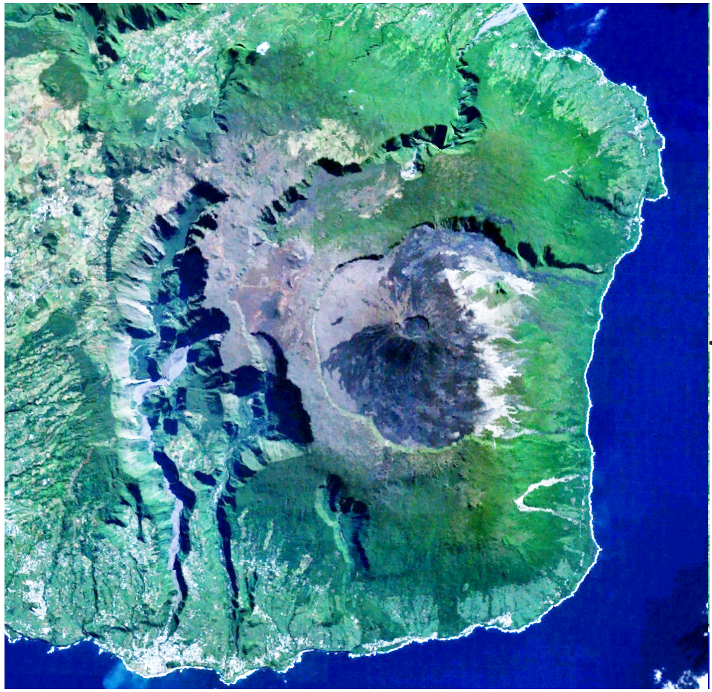
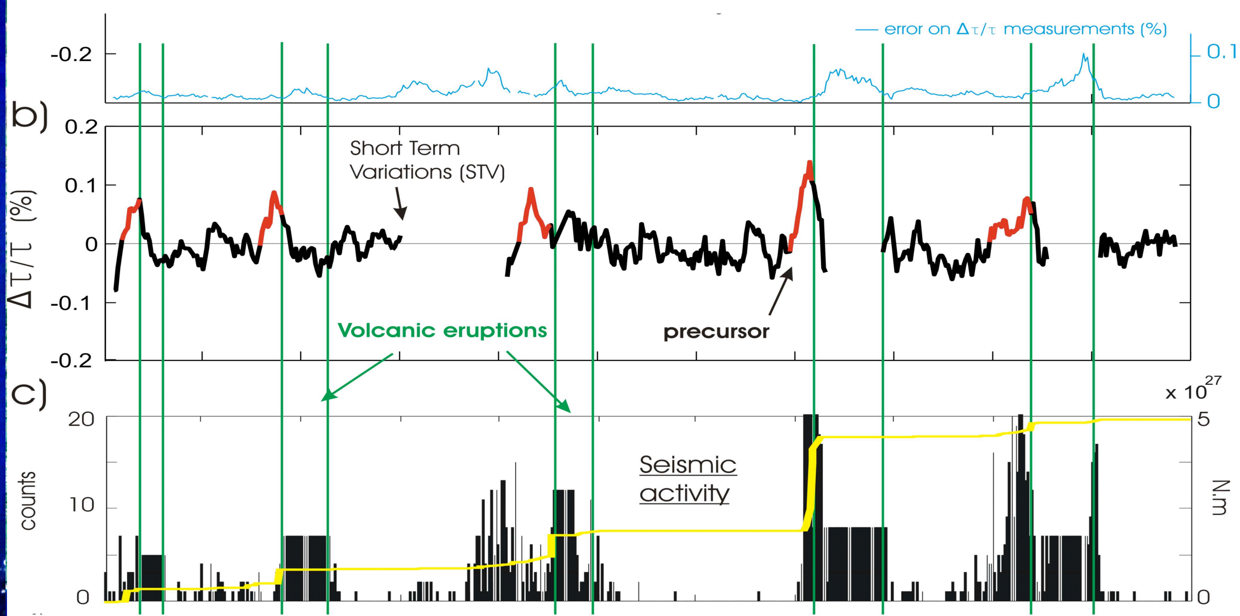
Quest for time precision in the recycling bin: monitoring the Earth evolution with ambient noise.

Michel Campillo
Université Joseph Fourier
Grenoble





Brenguier et al., 2008

Passive imaging and monitoring

The 'correlation relation' (under particular hypothesis):

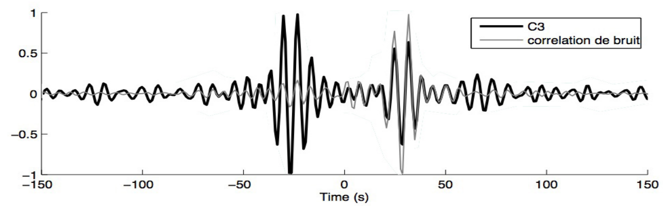
$$\partial_\tau C_{AB}(\tau) \propto G^+(A,B,\tau) - G^-(A,B,-\tau)$$

Correlation of fields in A and B

Green function between A and B (in negative times)

The correlation is equivalent to the record during an *active* experiment

Superposition of G(t) and G(-t)…….



Different representations…..

'Random' noise excitation

- Ward Identity and its variants

    - surface distribution

      (Wapenaar, van Manen,….)

    - volumic distribution of uncorrelated sources

      (Weaver and Lobkis, Roux and Kuperman, Colin de Verdière, …)

'Random' field

- multiple scattering and diffusion

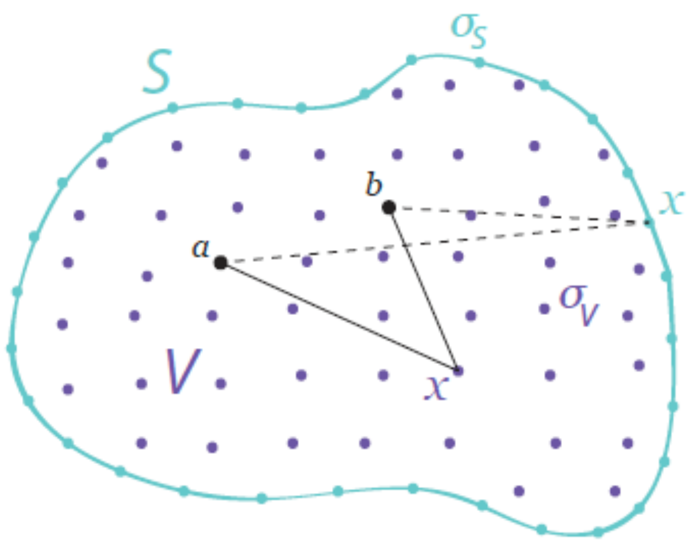
3D Ward's identity

$$\widetilde{G}_{ab} - \widetilde{G}^*_{ab} = \frac{4i\gamma\,\omega}{c^2}\int_V \widetilde{G}_{ax}\widetilde{G}^*_{bx}\,dV + \oint_S \left[\widetilde{G}_{ax}\,\overrightarrow{\nabla}\widetilde{G}^*_{bx} - \overrightarrow{\nabla}\widetilde{G}_{ax}\,\widetilde{G}^*_{bx}\right].\overrightarrow{dS}$$

Volume term

Surface term

Absorption coefficient



Different representations…..

‘Random’ noise

-volumic distribution of uncorrelated sources

(Weaver and Lobkis (2001) + Roux et al.+ Colin de Verdière, …)

strong mathematical results valid for complex media with absorption

Geophysical Prospecting, 2008, 56, 375–393 doi:10.1111/j.1365-2478.2007.00684.x

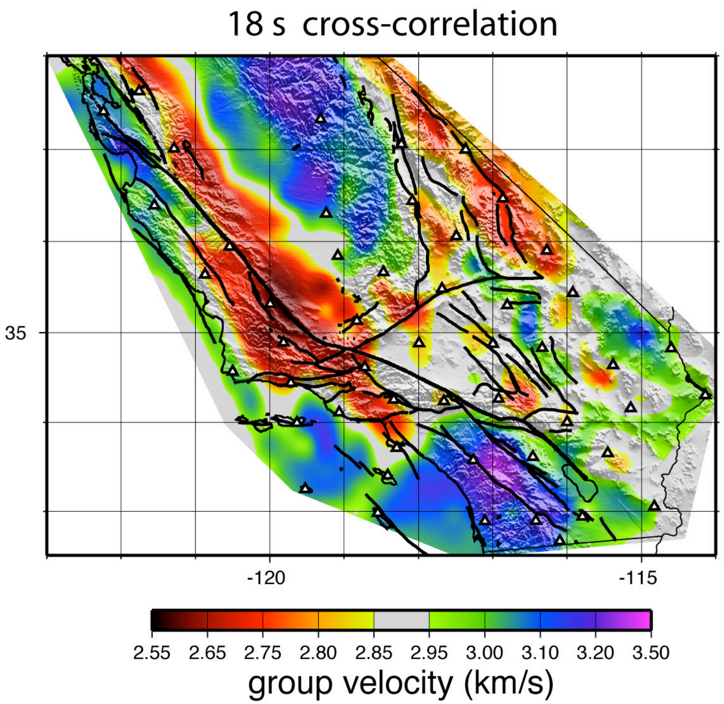
Cross-correlation of random fields: mathematical approach and applications

P. Gouédard[1*], L. Stehly[1,2], F. Brenguier[1,3], M. Campillo[1], Y. Colin de Verdière[4], E. Larose[1], L. Margerin[5], P. Roux[1], F. J. Sánchez-Sesma[6], N. M. Shapiro[3] and R. L. Weaver[7]

