ISTerre
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European Research Council

Adv. Grant Whisper

Ambient noise imaging

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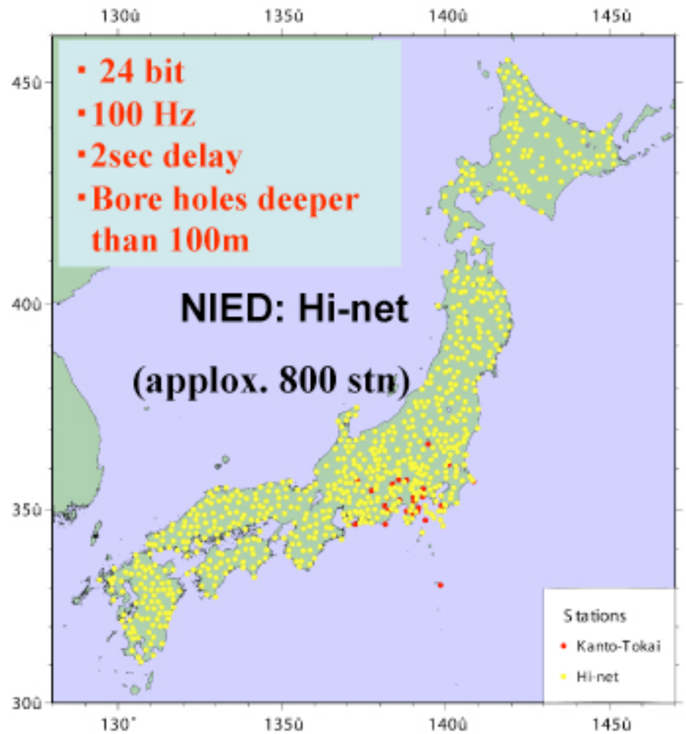
with Bérénice Froment, Piero Poli, Pierre Boué, Philippe Roux, Laurent Stehly, Gregor Hillers, Anne Paul, Nikolai Shapiro, Helle Pedersen, …

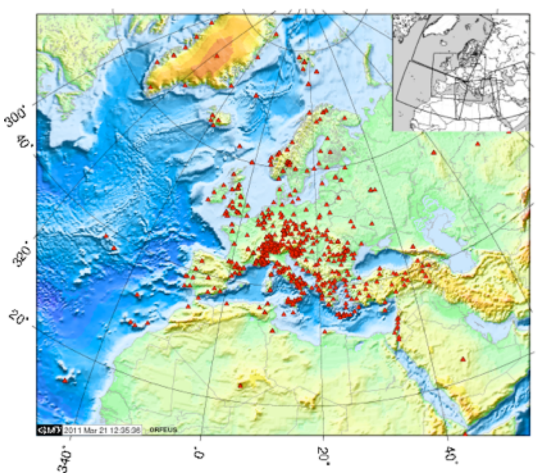
-Introduction

-Reconstruction and limits

-Surface waves and body waves

Large networks – continuous recordings



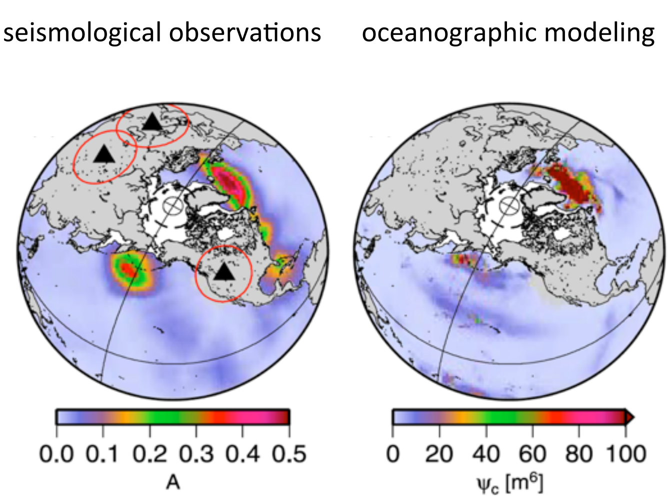


Seismology : huge data sets consisting for a large part of 'ambient noise'..
Availability: IRIS,…

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

Strong contribution from oceanic waves

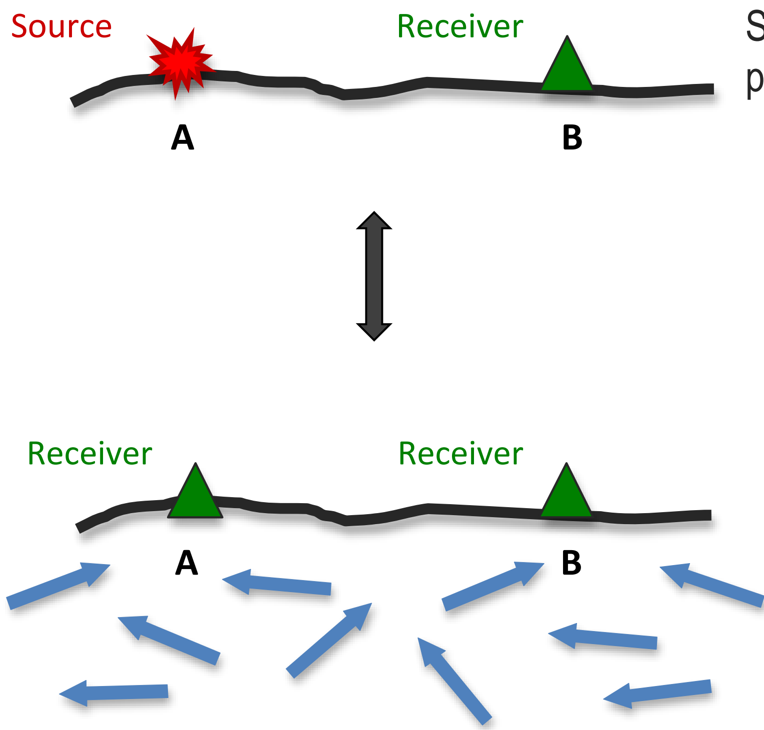
Example of a global comparison



Hillers et al., 2012

Deterministic description of the sources?

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

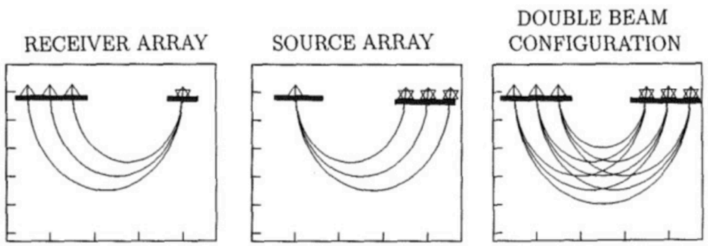
Experimentally verified with seismological data:
Coda waves: Campillo and Paul, 2003;…..
Ambient noise: Shapiro and Campillo, 2004,……

Processing:

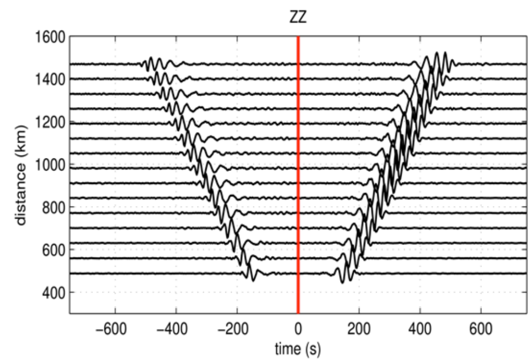
-preprocessing: stationarity of amplitude (ex: 1-bit introduced for coda waves)
-correlation of long time series (fluctuations decrease with integration time…)
-adaptative filtering…
-removing of earthquakes from ambient noise
-noise imaging/monitoring could involve large data sets and huge sets of CCs….

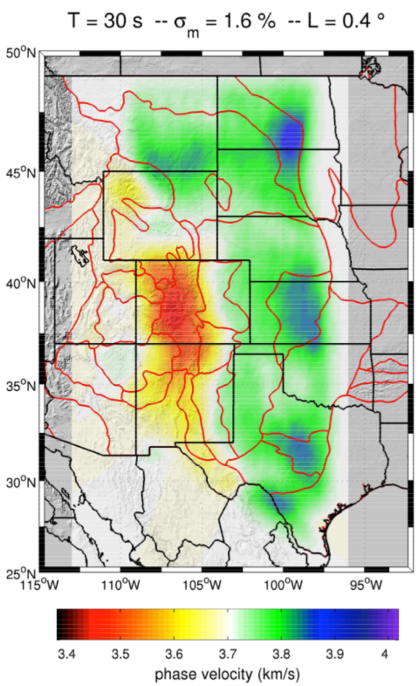
Refined imaging within a large array

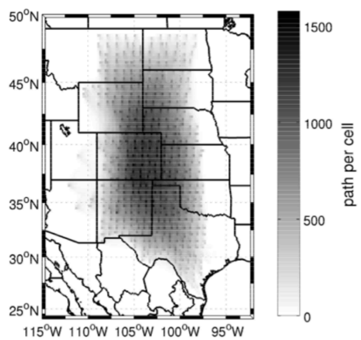
(*Pierre Boué 2013)*

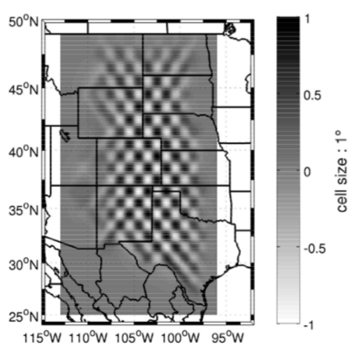


Weber et al., 1996





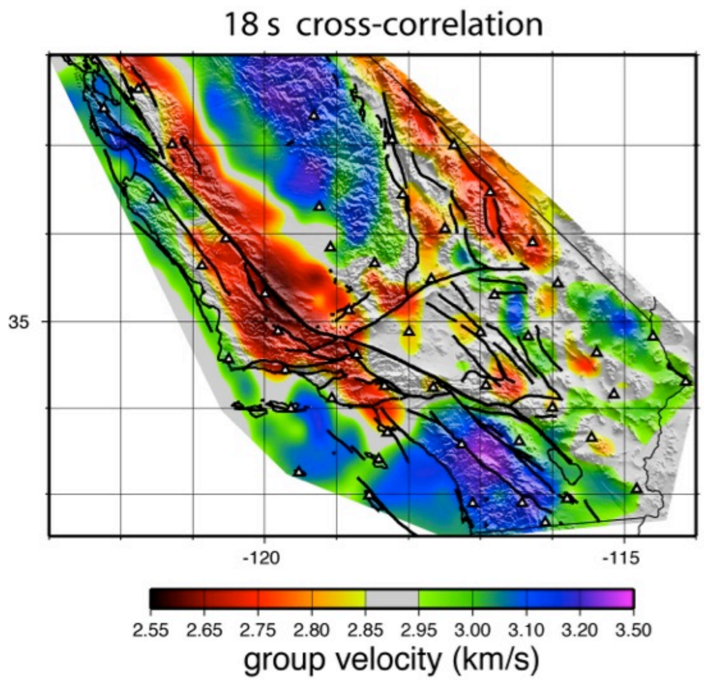




With ray bending

Surface wave imaging with seismic noise….. it works

Map of Rayleigh group velocity Vg (linear inversion)

