Ground Motion Prediction Using the Ambient Seismic Field

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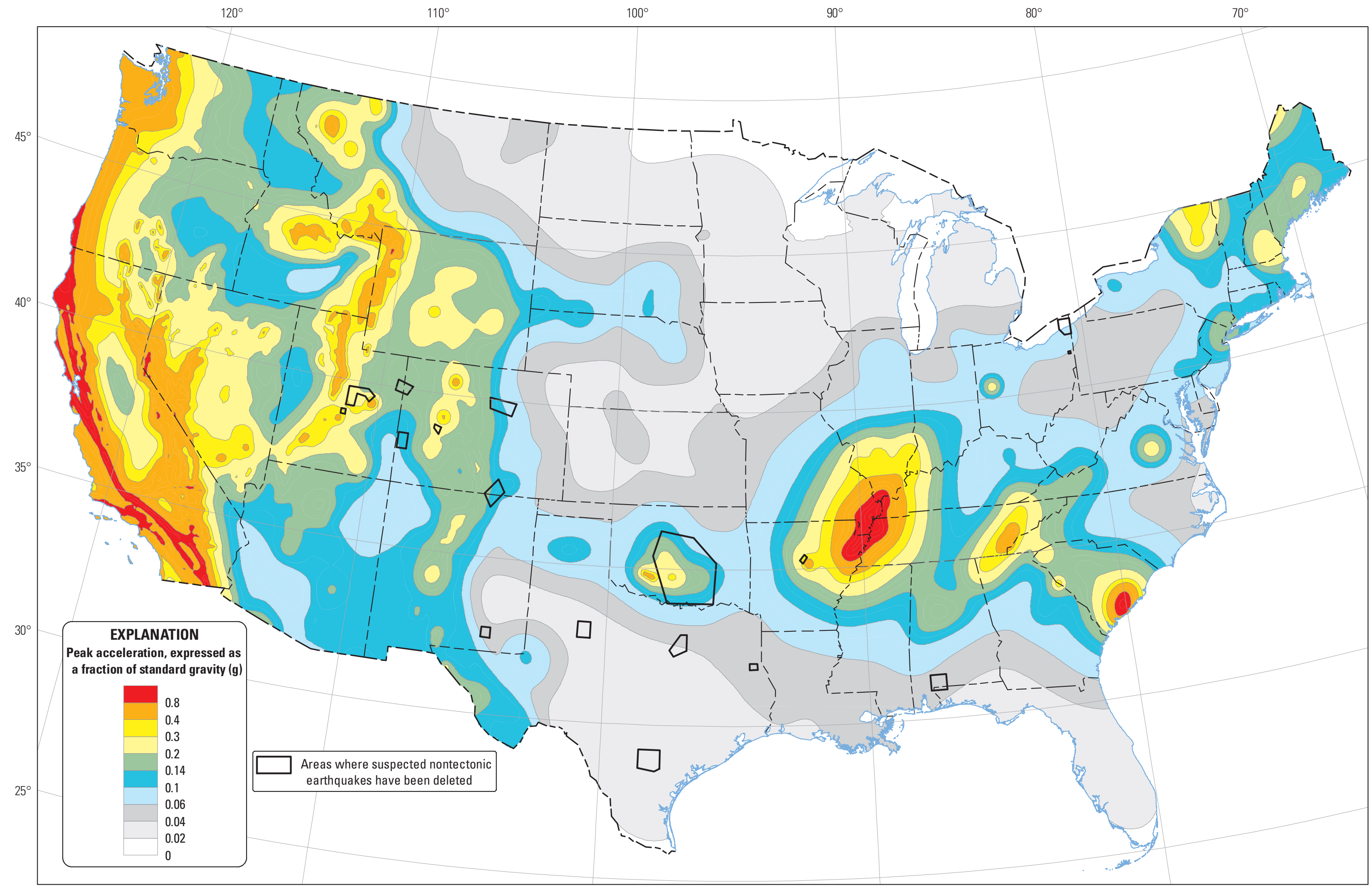
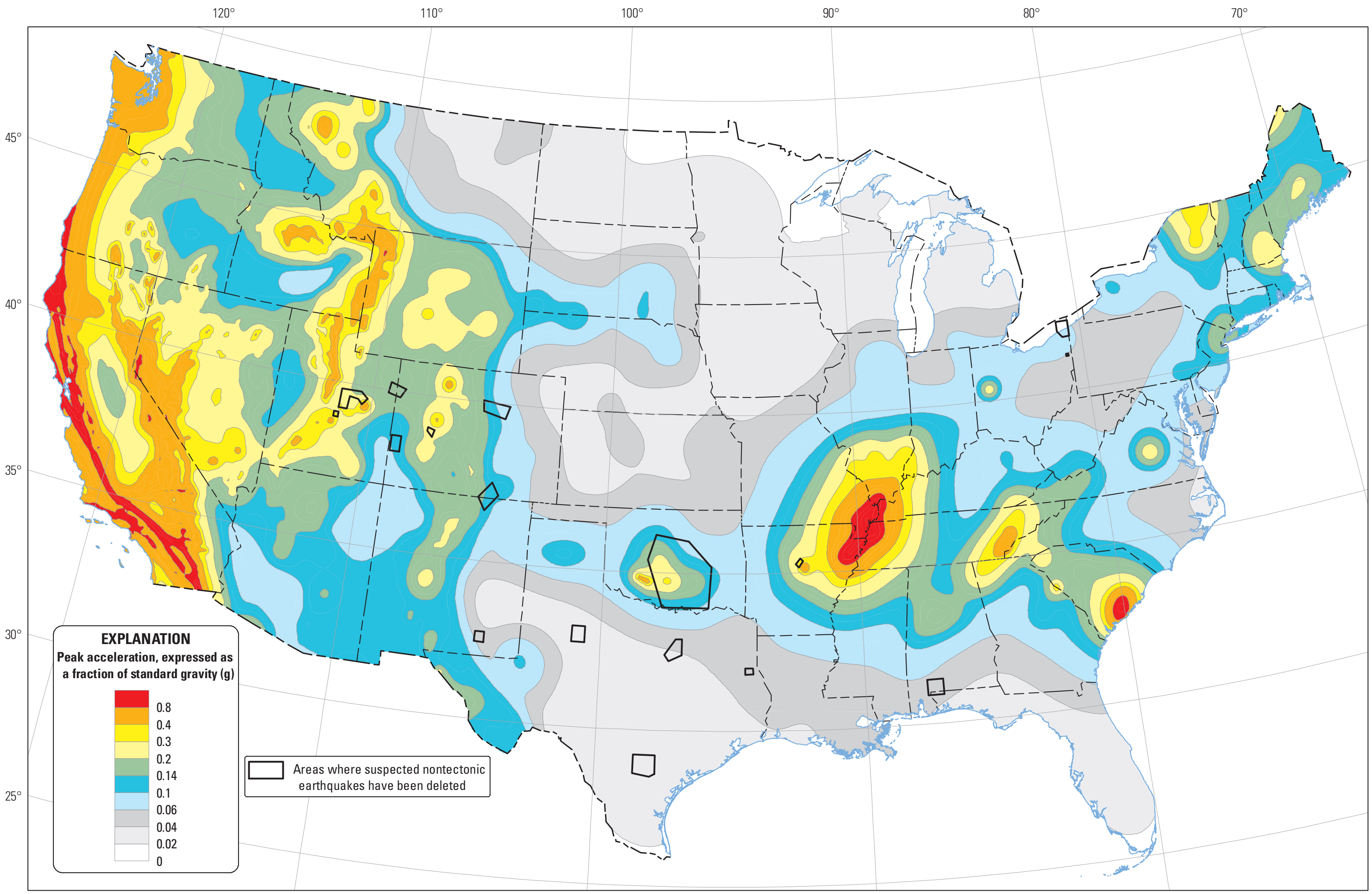
2014 National Seismic Hazard Map



Ground motion intensity with 2% exceedance probability in 50 years.

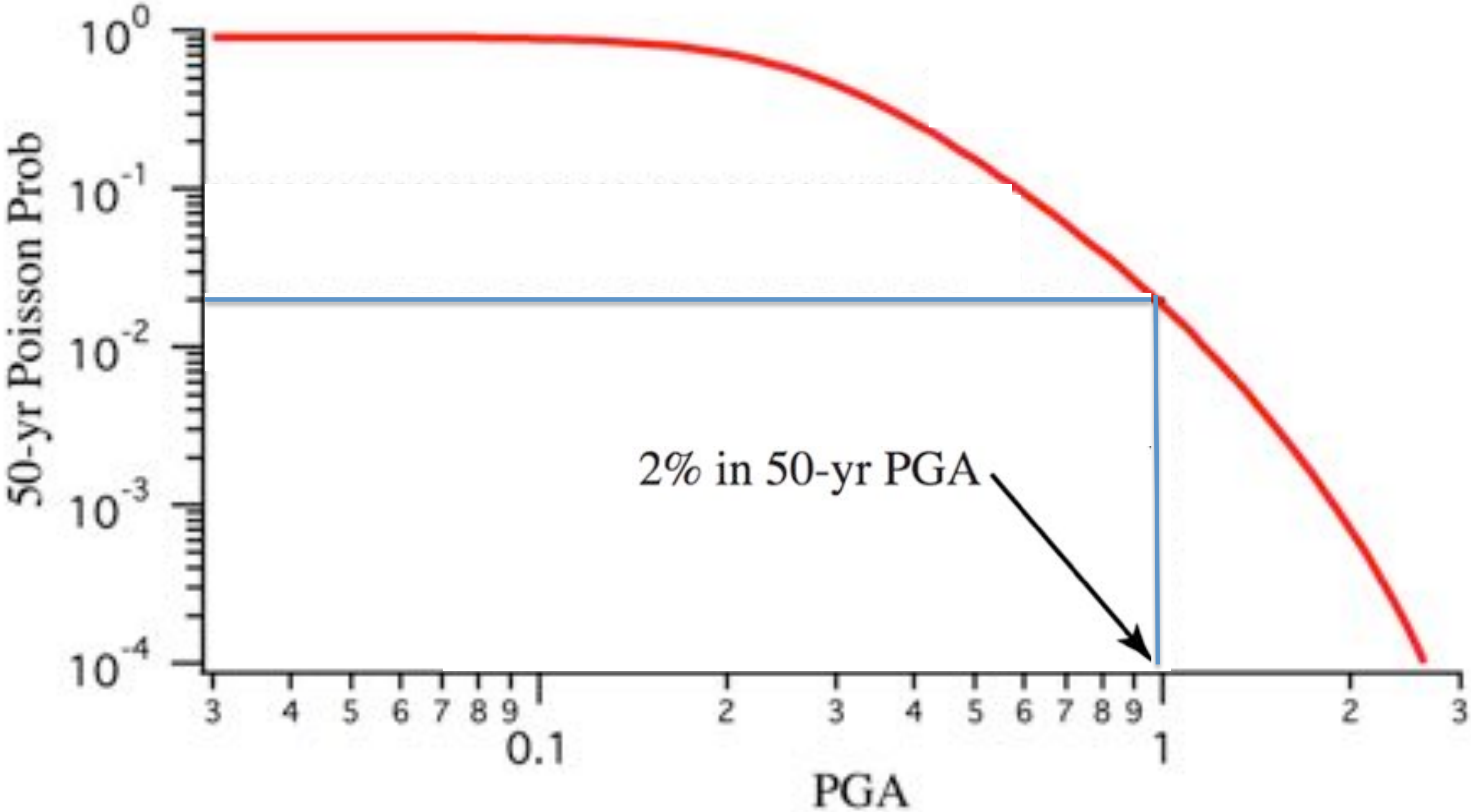
2014 National Seismic Hazard Map



Informs ~$1 trillion/yr in construction for 6 years

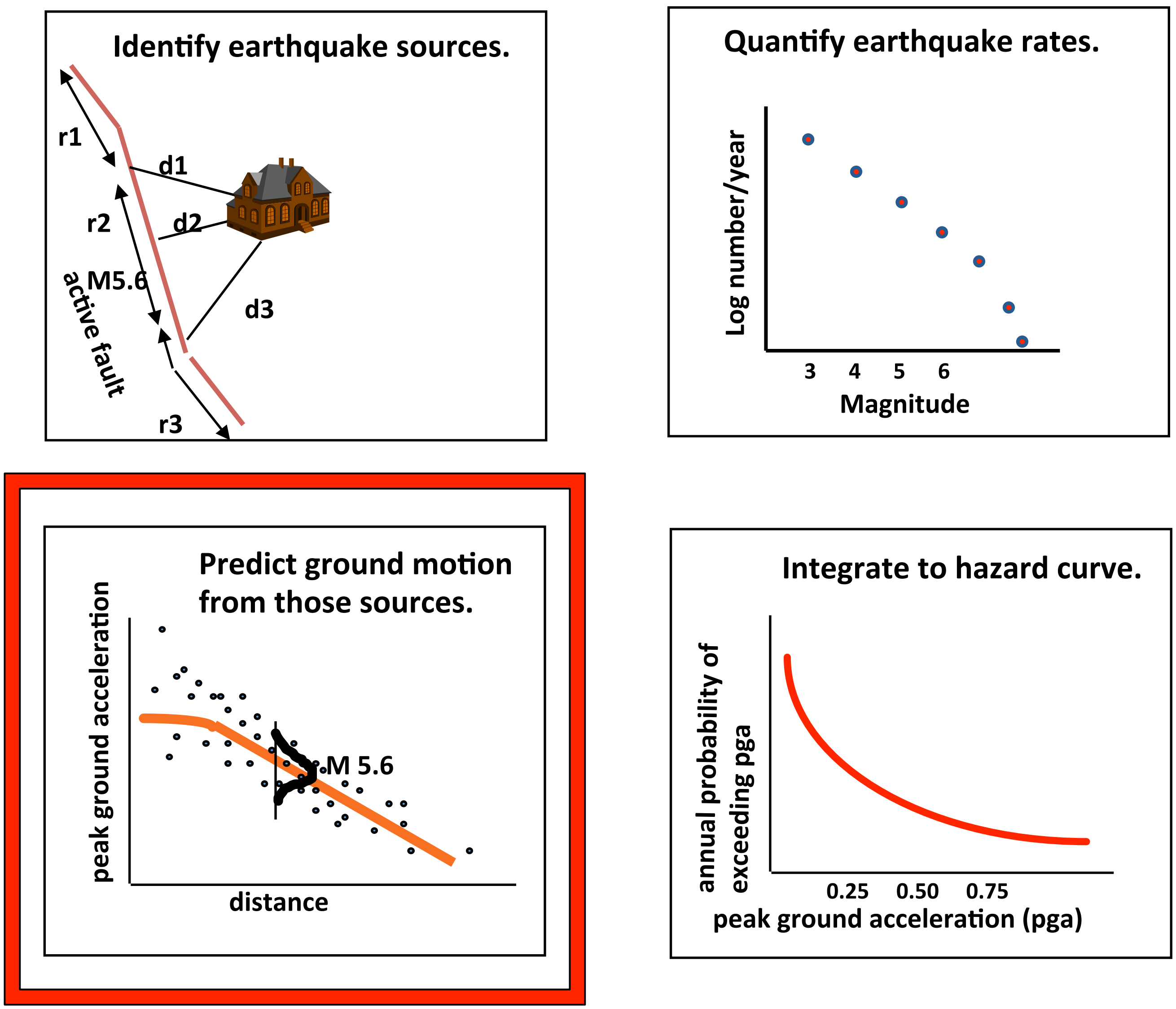
6 TeraDollars (0.7 PetaYen)

Hazard Curve

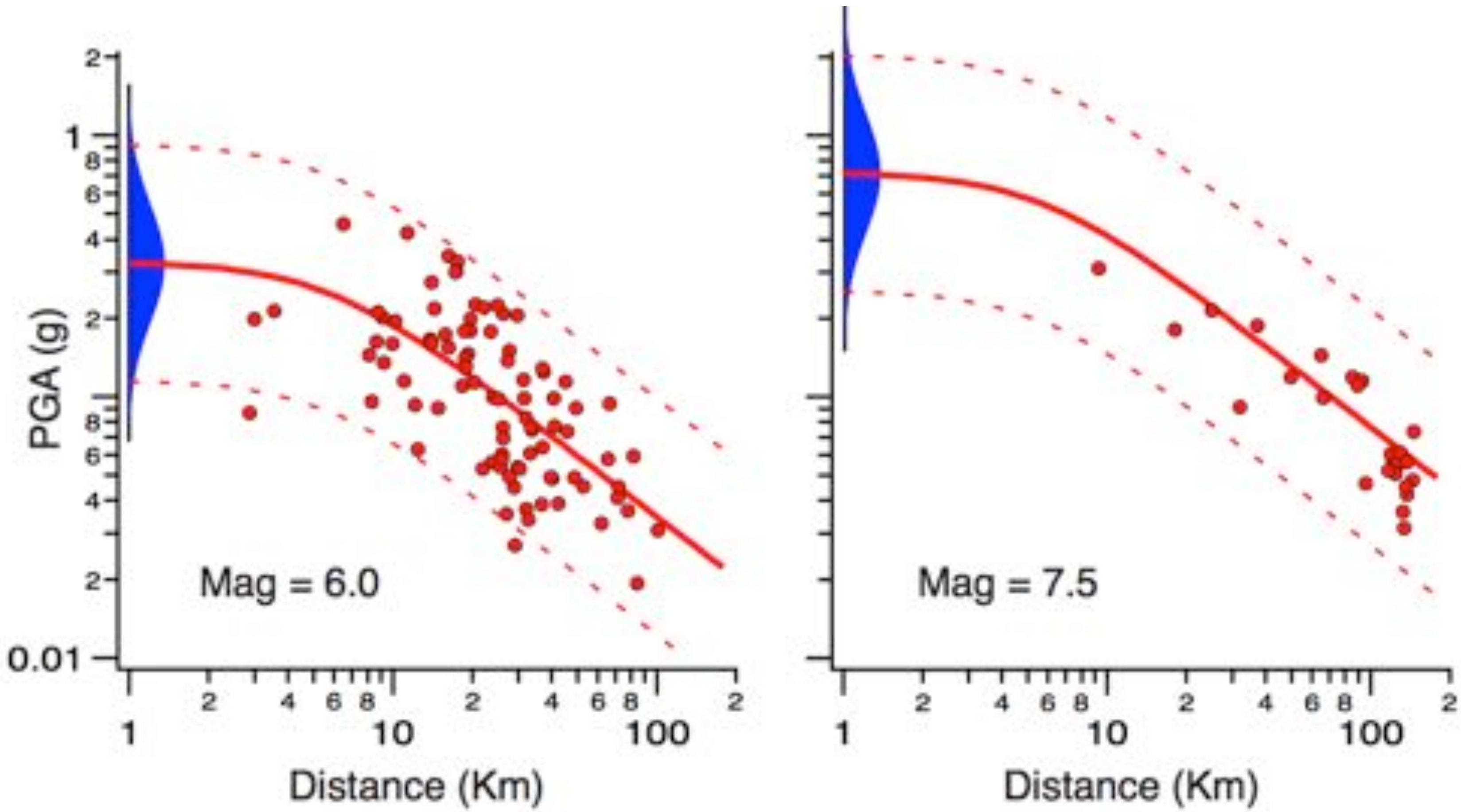


From "PSHA: A Primer" [*Field*]

Ingredients for PSHA

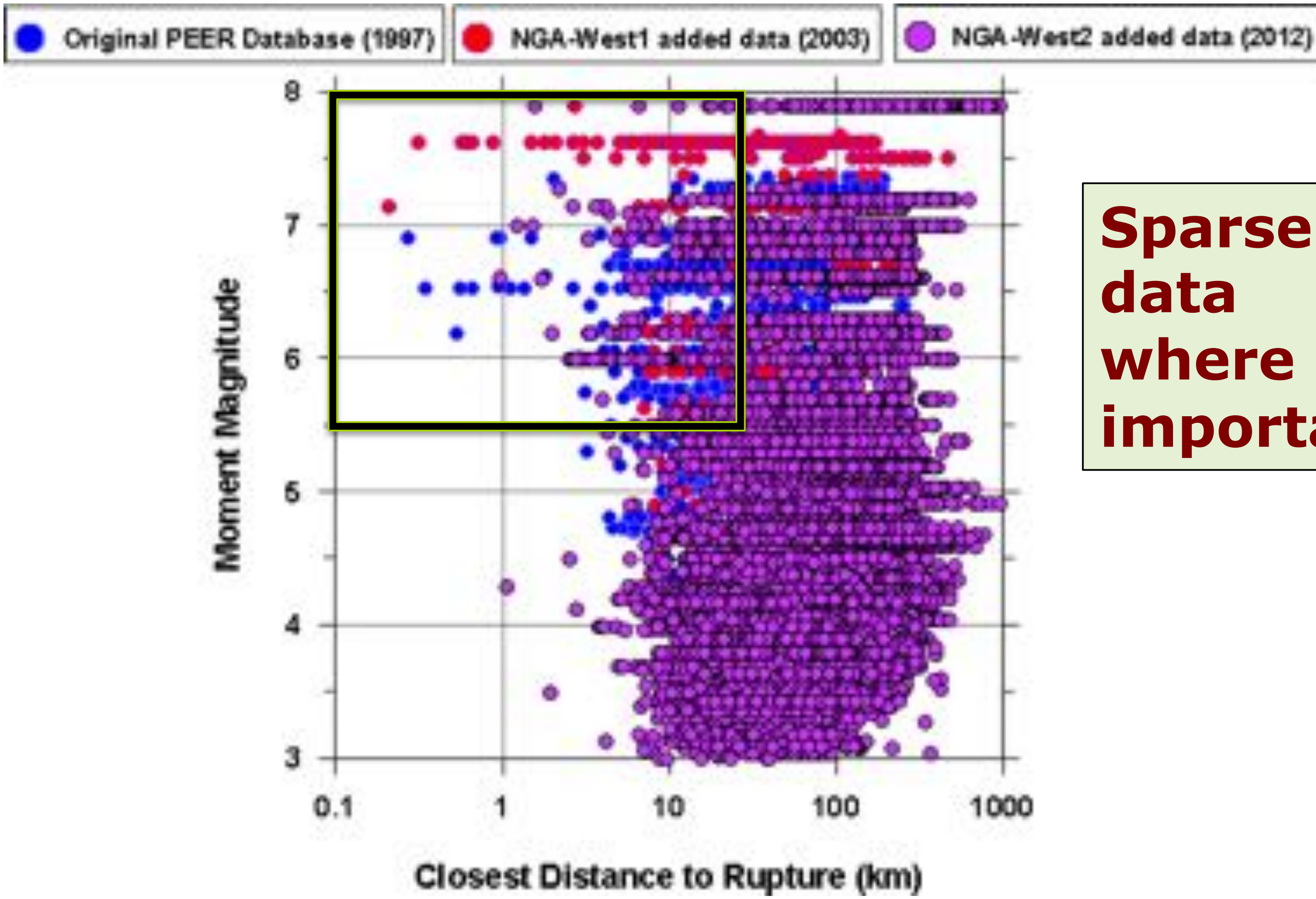


Ground Motion Prediction for California Earthquakes



From "PSHA: A Primer" [*Field*]

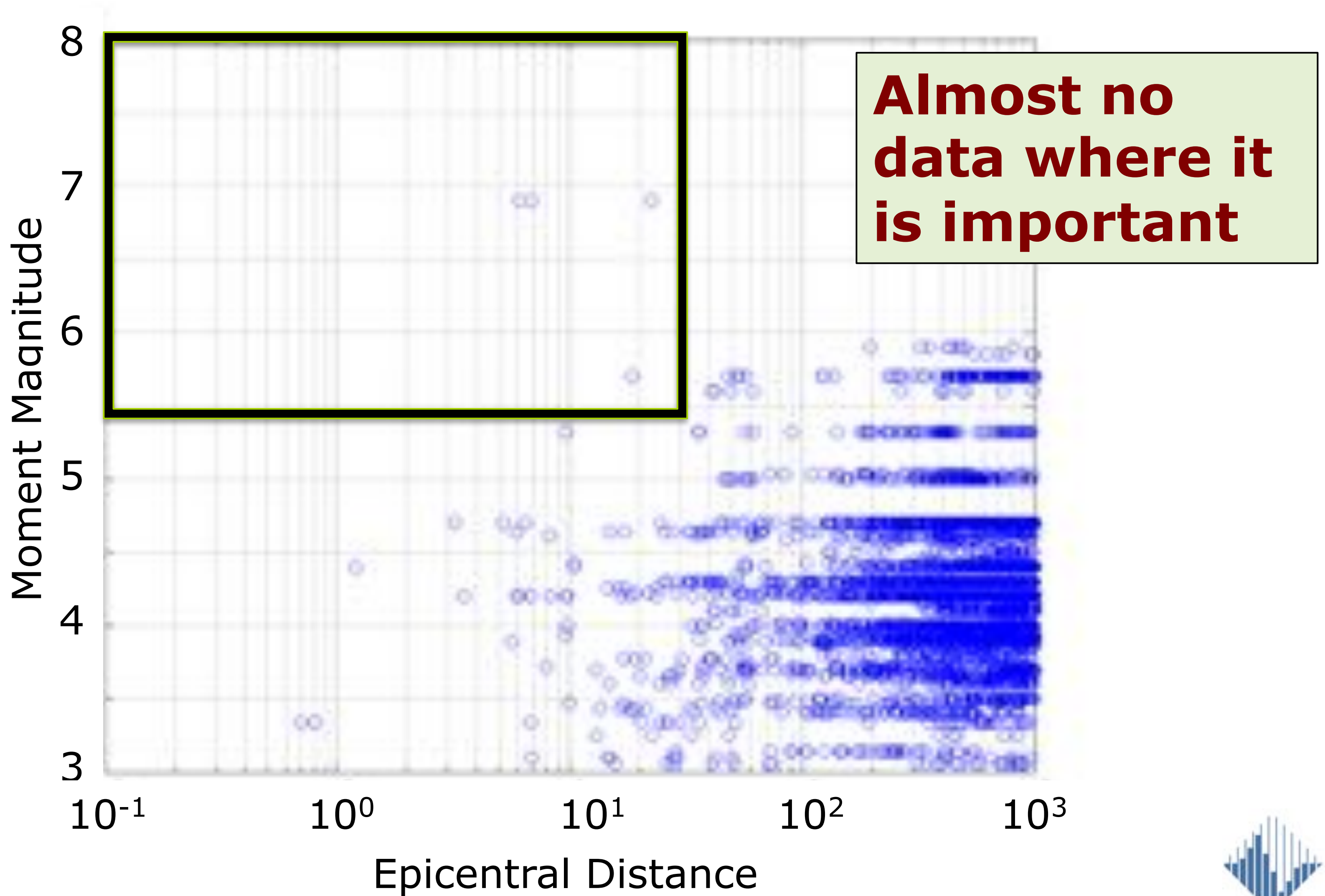
NGA-West2: Data Distribution



Sparse data where it is important

[*Courtesy of Yousef Bozorgnia*]

Stable Continents: Data Distribution
(CEUS, Eastern Canada, Gazli)



[*Courtesy of Christine Goulet*]

Approaches to Ground Motion Prediction

Data-Driven ⟷ **Model-Guided**

GMPEs

(Fit ground motions to equations)

- Empirical
- Lack of data
- Doesn't incorporate all that we know

Simulations

(Model waves in 3D structure)

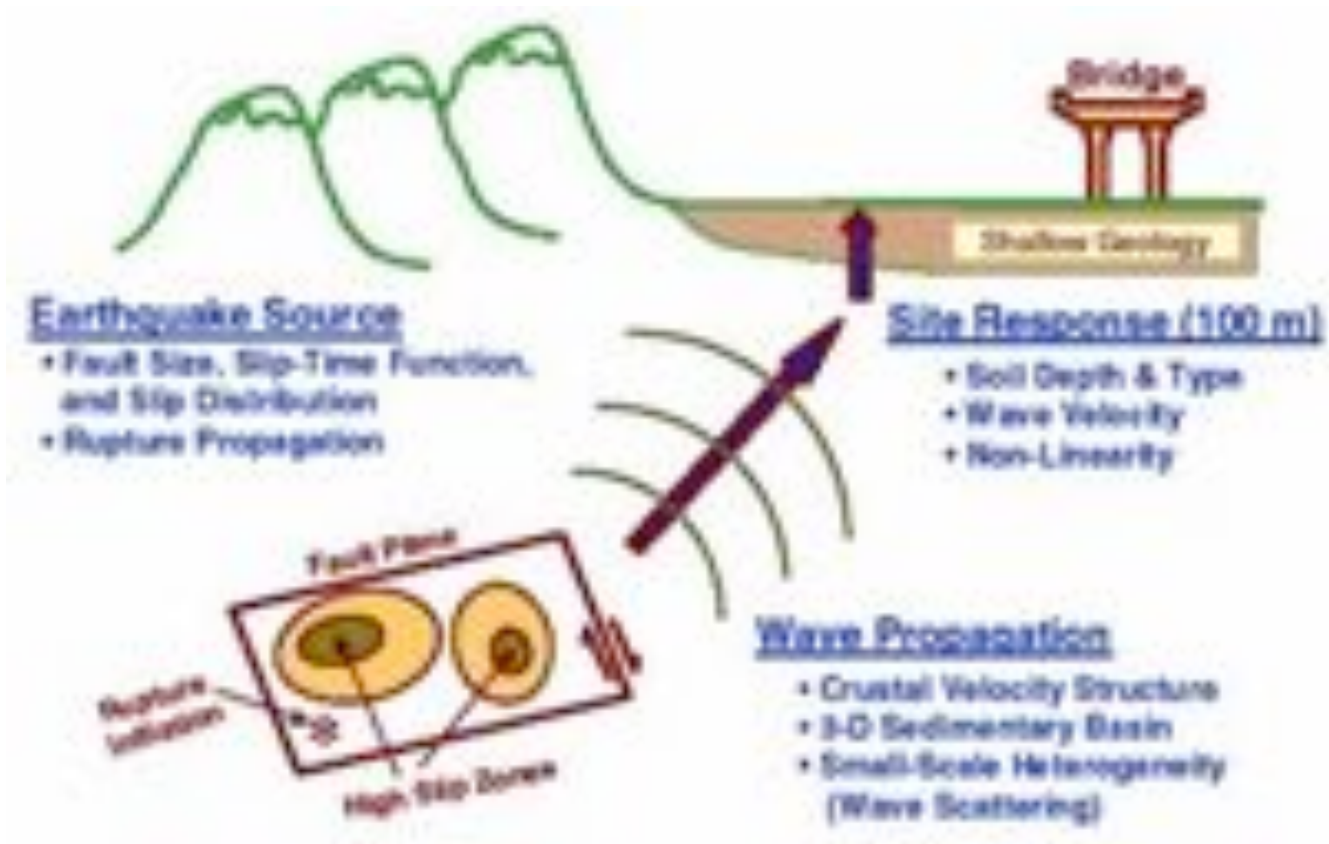
- Need lots of info
  - elastic
  - anelastic
  - plastic?
- HPC

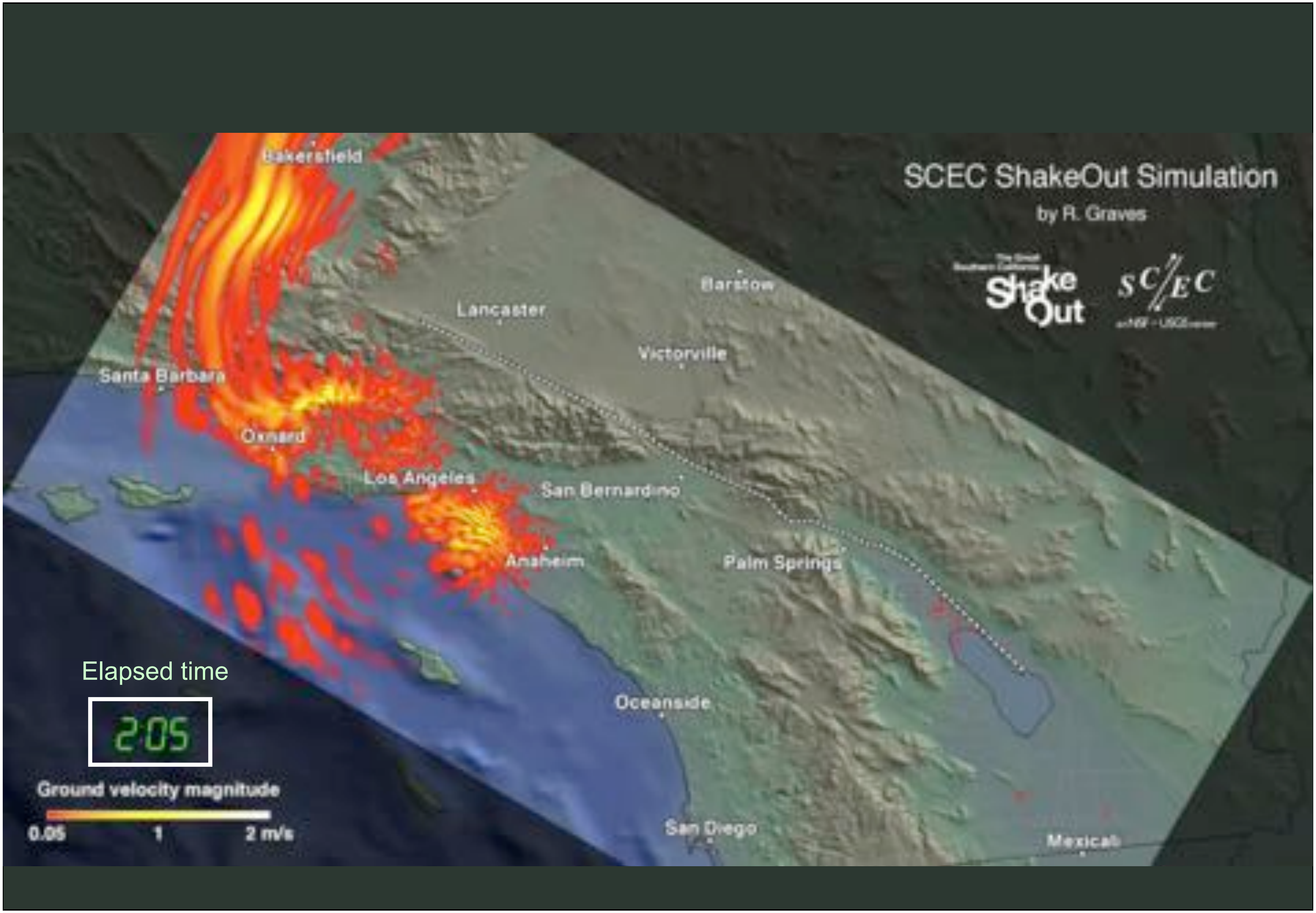
Model Ground Motion Using Simulation

1. Source

2. Path

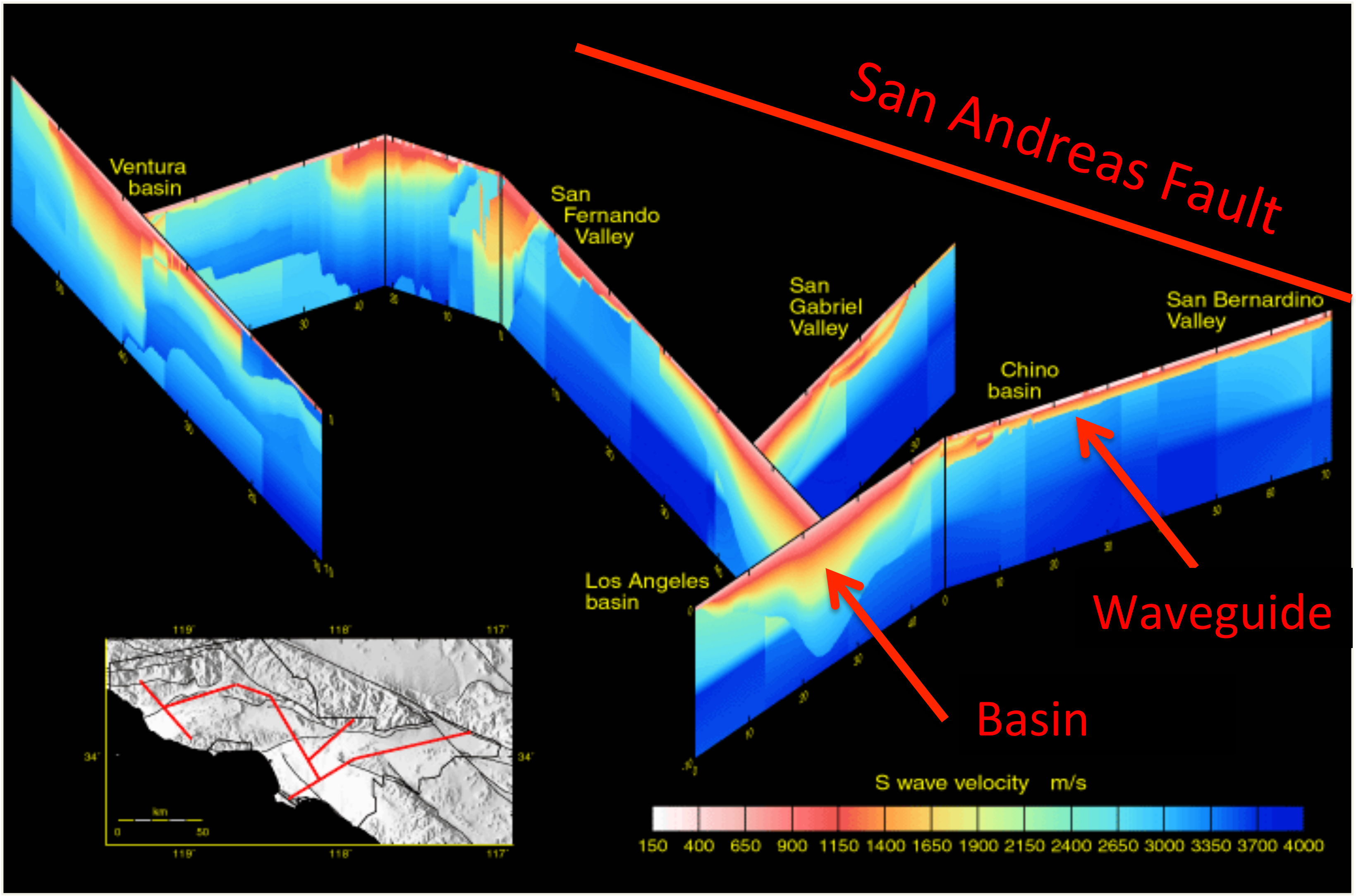
3. Site





SCEC ShakeOut Simulation
by R. Graves
Bakersfield
Barstow
Lancaster
Victorville
Santa Barbara
Oxnard
Los Angeles
San Bernardino
Anaheim
Palm Springs
Oceanside
San Diego
Mexicali
Elapsed time
2:05
Ground velocity magnitude
0.05
1
2 m/s