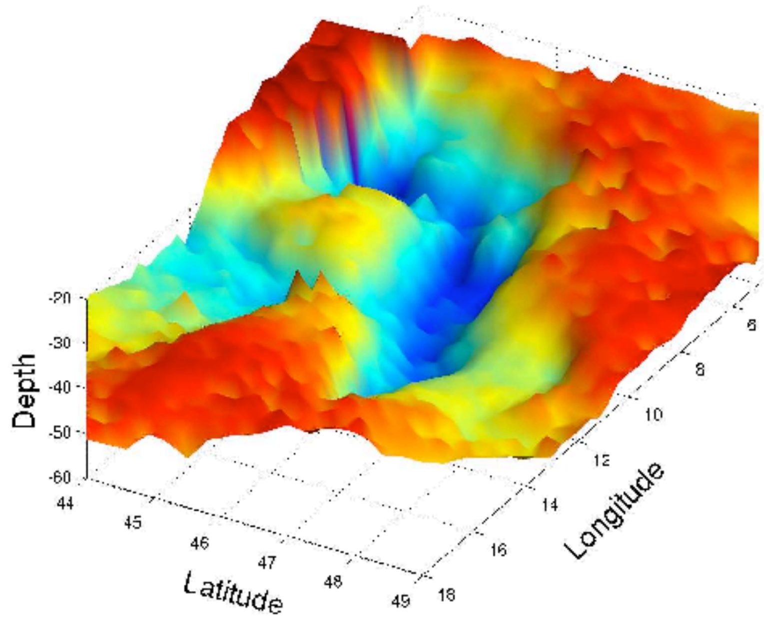
$$\frac{\partial^2 u}{\partial t^2} + 2a\,\frac{\partial u}{\partial t} - Lu = f$$

$$\frac{d}{d\tau}\,C(\tau, \vec{r}_A, \vec{r}_B) = \frac{-\sigma^2}{4a}\left(G_a(\tau, \vec{r}_A, \vec{r}_B) - G_a(-\tau, \vec{r}_A, \vec{r}_B)\right)$$

Imaging with seismic noise….. it works



Shapiro et al. Science 2005.



Moho beneath the Alps
Stehly et al. GJI 2009

(Surface wave tomograhy ➔ body waves?
See Piero Poli's poster!)

Indeed, the quality depends on the distribution of 'noise' sources

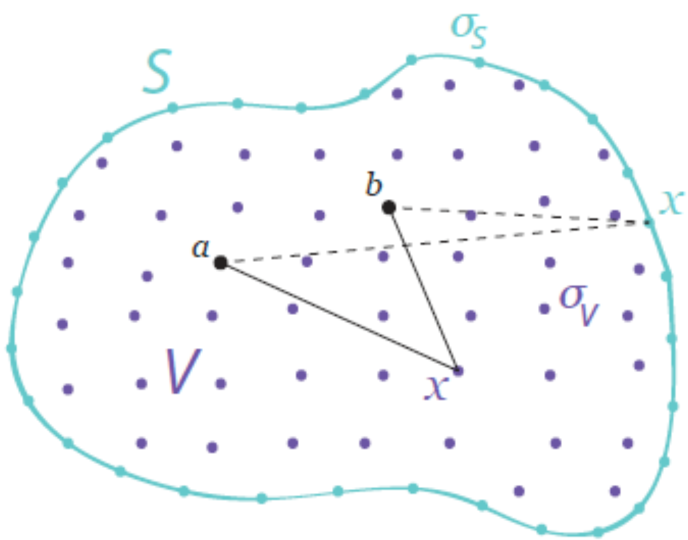
3D Ward's identity

$$\widetilde{G}_{ab} - \widetilde{G}^*_{ab} = \frac{4i\gamma\,\omega}{c^2}\int_V \widetilde{G}_{ax}\widetilde{G}^*_{bx}\,dV + \oint_S \left[\widetilde{G}_{ax}\,\vec{\nabla}\widetilde{G}^*_{bx} - \vec{\nabla}\widetilde{G}_{ax}\,\widetilde{G}^*_{bx}\right].\vec{dS}$$

Volume term

Surface term

Absorption coefficient



Different representations.....

'Random' noise

-surface distribution

(Wapenaar (2004) + van Manen,….)

PRL **93,** 254301 (2004) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2004

Retrieving the Elastodynamic Green's Function of an Arbitrary Inhomogeneous Medium by Cross Correlation

Kees Wapenaar*
Department of Geotechnology, Delft University of Technology, P.O. Box 5028, 2600 GA Delft, The Netherlands

(Received 18 August 2004; published 16 December 2004)

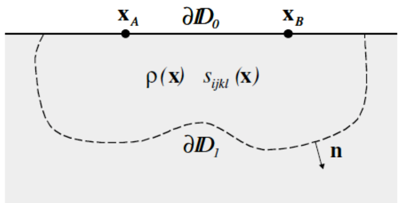


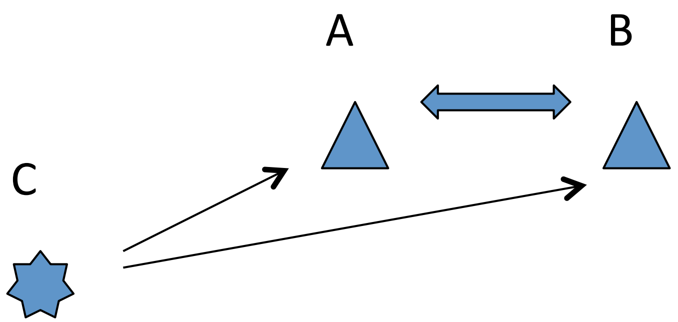
FIG. 1. Inhomogeneous anisotropic lossless medium, bounded by a free surface.

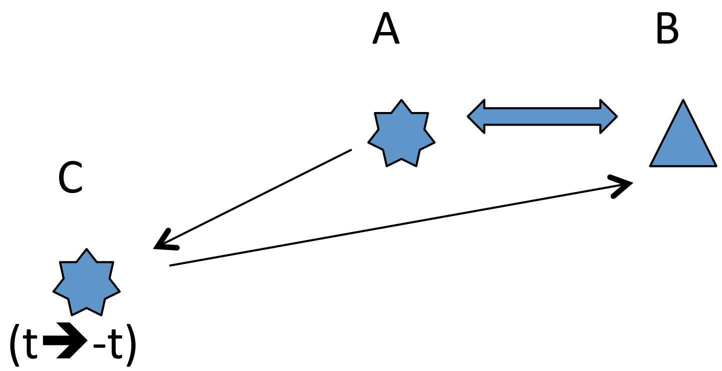
Here $\hat{v}_p^{\rm obs}(\mathbf{x}_A, \omega)$ and $\hat{v}_q^{\rm obs}(\mathbf{x}_B, \omega)$ are the observed particle velocities at $\mathbf{x}_A$ and $\mathbf{x}_B$ at the free surface due to a distribution of noise sources at an arbitrarily shaped surface $\partial\mathbb{D}_1$ inside the medium. The average in Eq. (6) is taken over different realizations of the source distribution. In the time domain Eq. (6) becomes

$$\int_{-\infty}^{\infty} \{G_{p,q}^{v,t}(\mathbf{x}_A, \mathbf{x}_B, -t') + G_{p,q}^{v,t}(\mathbf{x}_A, \mathbf{x}_B, t')\} S(t - t')dt' \approx -\left\langle \int_{-\infty}^{\infty} v_p^{\rm obs}(\mathbf{x}_A, t + t') \times v_q^{\rm obs}(\mathbf{x}_B, t')dt' \right\rangle. \tag{9}$$

According to this equation, the cross correlation of the observed particle velocities at $\mathbf{x}_A$ and $\mathbf{x}_B$ yields the elastodynamic Green's function between $\mathbf{x}_A$ and $\mathbf{x}_B$, convolved with the autocorrelation of the noise sources.

Time reversal mirrors (Fink and co-authors…)





Correlation vs Time Reversal

- C source
- A and B receivers

- A source
- C receiver
- C emits time-reversed field
- B receiver

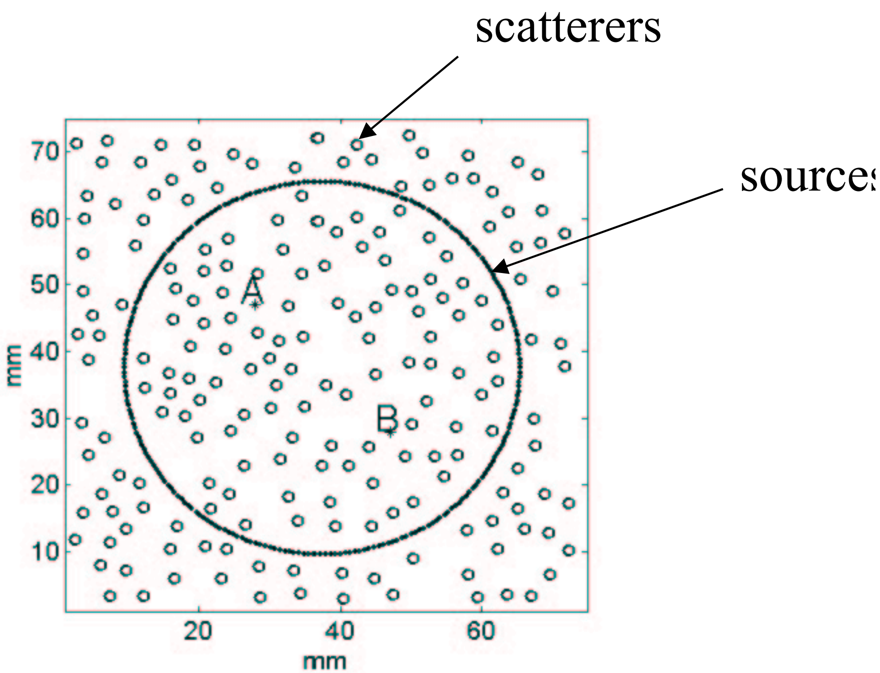
- Correlation :

