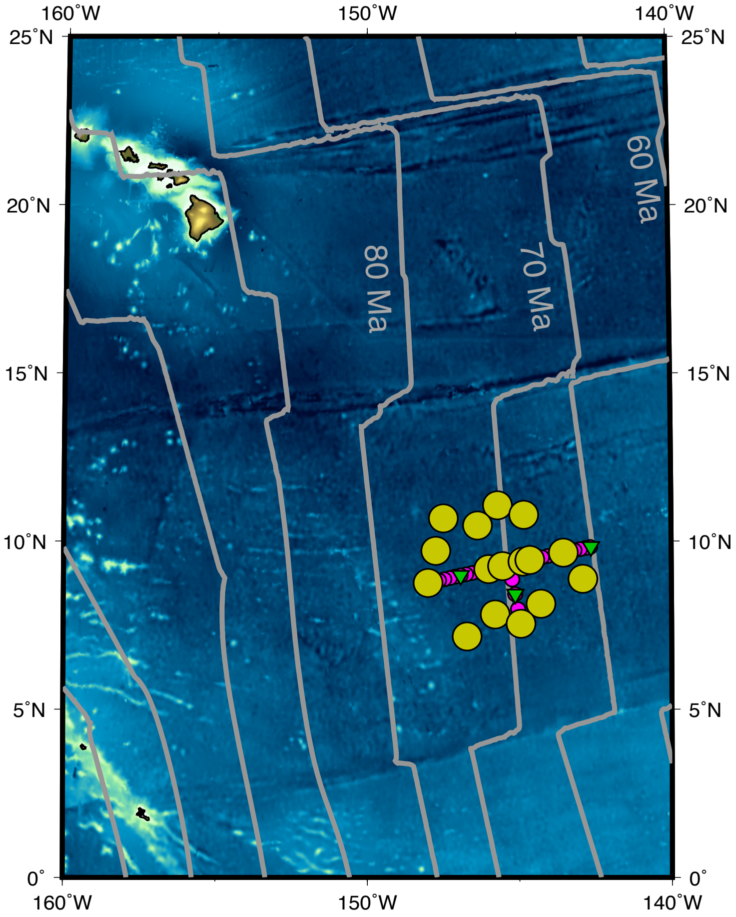
NoMelt Experiment

Situated on relatively pristine oceanic lithosphere (~70 Ma)

One year of continuous data collected in 2012

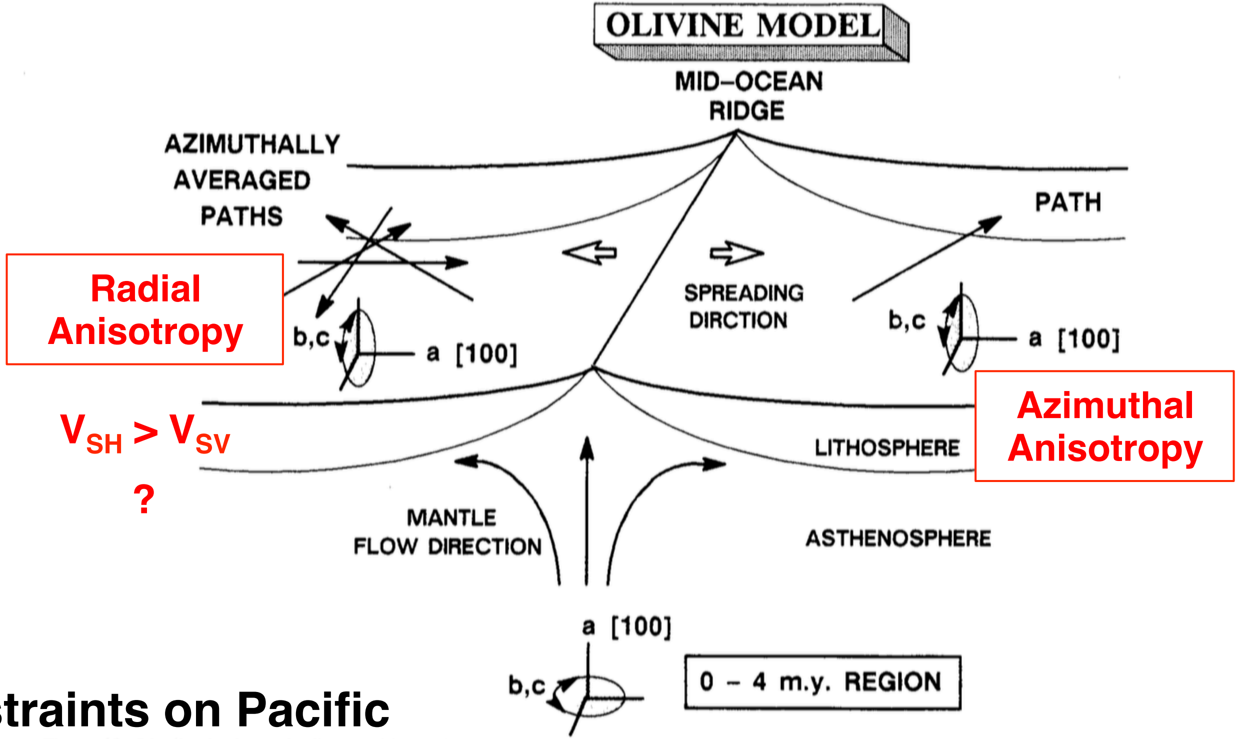
600x400 km footprint

- 16 broad-band OBS
- Short-period OBS
- Magnetotelluric array



Motivation

- Azimuthal and radial anisotropy constrain flow patterns within the mantle
- Horizontally aligned olivine fabric associated with **seafloor spreading**
- Inconsistencies between recent regional and global models of radial anisotropy in the lithosphere

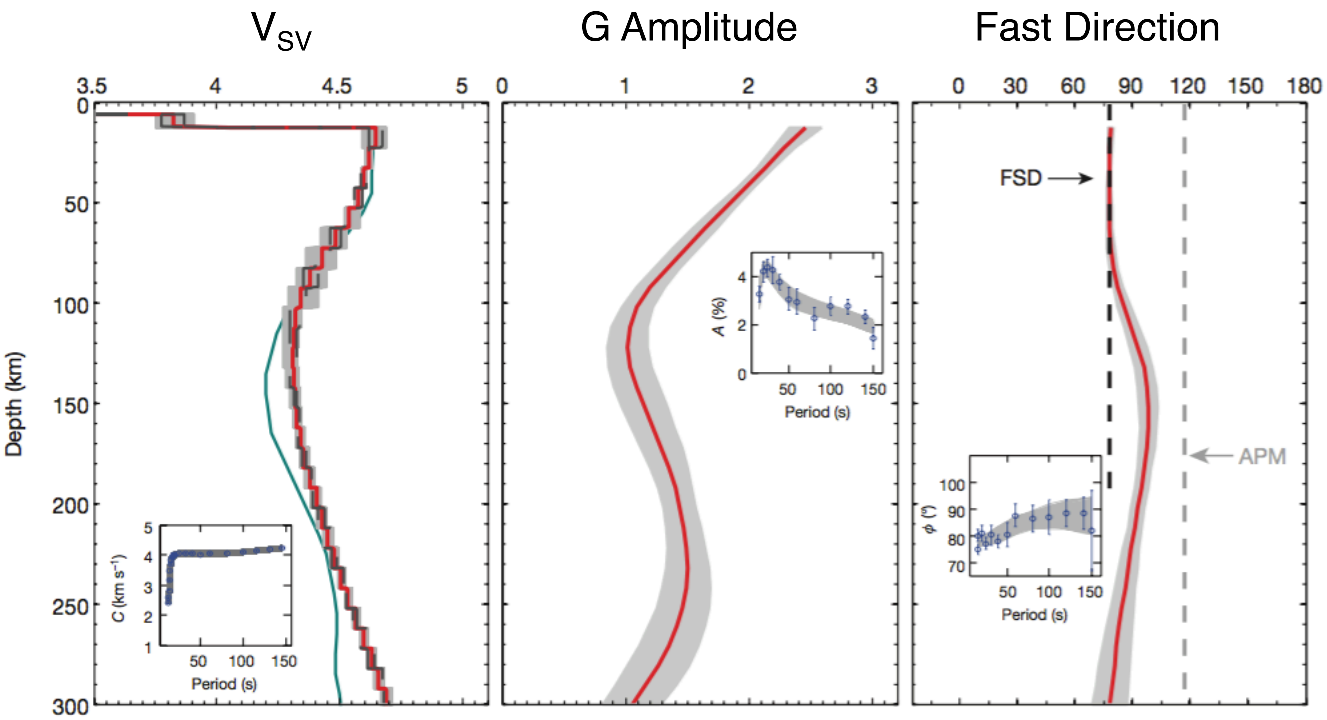


NoMelt provides new constraints on Pacific mantle anisotropy, measured at a local scale.

Nishimura & Forsyth, 1989

NoMelt azimuthal anisotropy (20-150 s Rayleigh)

Fast direction of Rayleigh wave phase velocities oriented parallel to the fossil spreading direction (~78º) in the lithosphere



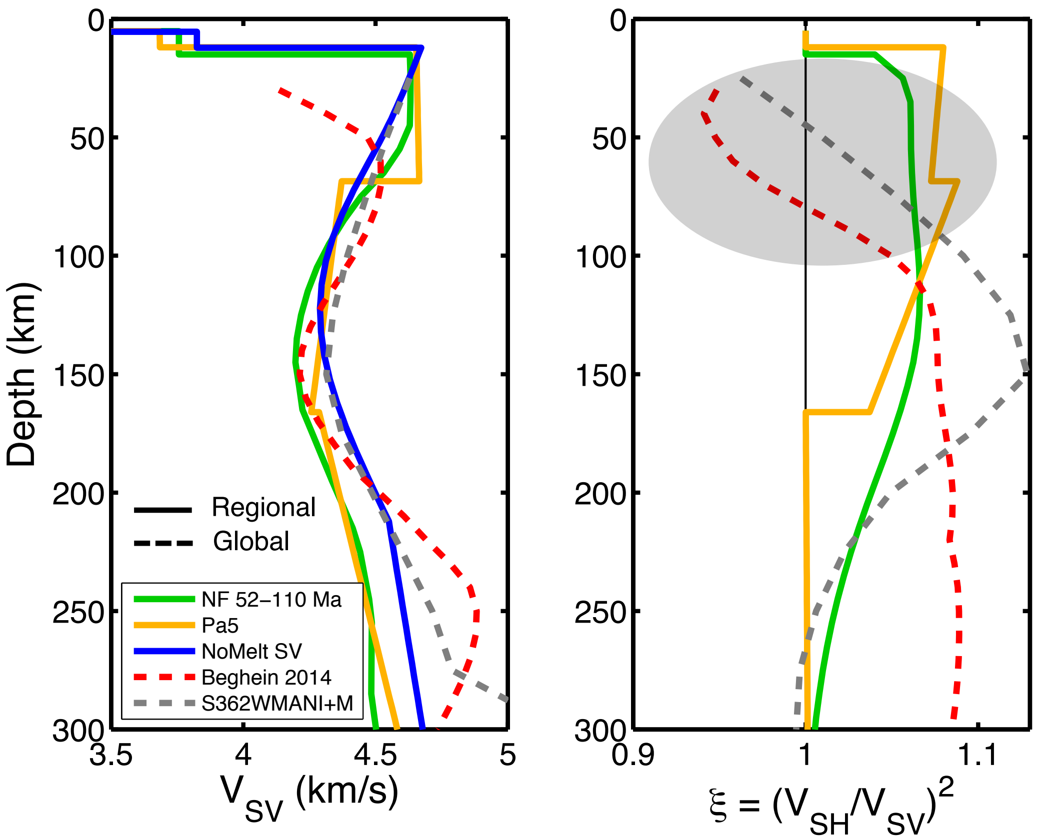
Lin et al., Nature (2016)

Motivation: Radial anisotropy

$$\xi = (V_{SH}/V_{SV})^2$$

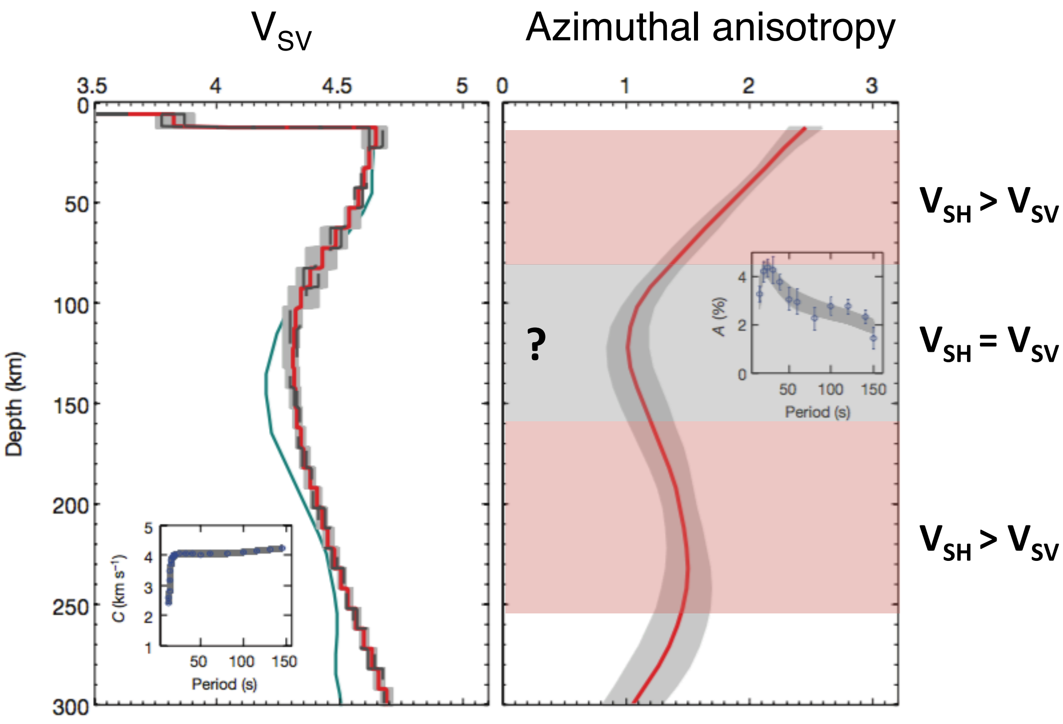
- ξ important for constraining upper-mantle circulation and evolution of the lithosphere-asthenosphere system
- Discrepancies between regional and global models of radial anisotropy
- Requires constraints from both **Love and Rayleigh** waves

Central Pacific Models



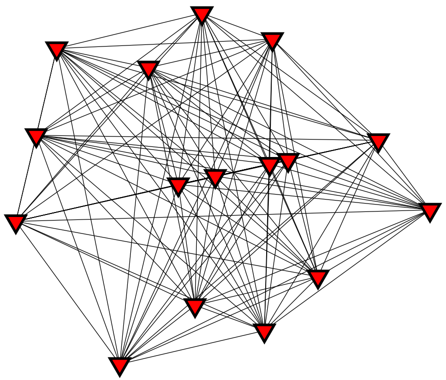
NoMelt radial anisotropy?