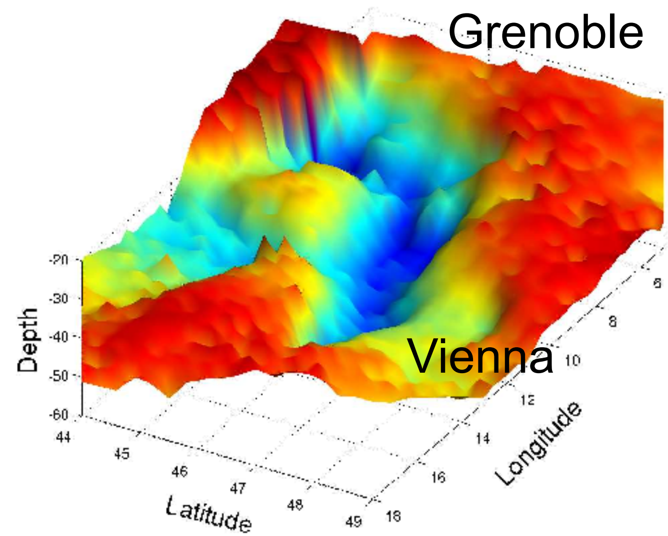


Shapiro et al. Science 2005.

3D shear velocity model

1) Vg(x,y,T)
2) Vs(x,y,z) local non linear inversion

The Moho beneath the Alps



Stehly et al. ,2009

Arbitrary medium: an integral representation written in the frequency domain

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

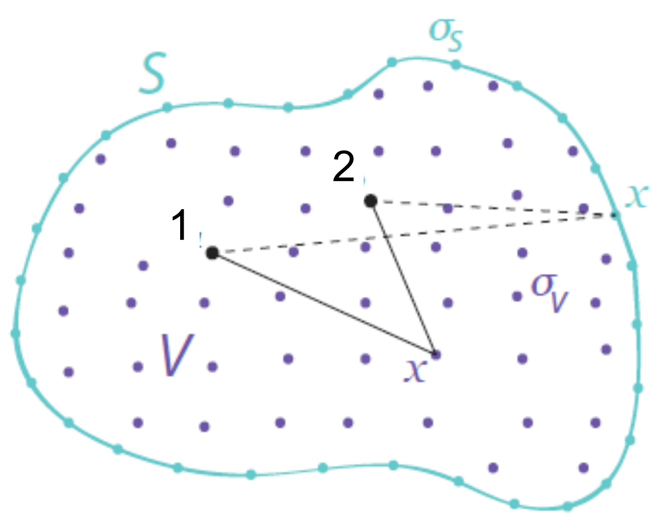
Volume term

Surface term

FT of $G(-t)$

Absorption coefficient

FT of $G(t)$



Surface term:

κ =0 (no attenuation)

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

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:

$$G_{12} - G_{12}^{*} = -2i\frac{\omega}{c} \oint_S G_{1x} G_{2x}^{*}\, dS$$

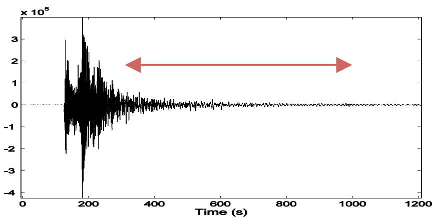
Volume term: $$G_{12} - G_{12}^* = \frac{4i\omega\kappa}{c} \int_{\mathcal{V}} G_{1x} G_{2x}^* \, dV$$

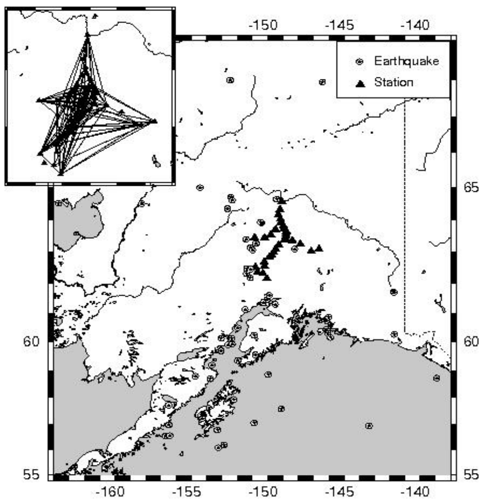
κ is finite (attenuation)

S is assumed to be sufficiently far away, for its contribution to be neglected (spreading and attenuation)

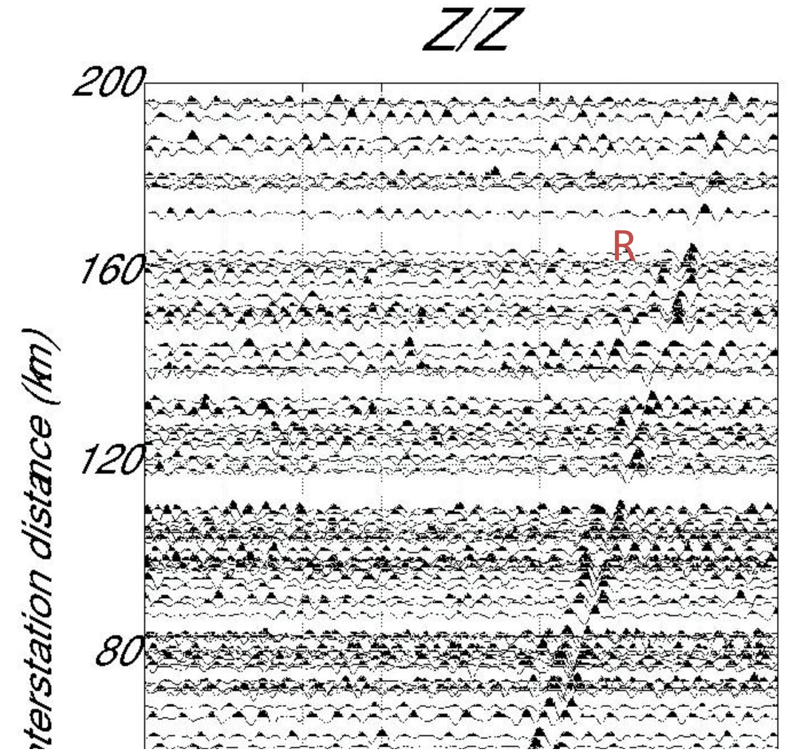
Note that scatterers can be regarded as internal sources ➔ coda correlations

BEAAR experiment



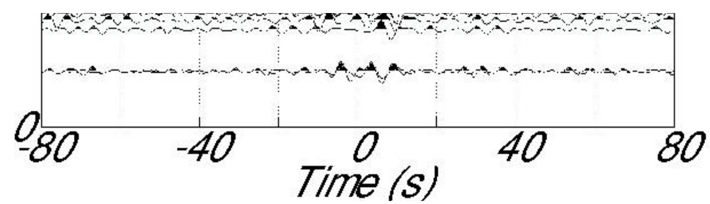


Coda Correlations



Time scales

Hours (coda) to months-years (ambient noise)



Short time windows

Time symmetry: energy flow

(Paul et al., 2005)

Using ambient noise

Let's be practical:

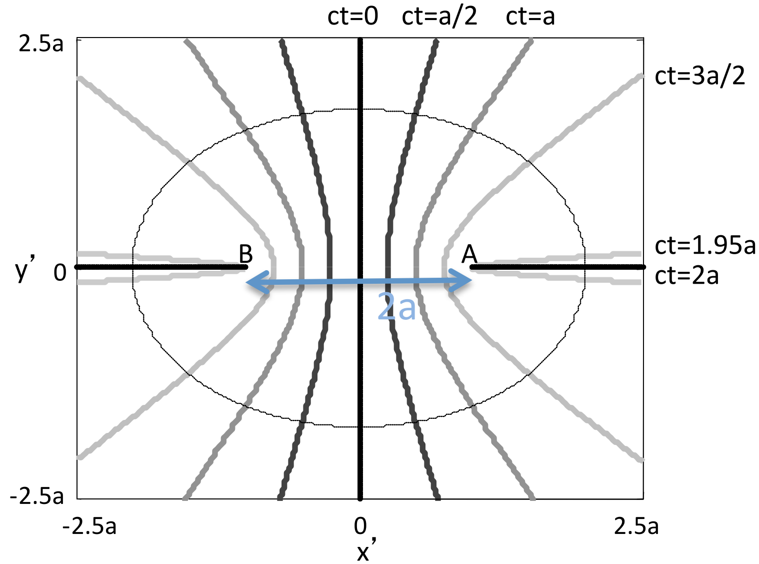
We have no control on the noise sources and we cannot perform field experiments with such ideal distribution of sources…

