Ground Motion Prediction for Induced Seismicity Using the Ambient Seismic Field

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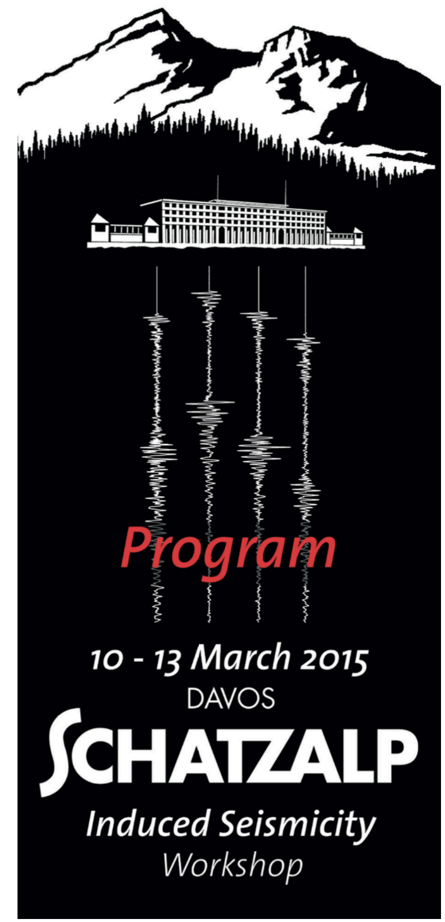
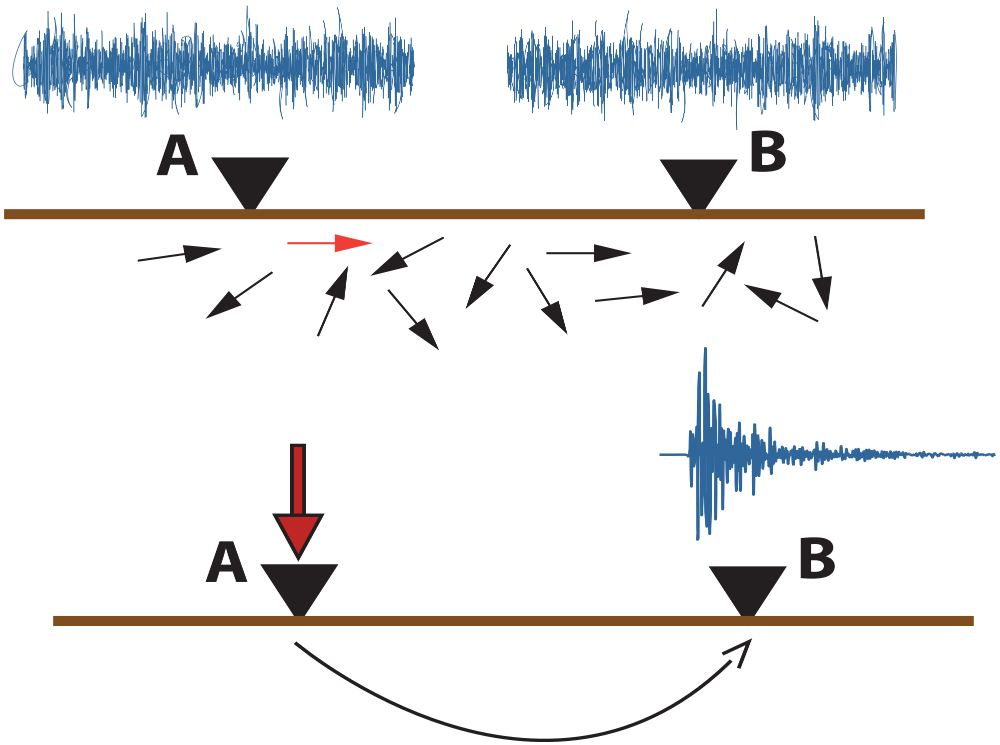


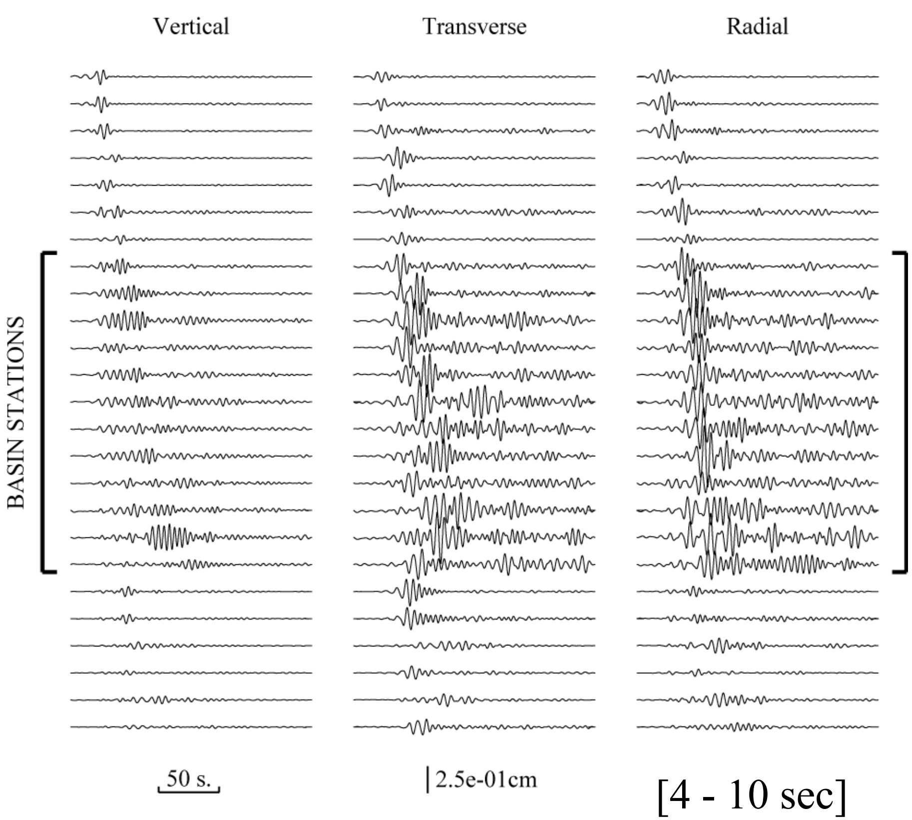
Ambient-Field Green's Functions

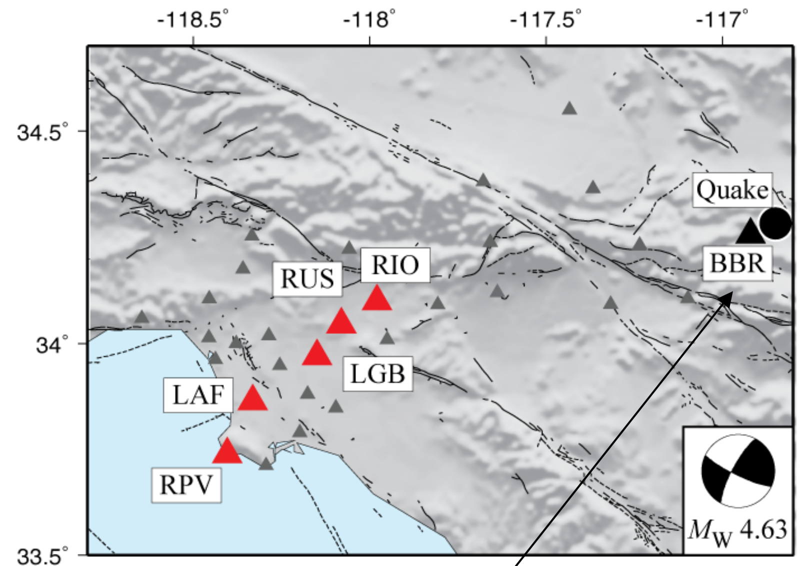


Cross-correlation of ground motion at two stations converges to the impulse response with sufficient averaging

Proof of Concept for *M* 4.6 Big Bear EQ

Earthquake records



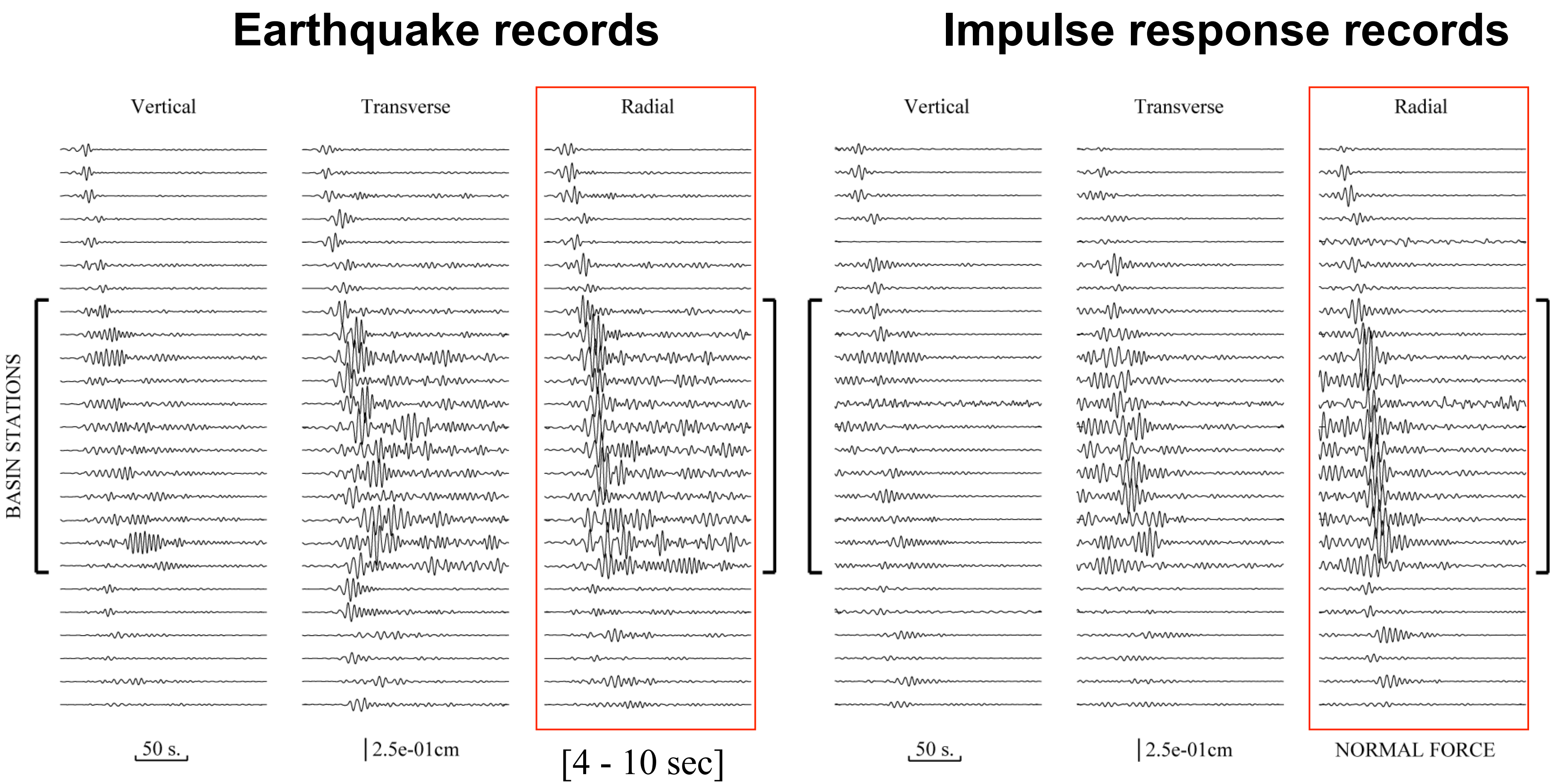


10 Feb 2001 M_w 4.6 Big Bear

***Graves* (2008)**

Amplitudes, duration, and waveform complexity are greater in the basin

Proof of Concept for *M* 4.6 Big Bear EQ



Prieto and Beroza **(2008)**

Amplitudes, duration, and waveform complexity in the basin are reproduced by the ambient field.