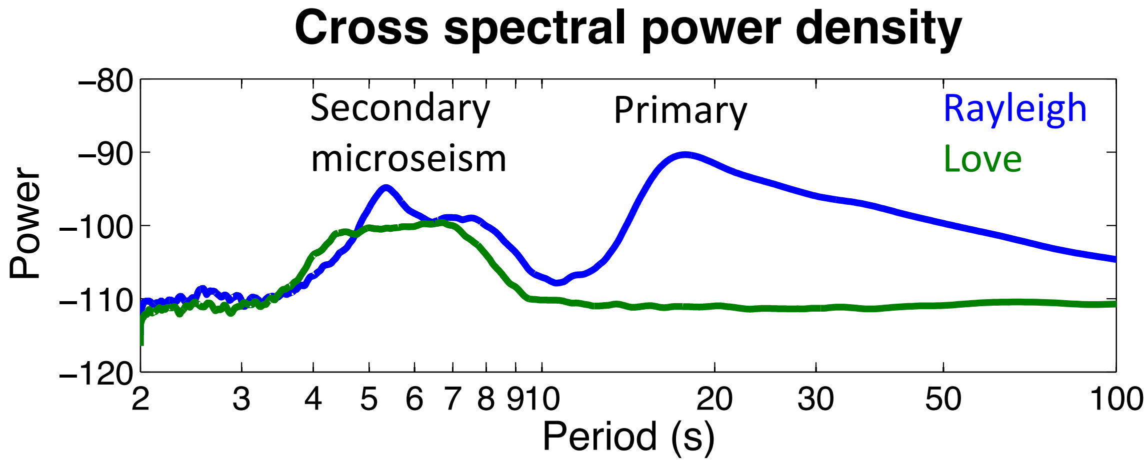
If lattice preferred orientation of olivine is responsible for azimuthal anisotropy, then radial anisotropy ($V_{SH} > V_{SV}$) should be correlated



NoMelt ambient noise signature

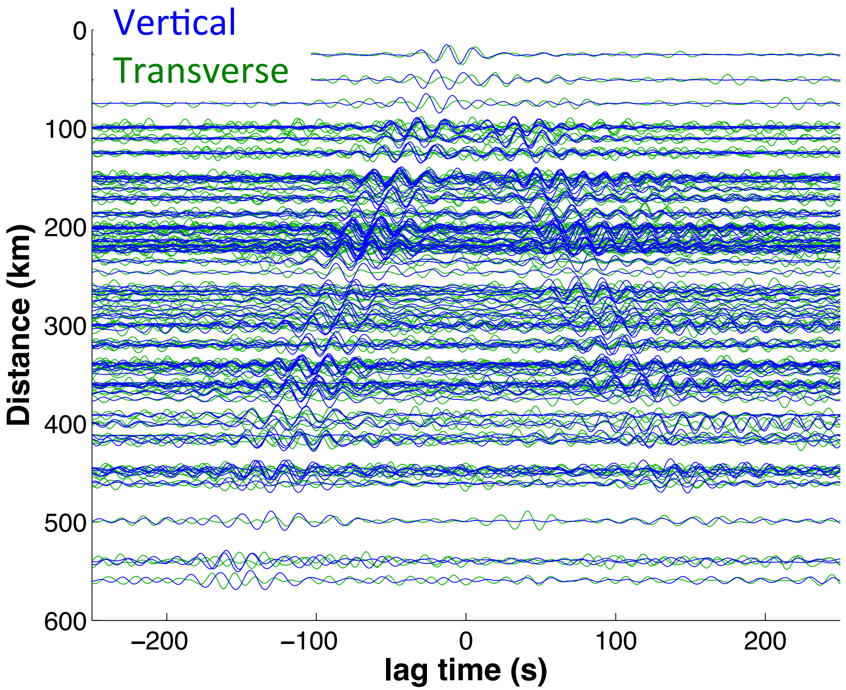
- Cross-correlate daily records to get interstation empirical Green's functions
- **Primary** and **secondary** microseism signals



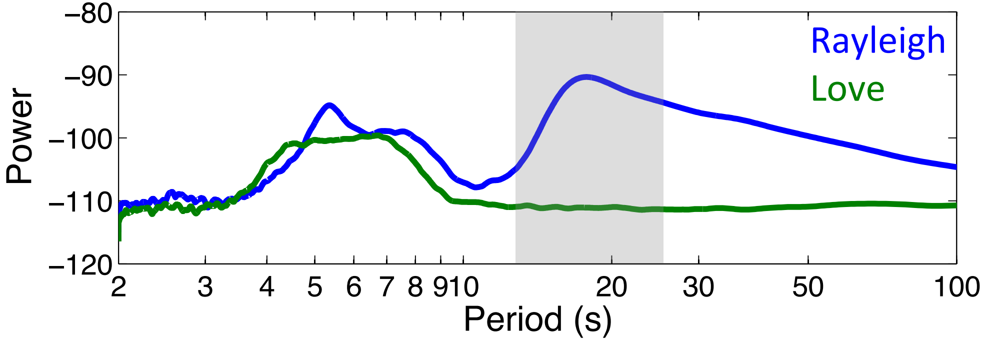


Primary Microseism (12-25 s)

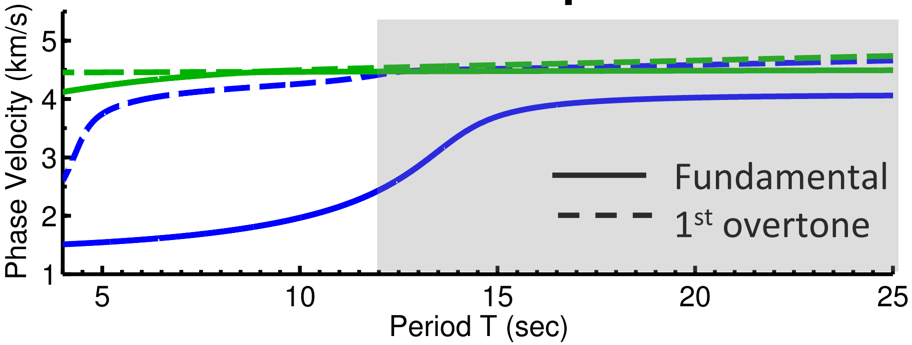
- **Rayleigh – Fundamental mode**
- **Love – No signal generated**



Cross spectral power density

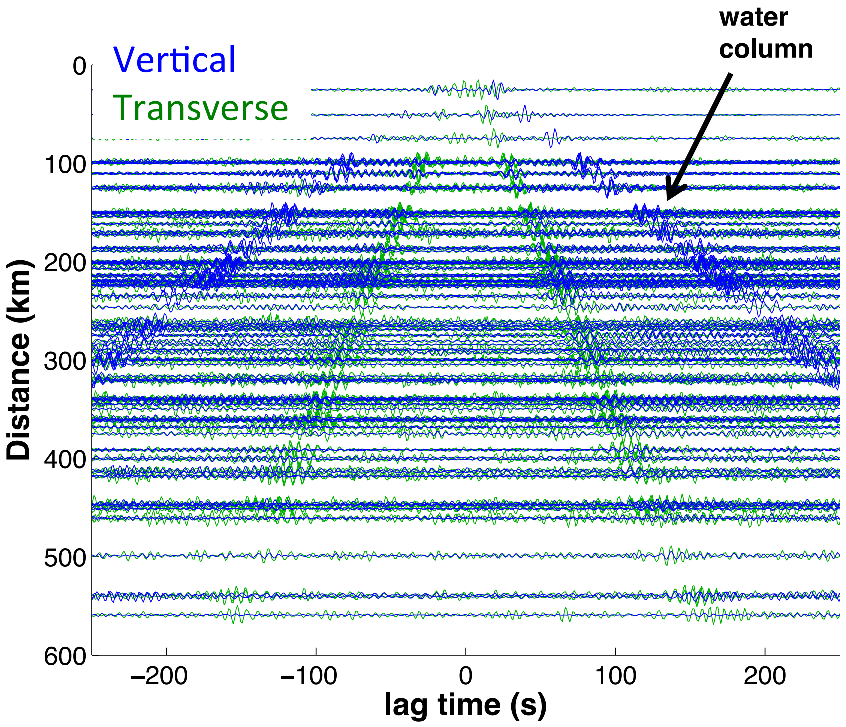


Estimated dispersion

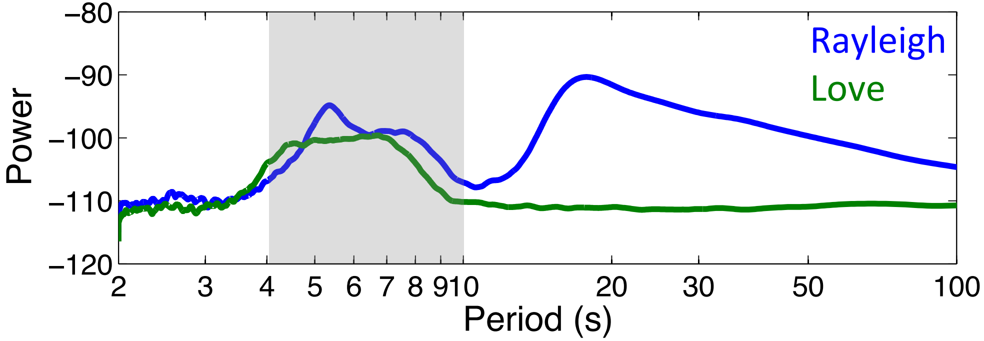


Secondary Microseism (4-10 s)

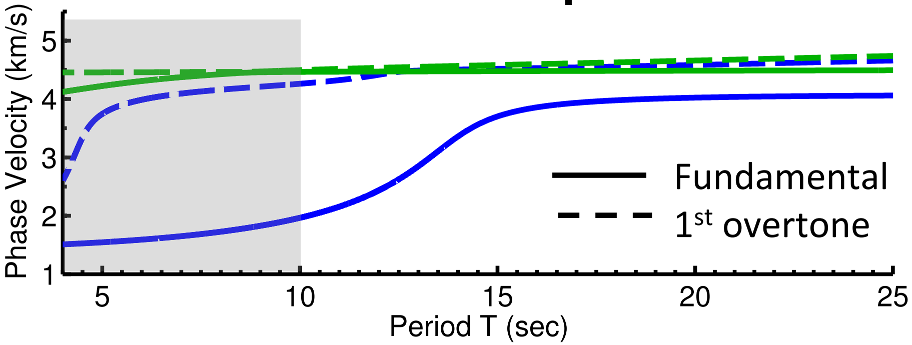
- **Rayleigh – 1st overtone**
- **Love – Fundamental mode**



Cross spectral power density



Estimated dispersion



Secondary Microseism (4-10 s)

- **Rayleigh – 1st overtone**
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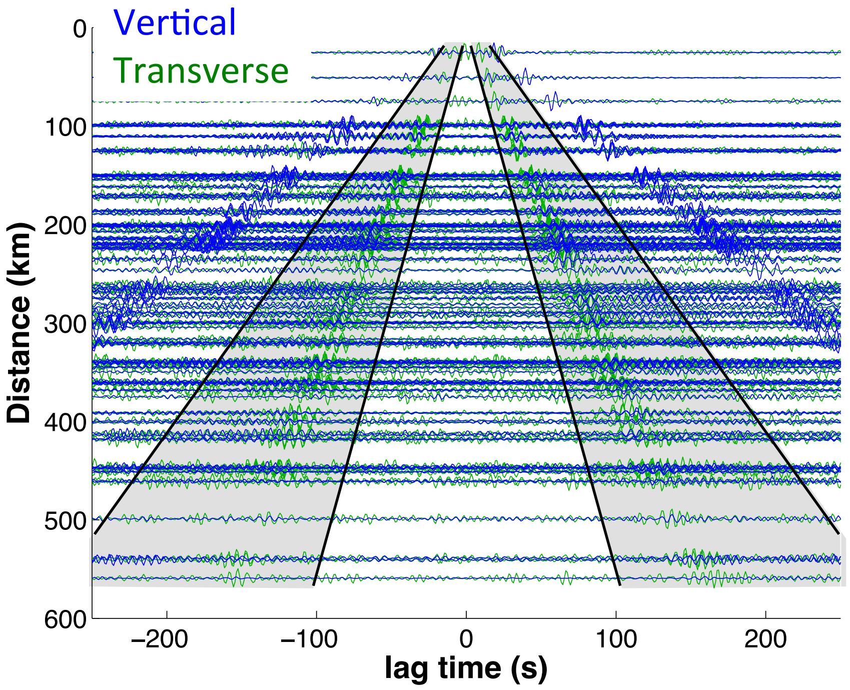
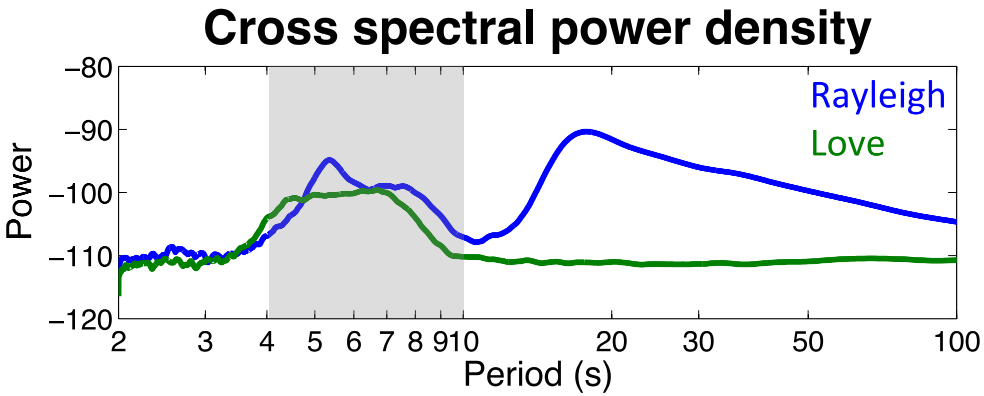
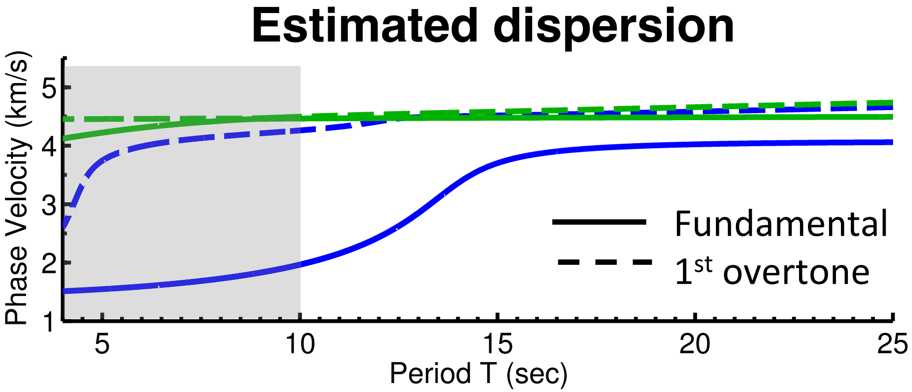