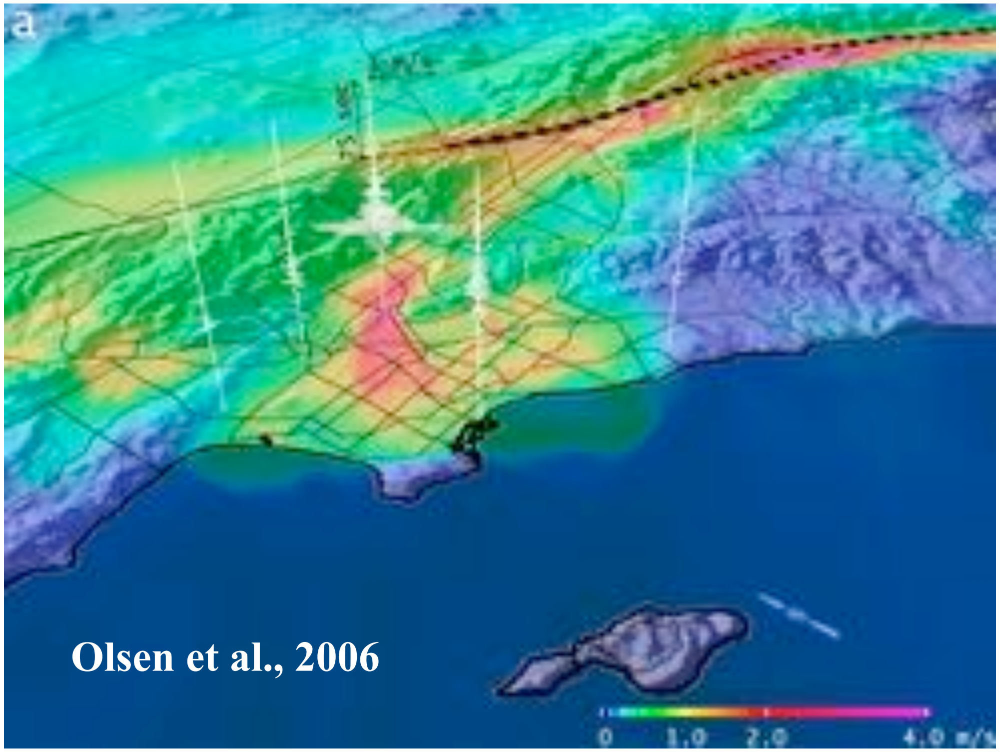
Waveguide-to-Basin Effect



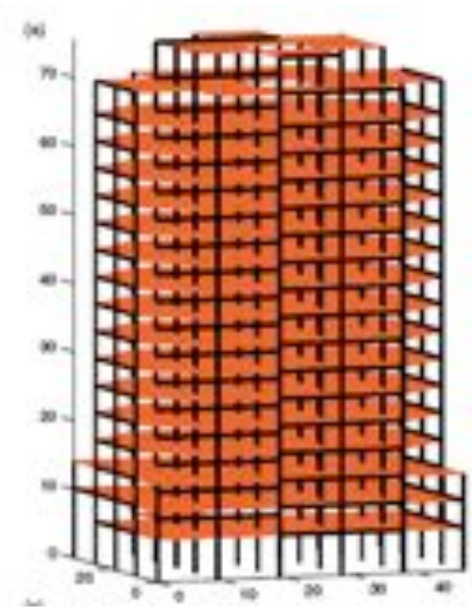
Love waves guided into basin where they resonate

Not anticipated - discovered through simulation

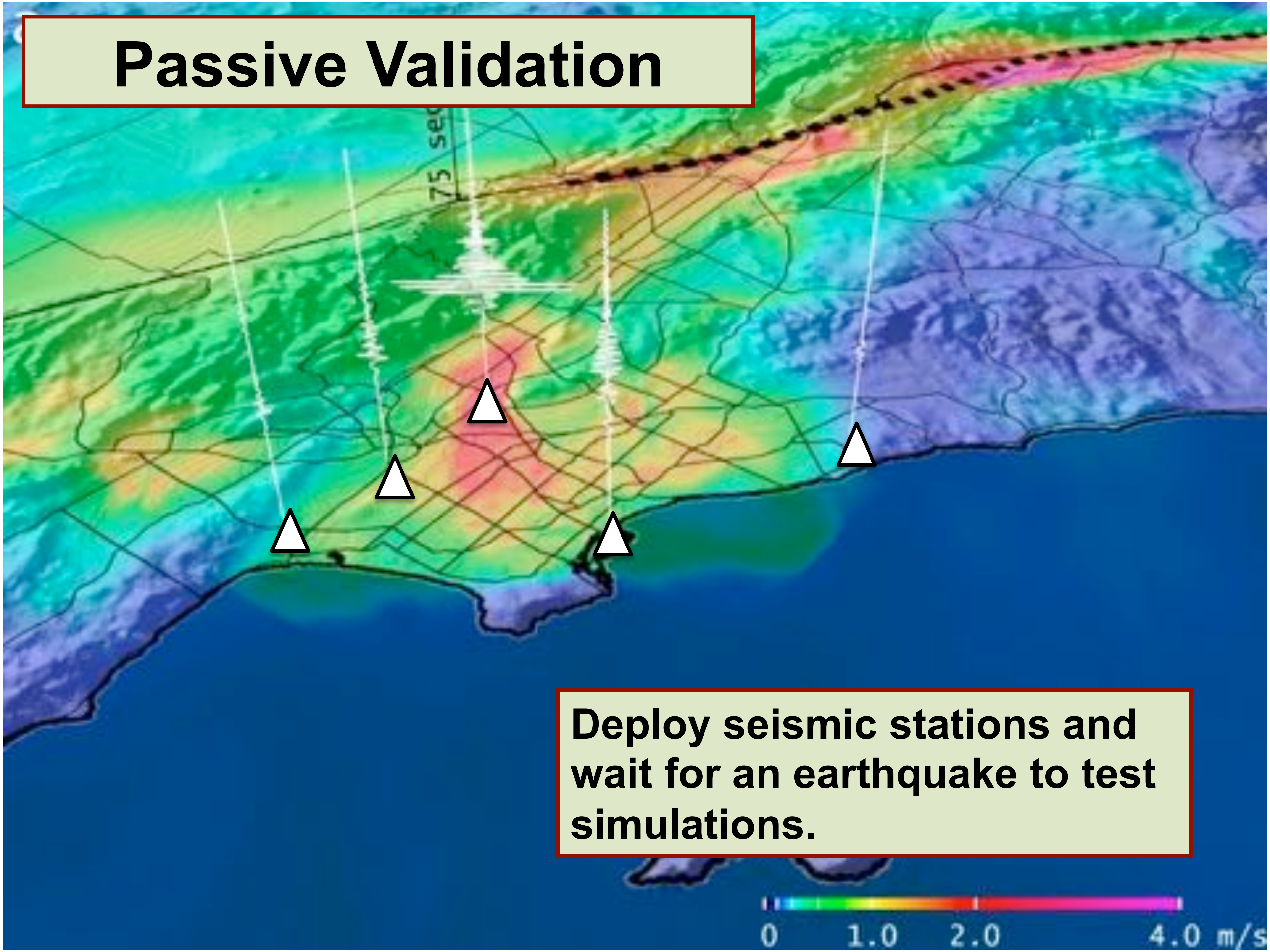
Are Simulations Accurate?



Krishnan et al. (2006)

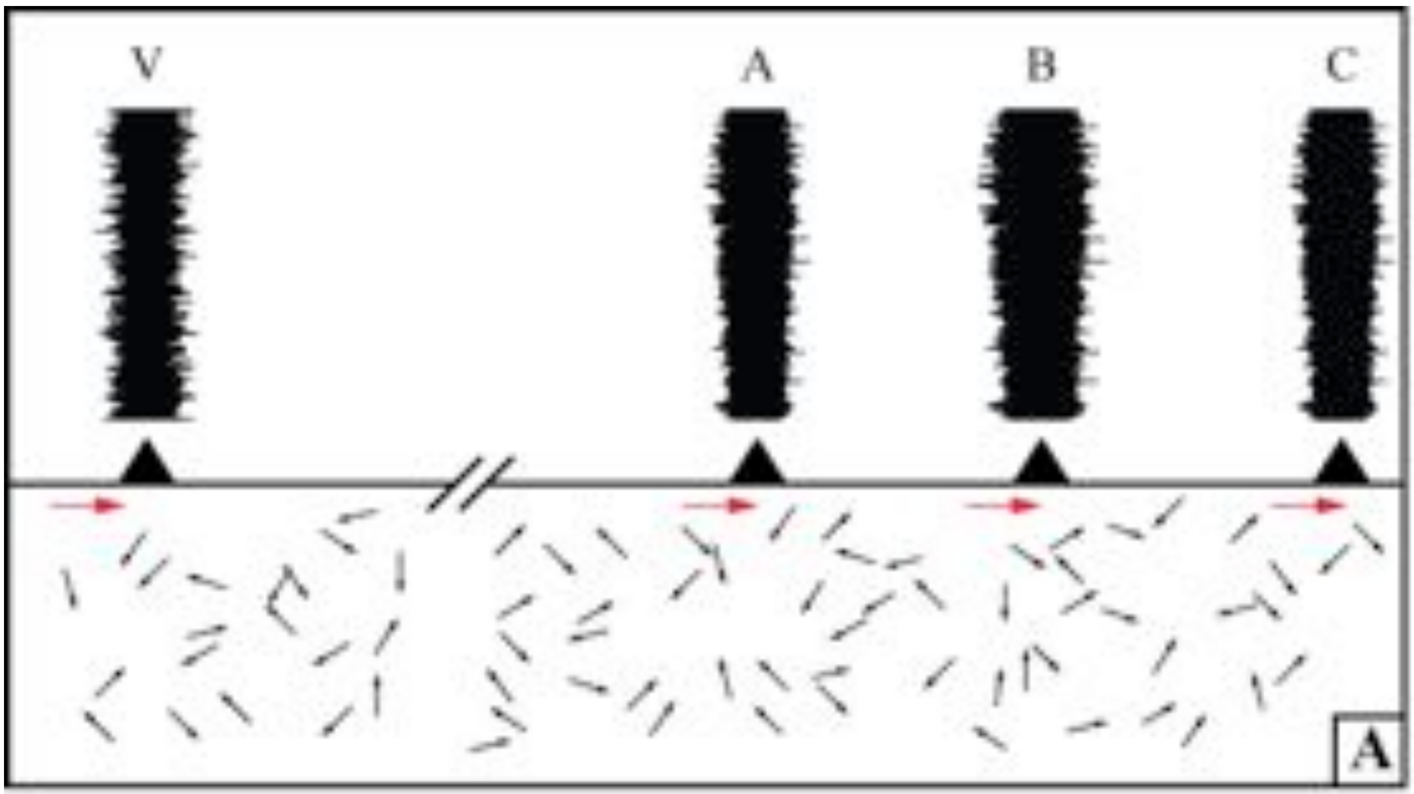


Passive Validation



Deploy seismic stations and wait for an earthquake to test simulations.

Ambient Seismic Field

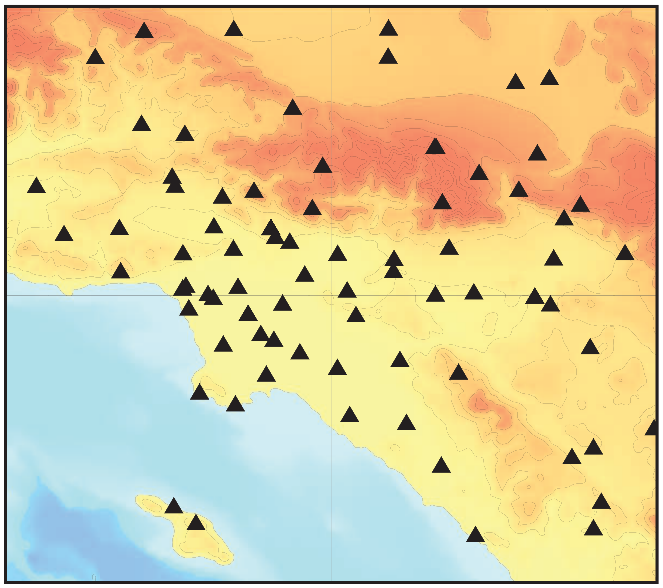


After Weaver (2005, Science perspectives)

How can we use ASF to improve/test simulations?

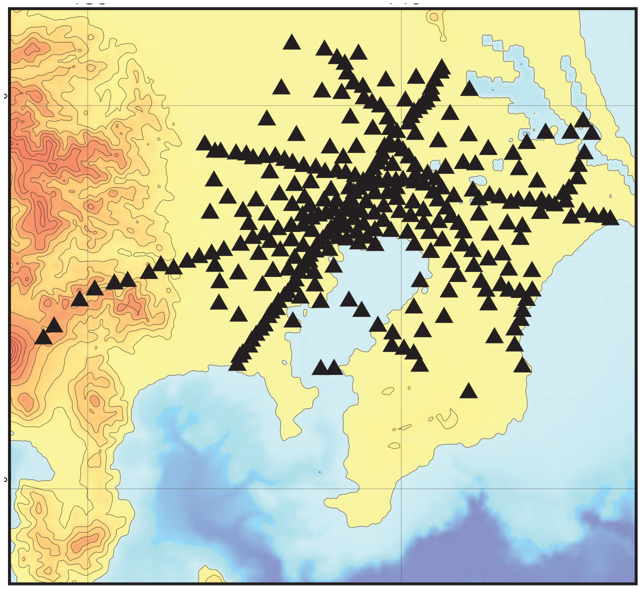
Results from Three Seismic Networks

SCSN



Sparse
~10 km spacing
10s of sensors

MeSO-net



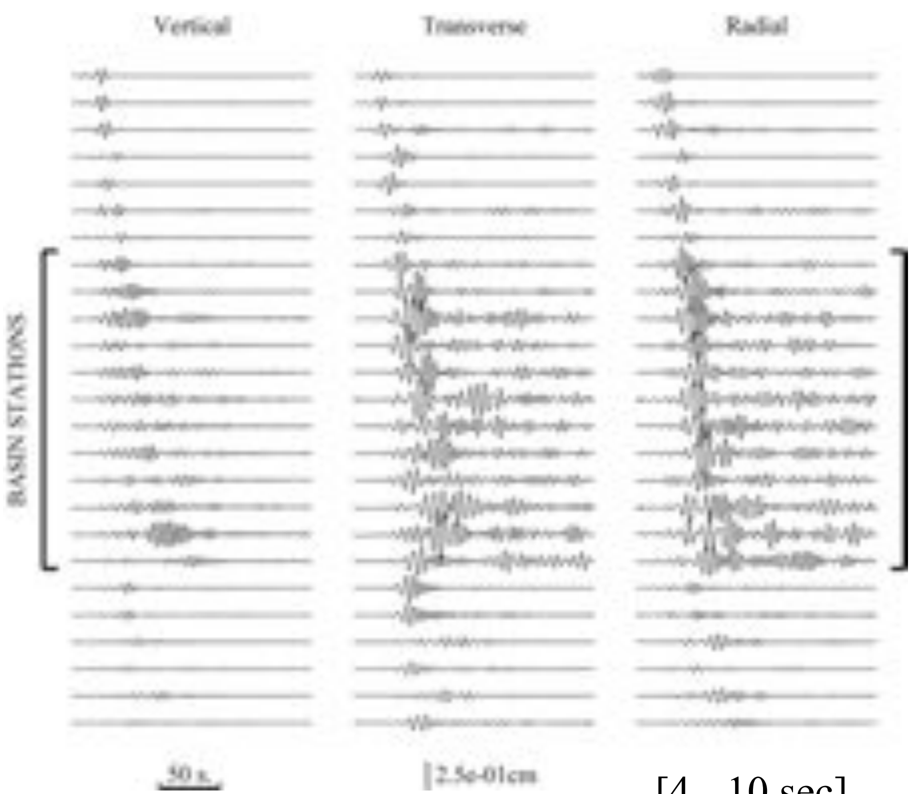
Dense
~1 km spacing
100s of sensors

Long Beach

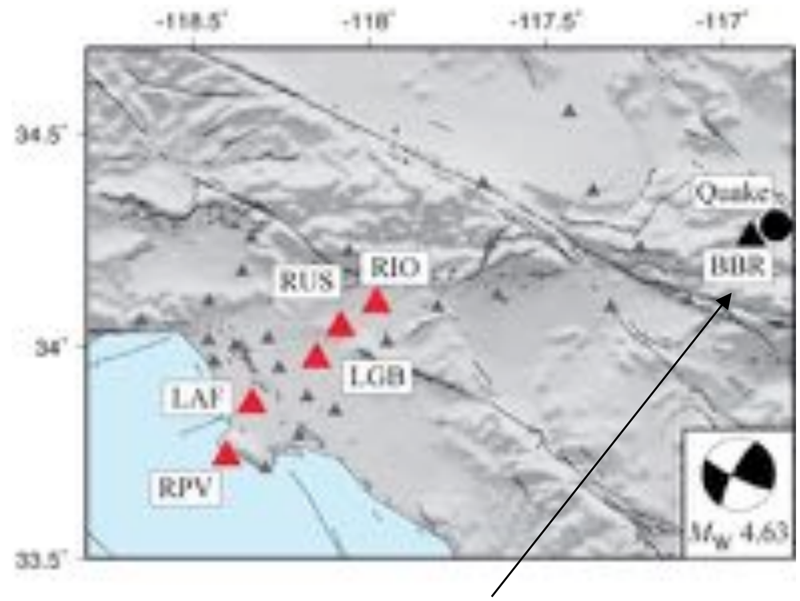
Very Dense
~0.1 km spacing
1000s of sensors

Proof of Concept for *M* 4.6 Big Bear EQ

Earthquake records



[4 - 10 sec]



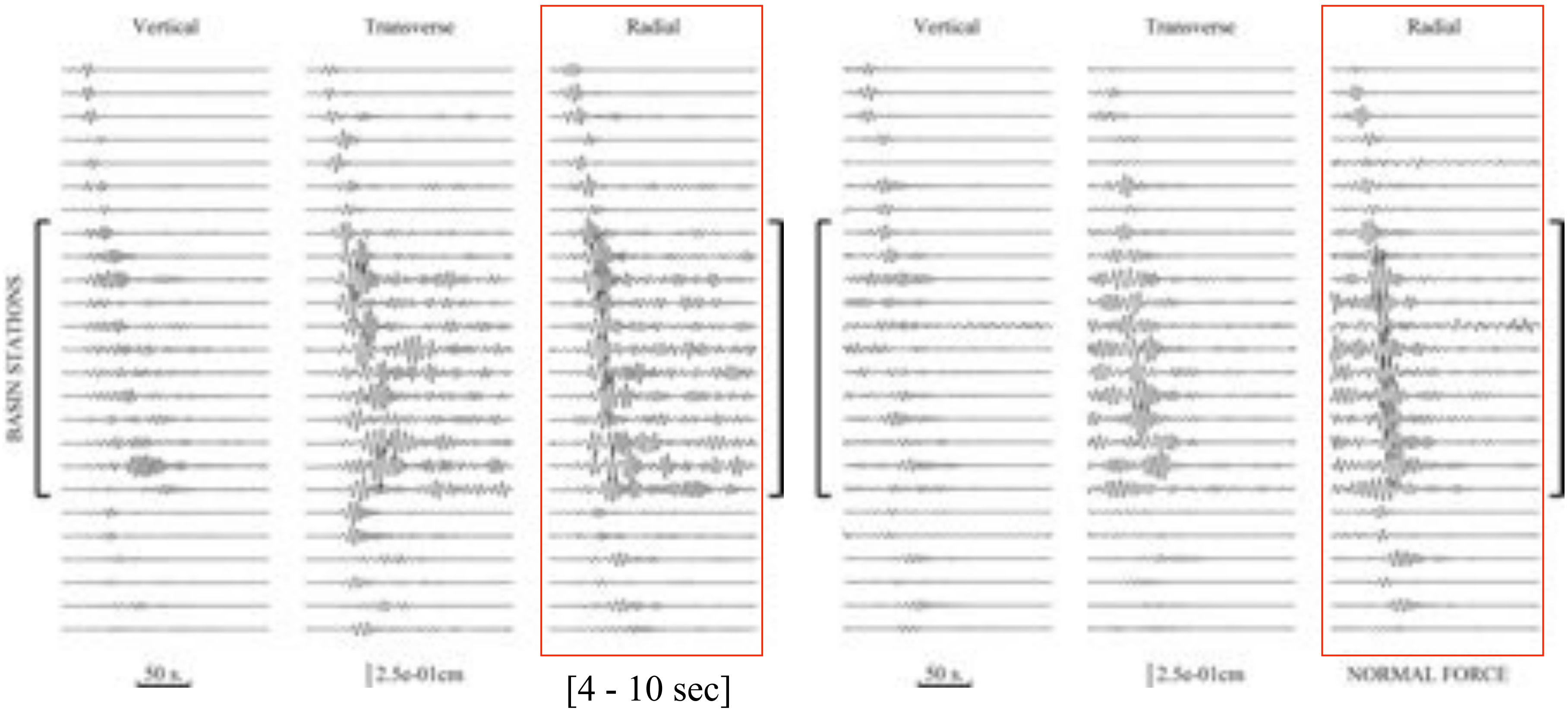
10 Feb 2001 M_w 4.6 Big Bear

Graves (2008)

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

Proof of Concept for *M* 4.6 Big Bear EQ

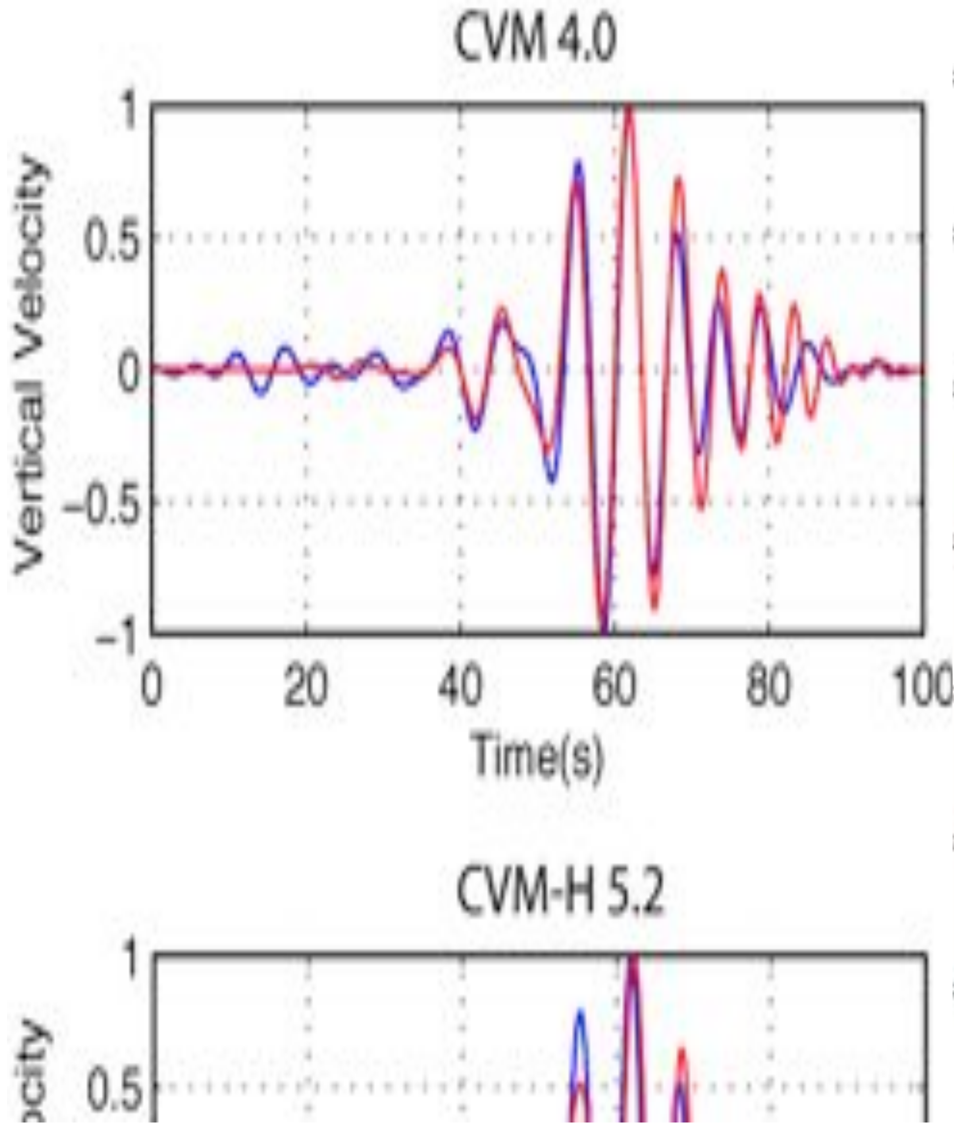
Earthquake records **Impulse response records**



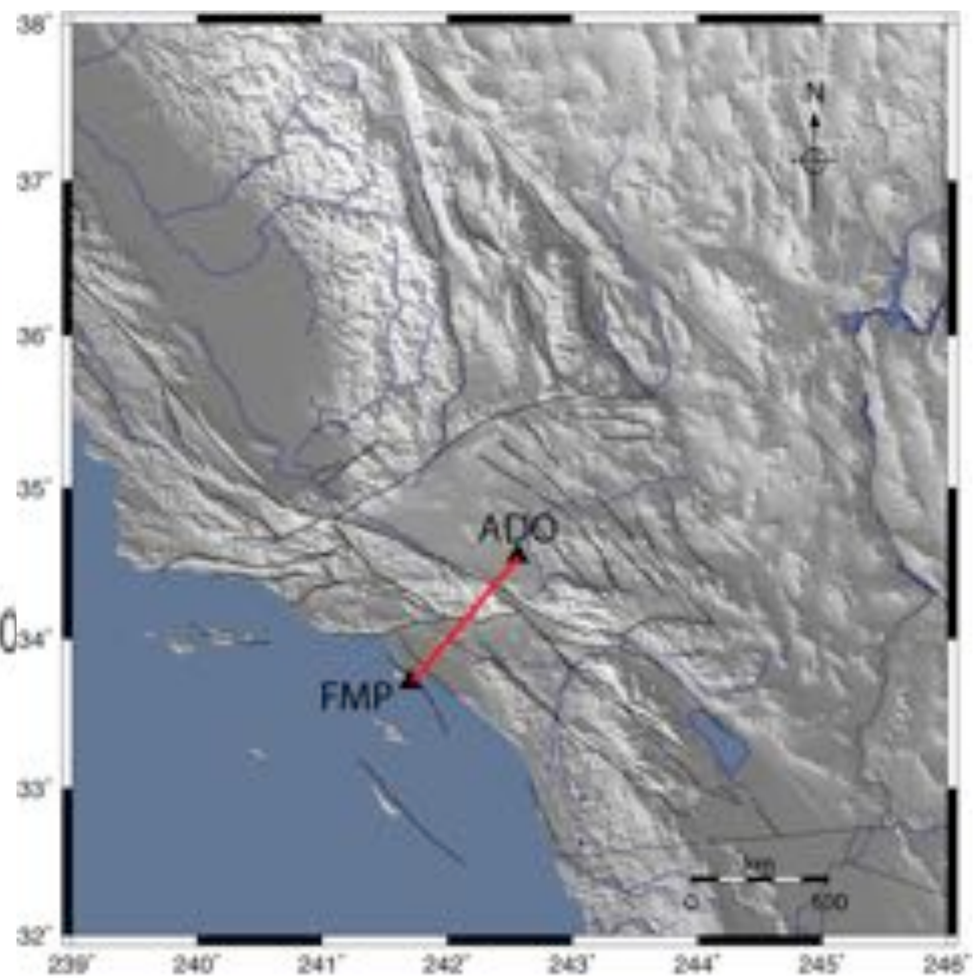
Prieto and Beroza (2008)

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

Ambient-Field GF (blue) vs. Finite-Element Prediction (red)

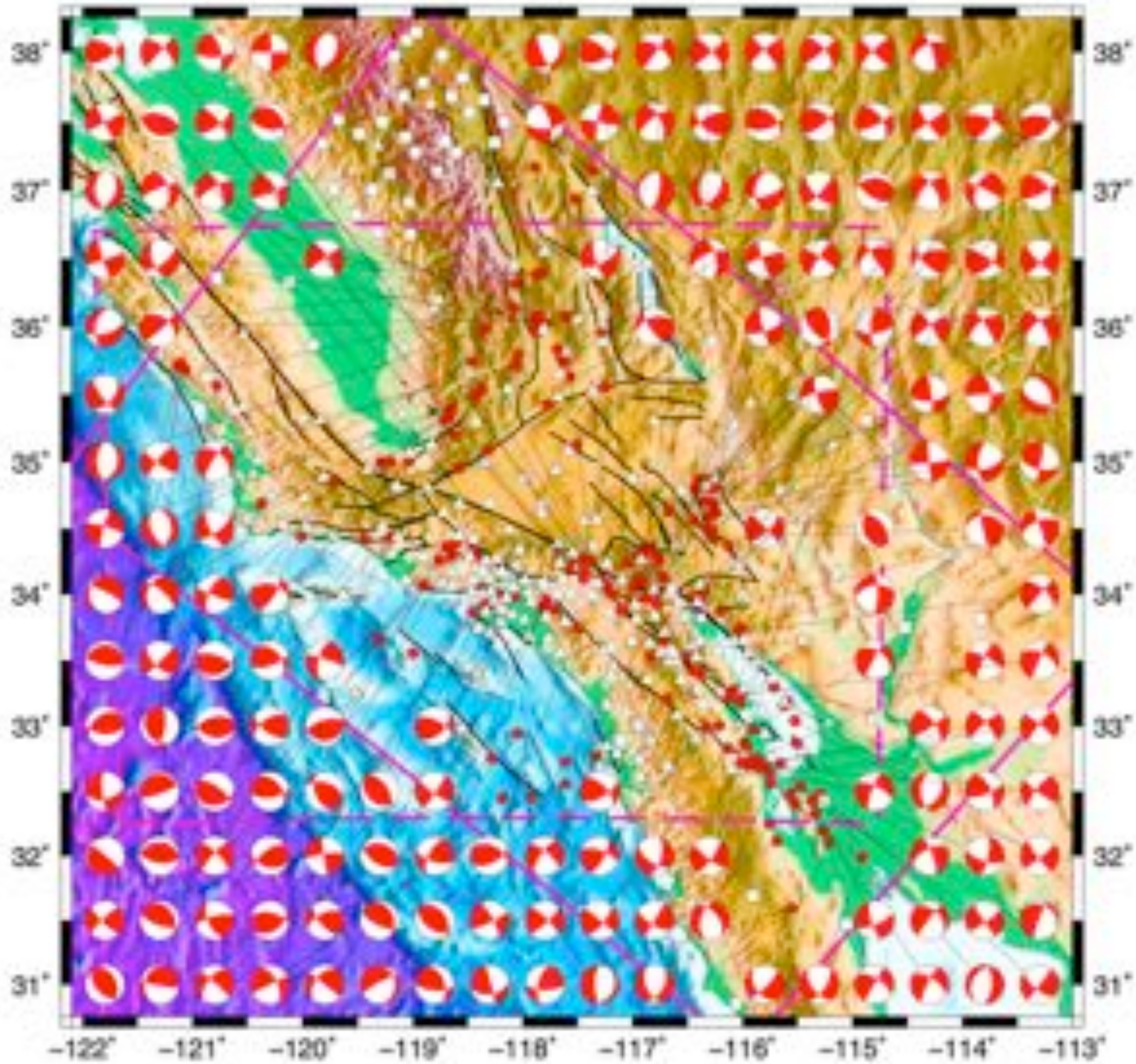


Periods: 5 – 10 s



Ma et al. (2008)

Waveform Data from Moderate Earthquakes



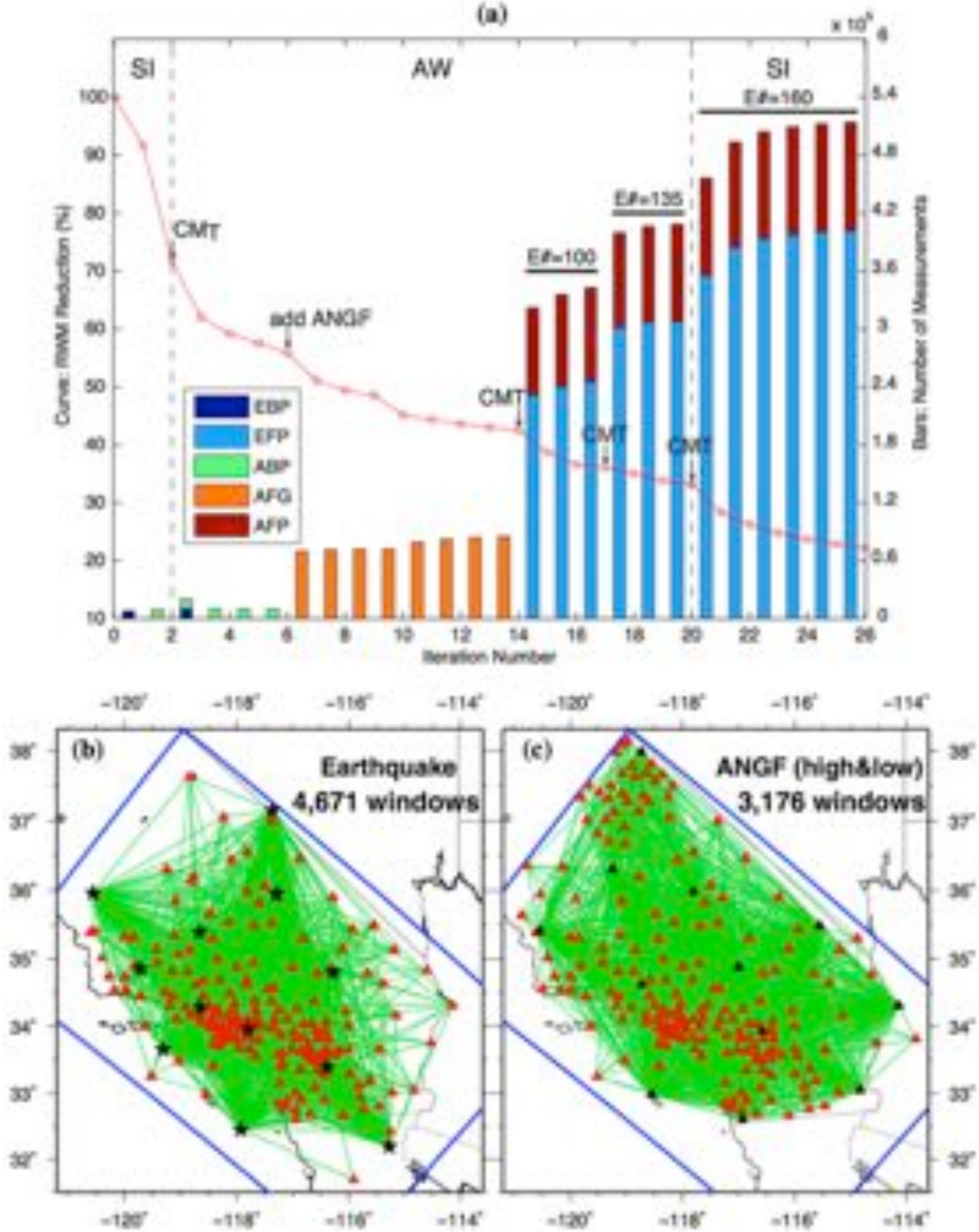
Very uneven coverage

Lee et al. (2014)

Ambient-field observations to improve simulations

- Data w/out earthquakes
- Constrains shallow structure relevant to GMP

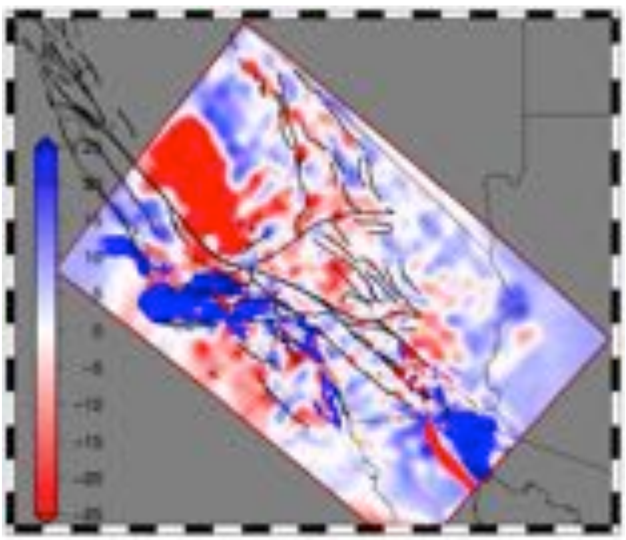
(*Lee et al.* 2014)