At short period, we are usually NOT in the far field of the heterogeneities

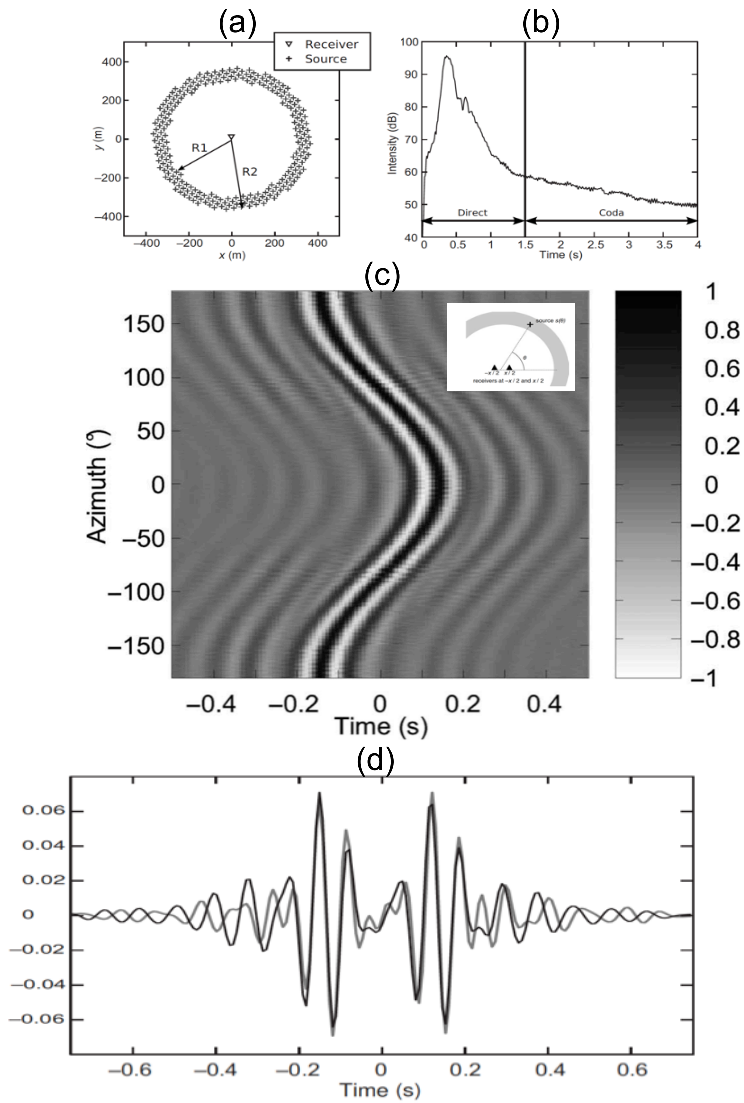
We cannot measure easily the gradients of the fields….

Location of the sources that contribute to the correlation.
Ray approximation for direct waves: the end fire lobes

Difference of travel time between A and B
wrt the position of the source

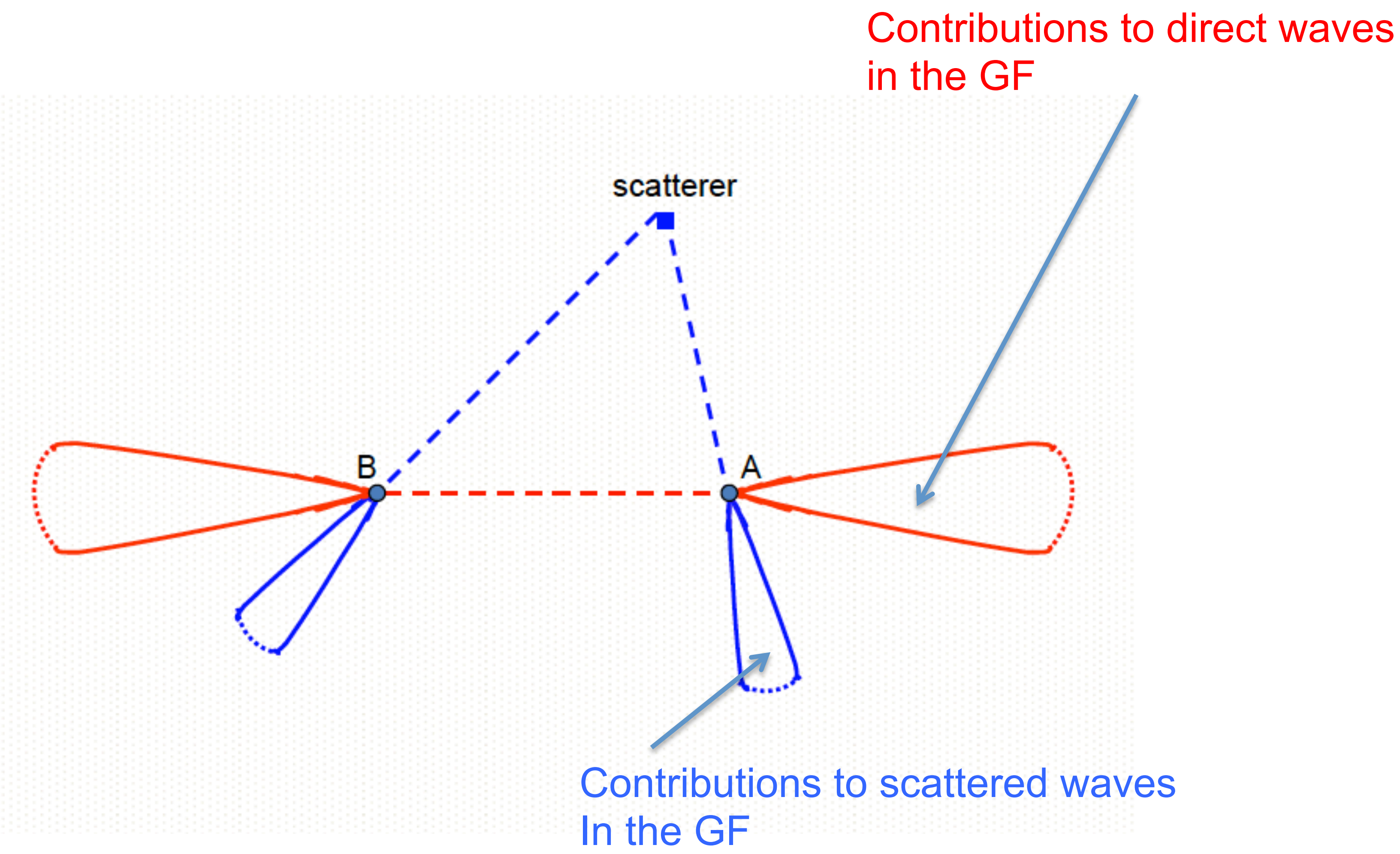


Stationary phase and end fire lobes: actual data



From Gouédard et al., 2008

End fire lobes



Extension to scattered waves by H. Sato

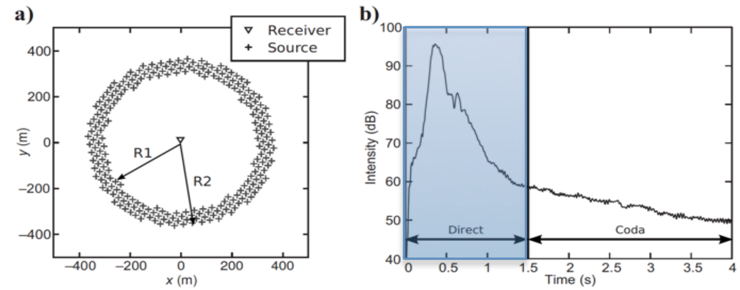
In practice, the noise sources are not evenly distributed and the field is not made isotropic by scattering.

At first order we can study the effect of non isotropy of the incident field intensity on the receivers.

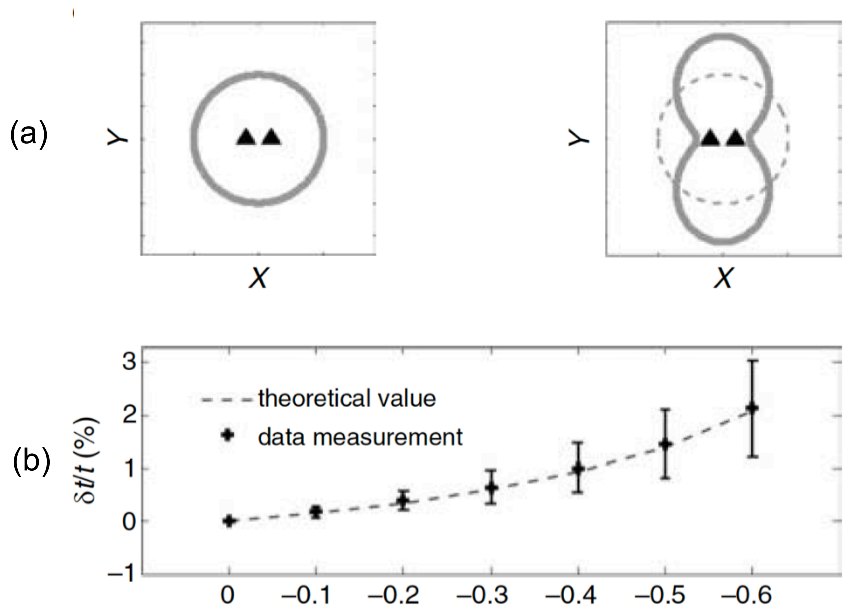
It results in bias on the measurements of direct path travel times.

Correlation of direct waves

Bias in the travel time



Increasing anisotropy of the noise intensity *B*

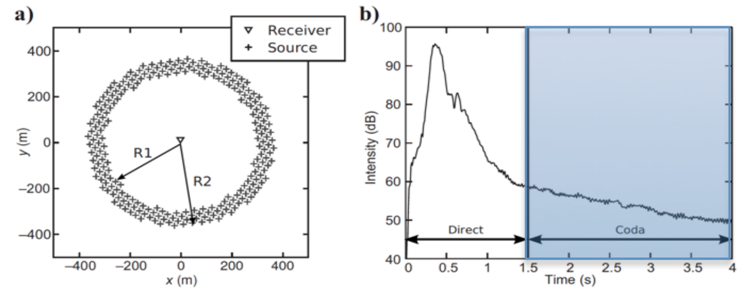


$$B(\theta) = 1 + B_2 \cos(2\theta)$$

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

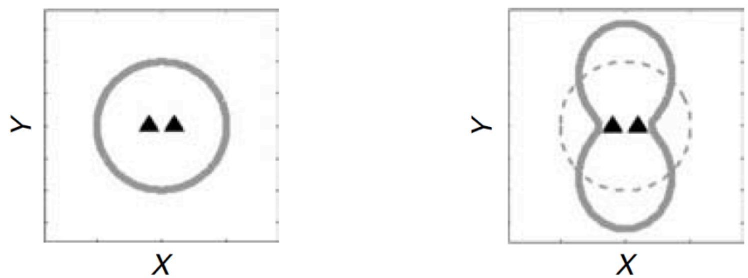
From Froment et al., 2011.