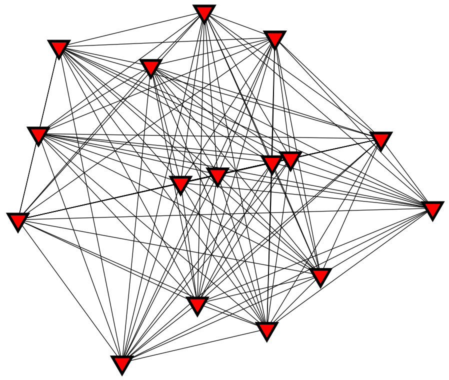
Method: Ambient Noise

Ambient noise provides constraints from both Rayleigh and Love wave fields

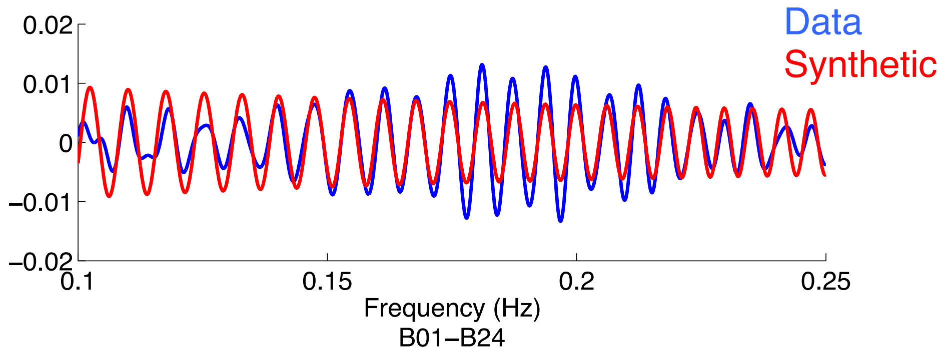
Phase velocities derived from waveform fitting of ambient-noise cross spectra [*Menke & Jin, BSSA 2015*]

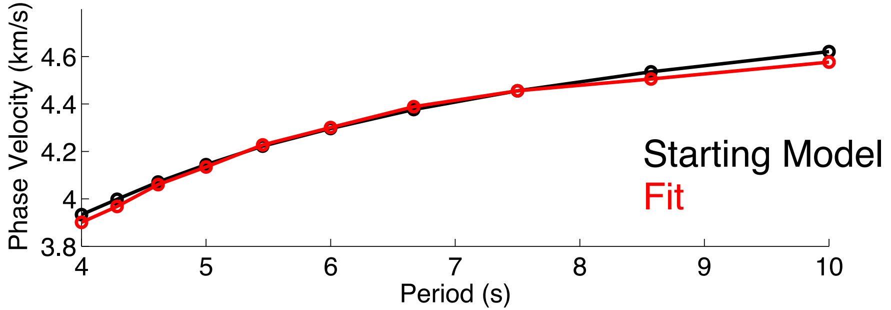
cross spectra: $$\rho(\omega, r) = AJ_0\left(\frac{\omega r}{c(\omega)}\right)$$

240 cross-correlation functions

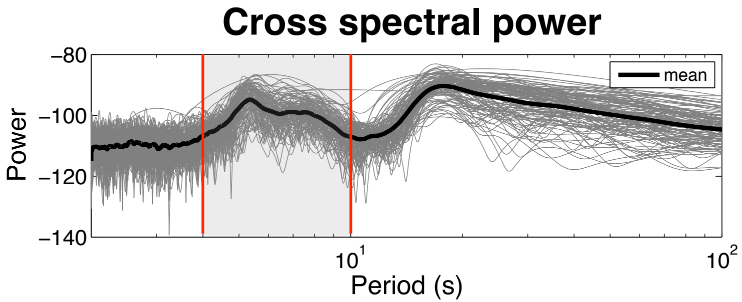


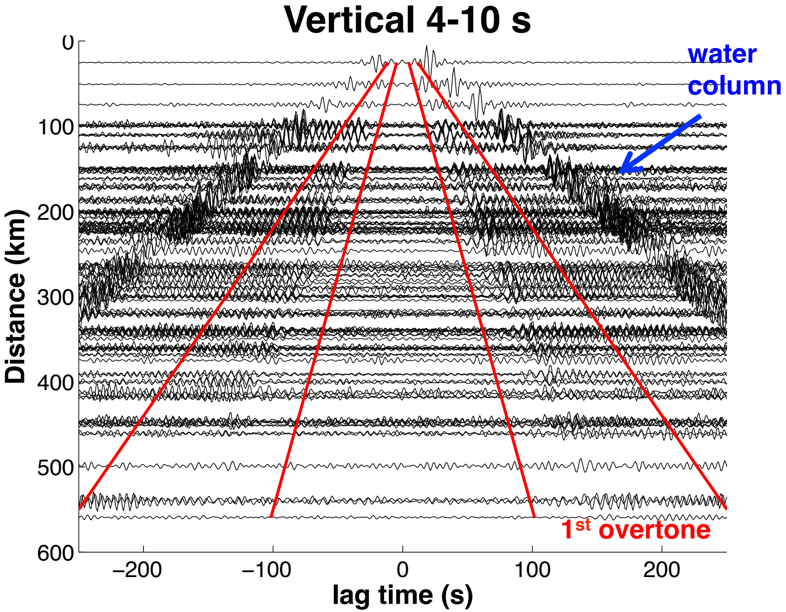
Real part of cross spectra





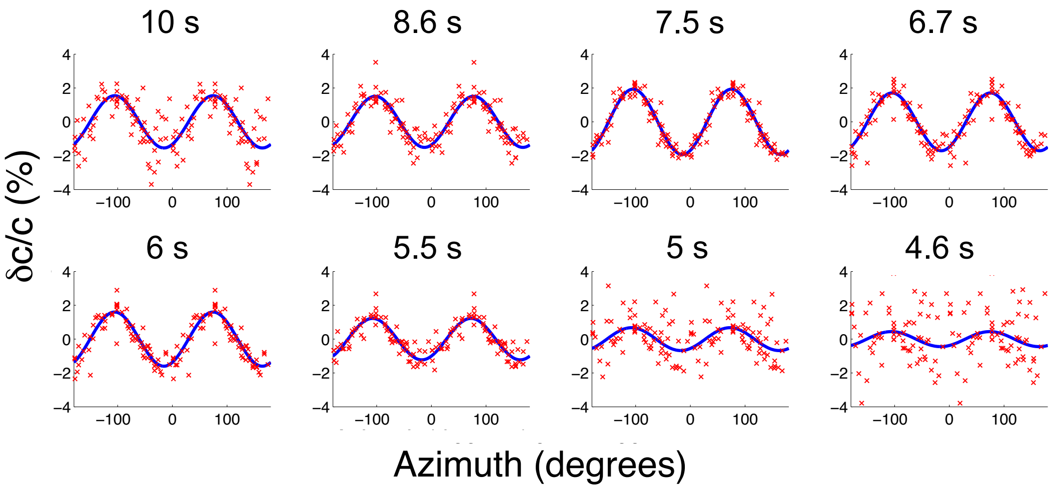
1st overtone Rayleigh waves (4-10 s)



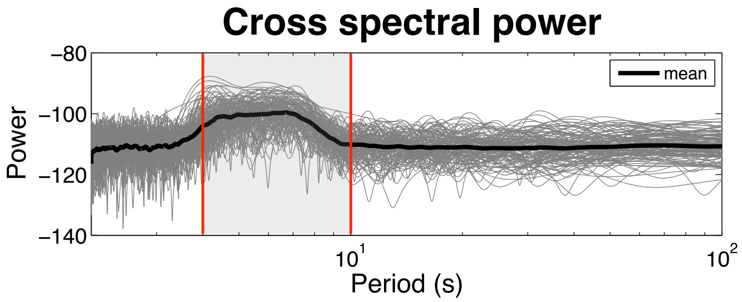


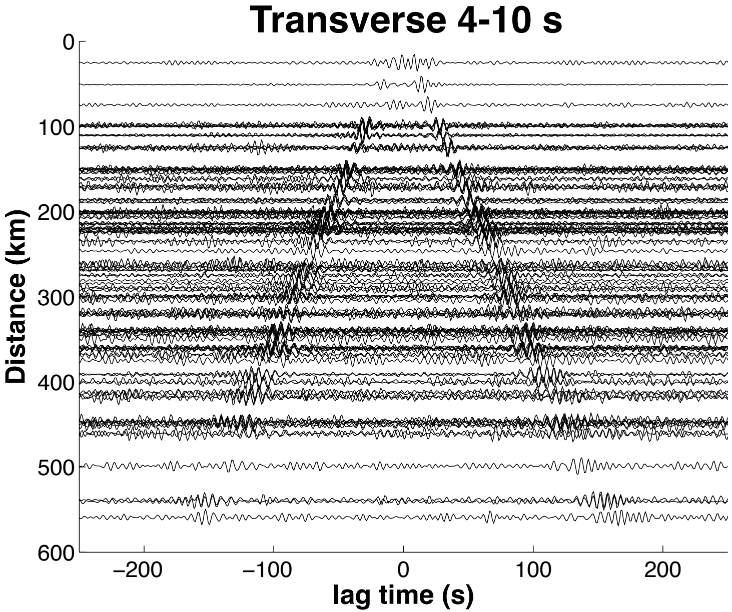
- Sensitivity of 1st overtone Rayleigh comparable to fundamental mode Love wave
- Strong 2θ azimuthal signal
  - Rayleigh fast direction parallel to fossil spreading (78°)

$$c^R(\theta) = c^R_{iso}\left[1 + \frac{A^R}{2}\cos\left(2\left(\theta - \psi^R\right)\right)\right]$$



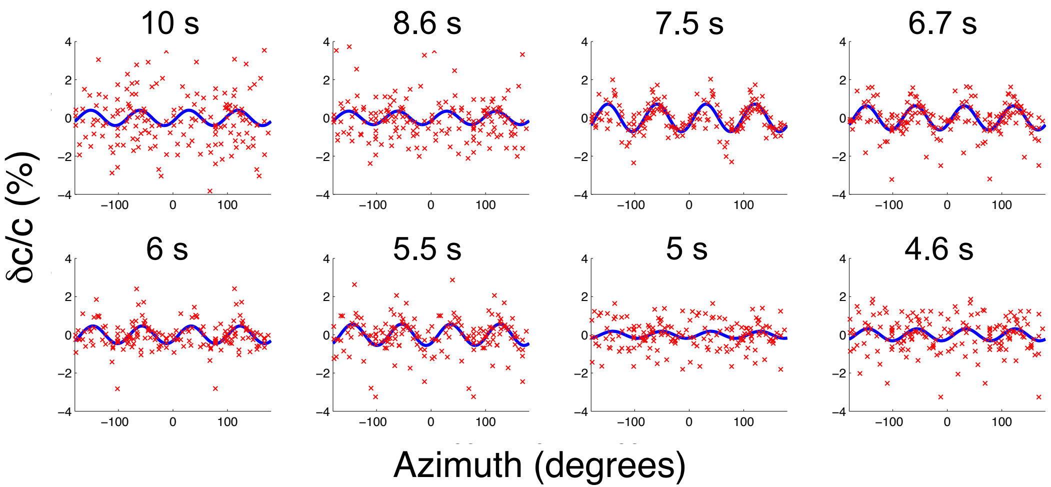
Fundamental mode Love waves (4-10 s)





- 4θ azimuthal signal
  - Love slow direction parallel to fossil spreading (78°)
  - Consistent with predictions of olivine fabric

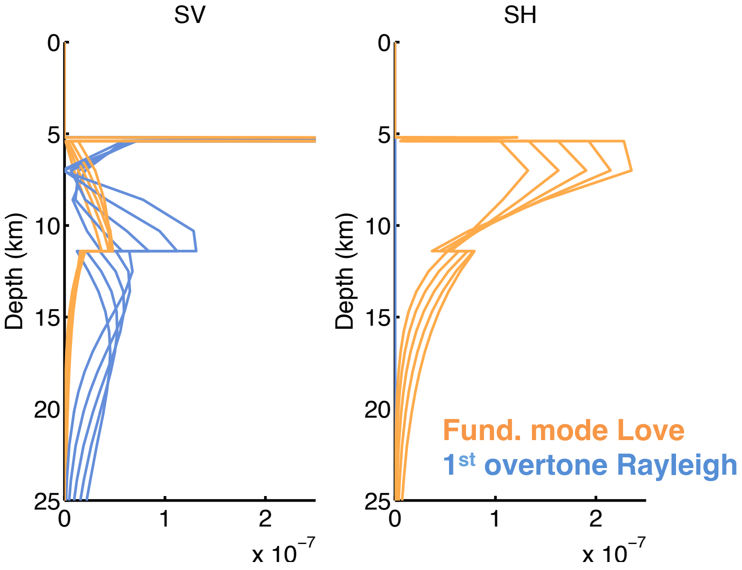
$$c^L(\theta) = c^L_{iso}\left[1 + \frac{A^L}{2}\cos\left(4\left(\theta - \psi^L\right)\right)\right]$$

