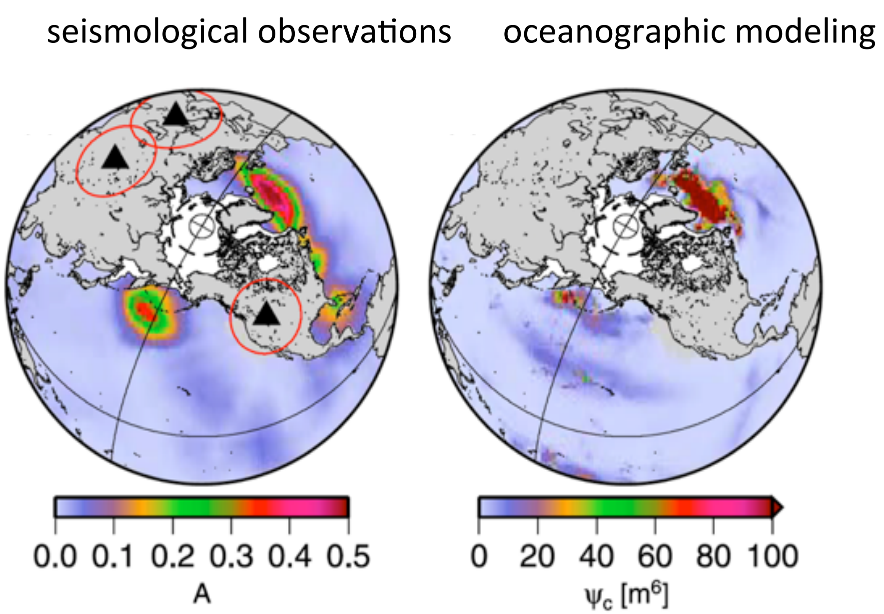
ICTP 2016 Michel Campillo

Passive imaging

Global 'noise' sources in the microseism band
(extended ≈2-50s)

Strong contribution from oceanic waves

Example of a global comparison
(secondary microseism-
Miche/Longuet-Higgins mechanism)

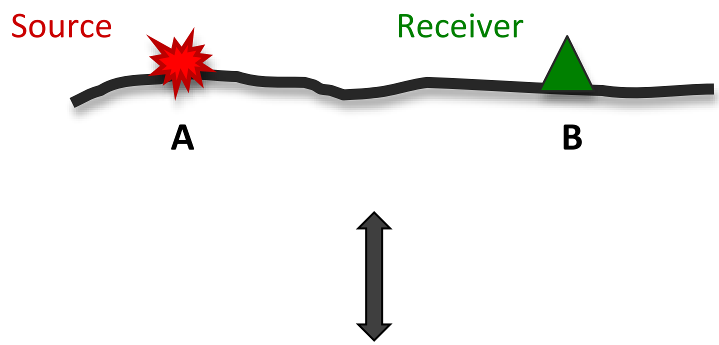


Hillers et al., 2012

Longer periods: infragravity waves, e.g Fukao et al. 2010

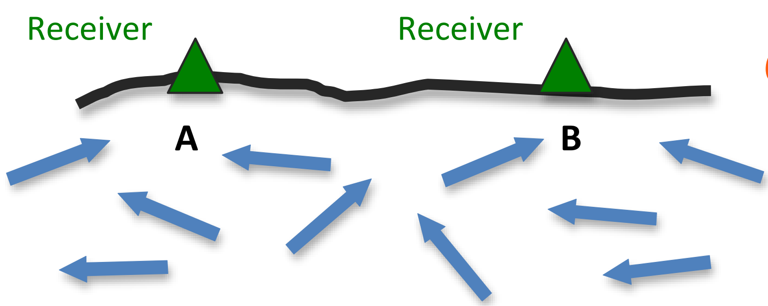
+EARTHQUAKES

Long range correlations



Source in A ⇒ the signal recorded in B characterizes the propagation between A and B.

➡ **Green function** between A and B: G_{AB}

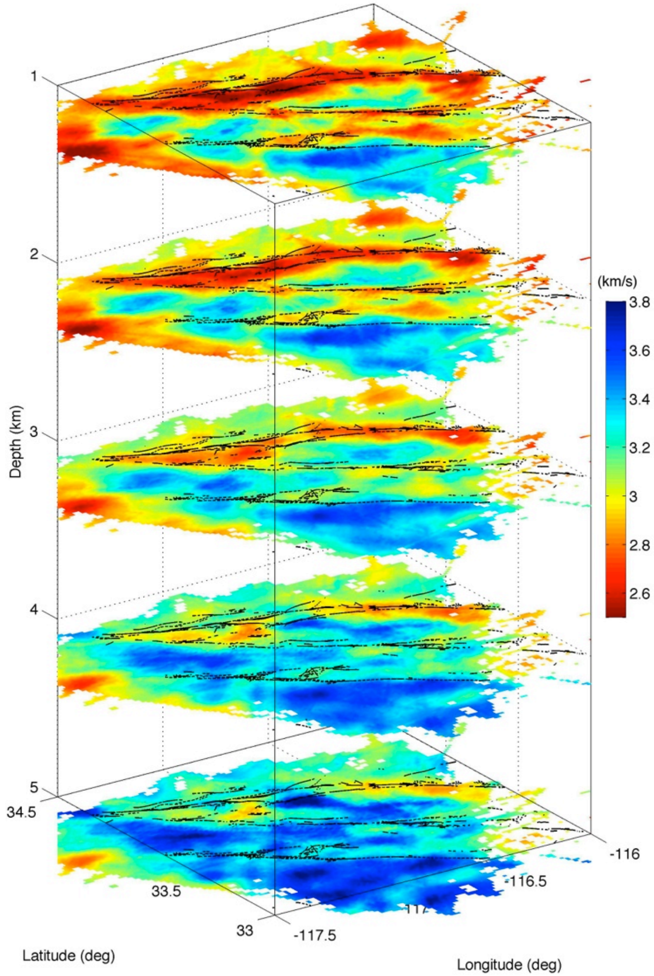


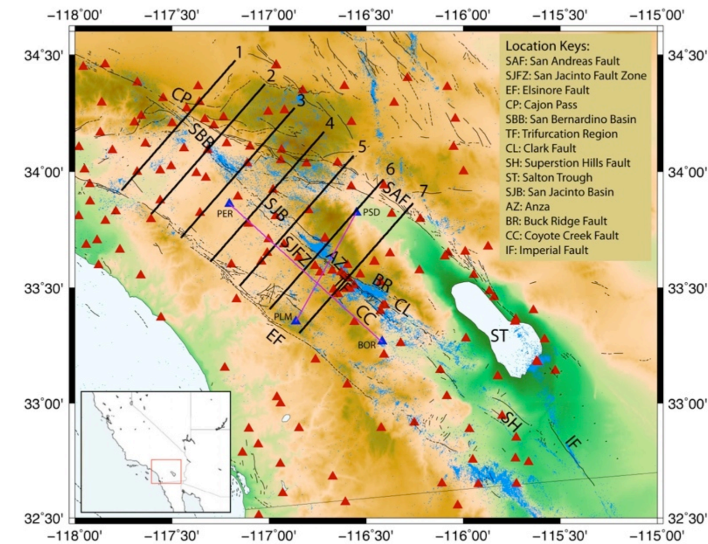
G_{AB} can be reconstructed by the correlation of noise or « diffuse » (equipartitioned) fields recorded at A and B (C_{AB})

A way to provide new data with control on source location and origin time

Experimentally verified with seismological data:
Coda waves: Campillo and Paul, 2003;…..
Ambient noise: Shapiro and Campillo, 2004,……

3D shear velocity : surface wave tomography





- -Damaged fault zone
- -Flower-like patterns
- -Diffuse seismicity associated with low-velocity (damaged) area between SAF and SJFZ

Noise correlations represent huge sets of virtual data, leading to better resolution.

From Zigone, Ben-Zion, Campillo and Roux, 2014

Representation theorem (evaluating the flux: $I = \oint_S \left[G_{1x} \vec{\nabla}\left(G_{2x}^{*}\right) - \vec{\nabla}\left(G_{2x}\right) G_{1x}^{*} \right] \overrightarrow{dS}$)

Arbitrary medium: an integral representation written in the frequency domain

G_{12} : elastic response between point 1 and 2 = Green function

$$G_{12} - G_{12}^{*} = \frac{4i\omega\kappa}{c} \int_{v} G_{1x} G_{2x}^{*} \, dV + \oint_S \left[G_{1x} \vec{\nabla}\left(G_{2x}^{*}\right) - \vec{\nabla}\left(G_{1x}\right) G_{2x}^{*} \right] \overrightarrow{dS}$$

Volume term

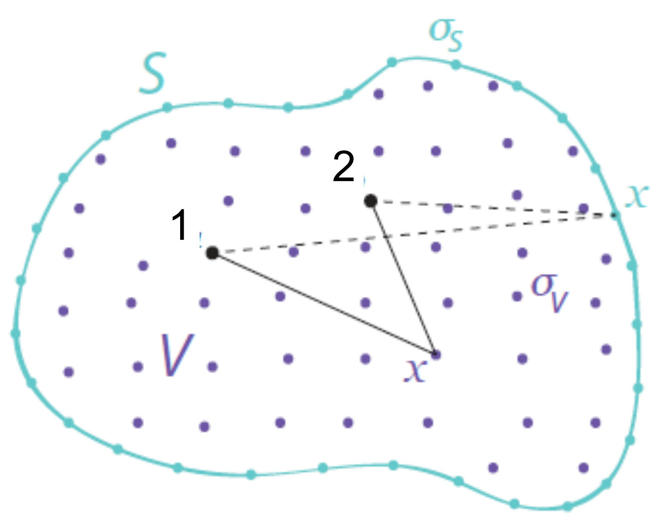
Surface term

FT of $G(-t)$

FT of $G(t)$

Absorption coefficient

Source average over « correlation terms »



Ward identity (e.g. Weaver et al., 2004, Snieder 2007,….)

Surface term: $$\oint_S \left[G_{1x} \vec{\nabla}\left(G_{2x}^*\right) - \vec{\nabla}\left(G_{1x}\right) G_{2x}^* \right] \overrightarrow{dS}$$

If the surface is taken in the far field of the medium heterogeneities

$$G_{1x} \sim \frac{1}{4\pi\left|\vec{x}-\vec{r}_1\right|} \exp\left(-ik\left|\vec{x}-\vec{r}_1\right|\right) \text{ and } \vec{\nabla}\left(G_{1x}\right) \sim i\vec{k}\, G_{1x}$$

and we obtain a widely used integral relation:

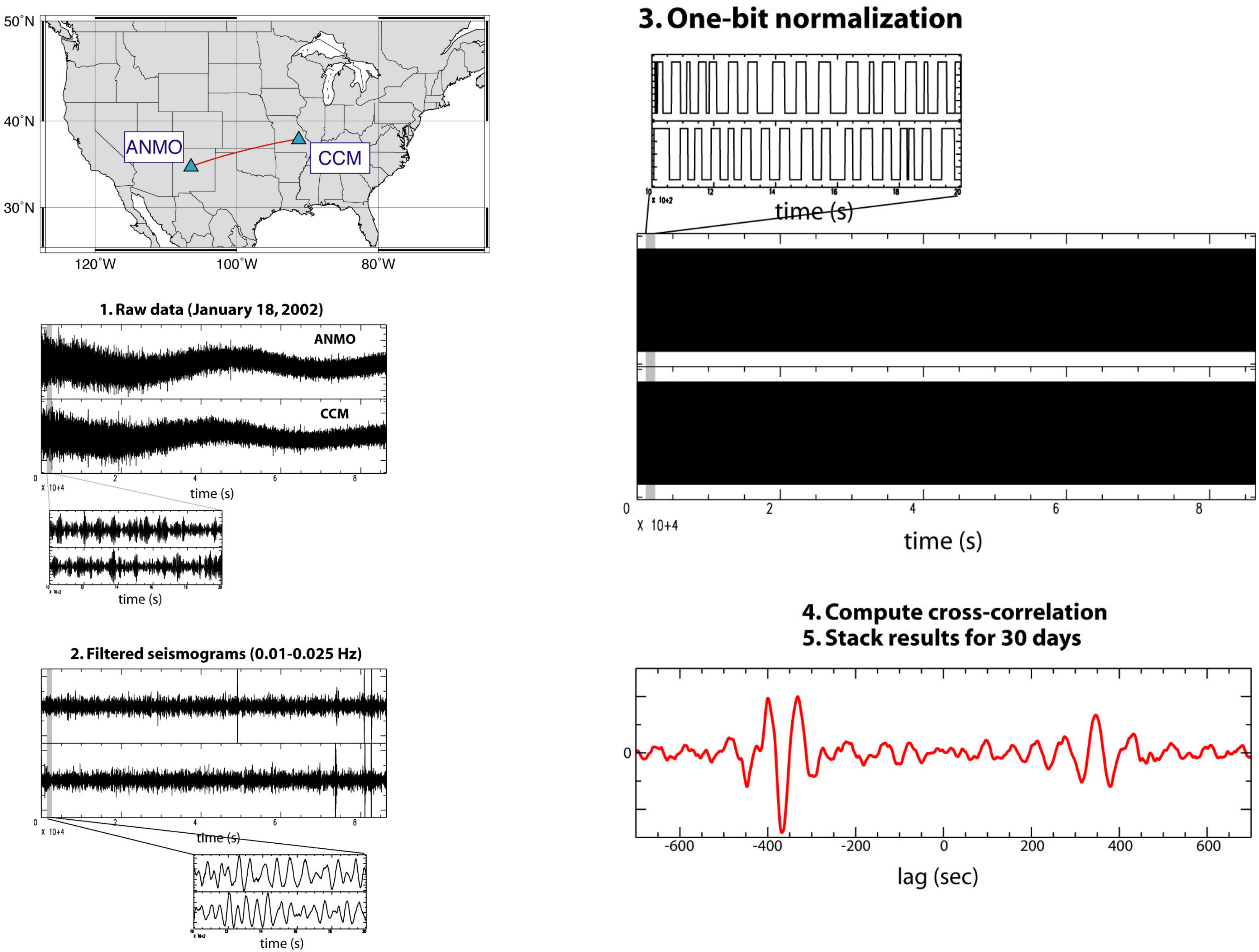
$$\oint_S \left[G_{1x} \vec{\nabla}\left(G_{2x}^*\right) - \vec{\nabla}\left(G_{1x}\right) G_{2x}^* \right] \overrightarrow{dS} \approx -2i\frac{\omega}{c} \oint_S G_{1x} G_{2x}^* \, dS$$