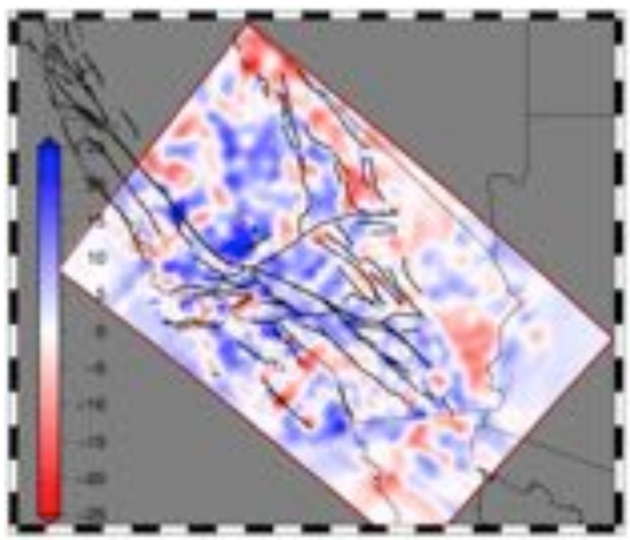
Comparison with CVM-H

(CVM-S4.26 – CVM-H11.9.1)/CVM-S4.26

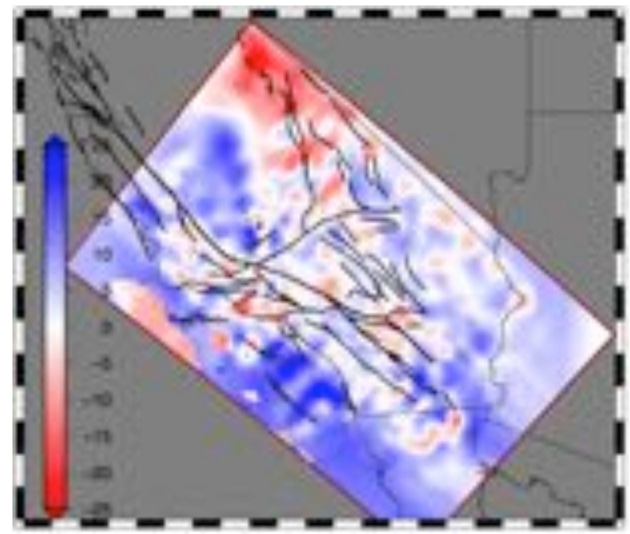
2 km



10 km

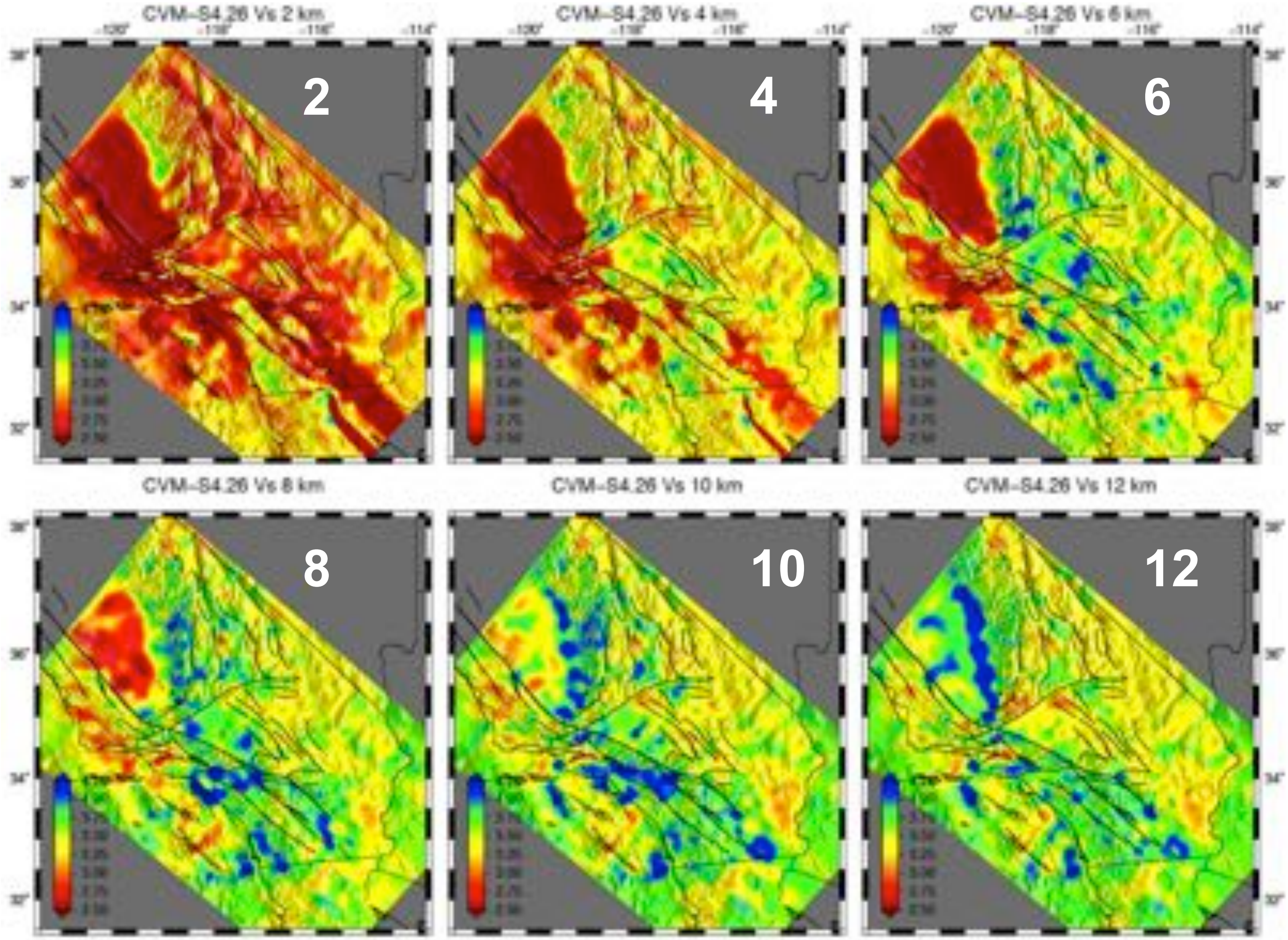


20 km

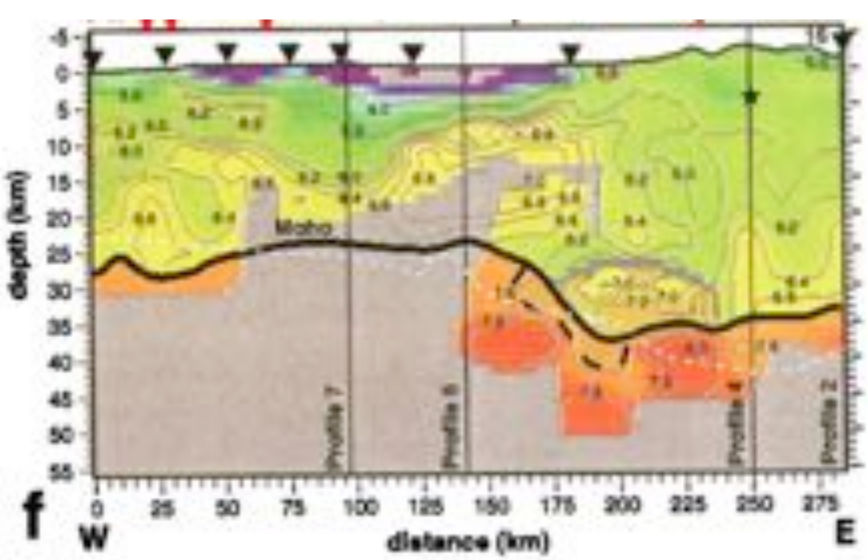


- **S-wave velocity**
- **Larger difference at shallower depths (ANGF)**
- **>25% max differences**

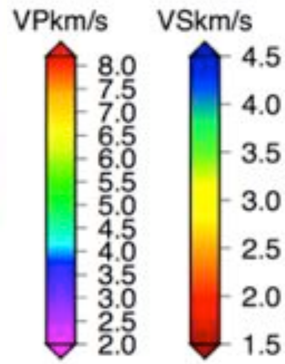
3D Tomography of Southern California

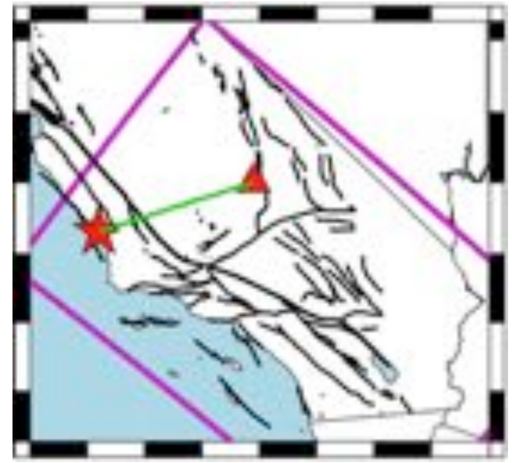


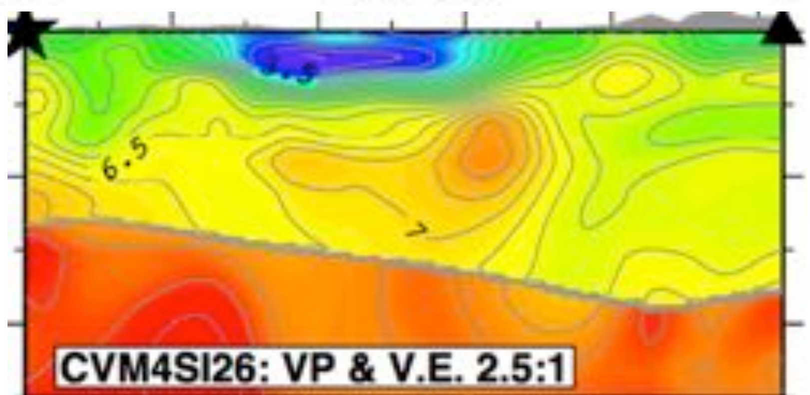
(*Lee et al.* 2014)

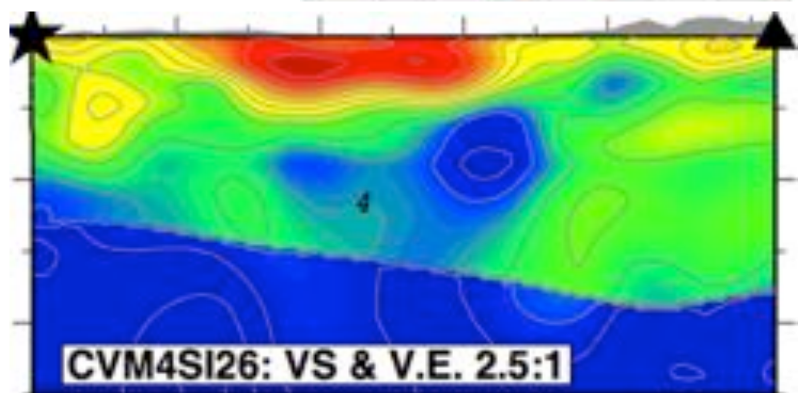


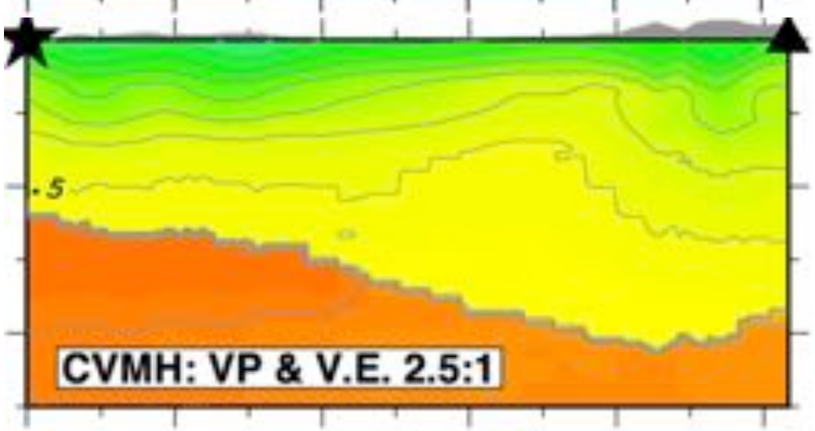
Fliedner et al. (2000, JGR)

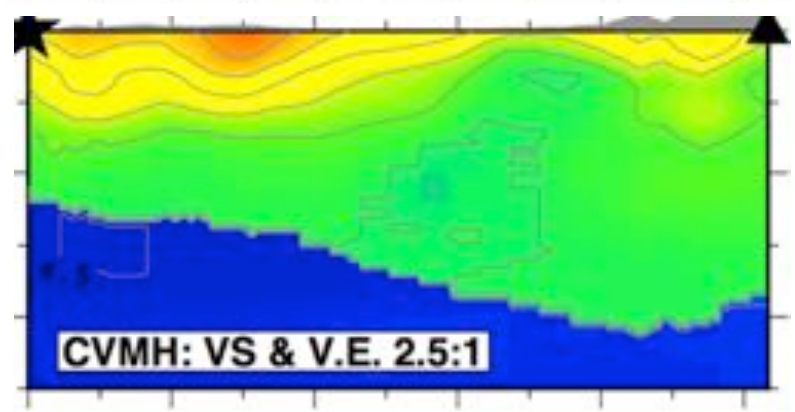




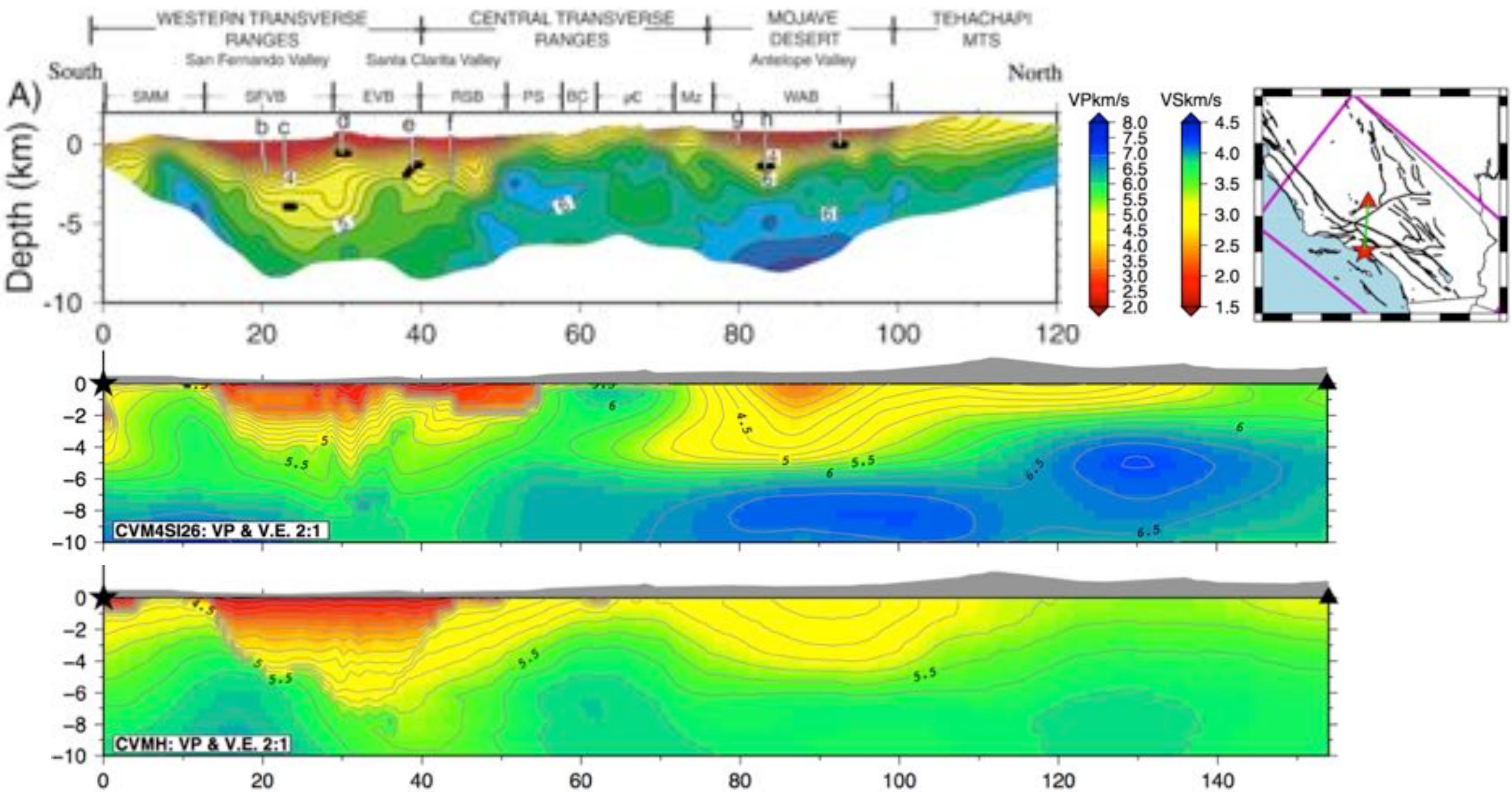


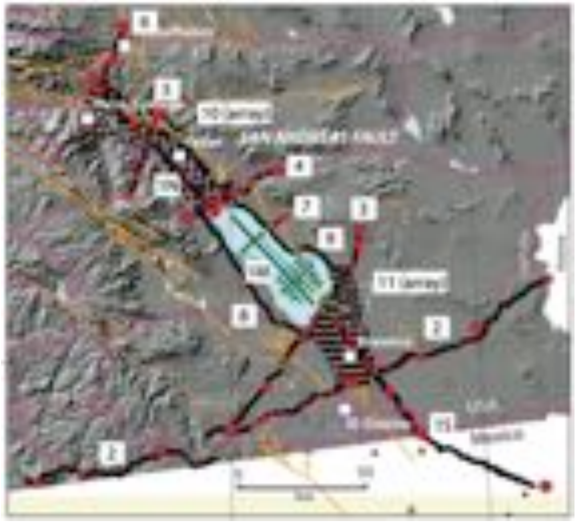




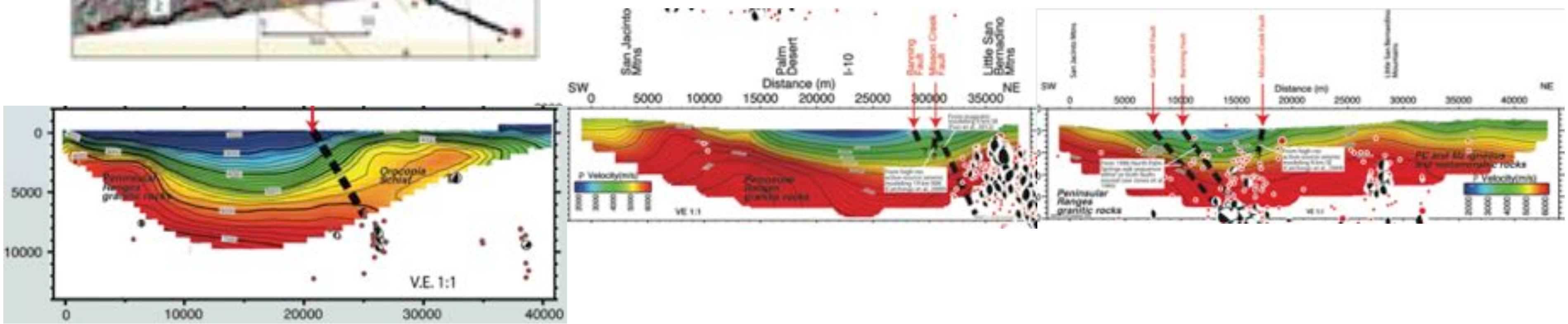


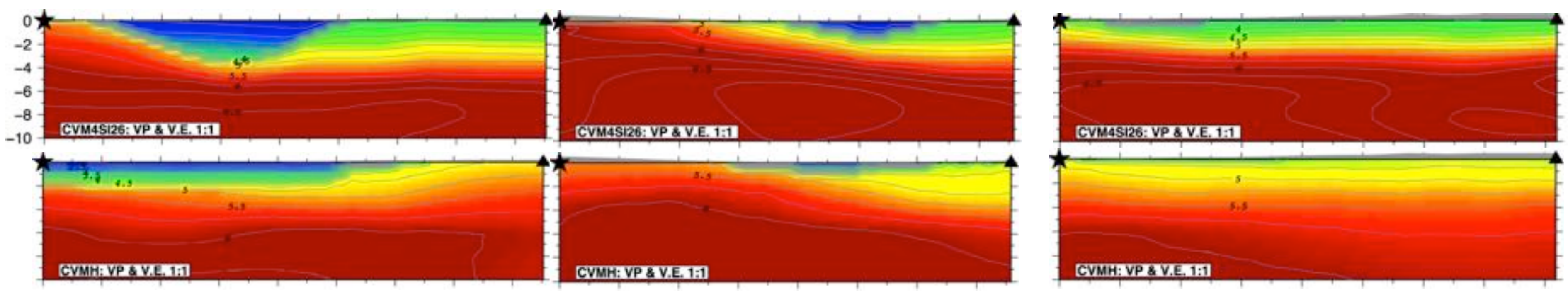
Los Angeles Region Seismic Experiment II (LARSE II), Lutter et al. (2004, BSSA)





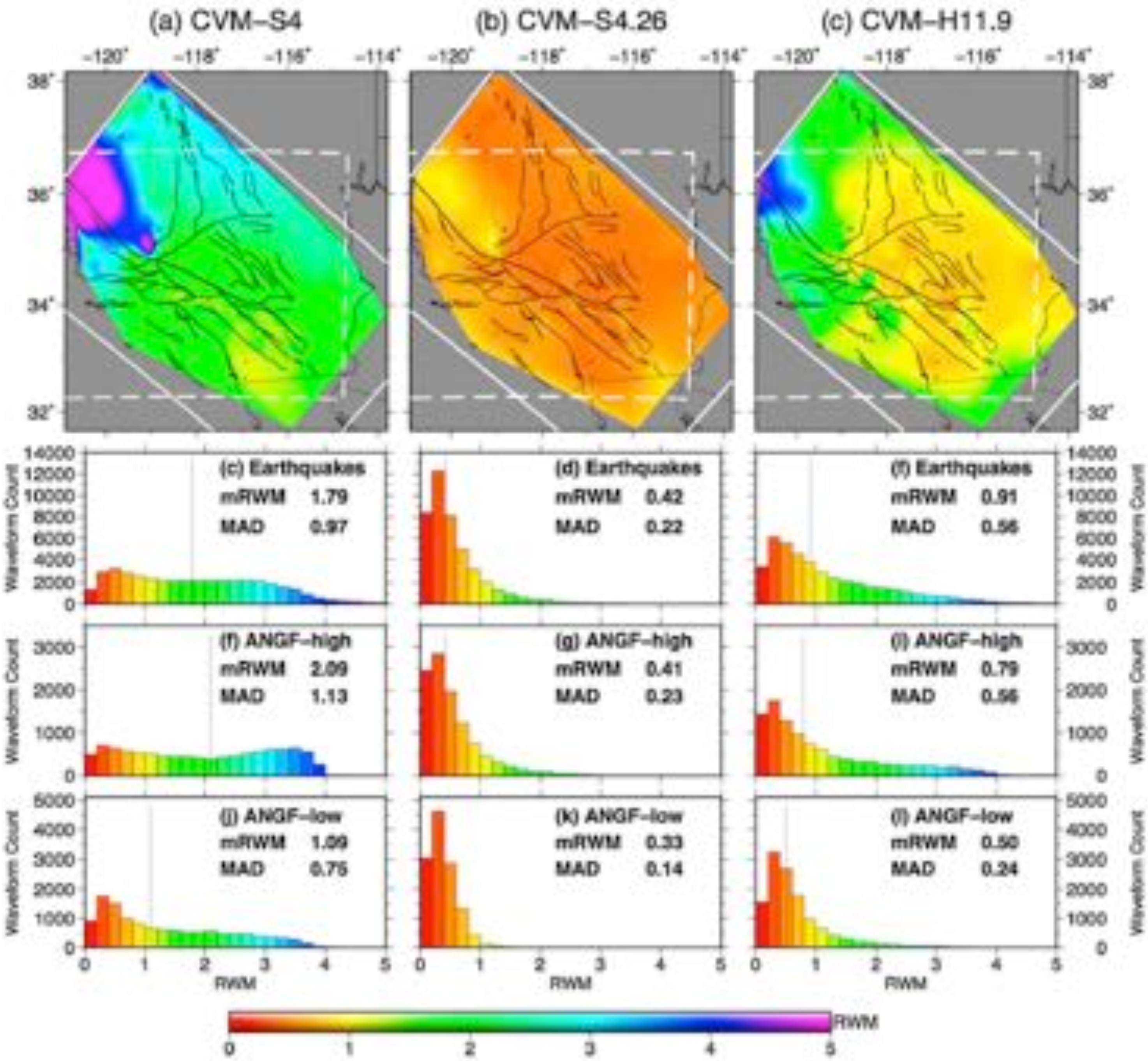
Salton Seismic Imaging Project (SSIP)
Fuis et al., AGU, 2012





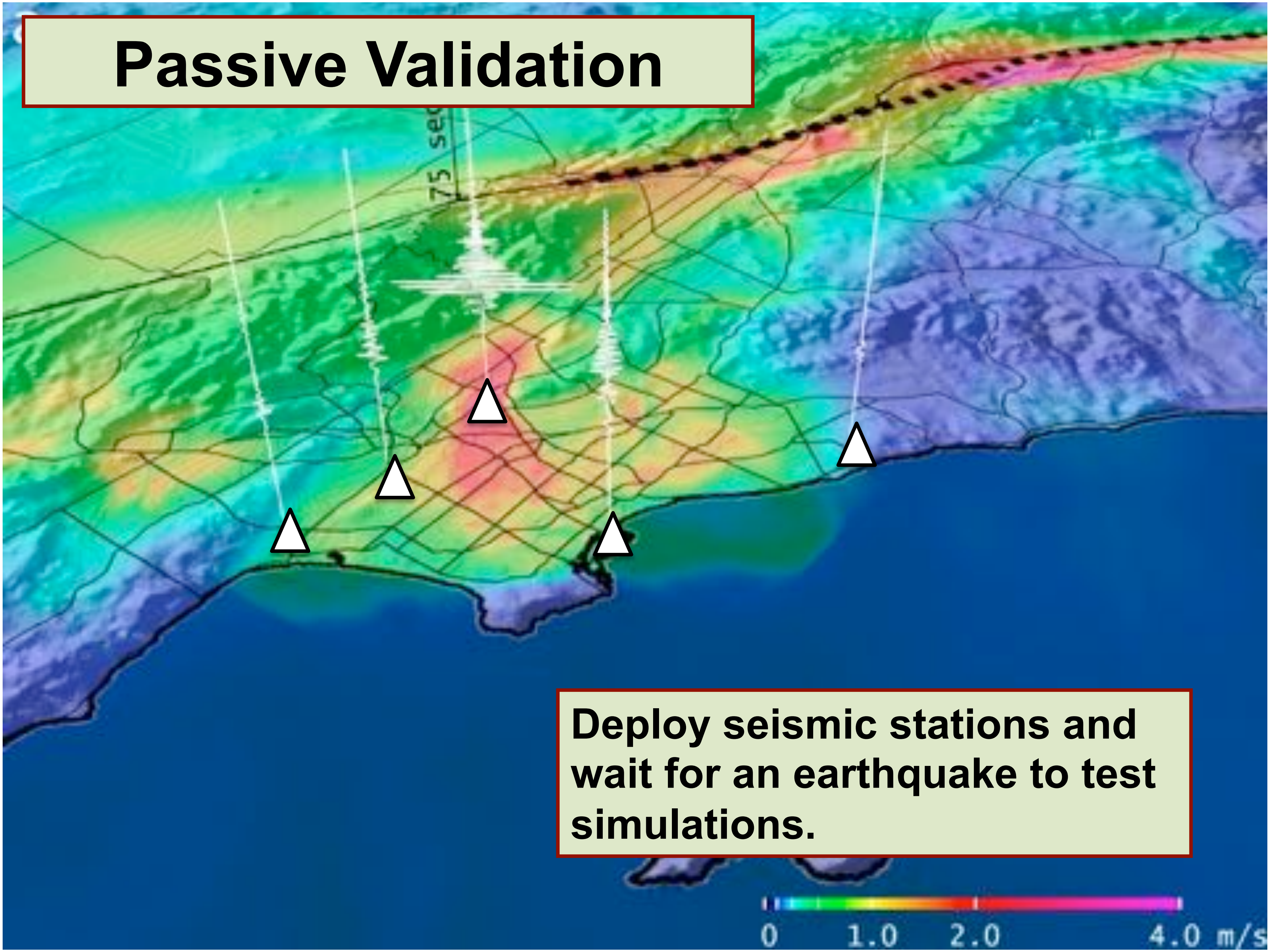
Line 4 ***Line 5*** ***Line 6***

Reduced Waveform Misfit



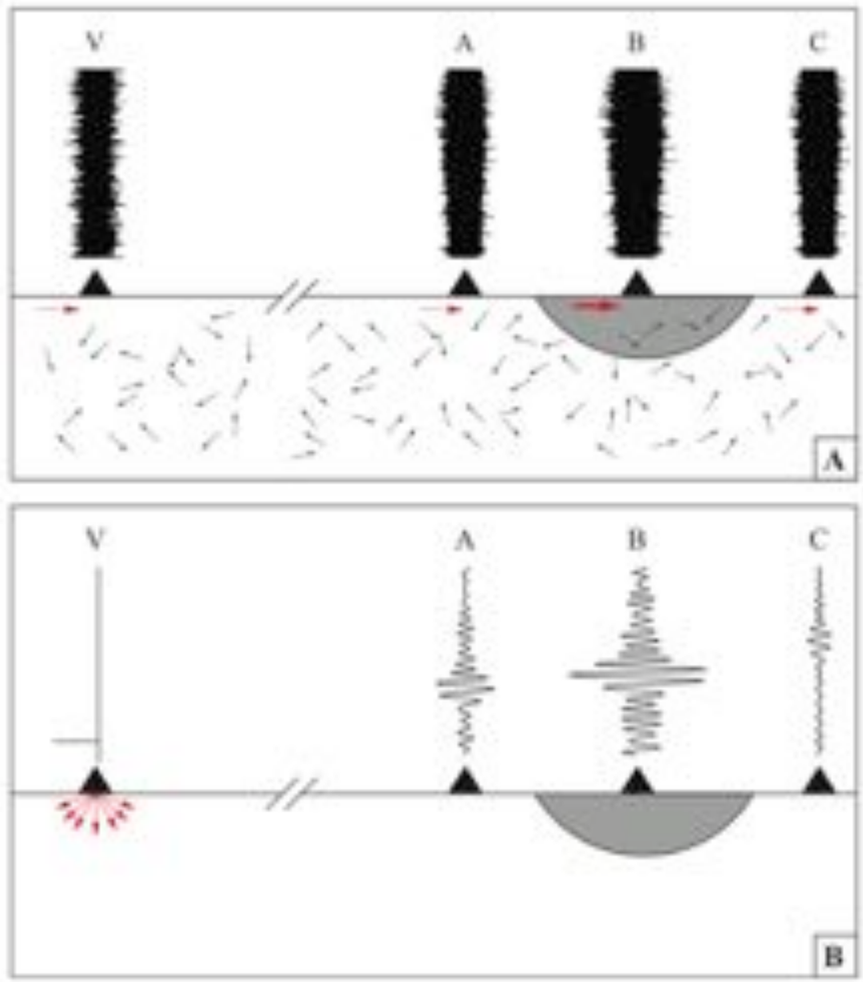
(*Lee et al.* 2014)

Passive Validation



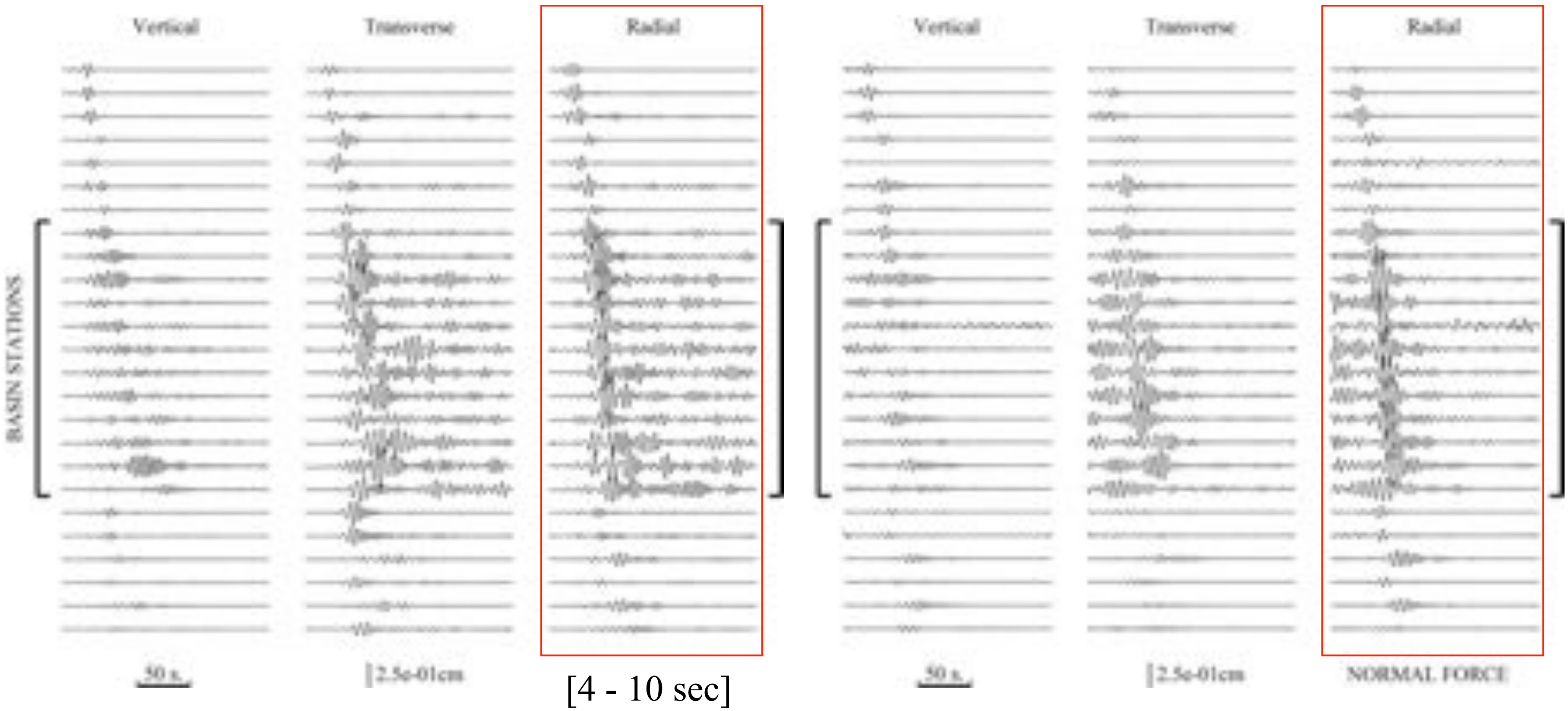
Deploy seismic stations and wait for an earthquake to test simulations.