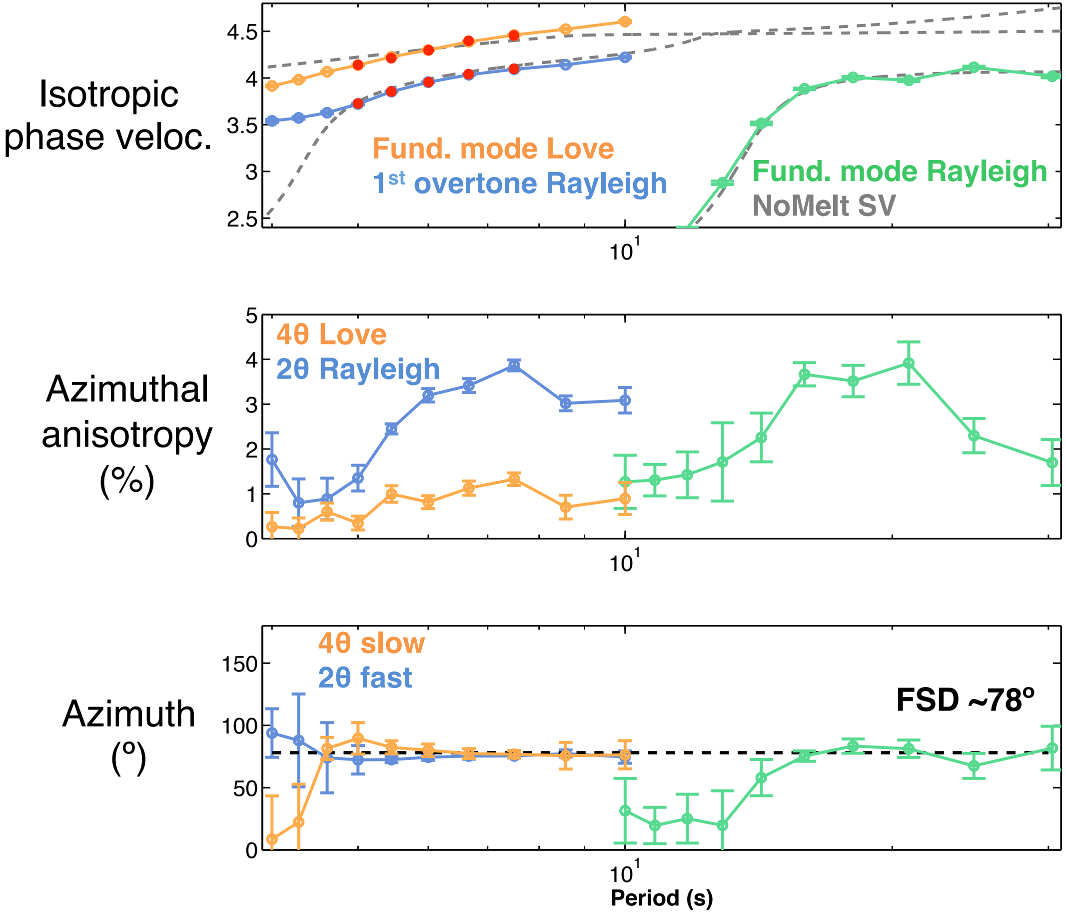


Summary of measurements

Strong azimuthal anisotropy suggests significant mantle sensitivity

Fréchet Kernels (5-7.5 s)





Radial anisotropy inversion

Invert for V_{PV}, V_{PH}, V_{SV}, V_{SH}, leaving η fixed.

Starting model

V_P

0-35km: NoMelt refraction model accounting for ~8% P-azimuthal anisotropy in the mantle
(D. Lizarralde personal communications)

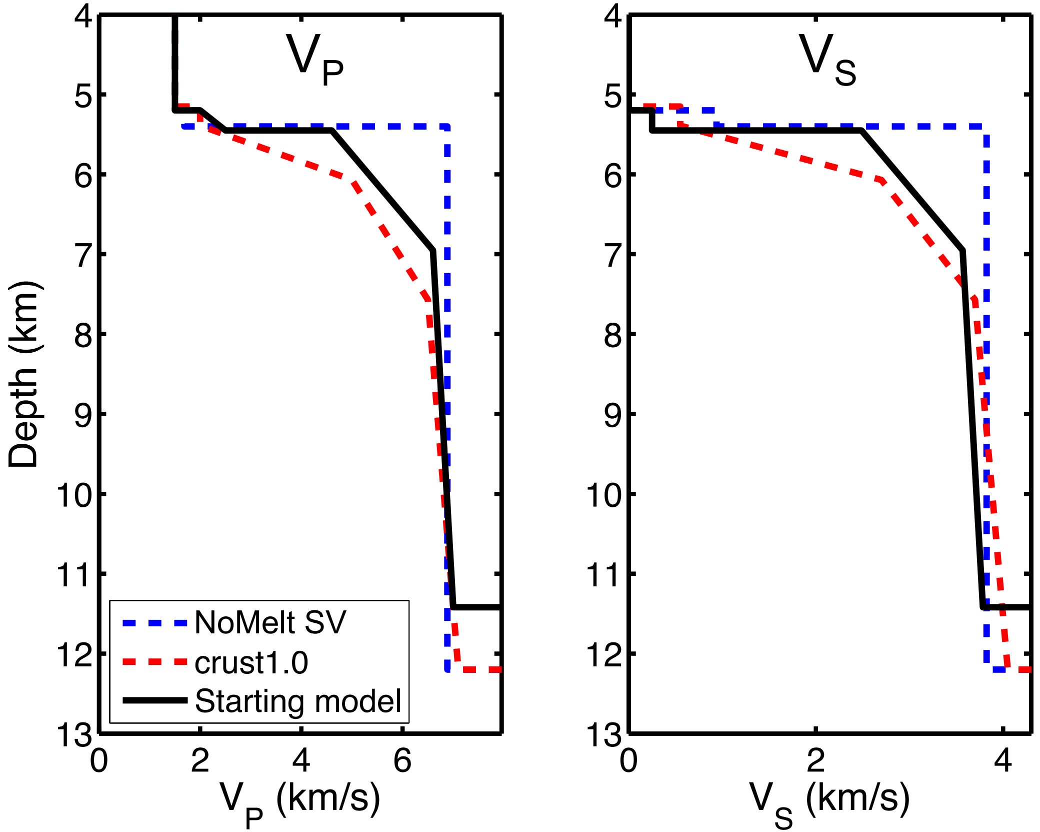
V_S

Sediments: Seafloor compliance
[*Ruan et al., JGR 2014*]

Crust: V_P/V_S = ~1.85 [*Brocher, BSSA 2005*]

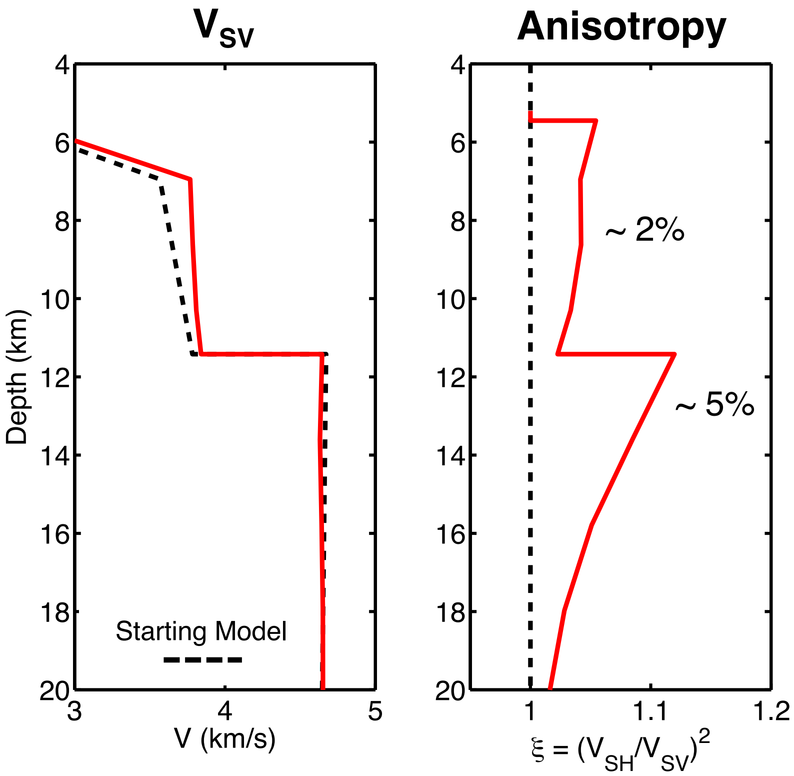
Mantle: NoMelt SV [*Lin et al., Nature 2016*]

Crustal Model



Inversion results

$V_{SH} > V_{SV}$ required in the mantle lithosphere and cannot be ruled out in the crust



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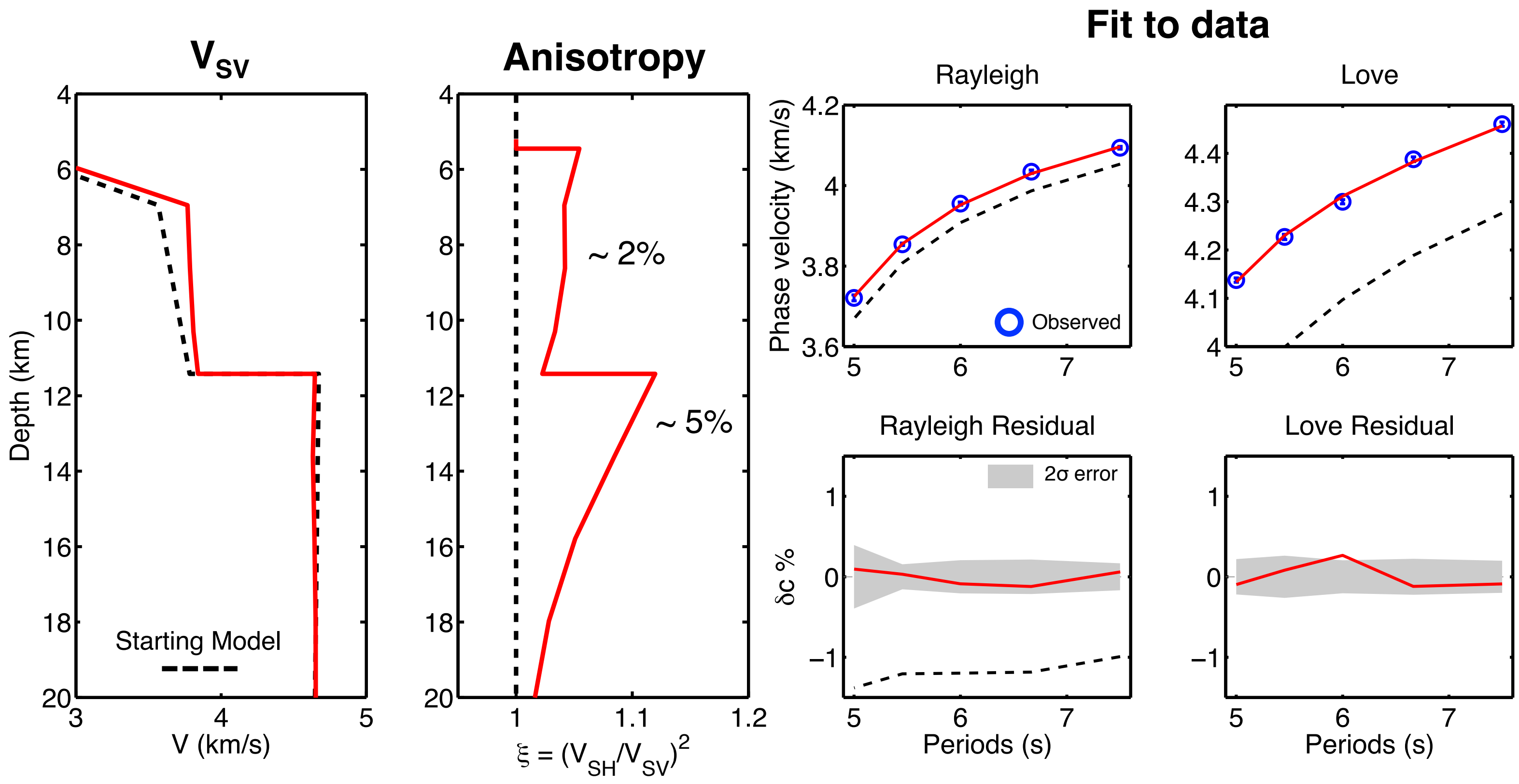


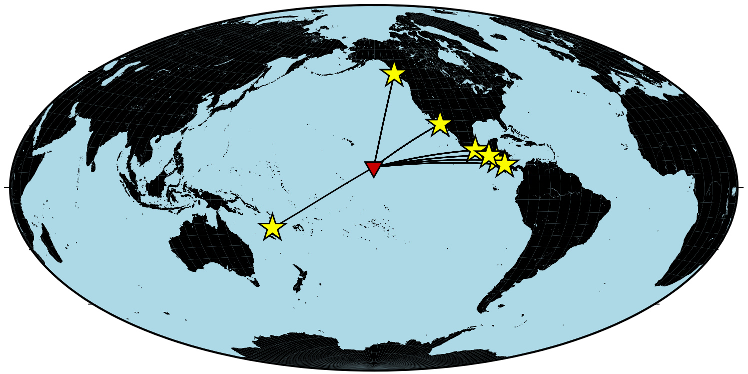
Observations from ambient noise

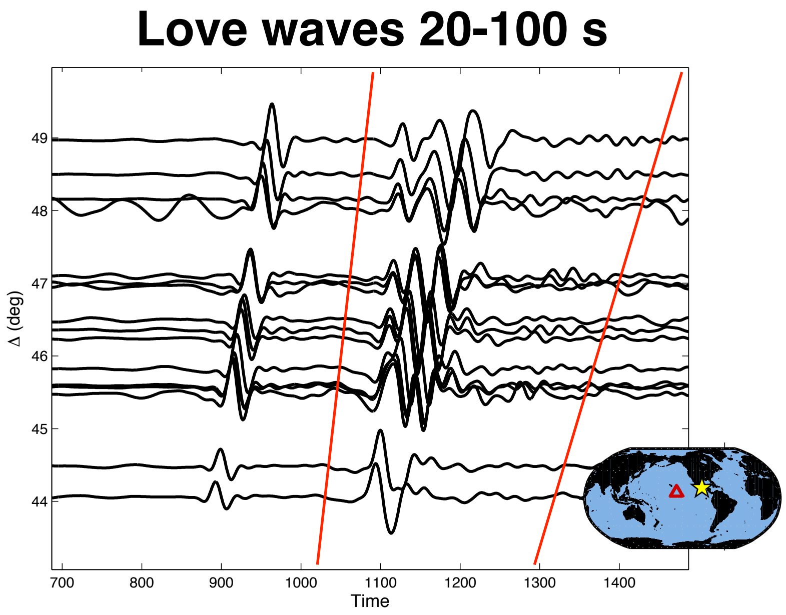
- **Azimuthal anisotropy**
  - Rayleigh **2θ fast** direction aligned with **fossil spreading** (~78º)
  - Love **4θ slow** direction aligned with **fossil spreading**

- **Radial anisotropy**
  - Mantle $V_{SH} > V_{SV}$ (~ 3-7%)
    - Mantle anisotropy required by data
  - Crust $V_{SH} > V_{SV}$ (~ 0-5%)?