Source average over « correlation terms »

➔Derode et al., 2003: Analogy with Time reversal mirrors

➔Wapenaar 2004

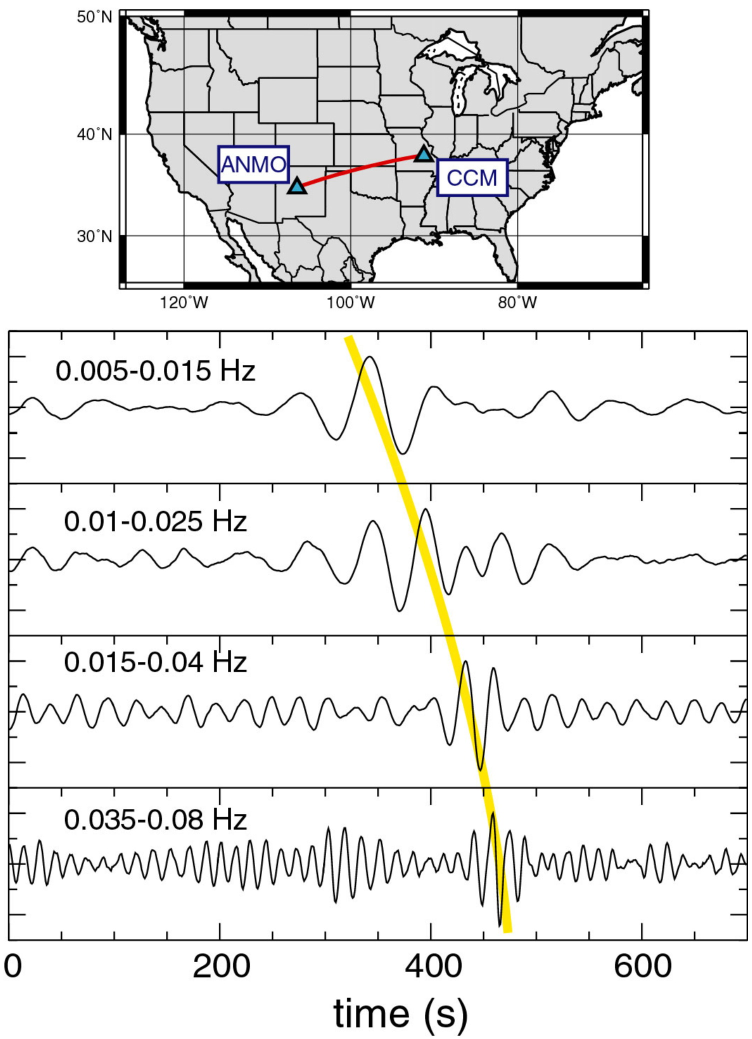
For *surface waves*: distant sources of noise at the surface of the sphere (≈2D problem)


50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM
1. Raw data (January 18, 2002)
ANMO
CCM
0
2
4
6
8
X 10+4
time (s)
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
0
2
4
6
8
X 10+4
time (s)
time (s)
3. One-bit normalization
10
12
14
16
18
20
X 10+2
time (s)
0
2
4
6
8
X 10+4
time (s)
4. Compute cross-correlation
5. Stack results for 30 days
0
-600
-400
-200
0
200
400
600
lag (sec)

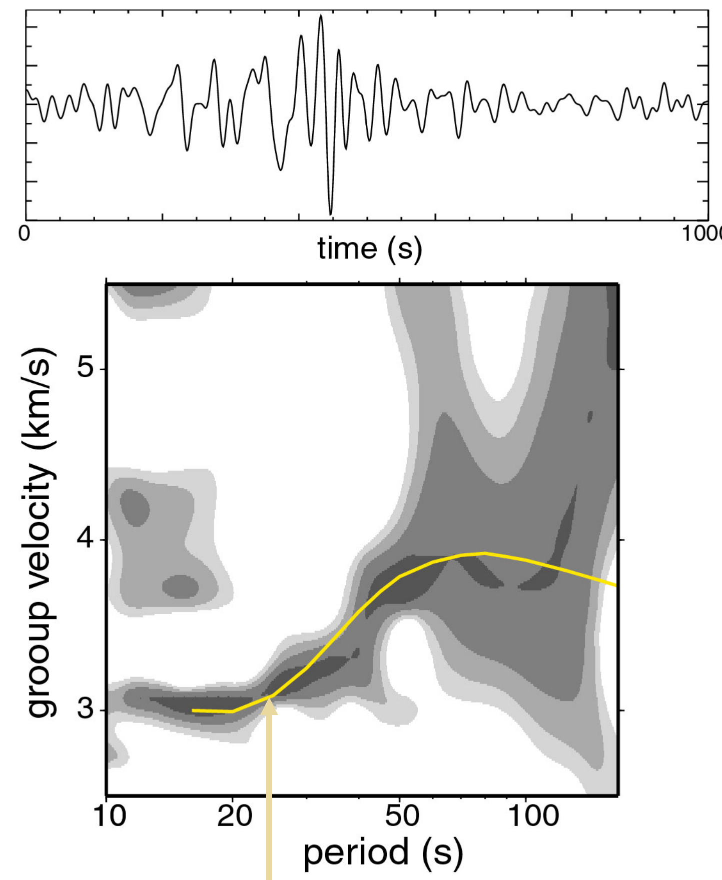
Cross-correlations of seismic noise: ANMO - CCM

(from Shapiro and Campillo, GRL, 2004)

