ISTerre
Institut des Sciences de la Terre

European Research Council
Adv. Grant Whisper

Introduction to ambient noise session

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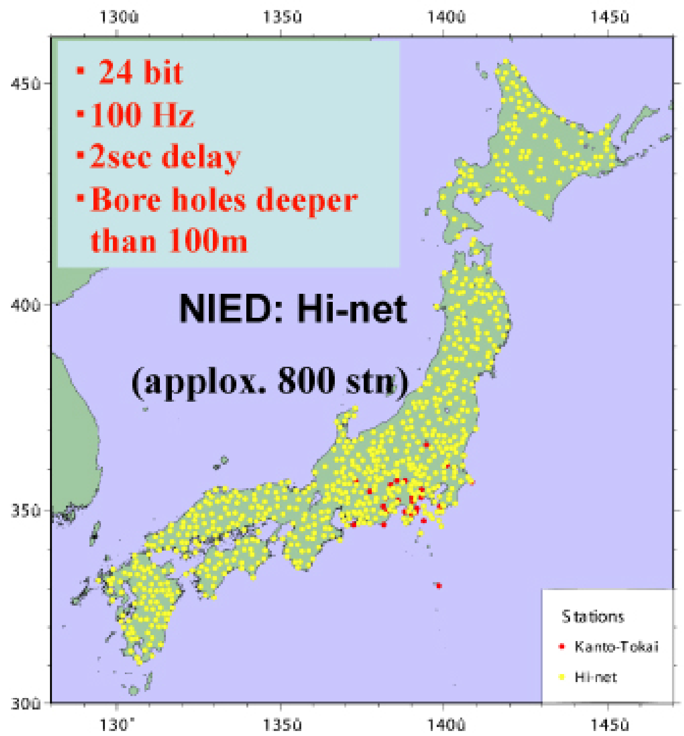
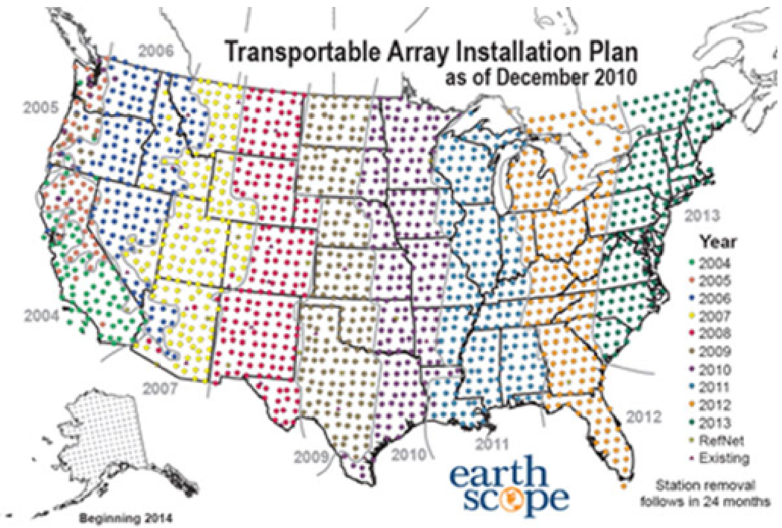
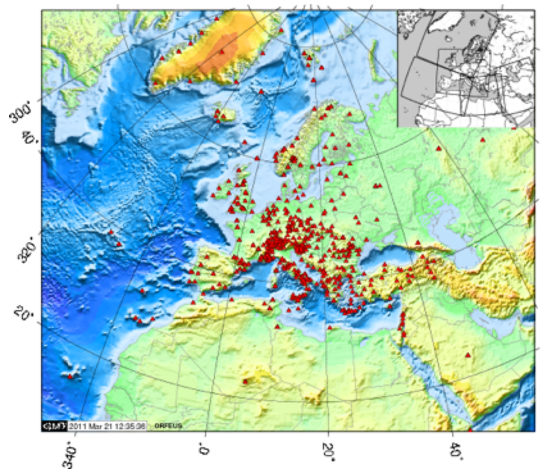
QUEST Benodet 2013

Large networks – continuous recordings





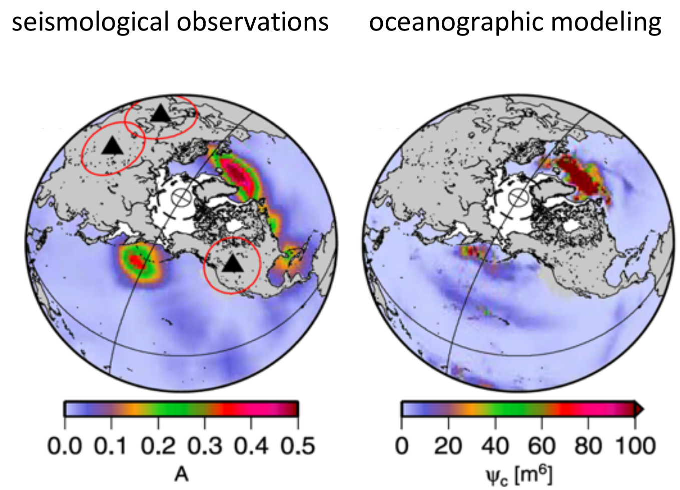


Seismology : huge data sets consisting for a large part of 'ambient noise'..

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

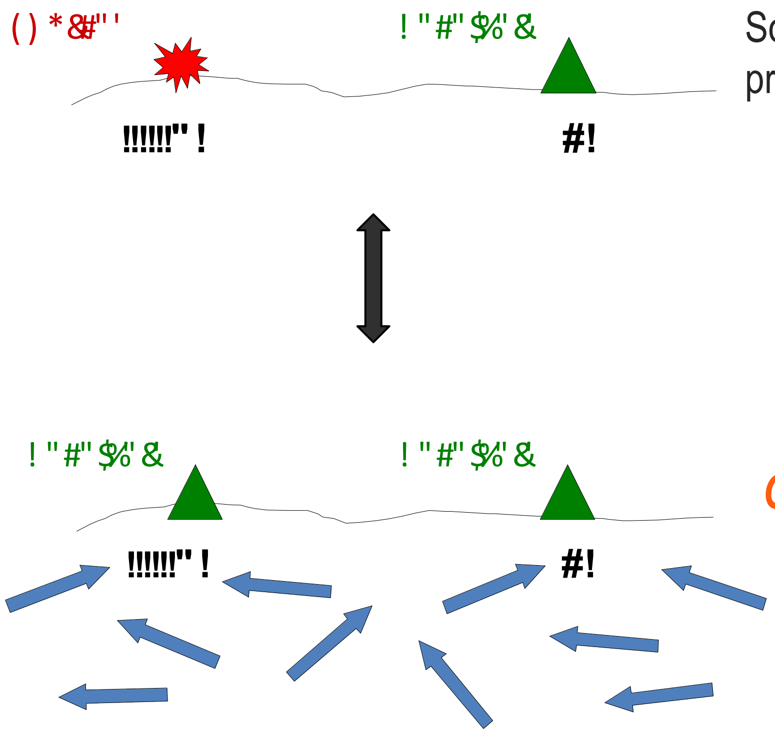
Strong contribution from oceanic waves

Example of a global comparison



Hillers et al., 2012

Talks by Stutzmann and Gualtieri



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})

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

Souvenirs, souvenirs….
(more objective story by Courtland Nature 2008)

One of a series of interdisciplibnary workshop on Multiple Scattering held in Cargese (Corsica) in 1999

❖ diffusion, radiative tranfert
background: energy density (x,t)
configuration average <medium disorder>
random phases (specific intensity => <energy>

coda enveloppes, still an open field

❖ observation of coherent backscattering (weak localization)
spot of enhanced intensity at the source at late lapse time
signature of interference of reciprocal multiply scattered waves
scale: λ / phase effect / mesoscopy

 Non random phase = correlation of wave fields

Discussion in Cargese (with Richard Weaver, Bart van Tiggelen, Arnaud Derode,..):

Detectable long range correlations in the form of the Green function?

(In geophysics: ‘local correlations’: 1950’s Aki, Cox, … 2D $J_0(kr)$ SPAC
1960’s Clearbout .. 1D reflectivity
+ helioseismology)

On an argument of equipartition, we expected that <u1,u1> ≅ G12

Tests:

Laboratory acoustics Weaver and Lobkis 10^5-10^7 Hz (reverberation cavity and thermal noise)

=> W&L 2001; L&W 2001

Seismology (coda waves) Paul and Campillo 10^{-1}-1 Hz GF tensor

=>P&C 2001 AGU; C&P 2003 (!)

Note (time average; source average; no configurational average (indeed))

Explanation, theoretical arguments

Physics toolbox

Statistical Physics: configuration average → average Green function (different realizations of Earth disorder?)

Representation theorems surface integral Wapenaar, ….
volume integral Roux-Kuperman, Colin de Verdière….

Playing ‘who was first?’