Approaches to Ground Motion Prediction

Data-Driven ⟷ **Model-Guided**

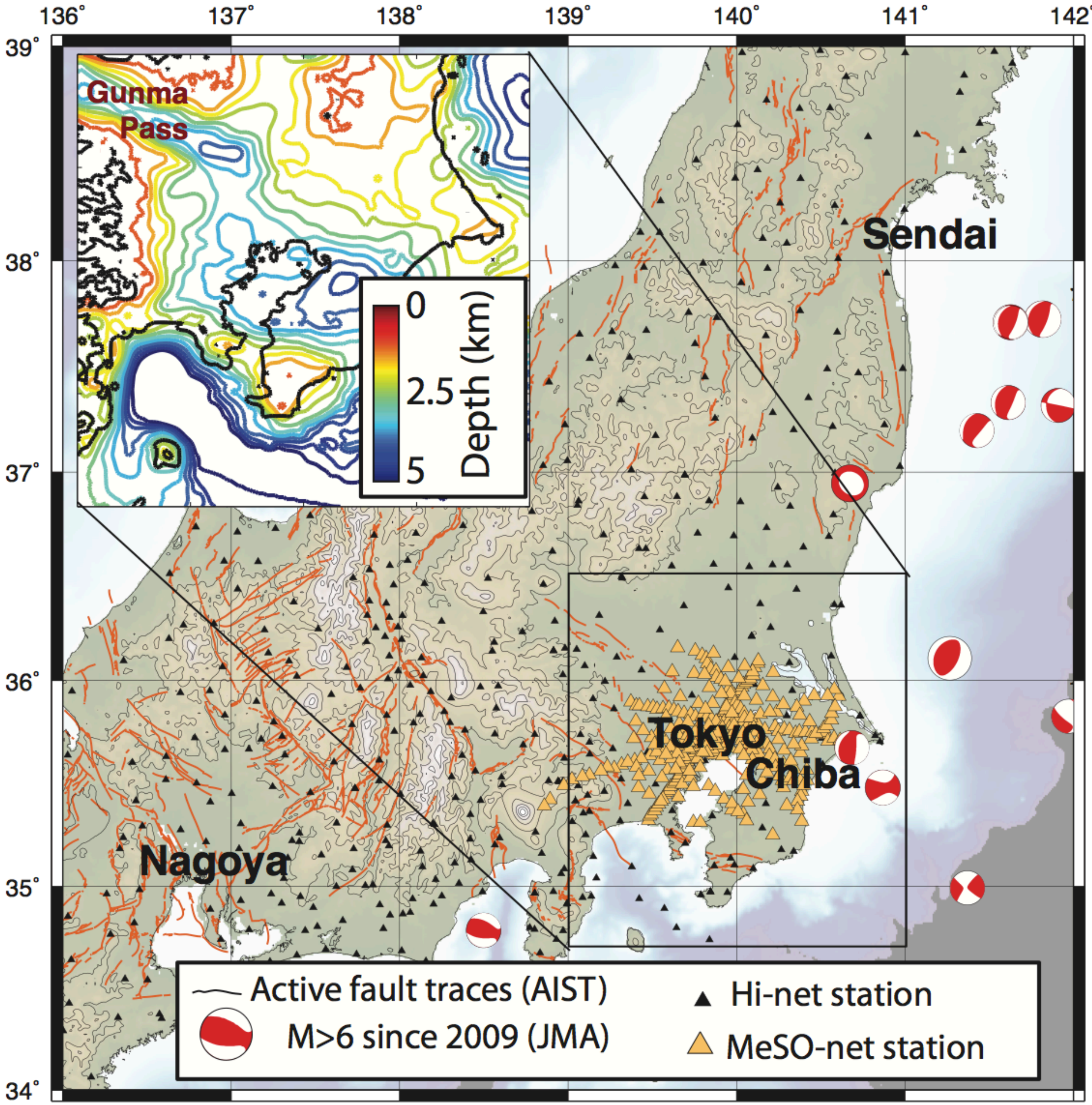
GMPEs

Fit ground motions to parameterized equations.

How can ambient-field measurements contribute?

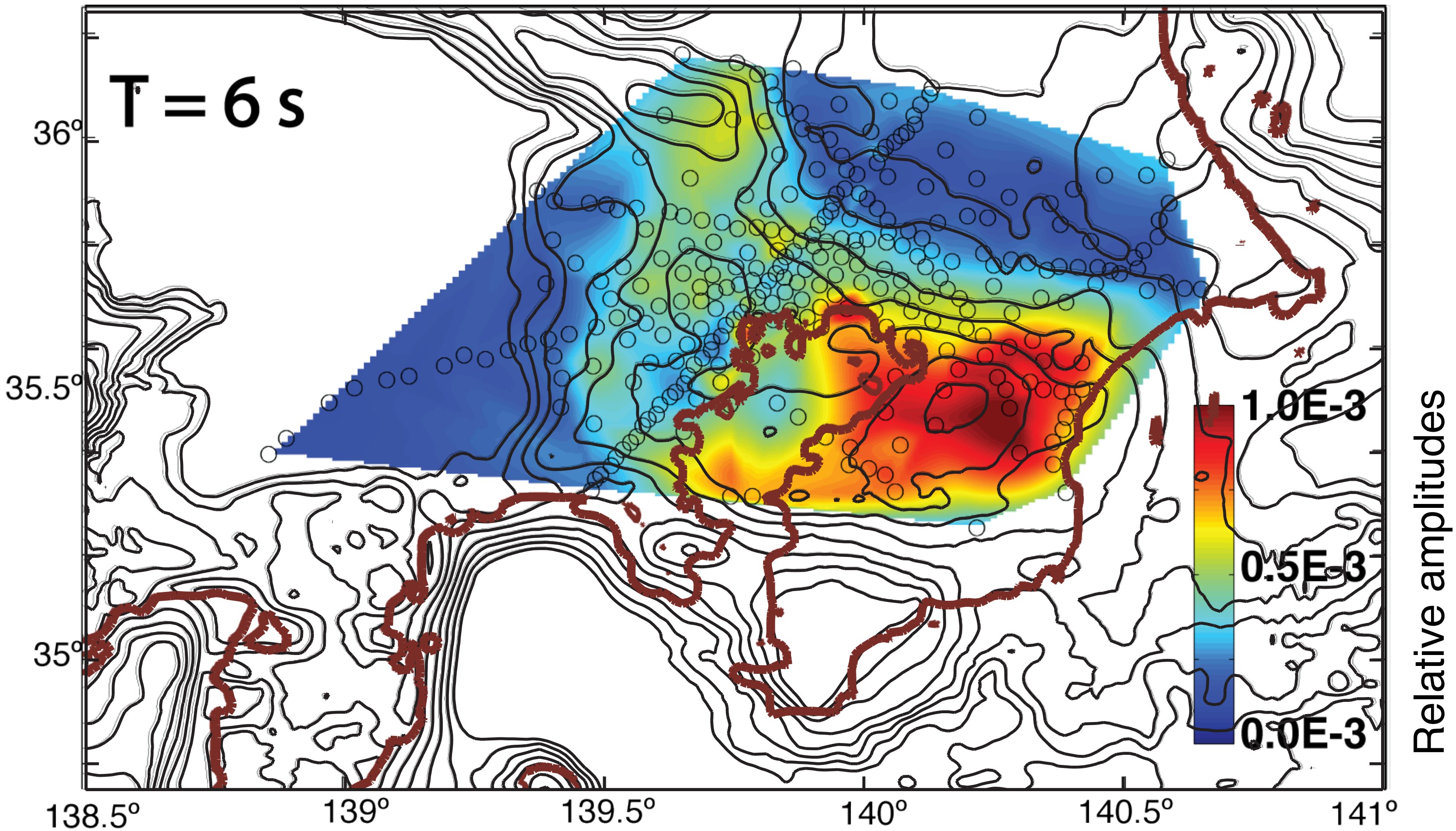
Hi-Net
(deep borehole)
+
MESO-Net
(shallow borehole)

#GFs= 9 x N(N-1)/2



Denolle et al. (2014b)

Average Basin Amplification vs. Basin Depth

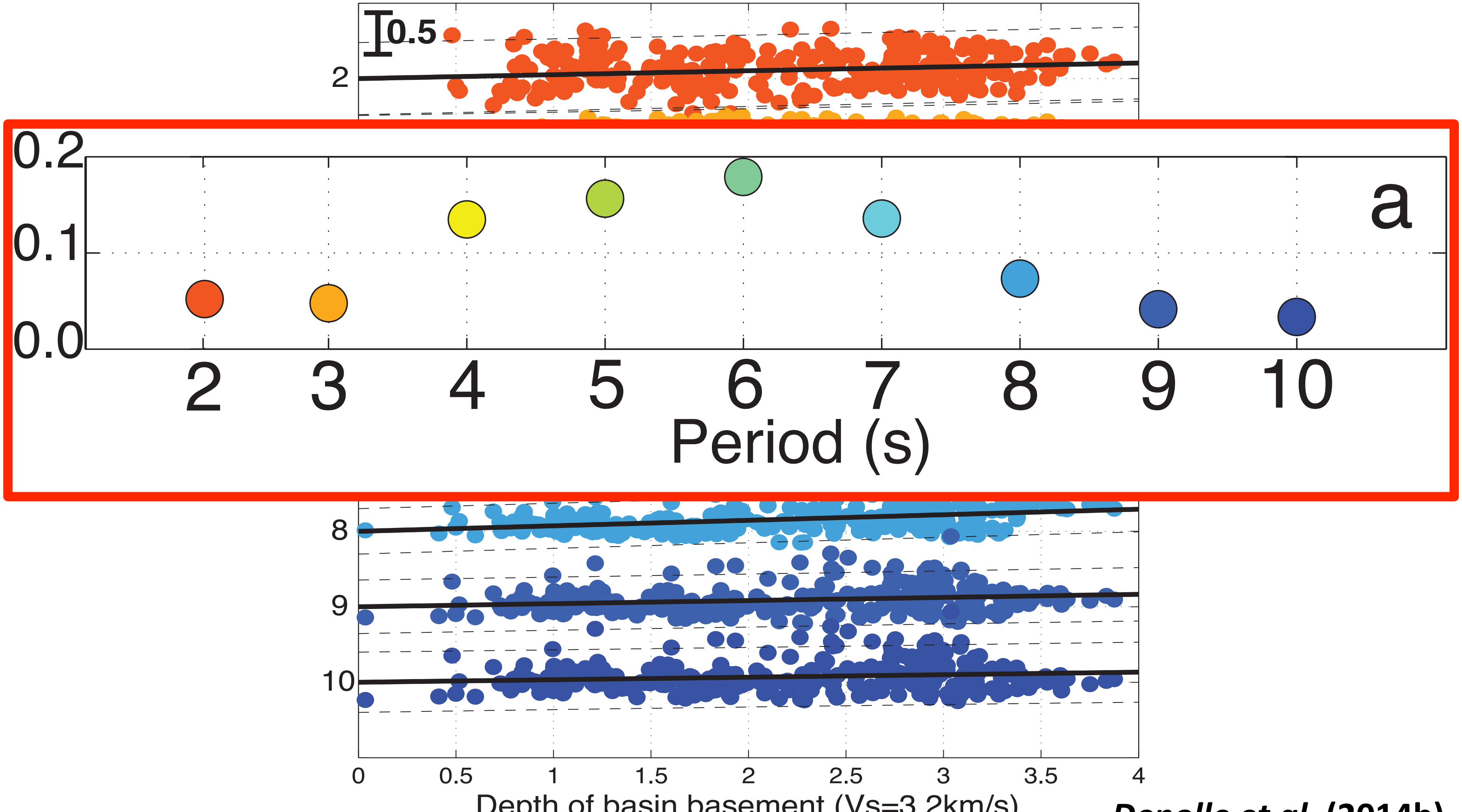


Contours show basin depth – Colors show amplification

Denolle et al. **(2014b)**

Basin Amplification ~ Basin Depth

$$\log A = a\,Z + b$$



***Denolle et al.* (2014b)**

Approaches to Ground Motion Prediction

Data-Driven ⟷ **Model-Guided**

GMPEs

Fit ground motions to parameterized equations.

Simulations

Model wave propagation through imaged 3D structure.