Correlation of coda waves



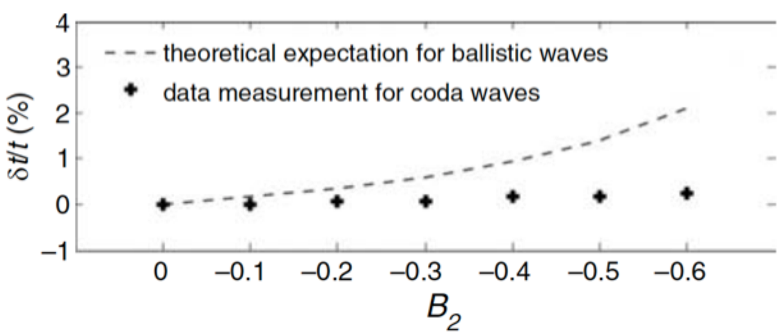
Increasing anisotropy of the noise intensity *B*

(a)



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

(b)



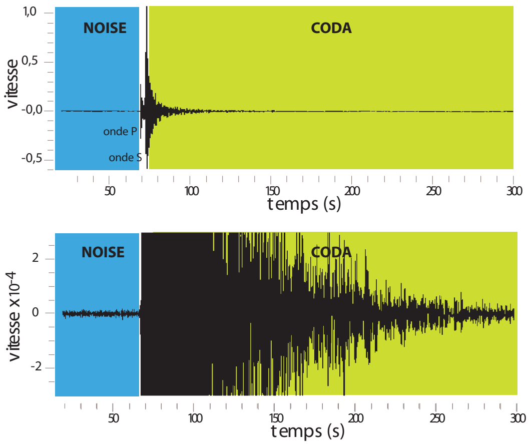
No bias in the correlation of coda waves!

From Froment et al., 2011.

Noise records contain direct and scattered waves

We can construct virtual seismograms between stations pairs from noise records.

They contain the information about structures, but also all the complexity of actual seismograms



Specifically they contain the scattered waves (coda waves). This is attested by the fact that we can also construct 'virtual' seismograms from the correlation of noise based virtual seismograms

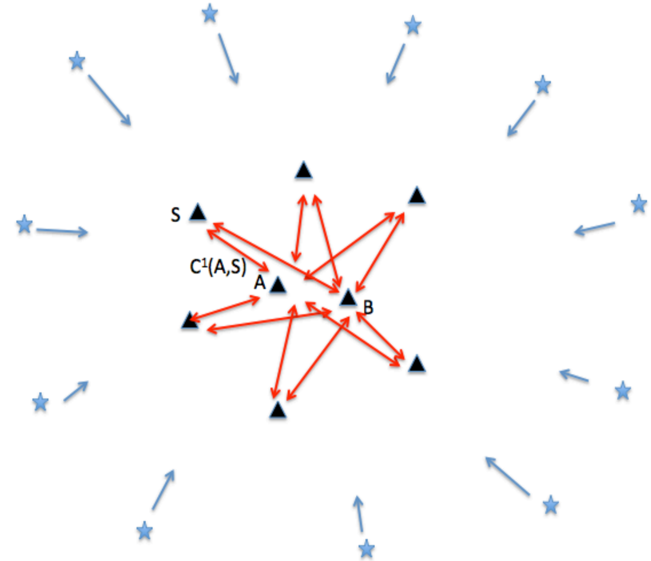
➔ C^3 method *(Stehly et al., 2008; Garnier et al., 2011)*

➔ can even be iterated in C^5.. *(Froment et al., 2011)*

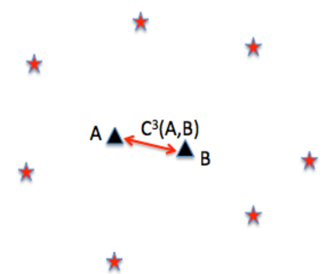
➔ long travel times = strong sensitivity to changes

Illustration of C3

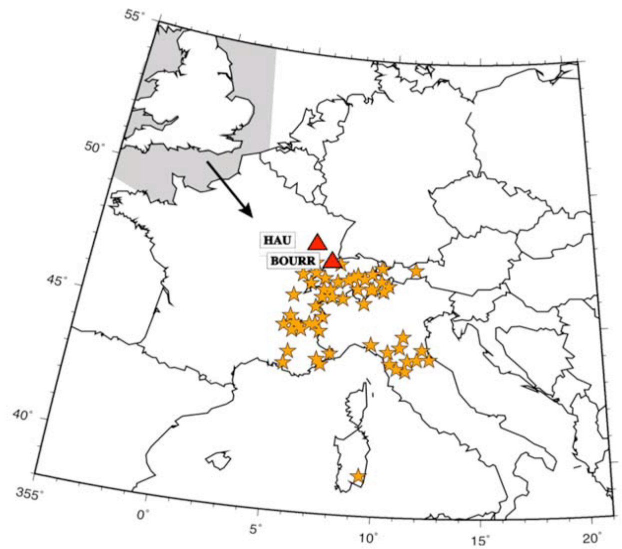
(a) Computation of noise correlations (virtual seismograms)

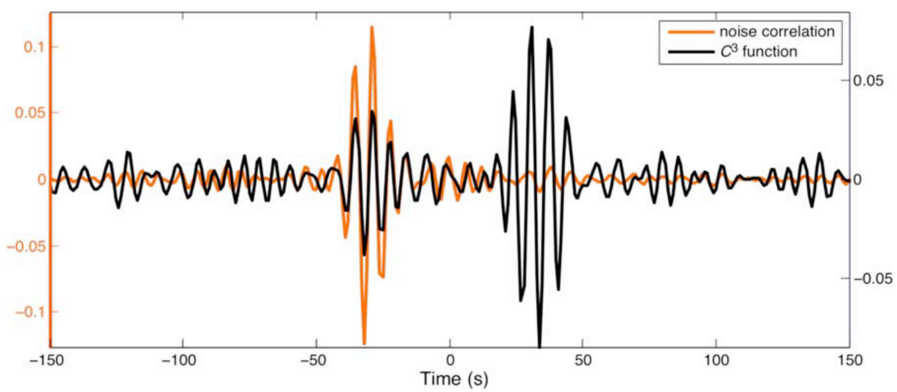


(b) Correlations of noise correlation codas (stations as virtual sources)



Remove the influence of actual source distribution- or extracting multiply scattered waves

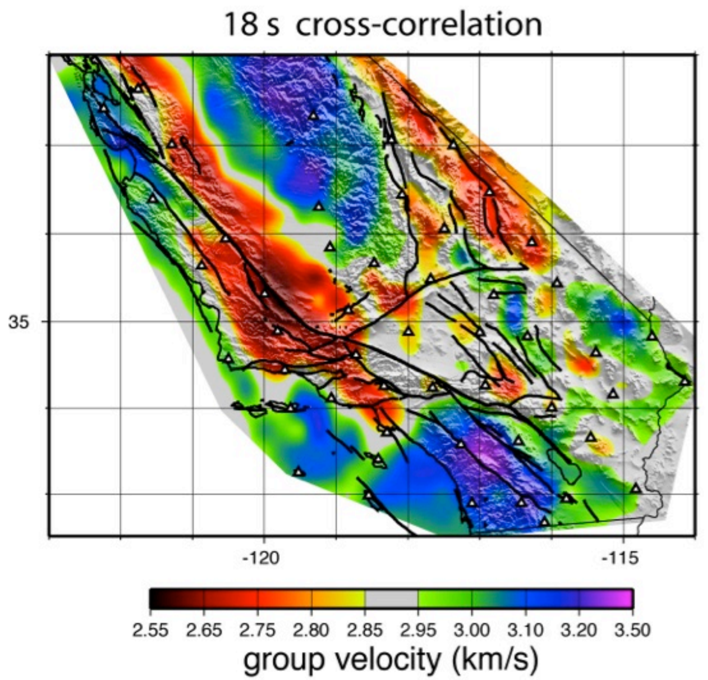




➔Physical significance of the coda of noise correlation

Surface wave imaging with seismic noise….. it works

Map of Rayleigh group velocity Vg
(linear inversion)



Shapiro et al. Science 2005.

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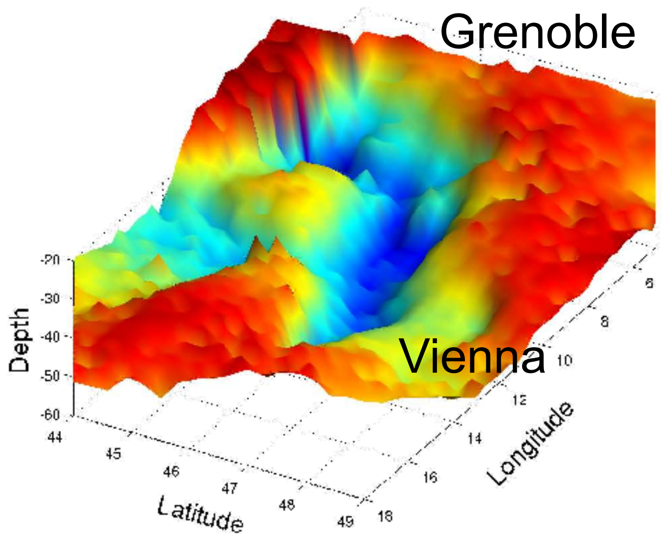
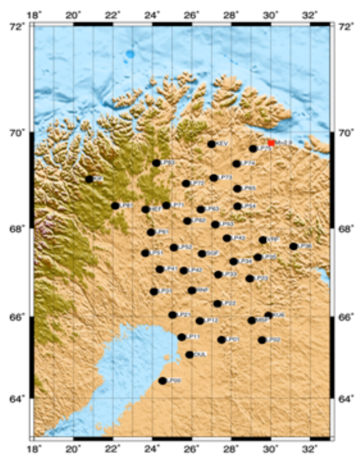