Ambient-Field Measurements to *Actively* Validate Ground Motion Prediction



Proof of Concept for *M* 4.6 Big Bear EQ

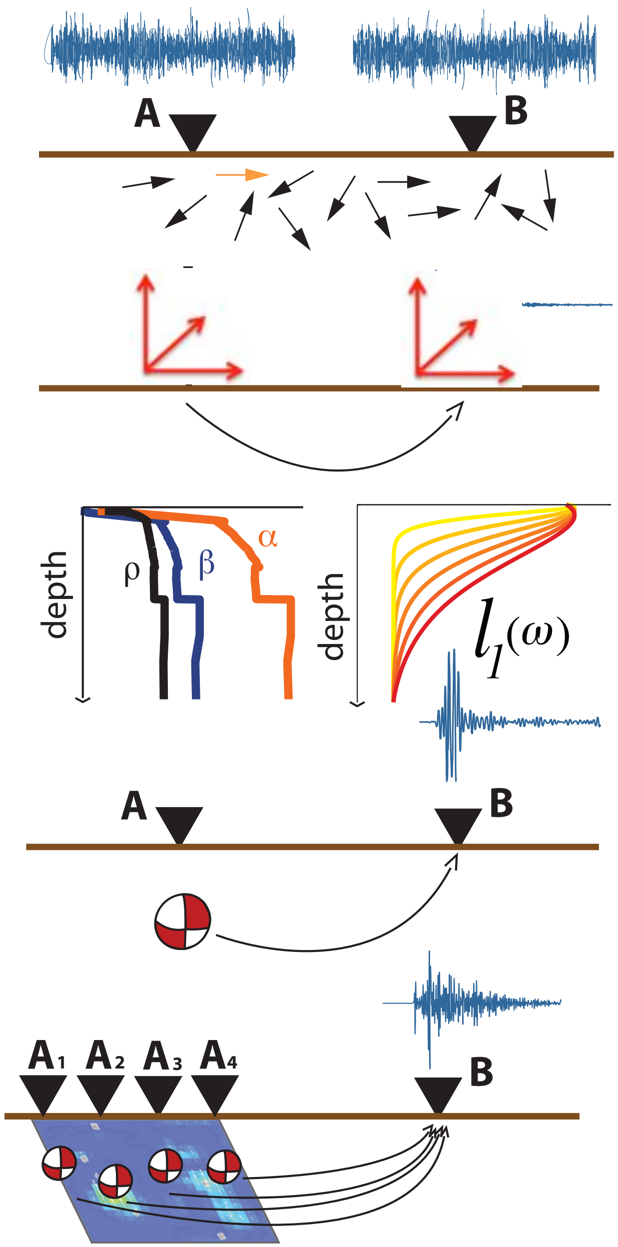
Earthquake records | **Impulse response records**



***Prieto and Beroza* (2008)**

Ignores depth and mechanism

Virtual Earthquake Method



Continuous Recording of ASF

Earth Response to Directed Forces

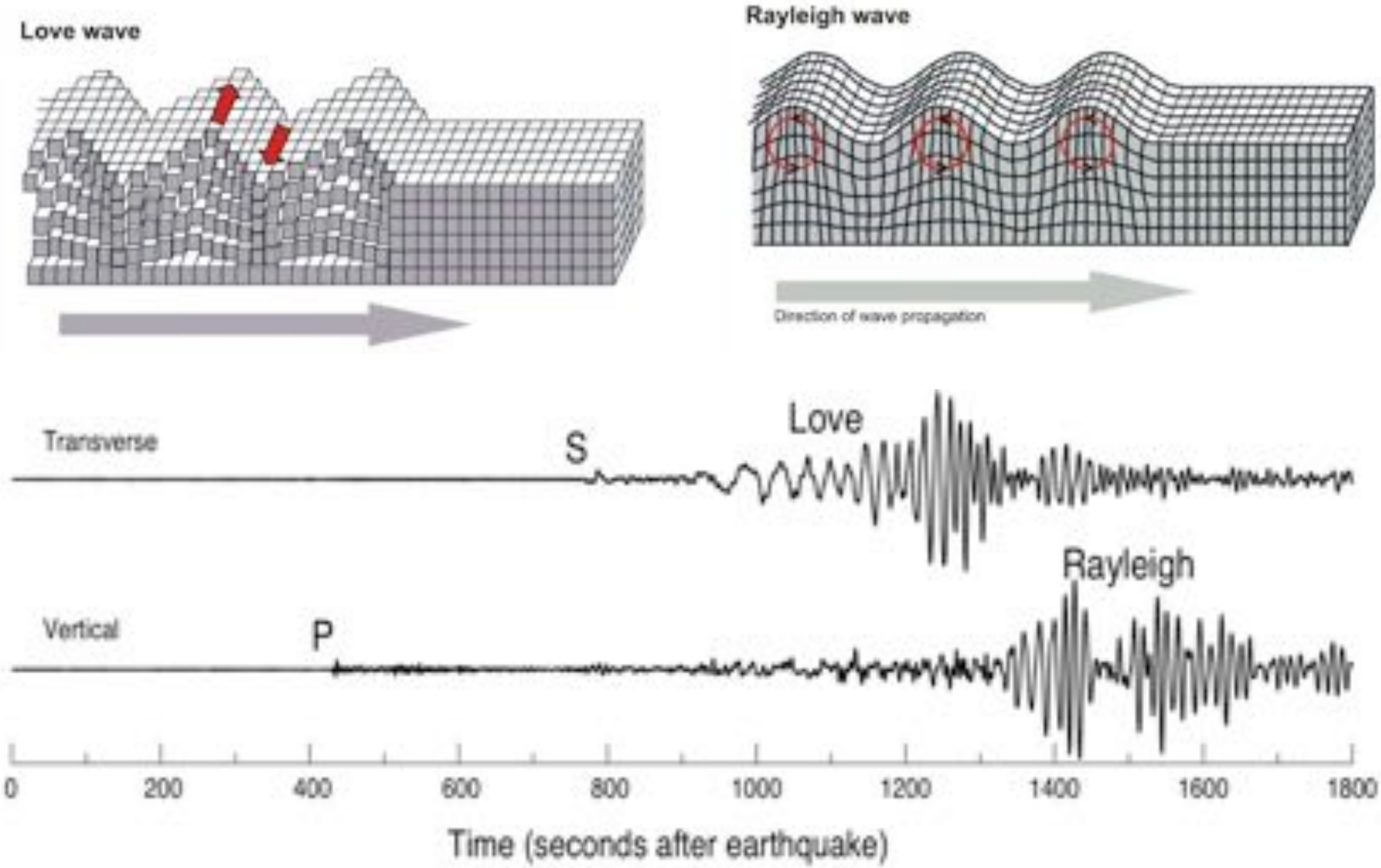
Source-Depth Correction

Double-Couple Correction

Finite-Source Correction

Denolle et al. **(2013)**

Surface waves



Assume Fundamental Mode Love/Rayleigh

Depth Correction:

$$\hat{G}_{TT}(h) = \frac{l_1(h)}{l_1(0)} \hat{G}_{TT}(0)$$

Surface-wave eigenfunction

Mechanism Correction:

$$\hat{u}_i(\mathbf{x}) = \hat{M}_{pq} \frac{\partial}{\partial x'_q} \hat{G}_{ip}(\mathbf{x}, \mathbf{x}')$$

Green's function derivative

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:

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

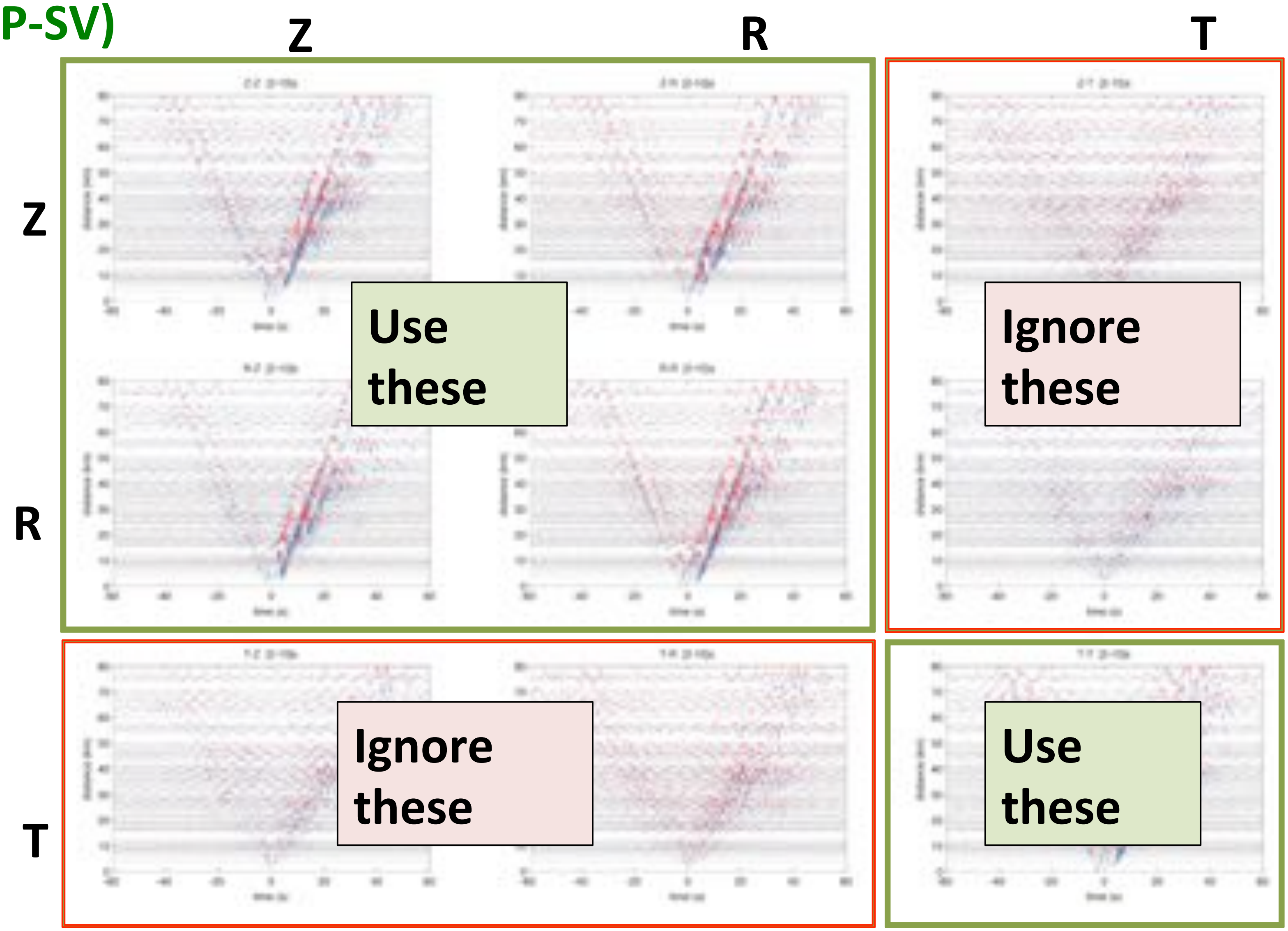
$$\hat{U}_D\left(\vec{\xi},\omega\right) = \frac{1}{r_1\left(\vec{\xi}',0,\omega\right)}\left[-ik_R\hat{M}_{RR}(\omega)r_1\left(\vec{\xi}',h,\omega\right) + \hat{M}_{RD}(\omega)l_1'\left(\vec{\xi}',h,\omega\right)\right]\hat{G}_{RD}\left(\vec{\xi}',\vec{\xi},\omega\right) +$$
$$\frac{1}{r_2\left(\vec{\xi}',0,\omega\right)}\left[-ik_R\hat{M}_{DR}(\omega)r_1\left(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

(1D simplification in excitation)

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

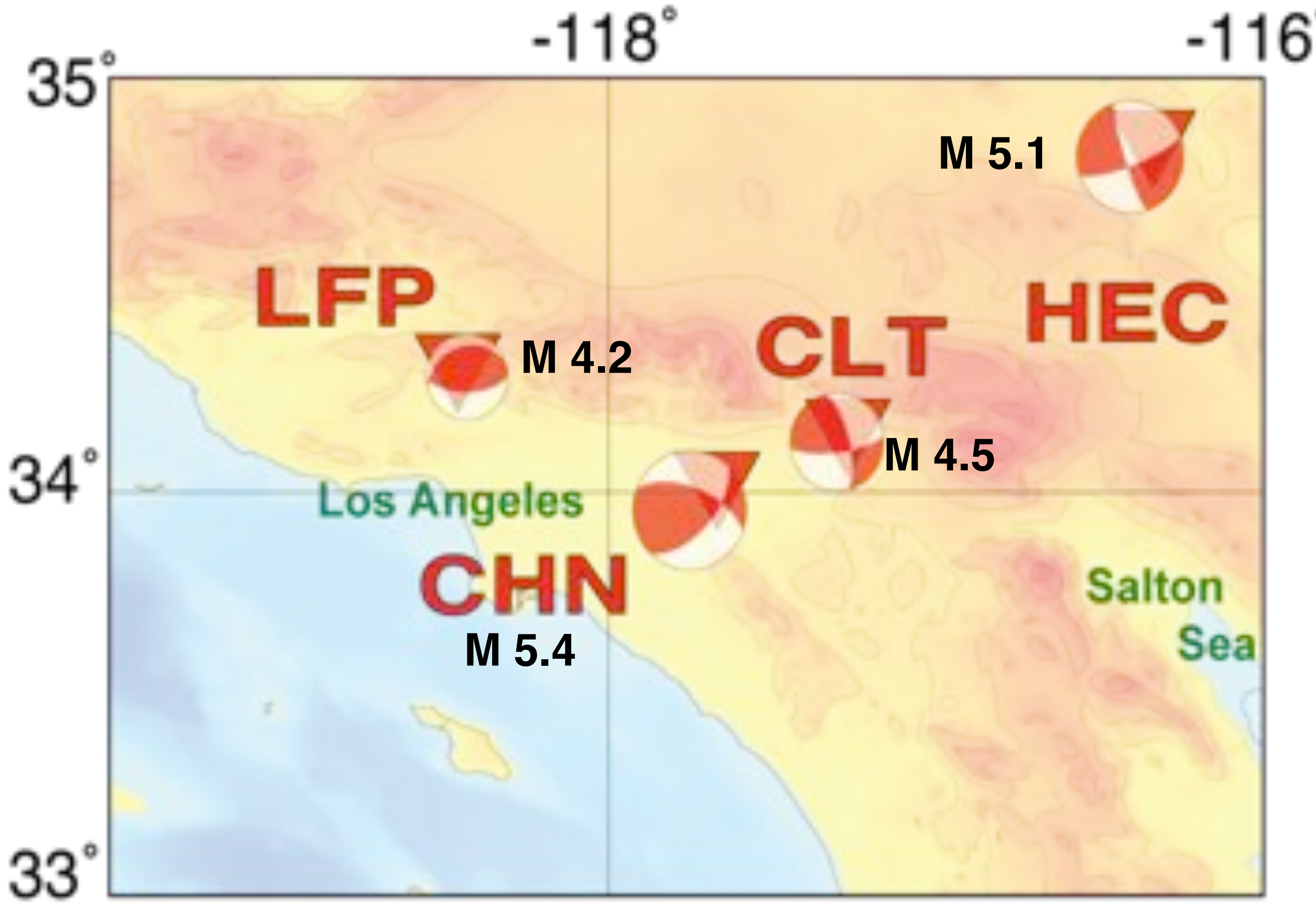
Rayleigh
(P-SV)

All 9 Components of GFs (2-10 s)



Love
(SH)

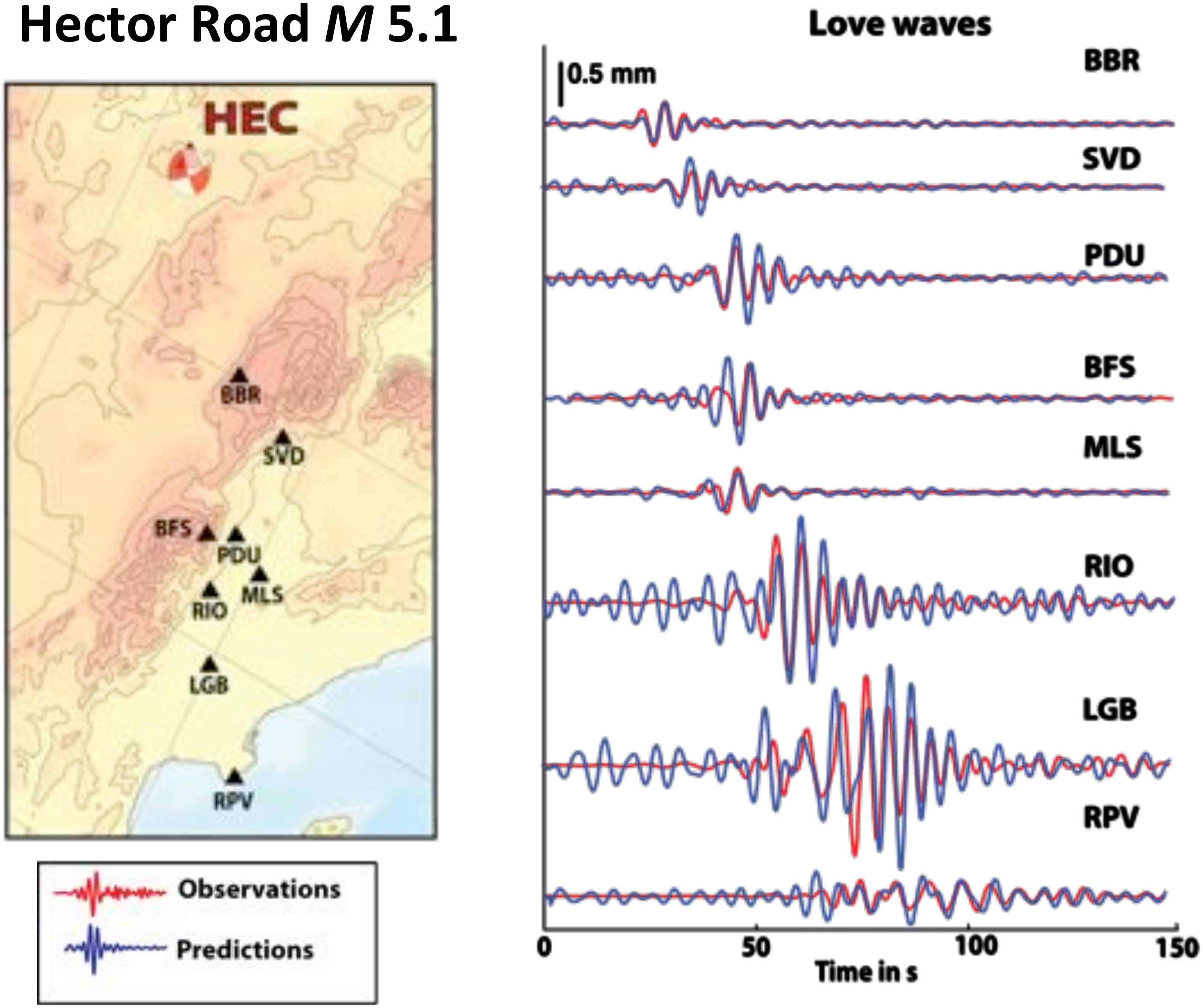
Validate Against 4 Moderate Earthquakes



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

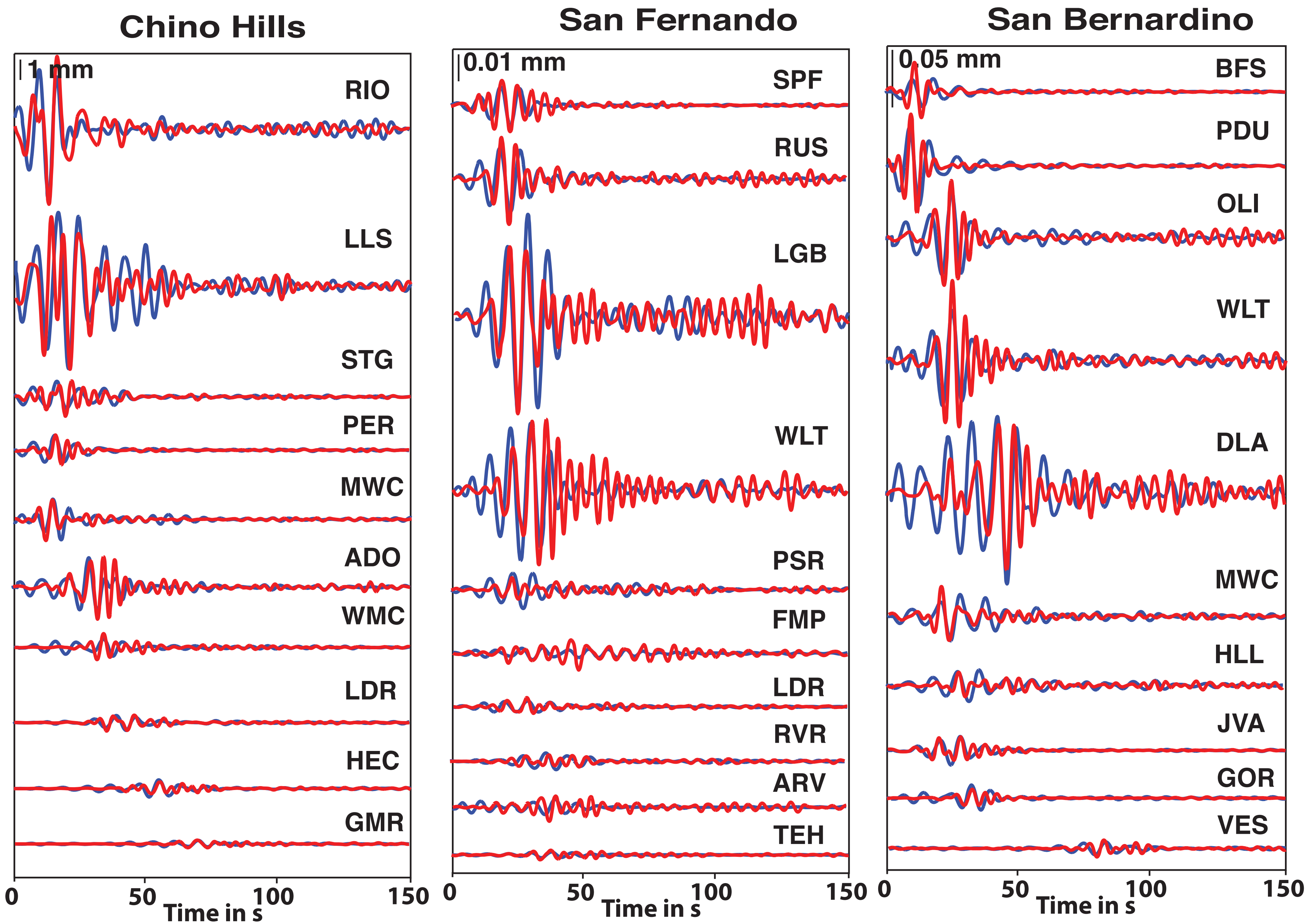
***Denolle et al.* (2013)**

Hector Road *M* 5.1



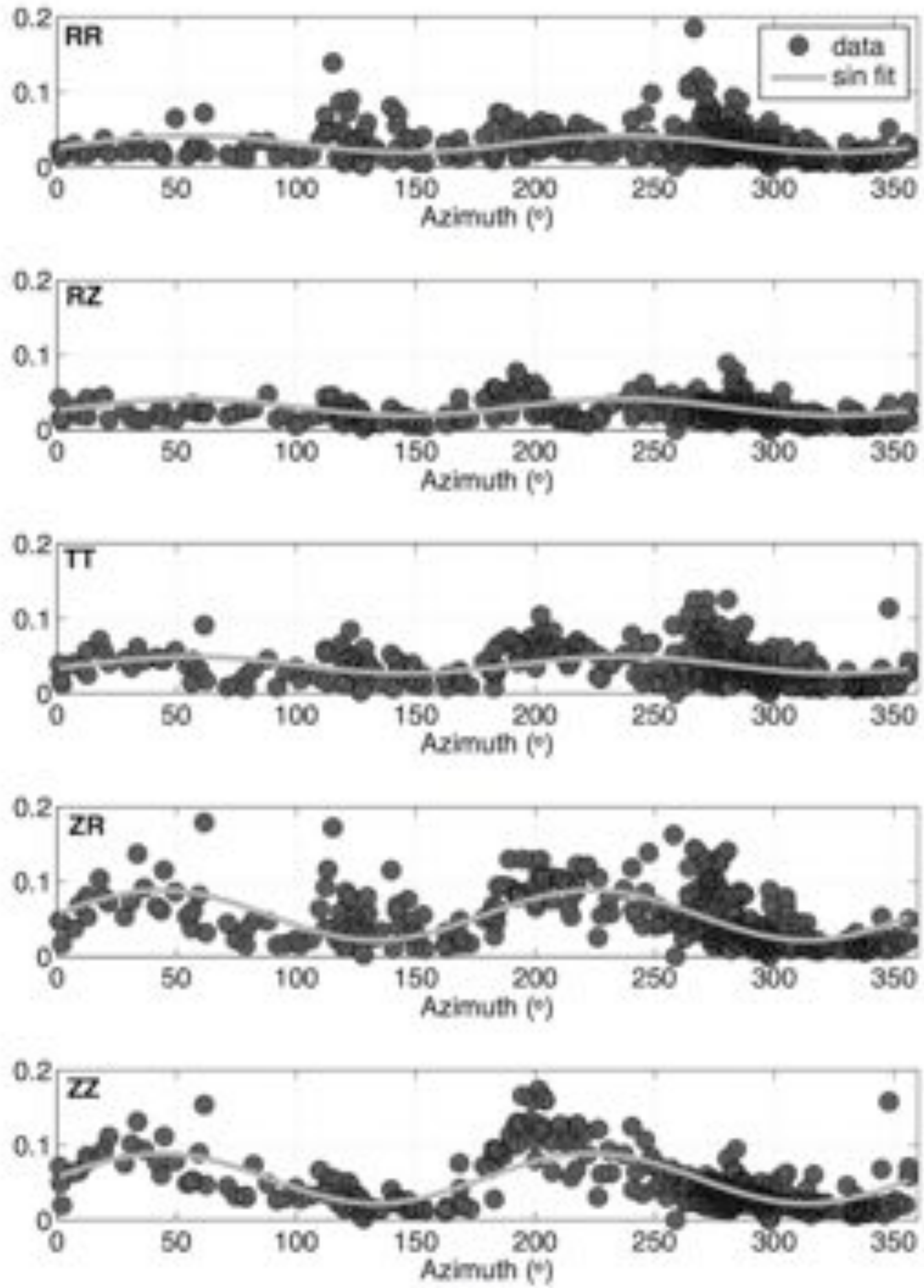
Denolle et al. (2013)

Further Validation with Moderate Earthquakes

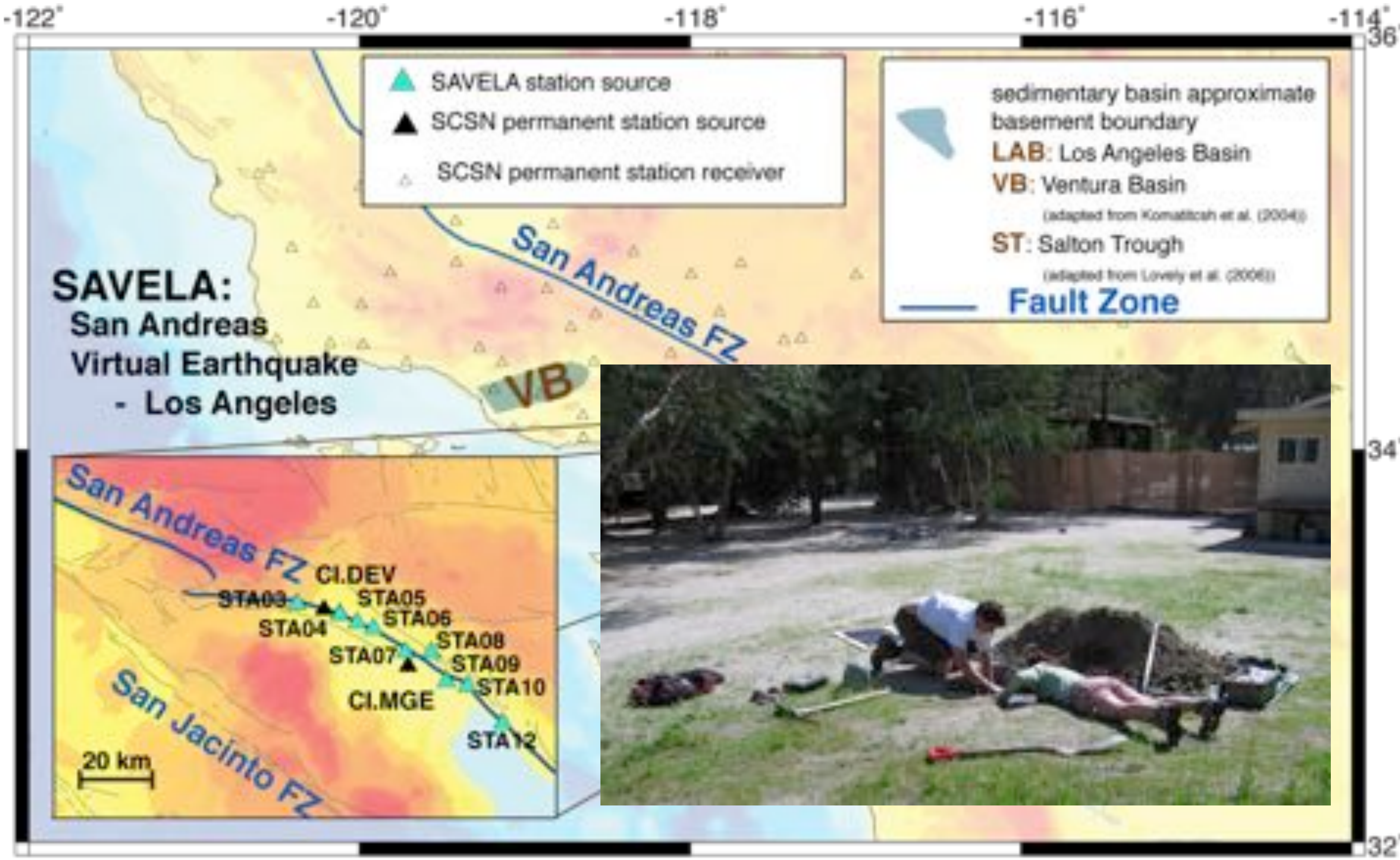


Use these earthquakes to calibrate amplitudes:

- Ponderosity correction
- Absolute amplitudes by matching moderate earthquakes

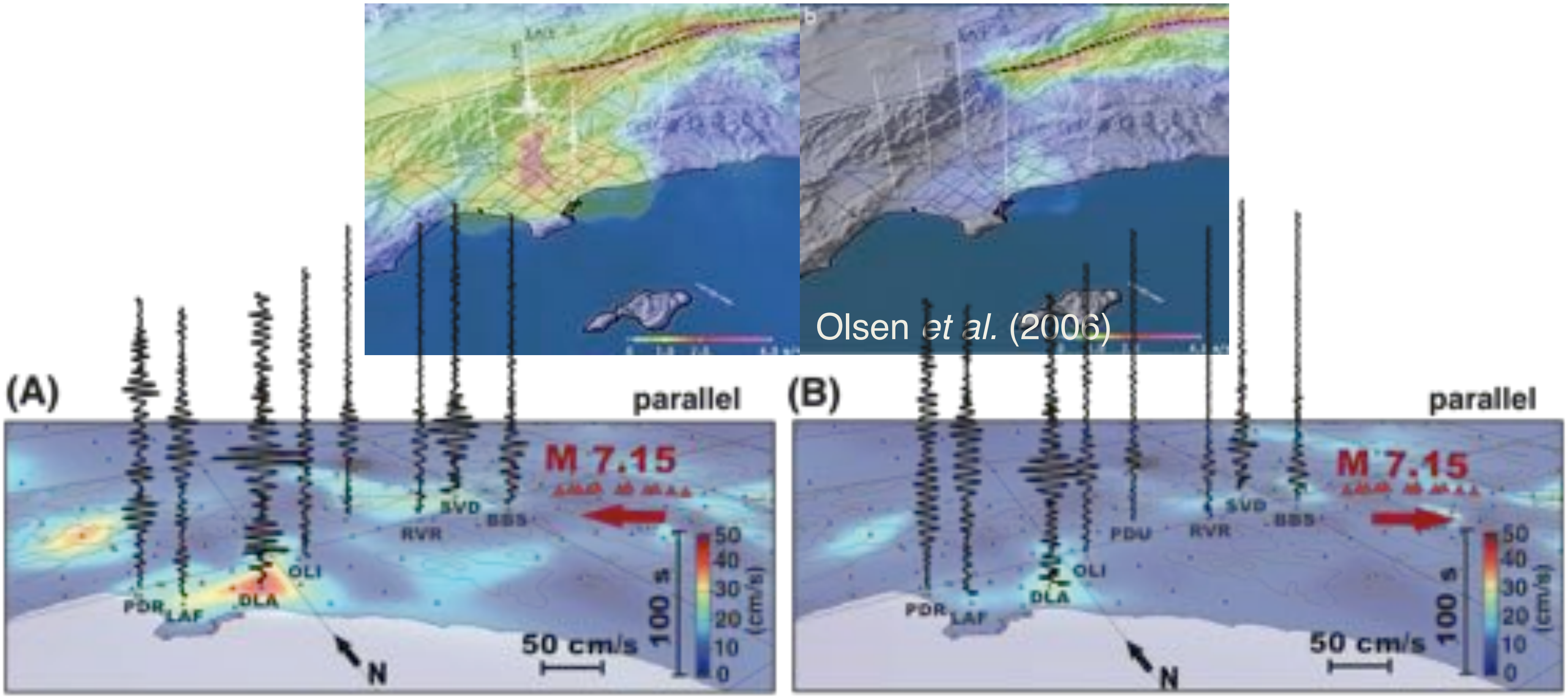


6-Month SAVELA Deployment



Denolle *et al.* (2014a)

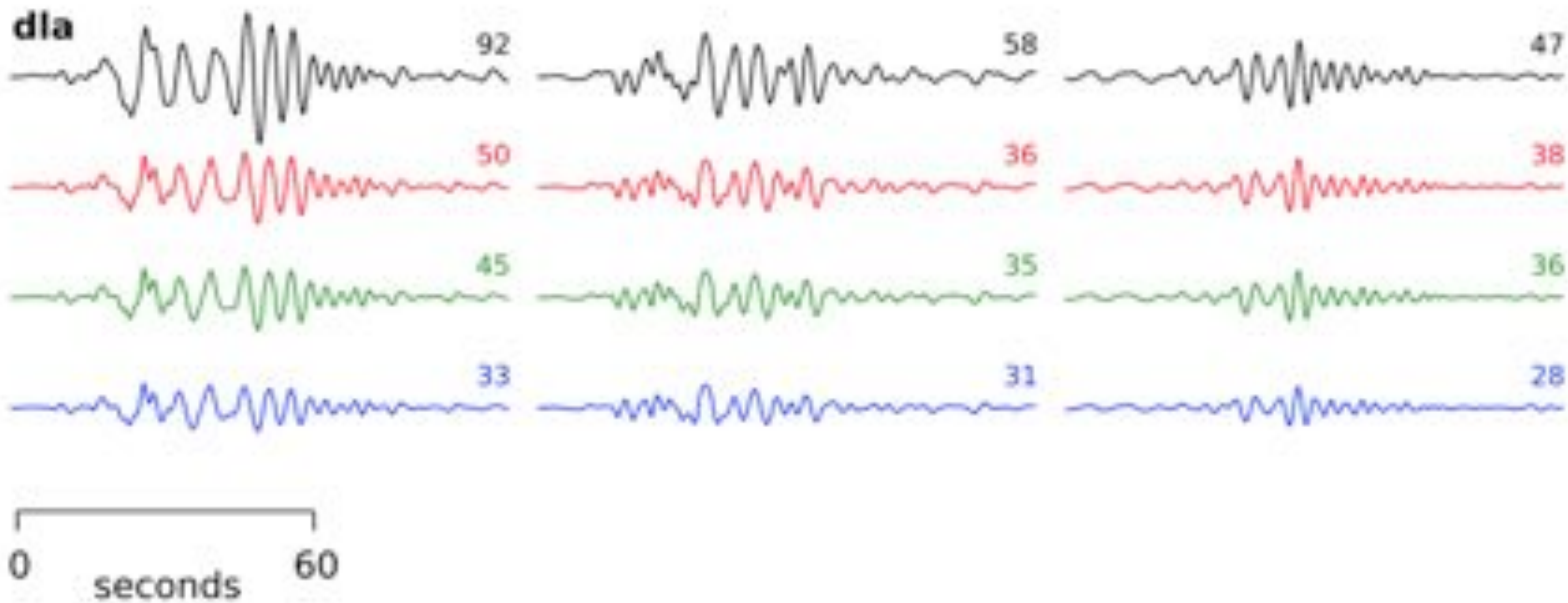
Confirms Waveguide-to-Basin Effect



Details of Amplification are Different

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

Important Caveat: Nonlinearity at Long Periods



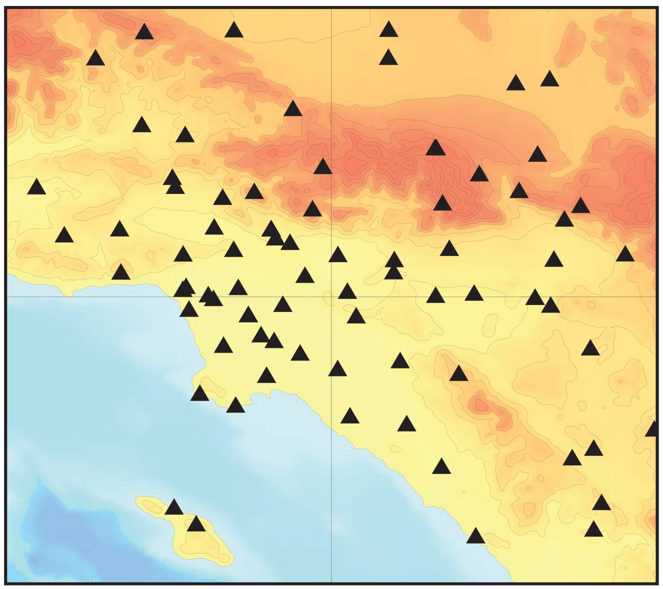
Linear – black

Nonlinear – color (under various assumptions)