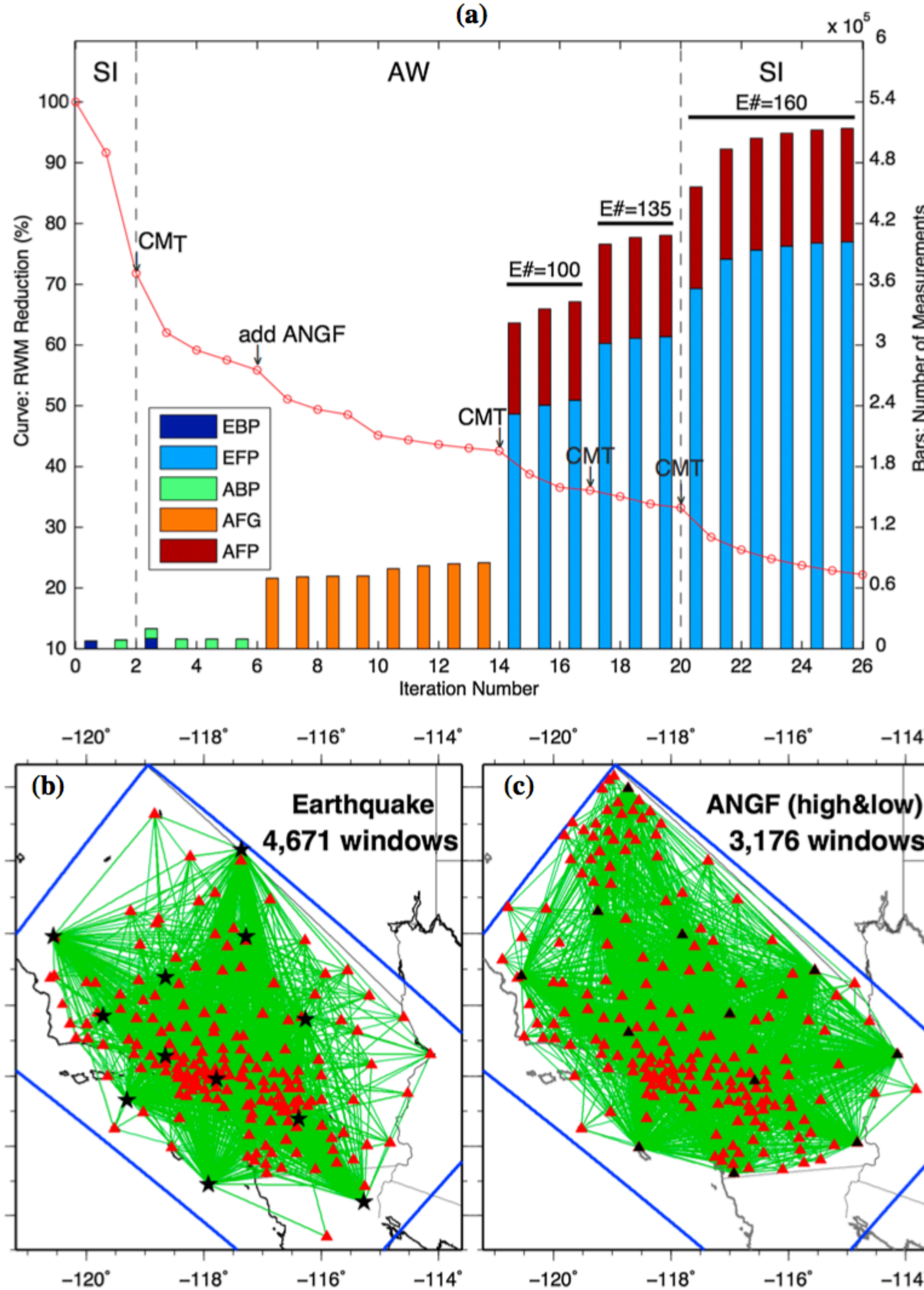
How can ambient-field measurements contribute?

Ambient-Field Observatons

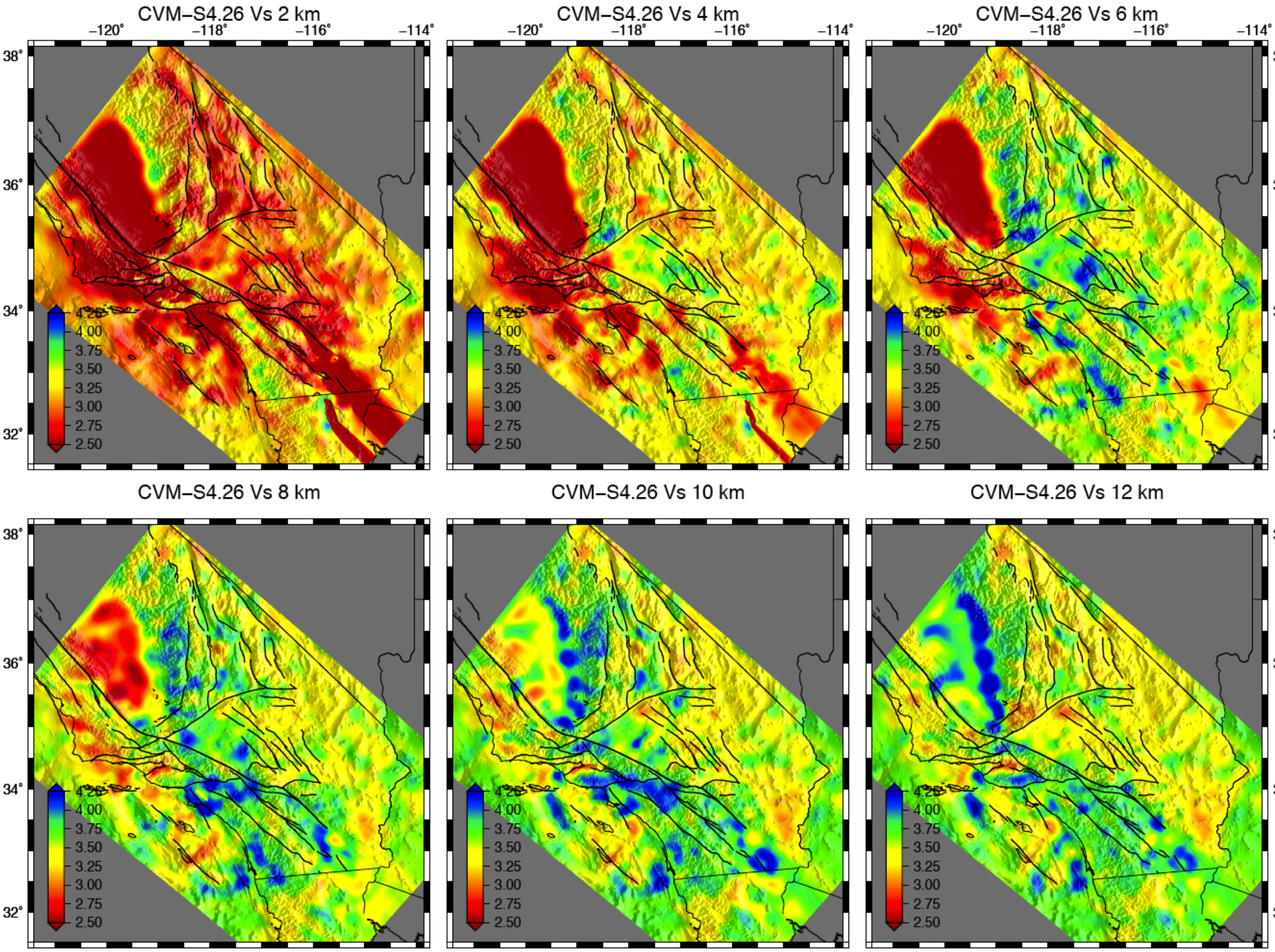
Data even in the absence of earthquakes

Constrain shallow structure relevant to ground motion prediction.

(*Lee et al.,* 2014)

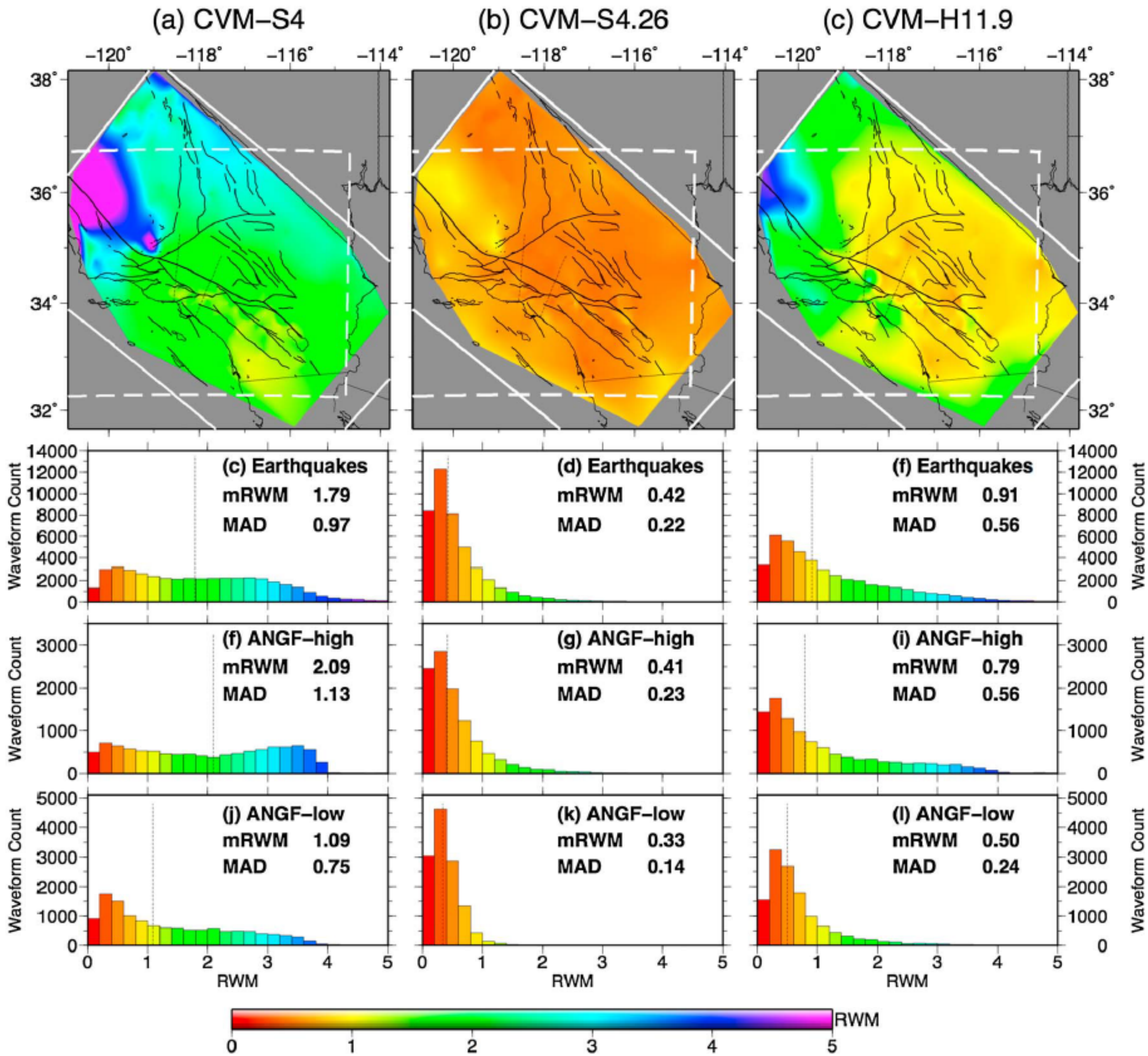


Full 3D Tomography of Southern California



(*Lee et al.,* 2014)

Reduced Waveform Misfit



(*Lee et al.,* 2014)

Approaches to Ground Motion Prediction

Data-Driven | **Hybrid** | **Model-Guided**

GMPEs

Fit ground motions to parameterized equations.

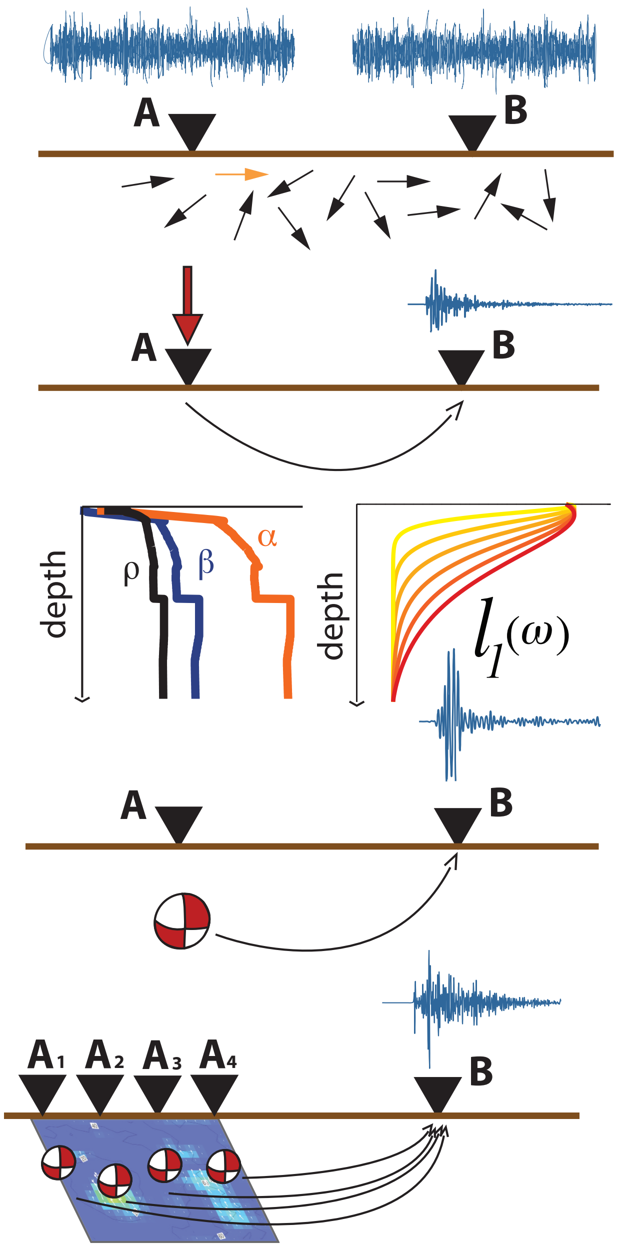
Virtual EQs

Use ambient seismic field to characterize effect of 3D structure.