Ward Identity (1950)
Fluctuation-dissipation theorem (1930?)
Einstein, Bolzmann, Green, Newton, Aristoteles???

→ Very general properties (no restriction ballistic waves, homogeneous media, far field…. Practical but limiting)

Arbitrary medium: an integral representation written in the frequency domain

(the Ward identity---*see discussions in e.g. Weaver et al. 2004, or Snieder, 2007)*

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

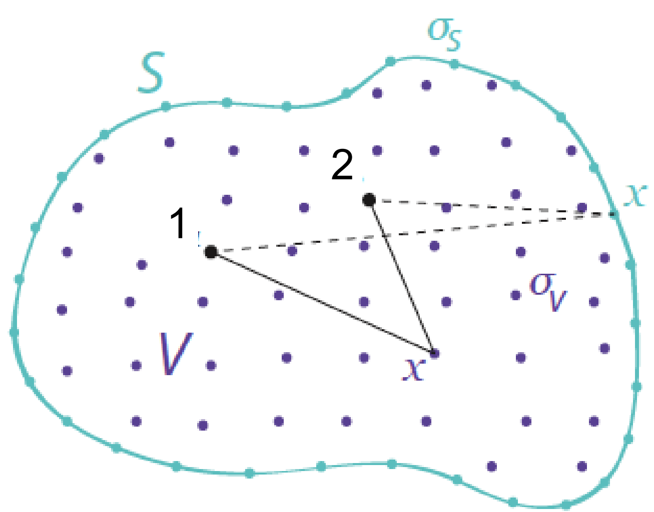
Volume term

Surface term

FT of $G(t)$

FT of $G(-t)$

Absorption coefficient



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:

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

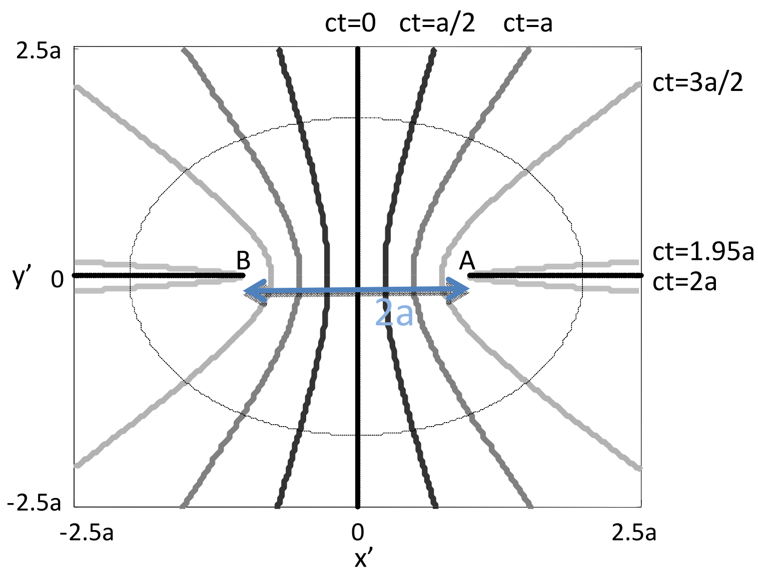
Volume term: $$G_{12} - G_{12}^{*} = \frac{4i\omega\kappa}{c} \int_{\mathcal{V}} G_{1x} G_{2x}^{*} \, dV$$

κ is finite (attenuation)

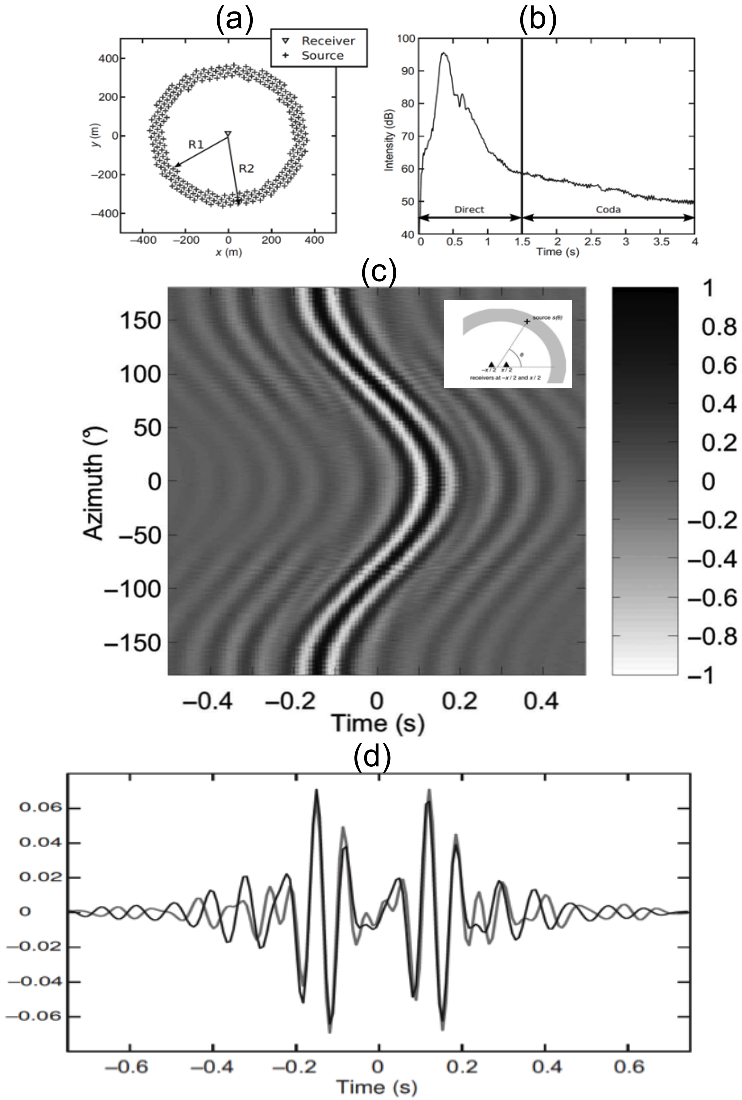
S is assumed to be sufficiently far away, for its contribution to be neglected (spreading and attenuation)