30 days of vertical motion

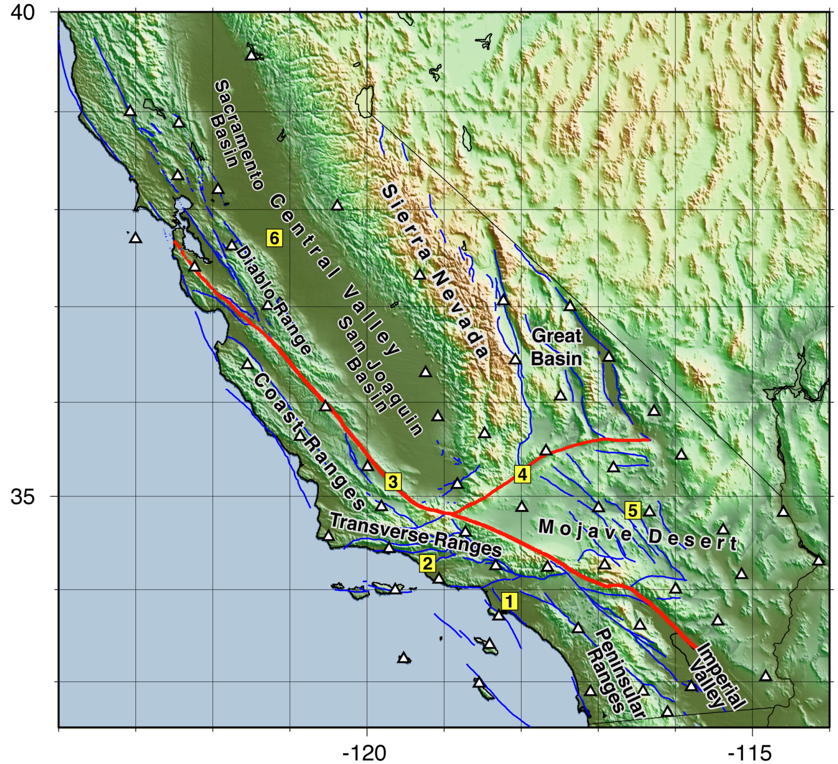


Dispersion analysis

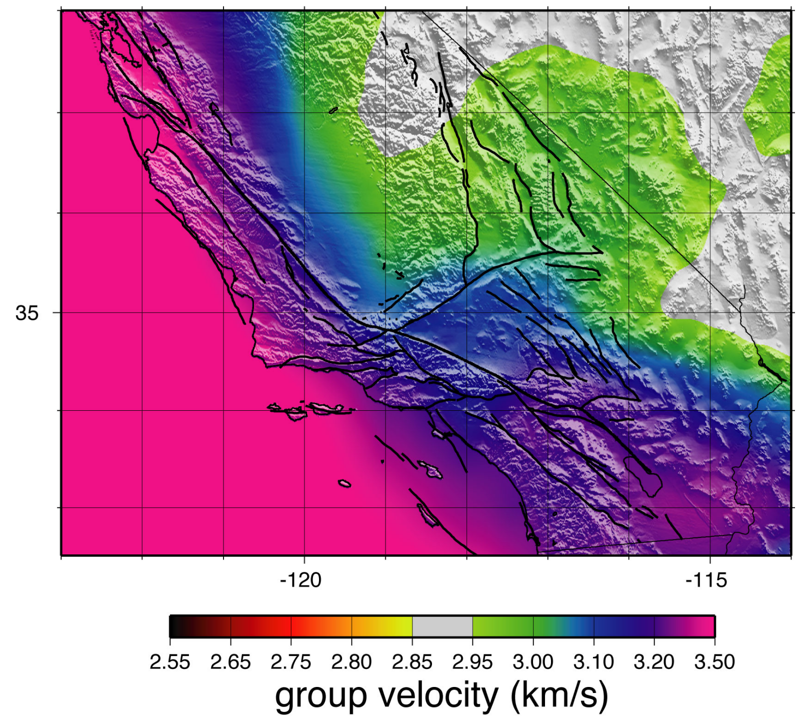


global model by
Ritzwoller et al. 2002

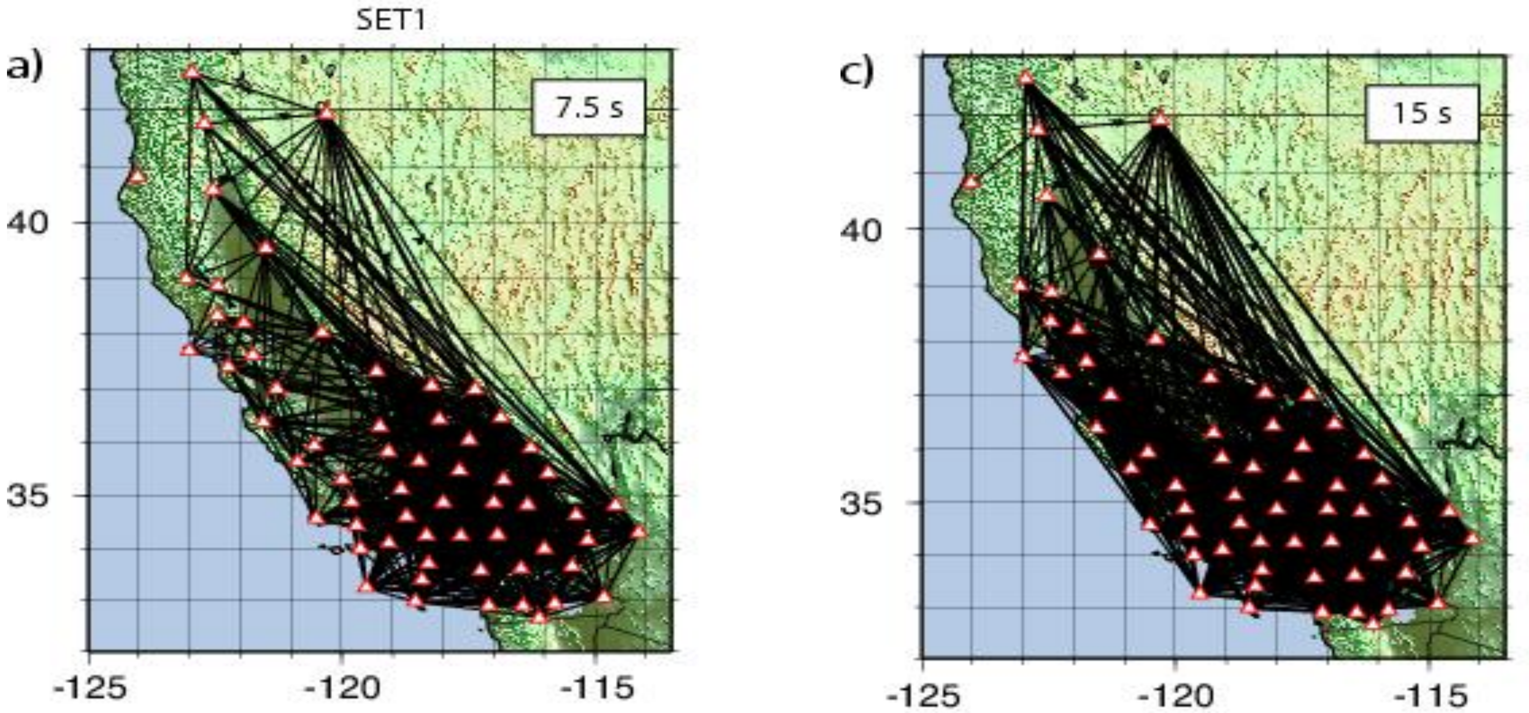
Imaging California with earthquake data



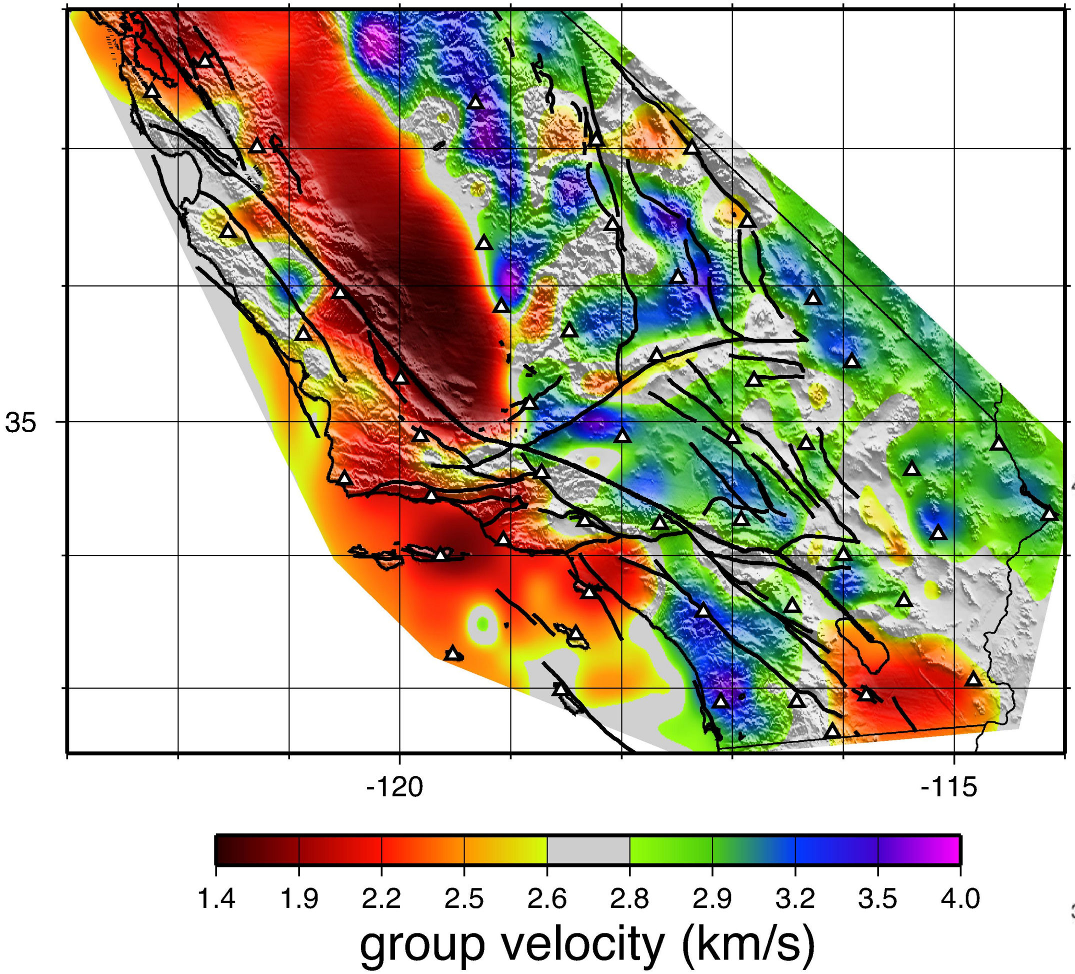
18 s global surface-wave measurements

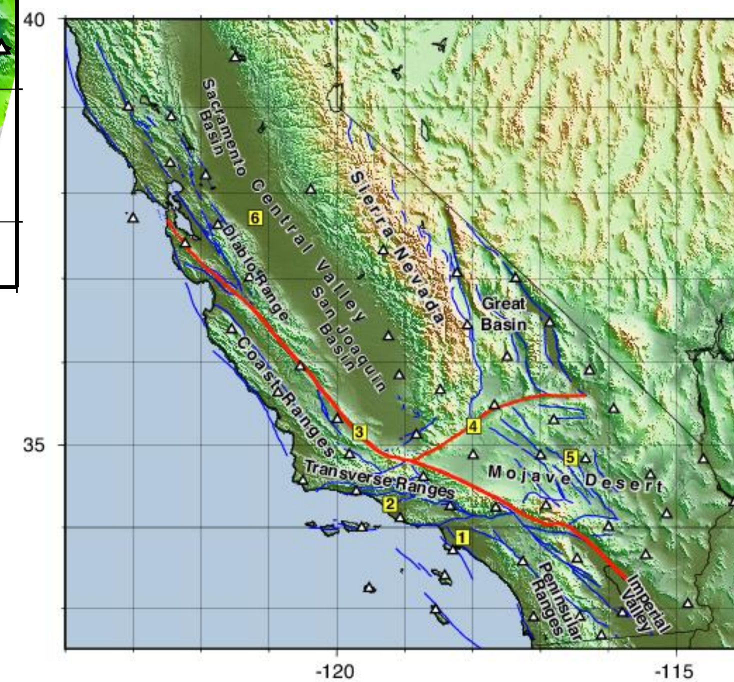


Trajets déduits du bruit (~3000 paires)



High resolution velocity map obtained from noise (Rayleigh 7.5 s)

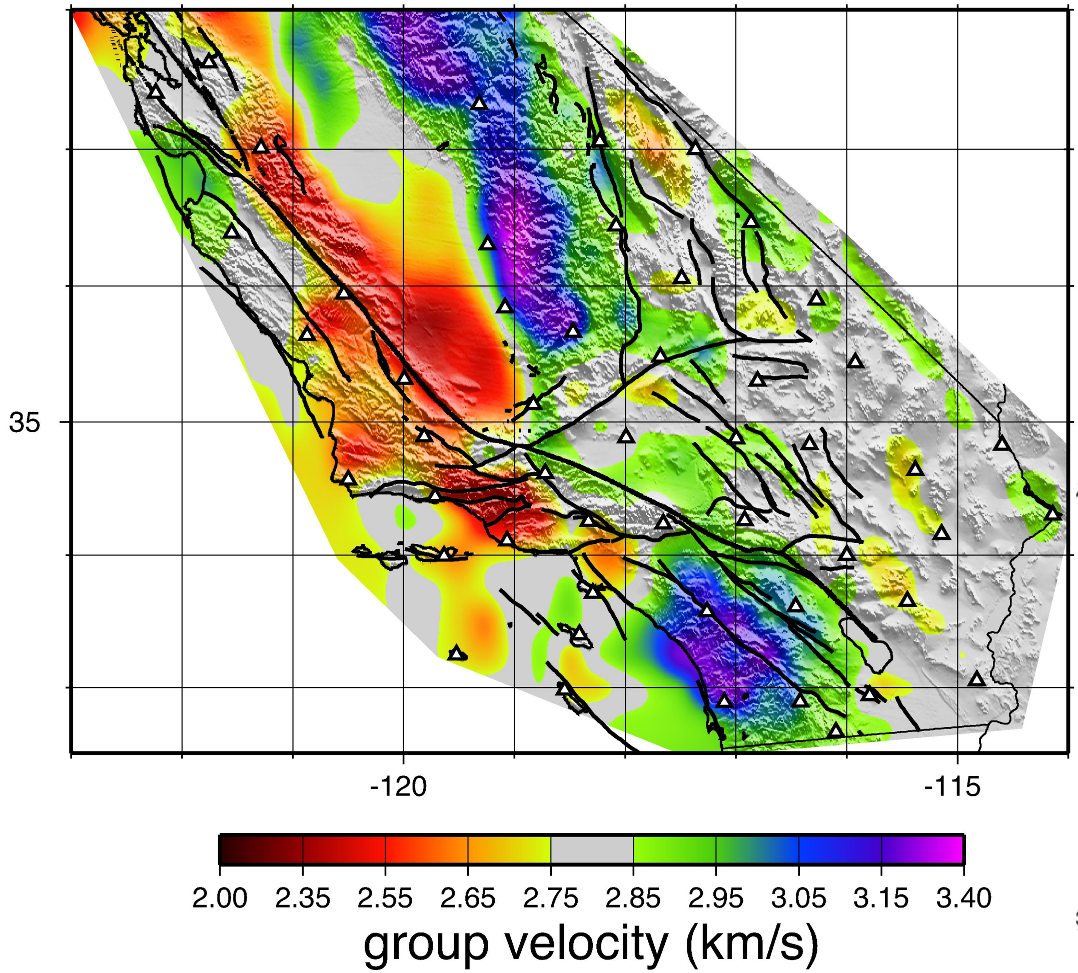


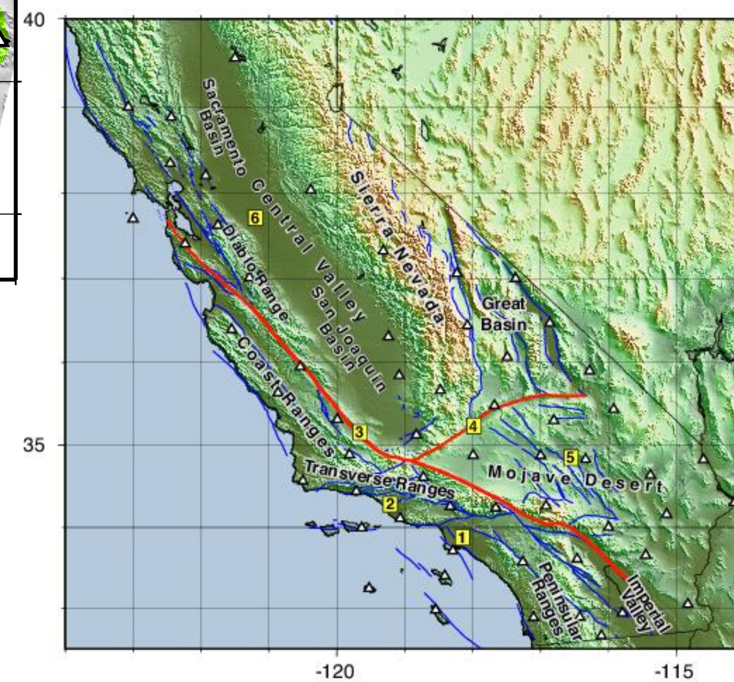


Main geological features

Shapiro, Campillo, Stehly et Ritzwoller, 2005

High resolution velocity map obtained from noise (Rayleigh 15 s ~ middle crust)

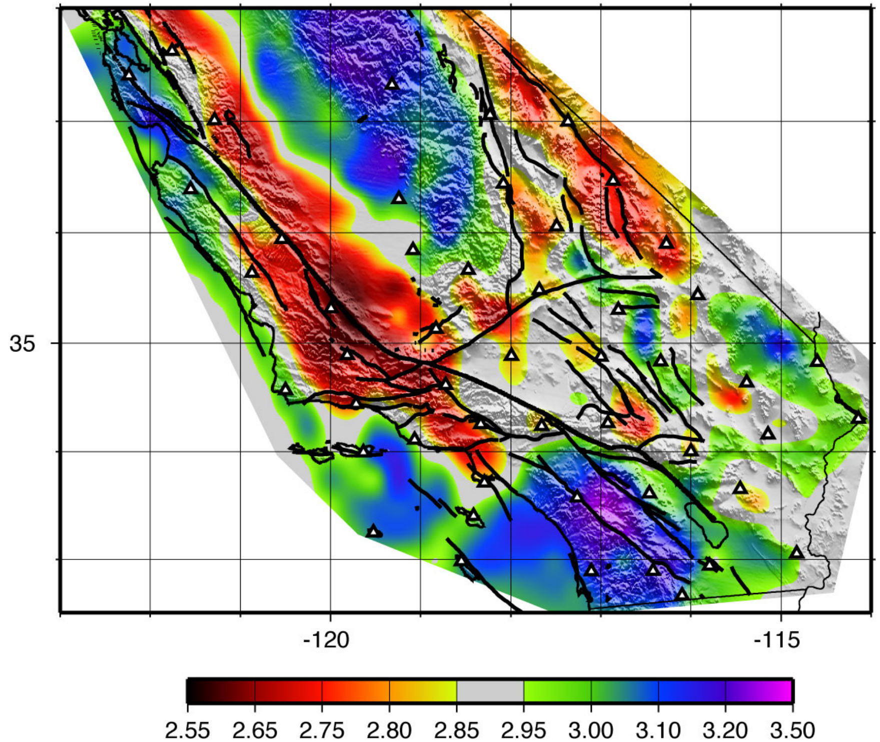




Main geological features

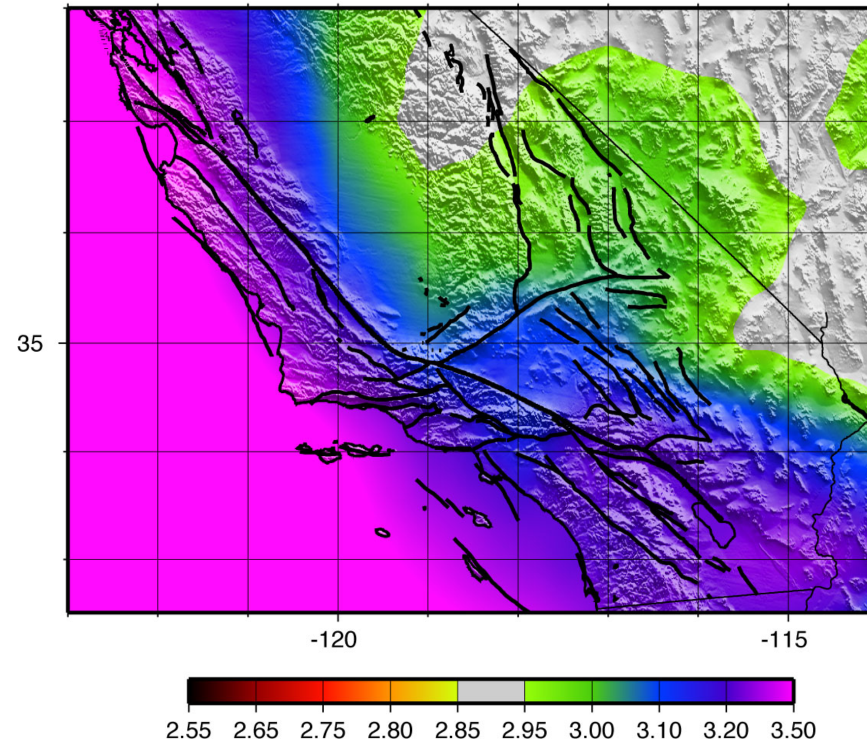
Comparison noise correlation vs earthquake data