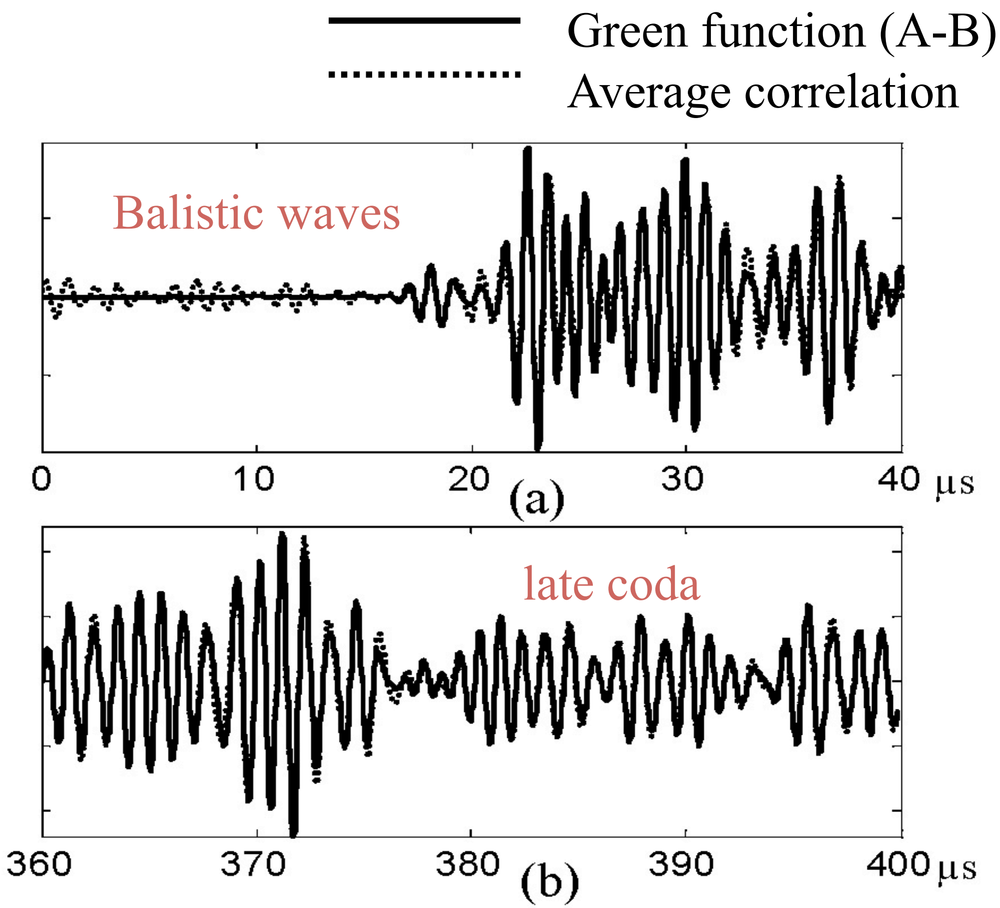
$C(S_{CA}(t) \;,\; S_{CB}(t)\;)$ =

- Convolution :

$S_{CA}(t) \otimes S_{CB}(-t)$

A numerical experiment with an open medium (absorbing boundaries):
Equivalent to a (almost perfect) time-reversal mirror





Indeed, no configuration average

A. Derode, E. Larose, M. Campillo and M. Fink (2003)

Different representations…..

‘Random’ field

-multiple scattering and diffusion

The ‘equipartition’ argument leads to the ‘correlation relation’ *(Lobkis and Weaver 2001, Campillo and Paul 2003,…)*

$$\partial_\tau C_{AB}(\tau) \propto G^+(A,B,\tau) - G^-(A,B,-\tau)$$

Green function , modes and correlation

Modes:

-Discrete frequencies in a finite homogeneous body
-Plane waves in an infinite half space
-Surface waves higher modes in a layered structure
…….

Definition of a pertinent phase space

Finite body: superposition of normal modes

Equipartition:

$$\Psi(\vec{r},t) = \Re(\sum a_n u_n(\vec{r}) exp(i\omega_n t))$$

with

$$\langle a_n \rangle = 0; \ \langle a_n a_m^* \rangle = E(\omega_n)\delta_{nm}$$

2 point field correlation:

$$C(\vec{r},\vec{r'},t-t') = \left\langle \Psi(\vec{r},t)\Psi(\vec{r'},t') \right\rangle = \sum_n E(\omega_n) u_n(\vec{r}) u_n(\vec{r'}) cos(\omega_n(t-t'))$$

of Fourier transform:

$$C(\vec{r},\vec{r'},\omega) = \pi \sum_n E(\omega_n) u_n(\vec{r}) u_n(\vec{r'})(\delta(\omega-\omega_n)+\delta(\omega+\omega_n))$$

Green function

$$G(\vec{r},\vec{r'},t) = \sum_n u_n(\vec{r}) u_n(\vec{r'}) \frac{sin(\omega_n t)}{\omega_n} H(t)$$

obtained by inverse Fourier transform ($\omega \to \omega - i\epsilon$ in the limit $\epsilon \to 0$) of the Green function in the frequency domain:

$$G(\vec{r},\vec{r'},\omega) = \sum_n \frac{u_n(\vec{r}) u_n(\vec{r'})}{(\omega - i\epsilon)^2 - \omega_n^2}$$

with u_n the eigenfunction solution of the spectral problem $Hu = \omega_n^2 u_n$ (of type $-C^2 \Delta u = \omega_n^2 u_n$) and ω_n^2 the eigenvalue.

$$\Im(G(\vec{r},\vec{r'},\omega)) = \pi \sum_n u_n(\vec{r}) u_n(\vec{r'})(\frac{\delta(\omega-\omega_n)+\delta(\omega+\omega_n)}{\omega})$$

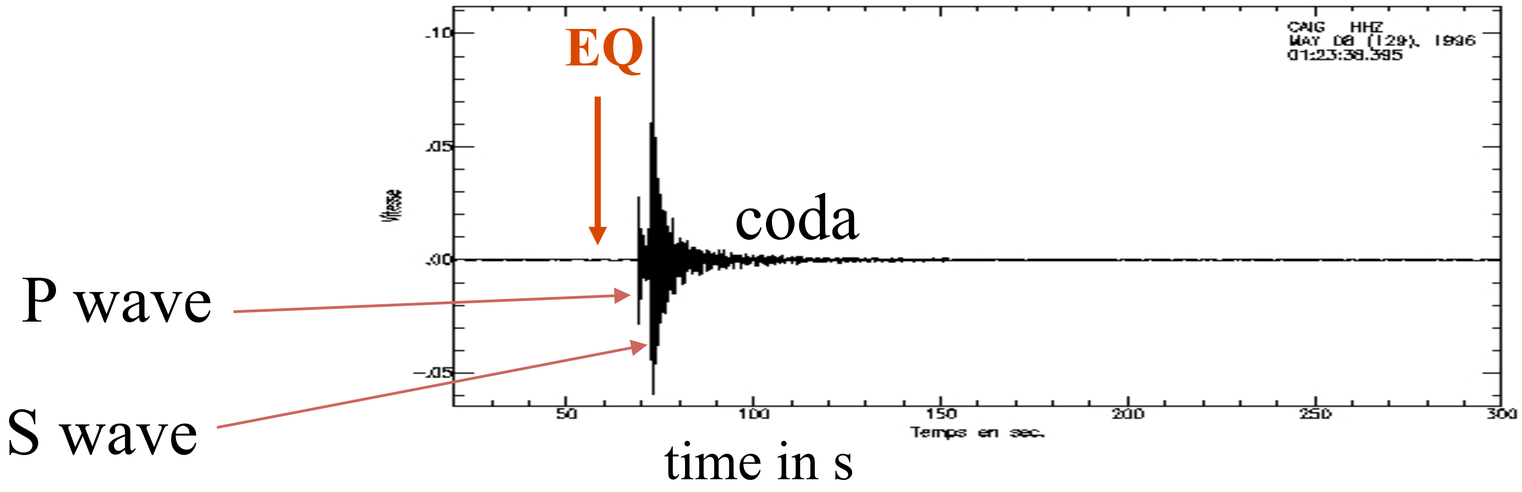
We can compare: with

Different representations…..