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

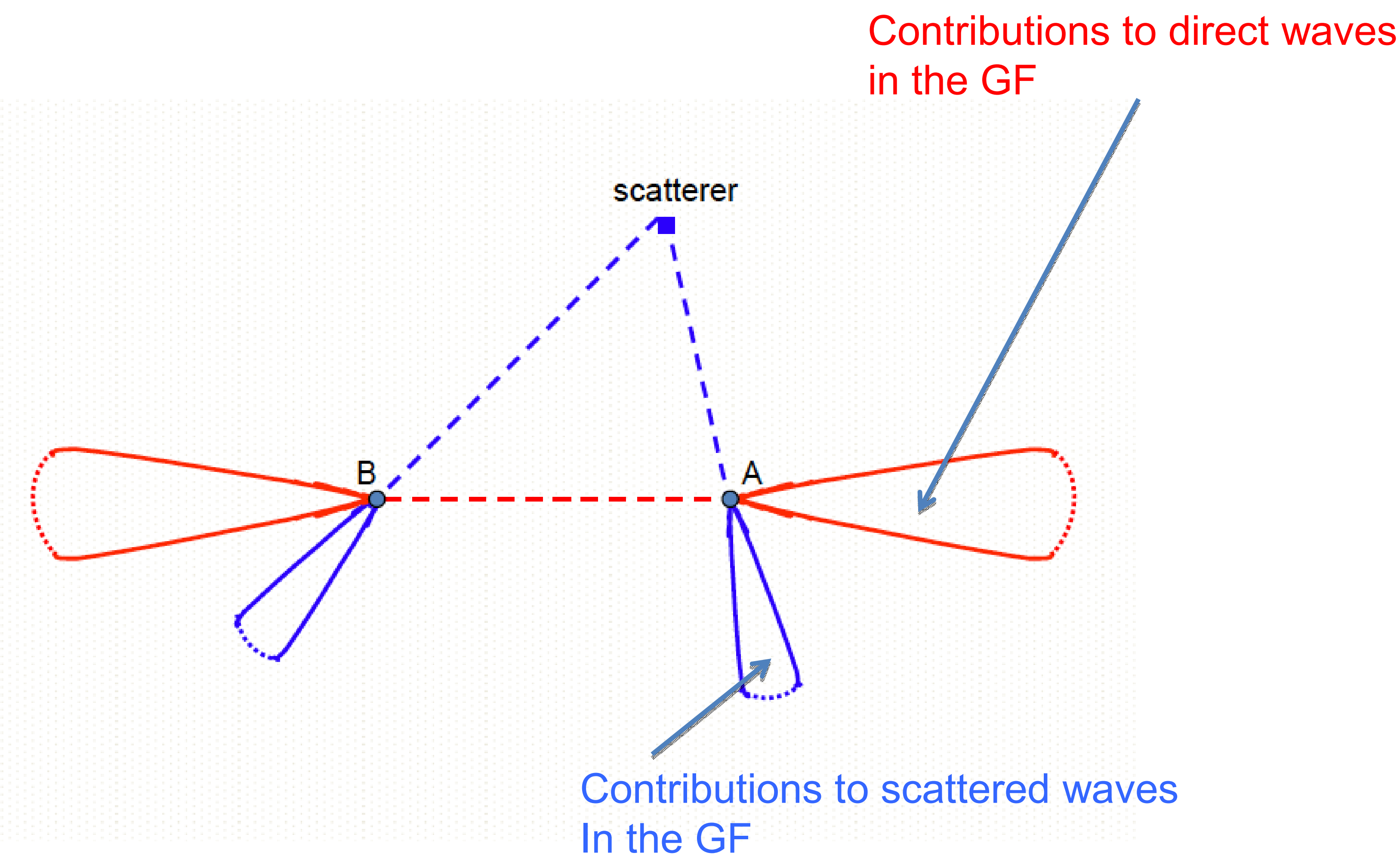


Stationary phase and end fire lobes: actual data



From Gouédard et al., 2008

End fire lobes



Extension to scattered waves by H. Sato

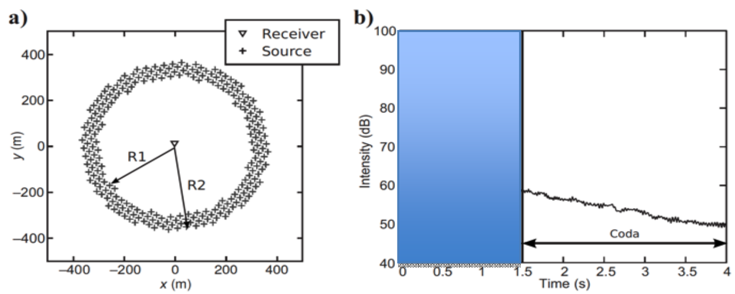
In practice, the noise sources are not evenly distributed and the field is not equipartitioned.

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

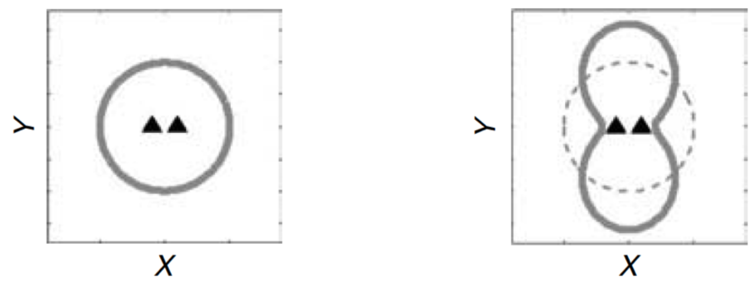
It results in bias on the measurements of direct path travel times.

Correlation of direct waves

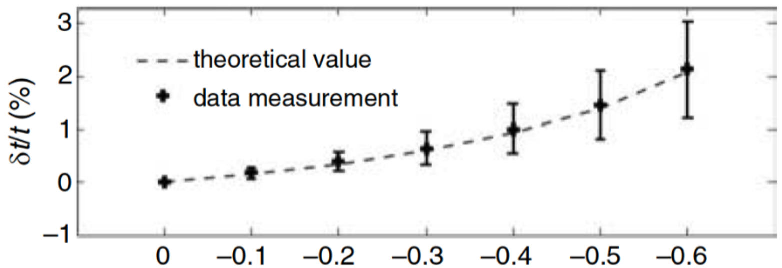
Increasing anisotropy of the noise intensity *B*



(a)



(b)



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

Bias in the correlation of direct waves

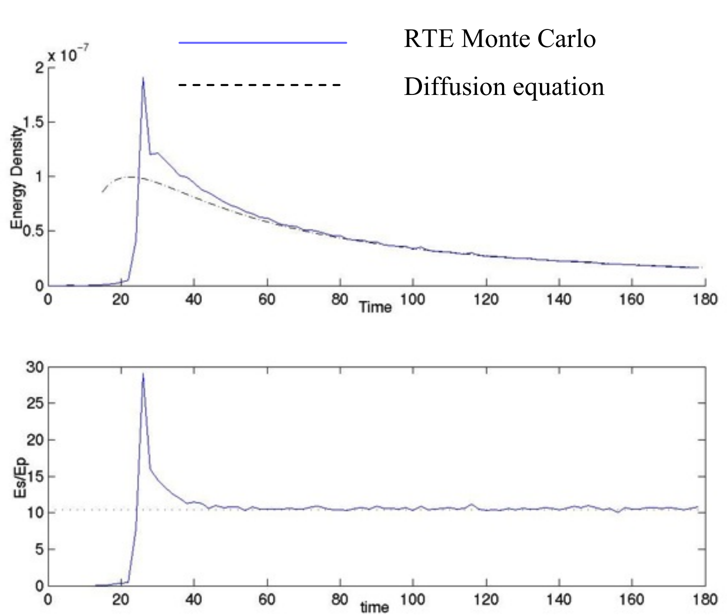
From Froment et al., 2011.

Multiple scattering and equipartition

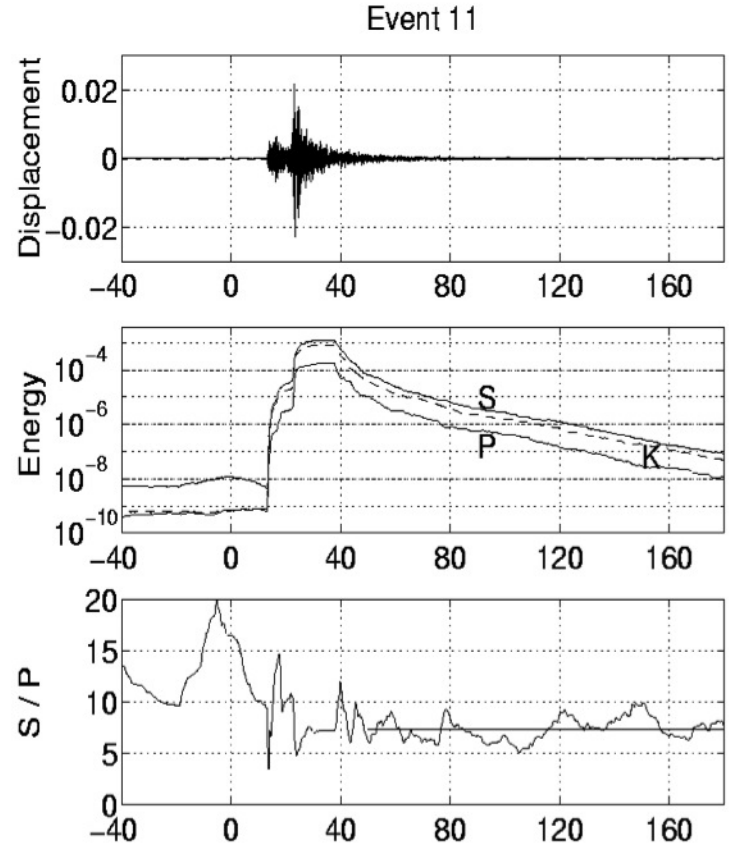
Equipartion principle for a completely randomized (diffuse) wave-field: in average, all the modes of propagation are excited to equal energy.

Implication for diffuse elastic waves *(Weaver, 1982, Ryzhik et al., 1996)*: P to S energy ratio stabilizes at a value independant of the details of scattering.

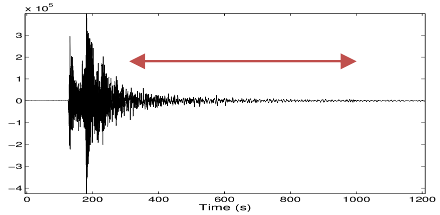
Numerical simulation *(Margerin et al.2000)*