Roten et al. **(2014)**

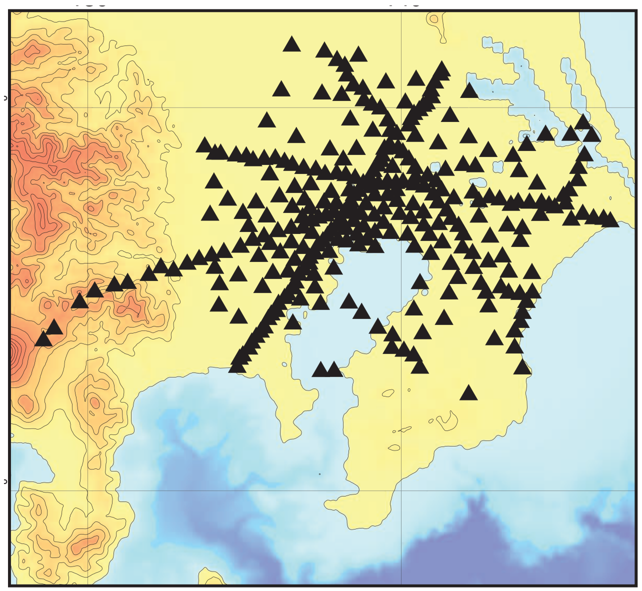
Results from Three Seismic Networks

SCSN



Sparse
~10 km spacing
10s of sensors

MeSO-net



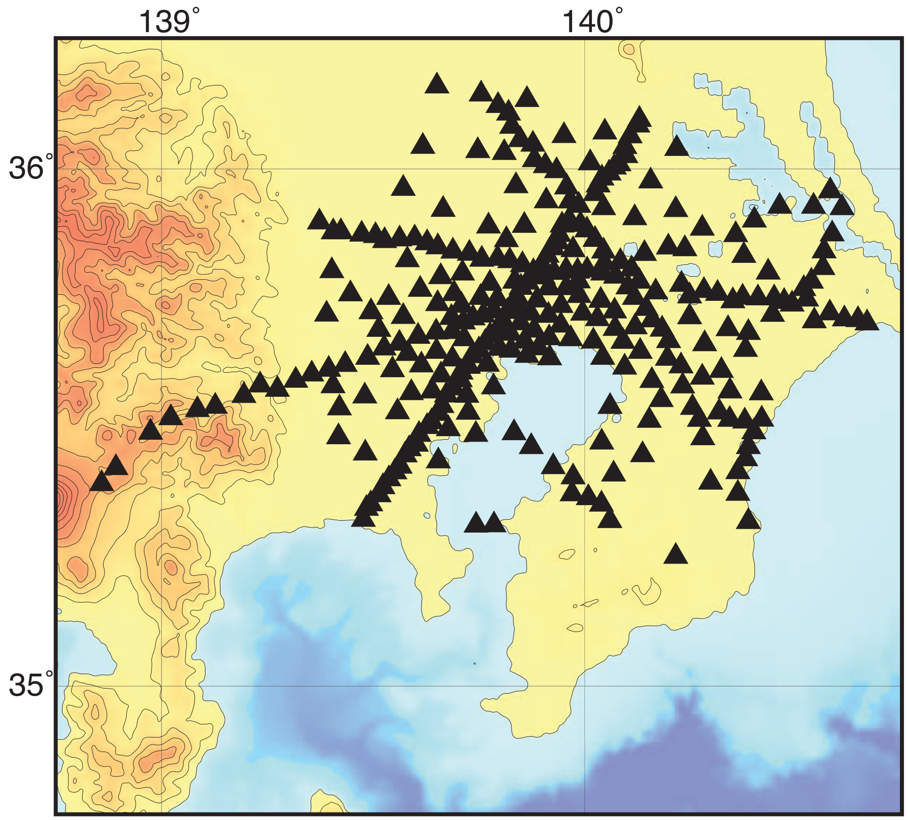
Dense
~1 km spacing
100s of sensors

Long Beach

Very Dense
~0.1 km spacing
1000s of sensors

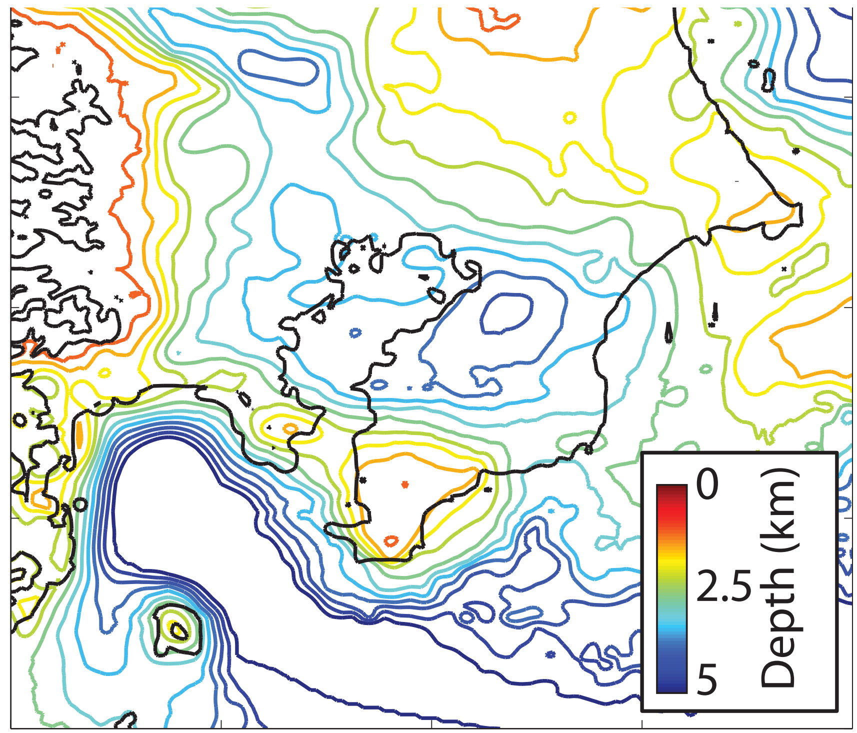
Kanto Basin, Japan: Tokyo

Metropolitan Seismic Observatory Network (MeSO-net)



<u>~290</u> shallow-boreholes 3-channel accelerometers *in the basin*

Kanto Basin basement

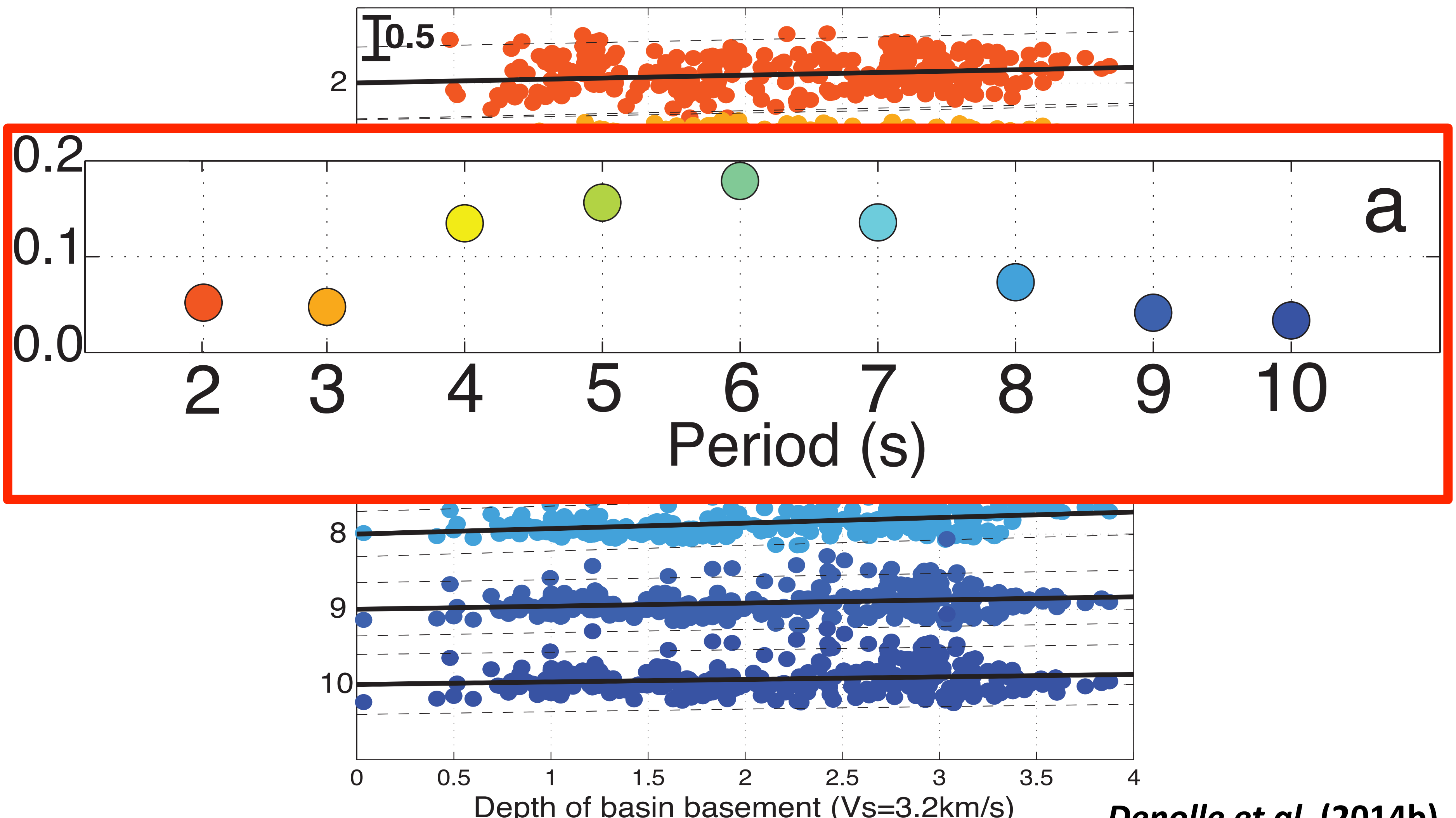


Adapted from Tanaka *et al.* (2006)

Denolle et al. **[2014b]**

Basin Amplification ~ Basin Depth

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

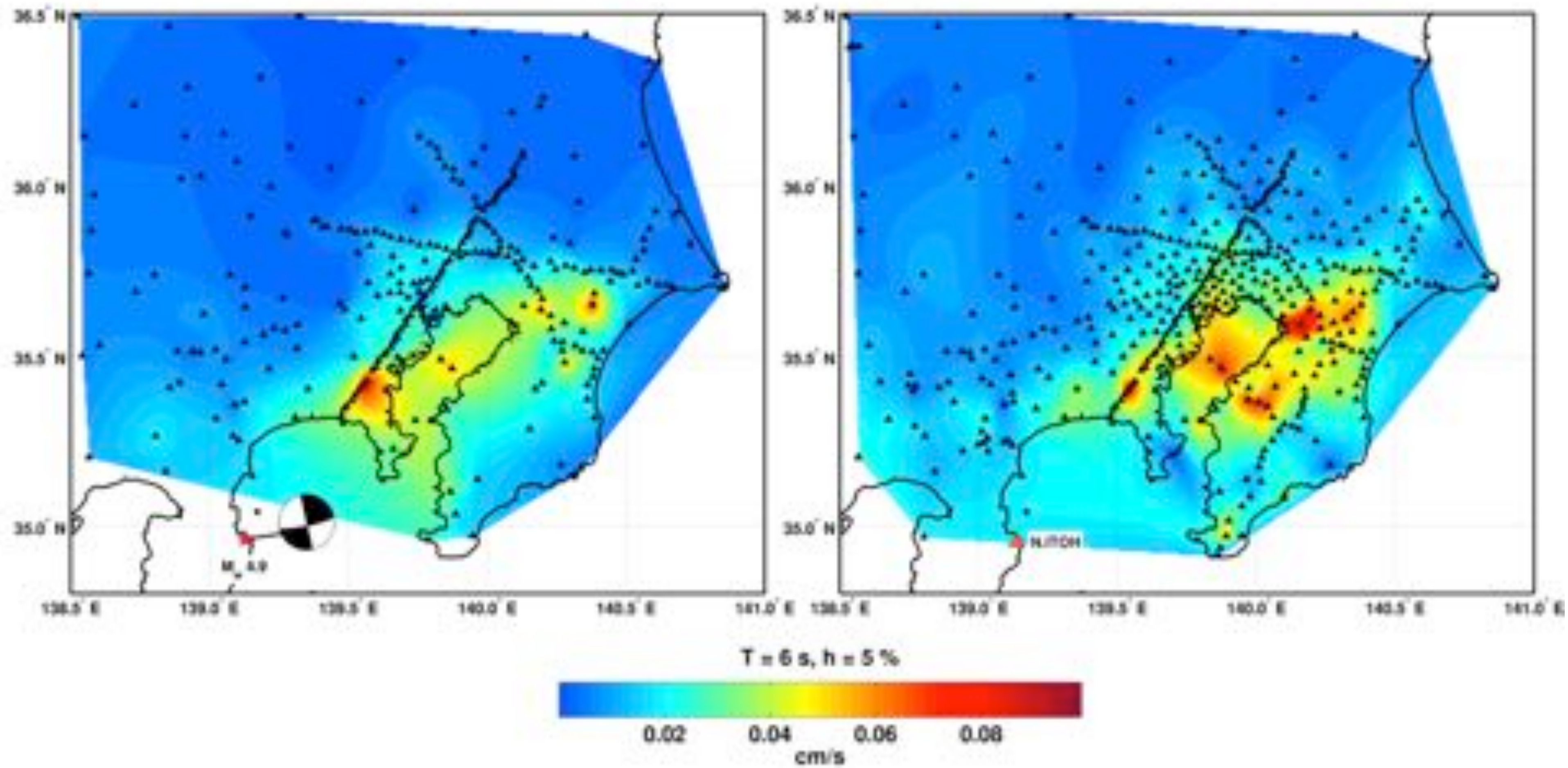


Denolle et al. (2014b)

Basin Effects

Earthquake

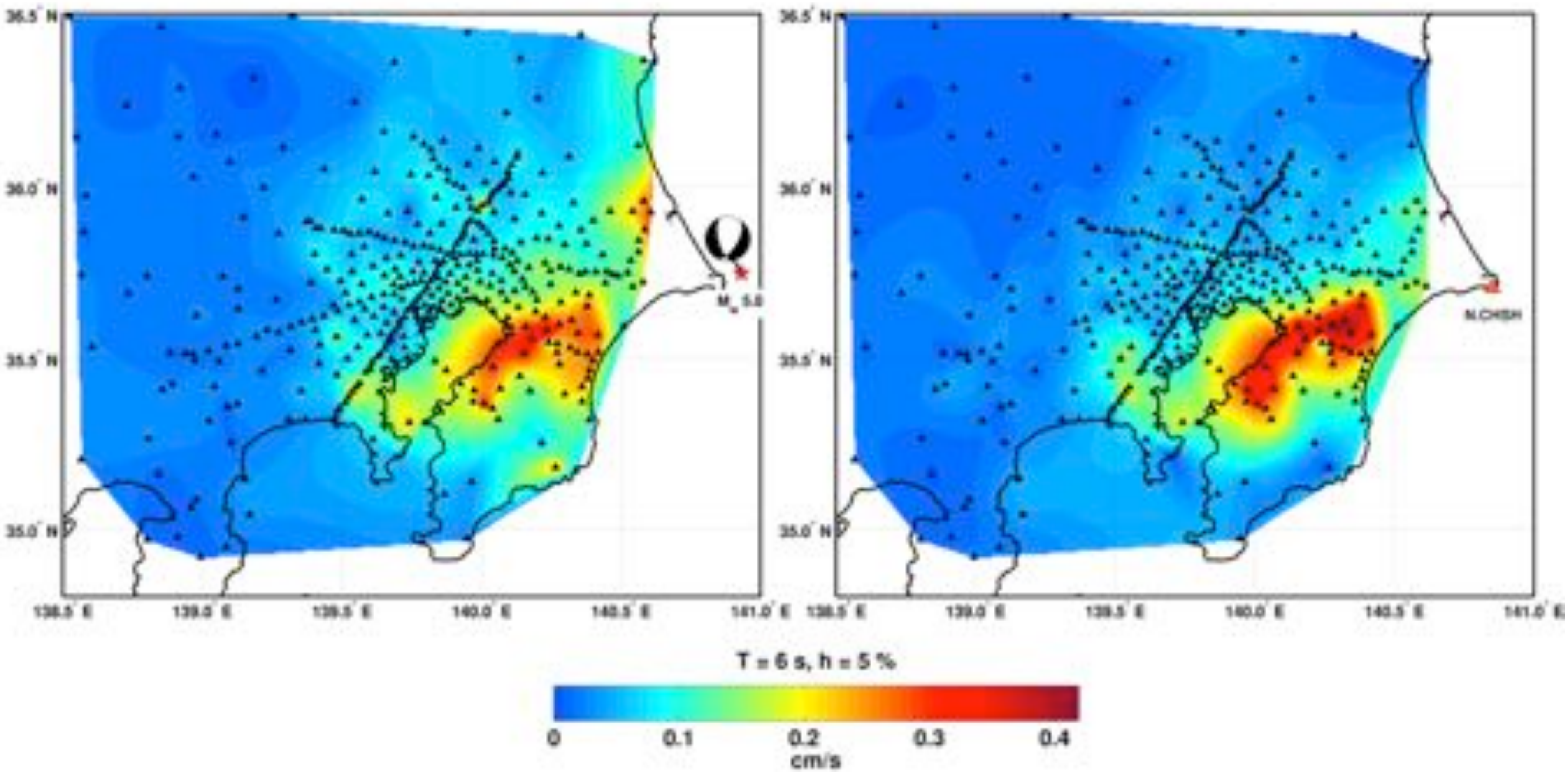
Ambient Field



Viens et al. (2015)

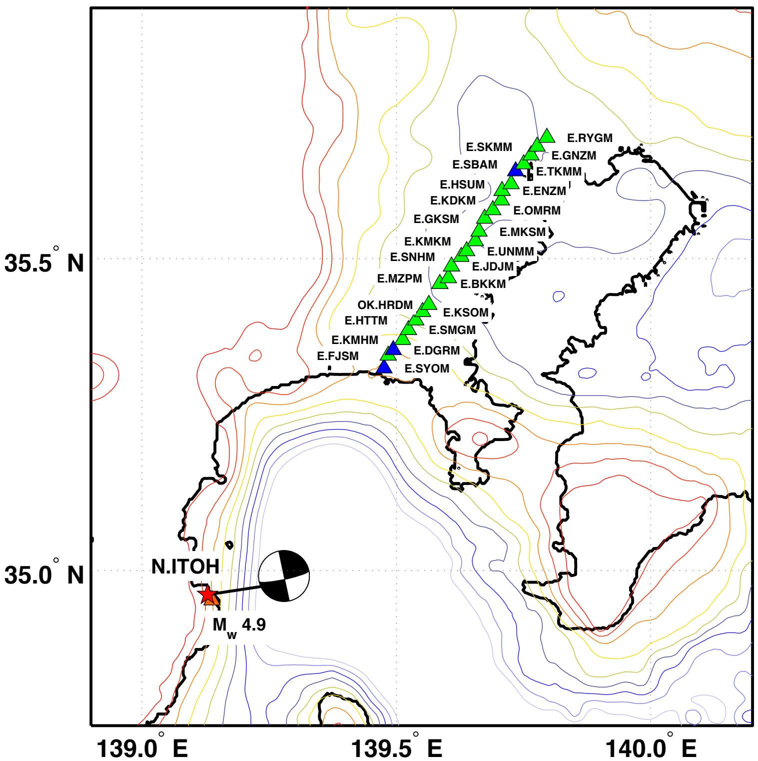
Basin Effects

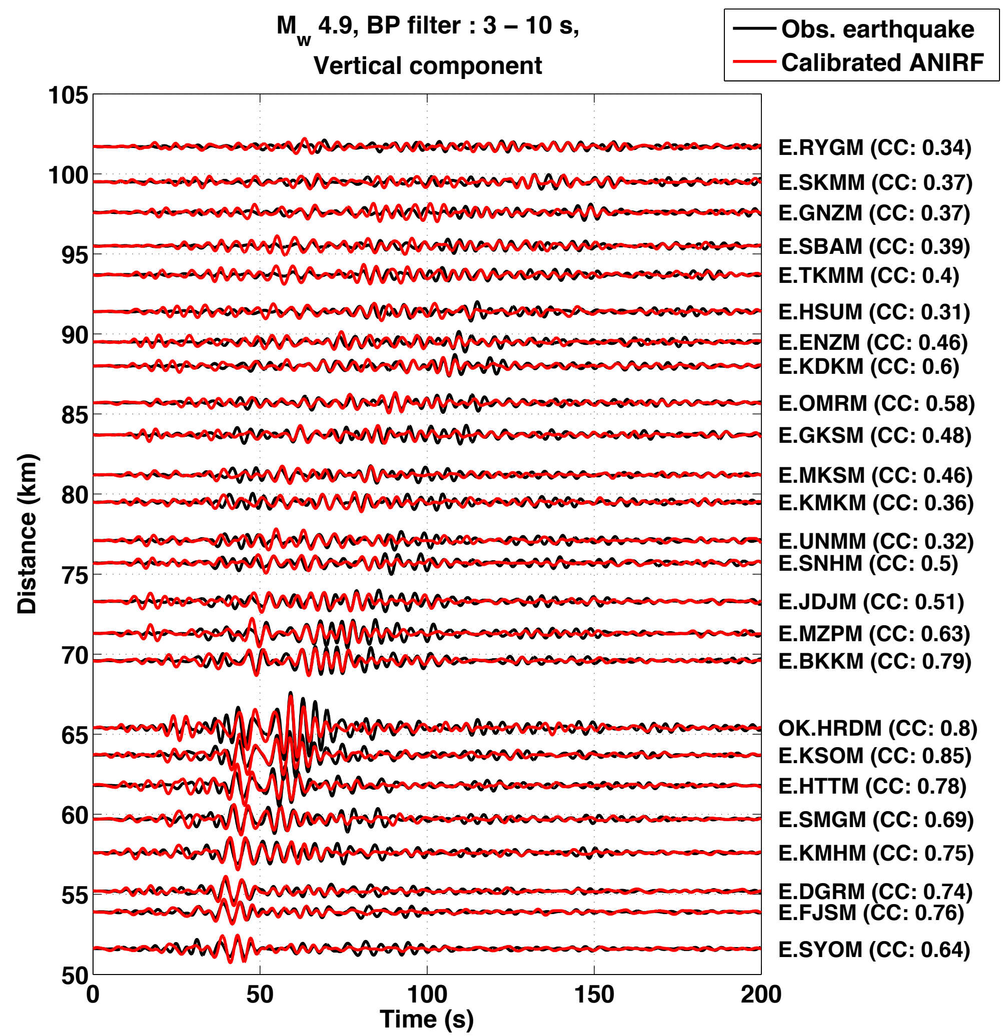
Earthquake **Ambient Field**



Viens et al. **(2015)**

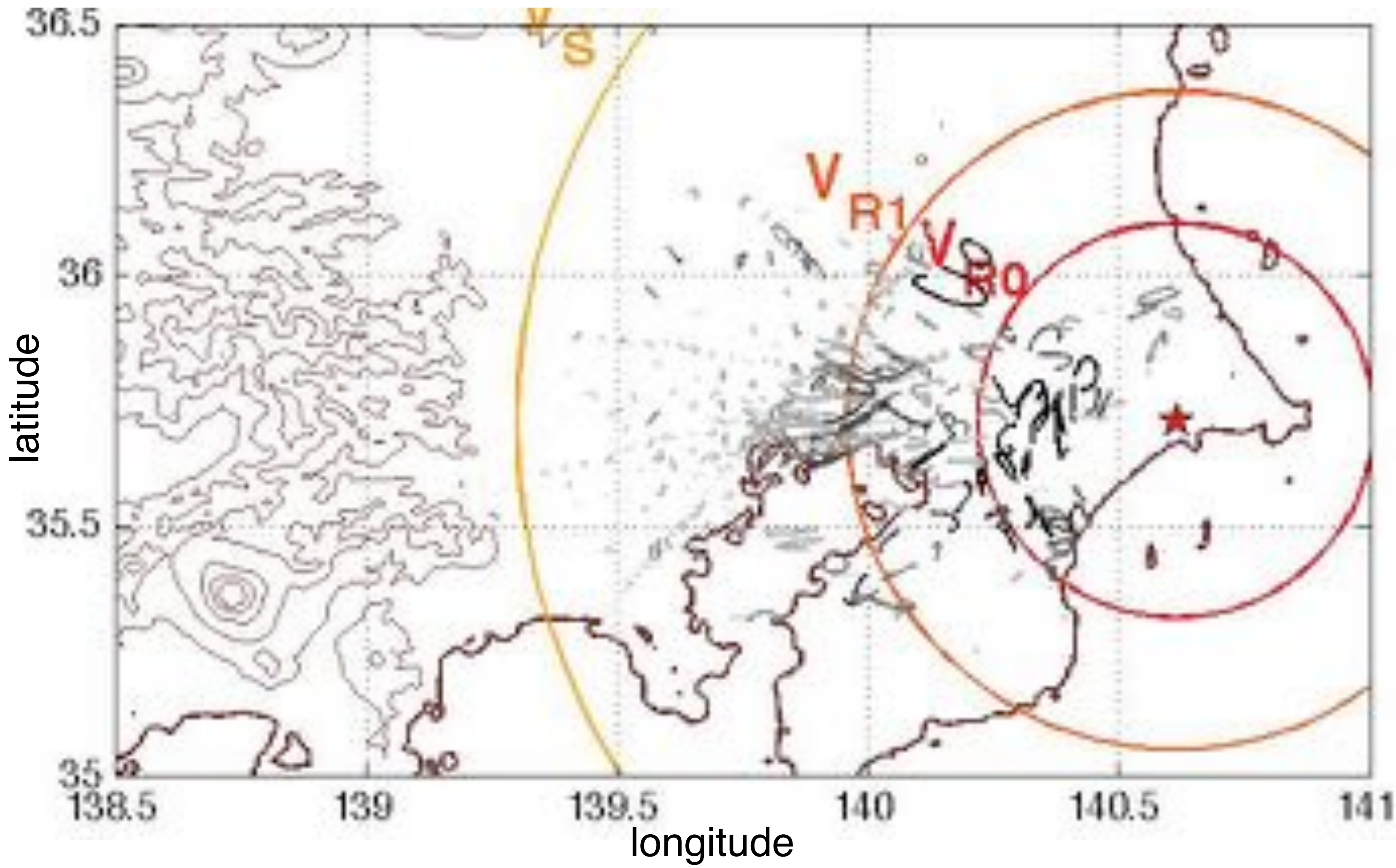
Basin Effects



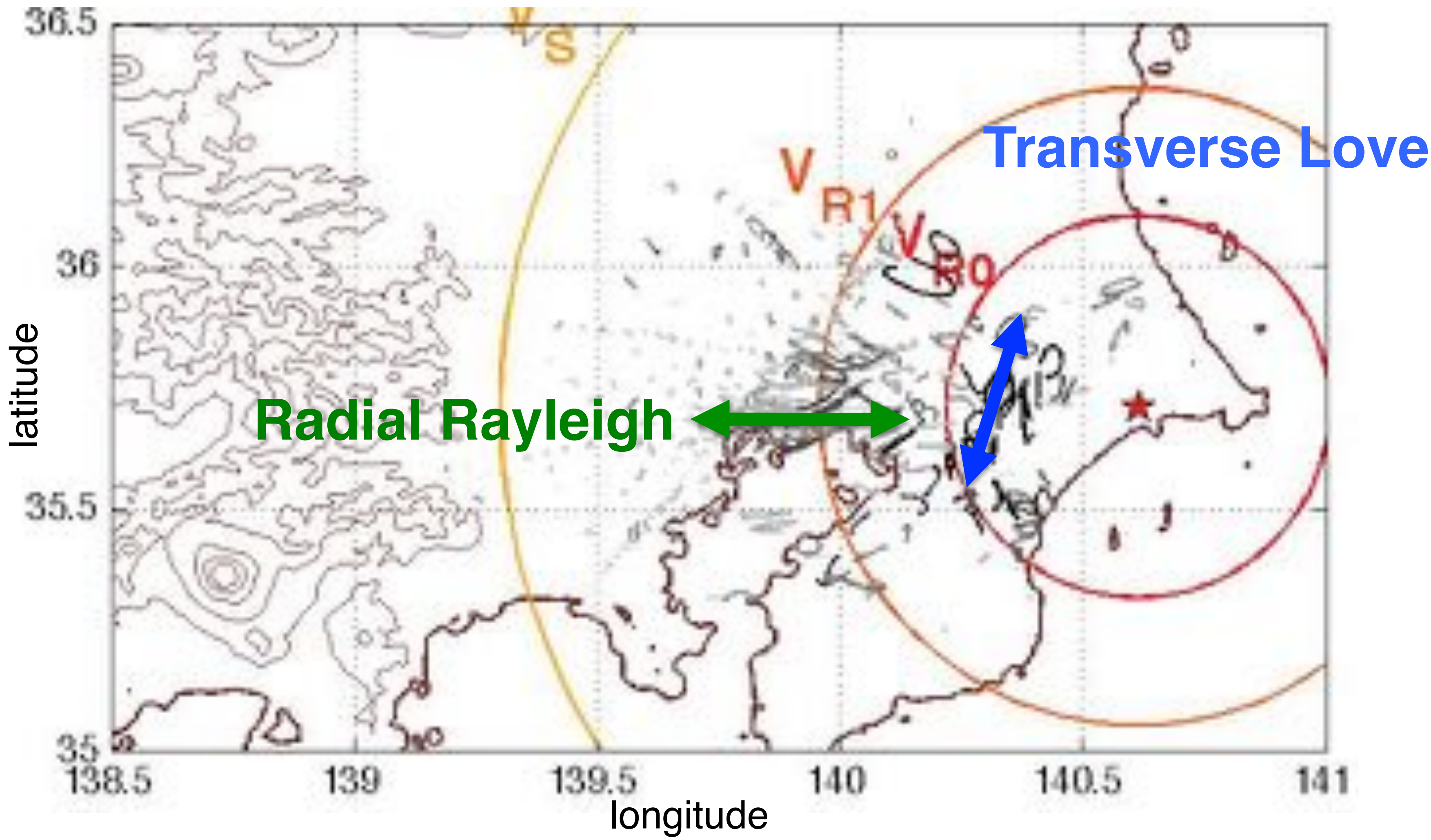


Viens et al. (2015)

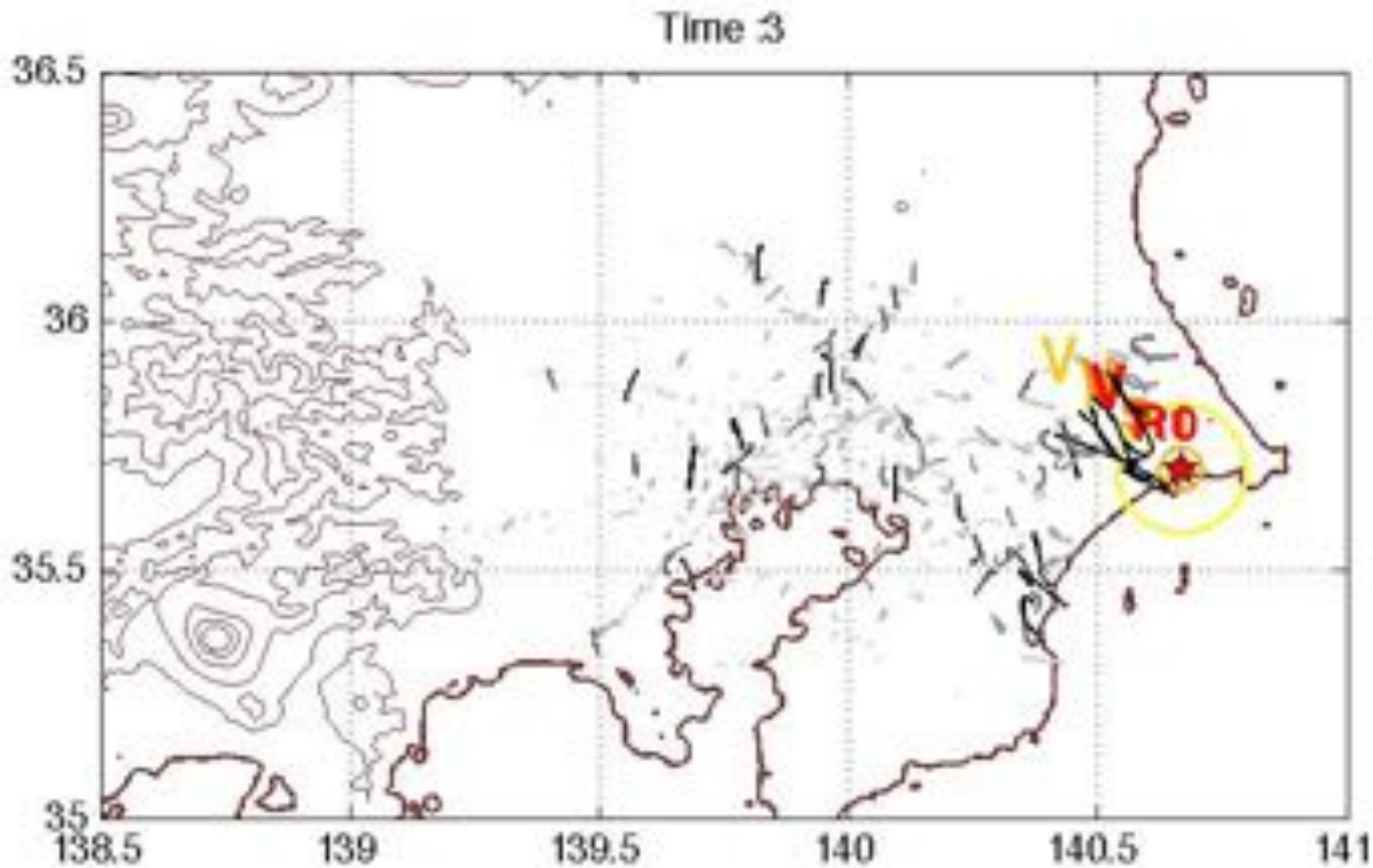
Basin-Edge Effects – Vertical Point Force