Simulations

Model wave propagation through imaged 3D structure.

Virtual Earthquake Method



Continuous Recording of ASF

Earth Response to an Impulsive Force

Source-Depth Correction

Double-Couple Correction

Finite-Source Correction

Denolle et al. **(2013)**

Depth and Mechanism Corrections

Love:

$$\hat{U}_T\left(\vec{\xi},\omega\right) = \frac{1}{l_1\left(\vec{\xi}',0,\omega\right)}\left[-ik_L(\omega)\hat{M}_{TR}(\omega)l_1\left(\vec{\xi}',h,\omega\right) + \hat{M}_{TD}(\omega)l_1'\left(\vec{\xi}',h,\omega\right)\right]\hat{G}_{TT}\left(\vec{\xi}',\vec{\xi},\omega\right)$$

Rayleigh:

$$\hat{U}_R\left(\vec{\xi},\omega\right) = \frac{1}{r_1\left(\vec{\xi}',0,\omega\right)}\left[-ik_R\hat{M}_{RR}(\omega)r_1\left(\vec{\xi}',h,\omega\right) + \hat{M}_{RD}(\omega)l_1'\left(\vec{\xi}',h,\omega\right)\right]\hat{G}_{RR}\left(\vec{\xi}',\vec{\xi},\omega\right) +$$

$$\frac{1}{r_2\left(\vec{\xi}',0,\omega\right)}\left[-ik_R\hat{M}_{DR}(\omega)r_1\left(\vec{\xi}',h,\omega\right) + \hat{M}_{DD}(\omega)l_1'\left(\vec{\xi}',h,\omega\right)\right]\hat{G}_{DR}\left(\vec{\xi}',\vec{\xi},\omega\right),$$

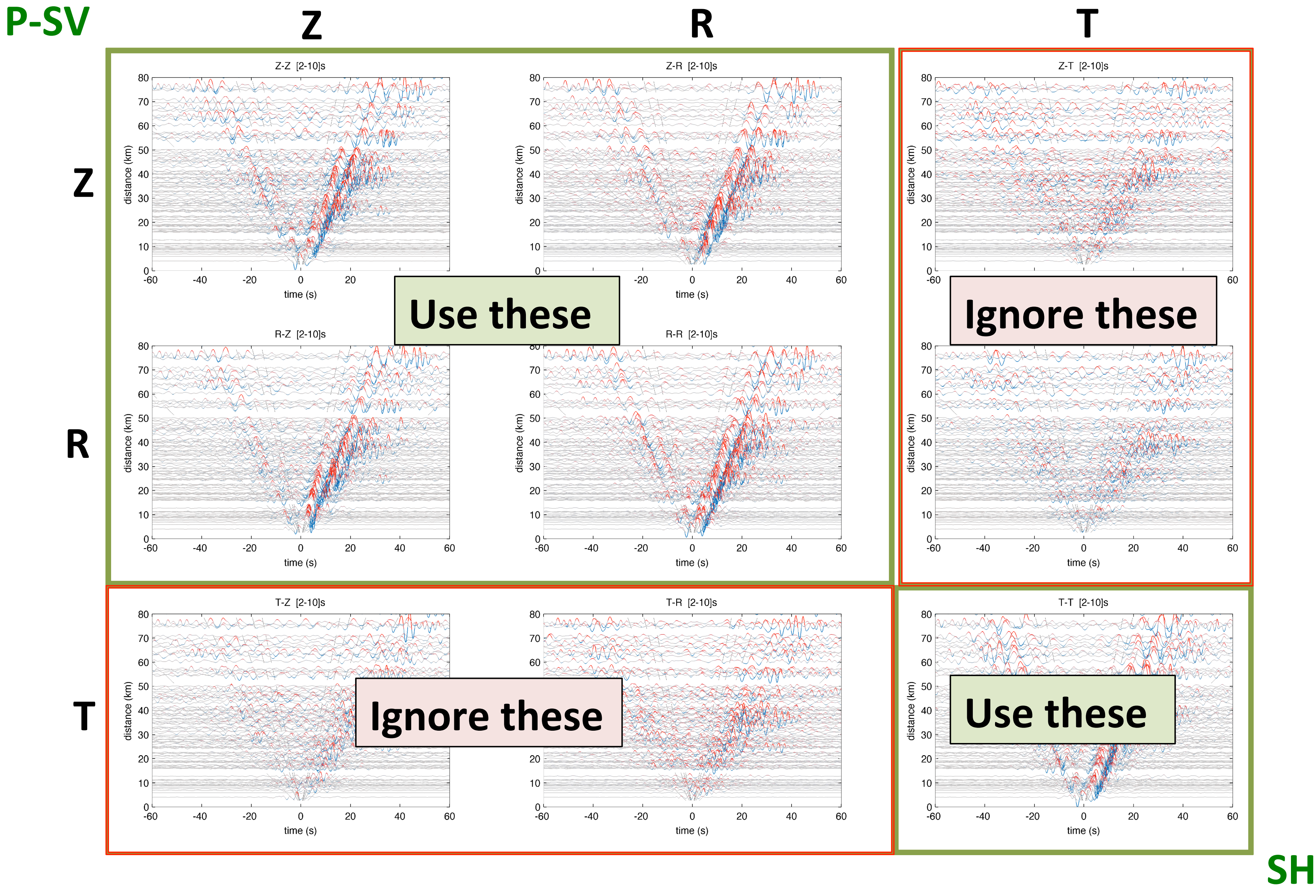
$$\hat{U}_D\left(\vec{\xi},\omega\right) = \frac{1}{r_1\left(\vec{\xi}',0,\omega\right)}\left[-ik_R\hat{M}_{RR}(\omega)r_1\left(\vec{\xi}',h,\omega\right) + \hat{M}_{RD}(\omega)l_1'\left(\vec{\xi}',h,\omega\right)\right]\hat{G}_{RD}\left(\vec{\xi}',\vec{\xi},\omega\right) +$$

$$\frac{1}{r_2\left(\vec{\xi}',0,\omega\right)}\left[-ik_R\hat{M}_{DR}(\omega)r_1\left(\vec{\xi}',h,\omega\right) + \hat{M}_{DD}(\omega)l_1'\left(\vec{\xi}',h,\omega\right)\right]\hat{G}_{DD}\left(\vec{\xi}',\vec{\xi},\omega\right),$$

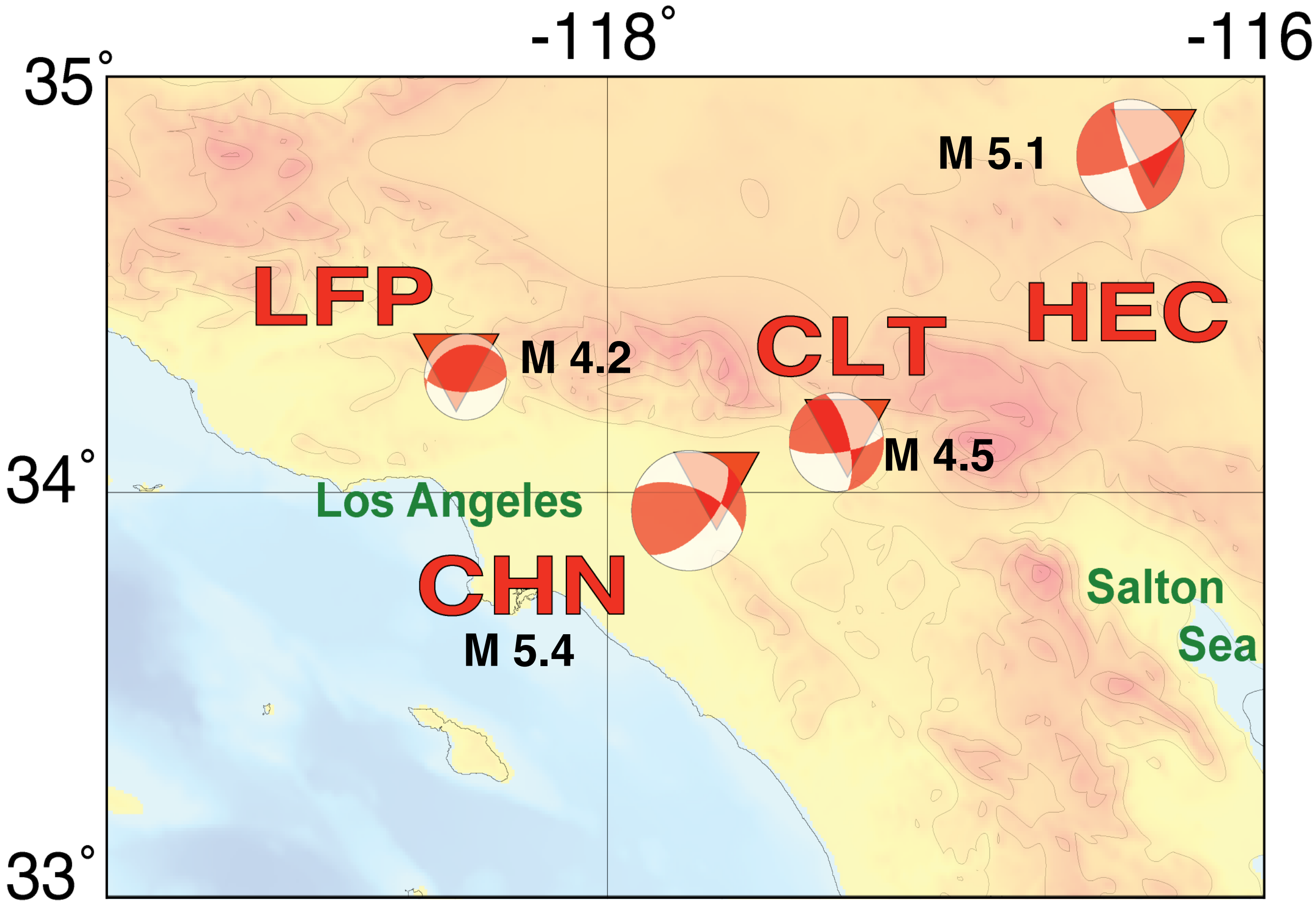
Make 1D approximation in excitation

***Denolle et al.* (2013)**

All 9 Components of GFs (2-10 s)