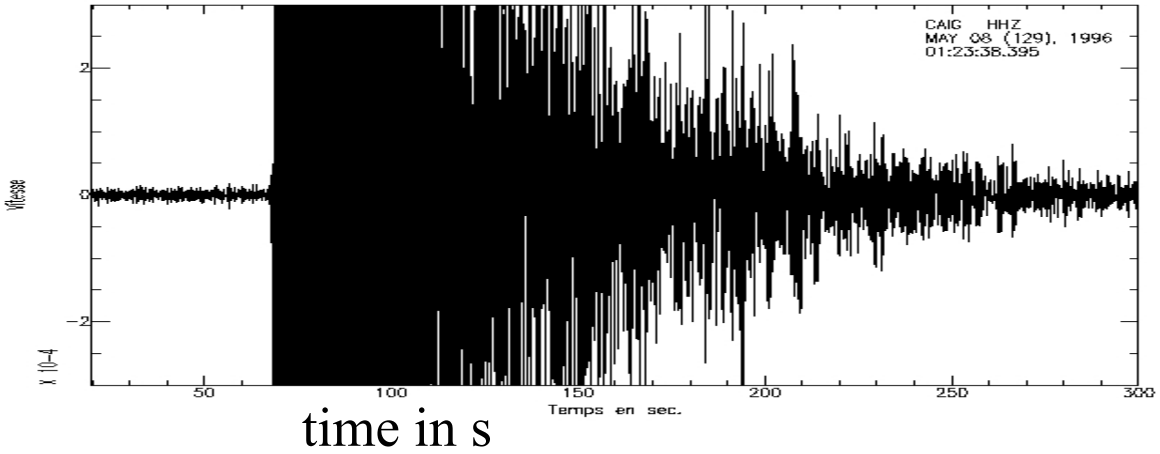
‘Random’ field

-multiple scattering and diffusion

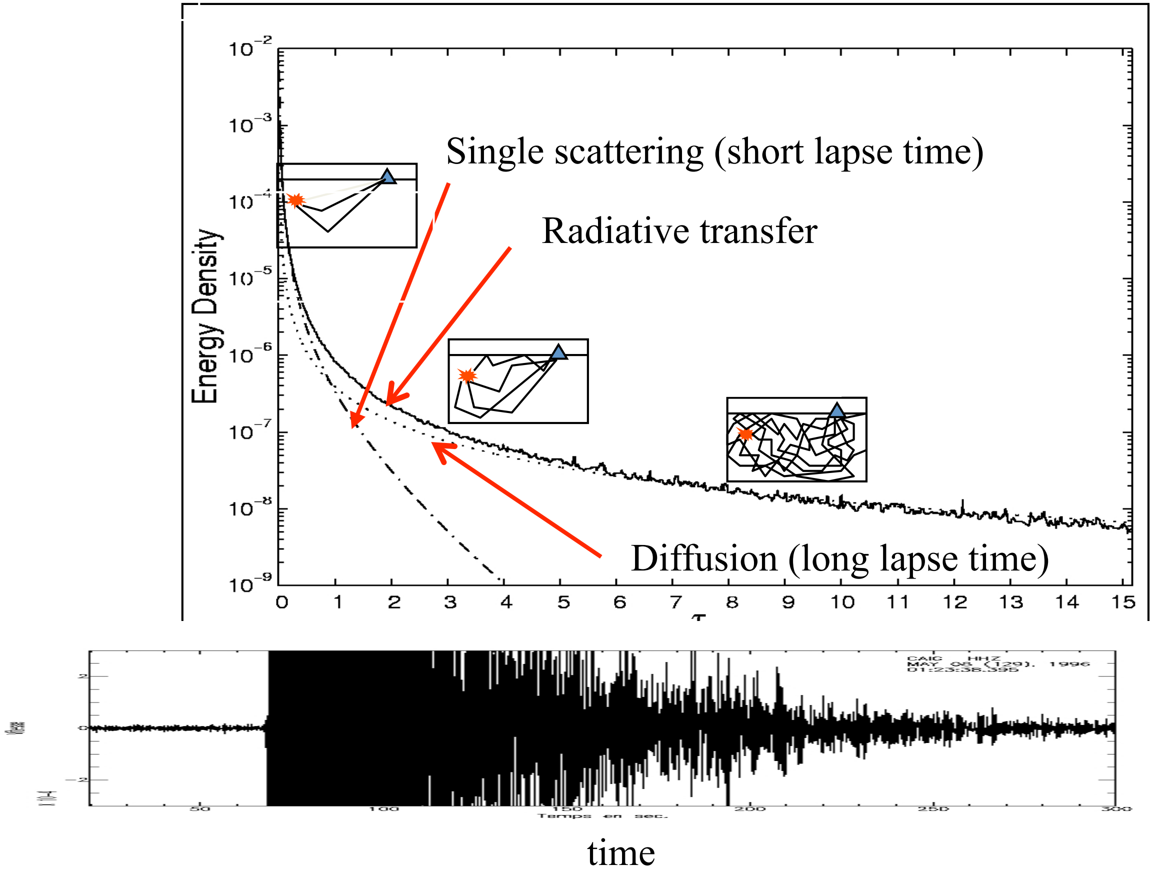
Example of a record of a local earthquake in the band .5-20Hz



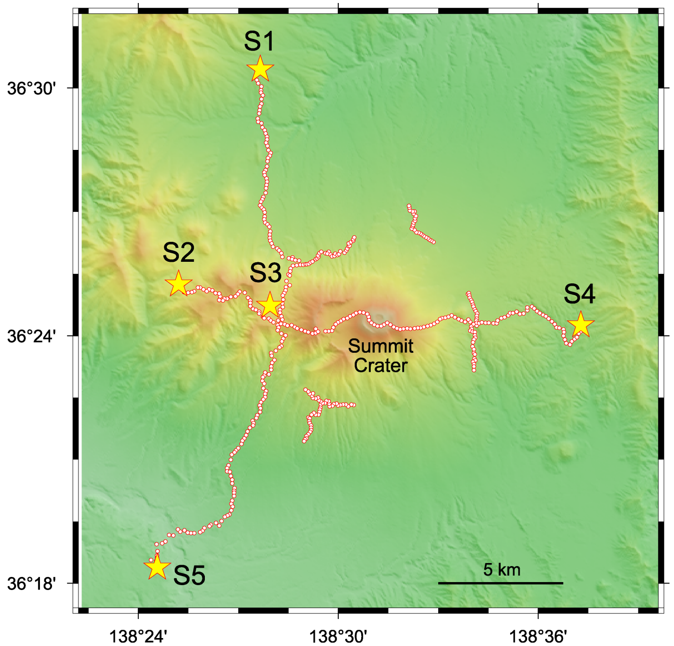
scale x 1000:



Propagation Regimes
& **E**nergy **D**ensity **D**ecay



Example of records from a volcano: figures from Dr. Mare Yamamoto, Tohoku University



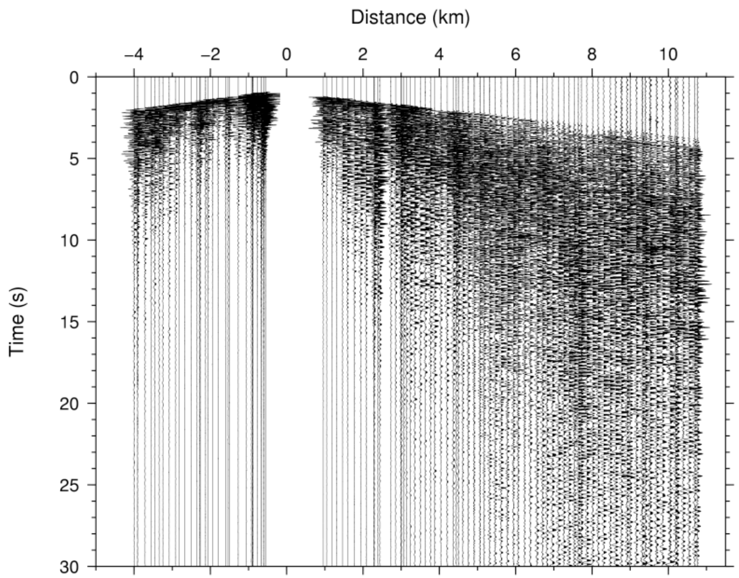
Active seismic experiment at Asama

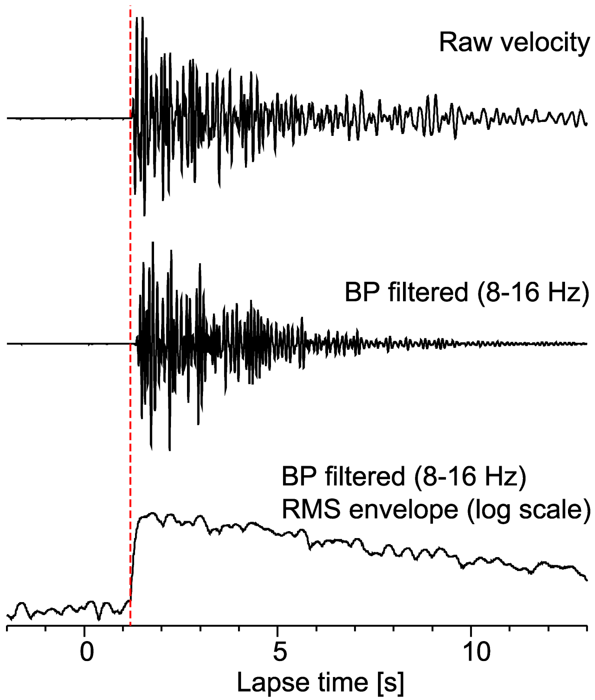
- Experiment: Oct. 13, 2006
- Artificial source: Five dynamite shots
  - Depth: around 60 m
  - Charge: 250–300 kg
- Observation
  - About 450 stations with 2Hz sensors (mainly vertical component)
  - Station spacing: every 50–150m
  - Recording: Scheduled record at 250Hz

Characteristics of observed waveforms:

- dominant energy around 10Hz (artificial source mainly emits P energy)
- characterized by spindle-like envelopes
  - … small P-onset and long coda

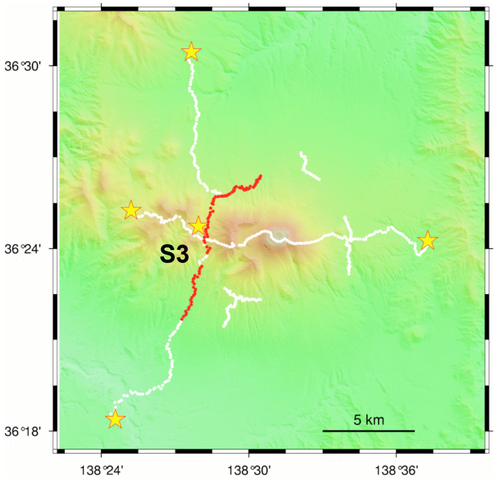
Shot record (Shot 3: EW-line)