18 s cross-correlation

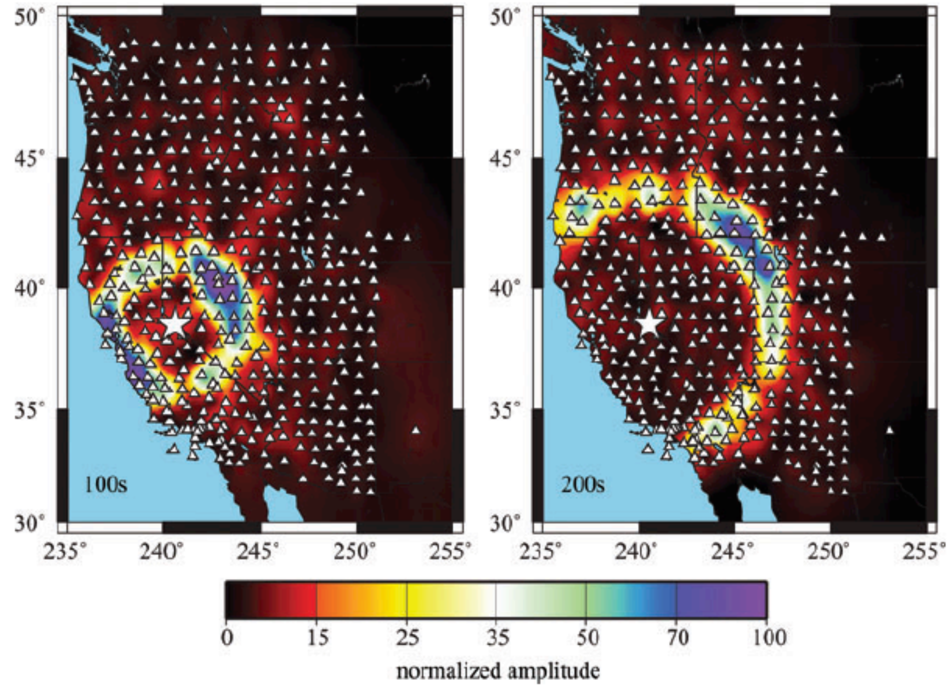


Vitesse des ondes de Rayleigh

18 s global surface-wave tomography

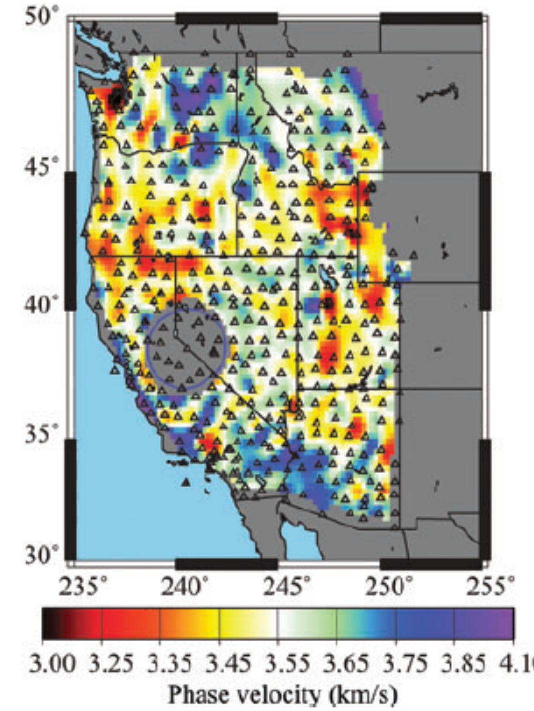


Vitesse des ondes de Rayleigh

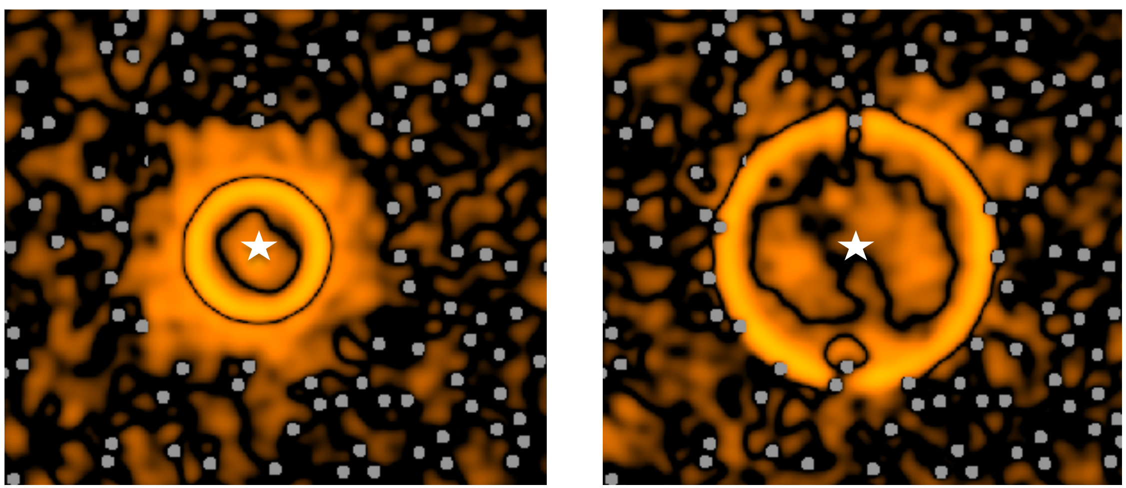


Snapshots of noise cross-correlations (surface waves)

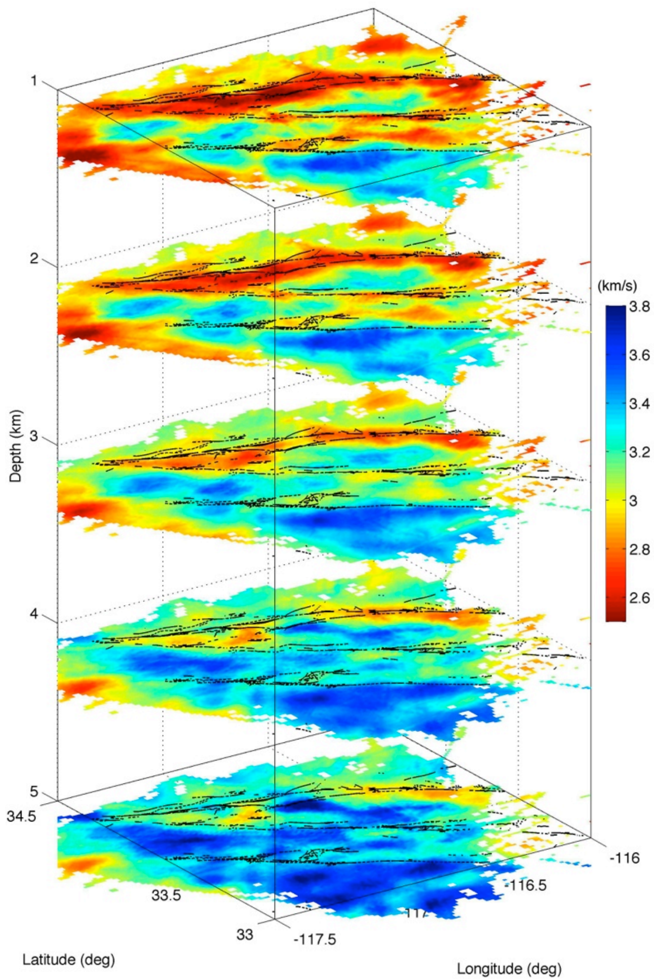
From Lin et al; 2009

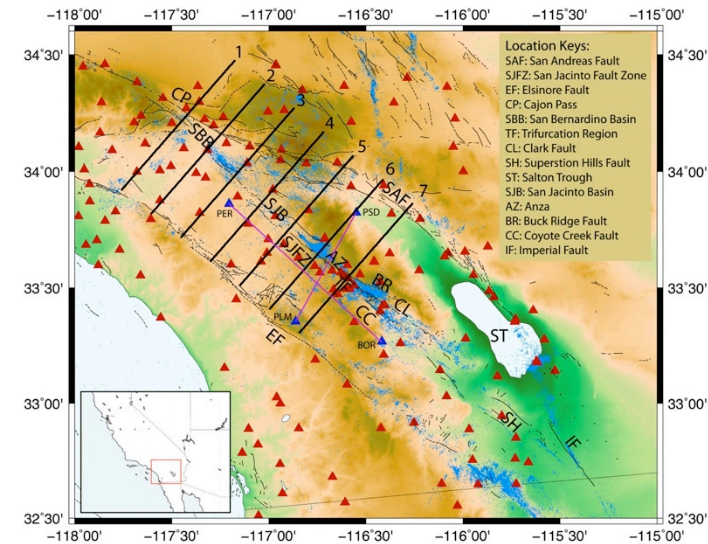


Direct measure of local velocity (eikonal eq.)



3D shear velocity





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Noise correlations represent huge sets of virtual data, leading to better resolution.

From Zigone, Ben-Zion, Campillo and Roux, 2014

Several hundreds of applications of surface wave velocity tomography in the last 10 years!

An issue for surface wave tomography:

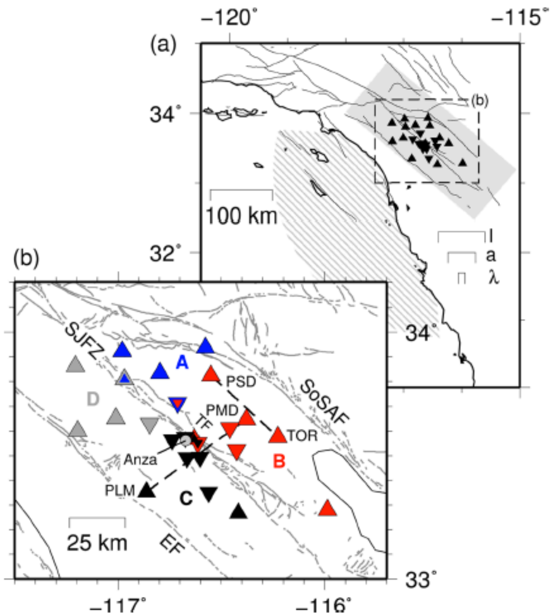
In practice, the noise sources are not evenly distributed and the field is not made fully isotropic by scattering.

We can study the effect of non isotropy of the intensity of the field incident on the receivers.

It results in a bias on the measurements of direct path travel times.

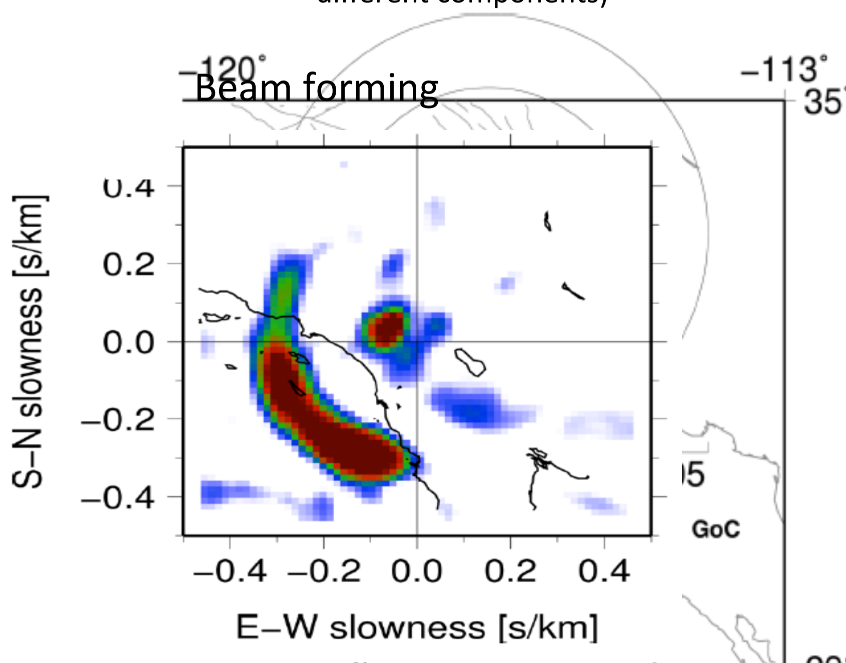
Anisotropic intensity of the noise: the example of the San Jacinto fault

From Hillers et al., 2013 G3



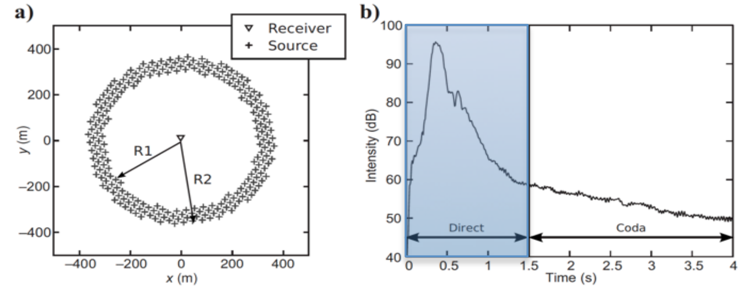
Anisotropic intensity of the noise
(measured for winter and summer and from different components)

Beam forming

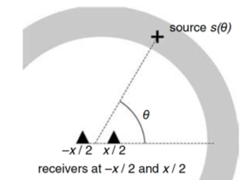


Correlation of direct waves:

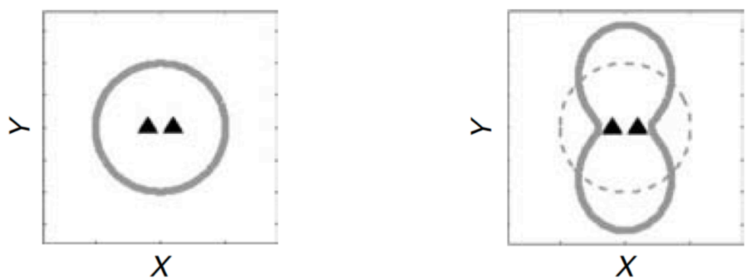
Bias in the travel time



Increasing anisotropy of the source intensity *B*

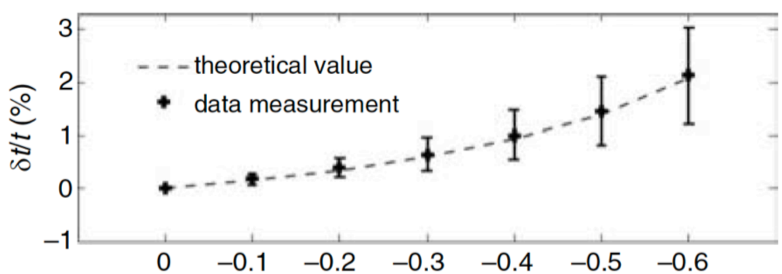


Azimuthal distribution of source intensity



$$B(\theta) = 1 + B_2 \cos(2\theta)$$

Travel time error wrt the observed Green function

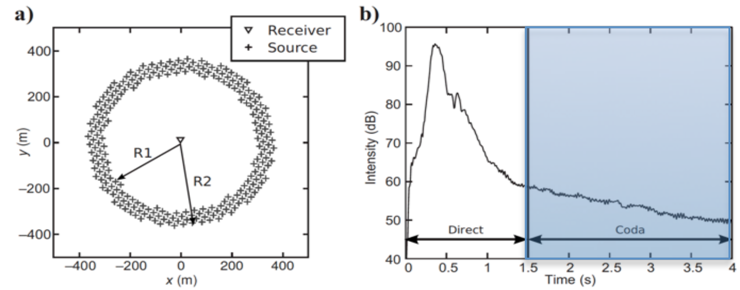


$$\delta t = \frac{1}{2t\,\omega_0^2 B(0)} \left. \frac{d^2 B(\theta)}{d\theta^2} \right|_{\theta=0}$$

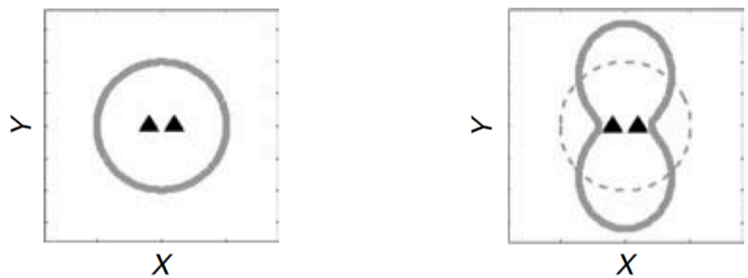
valid with t (travel time) > T (period)

From Weaver, Froment, Campillo (2009) and Froment, Campillo, Roux, Gouédard, Verdel and Weaver 2011.