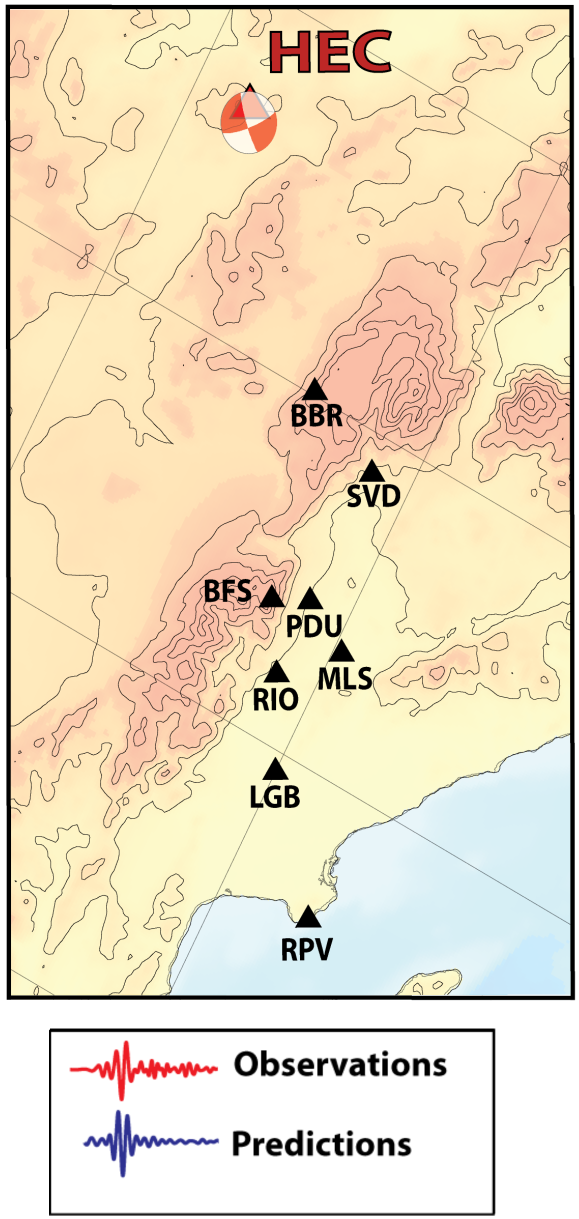
Validate Against 4 Moderate Earthquakes

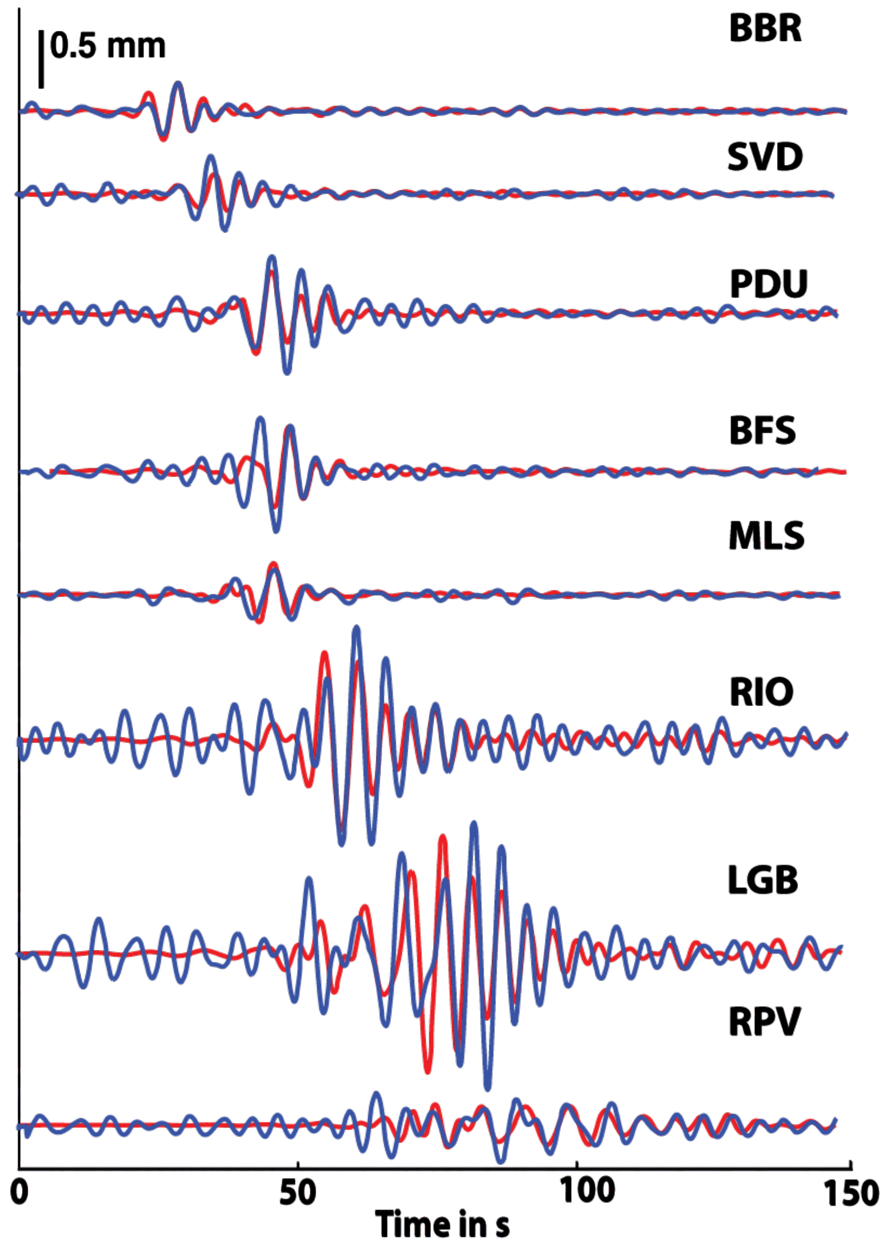


Each located near a BB station for which we construct a virtual earthquake to compare with seismograms from real earthquake

***Denolle et al.* (2013)**

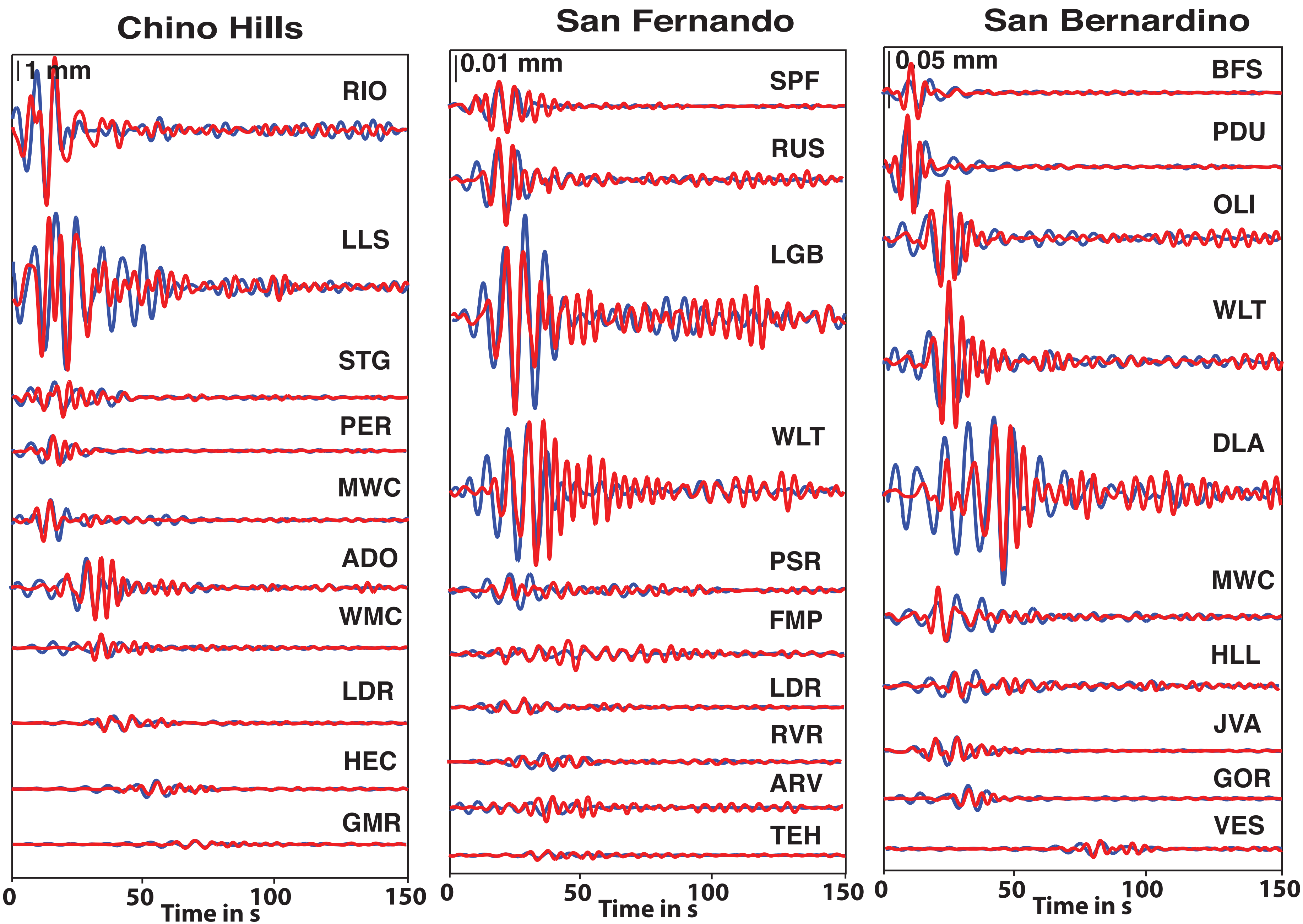
Hector Road *M* 5.1





Denolle et al. (2013)

Further Validation with Moderate Earthquakes



Application to GMP for Induced Seismicity

Linearity (weak motion)

Shallow - depth correction smaller

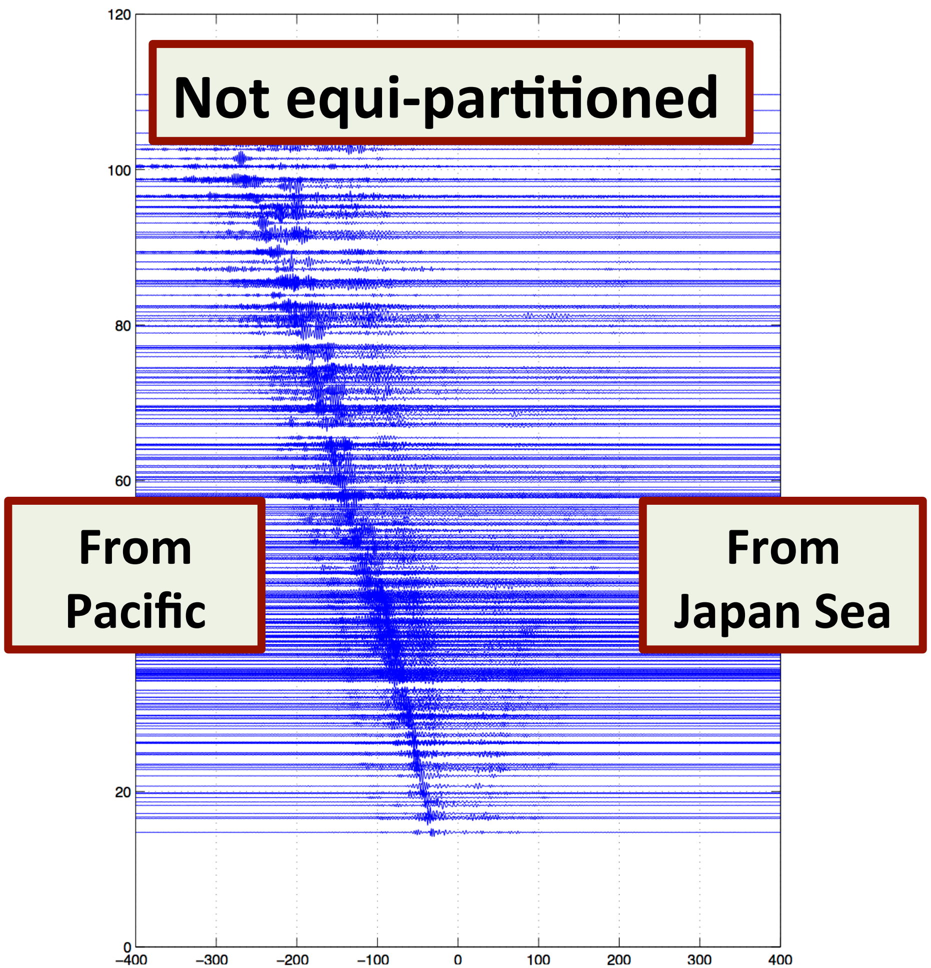
Amplitude bias – azimuthal/among components