Stehly et al. ,2009

Surface wave tomography ➔ body waves (deep reflections)

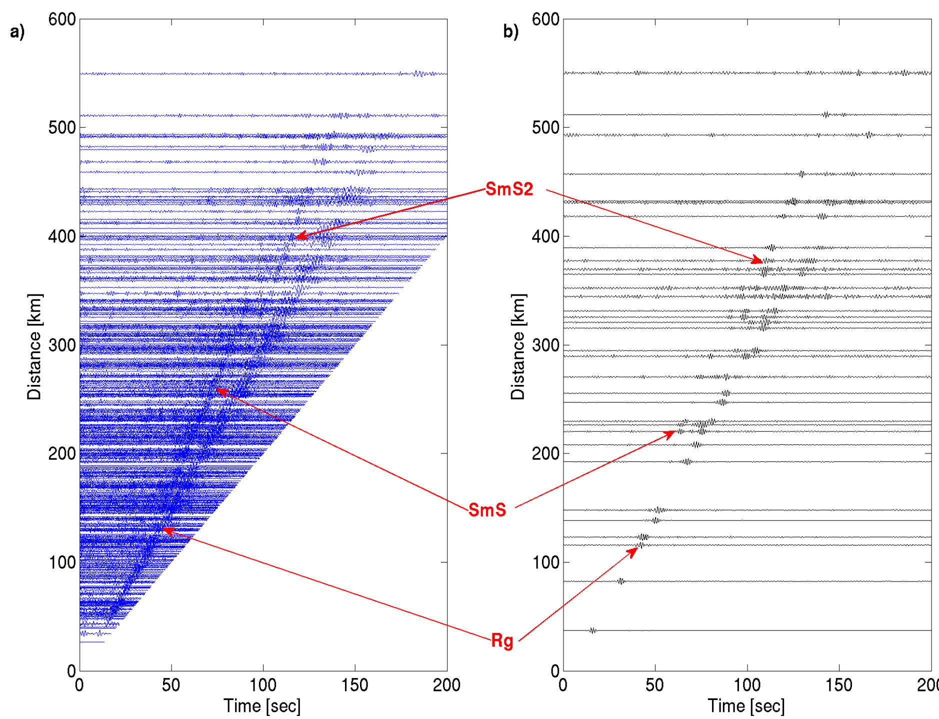
POLENET/LAPNET array in Finland



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

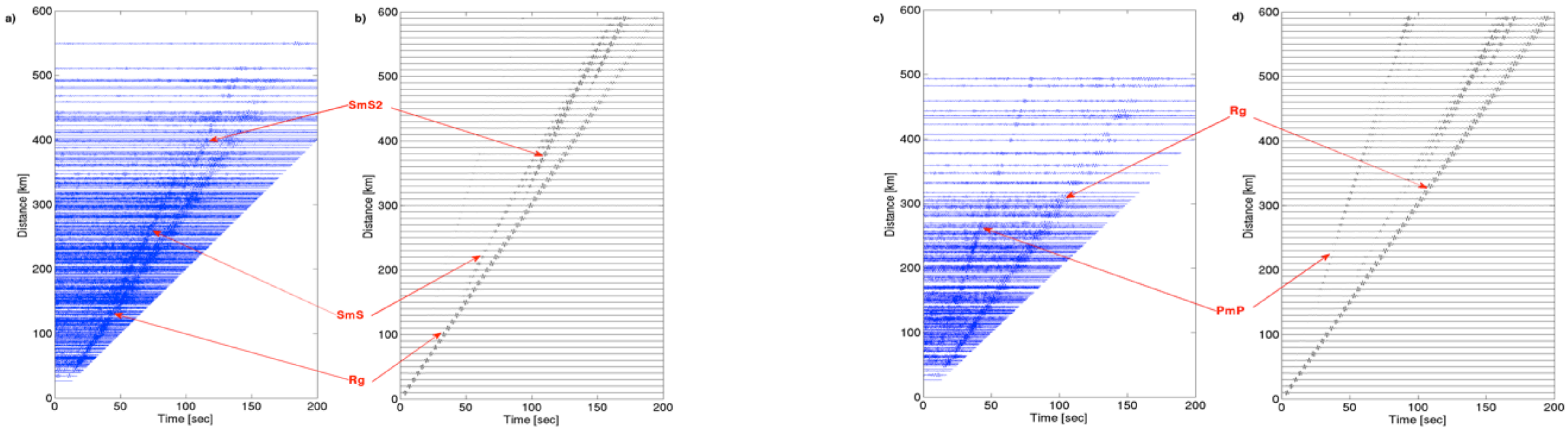
Poli et al. 2012a

Z-Z noise correlations Z comp. actual earthquake



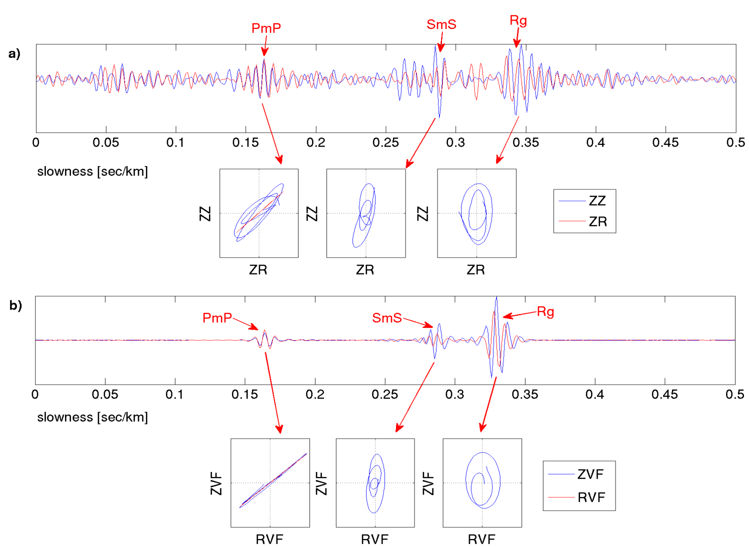
Comparison with synthetic Green functions

C_{ZZ} (data) GF_{ZZ} (theory) C_{RR} (data) GF_{RR} (theory)



Reconstruction of P and S multiple reflections

Polarisation: noise correlation vs synthetics



Good reconstruction of phase and relative amplitudes of the components of the reflected waves. (amplitude discussed by Prieto)

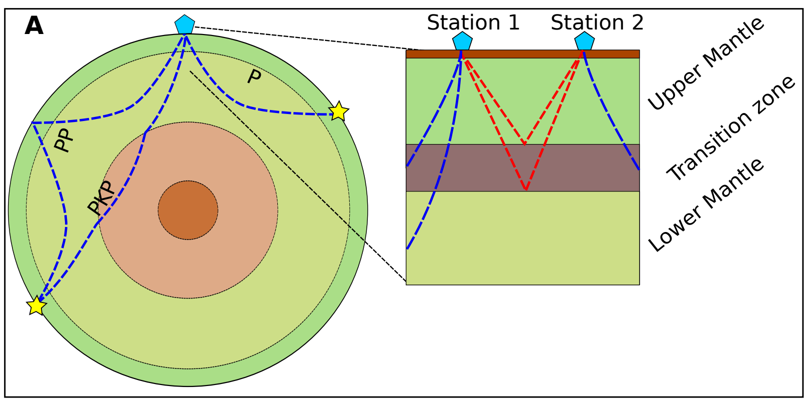
A favorable context: distance vs. mean free path, amplitude in actual earthquake records

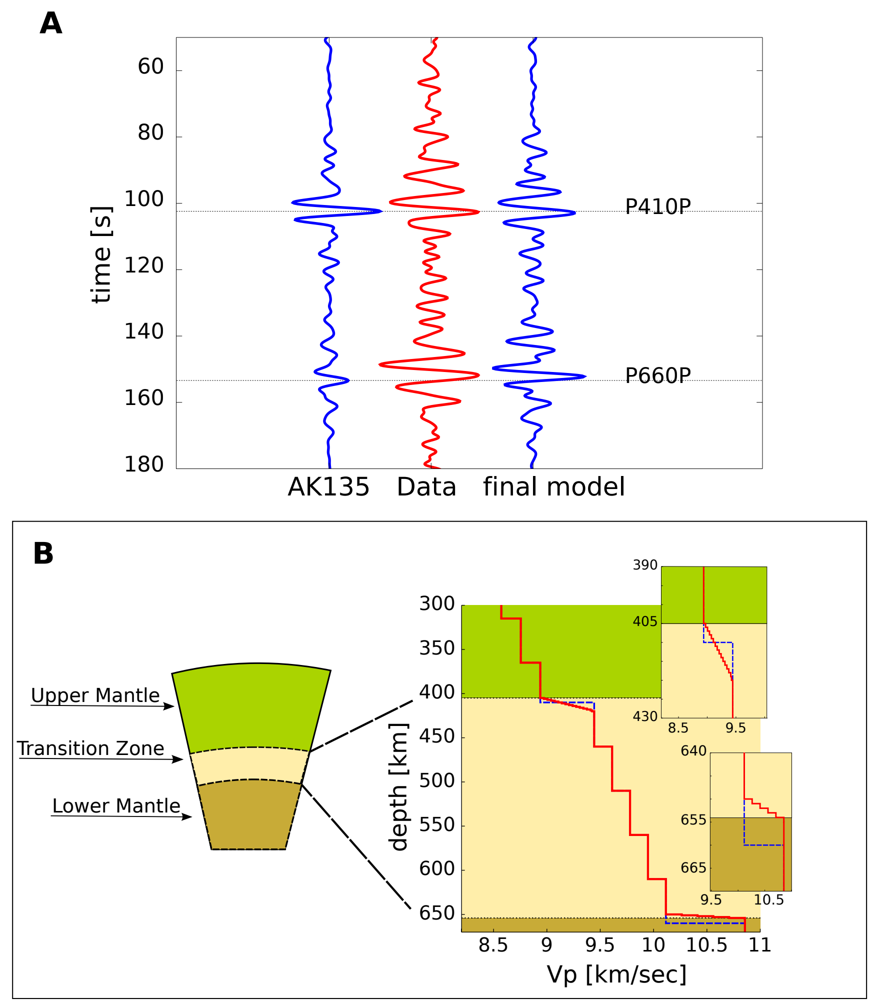
➔ Deep phases

Poli et al., 2012a

➔Earth's mantle discontinuities from ambient seismic noise (crystalline phase transition ➔ (P,T))