In presence of scattering:
Correlation of coda waves
-isotropy provided by multiple scattering

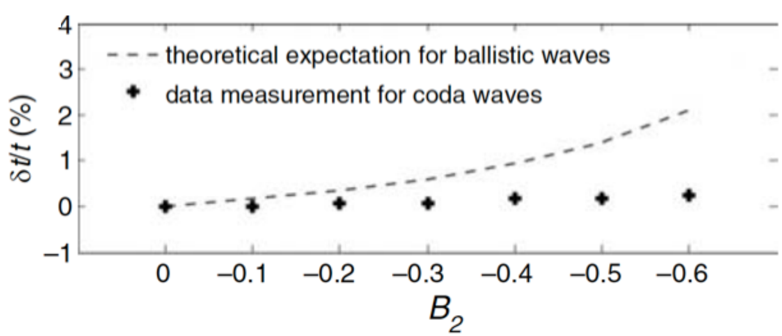


Increasing anisotropy of the source intensity *B*



$$B(\theta) = 1 + B_2 \cos(2\theta)$$

Scattering tends to isotropization of intensity



No bias in the correlation of coda waves!

Noise records contain direct **<u>and</u>** scattered waves:

➔ the biases of direct wave travel times are generally small enough for imaging purpose

➔ Importance of processing strategies

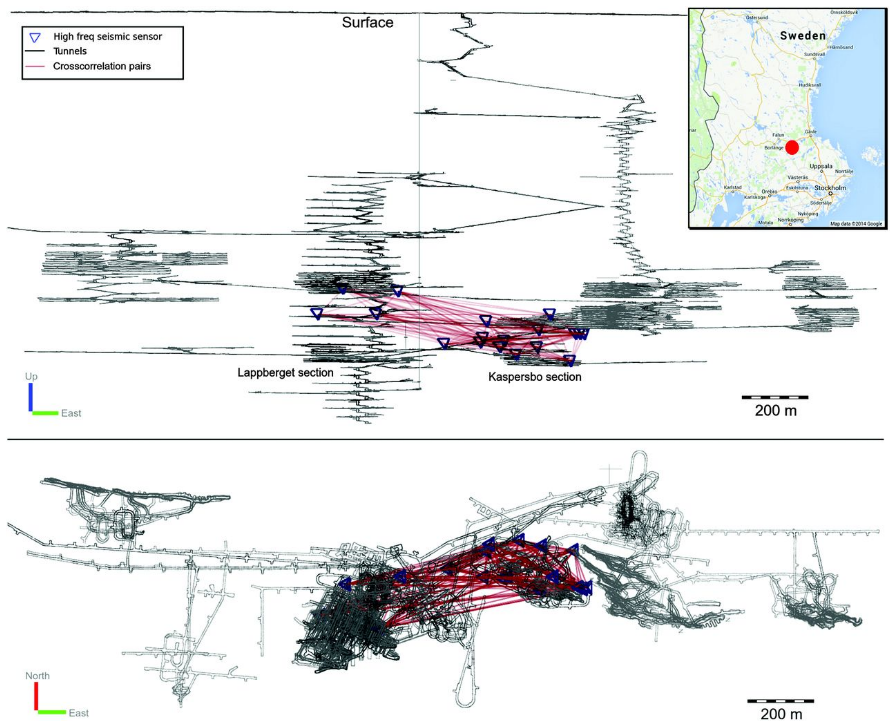
From Froment, Campillo, Roux, Gouédard, Verdel and Weaver 2011.

Smaller scale, industrial environment

Active mine: various sources of noise
tunnels (scattering)

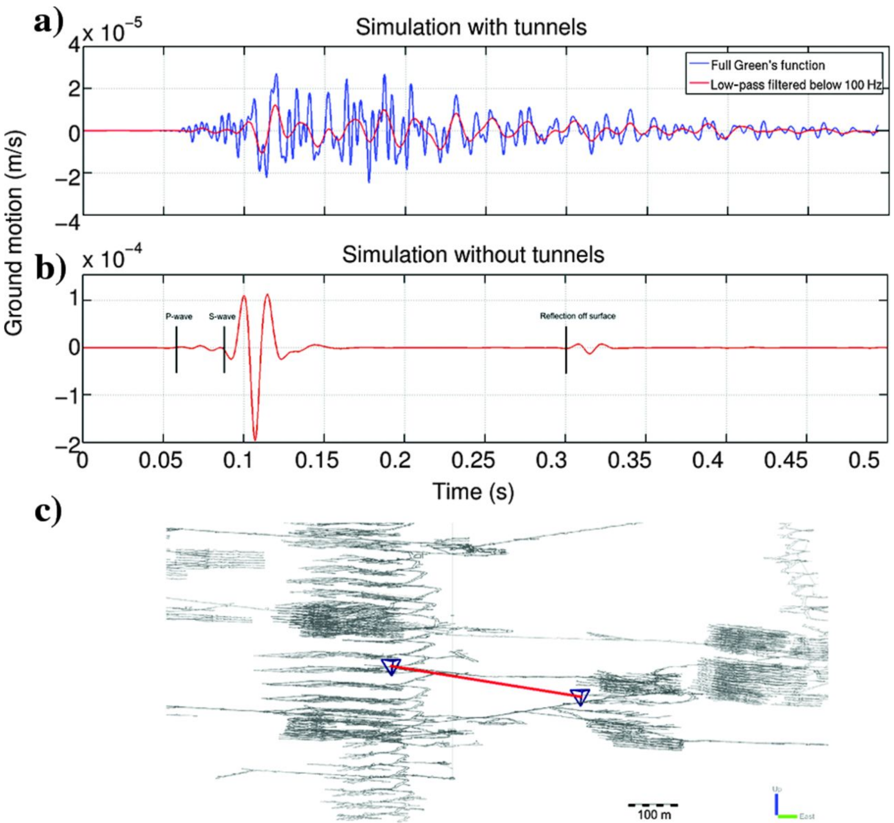
Section view

Plan view

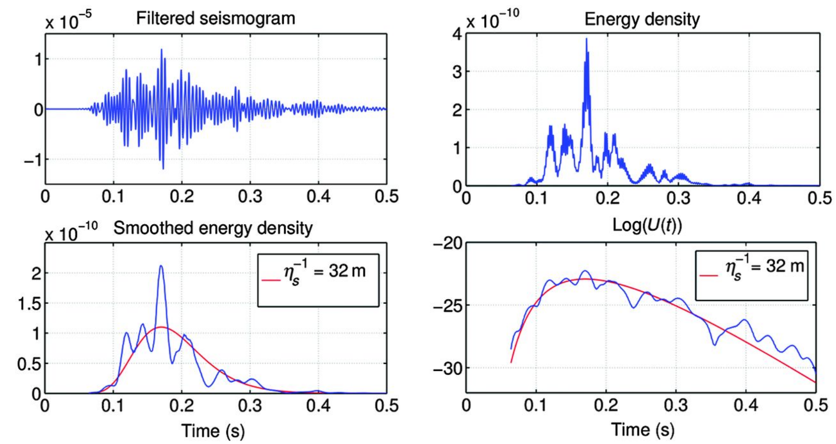


Results from Olivier, Brenguier, Campillo, Lynch and Roux, 2015
GEOPHYSICS, VOL. 80, NO. 3 (MAY-JUNE 2015); P. KS11–KS25

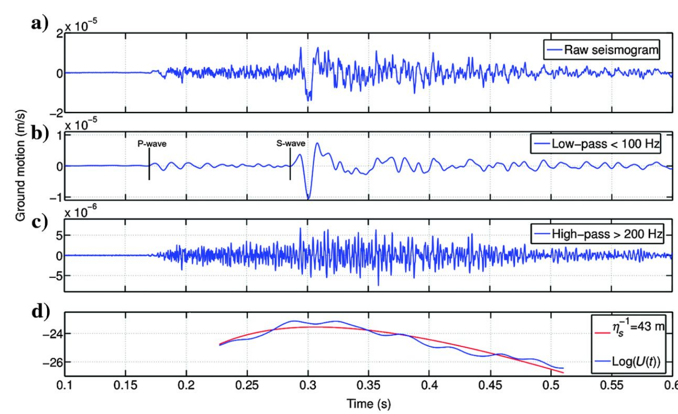
Numerical simulation in presence of the tunnels