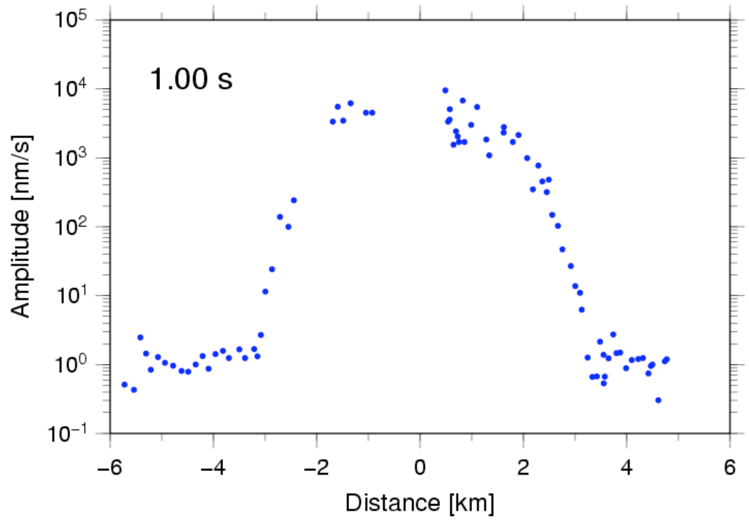


Figures from Dr. Mare Yamamoto, Tohoku University

Spatio-temporal distribution of propagating energy



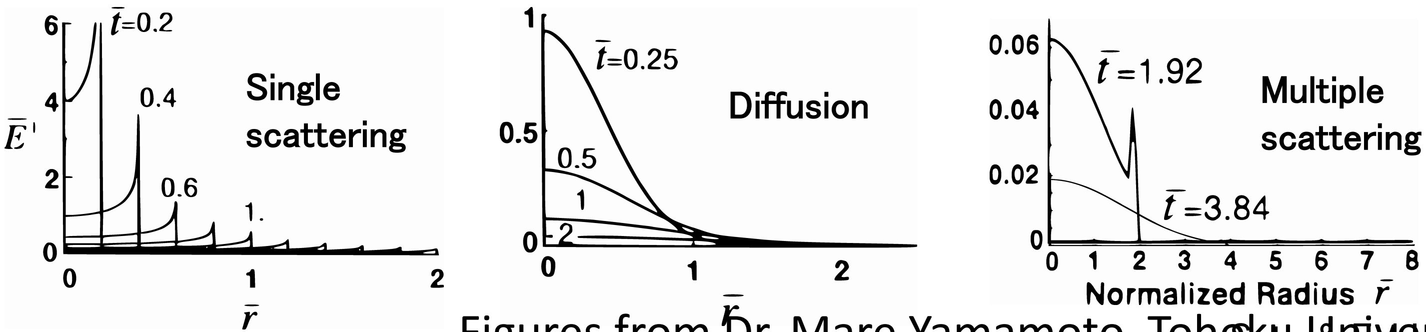
8-16Hz / Normalized by late coda level



Characteristics of spatio-temporal distribution of energy:

- Existence of wave front
- Large energy after P wave arrival

⇒ **Multiple scattering**



Figures from Dr. Mare Yamamoto, Tohoku University

Sato & Fehler, 1998

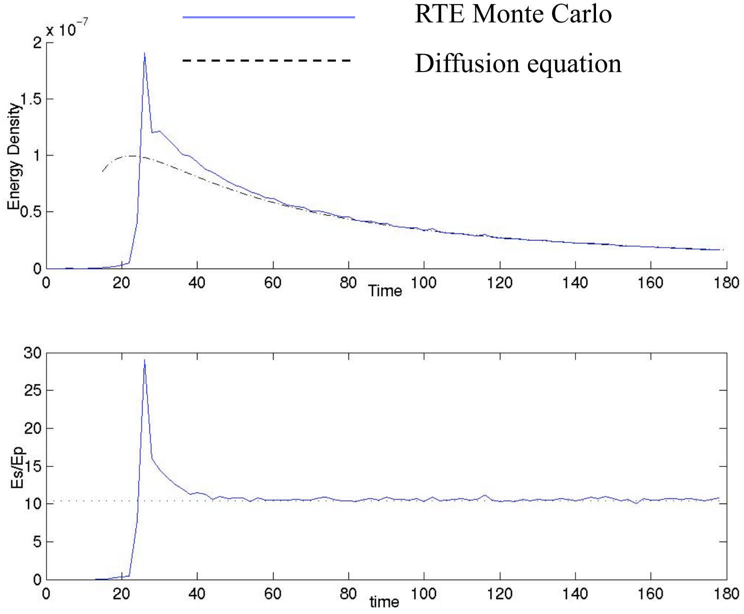
Searching for a marker of the regime of scattering...

Equipartion principle for a completely randomized (diffuse) wave-field: in average, all the modes of propagation are excited to equal energy ➔ *ISOTROPY FOR SCALAR WAVES IN HOMOGENEOUS SPACE*.

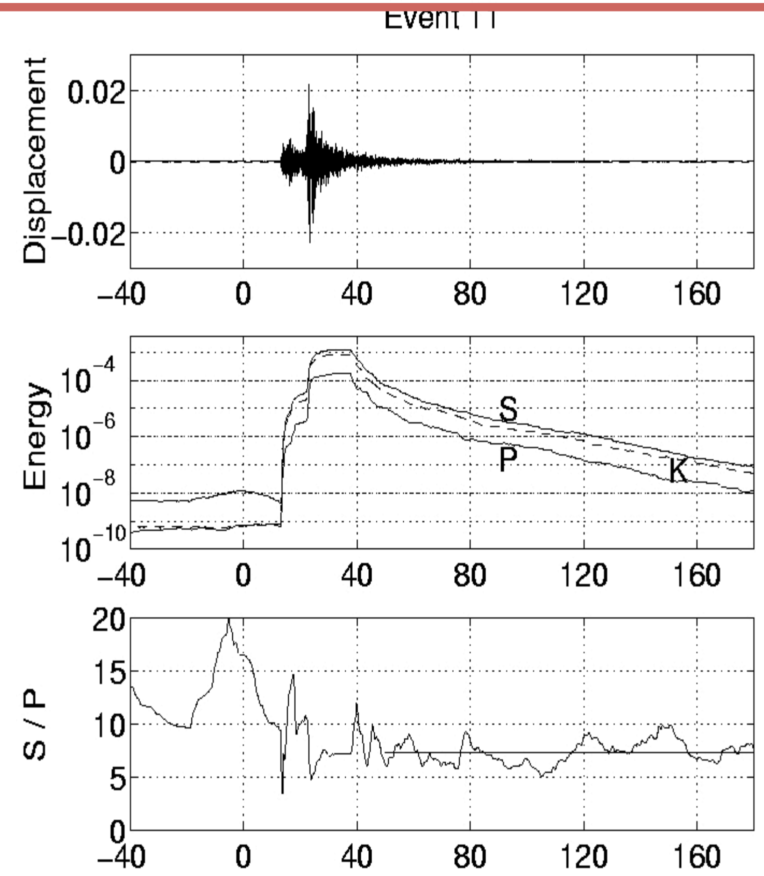
Implication for elastic waves (Weaver, 1982, Ryzhik et al., 1996): P to S energy ratio stabilizes at a value independant of the details of scattering!

Numerical simulation: full space

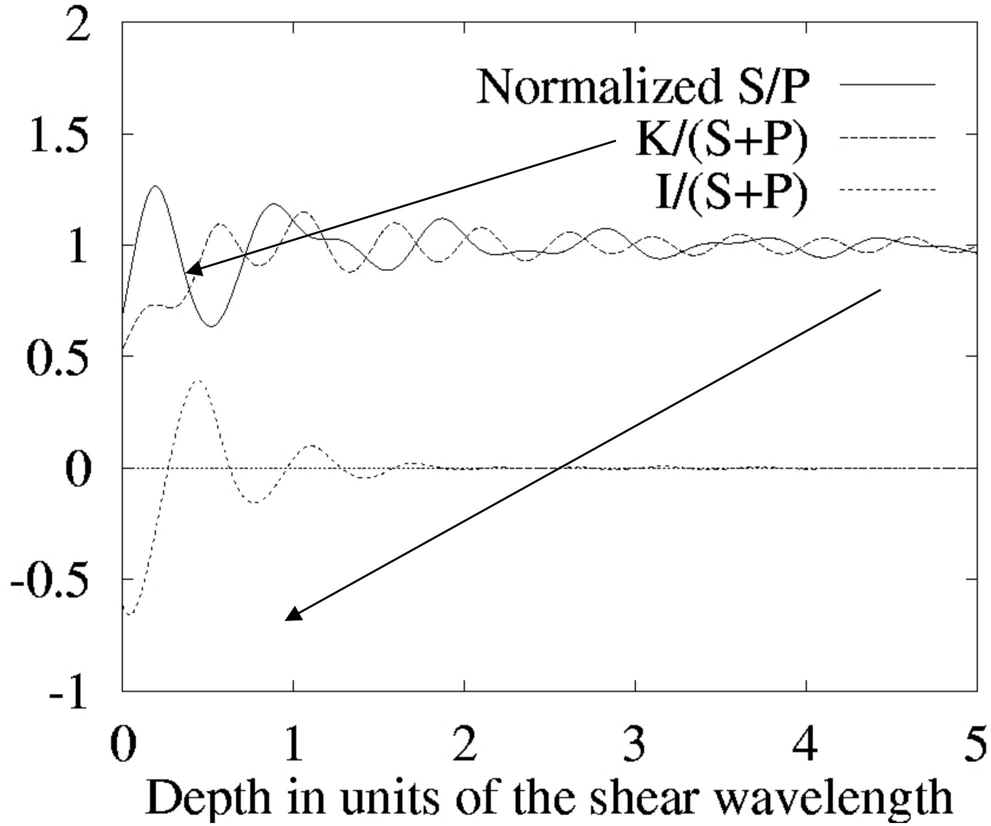
(Margerin et al, 2000)