Consistent with horizontal alignment of olivine a-axes

Love earthquake data (20-100 s)

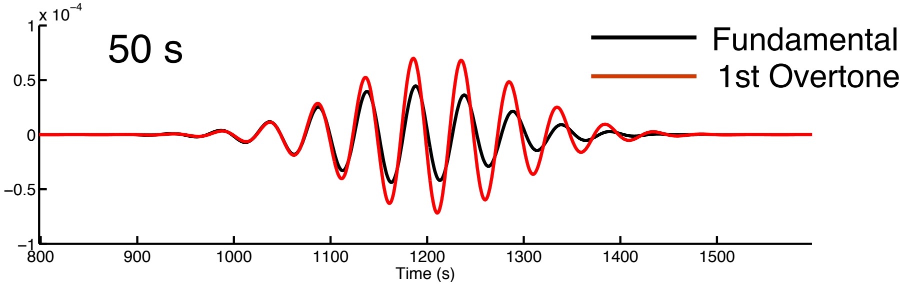




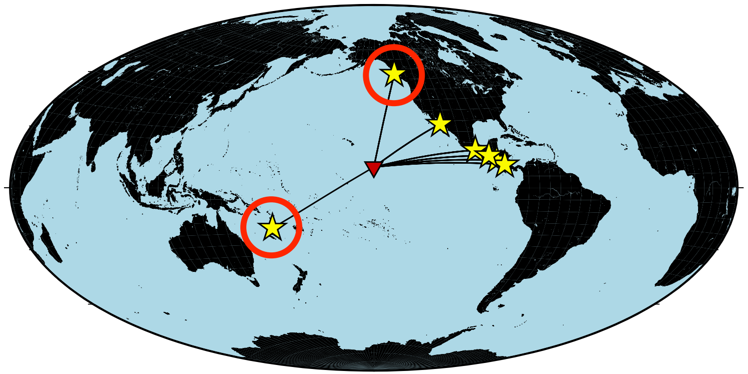
- 7 shallow events with high S/N **Love waves**

  > M6.5 and < 25 km depth

- **Overtone interference** complicates phase velocity measurements.



Love earthquake data (20-100 s)



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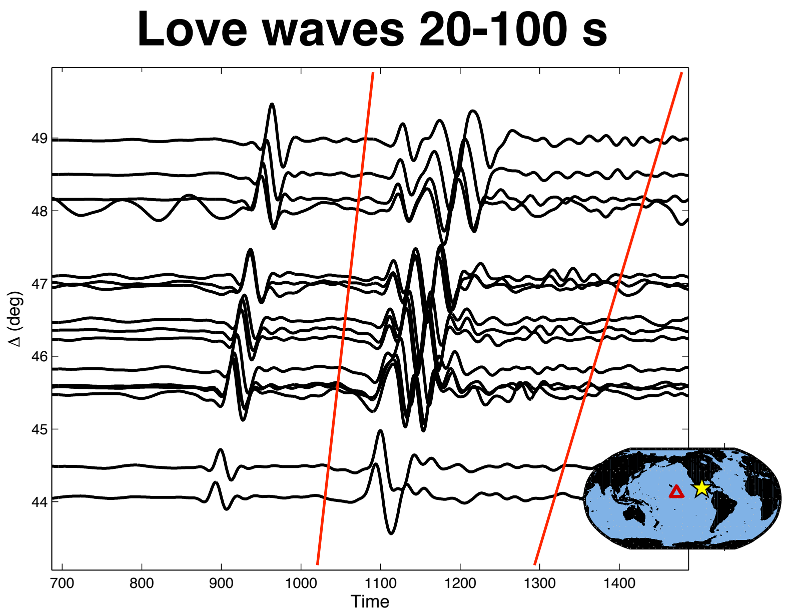
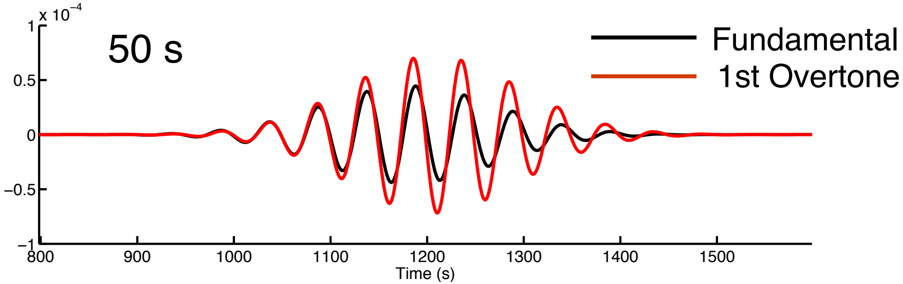


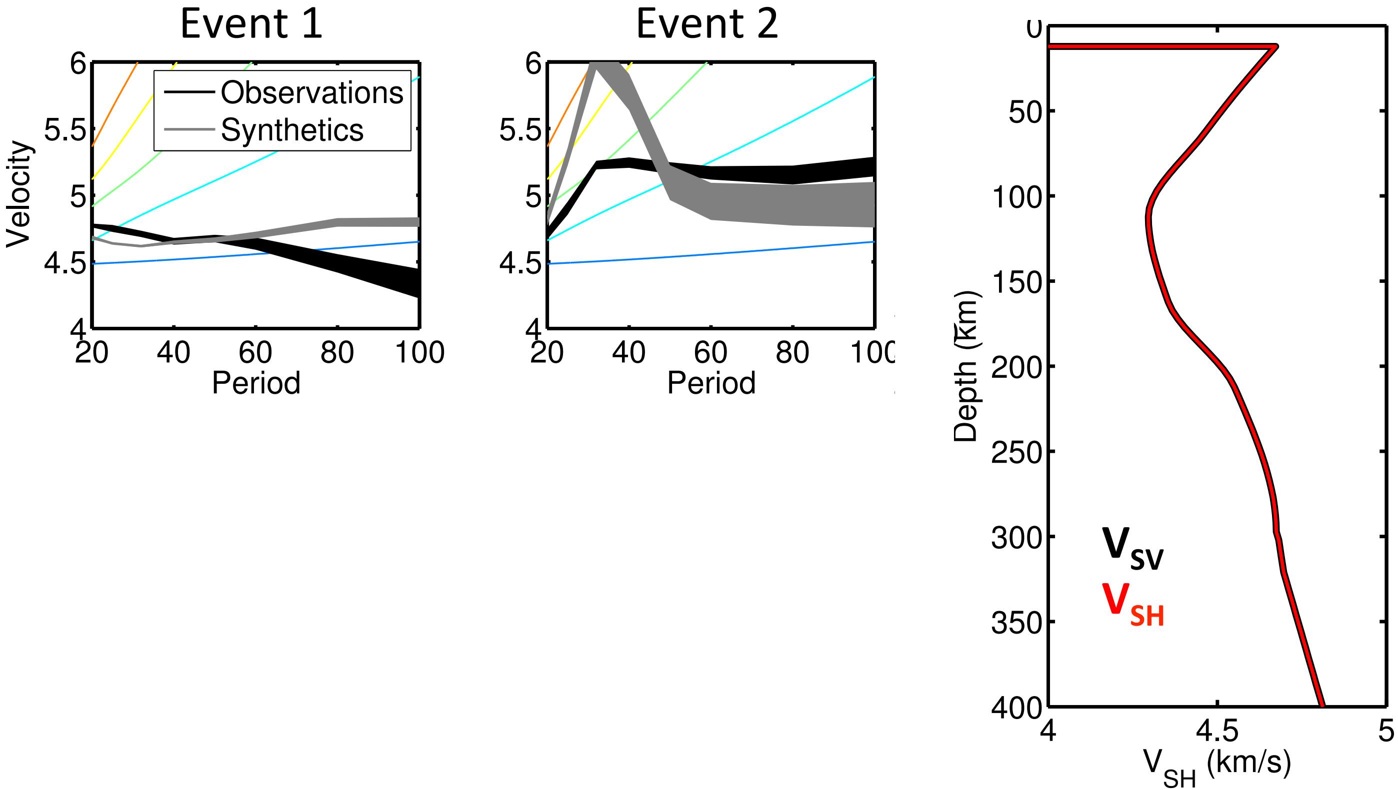


Multimode Love phase velocities

Forward model using multimode synthetics (first 8 mode branches)

Isotropic Model

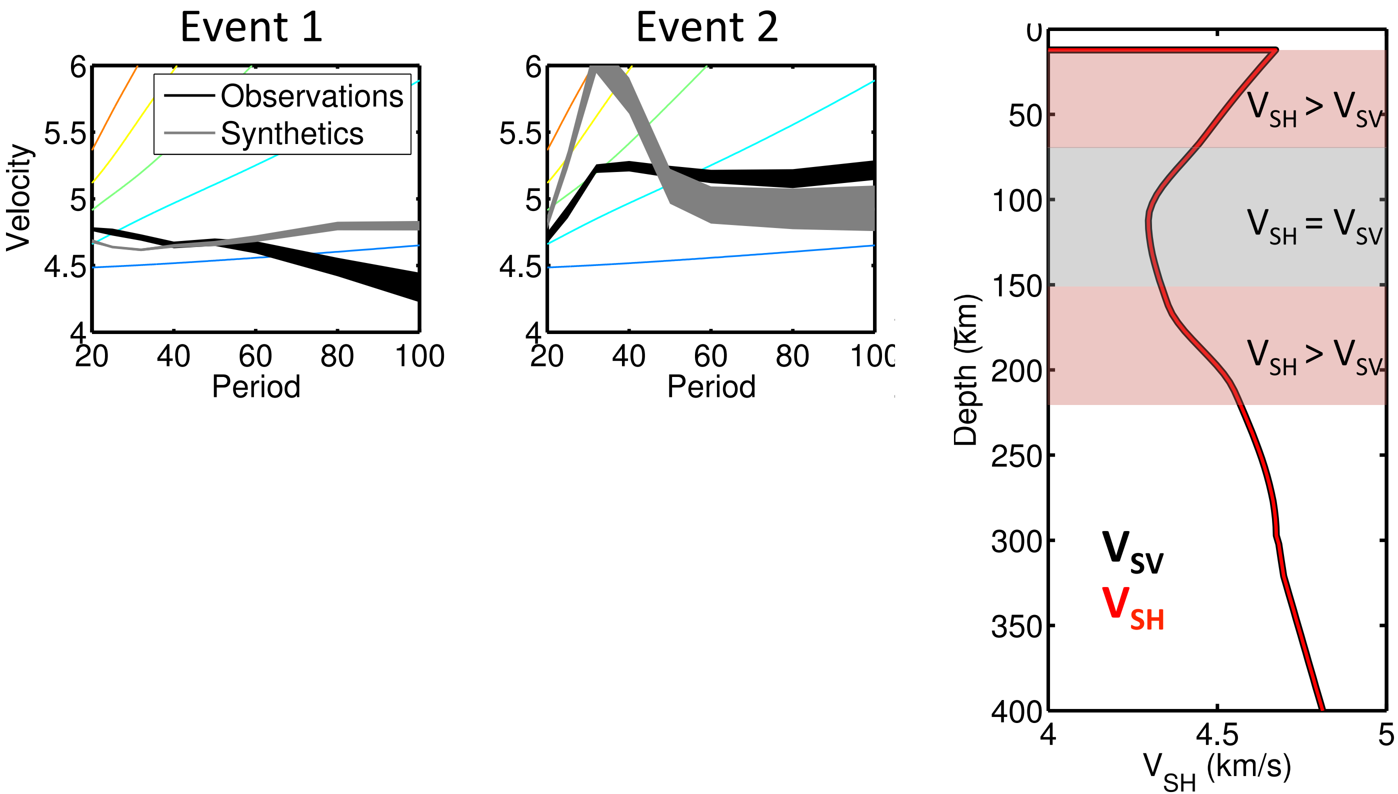
$\mathbf{V_{SV} = V_{SH}}$



Multimode Love phase velocities

Forward model using multimode synthetics (first 8 mode branches)