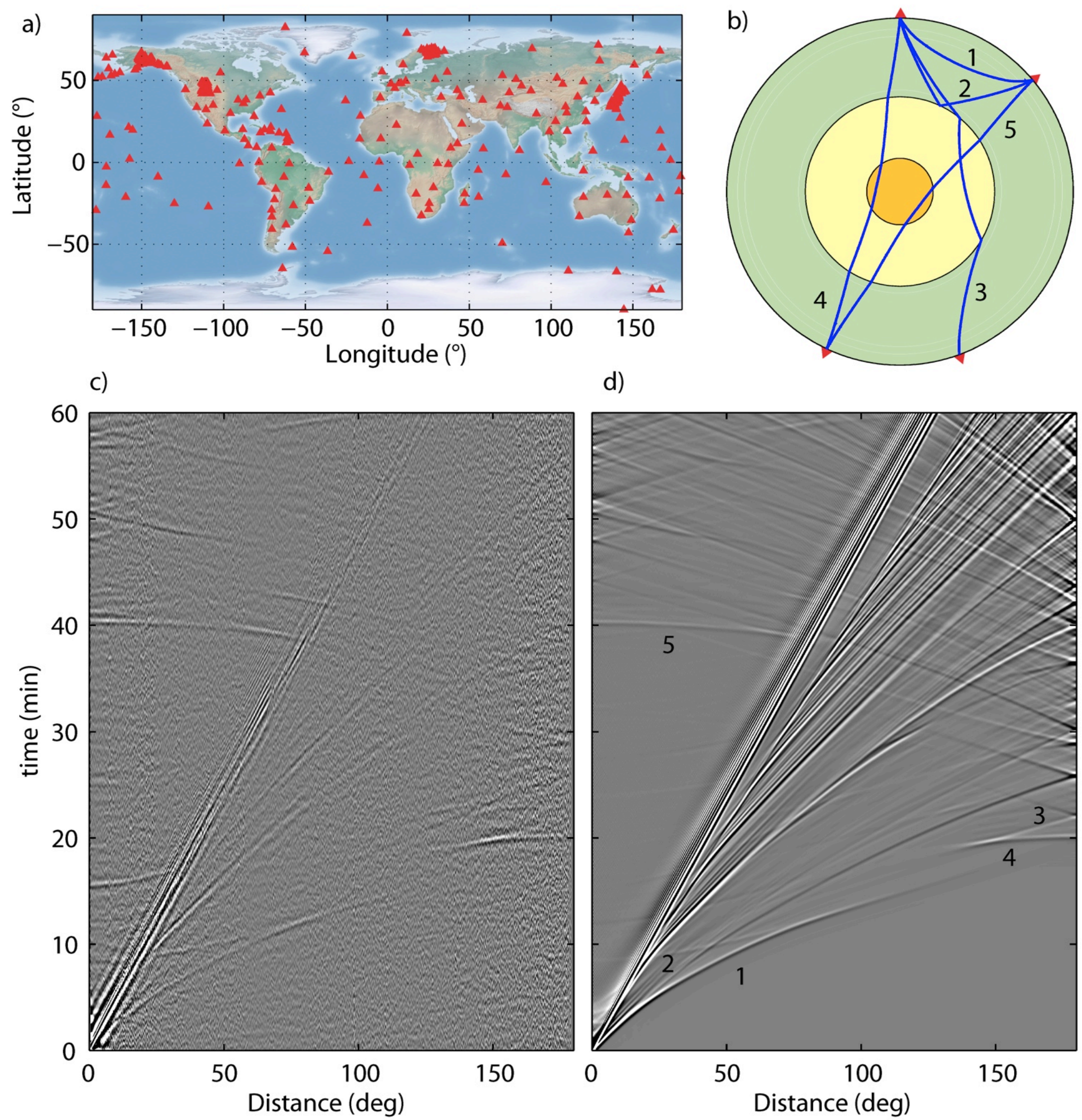
Poli et al. Science 2012



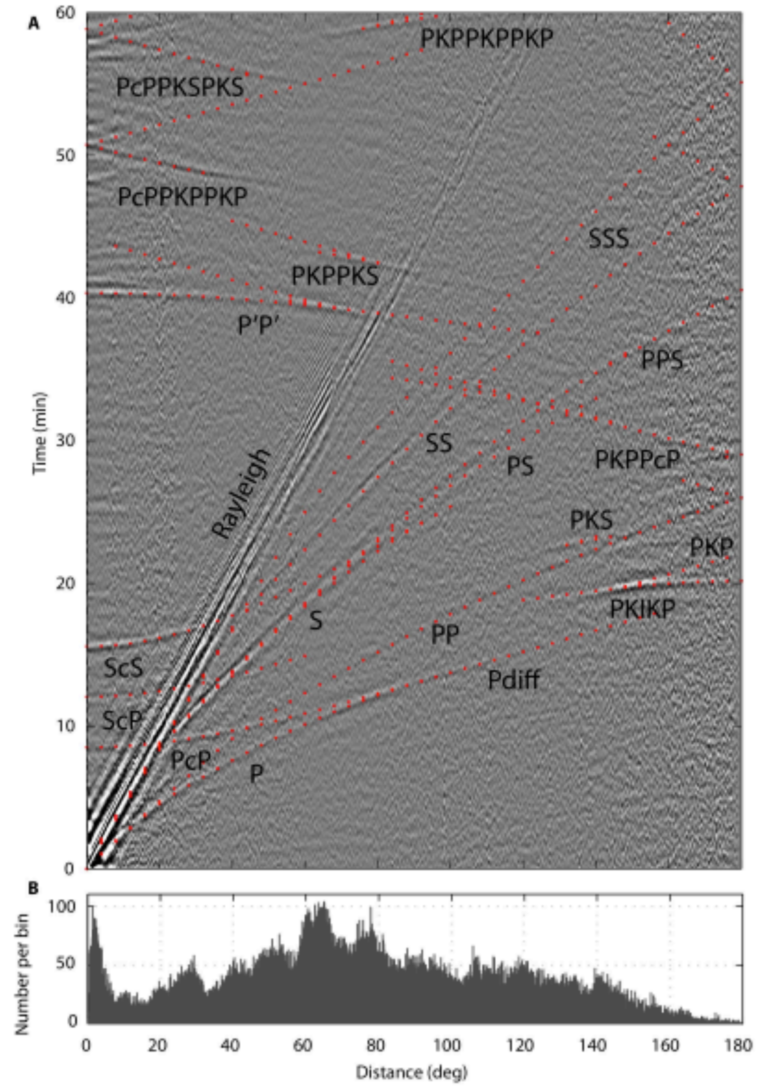


GLOBAL TELESEISMIC CORRELATIONS (periods 25-100s)