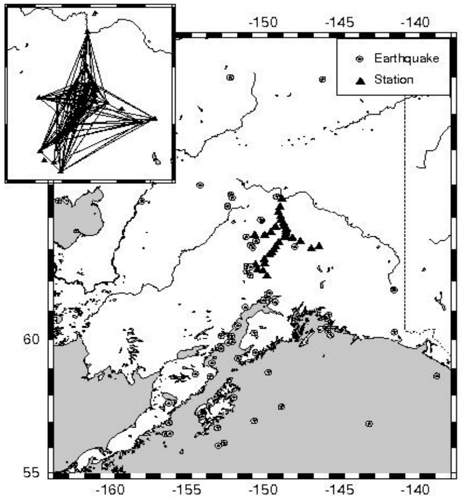


Observations *(Hennino et al., 2001)*



expérience BEAAR

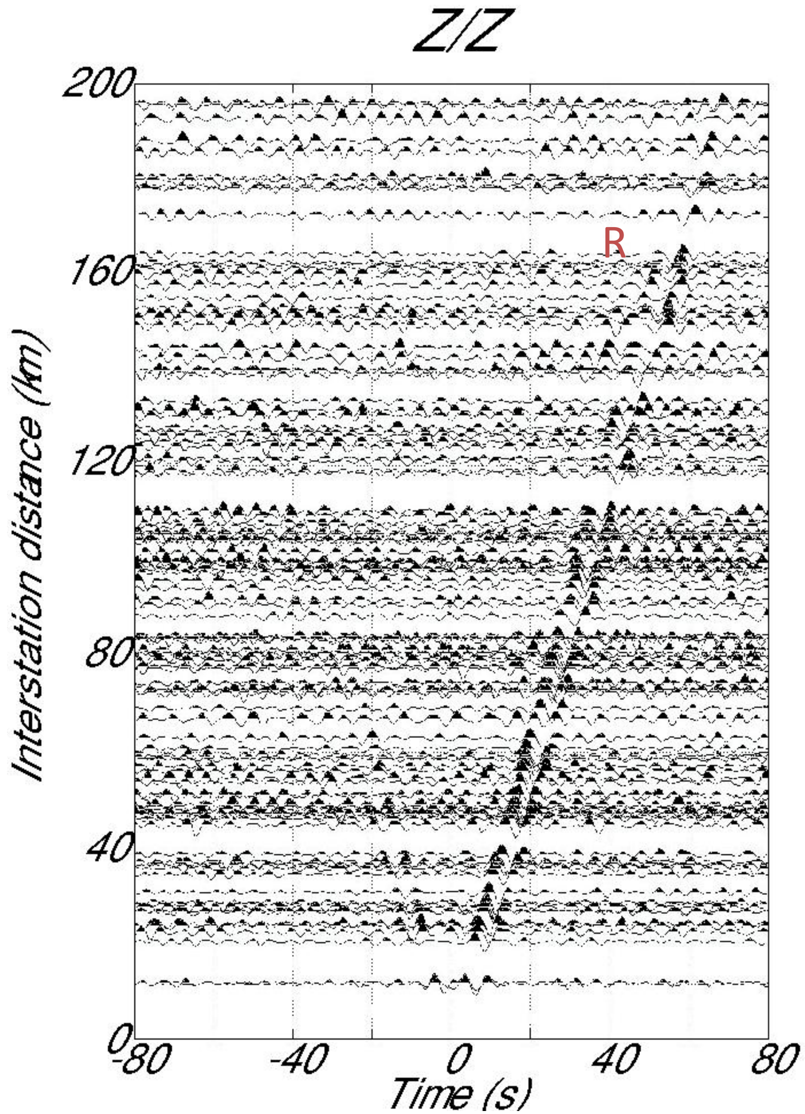




Short time windows

Time symetry: energy flow

Coda Correlations



(Paul et al., 2005)

Multiple scattering and equipartition: a simple argument (finite body)

equipartion

$$\phi(\vec{r};t) = \sum_n a_n U_n(\vec{r}) \cos(\omega_n t)$$

$$< a_n a_m^* > = F(\omega_n)\delta_{nm}$$

correlation

$$C_{1,2}(t) = \frac{1}{T}\int_0^T \phi(\vec{r}_1,\tau)\phi(\vec{r}_2,t+\tau)d\tau$$

Assuming a long recording interval T, this reduces to:

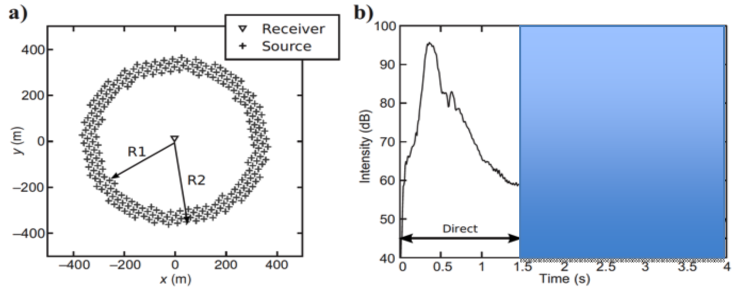
$$C_{1,2}(t) = \frac{1}{2}\sum_n F(\omega_n) U_n(\vec{r}_1) U_n(\vec{r}_2)\cos(\omega_n t)$$

Compare with:

$$G(\vec{r}_1,\vec{r}_2;t) = \sum_n U_n(\vec{r}_1) U_n(\vec{r}_2)\frac{\sin(\omega_n t)}{\omega_n}\Theta(t)$$

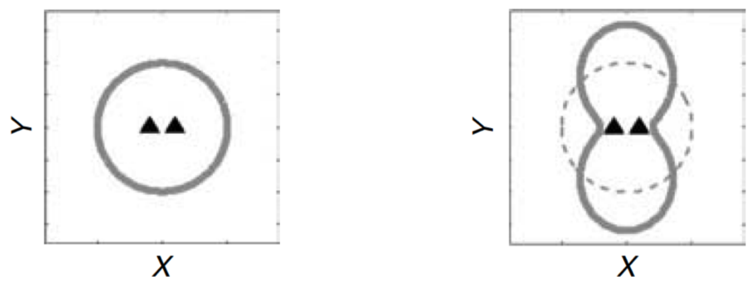
1 derivative 2 causality

Correlation of coda waves

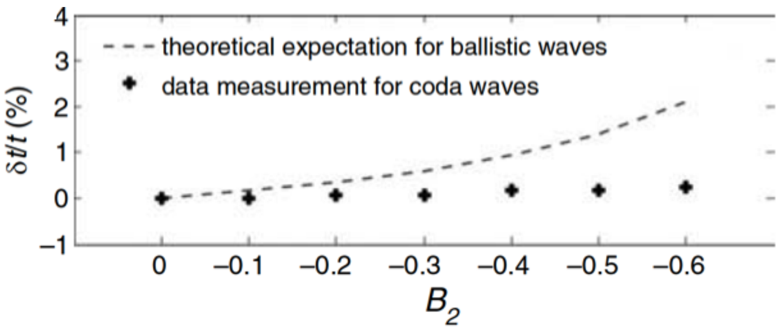


Increasing anisotropy of the noise intensity *B*

(a)



(b)



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

No bias in the correlation of coda waves!

From Froment et al., 2011.

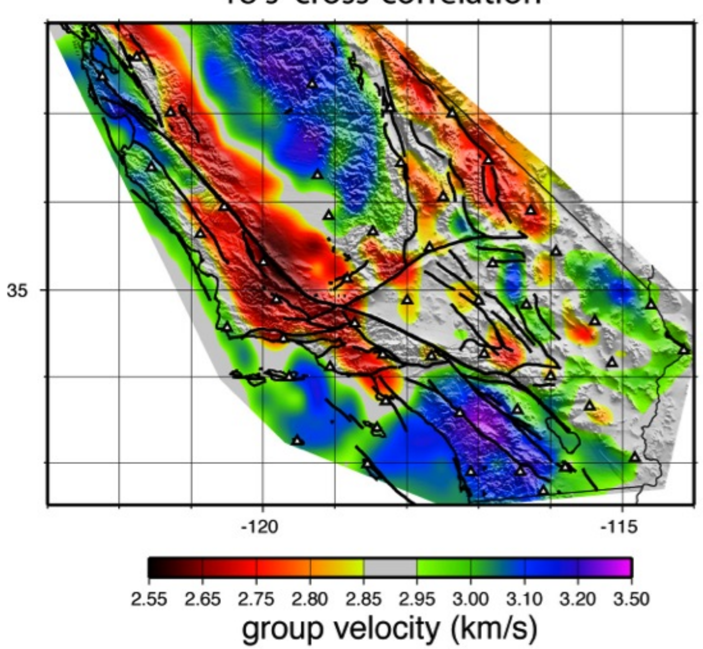
-Introduction

-**Passive Imaging**

-Passive monitoring

Surface wave imaging with seismic noise….. it works

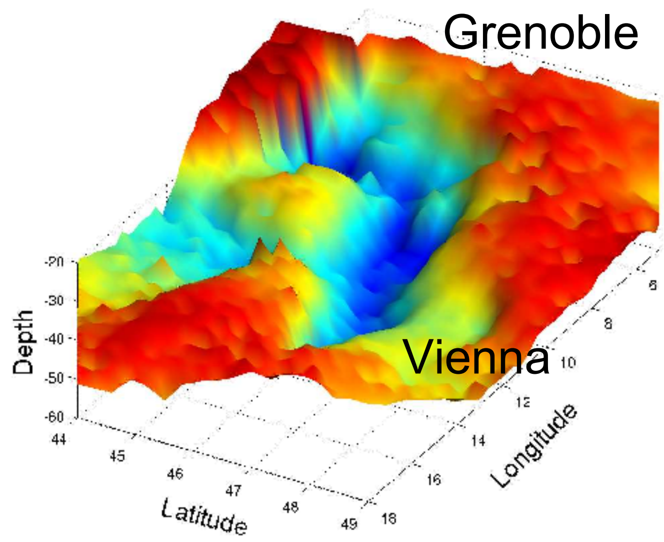
Map of Rayleigh group velocity Vg
(linear inversion)



Shapiro et al. Science 2005.