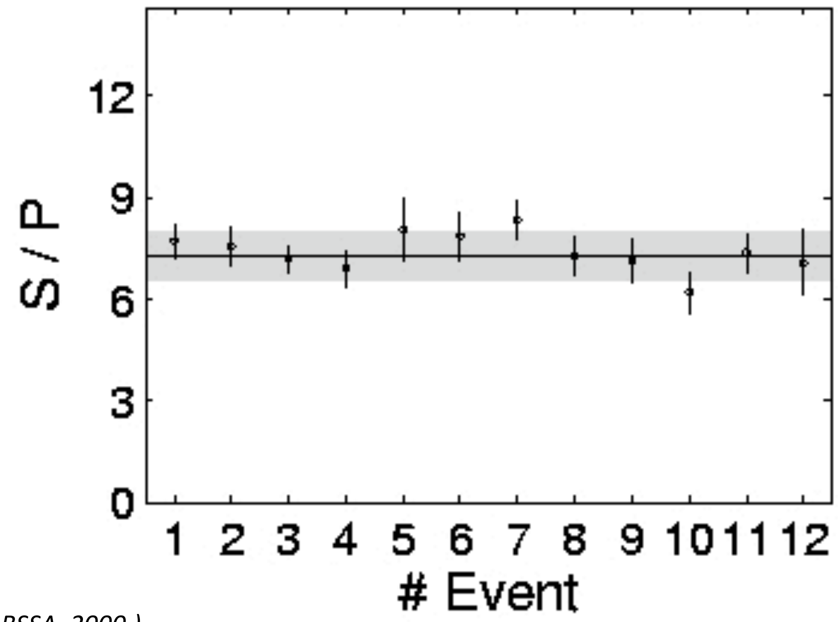
Observations (Hennino et al. 2001)



Effect of the free surface - A model including Rayleigh waves:



Values of stabilization for a series of events



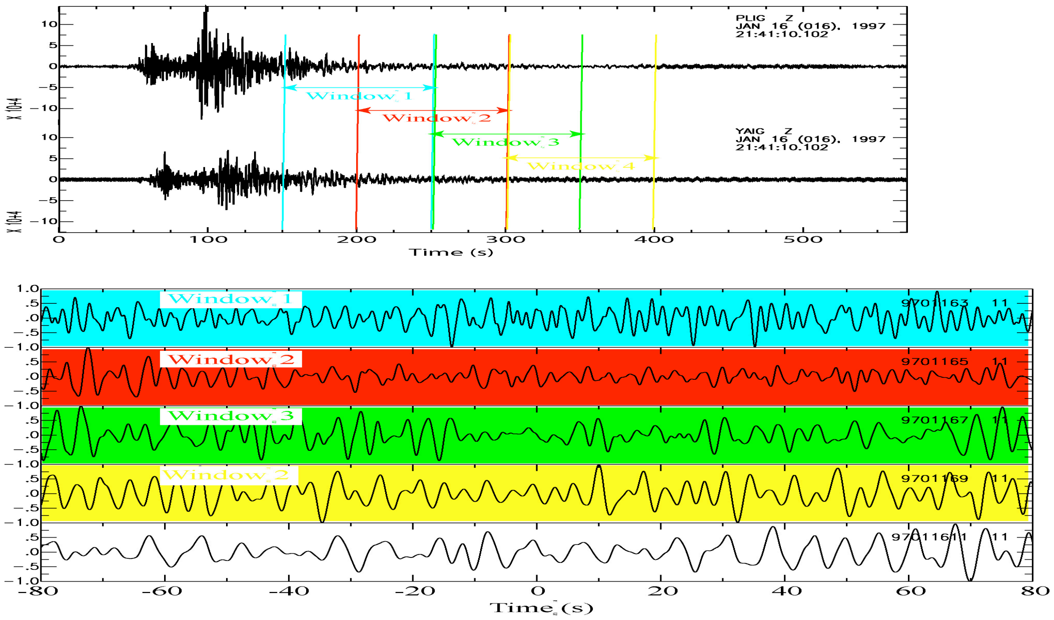
(Shapiro, Campillo, Margerin, Singh, Kostoglodov, Pacheco, BSSA, 2000.)

	OBSERVATIONS	THEORY FULL SPACE	THEORY HALF SPACE (BODY WAVES)	THEORY HALF-SPACE WITH RAYLEIGH
S/P	7.3	10.39	9.76	7.19

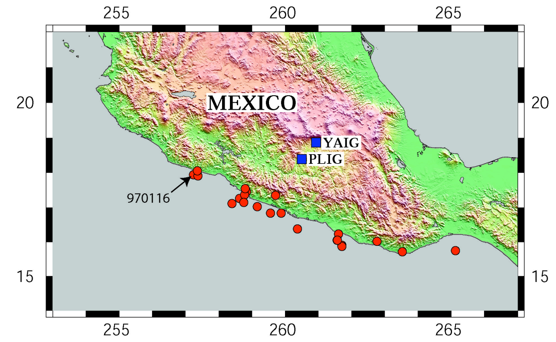
(Hennino et al., PRL, 2001)

Seismological application: coda waves

Individual cross-correlations:fluctuations dominate.



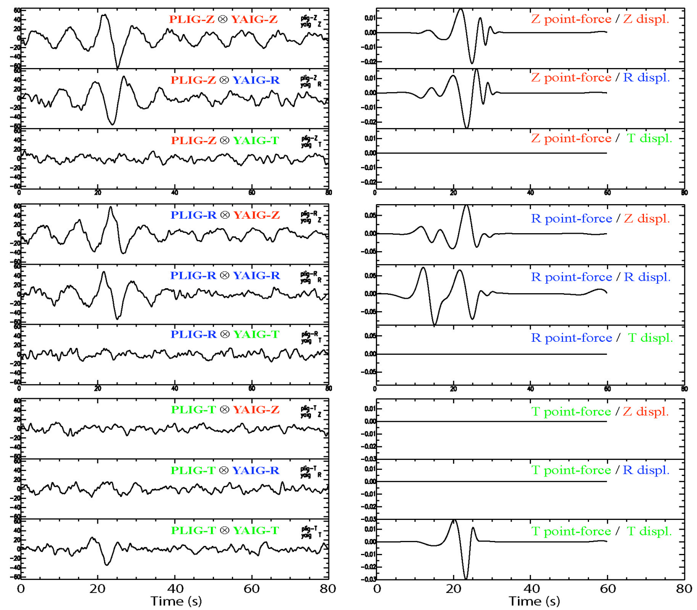
After averaging over 100 EQs➔



Emergence of the Green function

Stacks of 196 cross-correlations

Theoretical Green tensor at 69 km distance

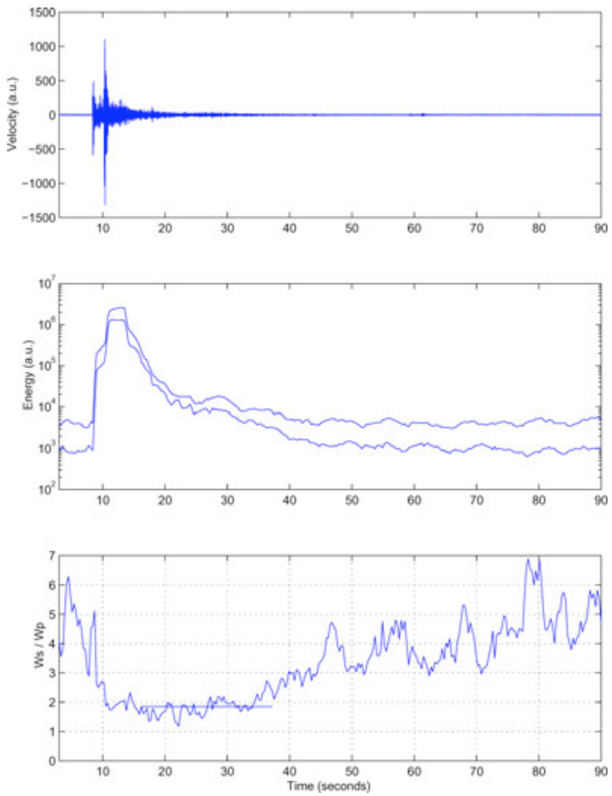


(Campillo and Paul, Science, 2003)

Is equipartition relevant for noise?