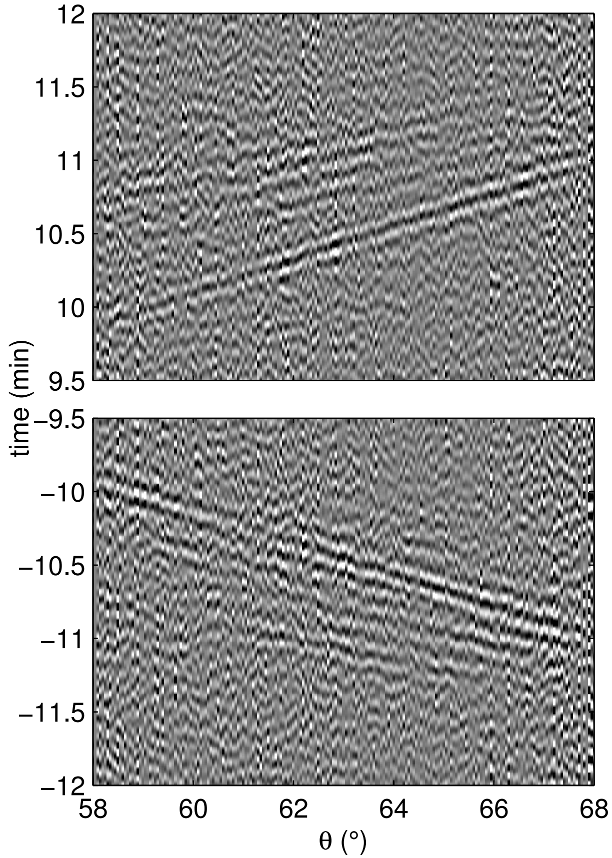
Boué, Poli et al., GJI 2013



Numerous phases can be identified



Short periods 5-10 s



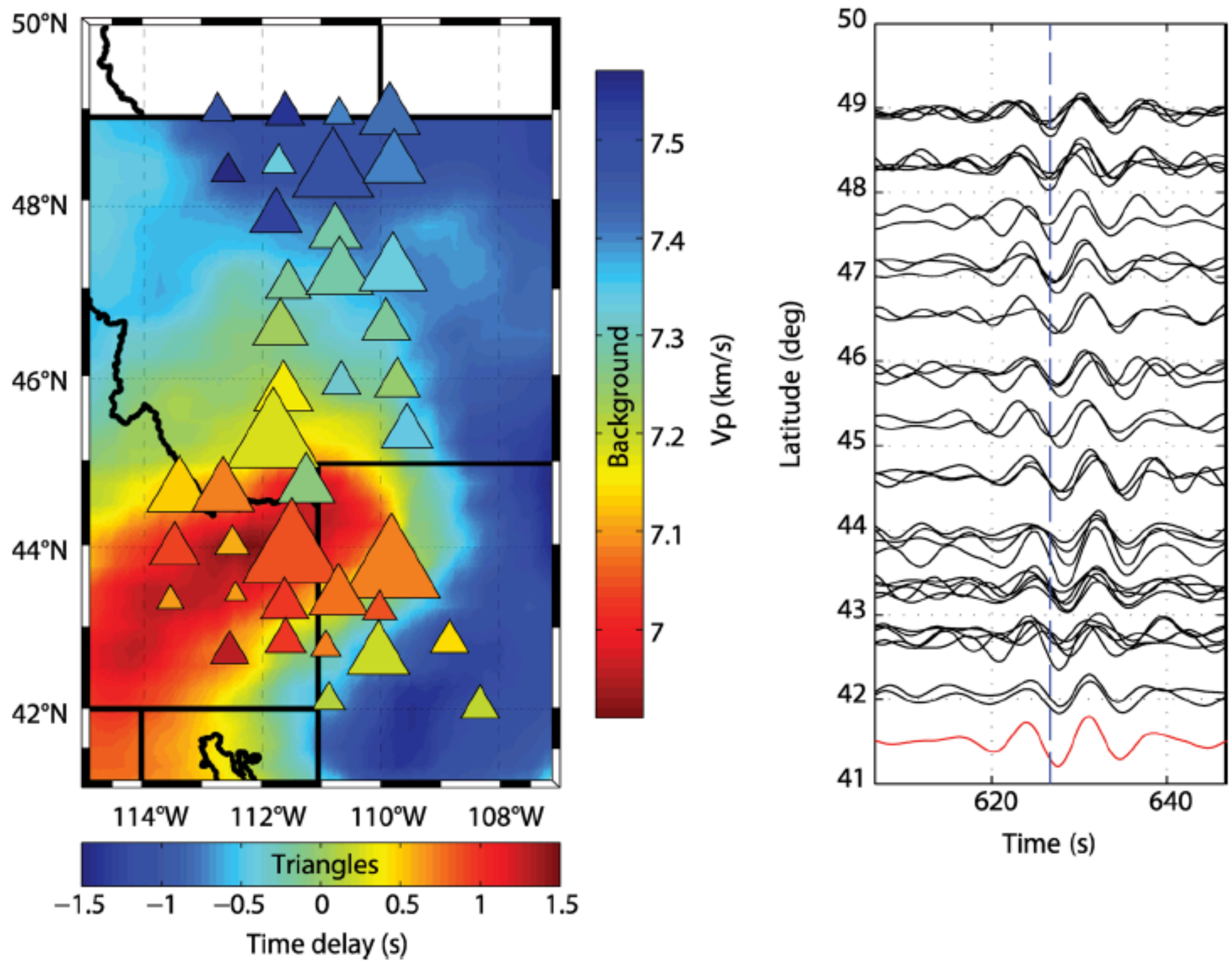
Japan to Finland

Finland to Japan

Standard pre-processing (Shapiro and Campillo, 2004; Sabra et al. 2005) eliminates the contamination by EQ ballistic waves.

Examples of applications:

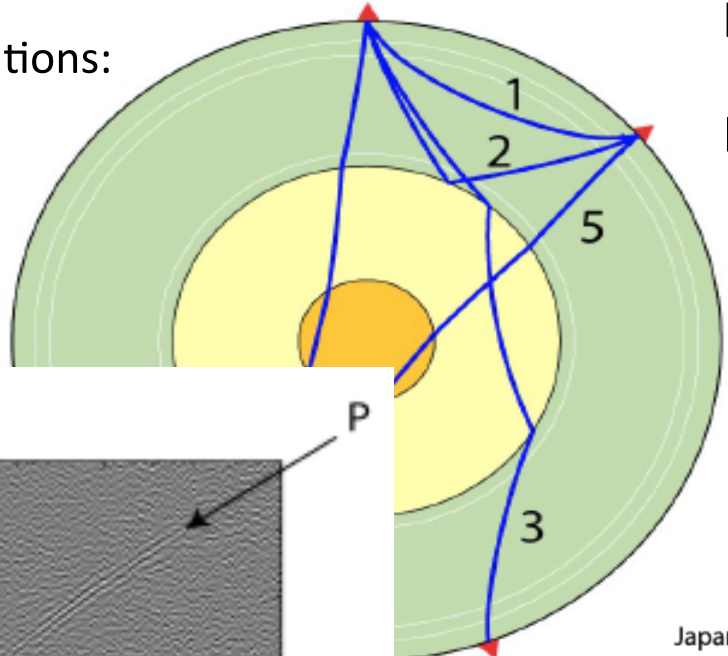
Teleseismic delays in the Yellowstone region using USArray-LapNet subarrays

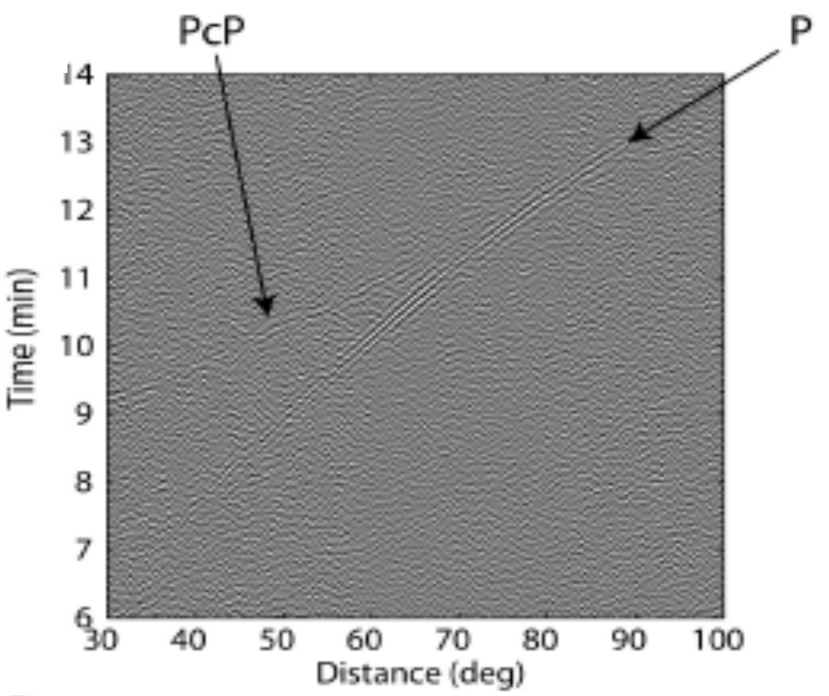


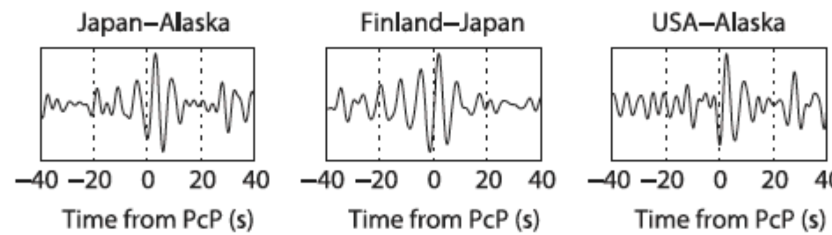
Examples of applications:

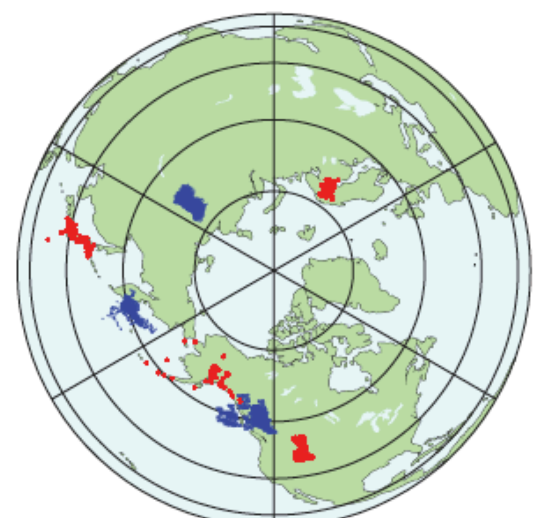
Periods 5-10s

Imaging the core-mantle boundary



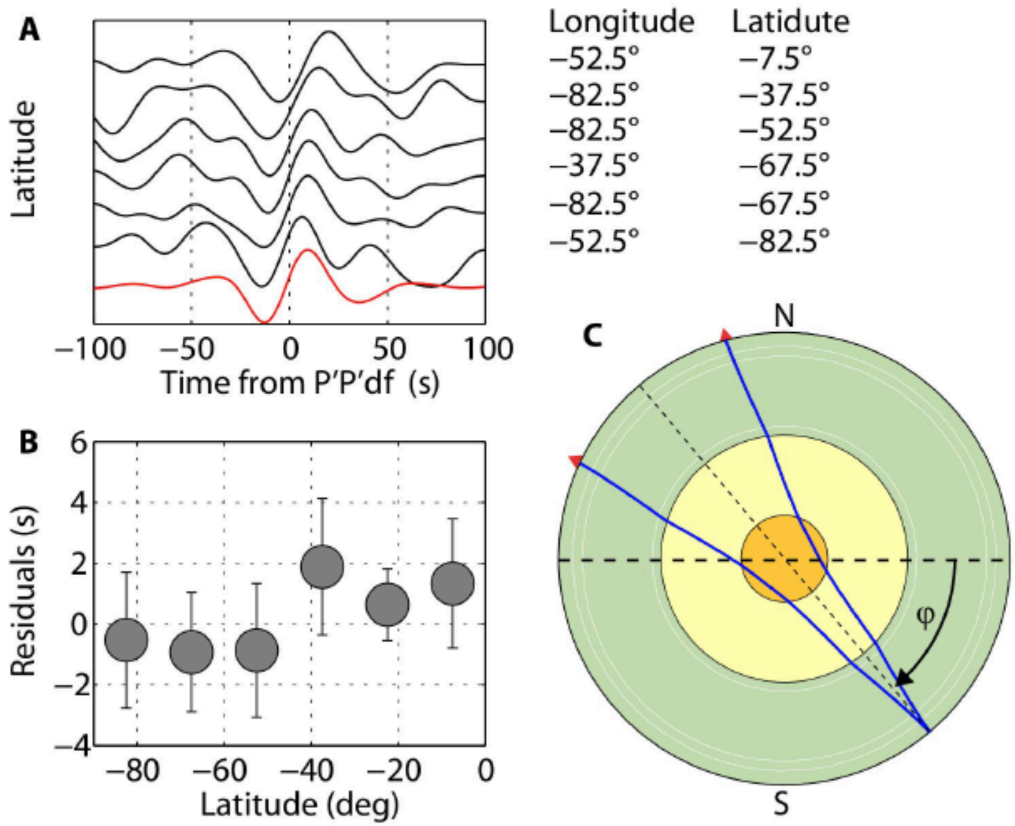






Examples of applications:

Measure of the anisotropy of the inner core:
(polar paths are faster than equatorial paths)

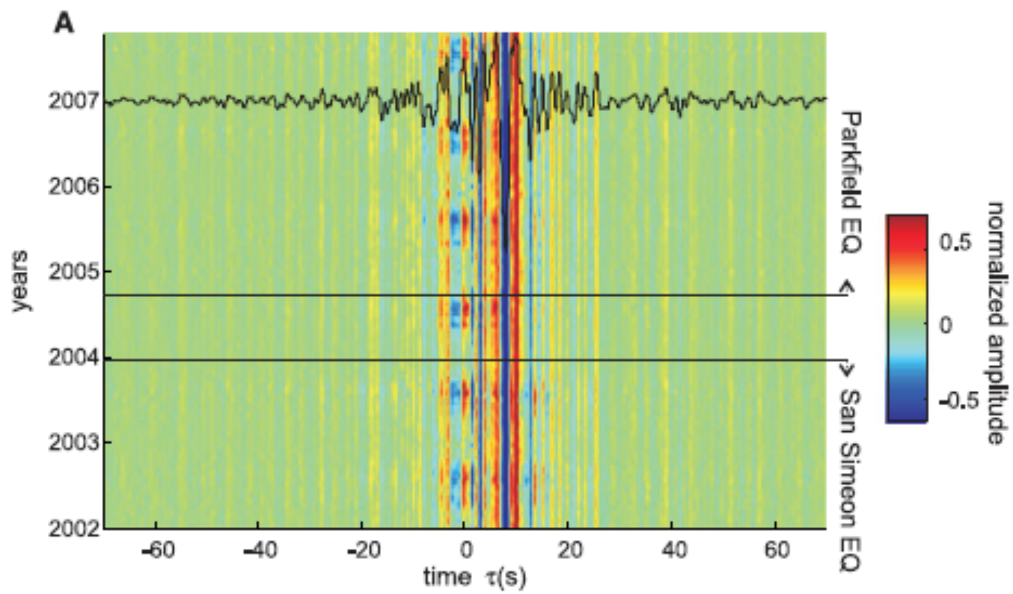


Boué, Poli et al., GJI 2013

➔ Numerous applications to come!

Perspectives: imaging and monitoring

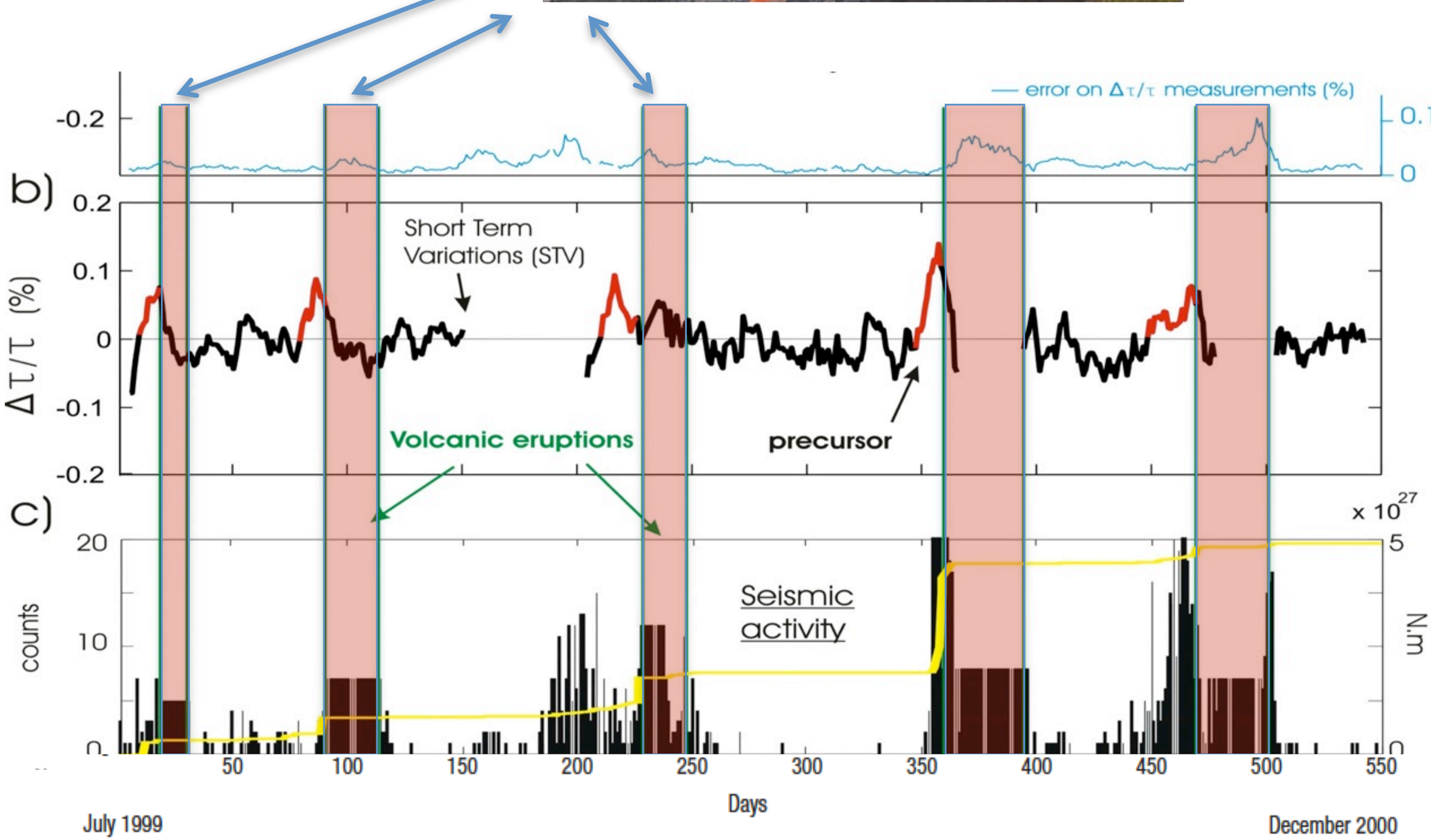
Correlation functions as approximate Green functions
)

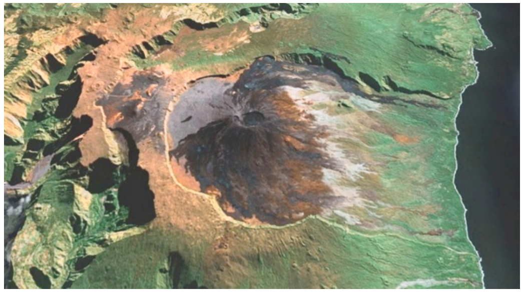


Direct waves are sensitive to noise source distribution (errors small enough for tomography (≤1%) but too large for monitoring (goal ≈ 10^{-4})

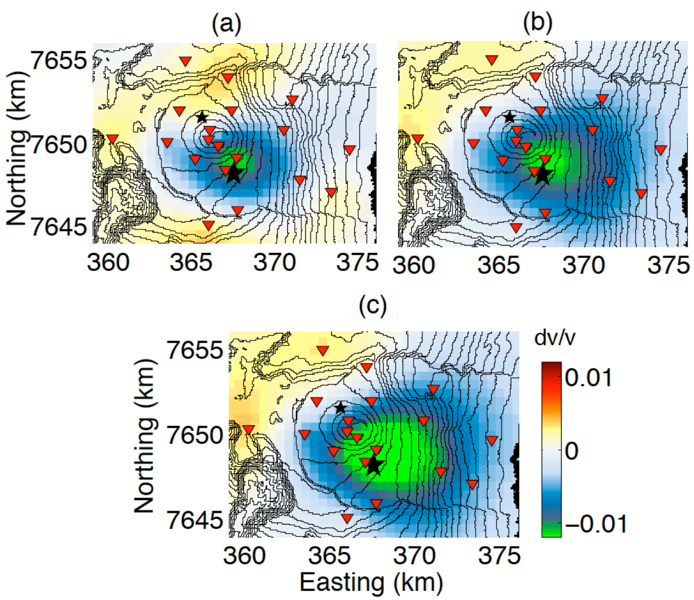
Stability of the 'coda' of the noise correlations = frozen distribution of scatterers

Seismic speed changes before the eruptions...

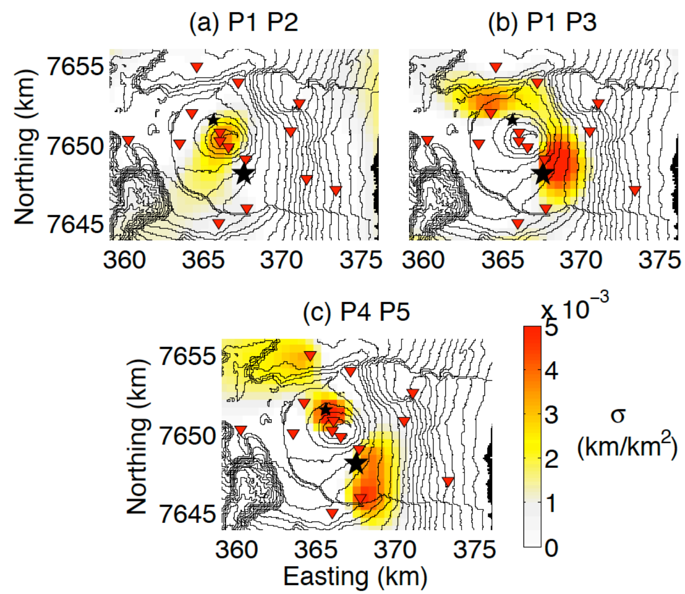




4D passive imaging of a volcano



Local change of speed



Local change of scattering properties

Anne Obermann PhD 2013