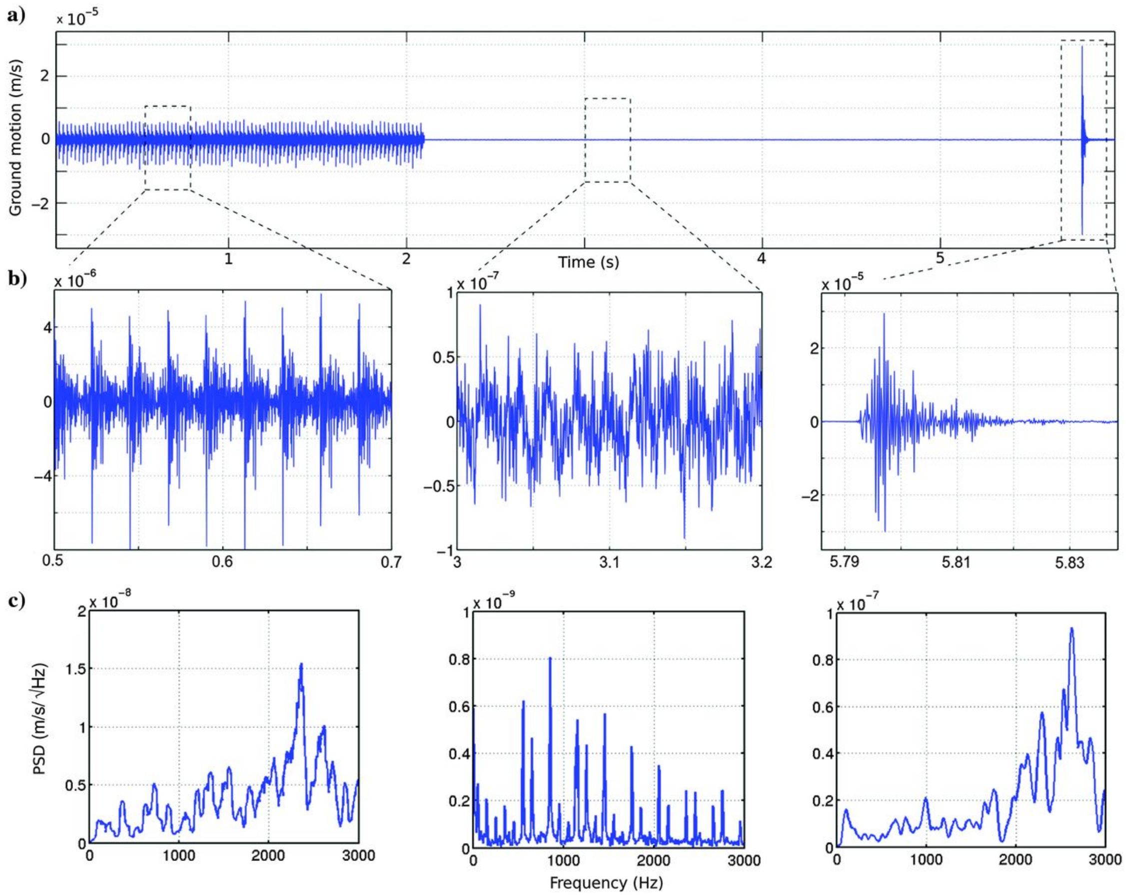
Synthetics vs Diffusion approximation



Actual event vs Diffusion approximation



Nature of the noise: example of a 5s record

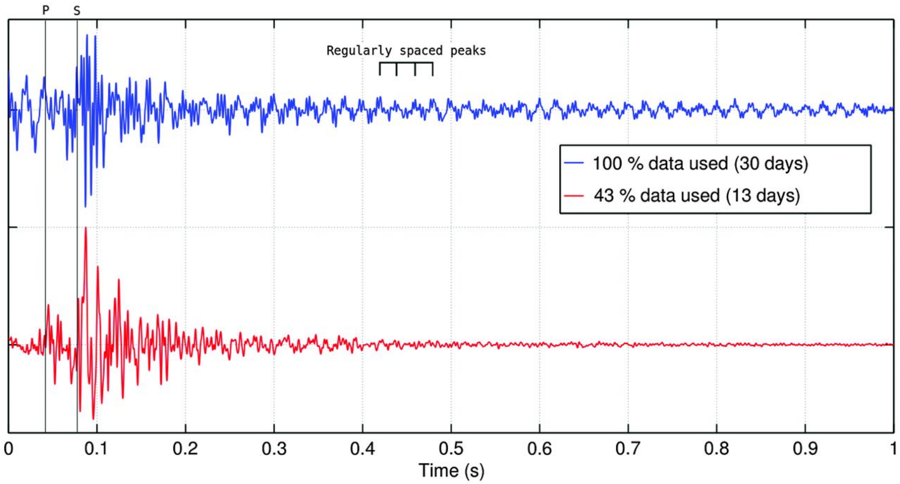


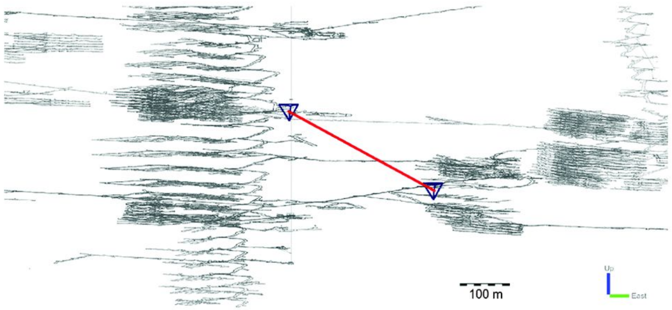
impacts of a hammer drill

microseismic event

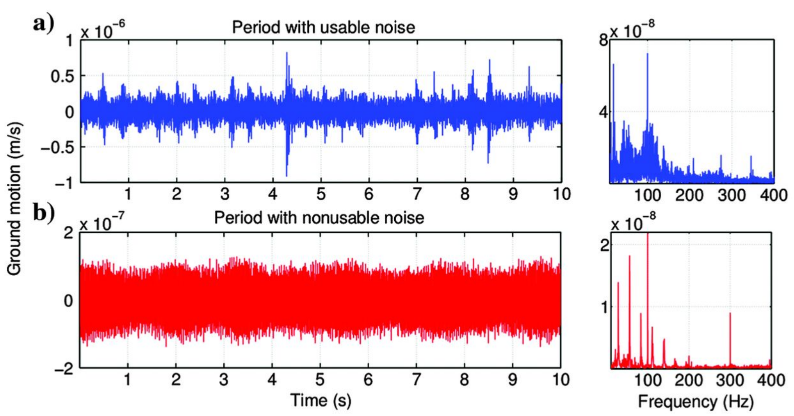
multiple sources
incl. (pumps, fans, etc.)

Correlation functions (ZZ)





Selective stacking: optimal time windows for body wave contributions:



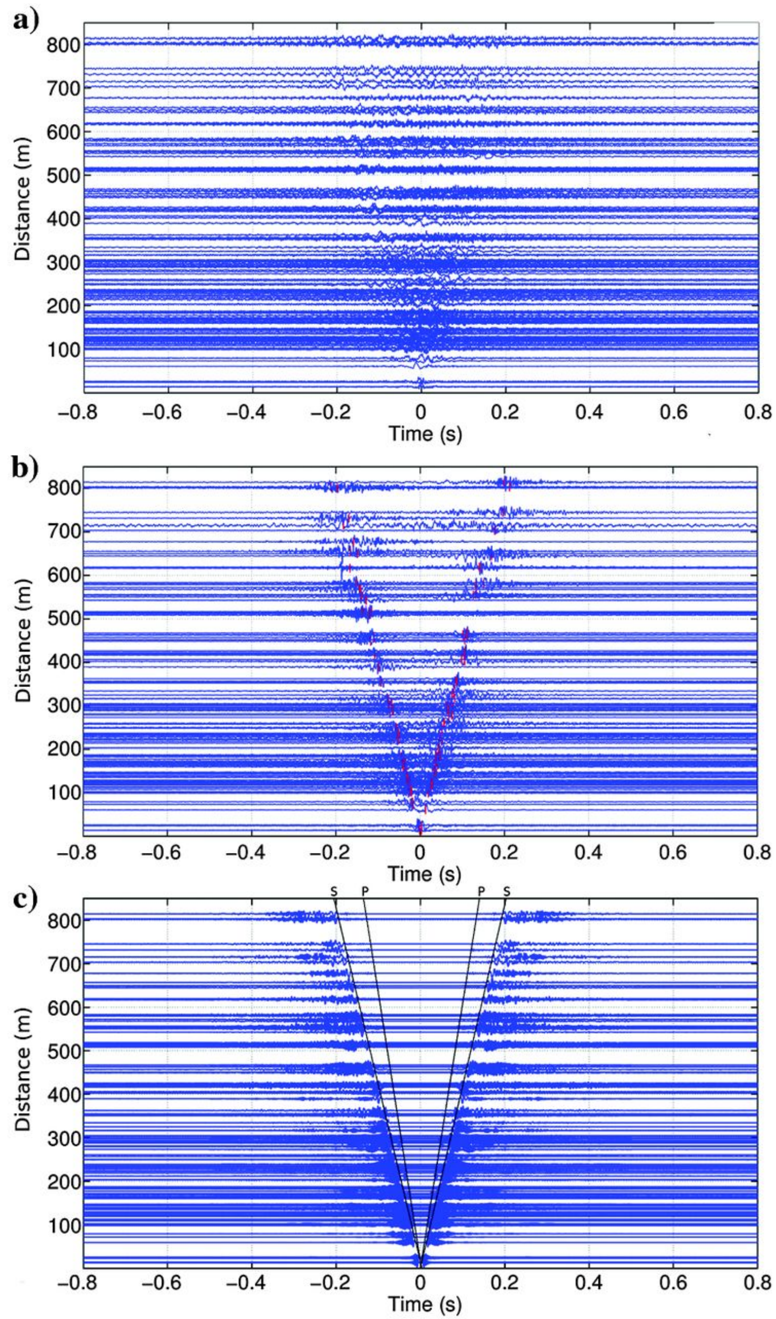
Removing of monochromatic sources

ZZ time-distance sections

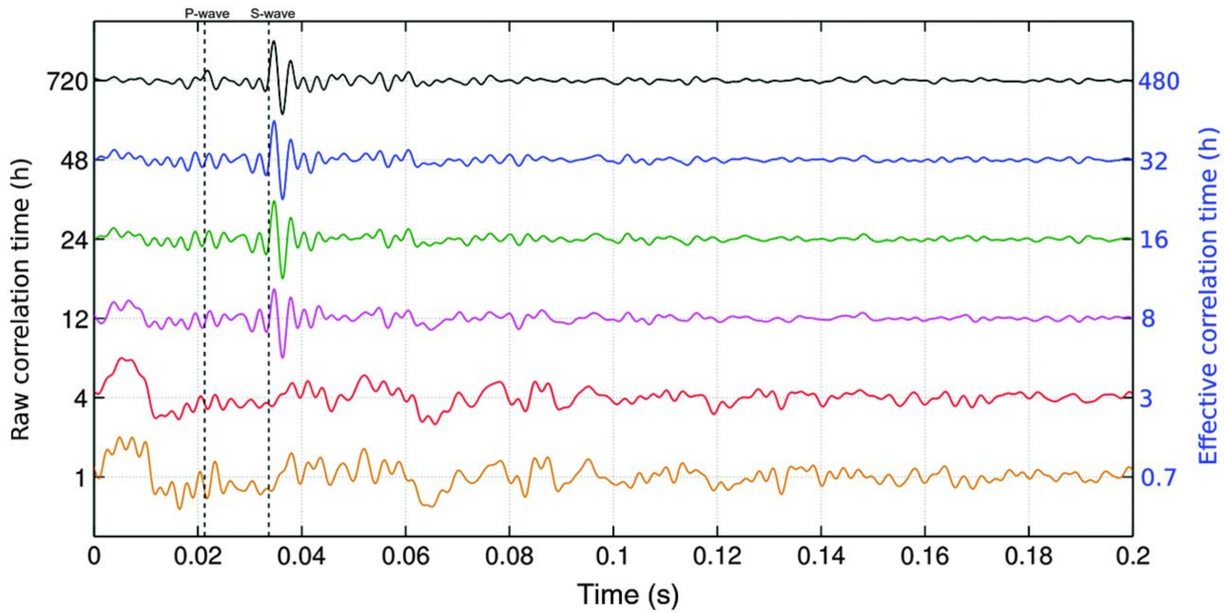
Noise correlations: blind stacking

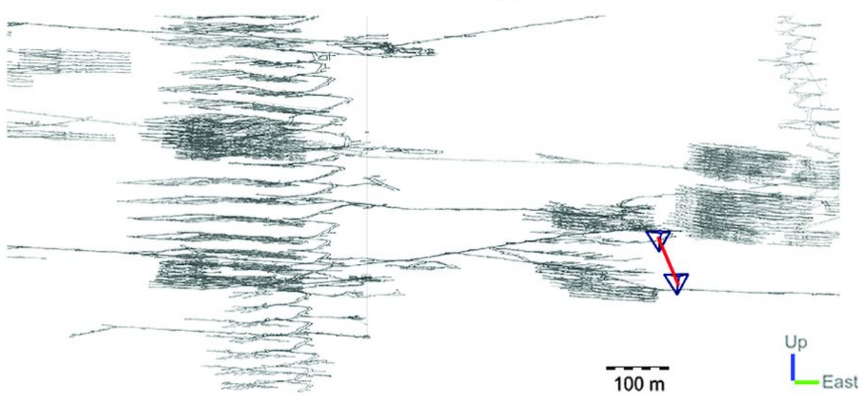
Noise correlations: optimal stacking

Synthetics

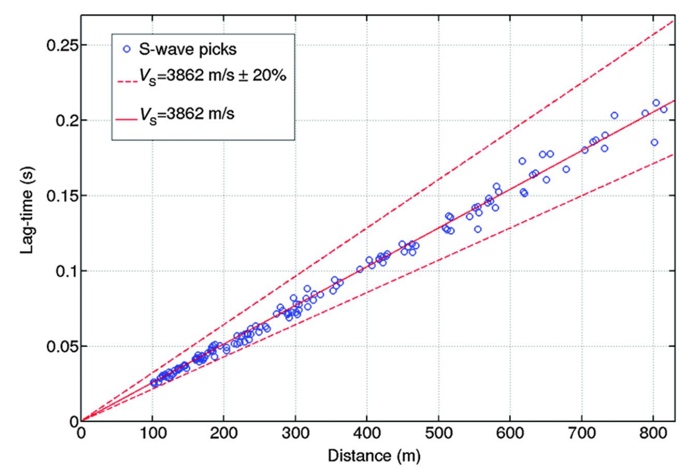


Convergence of the ZZ correlation function

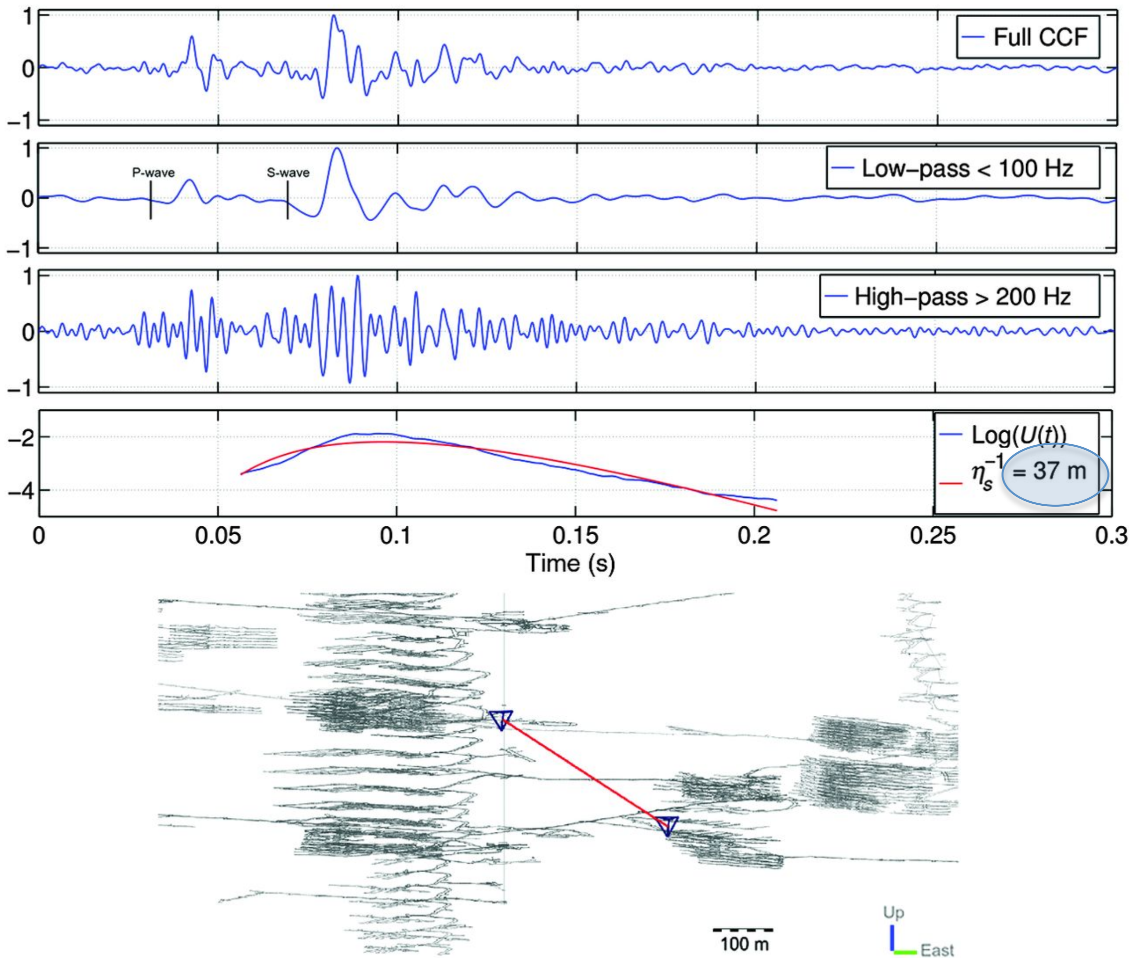




S wave velocity

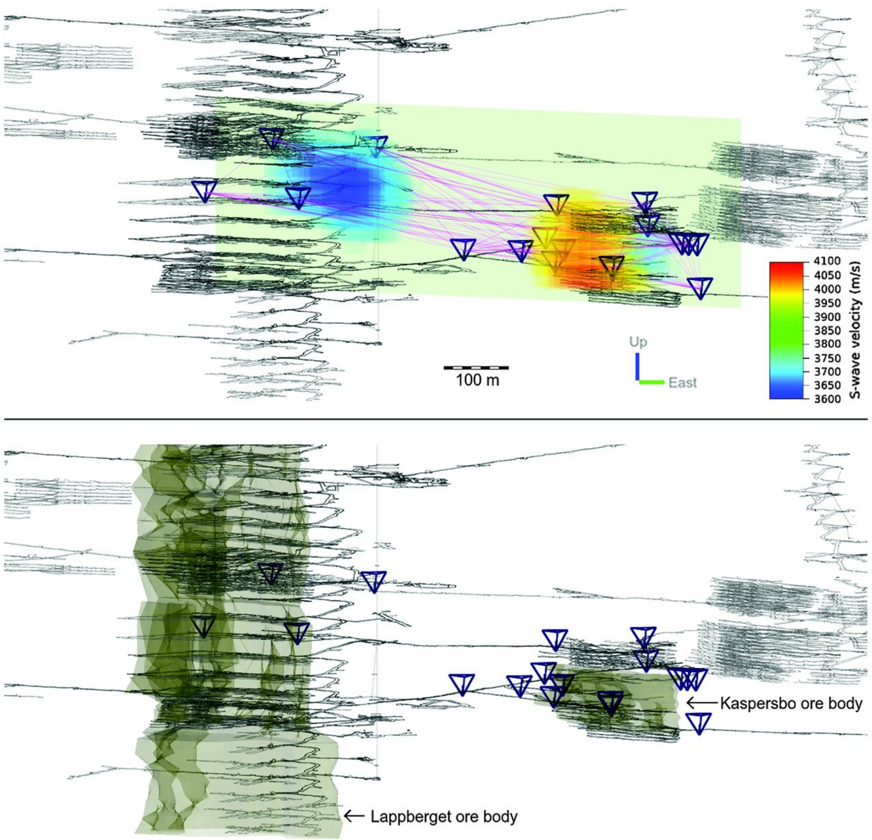


Scattering properties from noise correlations

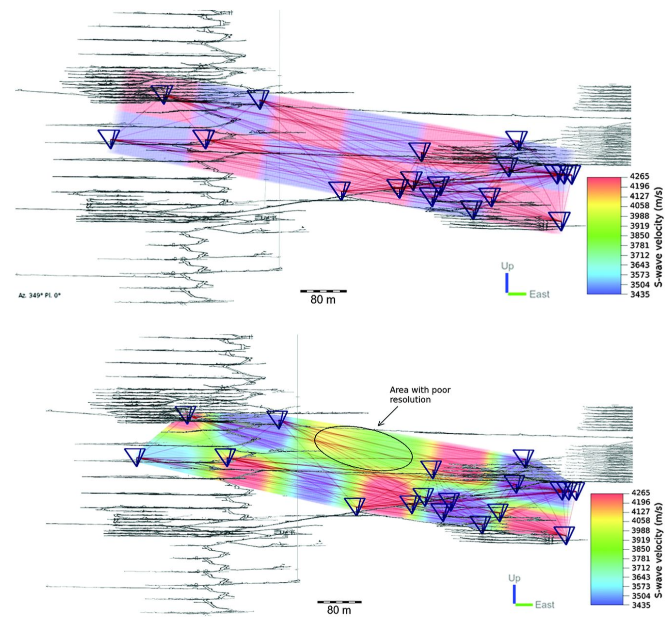


Diffusion approx.

Travel time tomography from noise correlations



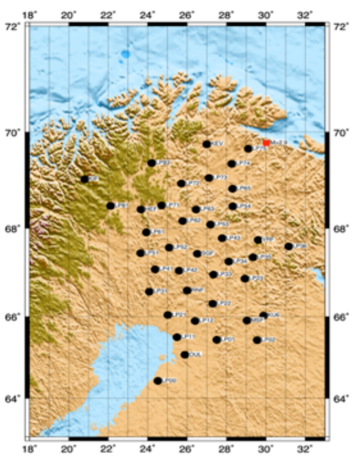
Checkboard test



Surface wave tomography ➔ body waves (deep reflections)

Moho reflections

POLENET/LAPNET array in Finland

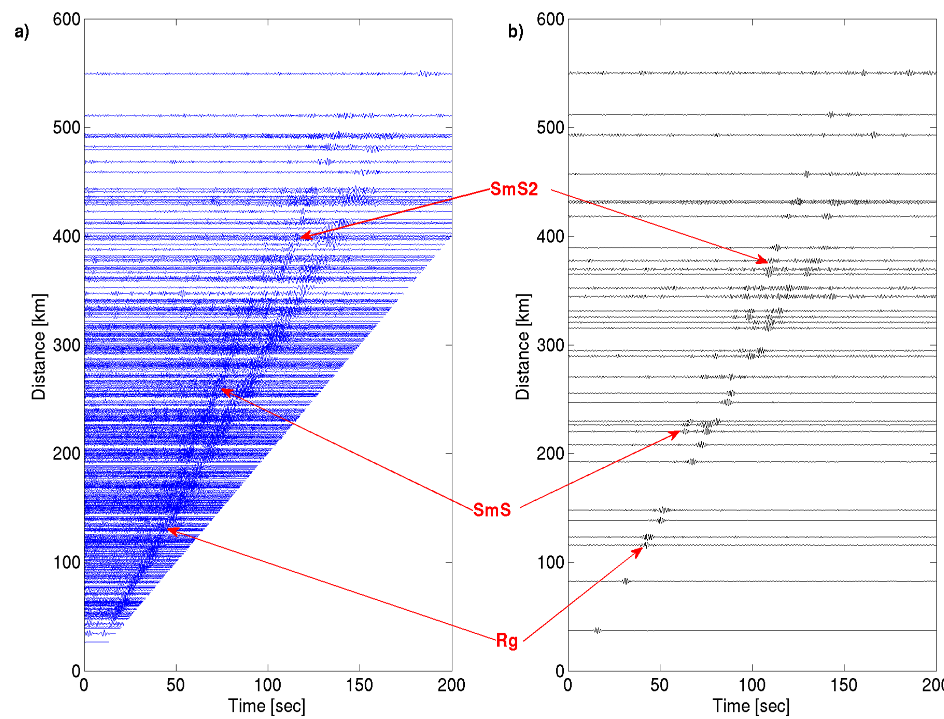


Comparison of high frequency (1Hz) 1-year noise correlation with earthquake data

Poli et al. 2012a

Z-Z noise correlations

Z comp. actual earthquake



Surface term: $$\oint_S \left[G_{1x} \vec{\nabla}\left(G_{2x}^*\right) - \vec{\nabla}\left(G_{1x}\right) G_{2x}^* \right] \overrightarrow{dS}$$

If the surface is taken in the far field of the medium heterogeneities

$$G_{1x} \sim \frac{1}{4\pi |\vec{x} - \vec{r}_1|} \exp\left(-ik|\vec{x} - \vec{r}_1|\right) \text{ and } \vec{\nabla}\left(G_{1x}\right) \sim i\vec{k}\, G_{1x}$$

and we obtain a widely used integral relation:

$$G_{12} - G_{12}^* = \oint_S \left[G_{1x} \vec{\nabla}\left(G_{2x}^*\right) - \vec{\nabla}\left(G_{1x}\right) G_{2x}^* \right] \overrightarrow{dS} \approx -2i \frac{\omega}{c} \oint_S G_{1x} G_{2x}^* \, dS$$

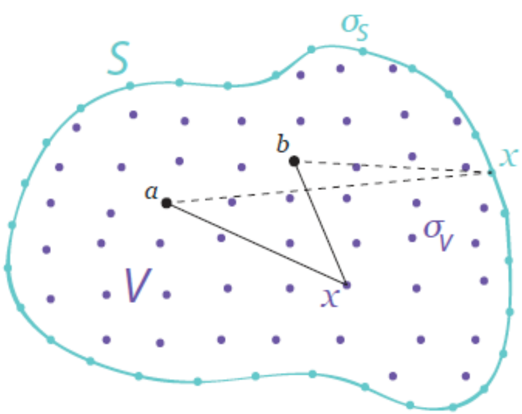
Source average over « correlation terms » for sources on the surface

➔ Derode et al., 2003: Analogy with Time reversal mirrors
➔ Wapenaar 2004

For *surface waves*: distant sources of noise at the surface of the sphere (≈2D problem)

Consider now the problem of body waves at the global scale with noise sources at the free surface:

A problem of a different nature, although the uneven distribution surface noise sources is still there.



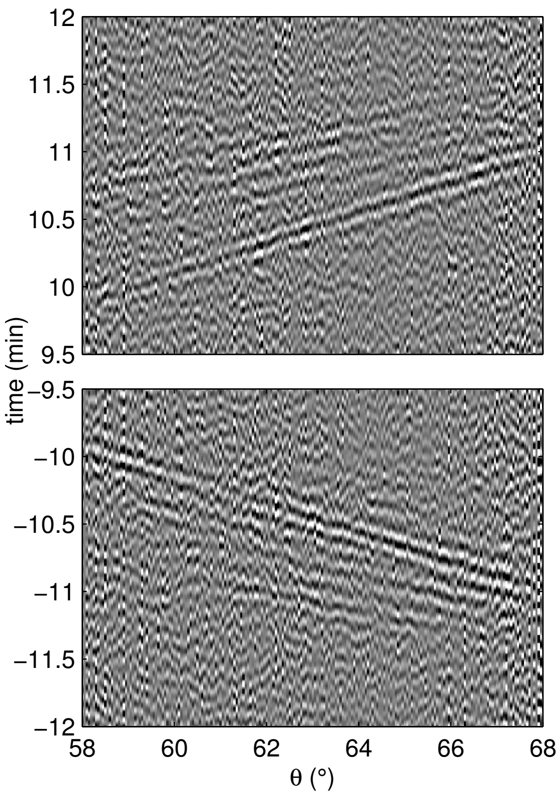
$$G_{12} - G_{12}^{*} = \oint_{S} \left[G_{1x} \vec{\nabla} \left(G_{2x}^{*} \right) - \vec{\nabla} \left(G_{1x} \right) G_{2x}^{*} \right] \overrightarrow{dS}$$ **?**

This representation is not formally valid on the free surface: the flux vanishes.

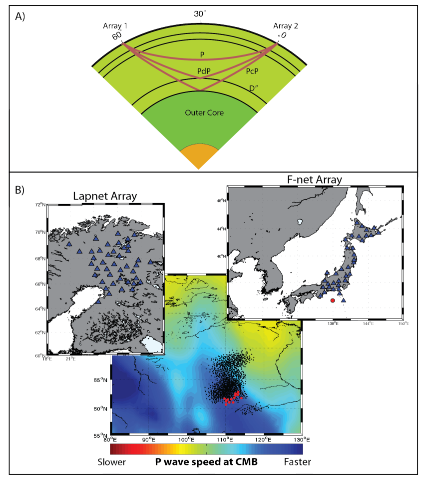
Here also, the correlation of multiply scattered waves should lead to the Green function.

Short periods 5-10 s ➔ scattering

P and PcP in teleseismic correlations



Japan to Finland (F-net to LapNet)



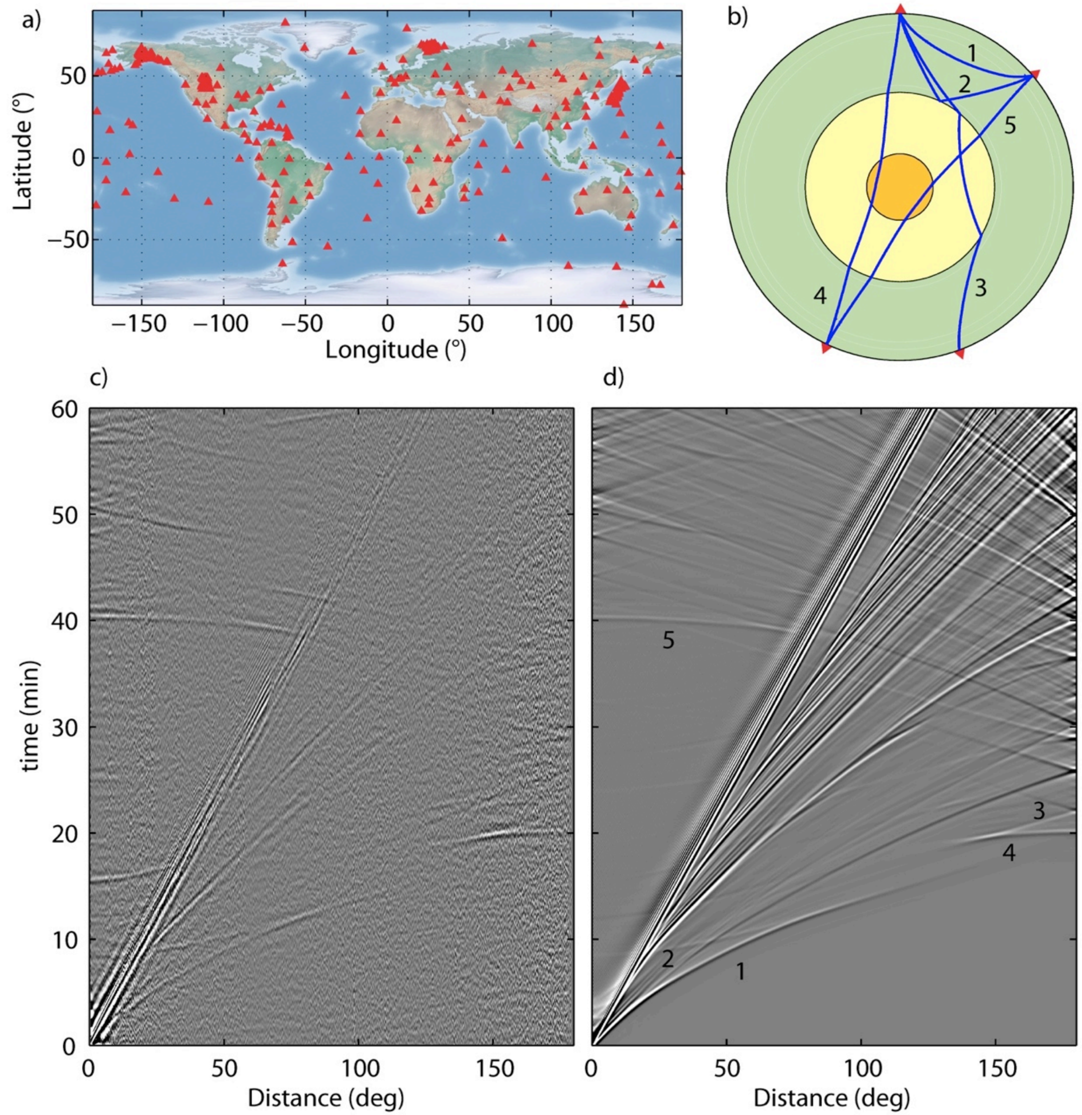
Finland to Japan (LapNet to F-net)

➔ PcP, PdP, P660P, P410P,…

Standard (surface-wave) pre-processing eliminates the contamination by EQ ballistic waves (at short periods).