Bandwidth limitation – depends on distance, site

Body waves vs. surface waves

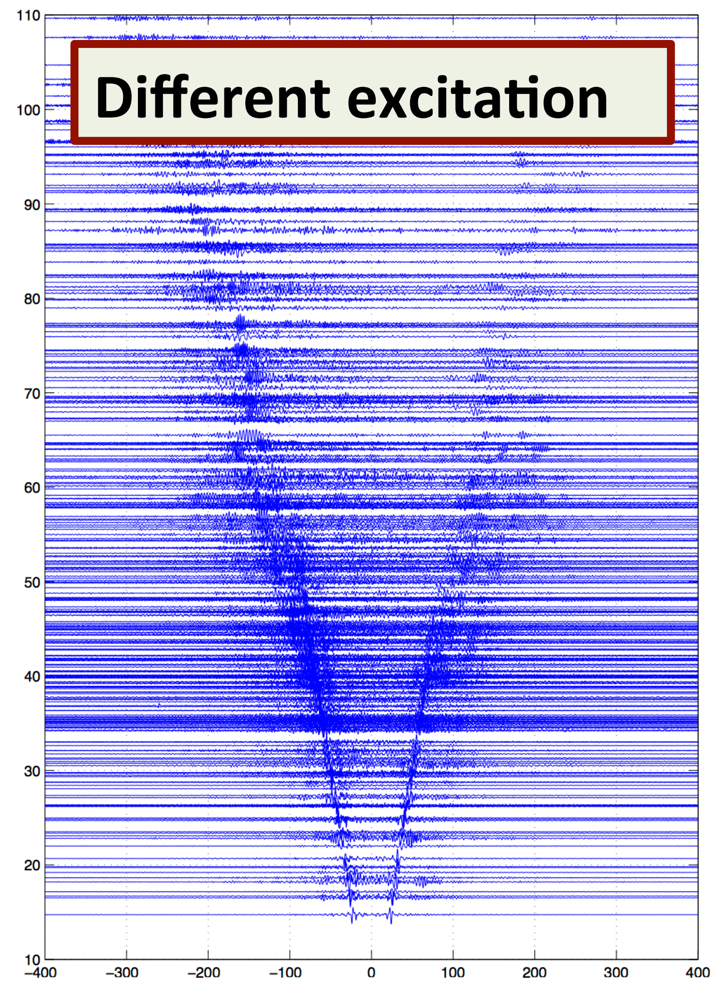
Amplitude Biases – Data from Japan

ZZ



By Azimuth

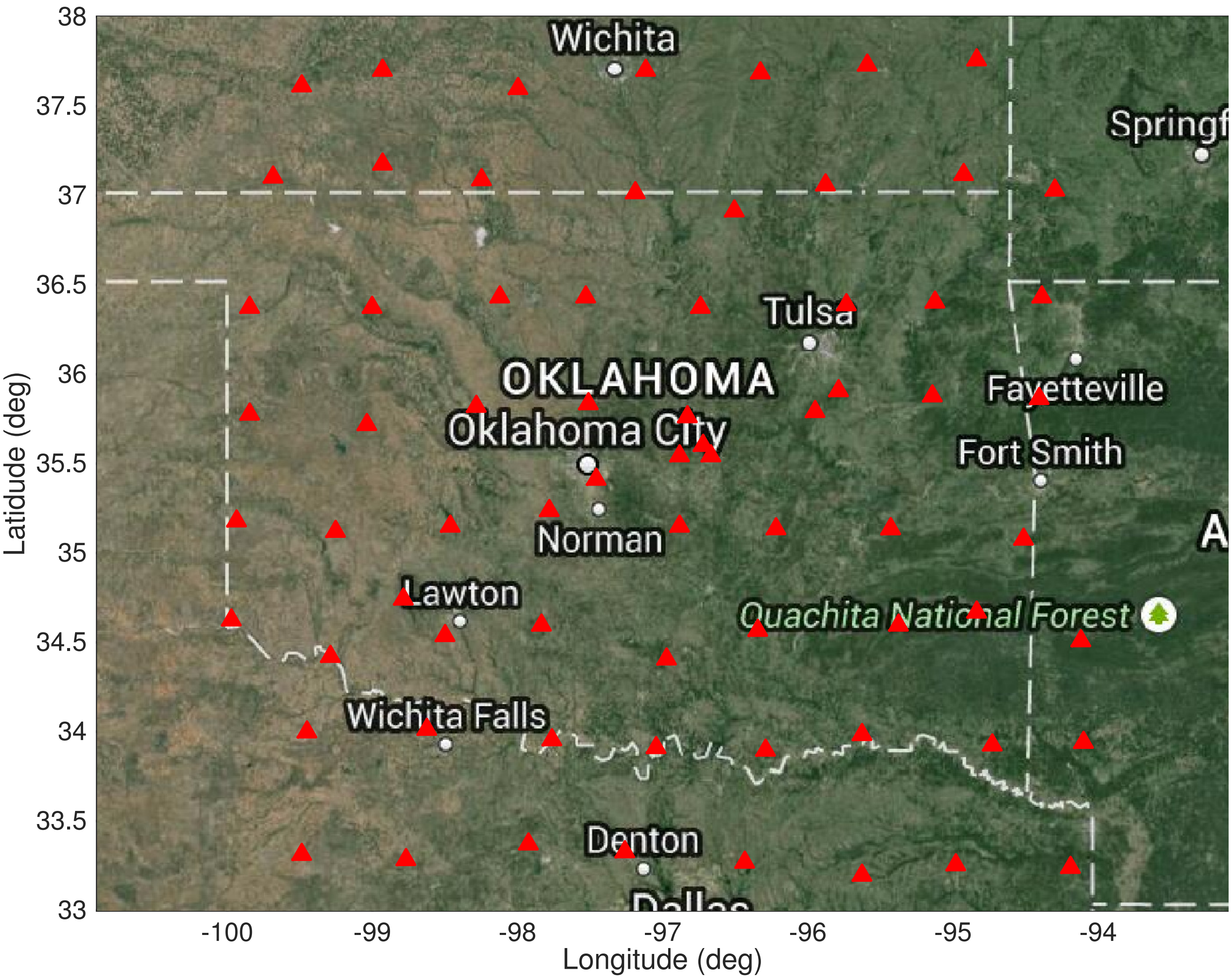
TT



By Component

Denolle et al. (2014b)

TA Across Oklahoma

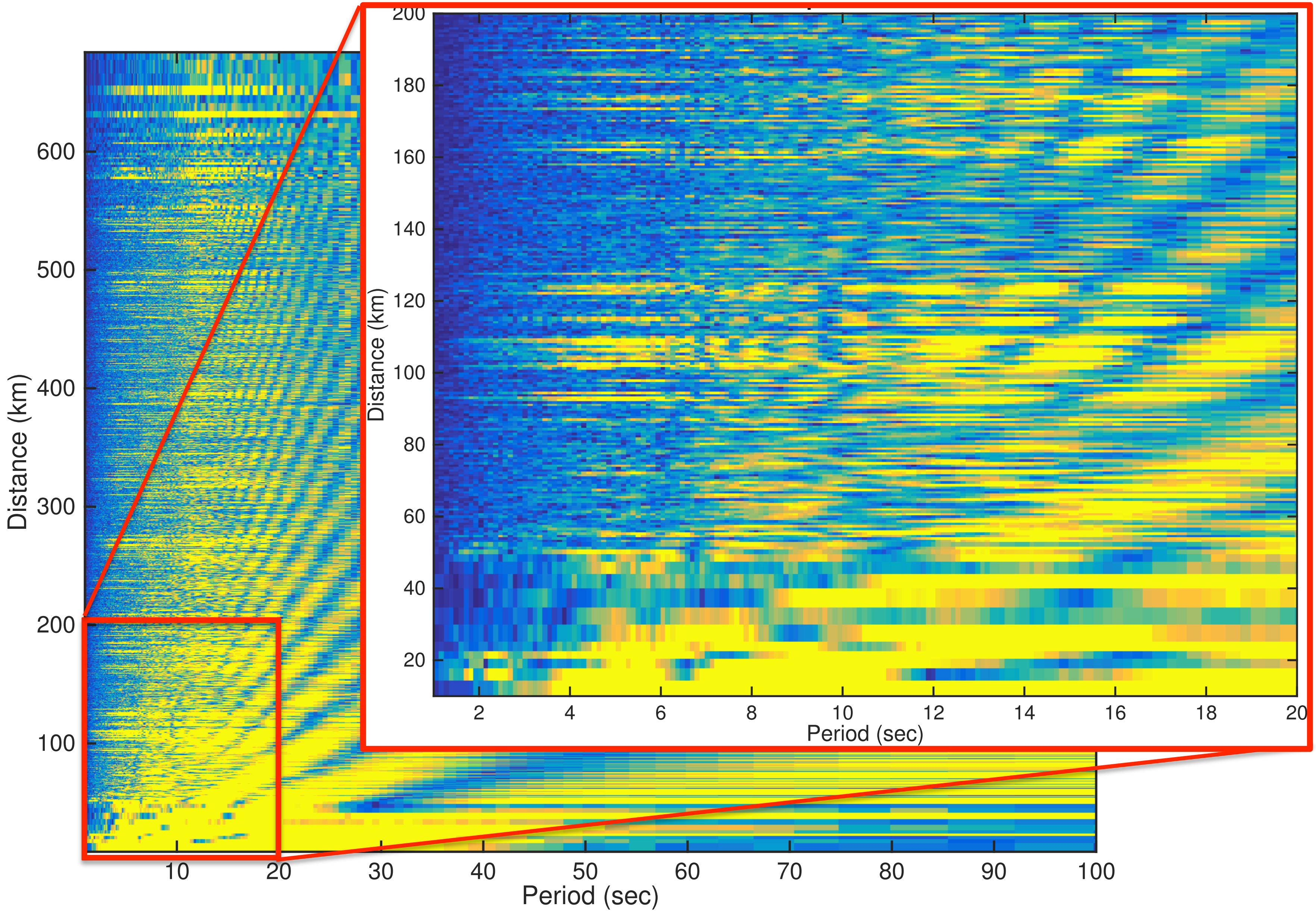


~1.5 years continuous broadband data

~75 km station spacing

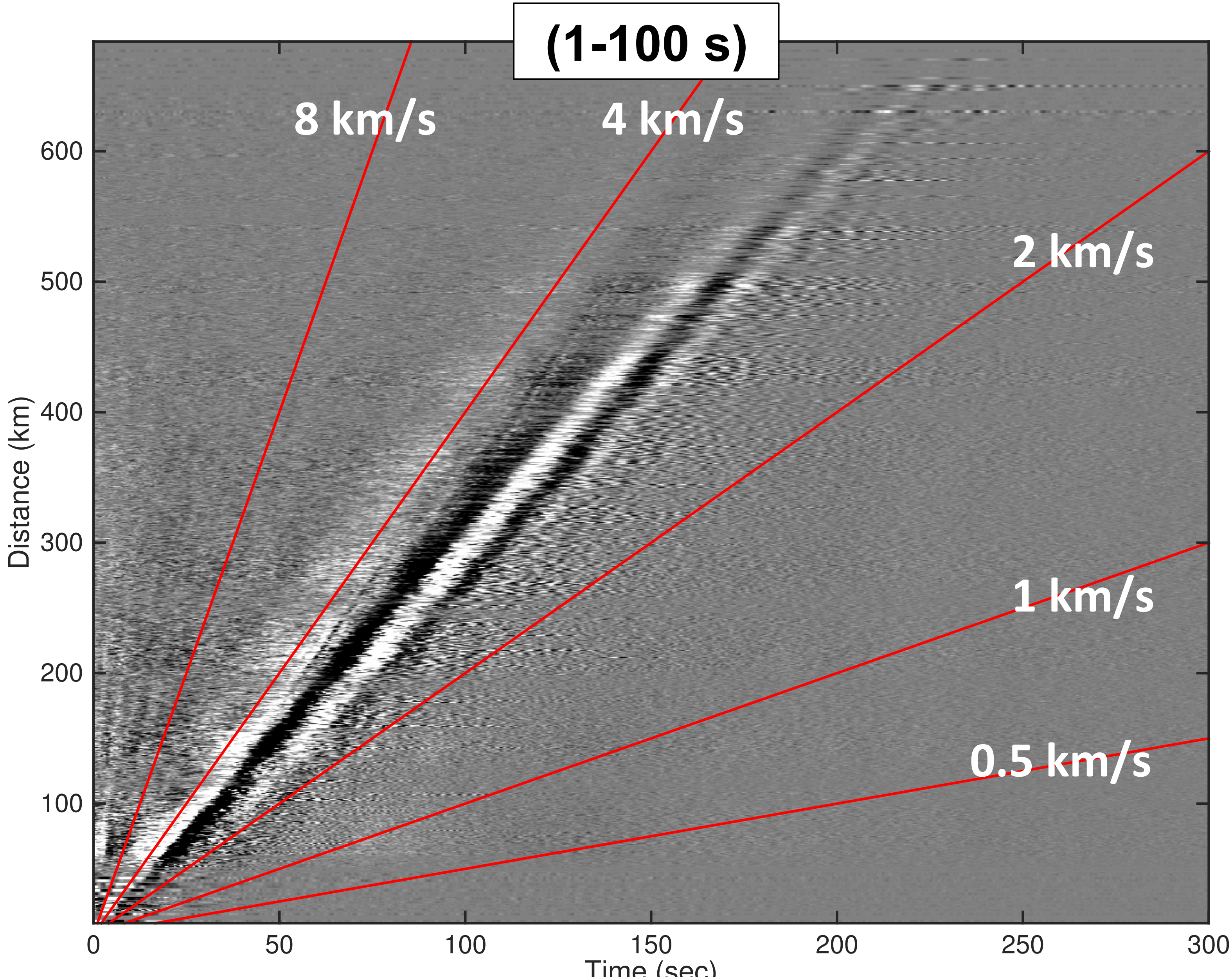
Courtesy of Pierre Boue'