3D shear velocity model
1)Vg(x,y,T)
2)Vs(x,y,z) local non linear inversion

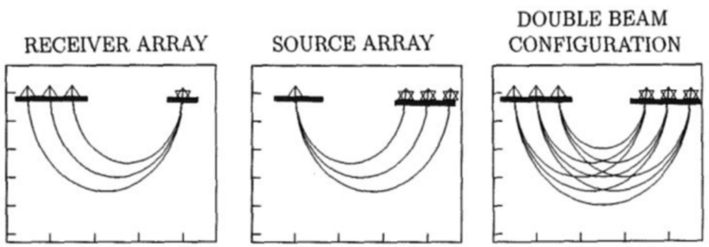
The Moho beneath the Alps



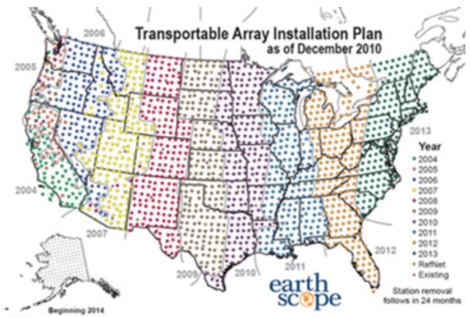
Stehly et al. ,2009

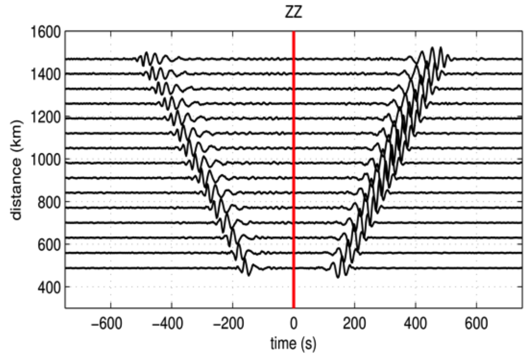
Refined imaging within a large array

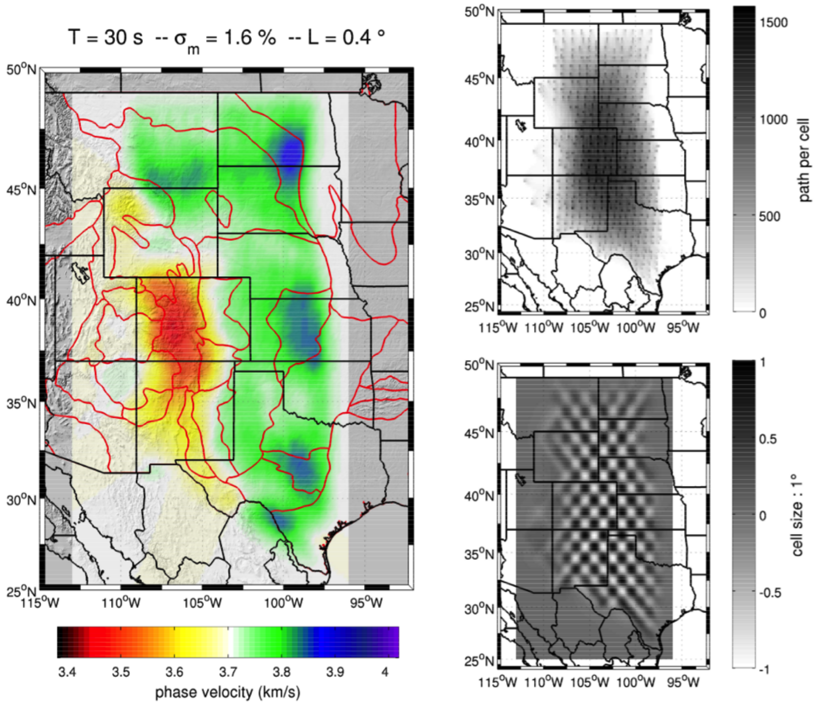
(*Pierre Boué 2013)*



Weber et al., 1996





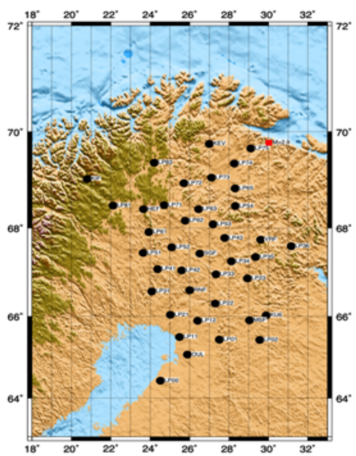


With ray bending

Talks by Ekström, Kennett, and Basini

Surface wave tomography body waves (deep reflections)