Isotropic Model
$V_{SV} = V_{SH}$

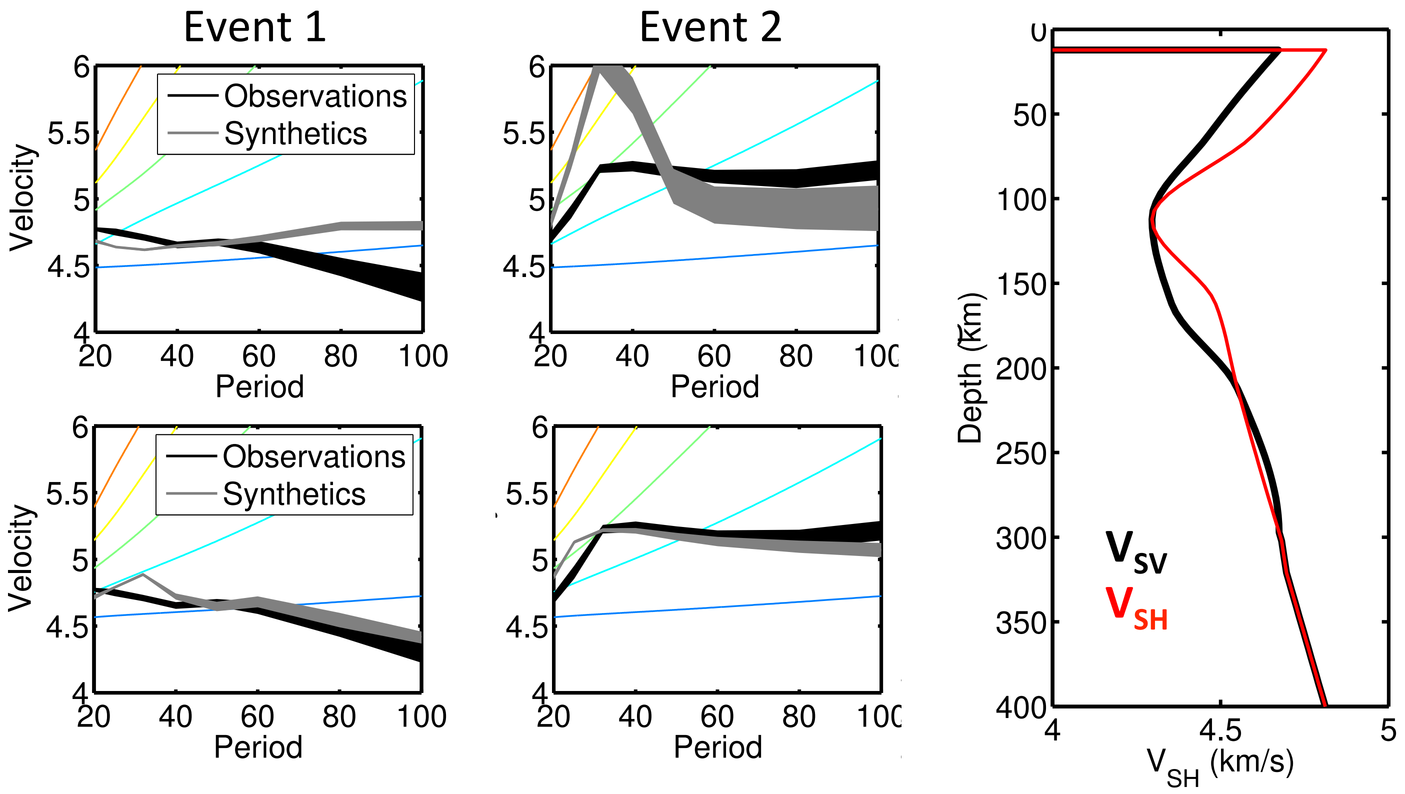


Multimode Love phase velocities

Forward model using multimode synthetics (first 8 mode branches)

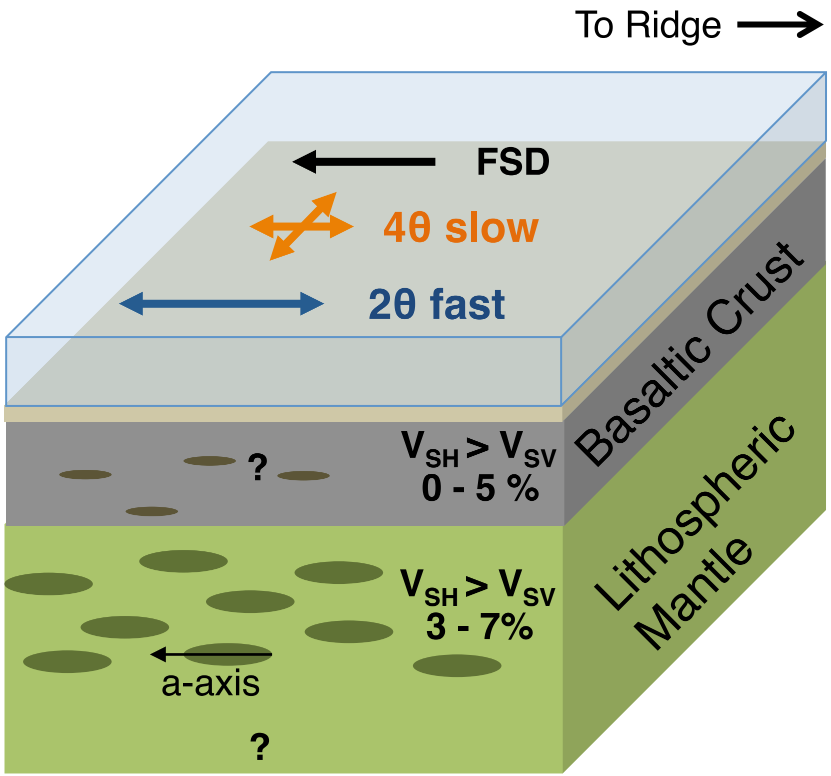
Isotropic Model
$V_{SH} = V_{SV}$

Anisotropic Model
$V_{SH} > V_{SV}$



Summary & Interpretation

Both azimuthal and radial anisotropy required in the lithospheric mantle



Mantle

- ➢ **Radial anisotropy: $V_{SH} > V_{SV}$ (~ 3-7%)**
- ➢ **Clear 2θ and 4θ azimuthal anisotropy**
- Consistent with petrologic models of olivine with orthorhombic or hexagonal symmetry
- Horizontal preferred alignment of olivine a-axis associated with fossil spreading

Crust

- ➢ $V_{SH} > V_{SV}$ (0-5%)
- Horizontal crustal fabric?
  - Layering processes? Cracks? Fluids?

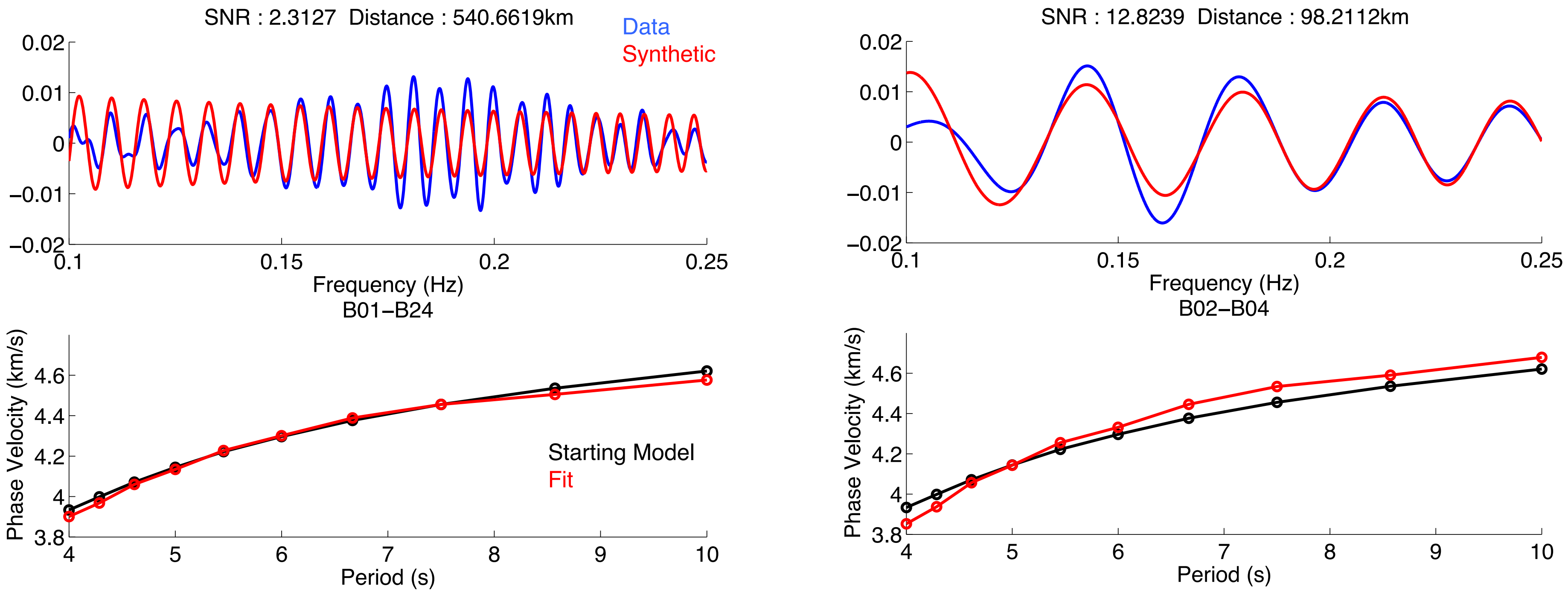
Future Directions

Ambient noise (4-10 s)

- Invert for sediment V_{SV} directly using **seafloor compliance**
  - Avoid tradeoffs in crust/mantle velocity structure
- Invert azimuthal anisotropy for lithospheric **G** (2θ), **B** (2θ), and **C** (4θ)
  - Constrain elastic C_{ij} matrix and compare with petrologic models of olivine

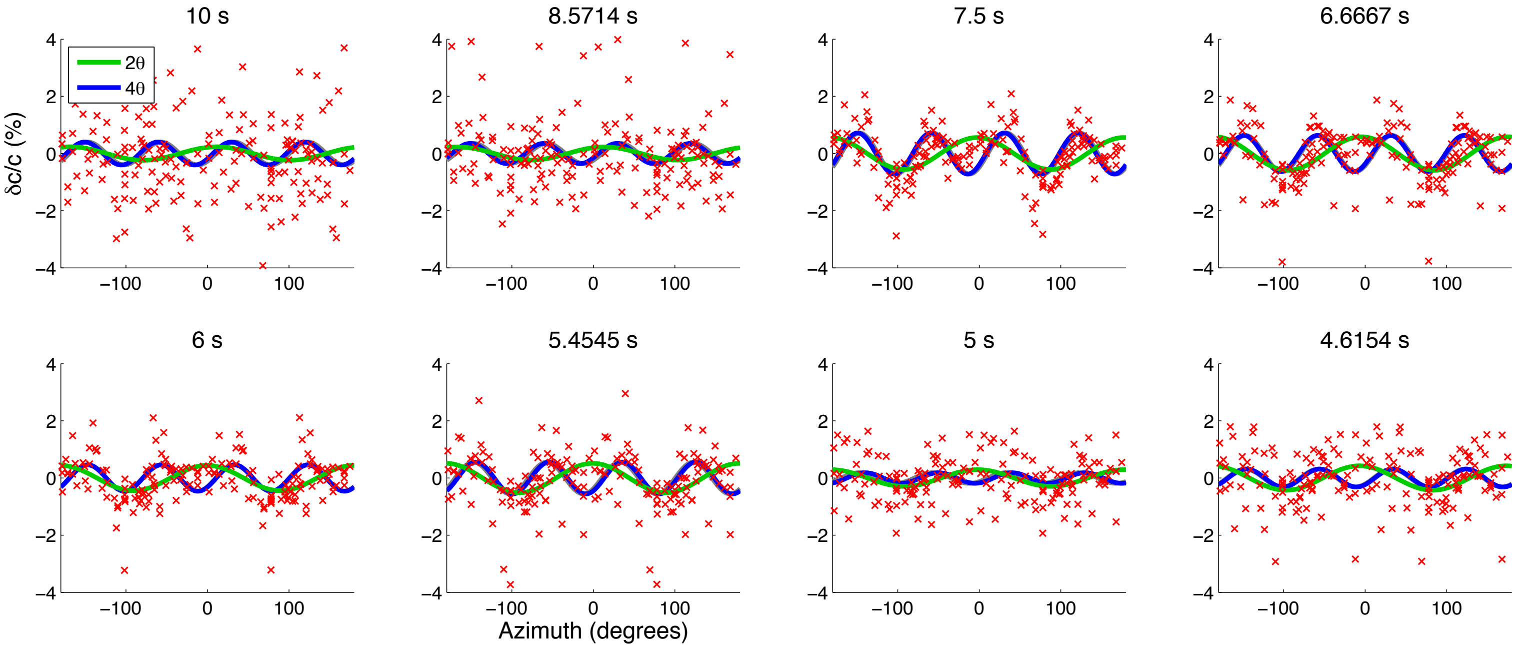
Earthquake Data (20-100 s)

- Devise a method to measure multimode Love phase velocities and invert for mantle V_{SH} (ξ) down to 300 km depth
  - Overtone separation? Multimode kernels? Full waveform inversion?



SNR : 2.3127 Distance : 540.6619km
Data
Synthetic
Frequency (Hz)
B01–B24
Phase Velocity (km/s)
Starting Model
Fit
Period (s)
SNR : 12.8239 Distance : 98.2112km
Frequency (Hz)
B02–B04
Phase Velocity (km/s)
Period (s)

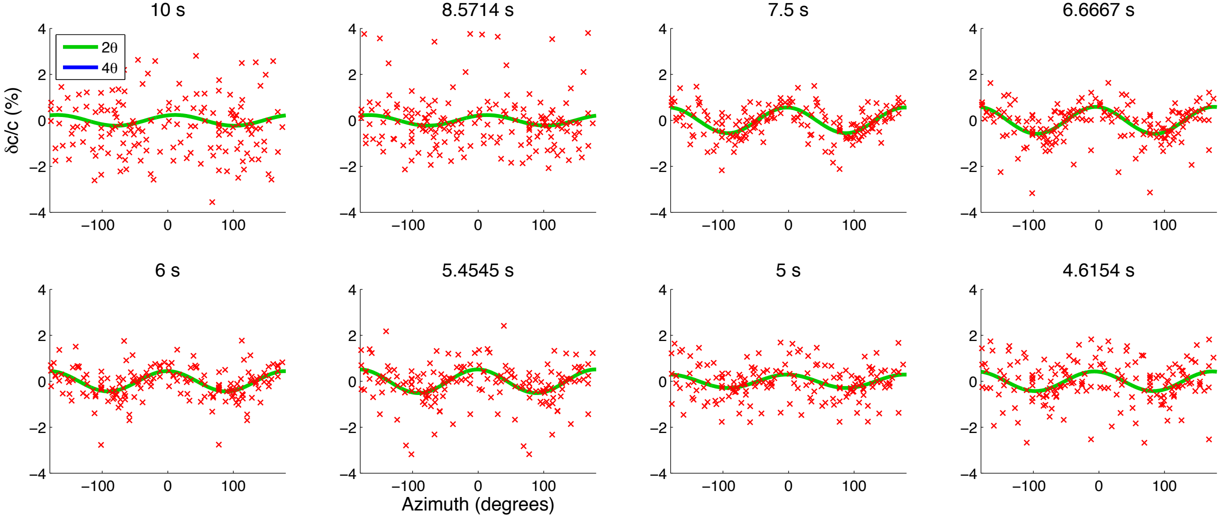
Love



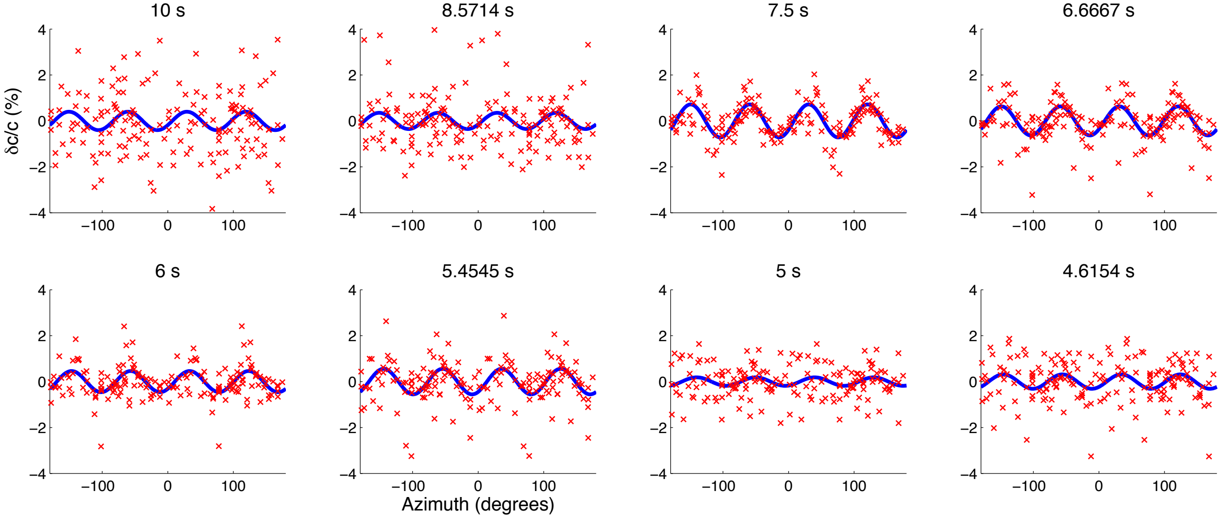
10 s
8.5714 s
7.5 s
6.6667 s
6 s
5.4545 s
5 s
4.6154 s
2θ
4θ
δc/c (%)
Azimuth (degrees)