TA Station Pairs - GF Recovery



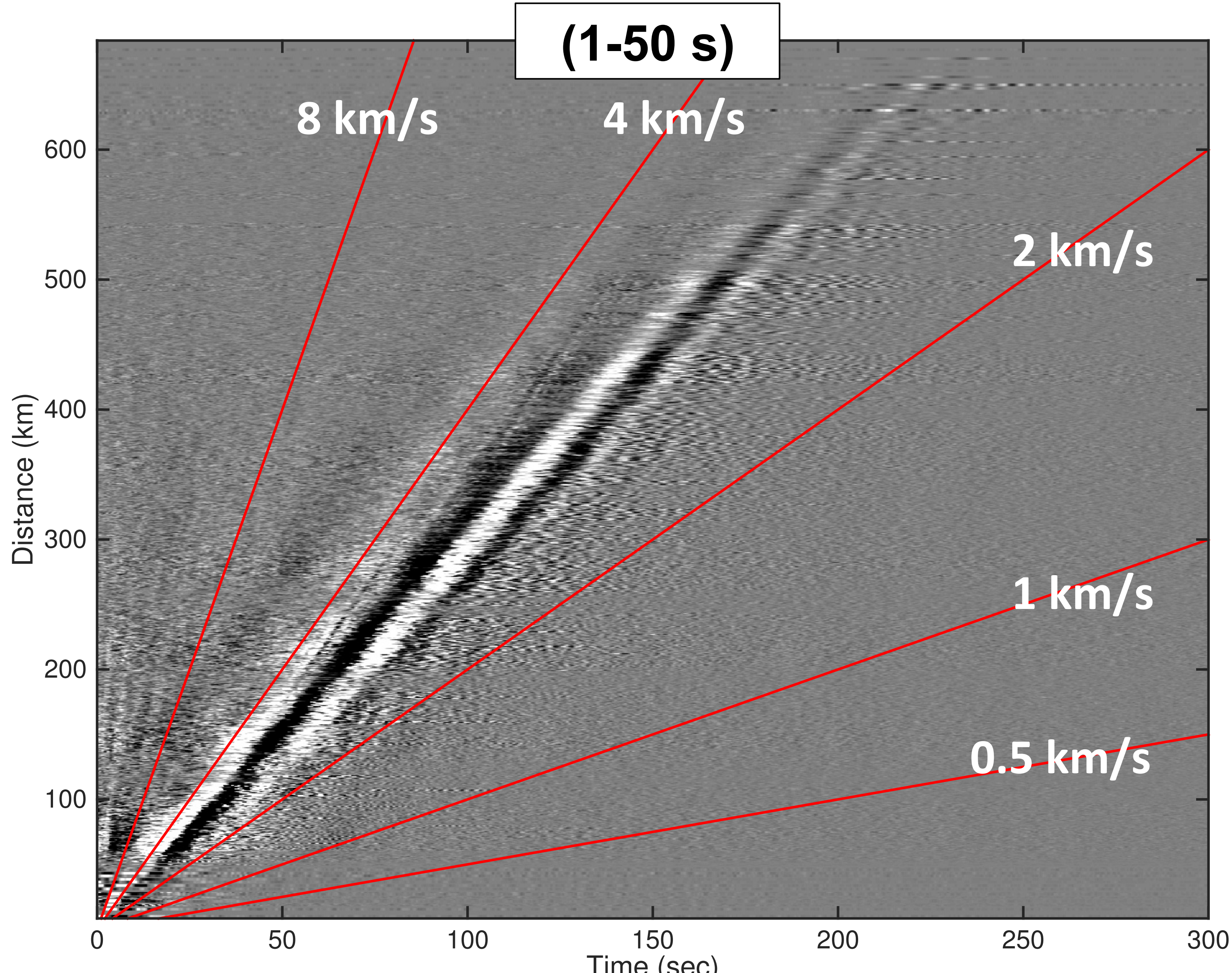
Courtesy of Pierre Boue'

TA Green's Functions



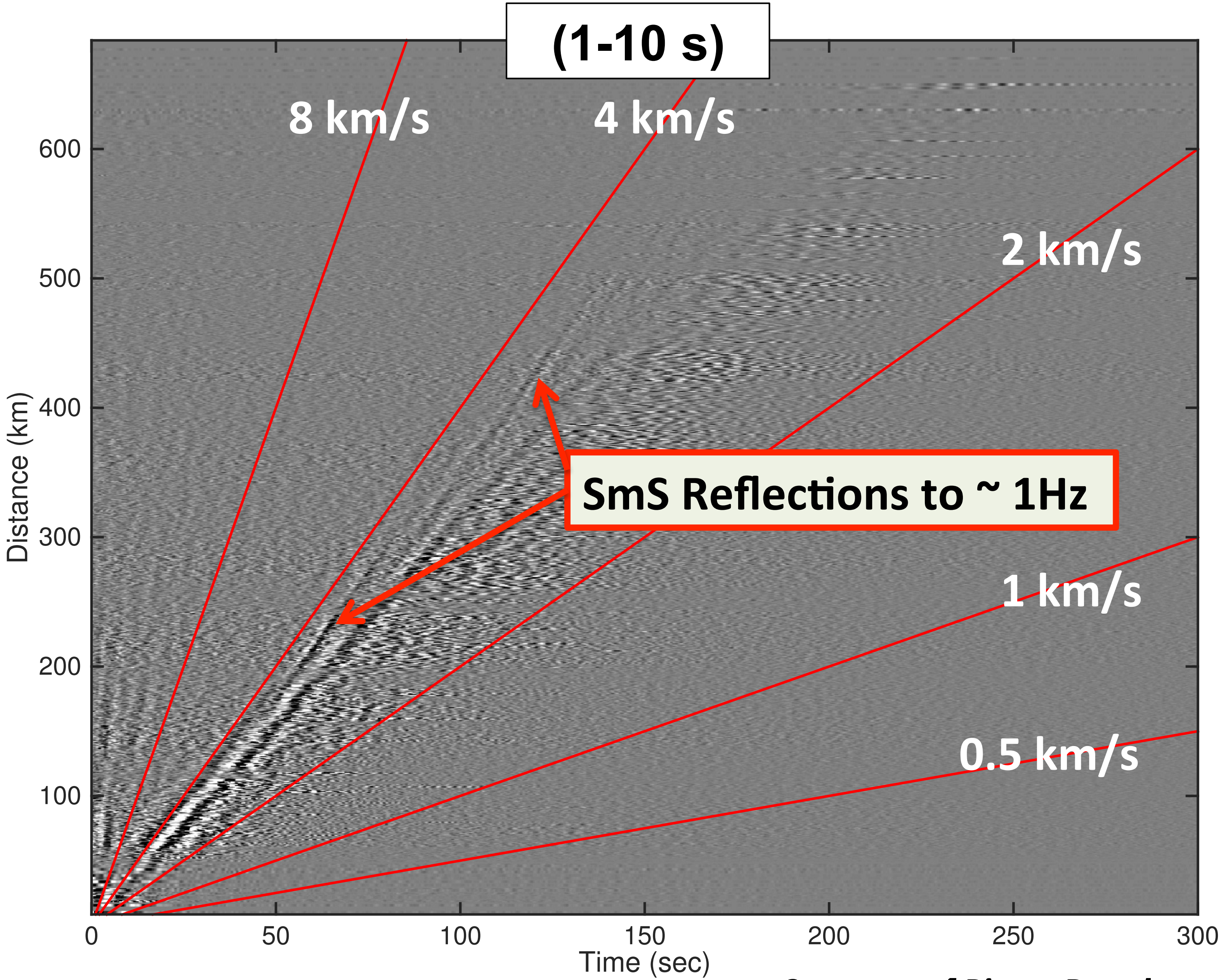
Courtesy of Pierre Boue'

TA Green’s Functions



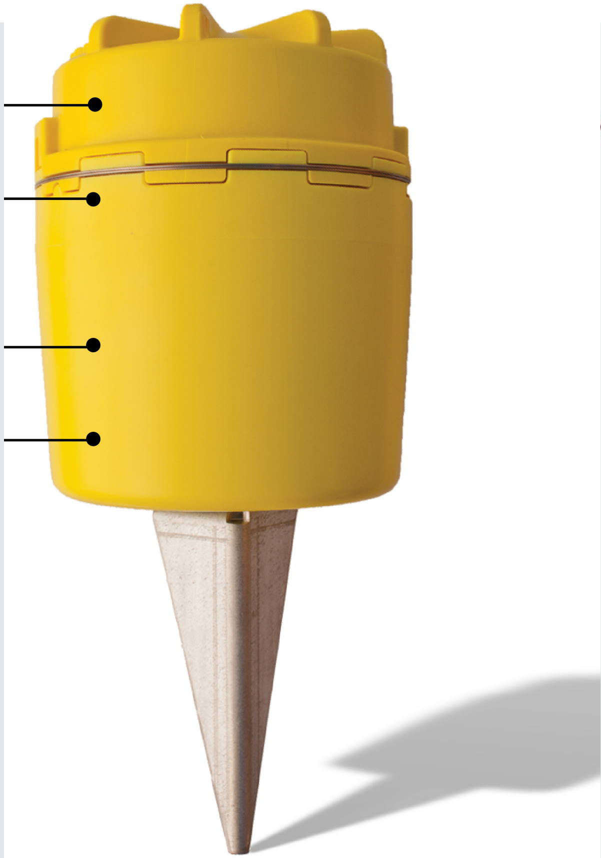
Courtesy of Pierre Boue’

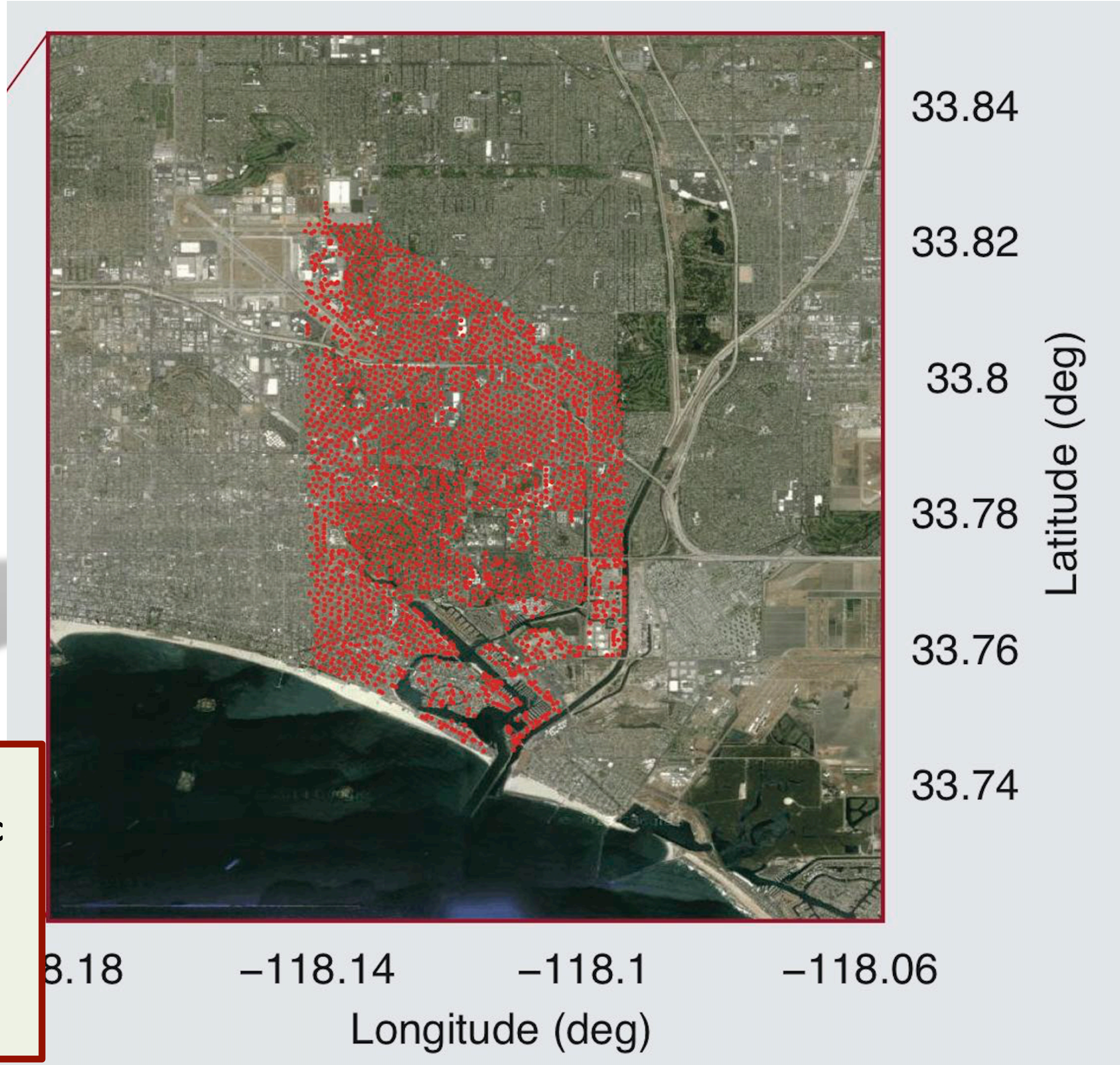
TA Green's Functions



Courtesy of Pierre Boue'