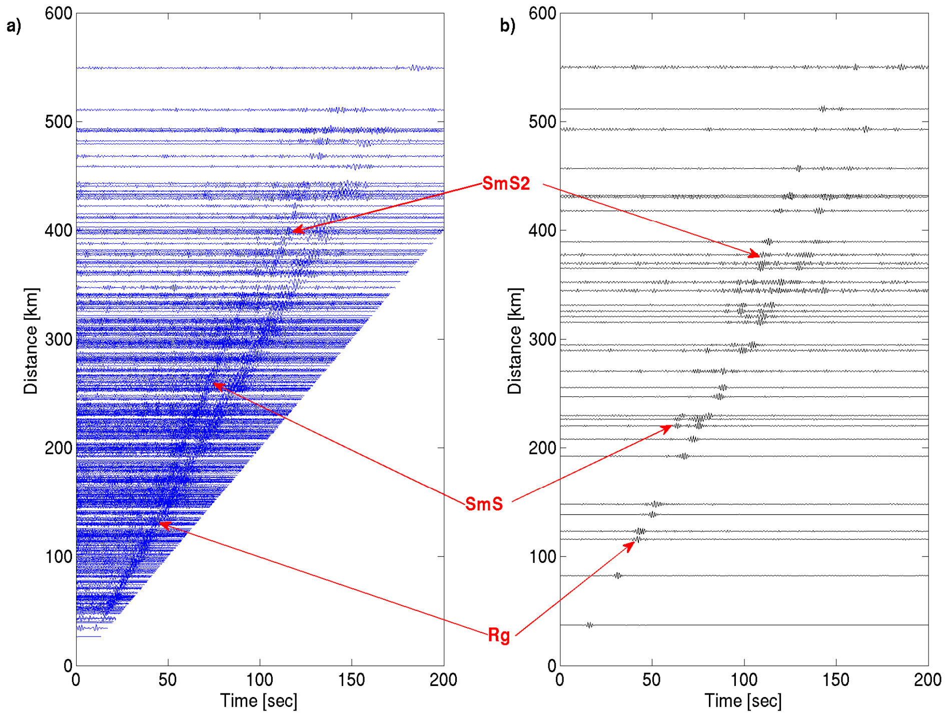
POLENET/LAPNET array in Finland



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

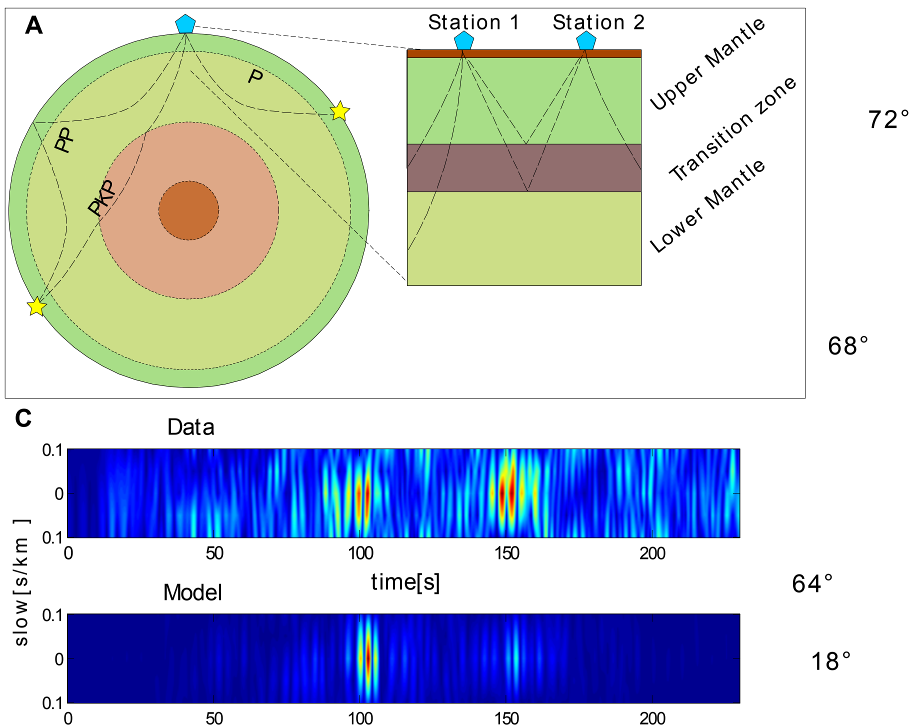
Poli et al. 2012a

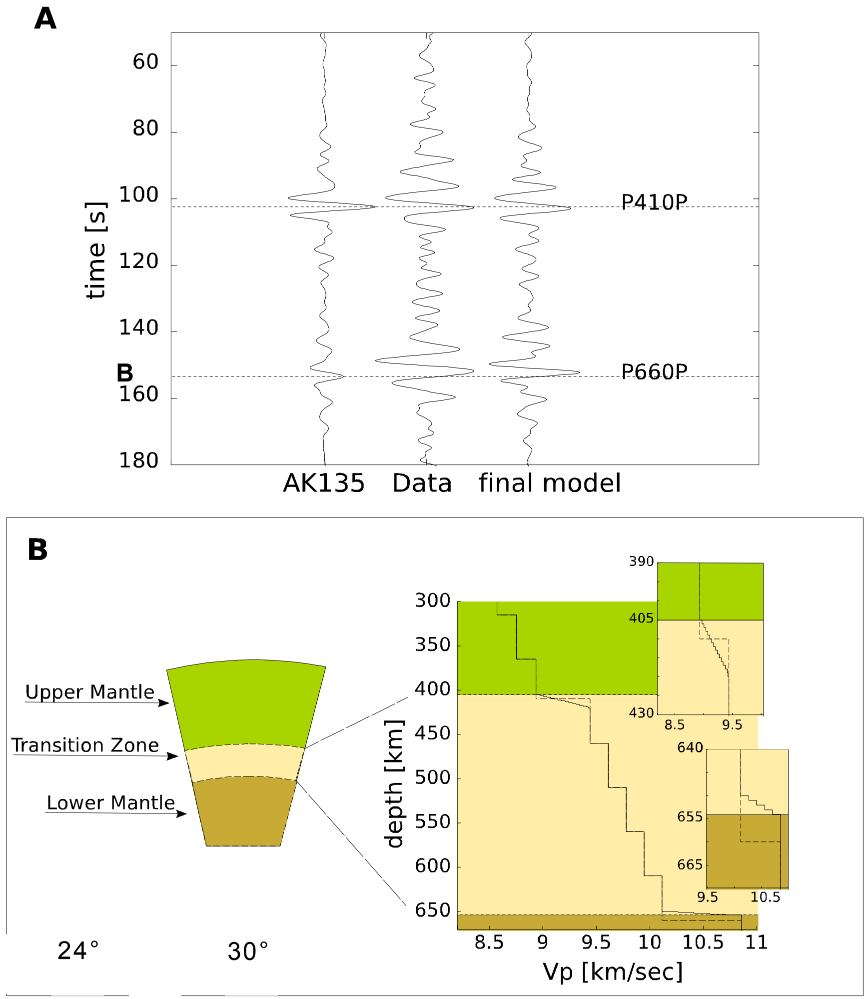
Z-Z noise correlations   Z comp. actual earthquake



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

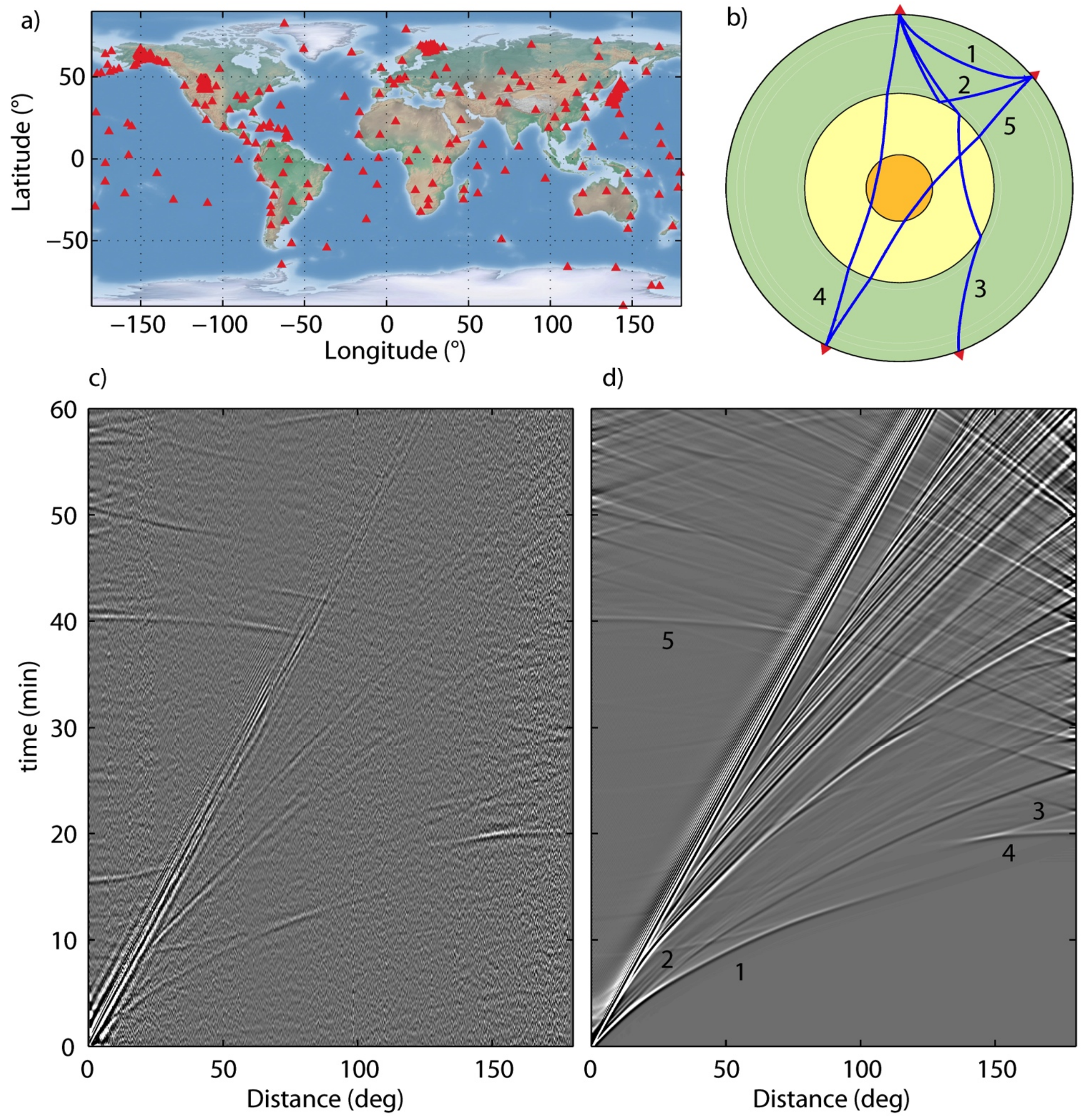
Poli et al. Science 2012





GLOBAL TELESEISMIC CORRELATIONS (periods 25-100s)

Boué, Poli et al., GJI 2013



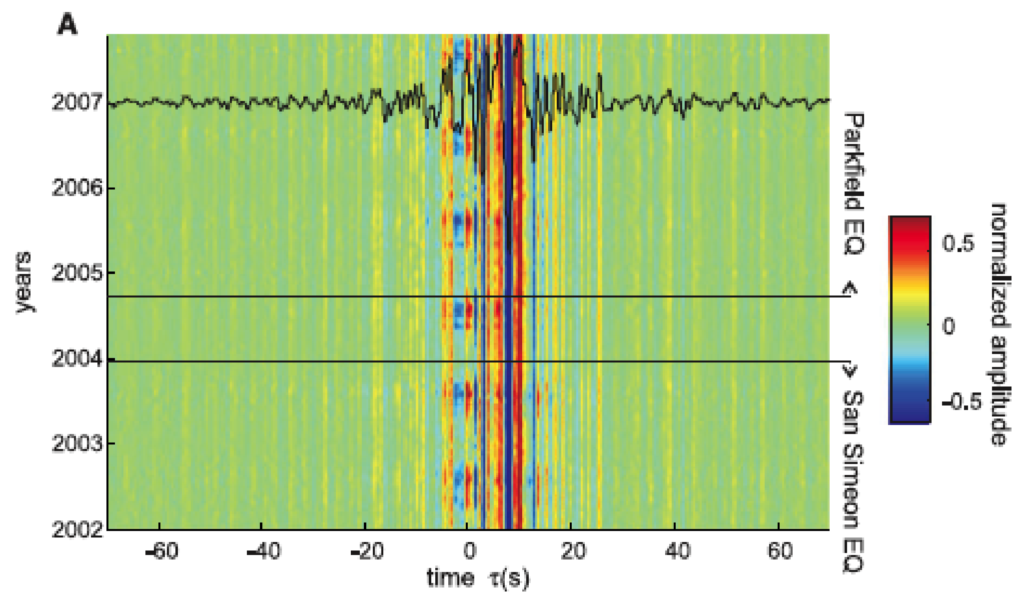
Talks by Nishida, Tsai and Poli

-Introduction

-Passive Imaging

-**Passive monitoring**

Correlation functions as approximate Green functions
(ex: period band:2-8s Parkfield, Brenguier et al., 2008)