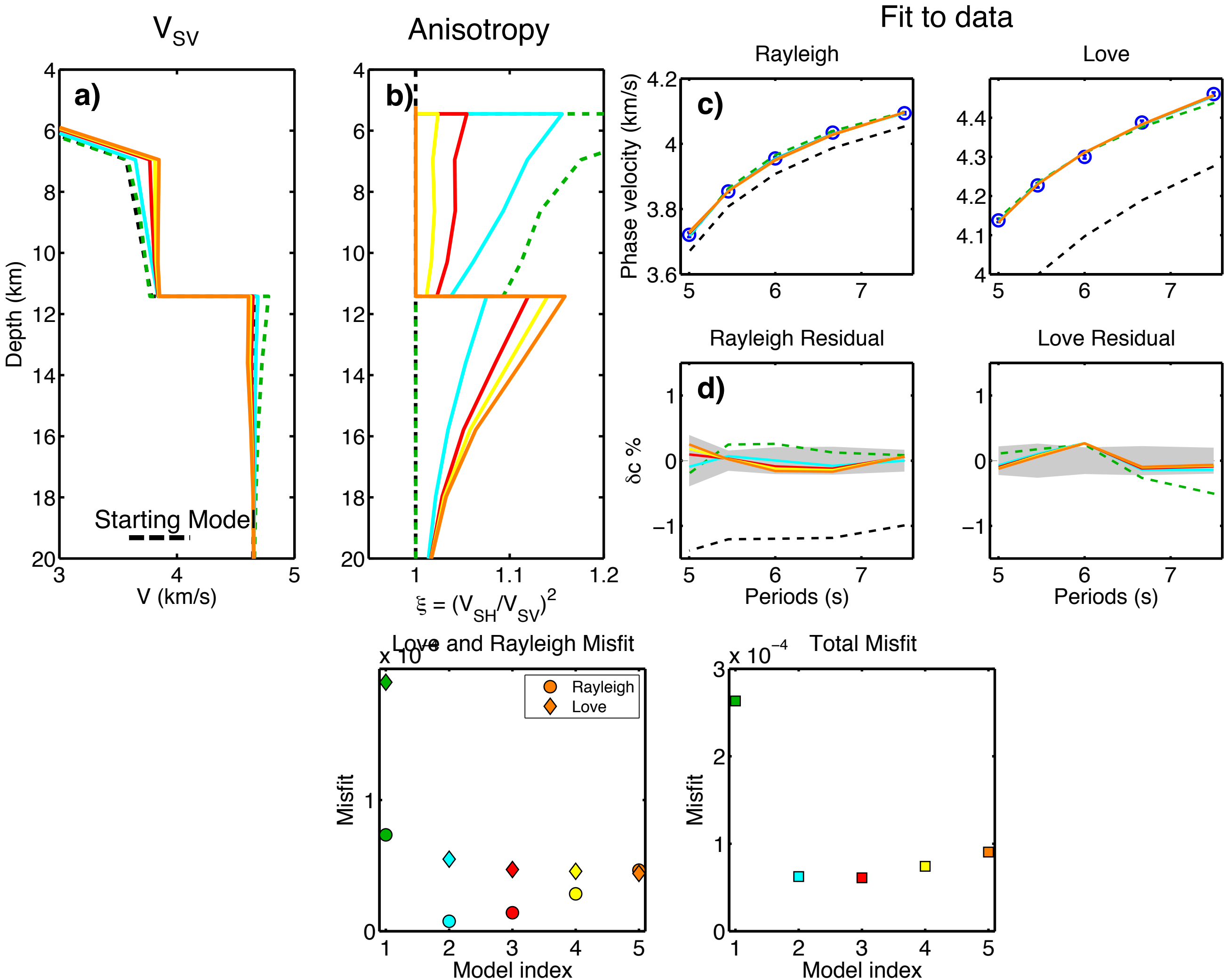
Love

2θ part



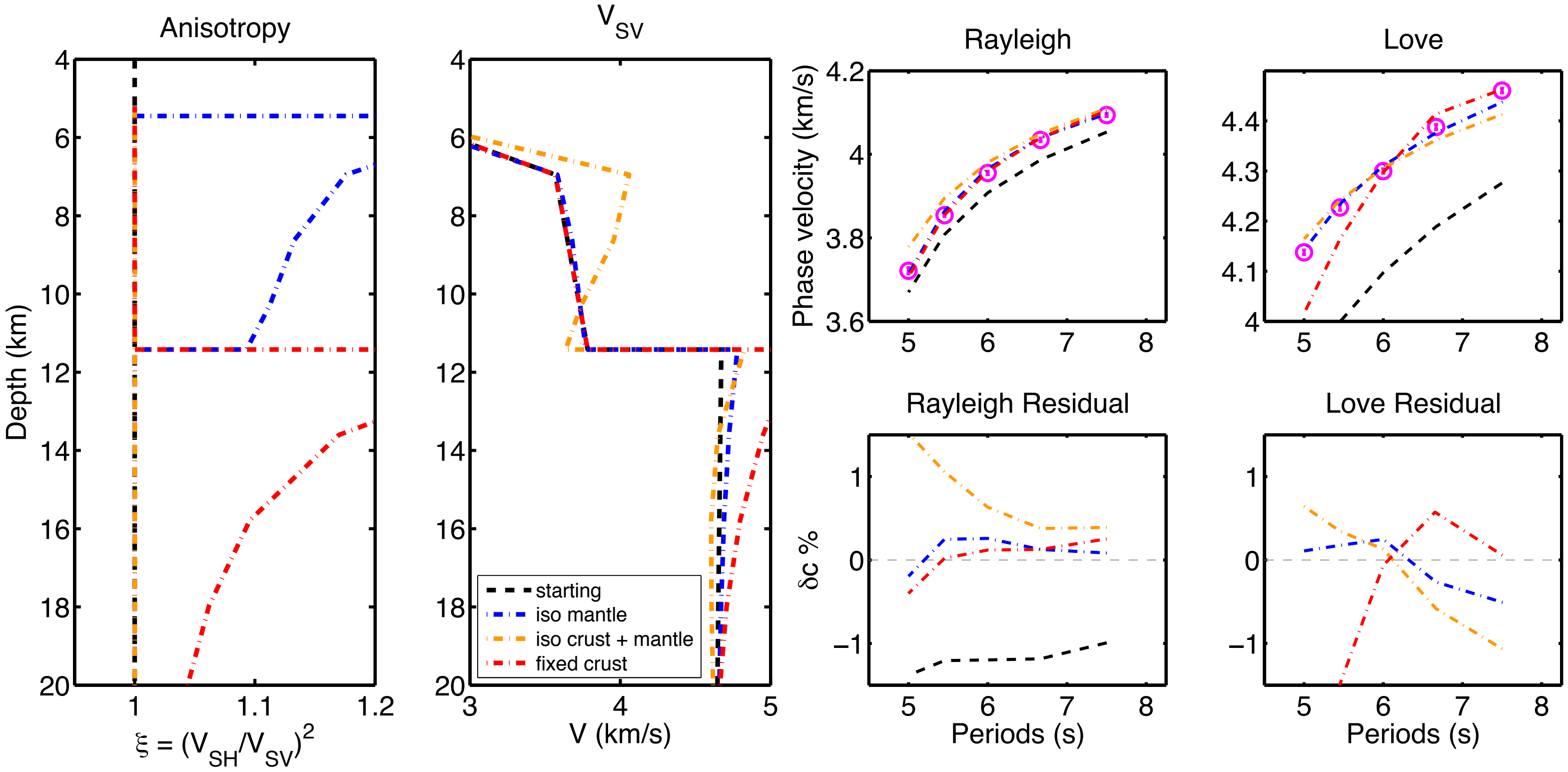
4θ part





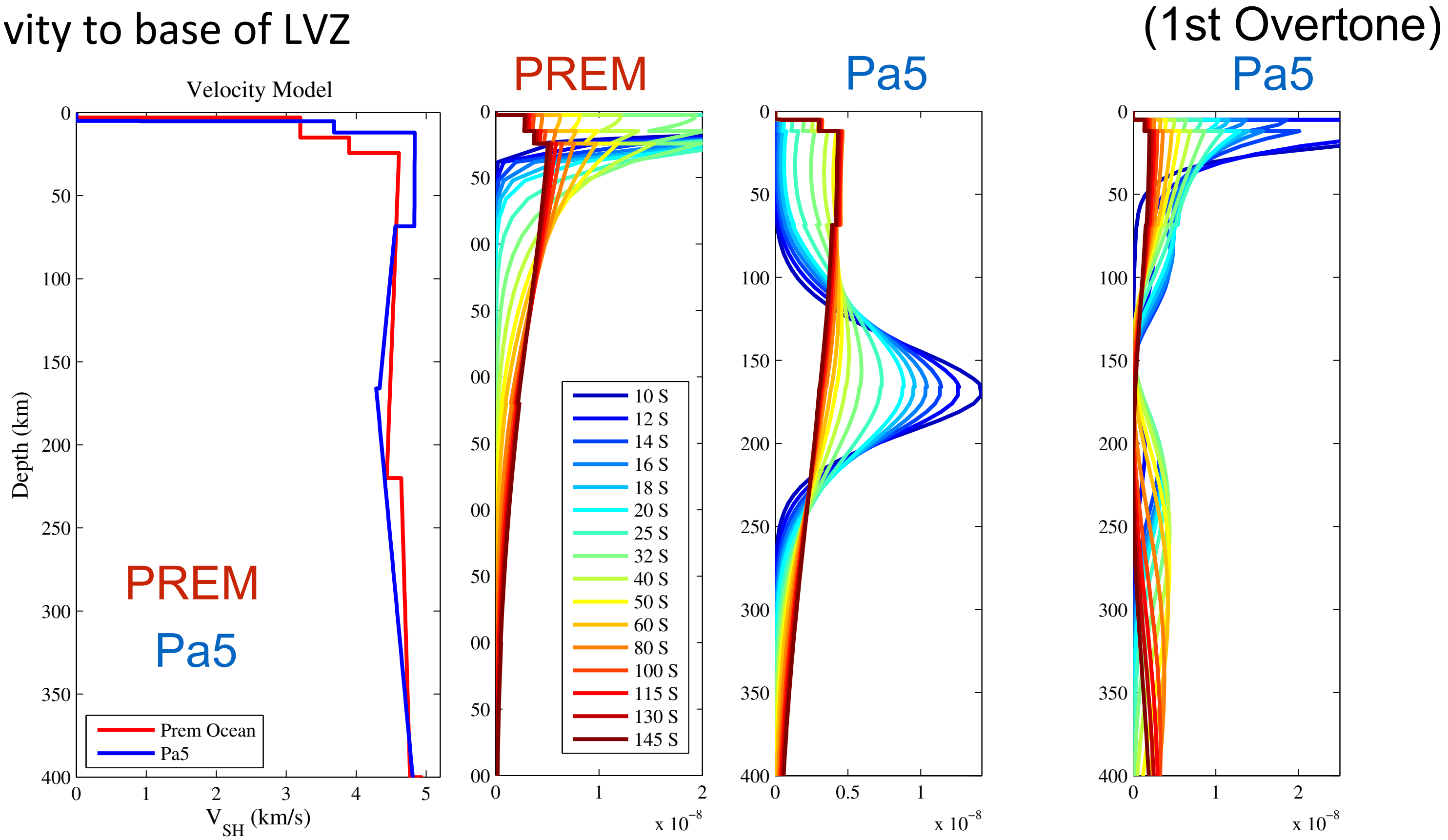
V_{SV}
Anisotropy
Fit to data
Rayleigh
Love
a)
b)
c)
d)
Starting Model
Depth (km)
V (km/s)
$\xi = (V_{SH}/V_{SV})^2$
Phase velocity (km/s)
Rayleigh Residual
Love Residual
δc %
Periods (s)
Love and Rayleigh Misfit
x 10
Rayleigh
Love
Misfit
Model index
Total Misfit
x 10^{-4}