Value of Dense Recording



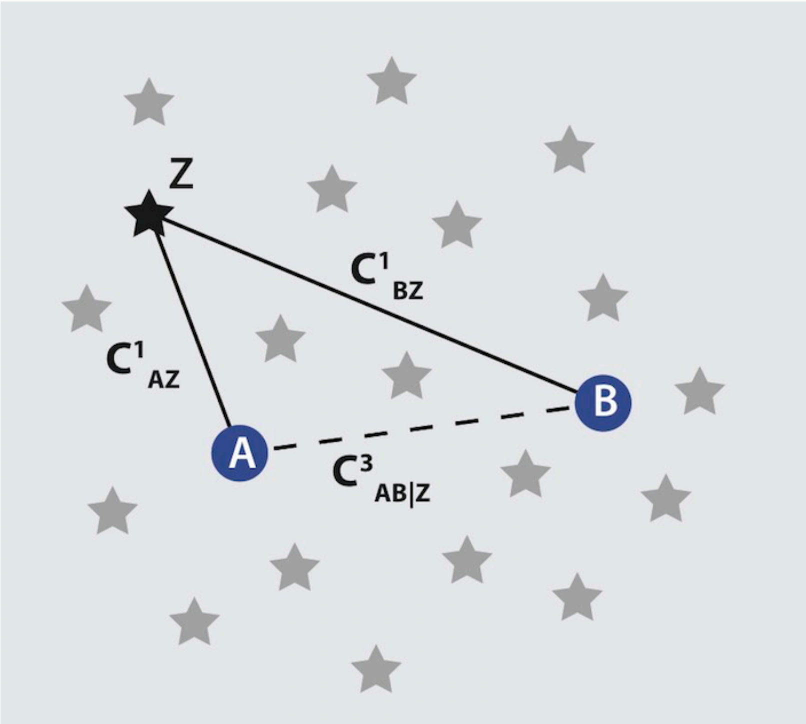


Data provided by Signal Hill Petroleum and NodalSeismic

~2500 vertical Sensors
~100 m Spacing
#obs = N(N-1)/2

Correlation of Correlations

(*Stehly et al.*, 2008)

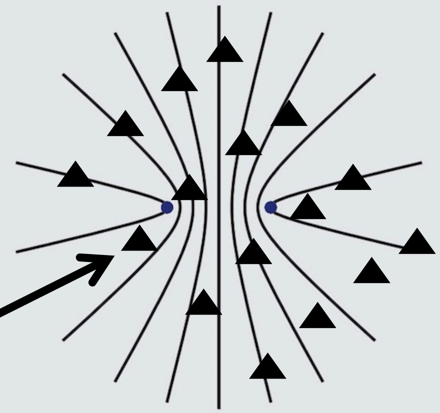


Correlation of Green's functions derived from correlations

Approximates equi-partitioned ideal

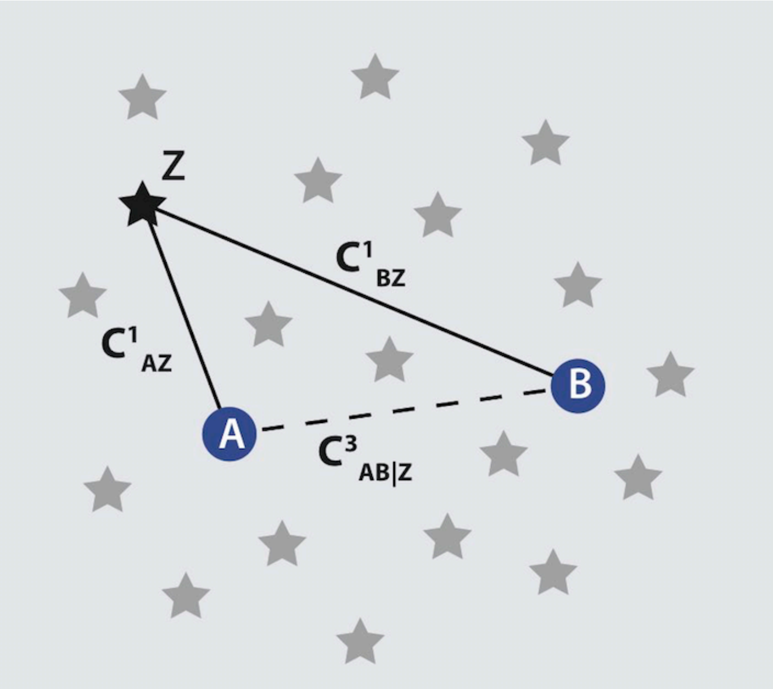
Can compare theoretical and observed kernels to understand and remove amplitude bias

Map this contribution using the virtual sources at each station in Long Beach array.



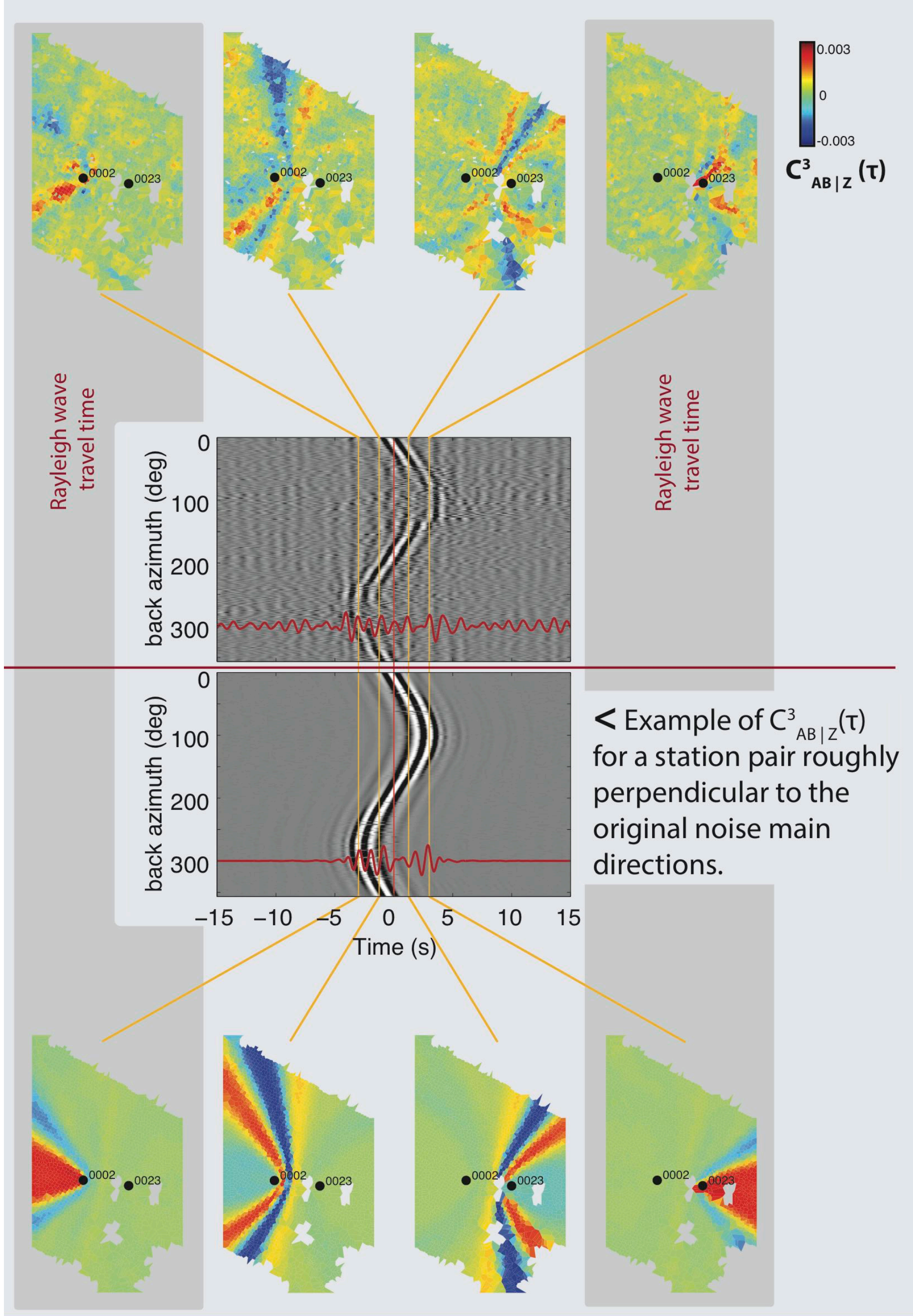
For a given receiver pair, the regions that contribute to a given time in the correlation function are hyperbolas. The vertical line correponds to the zero-lag time contribution (Roux et al., 2005)

Correlation of Correlations



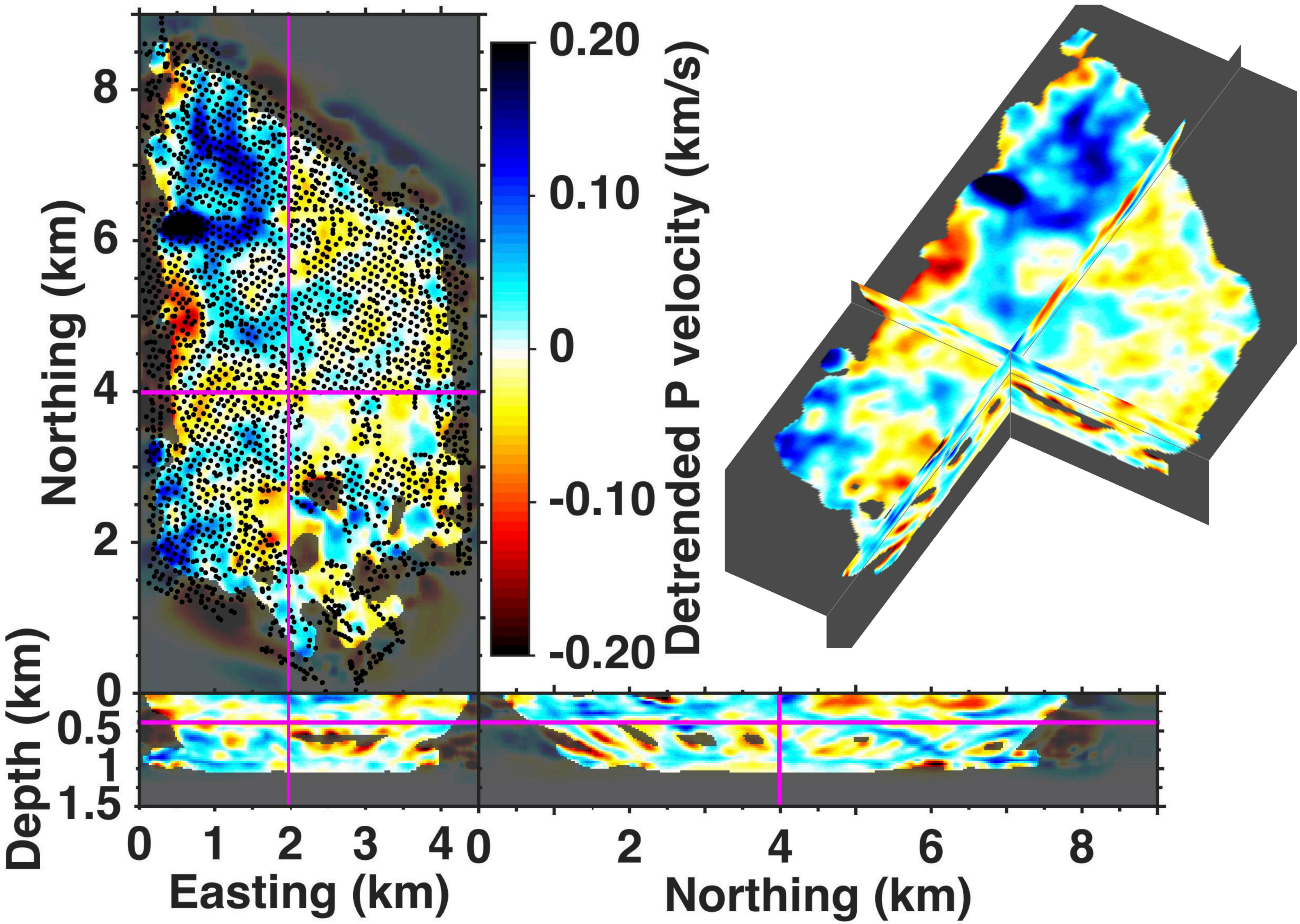
Can correct for remaining bias from lack of equi-partitioning

With 3 component data could correct for excitation bias as well



< Example of $C^3_{AB|Z}(\tau)$ for a station pair roughly perpendicular to the original noise main directions.

3D Body-Wave Tomography with ASF



Nakata, Chang, Lawrence, and Boue' (in press)

Conclusions – ASF for GMP

Caveats:

1. Only part of the problem (source, nonlinearity)
2. Bias (azimuthal, multi-component)
3. Bandwidth limitations
4. Body waves

Promise:

1. New approaches to an important problem
2. Active, not passive
   – no need to wait for real earthquakes
   – can sample sources/sites of strategic interest
   – can revisit past earthquakes
3. Resolves 3D effects – Earth does the experiment

An Assertion

GMP prediction for IS is a solvable problem

- **we know where to put the instruments**
- **small, frequent earthquakes are important**
- **we can trigger the earthquakes**
- **reducing epistemic uncertainty and characterizing variability is *much* easier than for tectonic events**

A Recommendation

Dense 3-component instrumentation of IS sequence(s)

- **Don't need to record very long for high frequencies**
- **Can gather critical data even without earthquakes**
- **If earthquakes occur then a wealth of data for GMP**