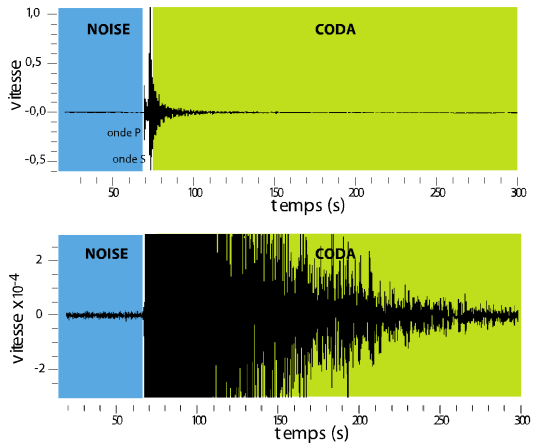


Direct waves are sensitive to noise source distribution (errors small enough for tomography (≤1%) but too large for monitoring (goal ≈ 10^{-4})

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

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

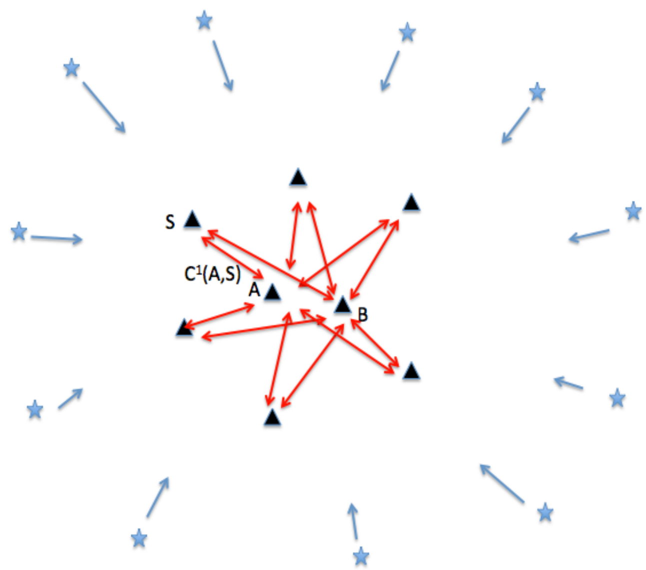
 C^3 method *(Stehly et al., 2008; Garnier et al., 2011)*

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

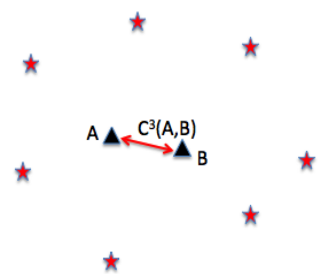
 long travel times = strong sensitivity to changes

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

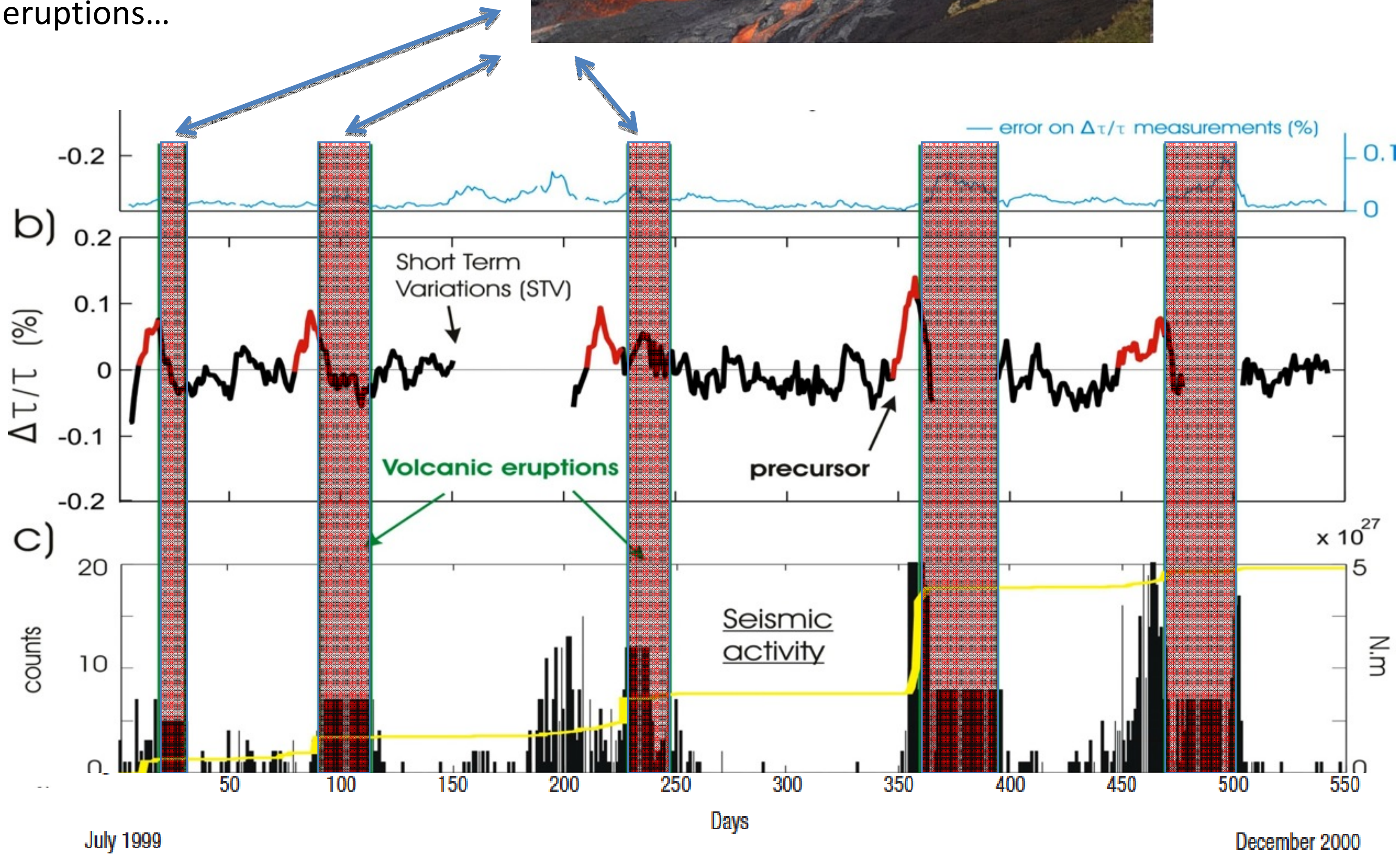
Monitoring:

Shallow effects: Volcanoes, strong motions, landslides,…

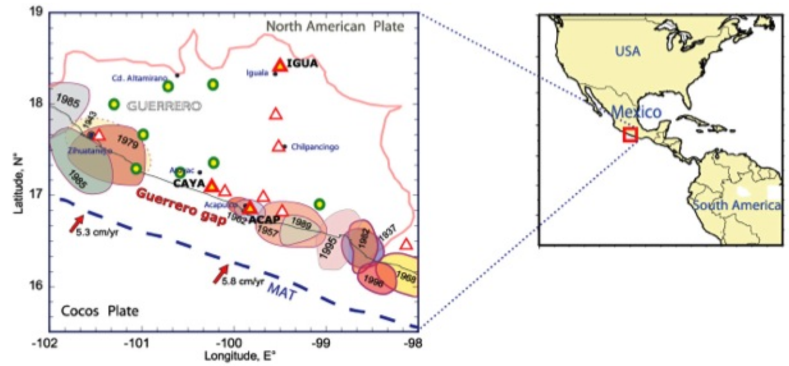
Deep deformation: 40 km deep Slow Slip events