Additional inversions: Poor fits

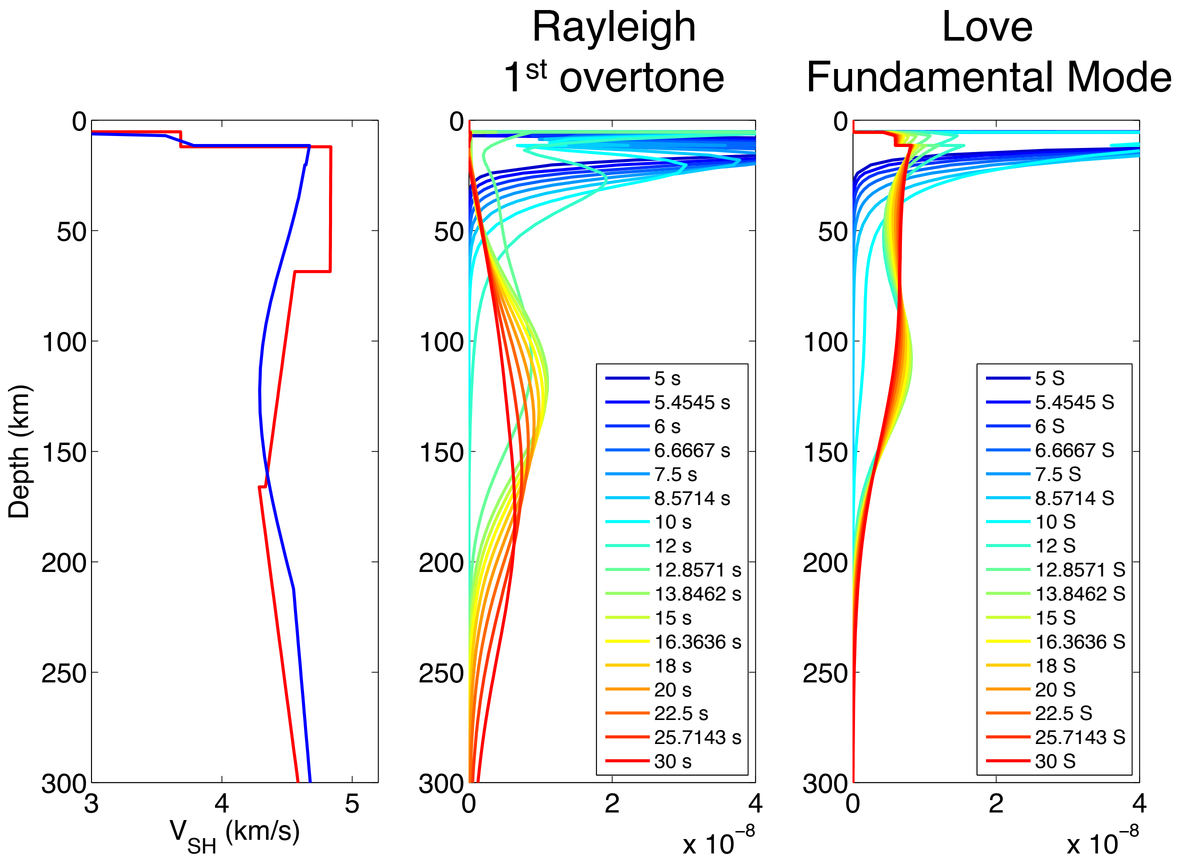


Love Kernel Nonlinearity

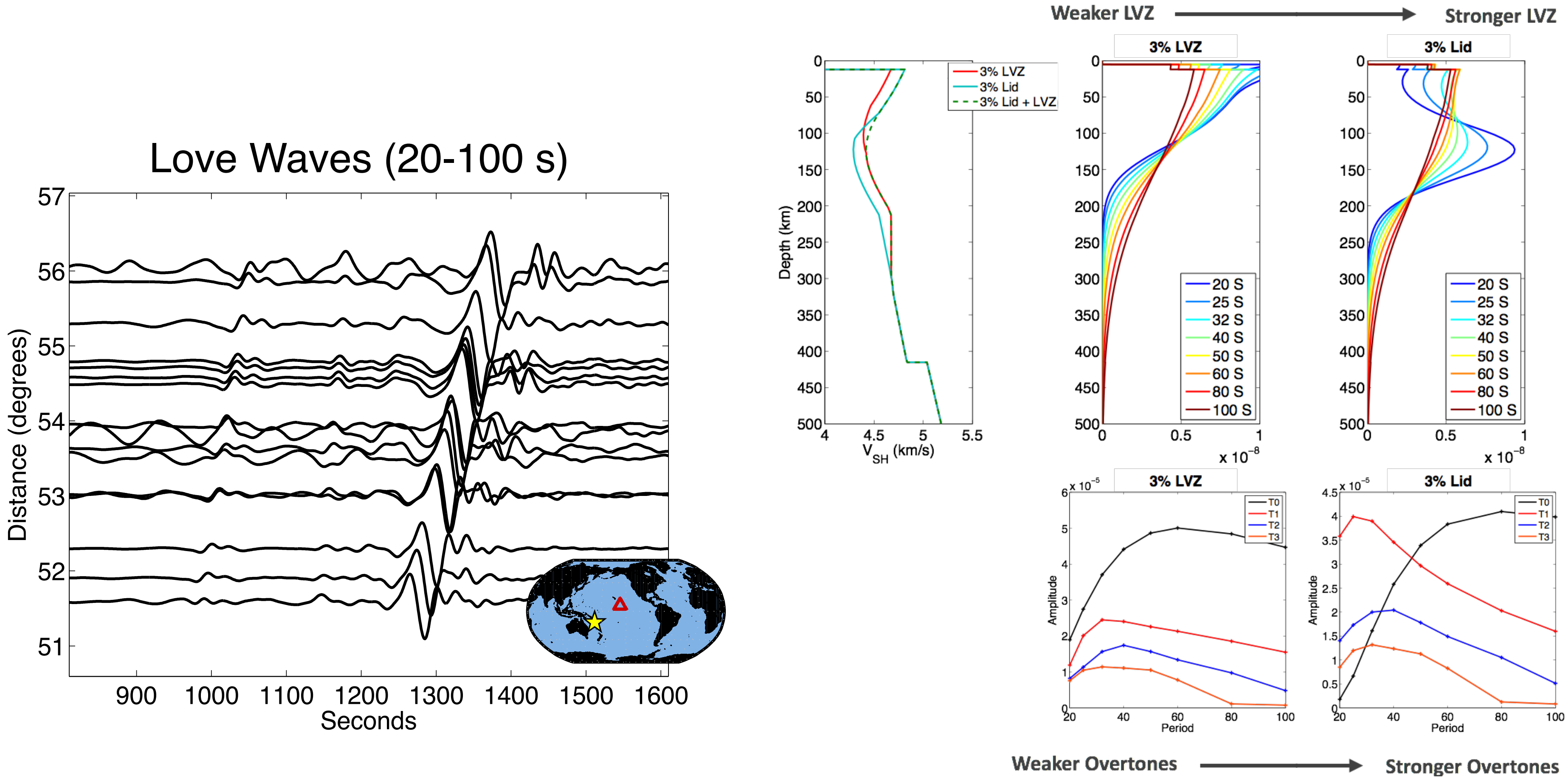
Low velocity zone (LVZ) beneath the plate causes increased sensitivity to base of LVZ



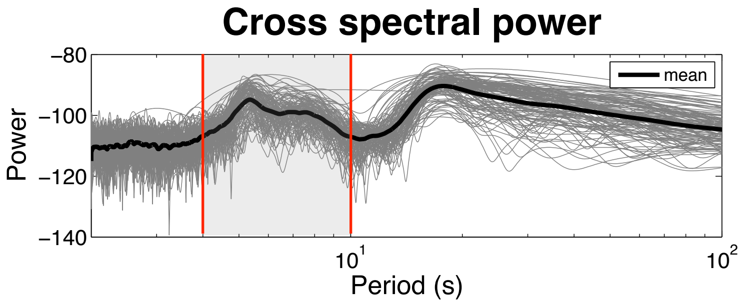
Kernel Nonlinearity: 4-30 s

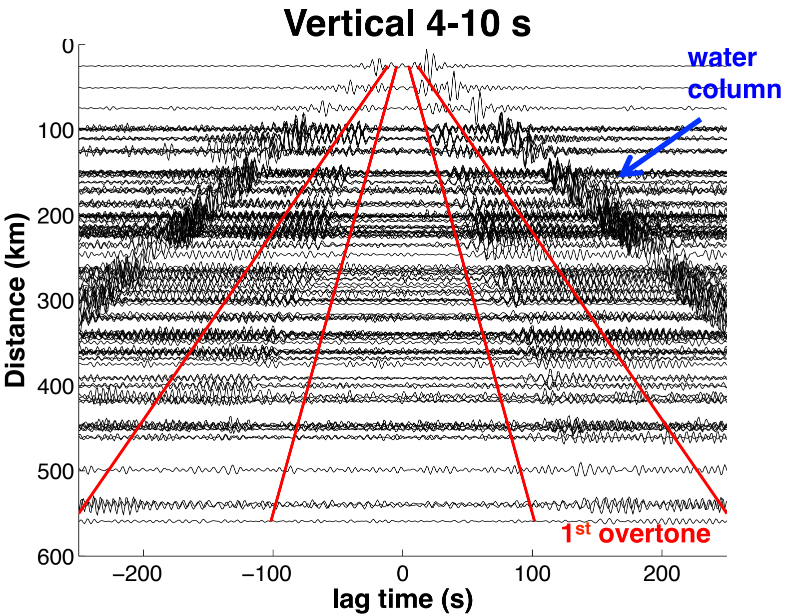


Kernel Nonlinearity: Love waves (20-100 s)

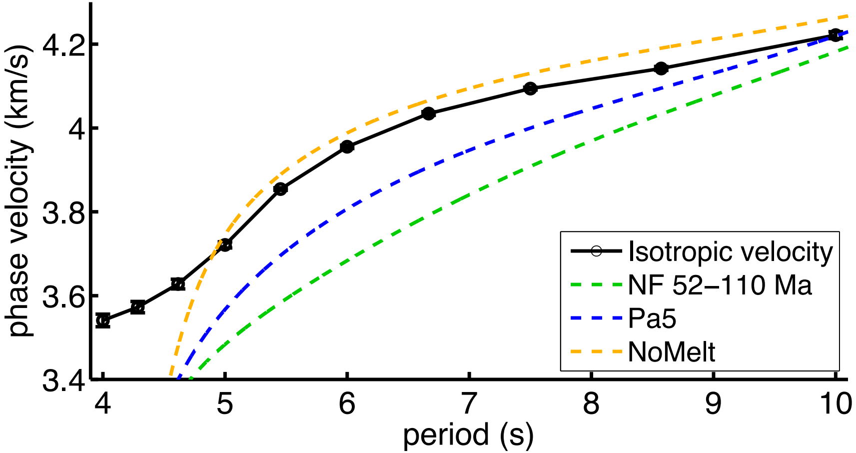


1st overtone Rayleigh waves (4-10 s)

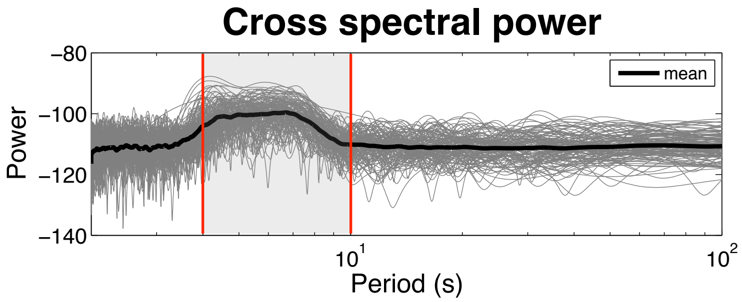


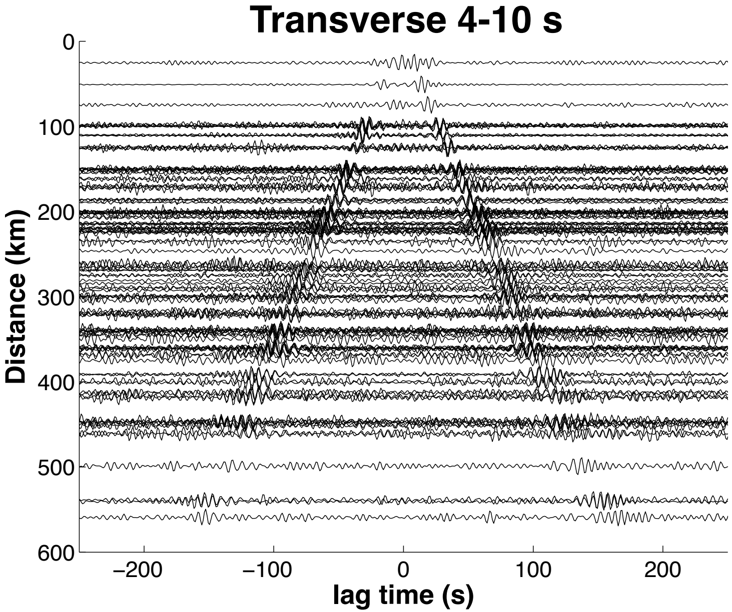


- Sensitivity of 1st overtone Rayleigh comparable to fundamental mode Love wave
- Strong 2θ azimuthal signal
  - Rayleigh fast direction parallel to fossil spreading (78º)

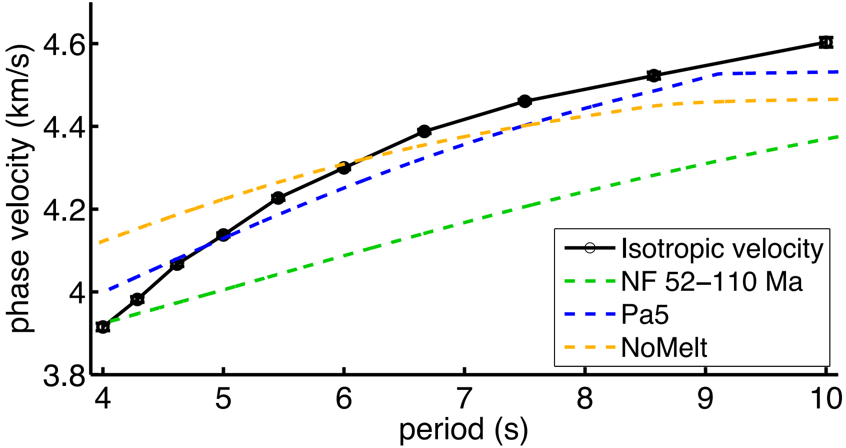


Fundamental mode Love waves (4-10 s)





- Clear 4θ azimuthal signal
  - Love slow direction parallel to fossil spreading (78º)
  - Consistent with predictions of olivine fabric



Azimuthal Anisotropy

$$c^R(\theta) = c^R_{iso}\left[1 + \frac{A^R}{2}\cos\left(2\left(\theta - \psi^R\right)\right)\right]$$

$$c^L(\theta) = c^L_{iso}\left[1 + \frac{A^L}{2}\cos\left(4\left(\theta - \psi^L\right)\right)\right]$$