In general: no

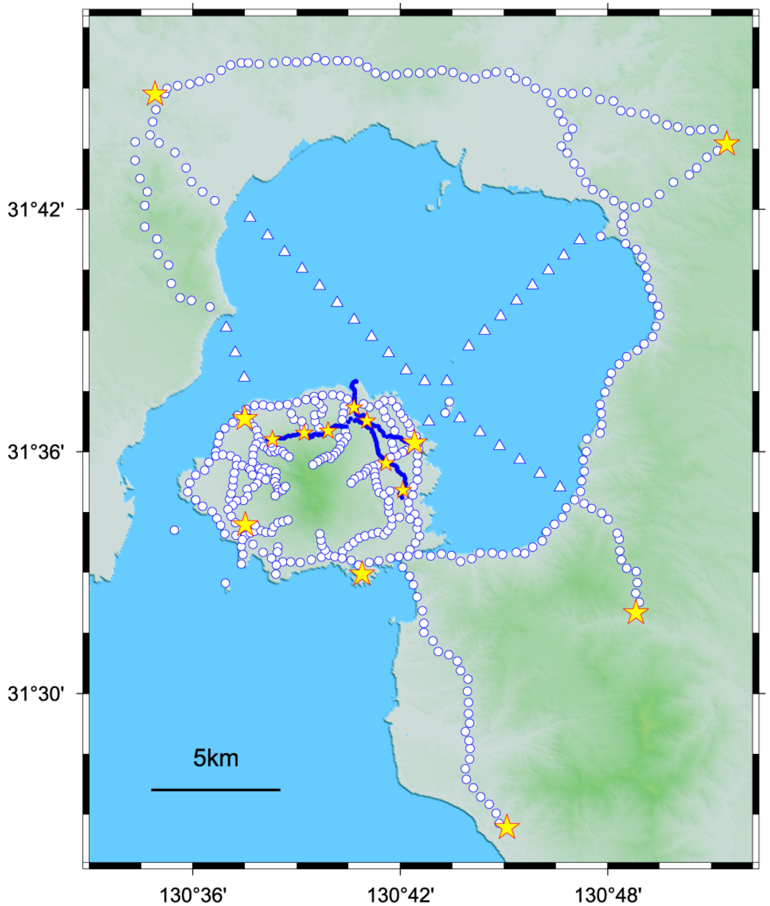
Example from records at PFO (Margerin et al., 2009)

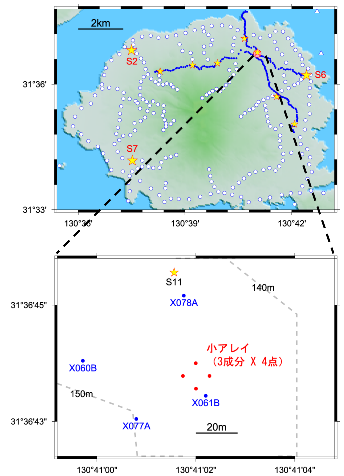


Seismic experiment at Sakurajima volcano

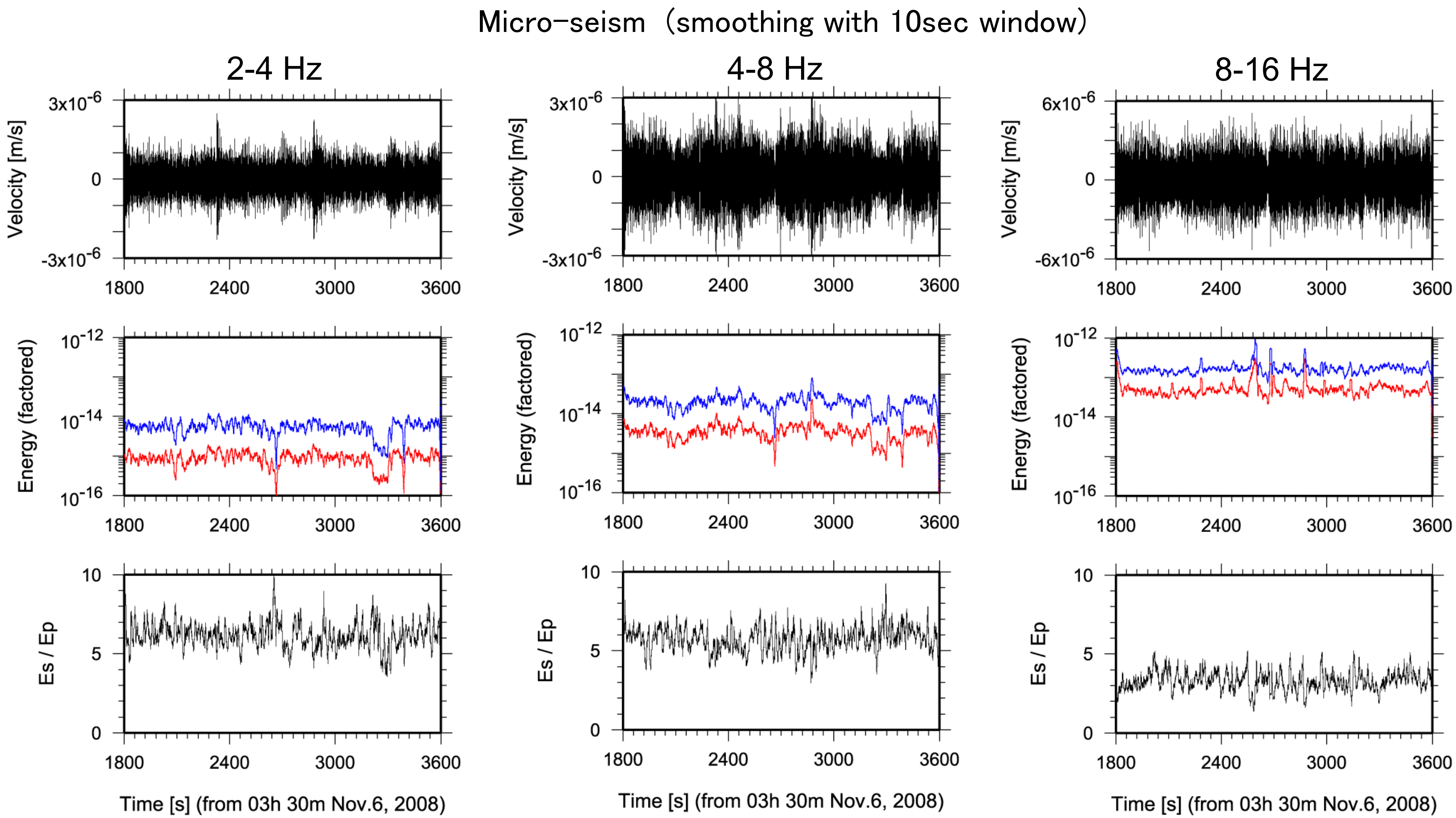
Sakurajima volcano is an active volcano in southern Japan

Another active seimic experiment was conducted in Nov. 2008 as a part of the national project for the prediction of volcanic eruptions.





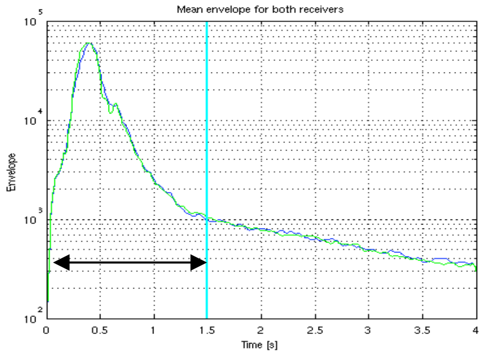
Seismic experiment at Sakurajima volcano



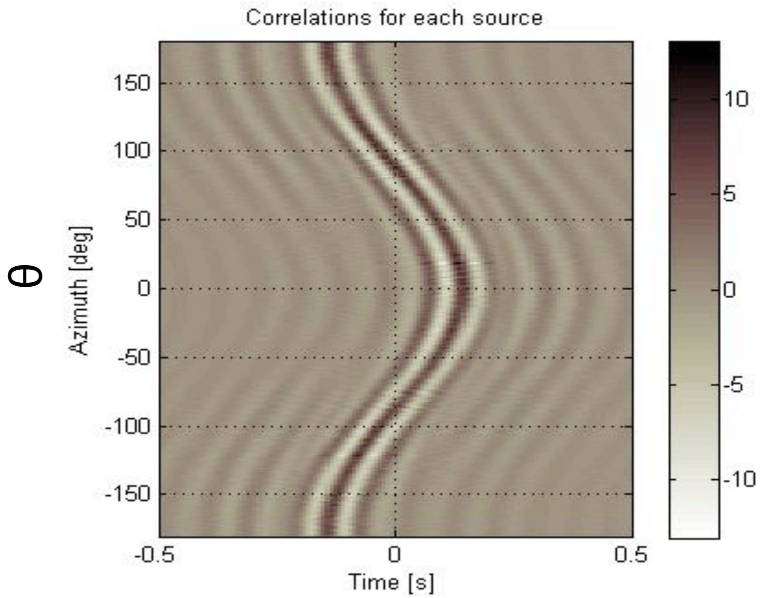
Figures modified from Dr. Mare Yamamoto, Tohoku University

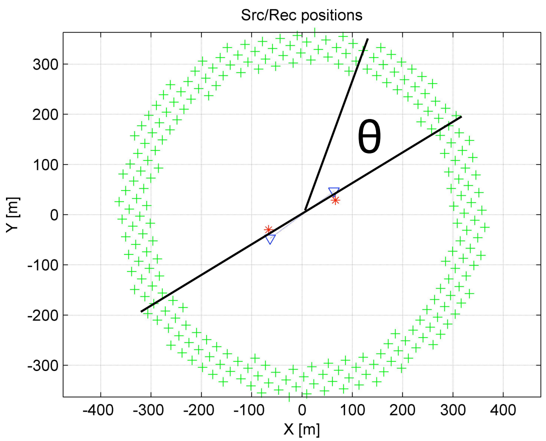
ILLUSTRATION: AN EXPERIMENT WITH REAL DATA:

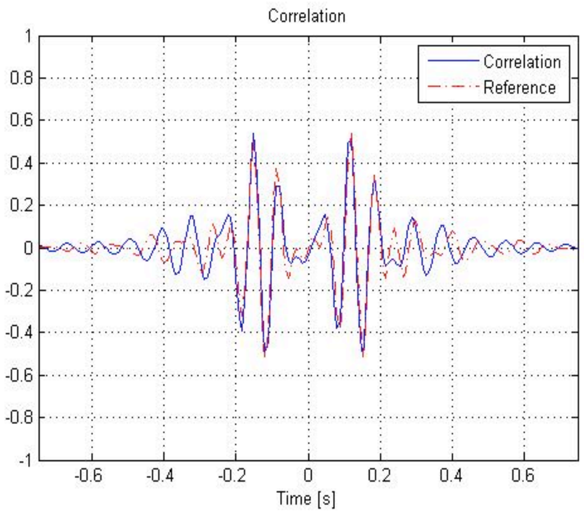
Time window of analysis



Direct arrivals







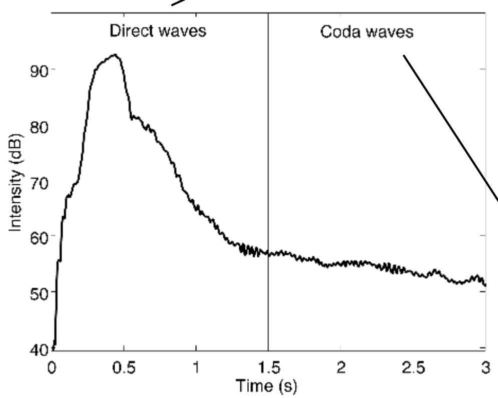
Interpretation: stationary phase (Snieder 2004; Roux et al., 2005)