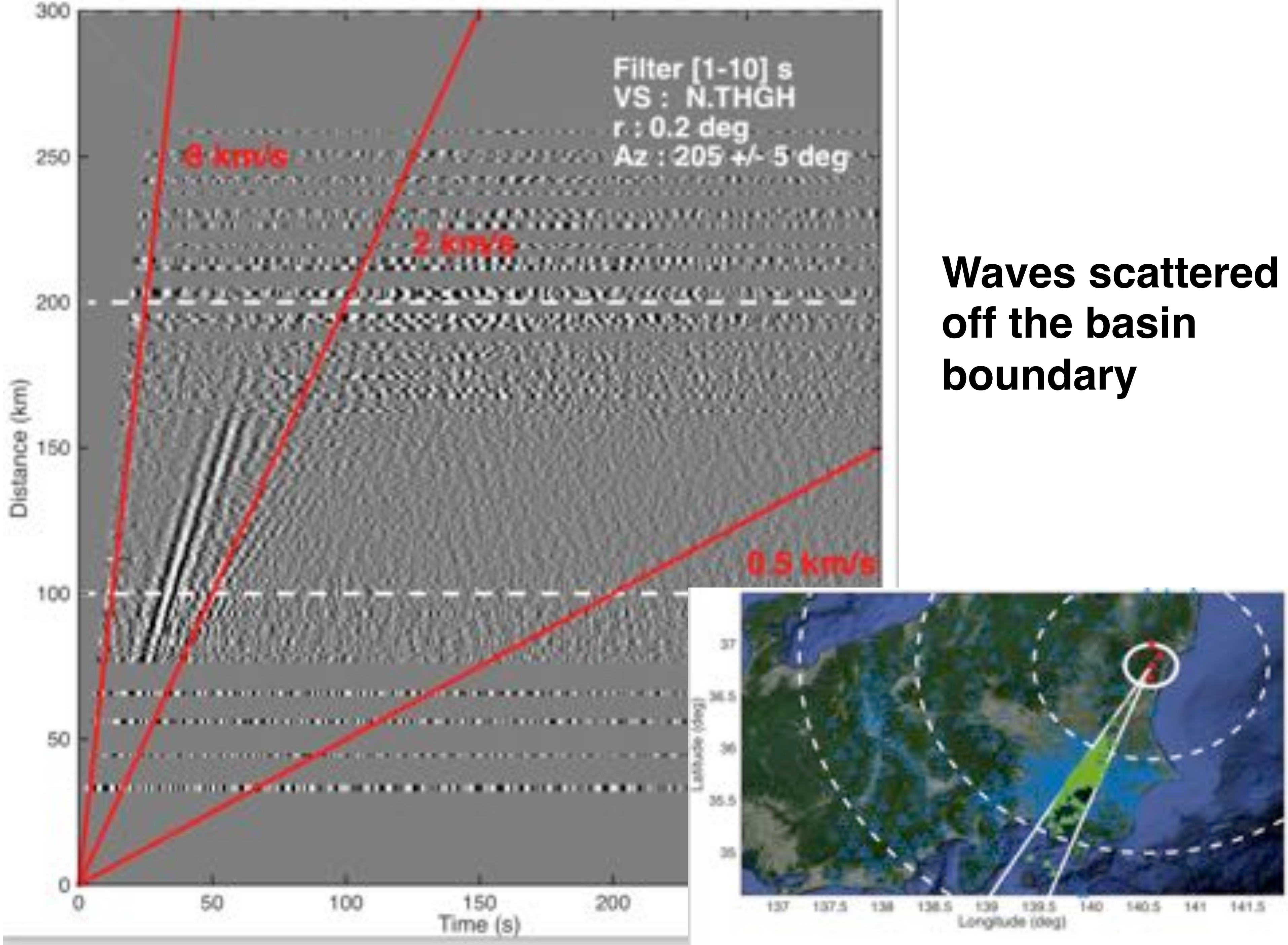


Basin-Edge Effects – Conversion



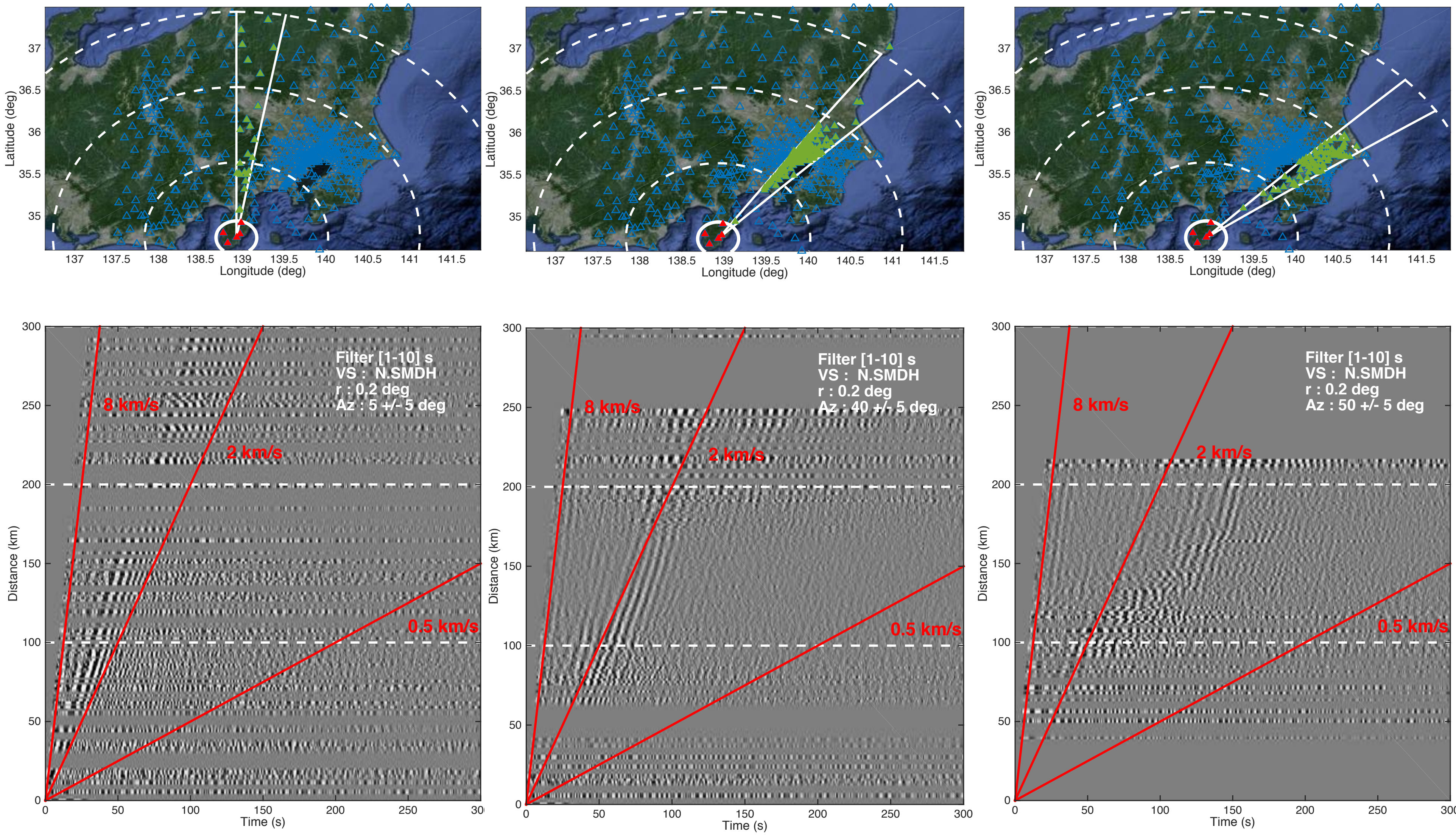
Basin-Edge Effects – Conversion



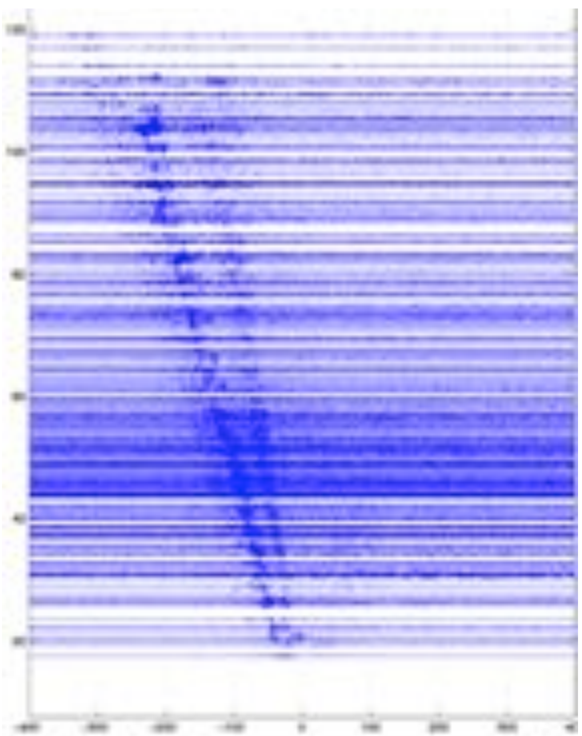


Waves scattered off the basin boundary

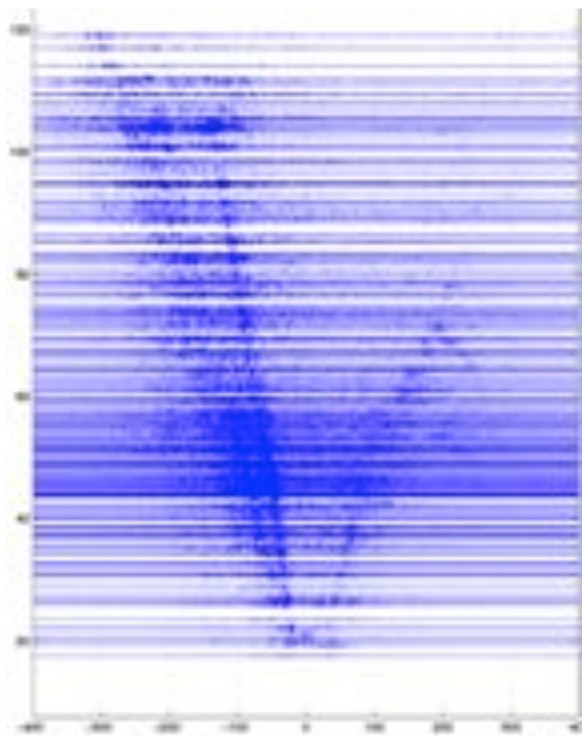
Constraints on Basin Structure



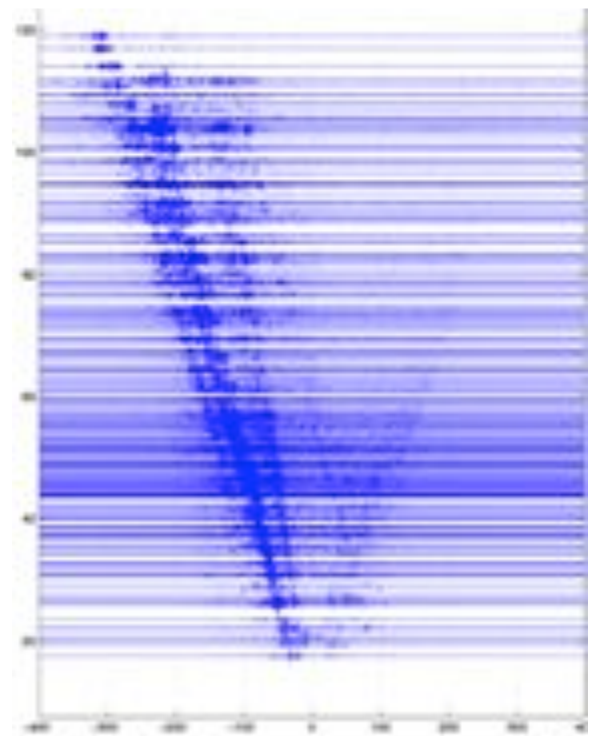
ZR



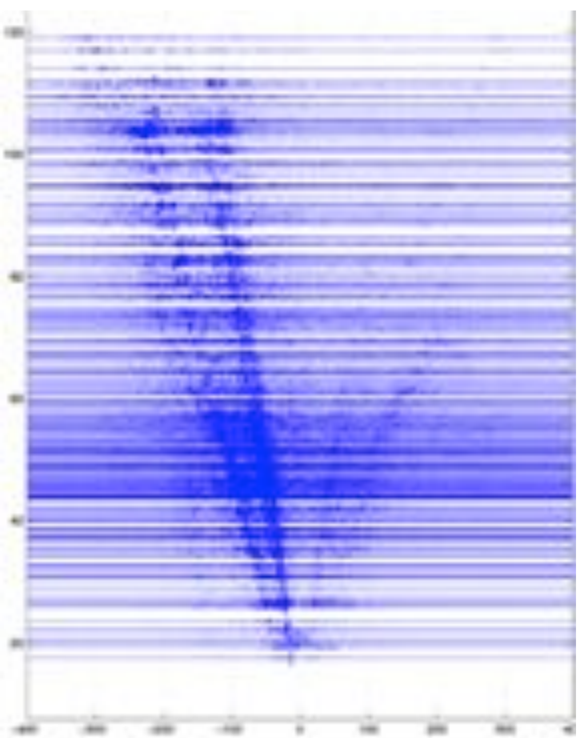
ZT



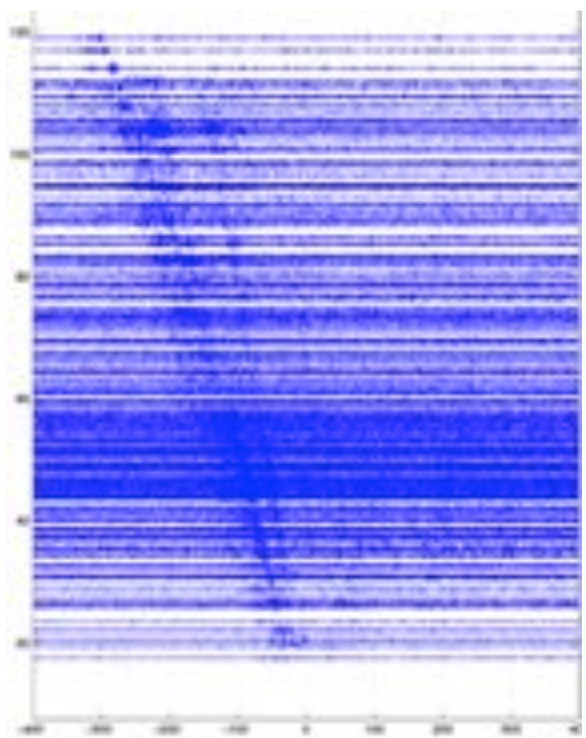
ZZ



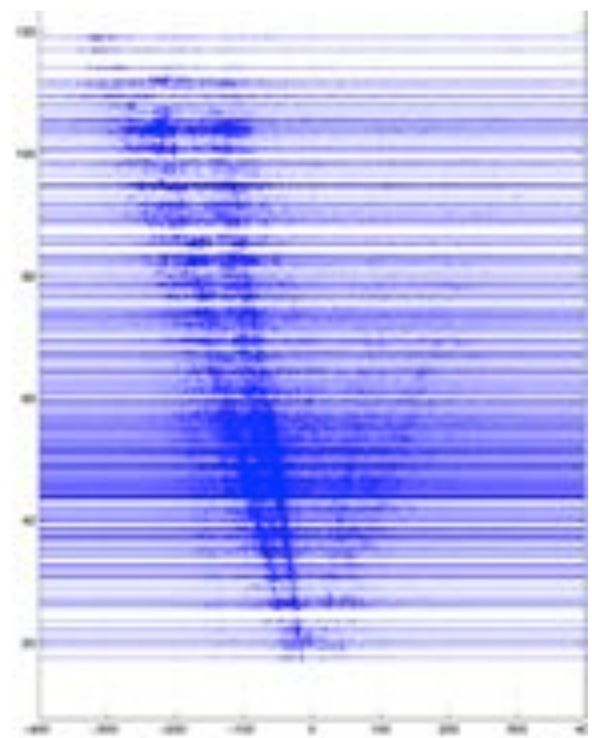
RR

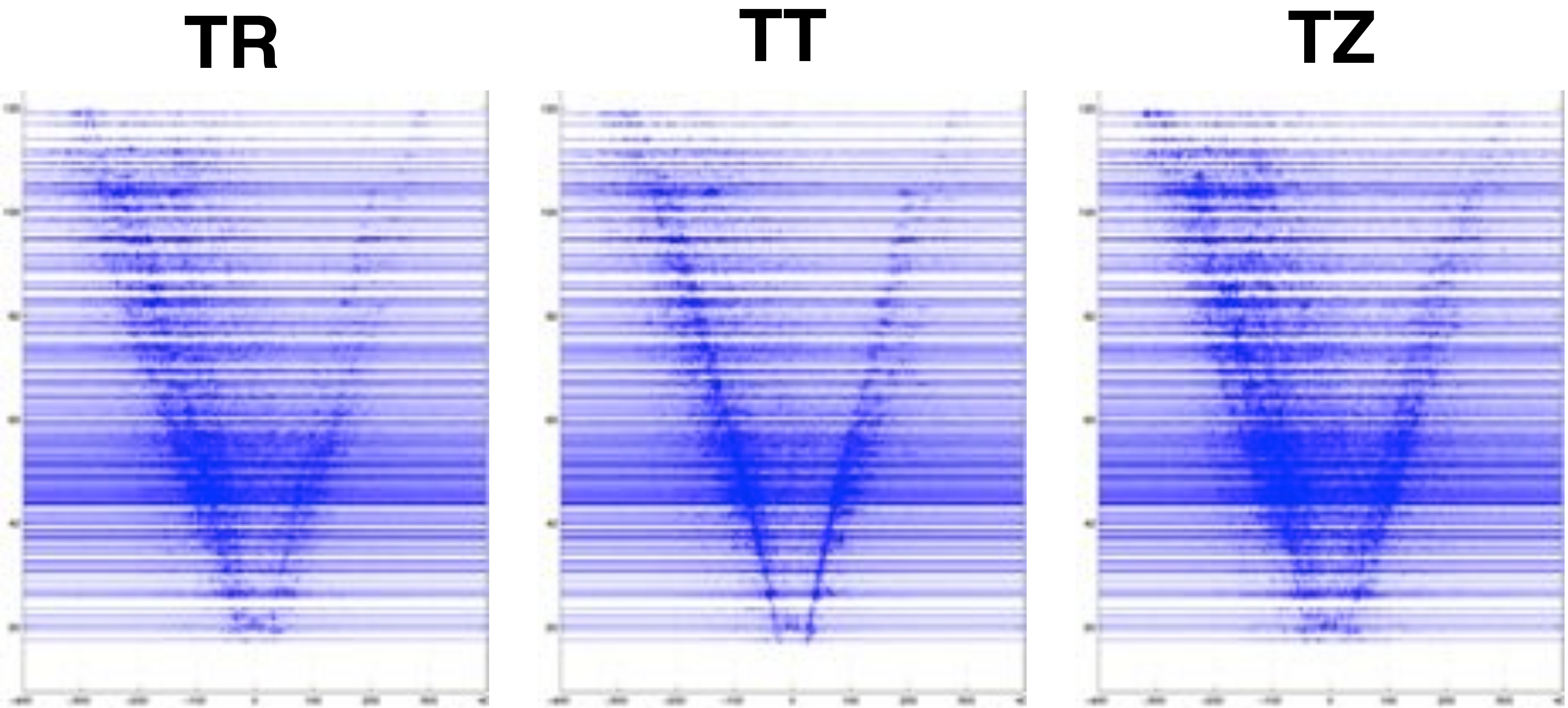


RT

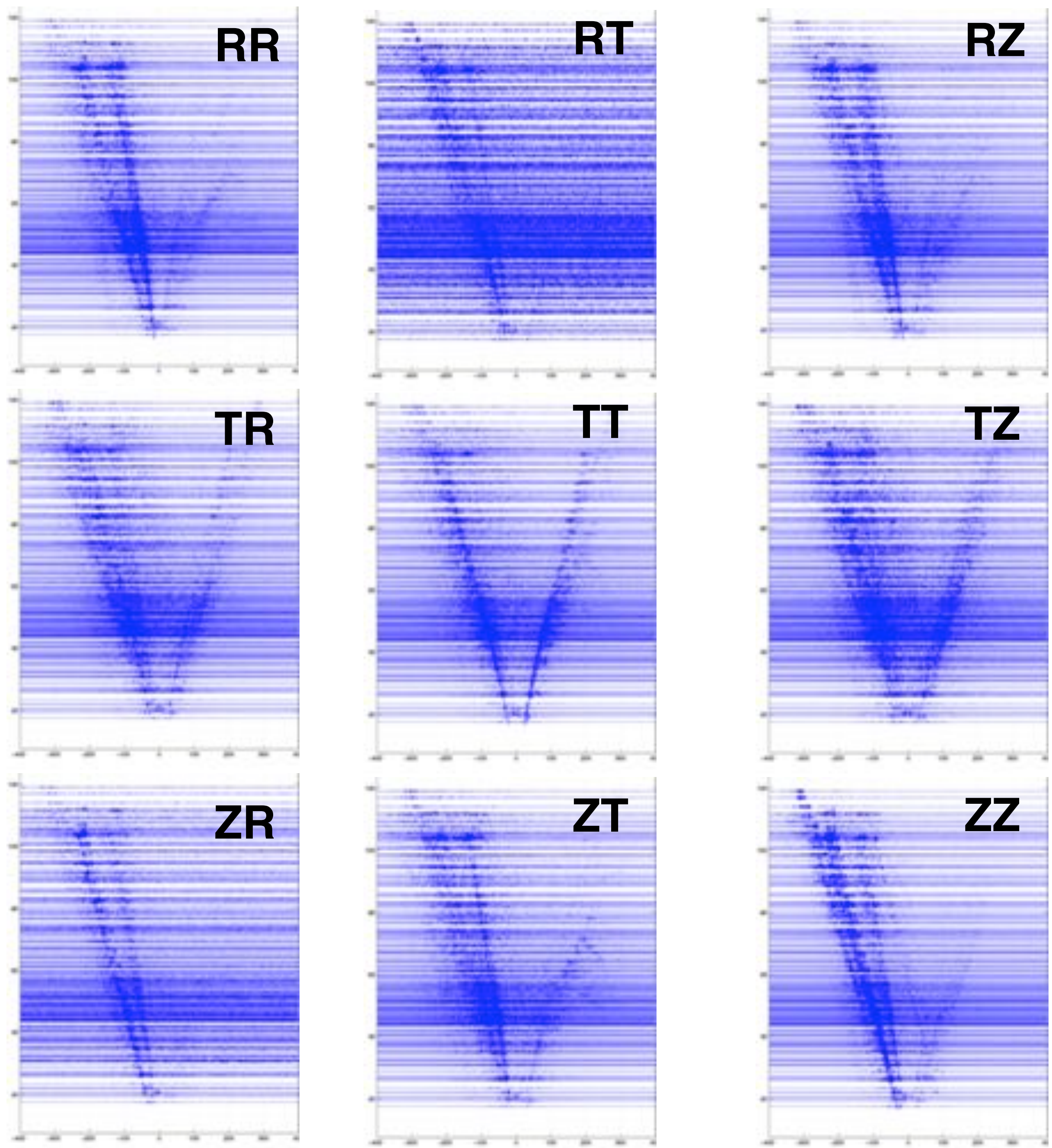


RZ



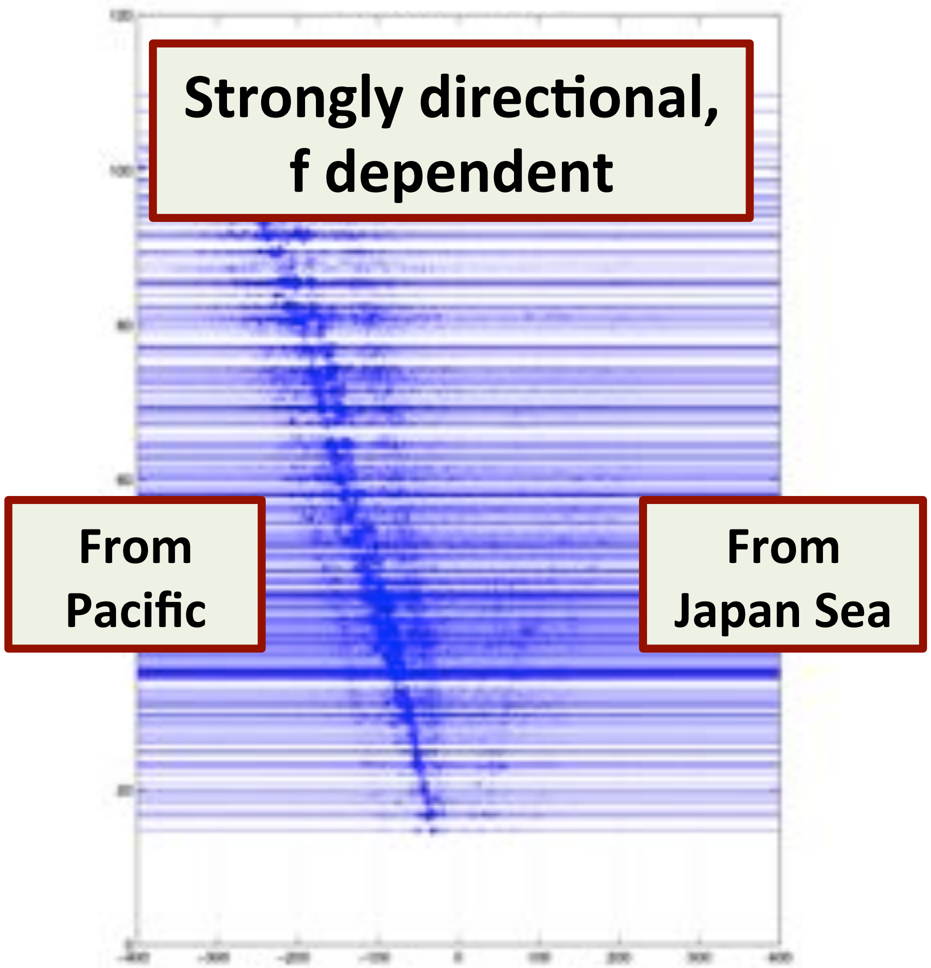

TR
TT
TZ

There's more to basin response than resonance



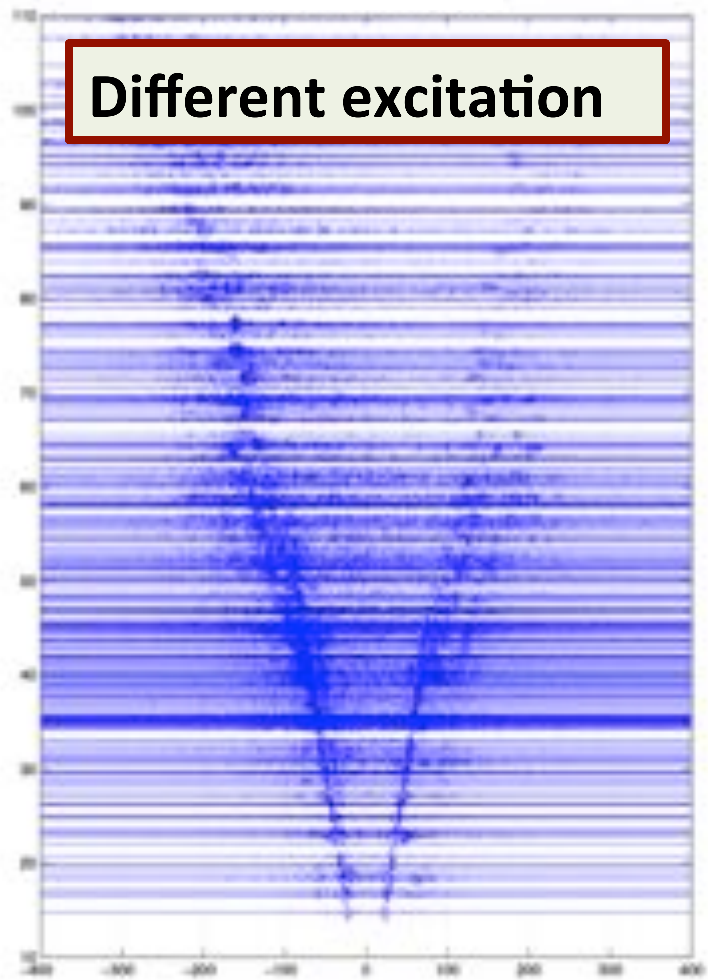
Amplitude Biases – Data from Japan

ZZ



By Azimuth

TT

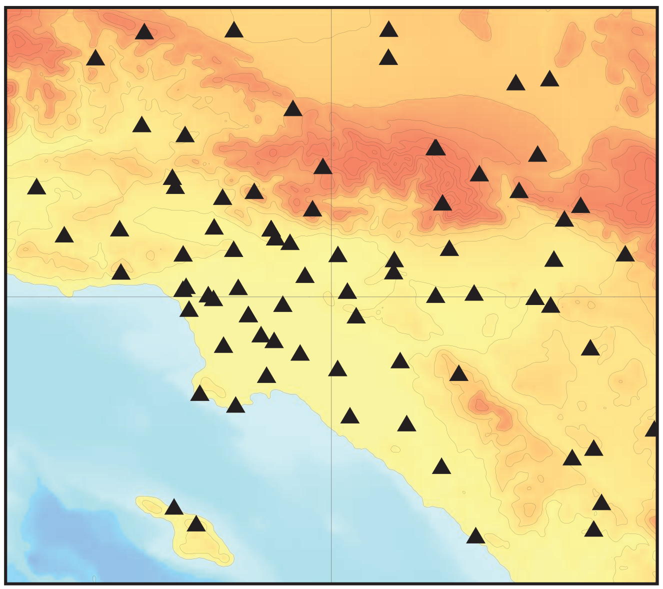


By Component

Denolle et al. (2014b)

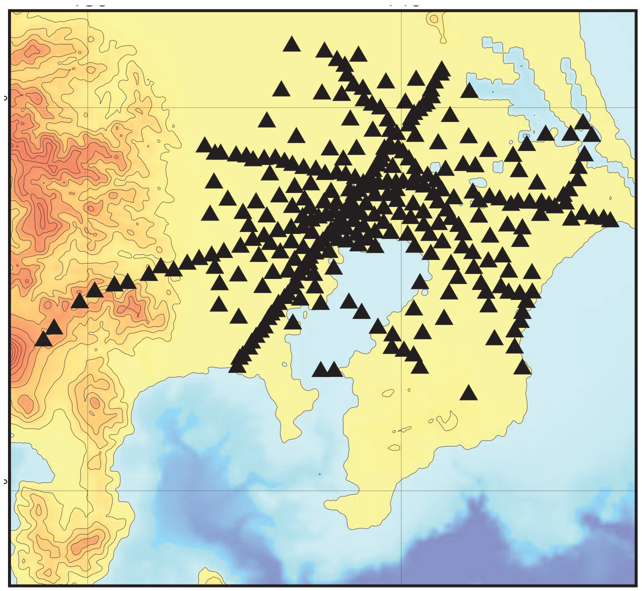
Results from Three Seismic Networks

SCSN



Sparse
~10 km spacing
10s of sensors

MeSO-net

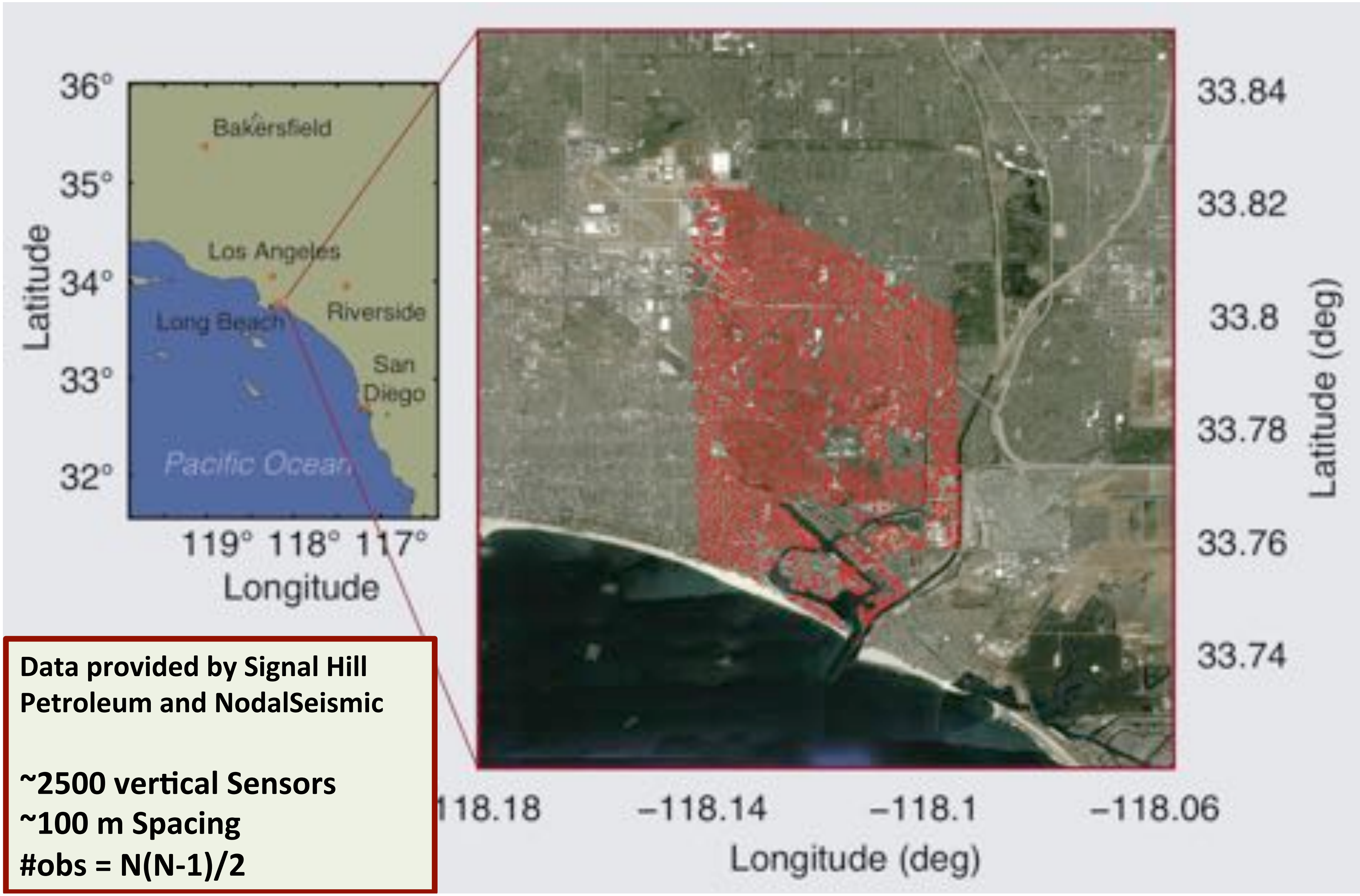


Dense
~1 km spacing
100s of sensors

Long Beach

Very Dense
~0.1 km spacing
1000s of sensors

Value of Dense Recording

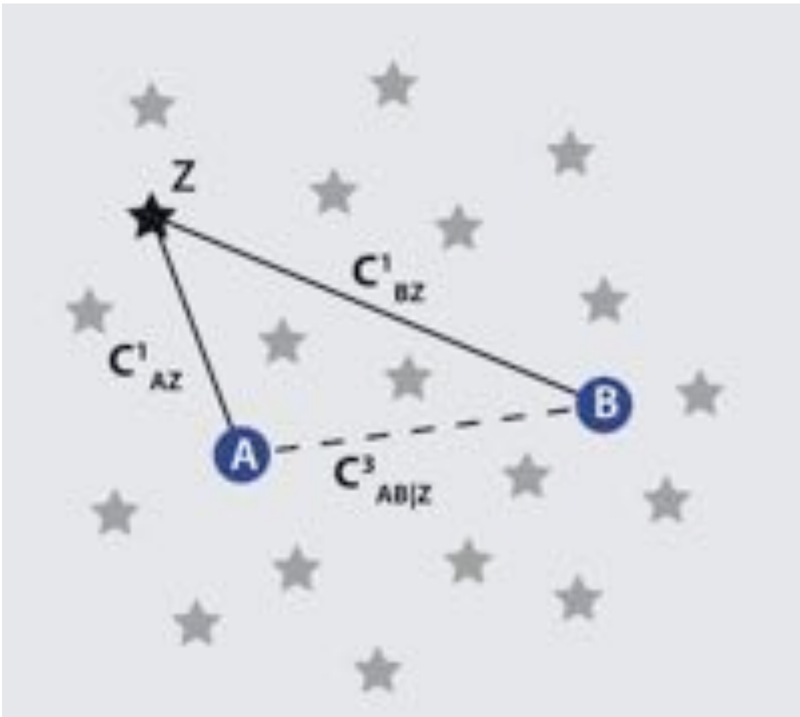


Data provided by Signal Hill Petroleum and NodalSeismic

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

Correlation of Correlations

(*Stehly et al.*, 2008)

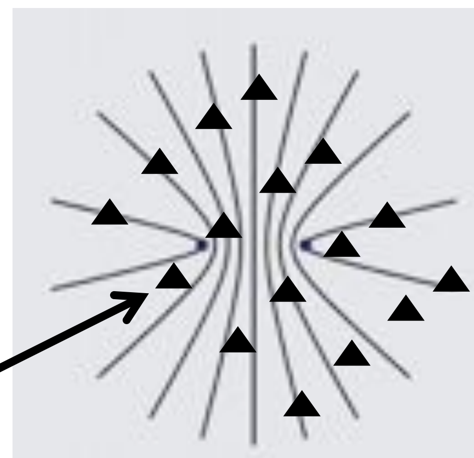


Correlation of Green's functions derived from correlations

Better approximates assumptions

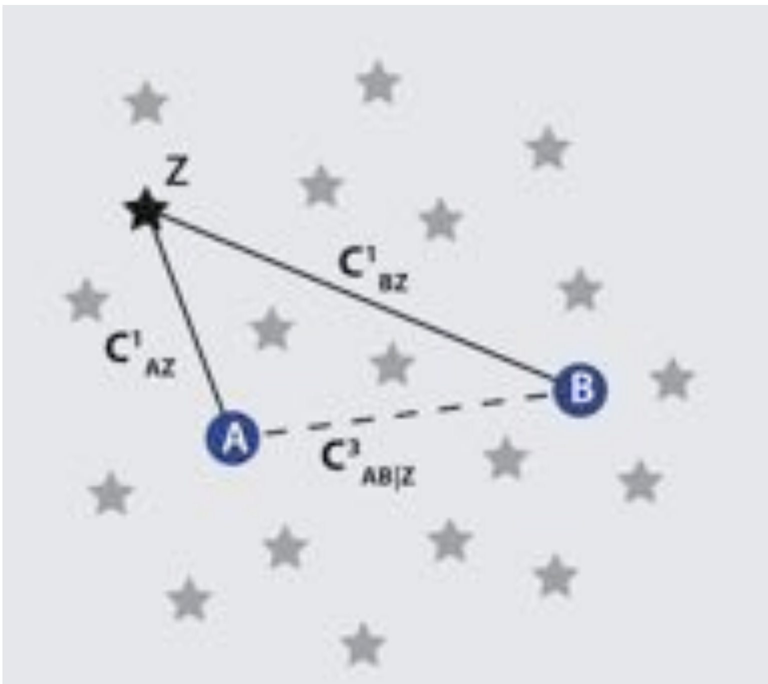
Can compare theoretical vs. observed kernels to understand (and remove?) amplitude bias

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



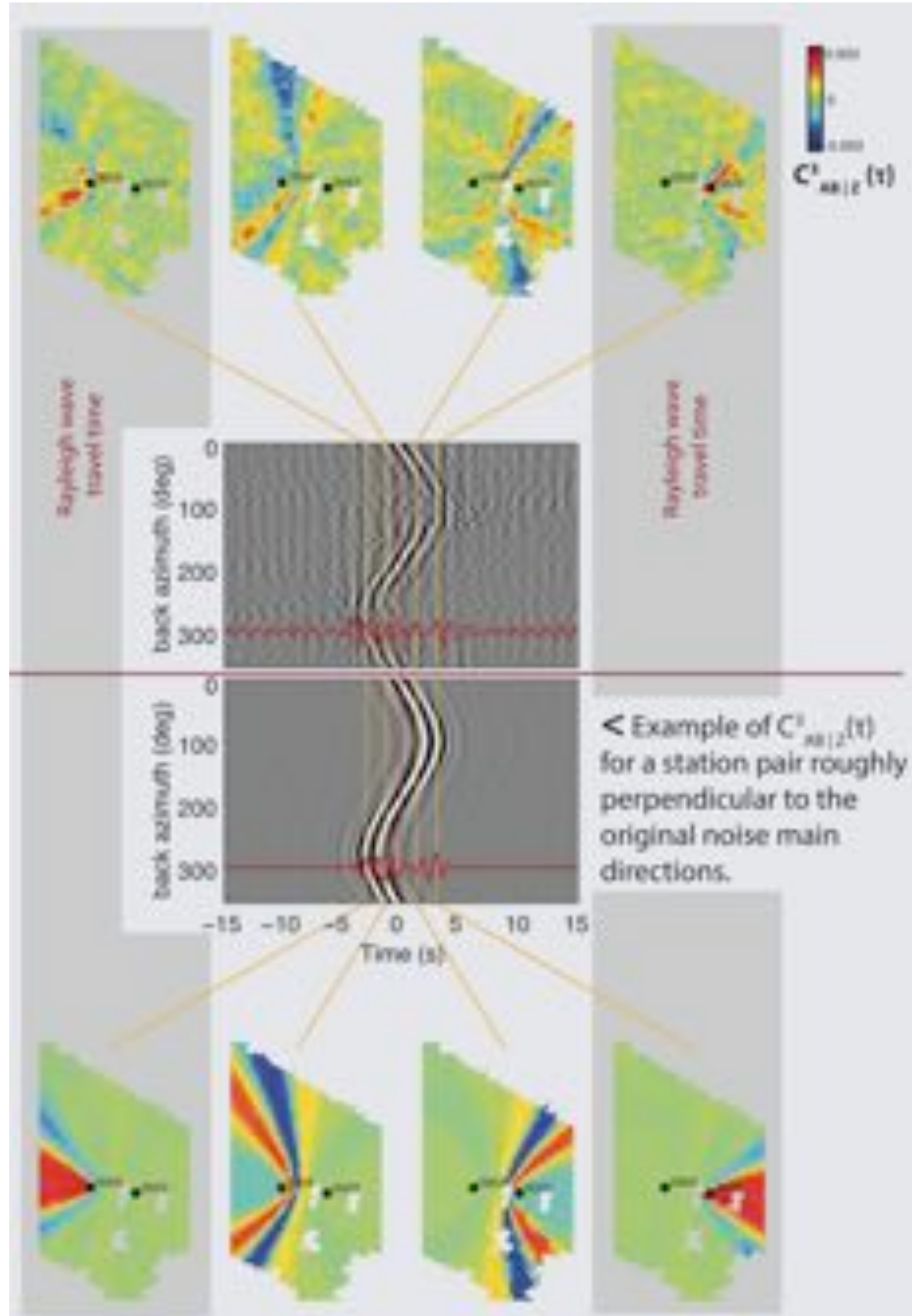
For a given receiver pair, the regions that contribute to a given time in the correlation function are hyperbolas. The vertical line correponds to the zero-lag time contribution (Roux et al., 2005)