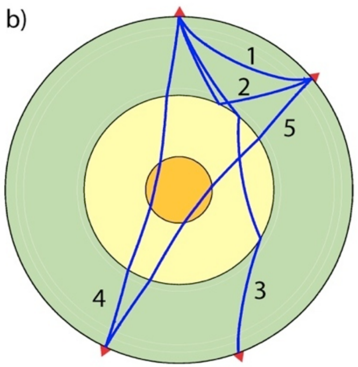
GLOBAL TELESEISMIC CORRELATIONS (periods 25-100s vertical components)

Weak scattering

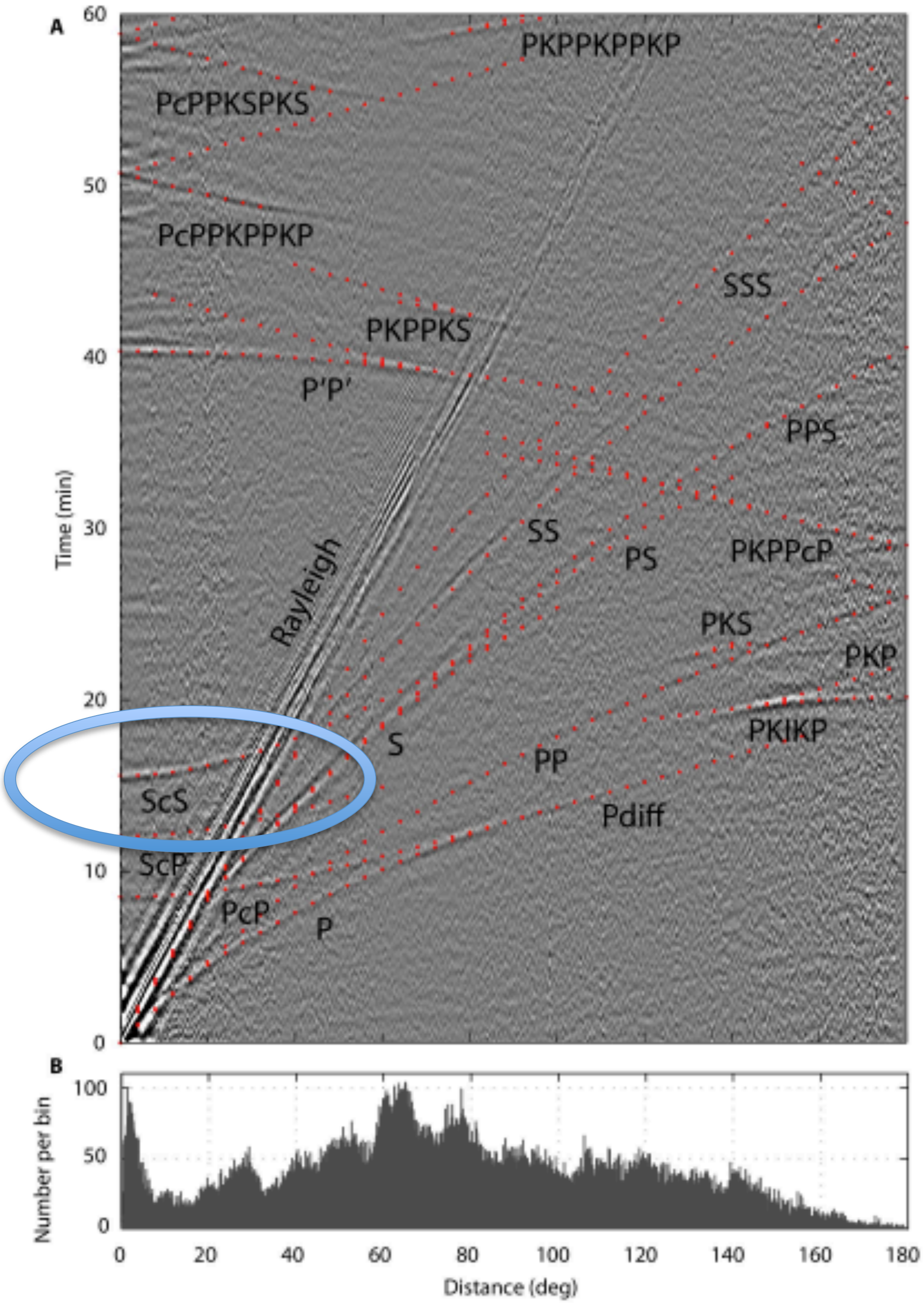


Boué, Poli et al., GJI 2013

Numerous phases can be identified



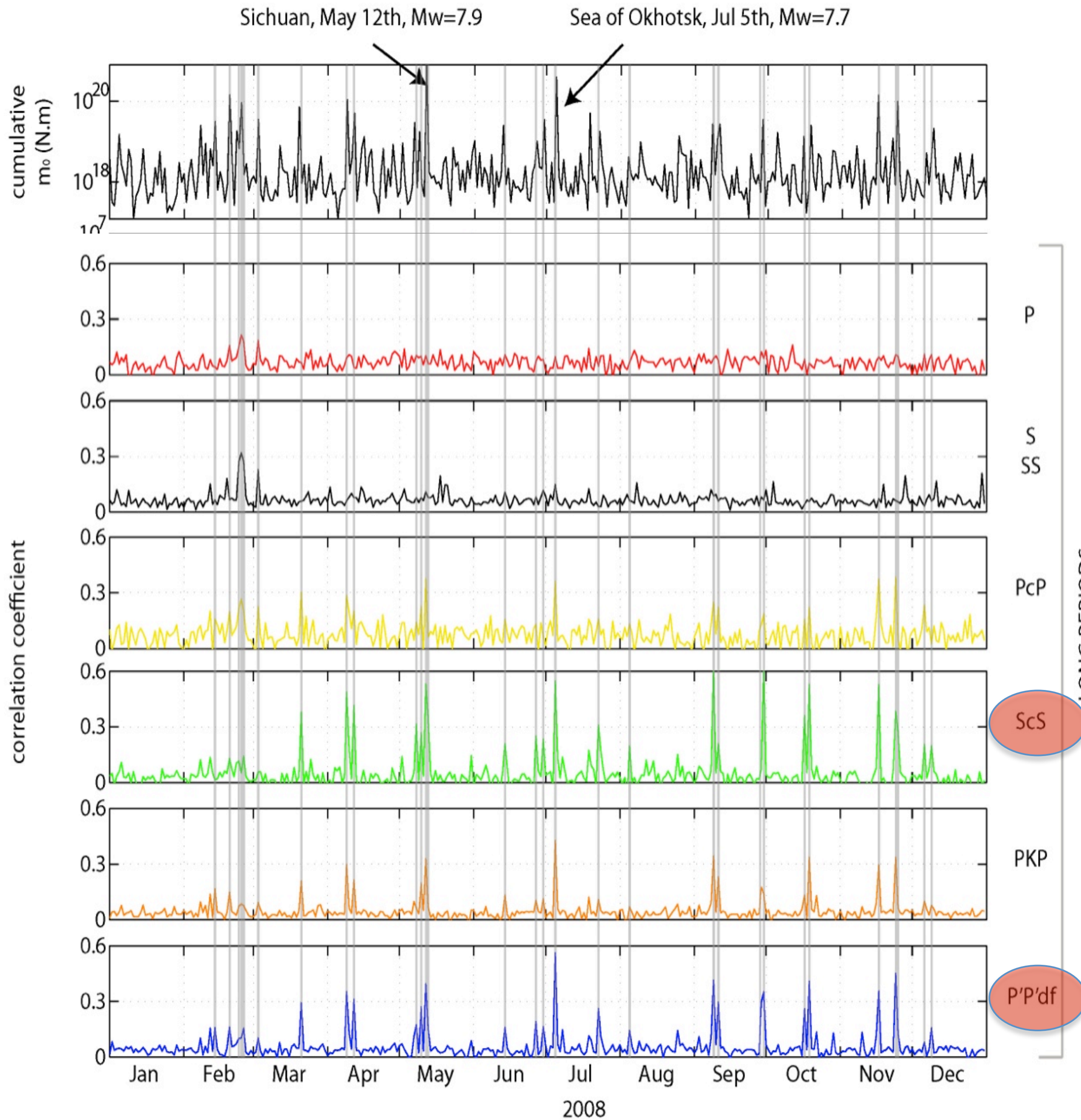
Vertically incident S waves on the vertical component??



Global data set:

Coherent contribution of earthquakes (lasting days)

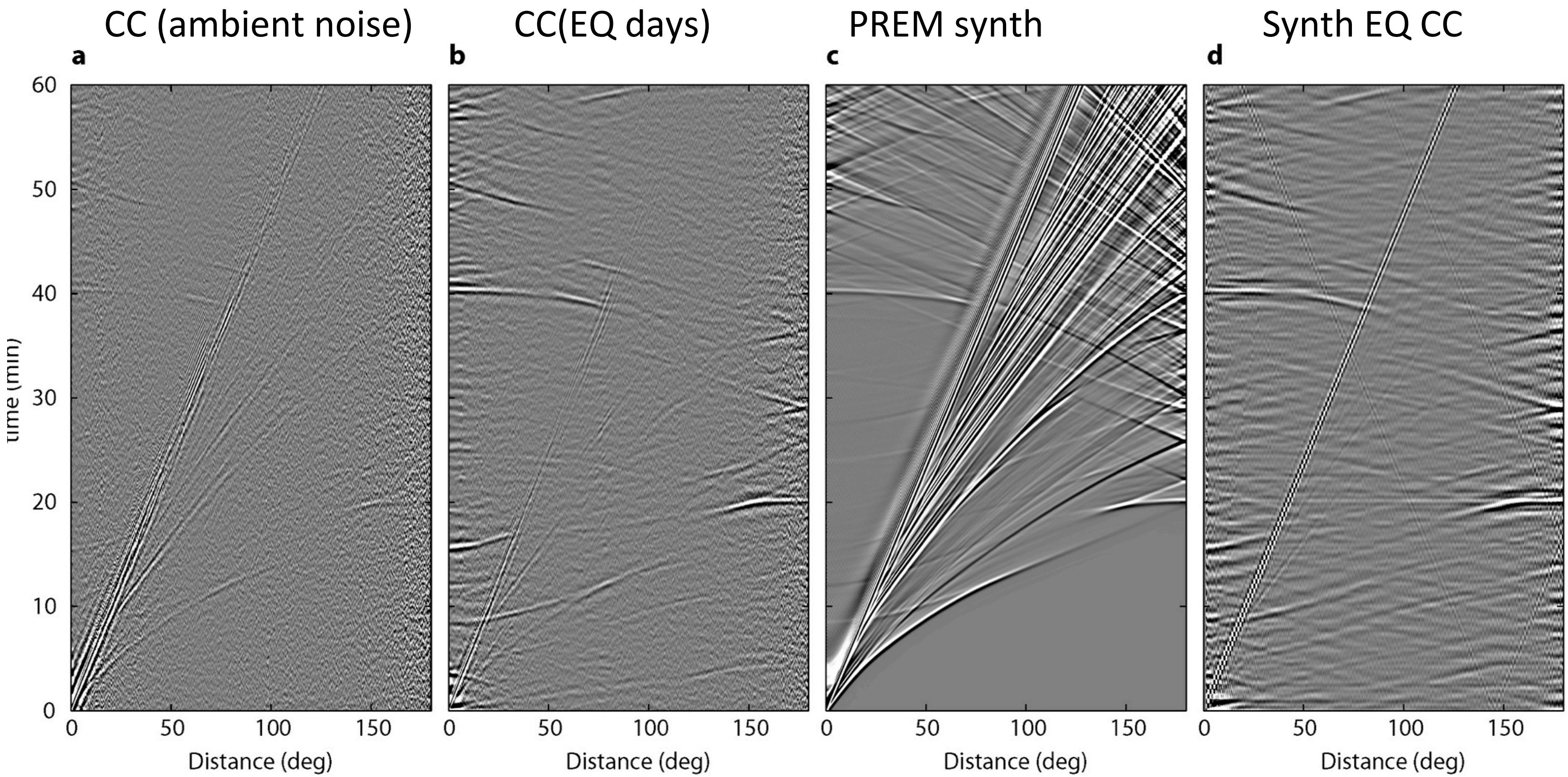
Inefficient pre-processing



Long periods (25-100s)

Spurious arrivals and simulation

Simulations in PREM (no scattering)



From Boué et al., 2014