Talks by Sens-Schönfelder and Montagner

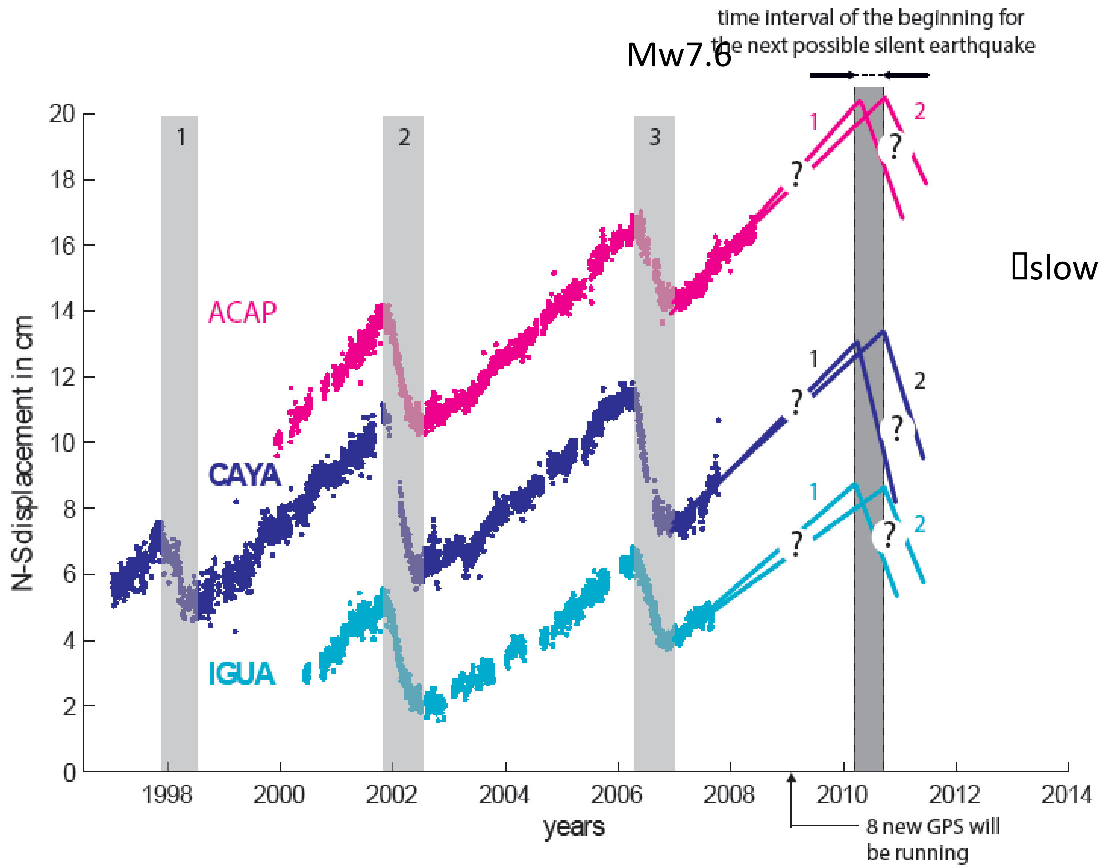
Seismic speed changes before the eruptions…



‘Silent’ event of slip on the Subduction plane (40km deep)



GPS motion towards the North during interseismic periods (NO significants events)

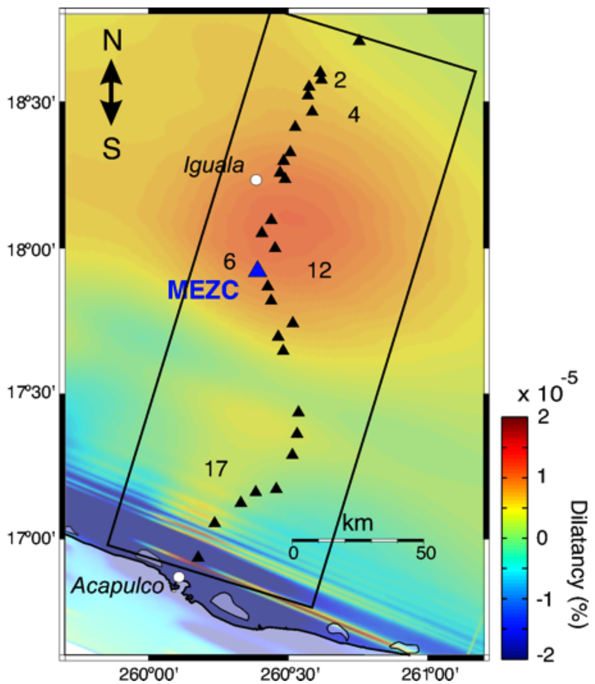


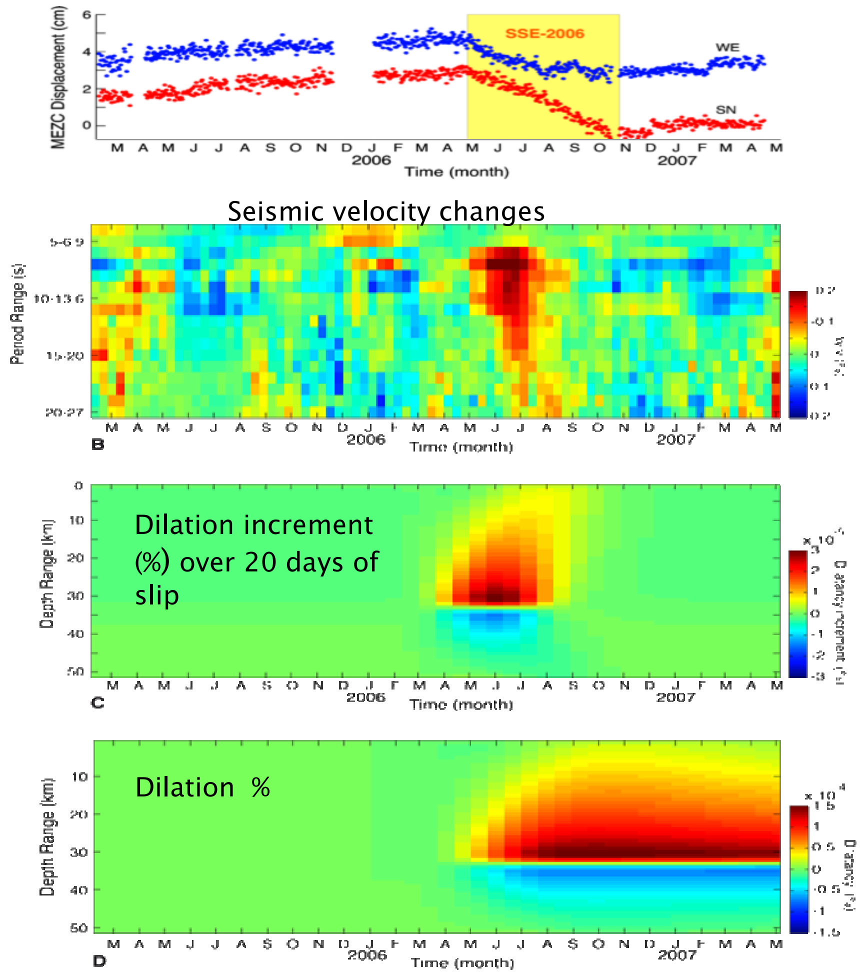
slow slip events (SSEs)

(Cotte et al., 2009)

Temporal relation between velocity change and dilatation

Dilation at 15km depth





- The minimum of velocity and maximum of dilation rate produced by the SSE occurs in June 2006
- The dilation and the velocity perturbation affect the volume and are not localized at the surface

Rivet et al., 2011

Deep velocity drop associated with the Wenchuan EQ (Froment et al. 2013)

Depth sensitivity (Obermann et al;, 2013)

Conclusions:

Long range field correlations of seismic records contains deterministic information on the structure and the evolution of the Earth.

The principle of emergence of the Green function relies on even distribution of sources (unlikely) or even distribution of intensity (medium heterogeneity and scattering help). The method demonstrated its robustness.

The limits of the method are not reached…..

Helmholtz equation $\quad G_{1x} = G(\vec{r}_1, \vec{x}; \omega)$

$$\Delta G_{1x} + V(\vec{x})G_{1x} + (k + i\kappa)^2 G_{1x} = \delta(\vec{x} - \vec{r}_1)$$

where the potential $V(\vec{x})$ describes the scattering contribution does not extend to infinity.

As for the classical representation theorem, we consider a combination of the fields from source at 1 and 2 and compute the flux:

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

With the divergence theorem:

$$I = \int_{\mathcal{V}} \vec{\nabla}\left[G_{1x} \vec{\nabla}\left(G_{2x}^*\right) - \vec{\nabla}\left(G_{1x}\right) G_{2x}^* \right] dV$$

$$I = \int_{\mathcal{V}} \vec{\nabla}\left[G_{1x} \vec{\nabla}\left(G_{2x}^{*} \right) - \vec{\nabla}\left(G_{1x} \right) G_{2x}^{*} \right] dV$$ reduces to

$$I = \int_{\mathcal{V}} \left(G_{1x} \Delta G_{2x}^{*} - \Delta G_{1x} G_{2x}^{*} \right) dV$$

Using the definition of the GF:

$$\Delta G_{1x} = \delta\left(\vec{x} - \vec{r}_1 \right) - V\left(\vec{x} \right) G_{1x} - \left(k + i\kappa \right)^2 G_{1x}$$

we obtain:

$$I = G_{12} - G_{21}^{*} - \frac{4i\omega\kappa}{c} \int_{\mathcal{V}} G_{1x} G_{2x}^{*} \, dV$$

and finally:

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