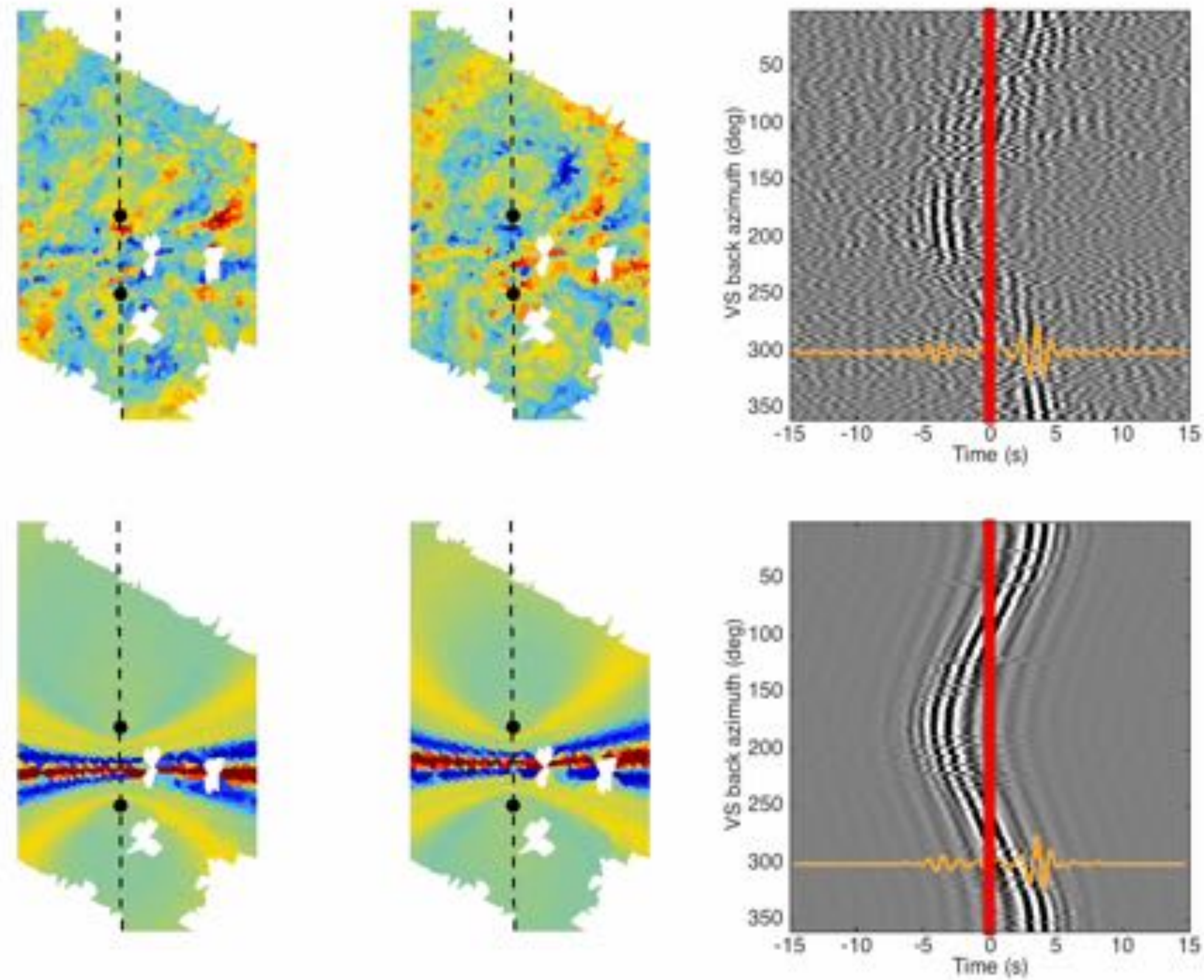
Correlation of Correlations



Can correct for bias from lack of equi-partitioning

With 3 component data could correct for excitation bias as well



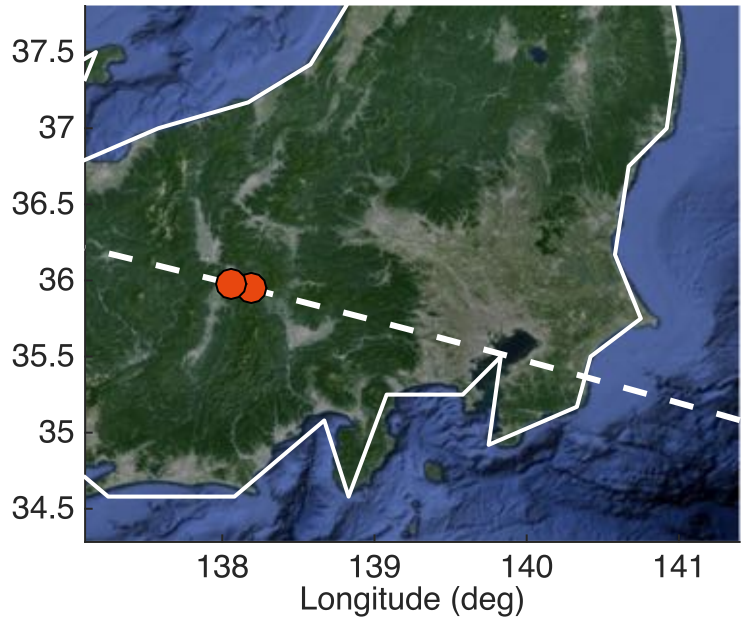


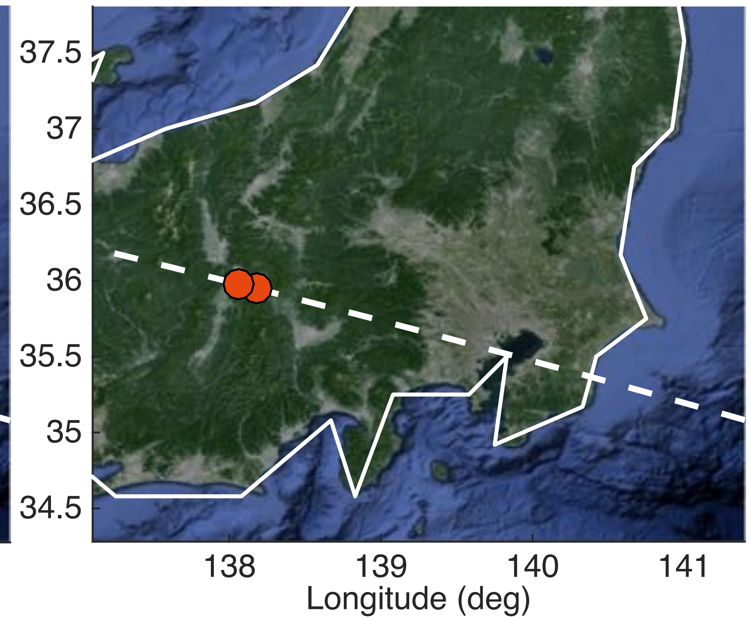
VS back azimuth (deg)
50
100
150
200
250
300
350
-15
-10
-5
0
5
10
15
Time (s)
VS back azimuth (deg)
50
100
150
200
250
300
350
-15
-10
-5
0
5
10
15
Time (s)

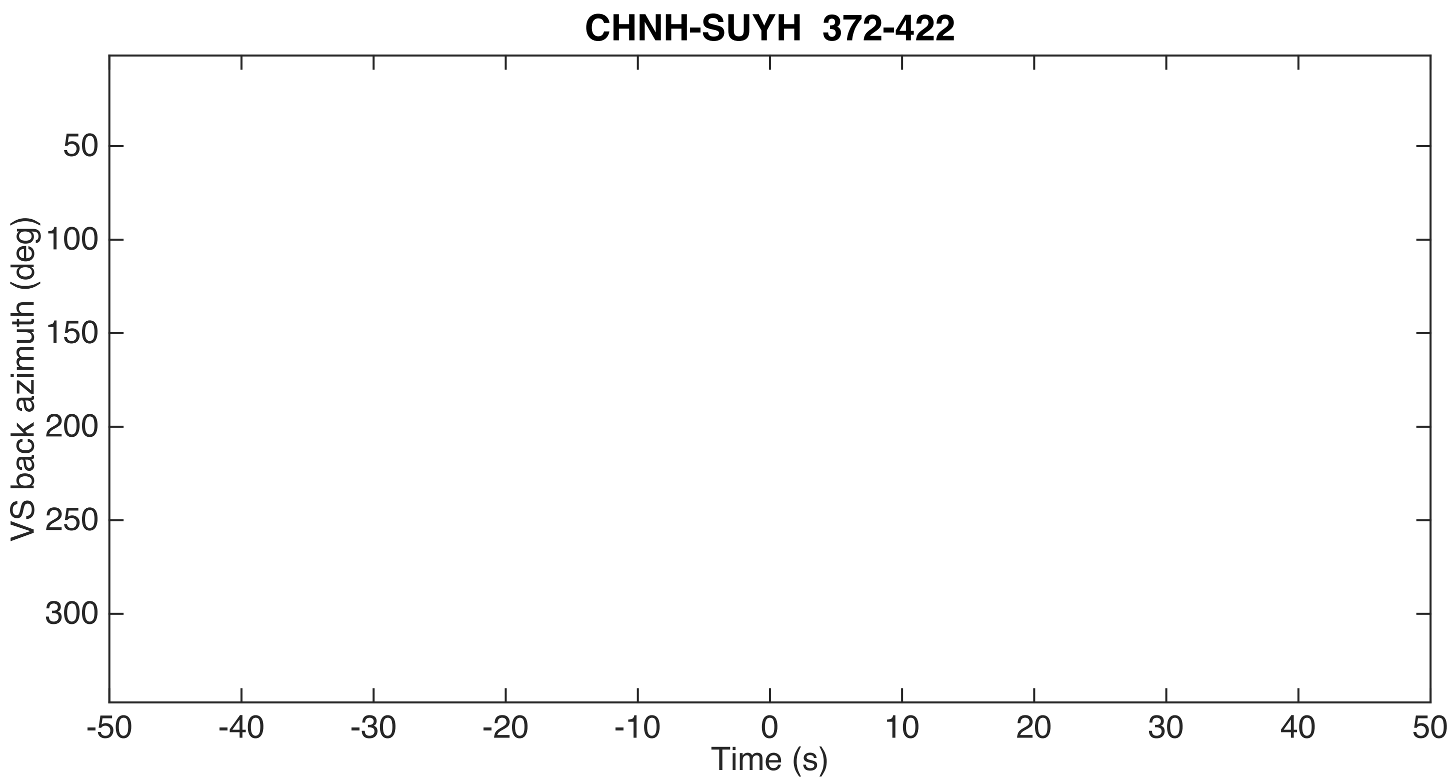
C3

Geometry

HiNet + MesoNet



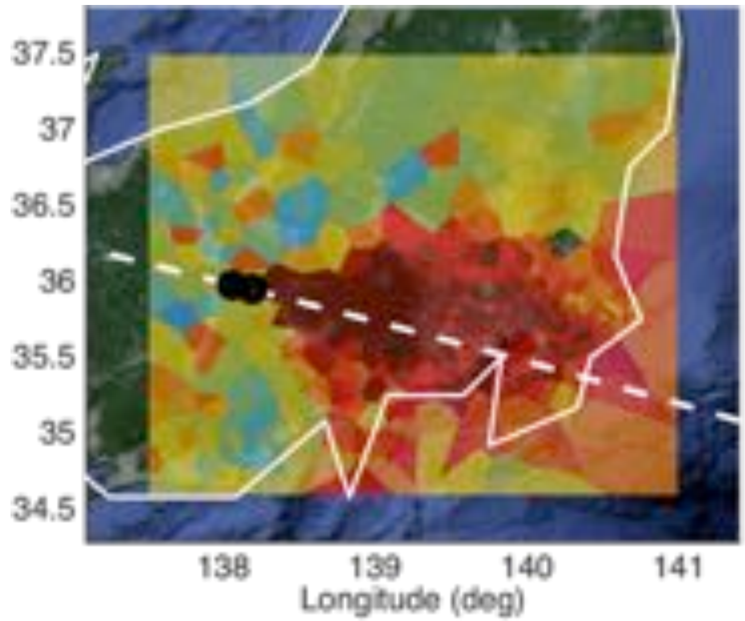


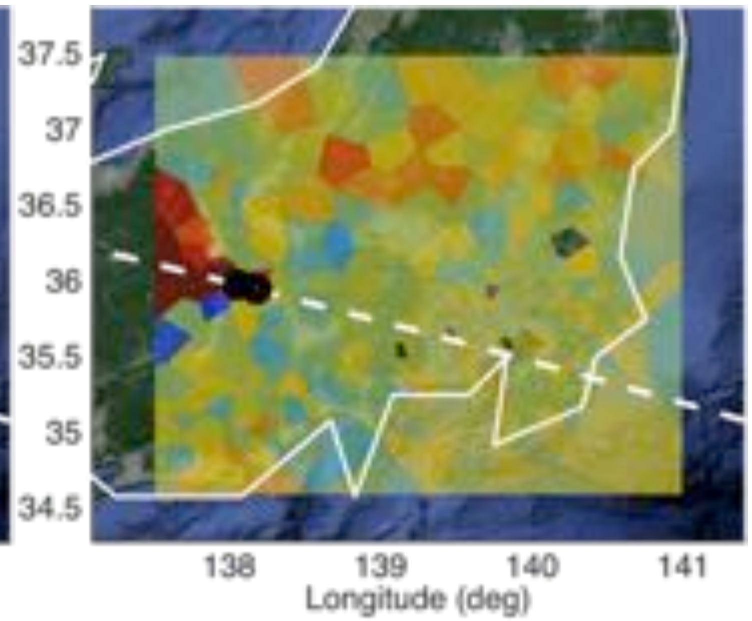


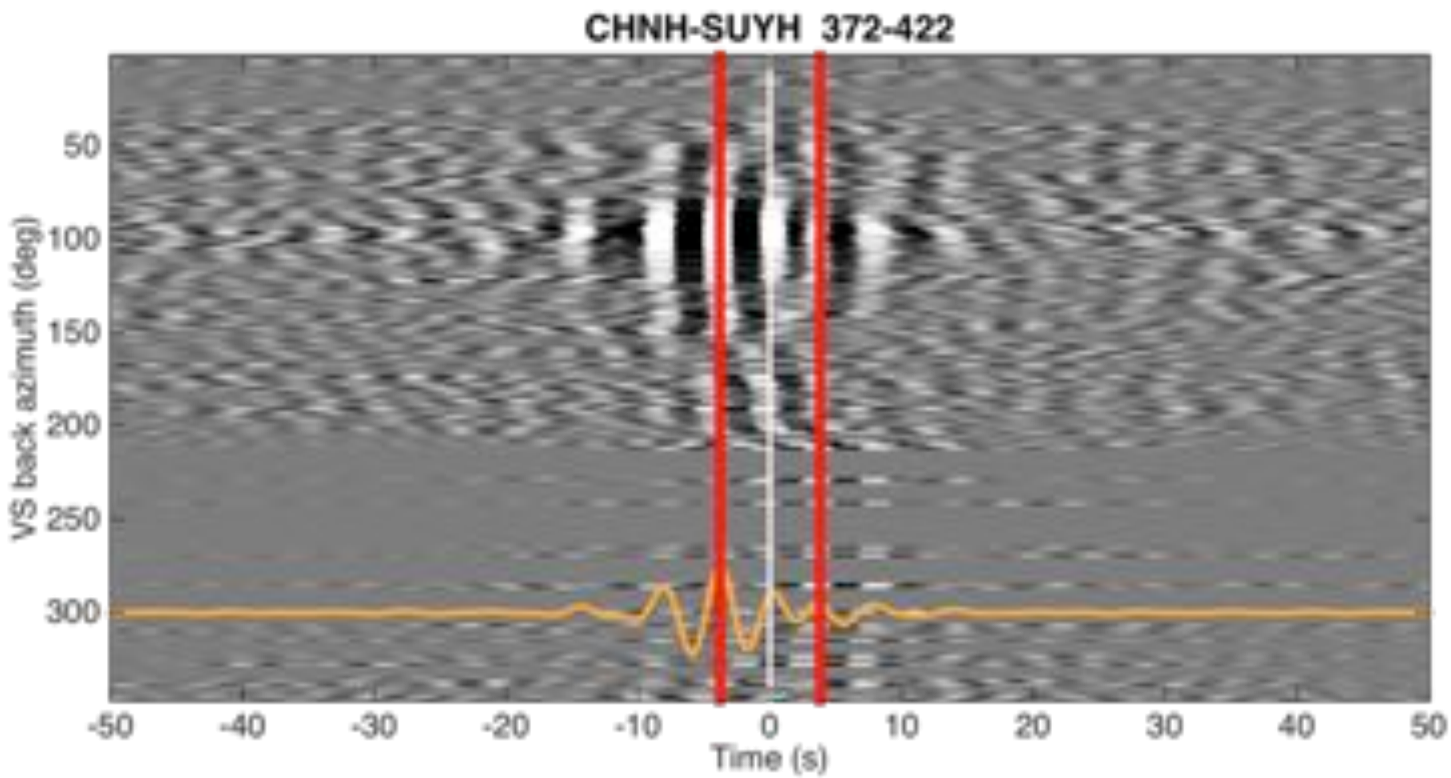
C3

Coherence

HiNet +
MesoNet



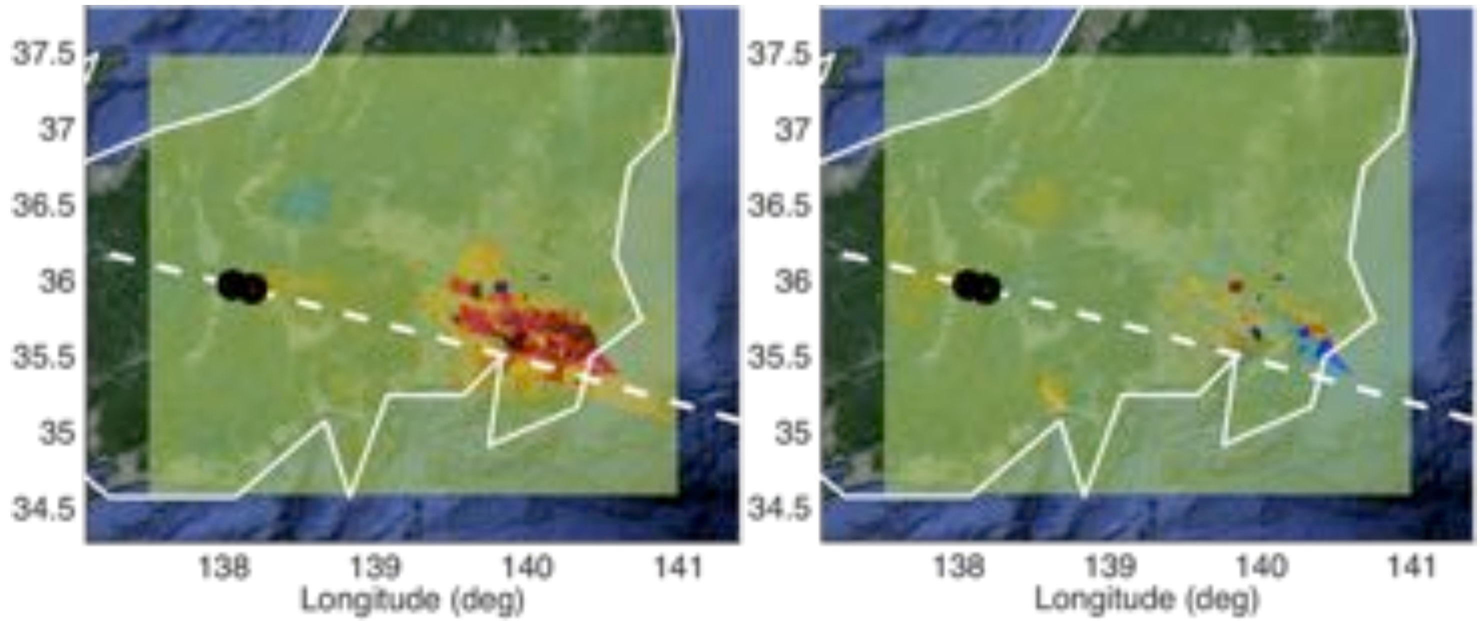


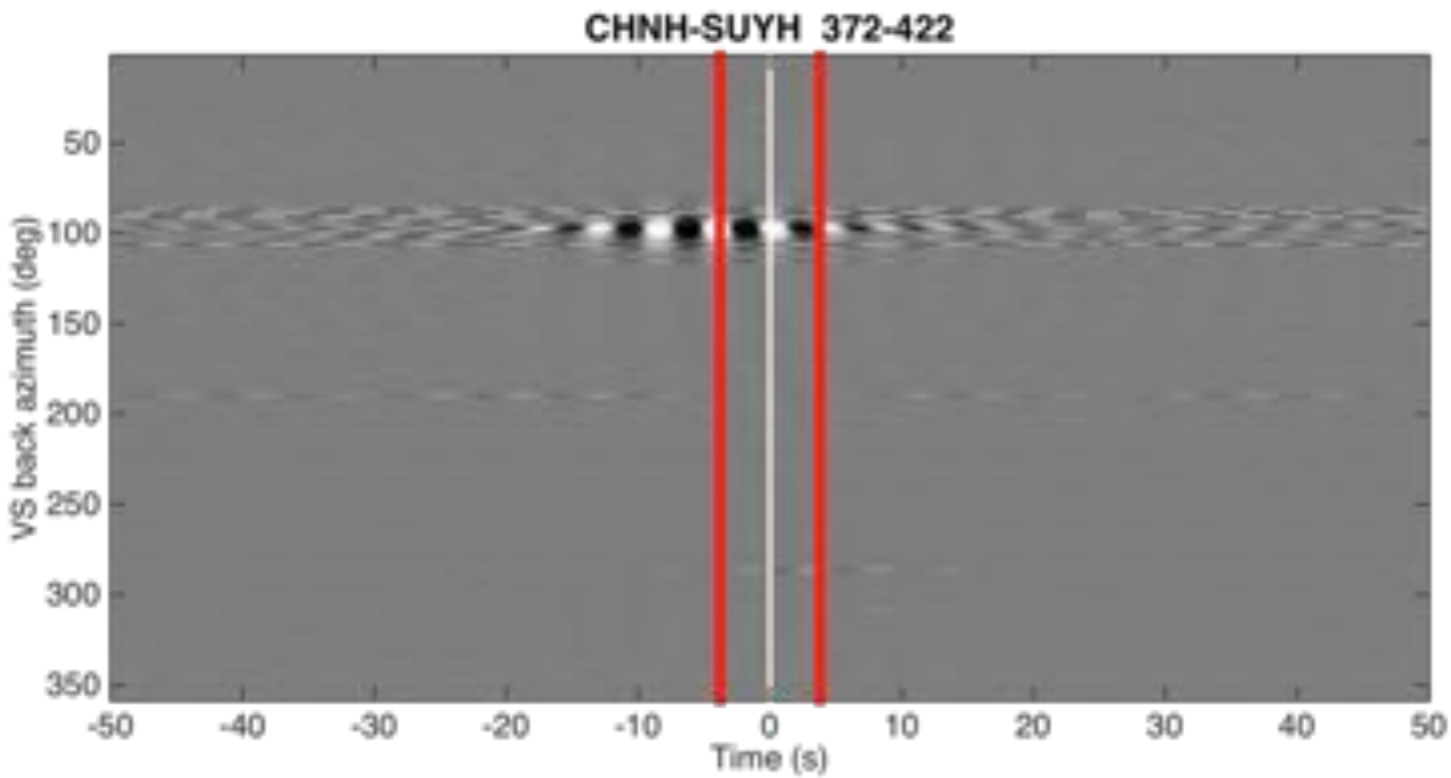


C3

<u>Correlation</u>

HiNet + MesoNet

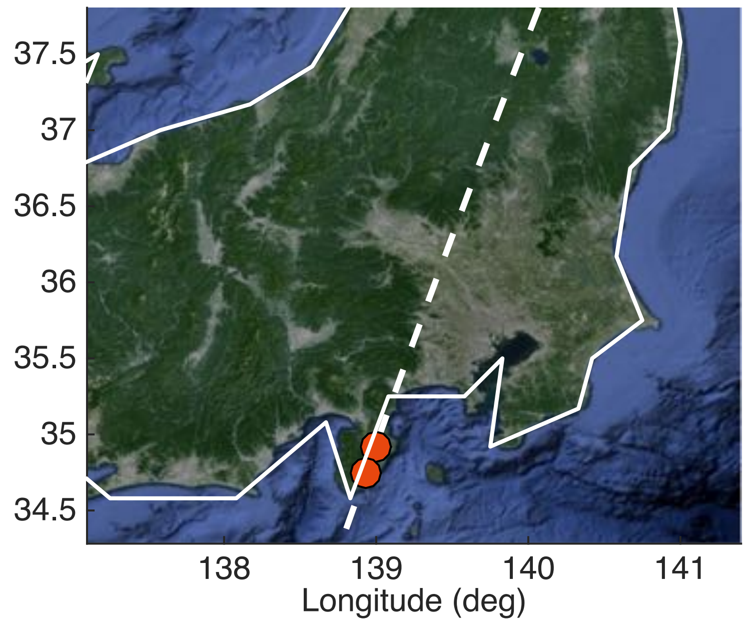


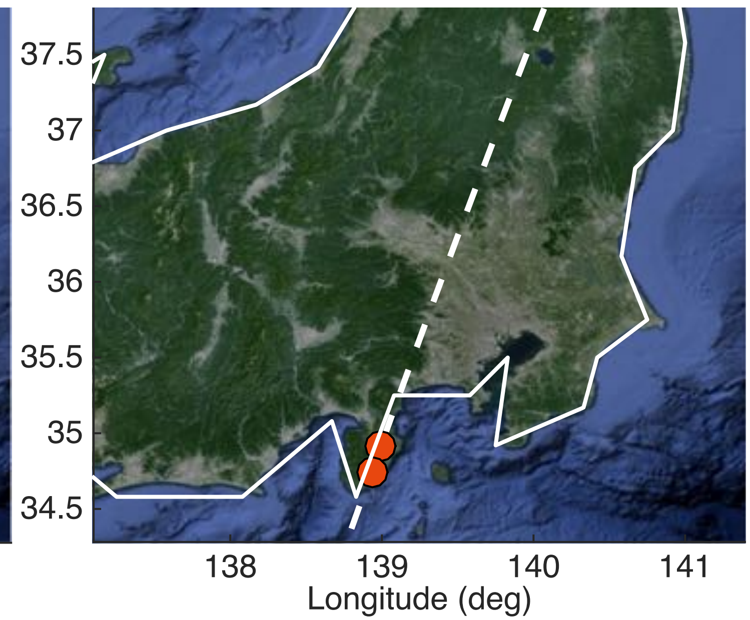


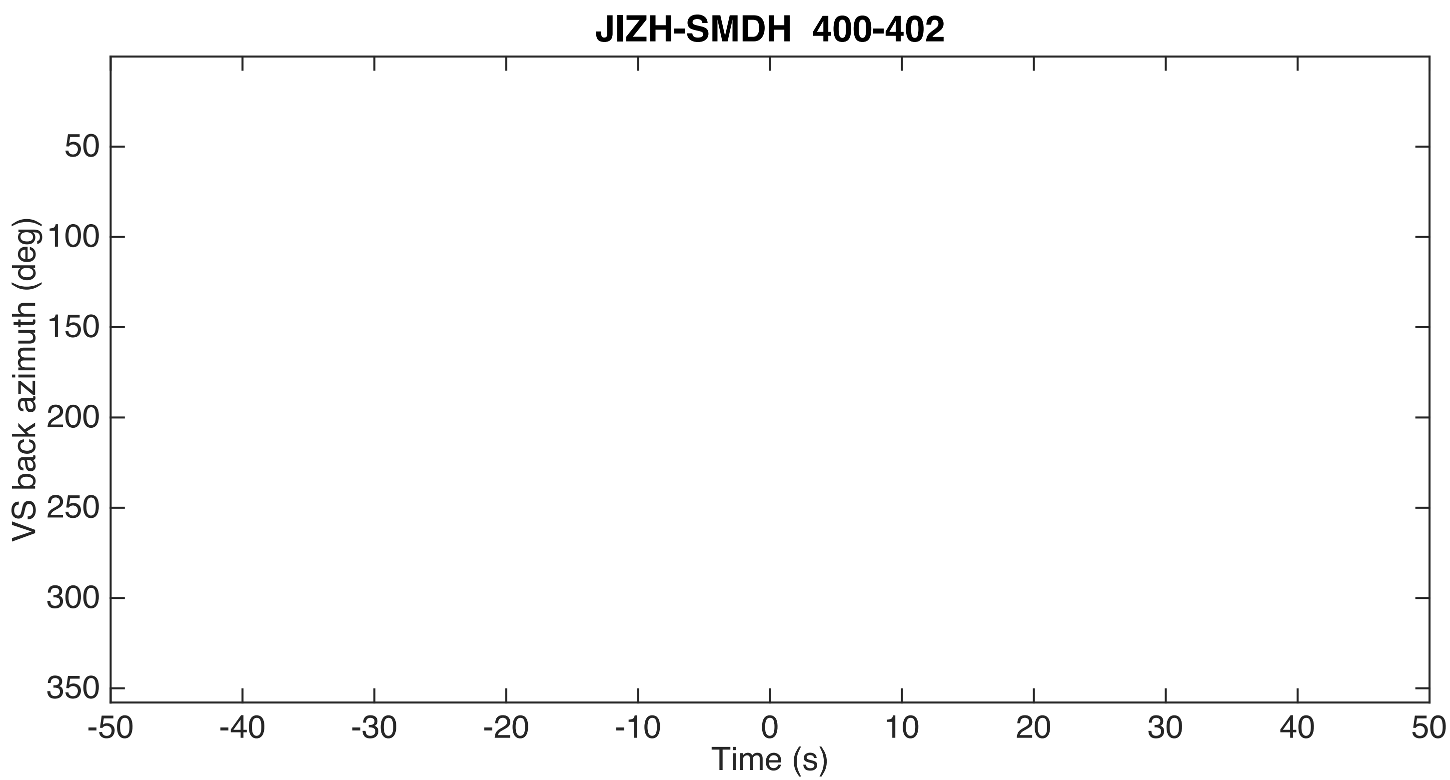
C3

Geometry

HiNet +
MesoNet



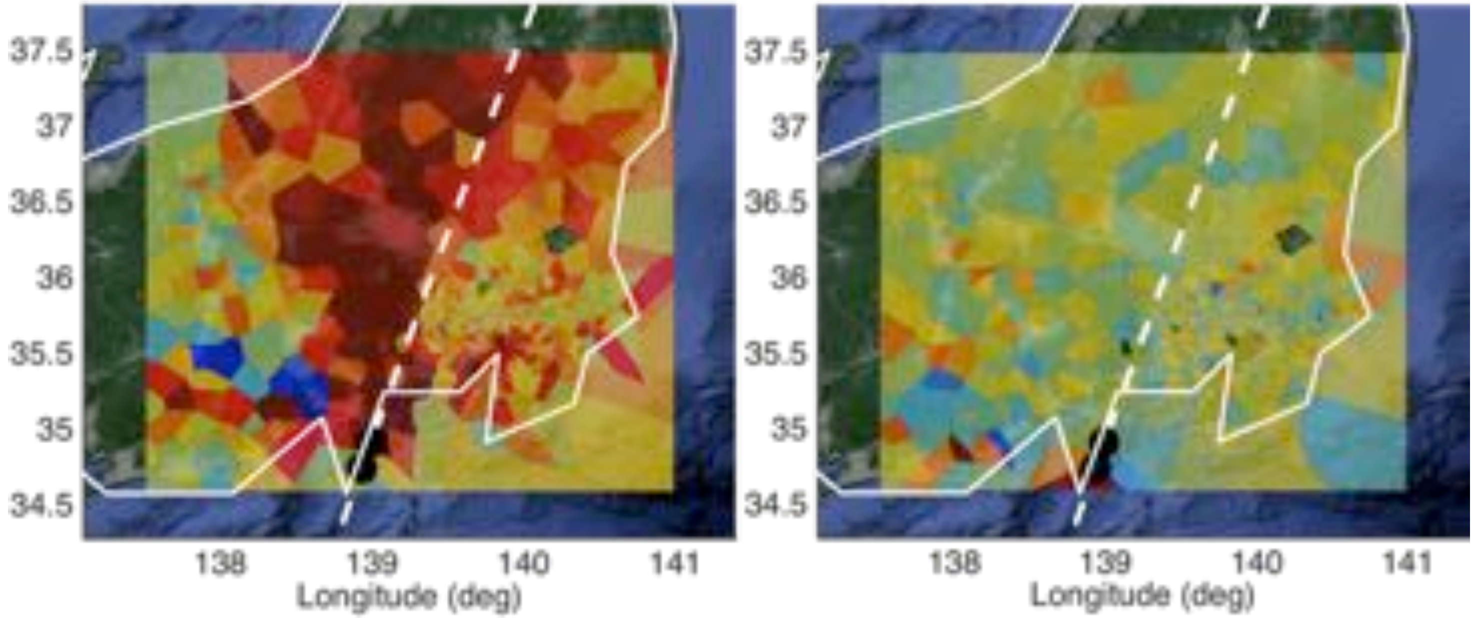


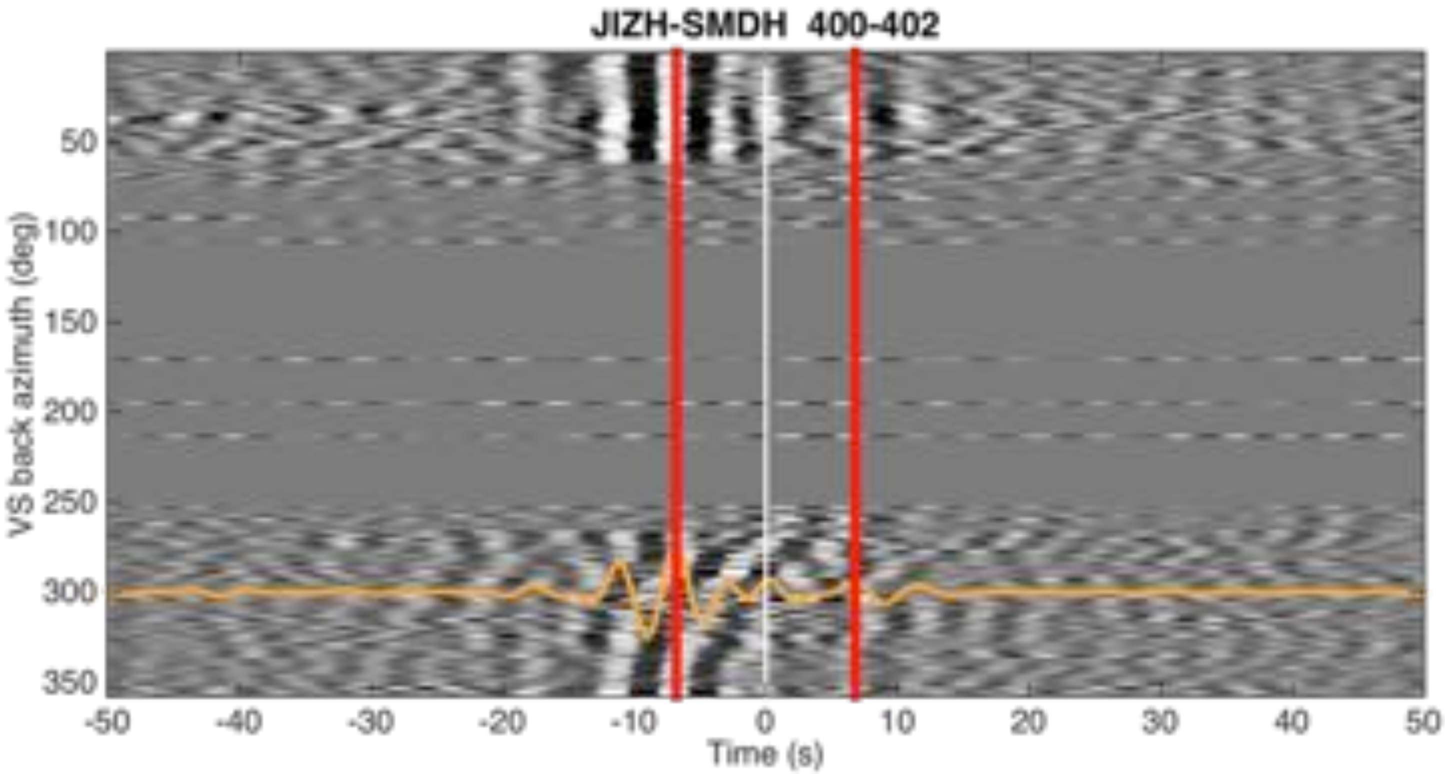


C3

<u>Coherence</u>

HiNet + MesoNet

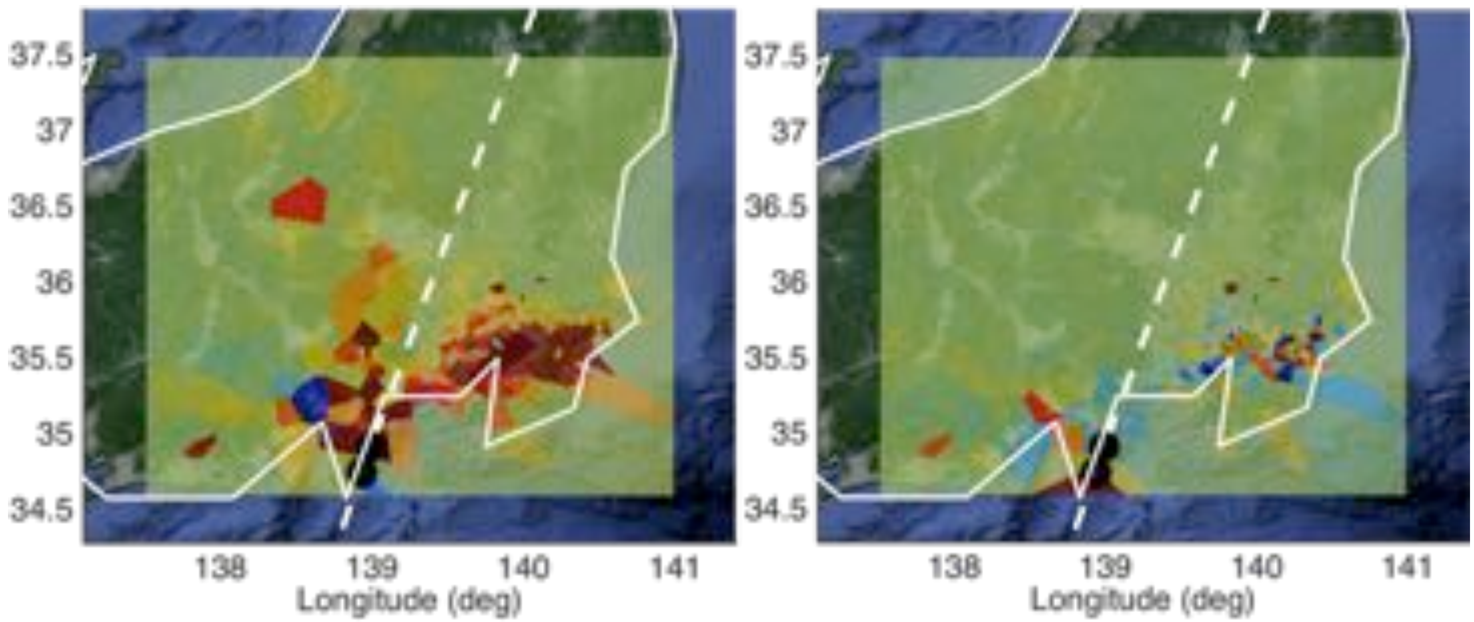


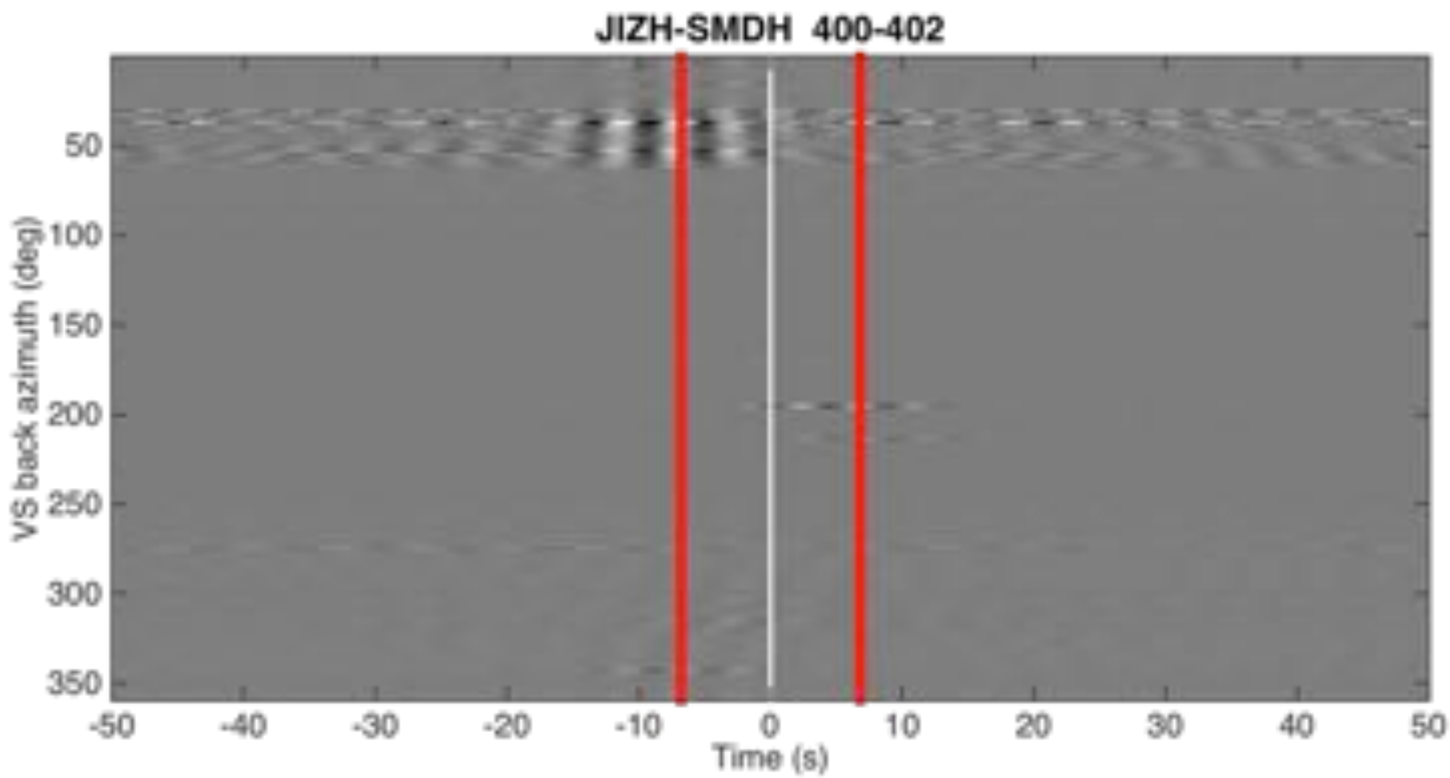


C3

<u>Correlation</u>

HiNet +
MesoNet

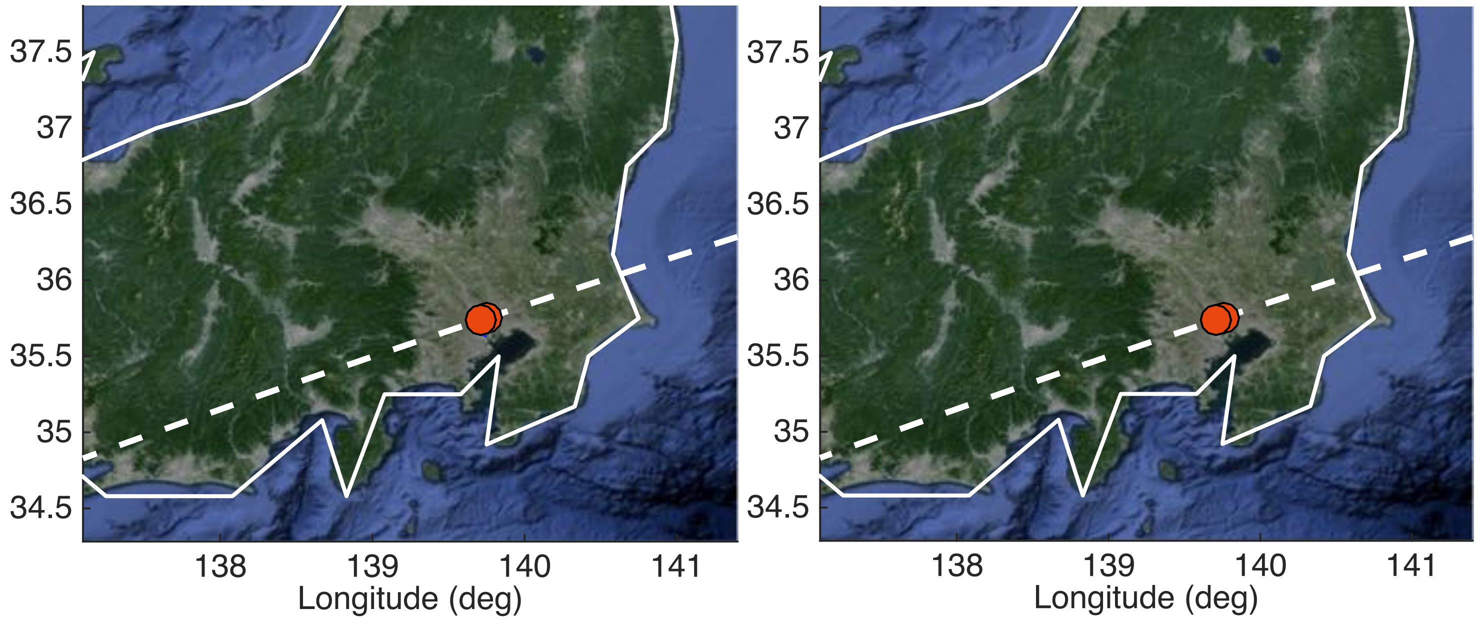


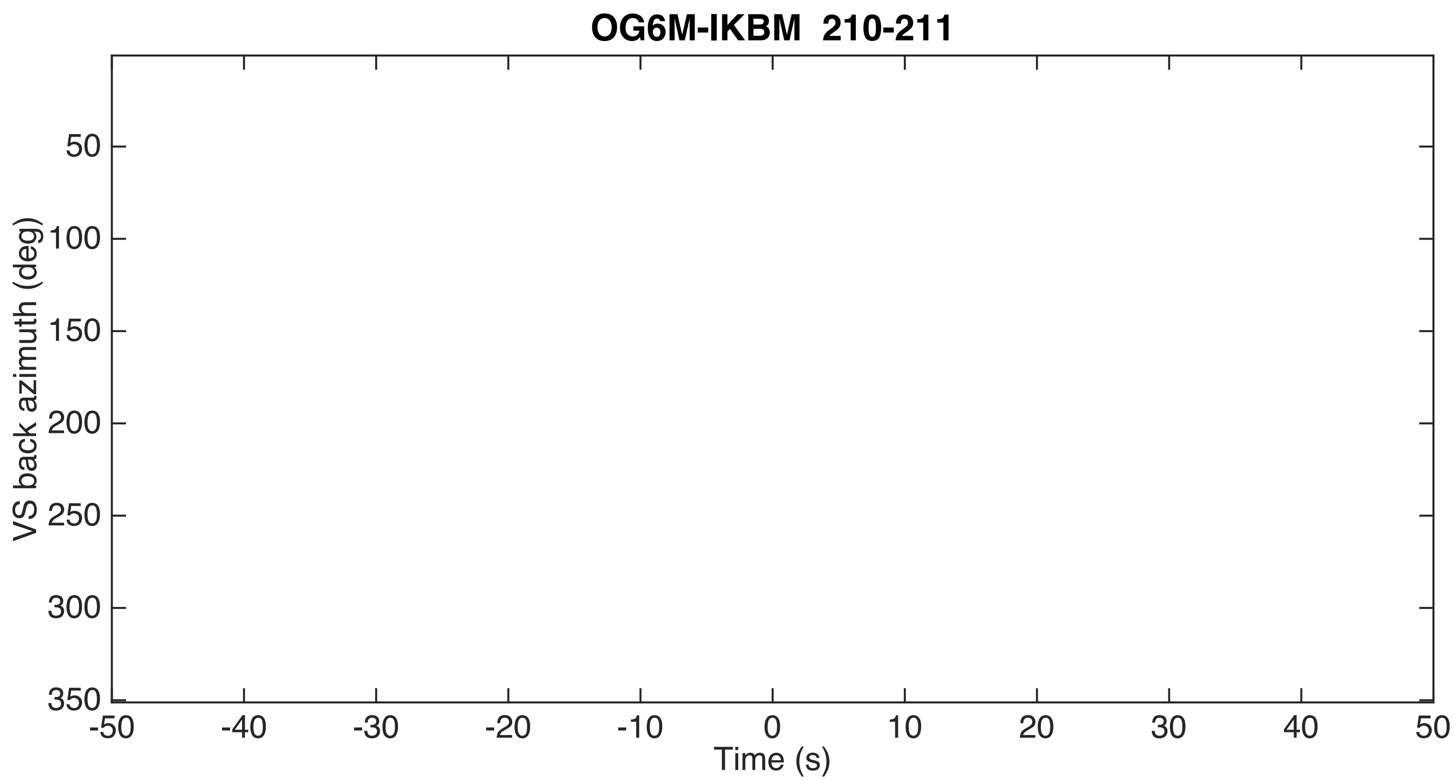


C3

Geometry

HiNet +
MesoNet

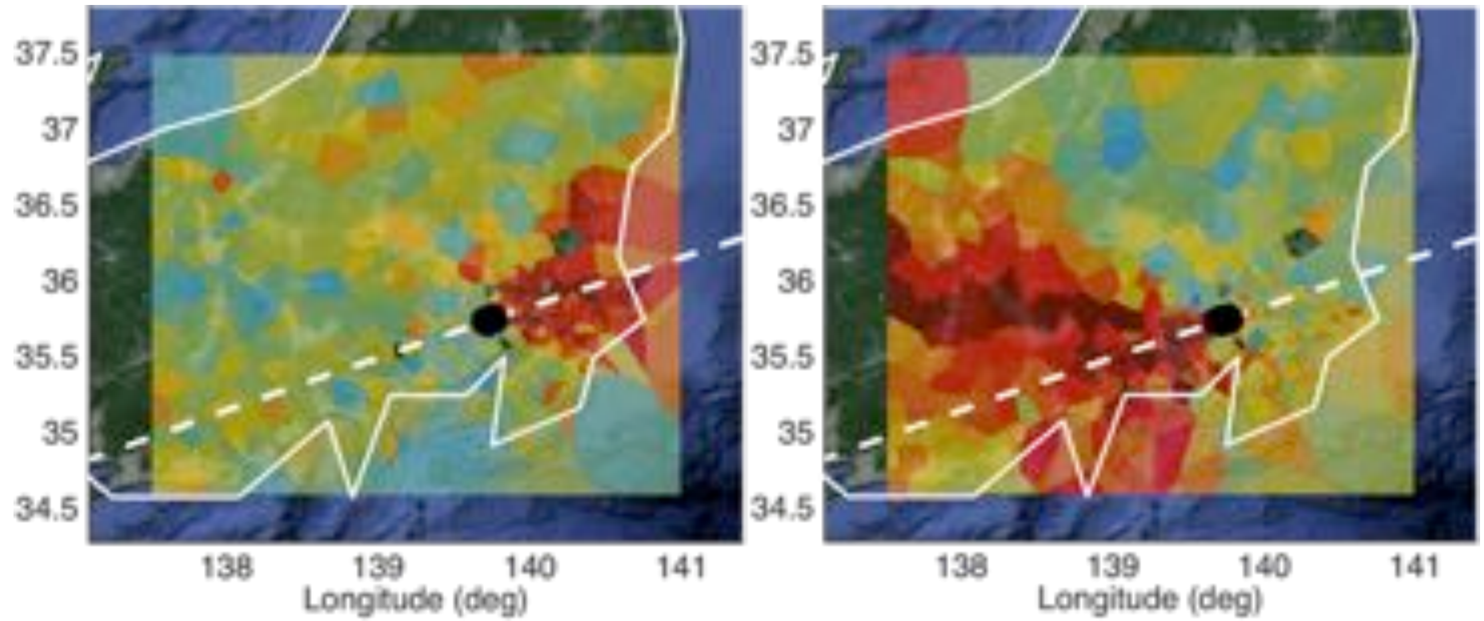


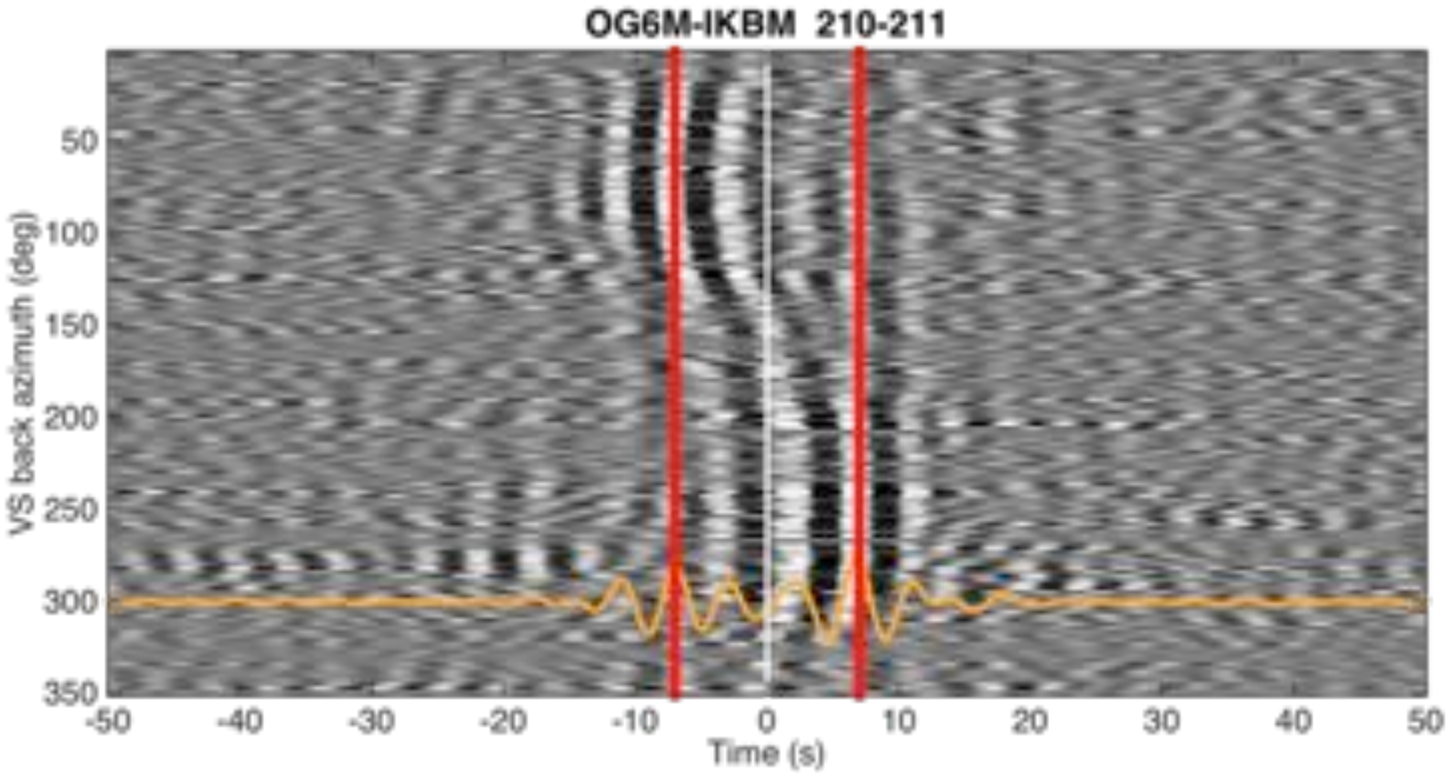


C3

<u>Coherence</u>

HiNet + MesoNet

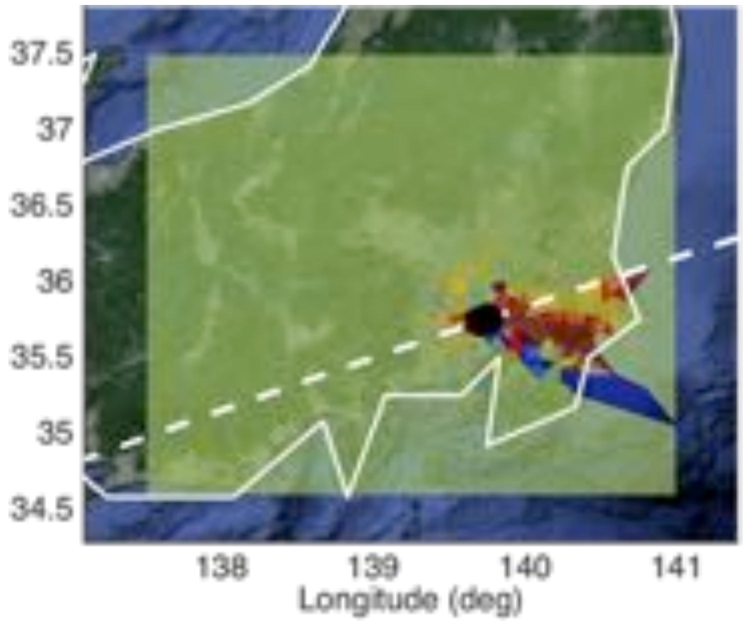


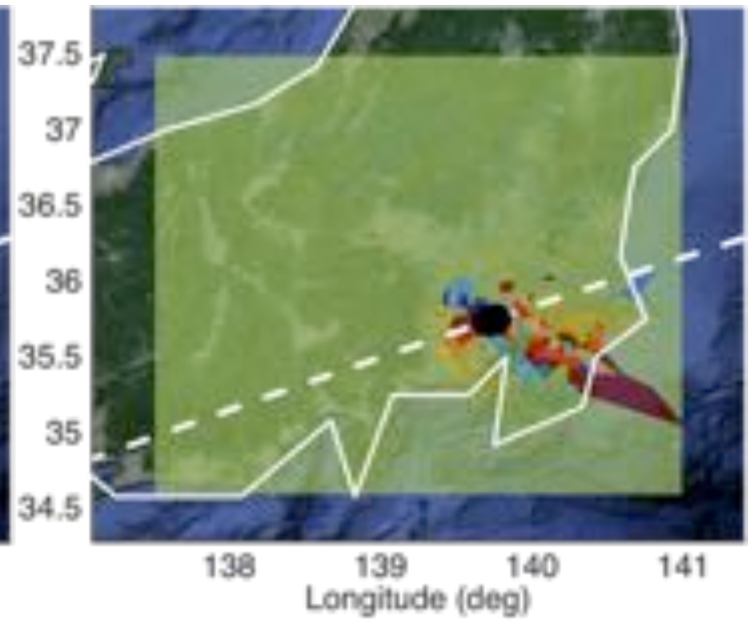


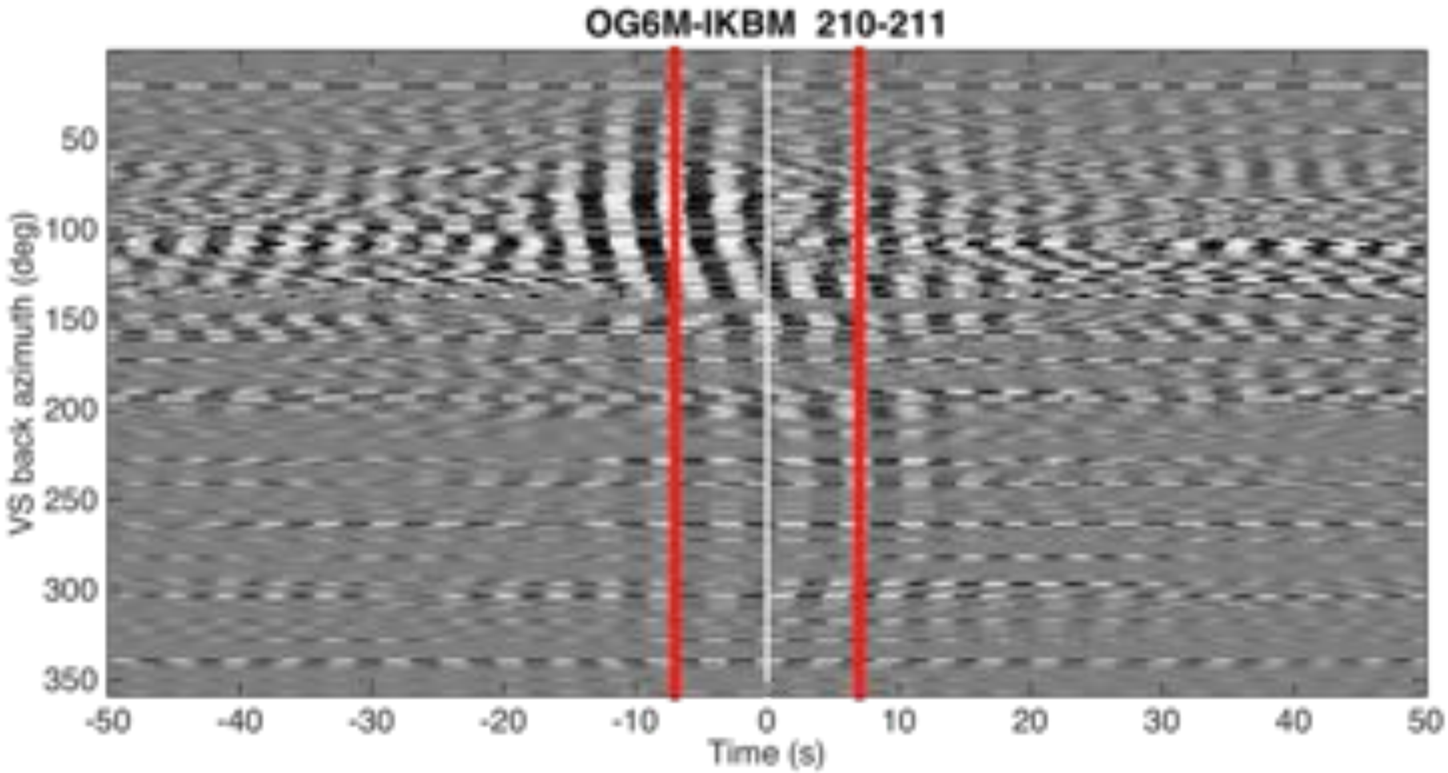
C3

<u>Correlation</u>

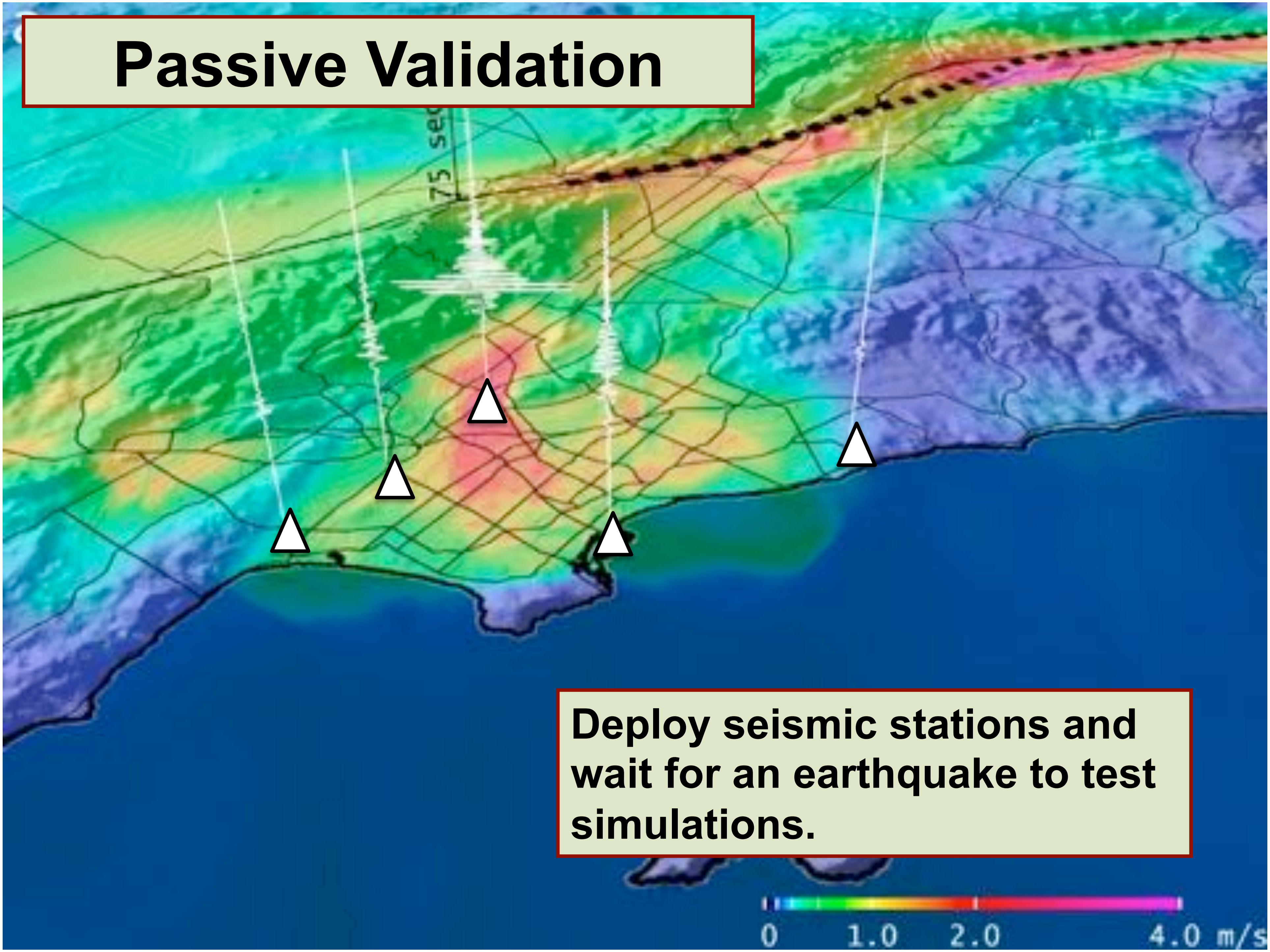
HiNet +
MesoNet





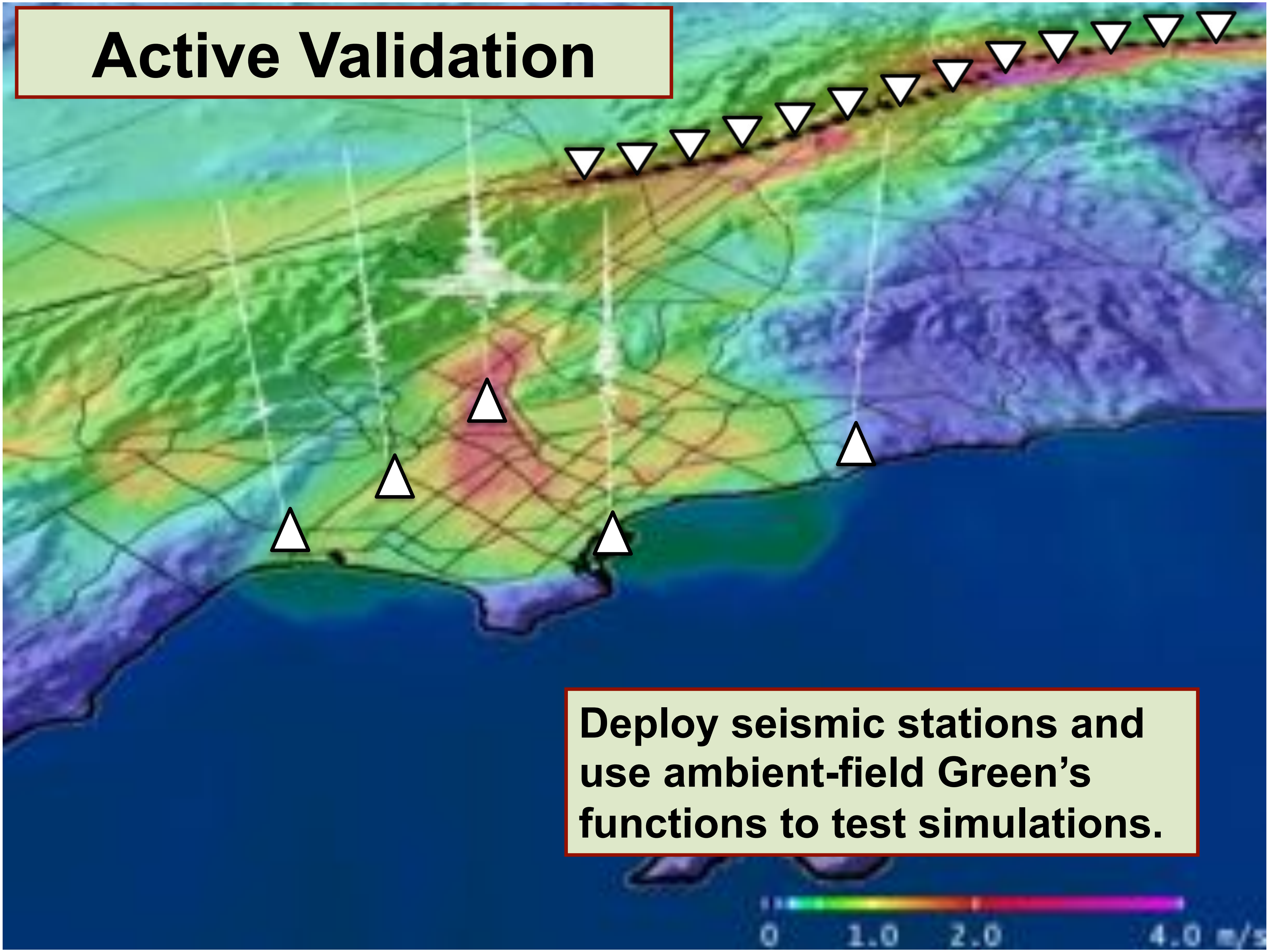


Passive Validation



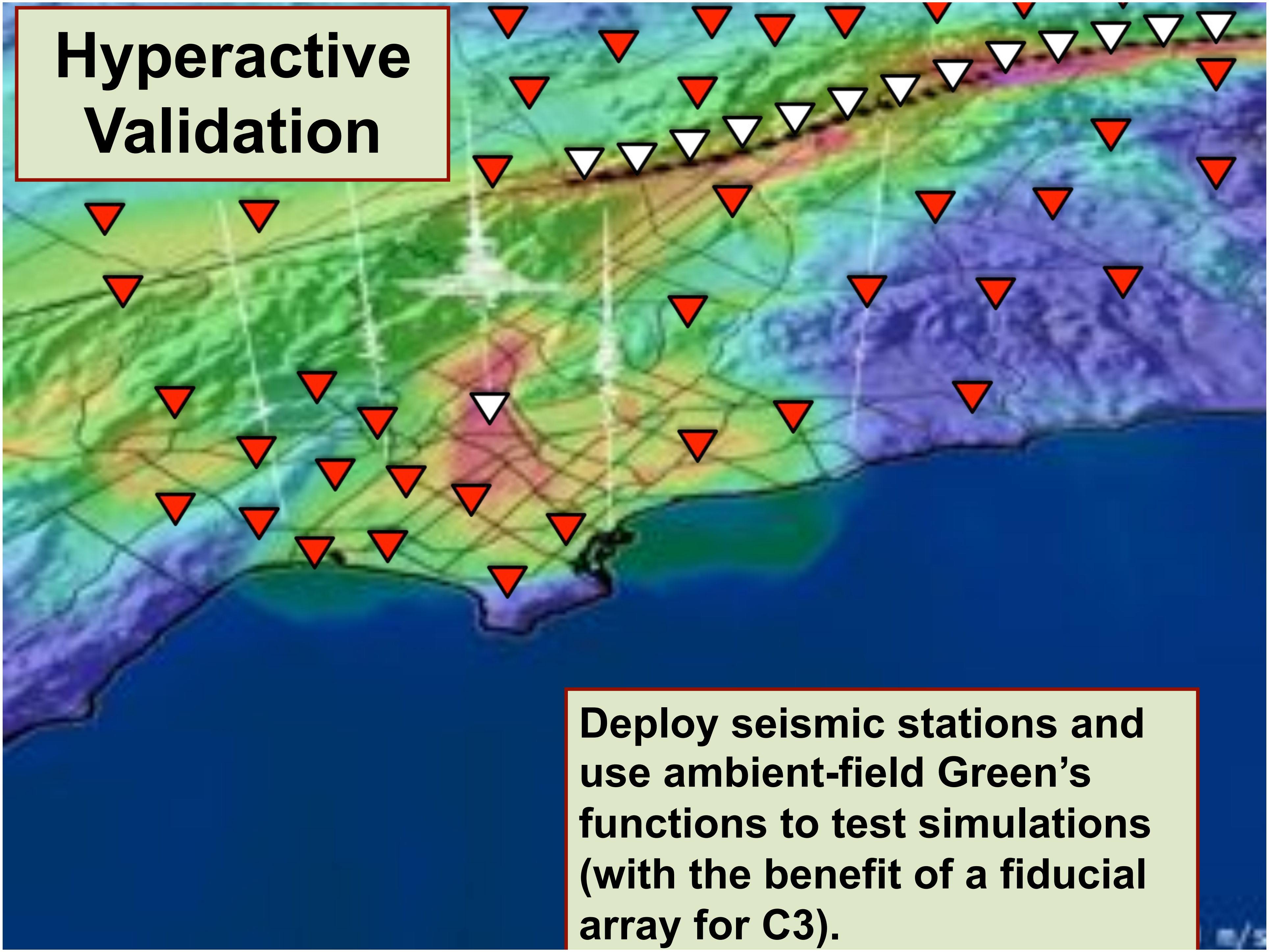
Deploy seismic stations and wait for an earthquake to test simulations.

Active Validation



Deploy seismic stations and use ambient-field Green's functions to test simulations.

Hyperactive Validation



Deploy seismic stations and use ambient-field Green's functions to test simulations (with the benefit of a fiducial array for C3).

Approaches to Ground Motion Prediction

Data-Driven — **Hybrid** — **Model-Guided**

GMPEs

(Fit ground motions to equations)

- Empirical
- Lack of data
- Doesn't incorporate all that we know

Virtual EQs

(Use ambient field for effect of 3D structure)

- Bandwidth
- Body waves?
- Amplitudes
- Biases

Simulations

(Model waves in 3D structure)

- Need lots of info
  - elastic
  - anelastic
  - plastic?
- HPC

Ambient Seismic Field for GMP

Caveats:

1. Only part of the problem (source, nonlinearity)
2. Biases (azimuthal, inter-component, frequency)
3. Bandwidth limitations
4. Primarily surface waves

Potential:

1. New approach to an important problem
2. Active, not passive
   – no need to wait for real earthquakes
   – can sample sources/sites of strategic interest
3. Can revisit past earthquakes
4. Can anticipate future earthquakes
5. Resolves 3D effects – Earth does the experiment
6. Dense observations can resolve basin-edge effects