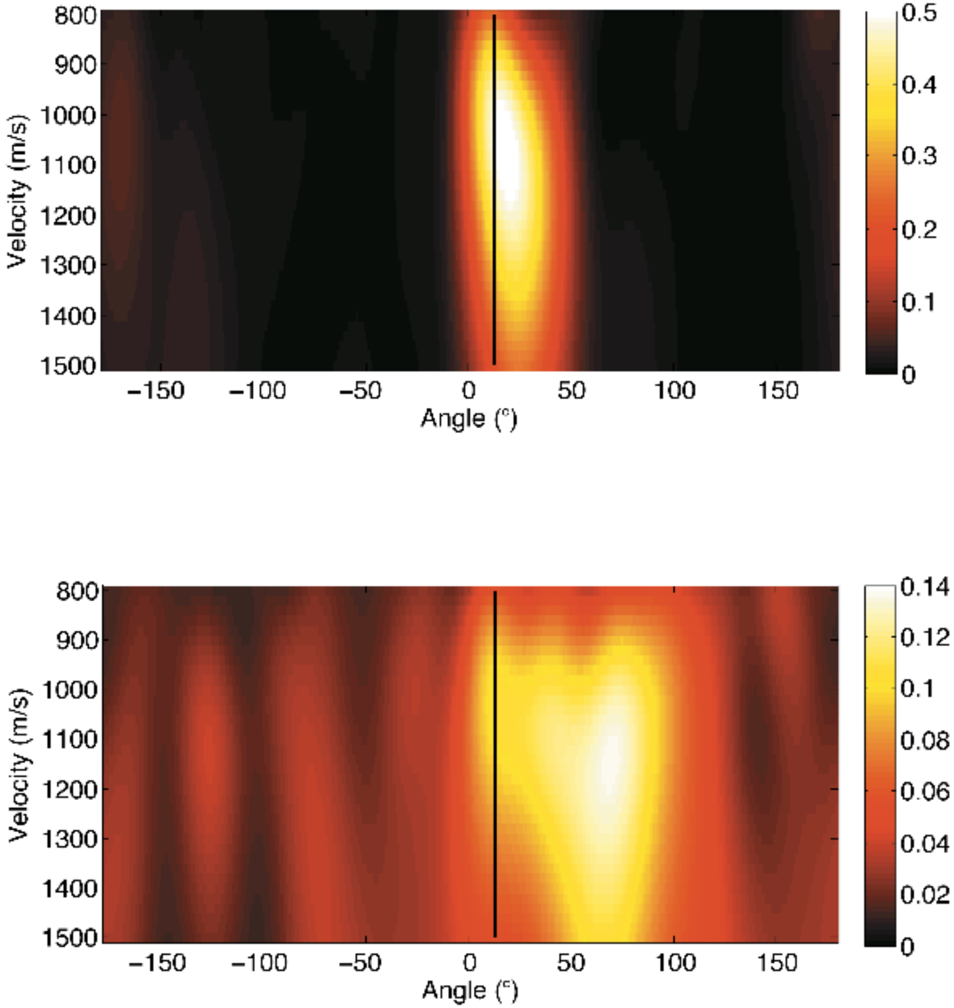
P. Gouédard, P. Roux, M. Campillo and A. Verdel (2008)

Coda waves: mitigation of non-isotropic effects

Beam forming

A single source



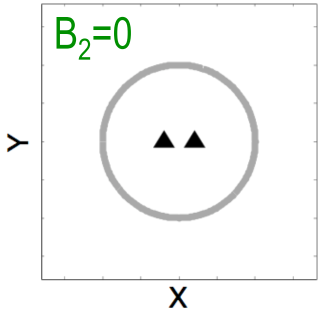


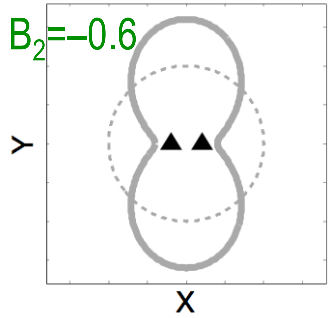
Direct waves: comparison with measurement on real data

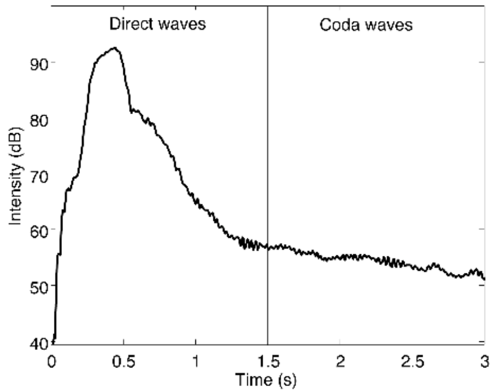
Real data

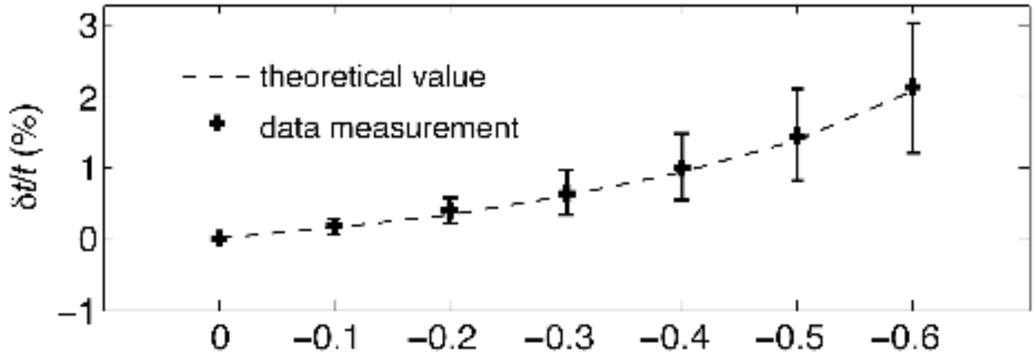
Non-isotropic illumination:

$$B(\theta) = 1 + B2\cos 2\theta$$







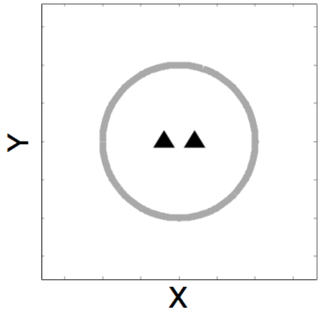


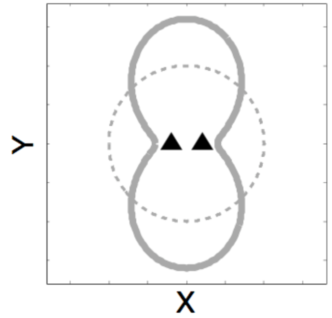
Froment et al., Geophysics 2010

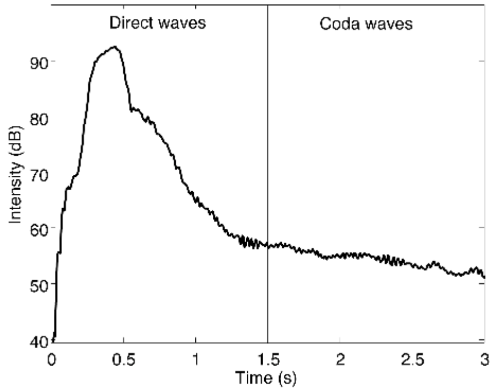
Coda waves: mitigation of non-isotropic effects

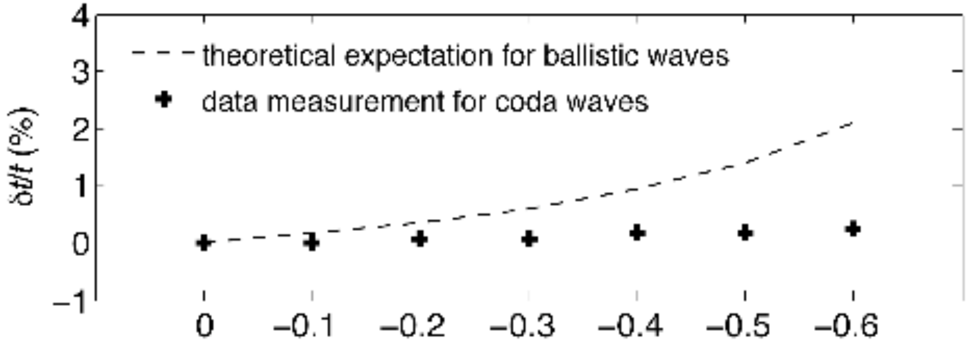
Non-isotropic illumination:

$$B(\theta) = 1 + B2\cos 2\theta$$









Earth heterogeneity helps…

Froment et al., Geophysics 2010

Measuring Seismic Velocity Variation from Continuous Seismic recordings

In the ideal case when the noise is a random field, we expect that

$$\partial_\tau C_{AB}(\tau) \propto G^+(A,B,\tau) - G^-(A,B,-\tau)$$

Correlation of fields in A and B

Green function between A and B

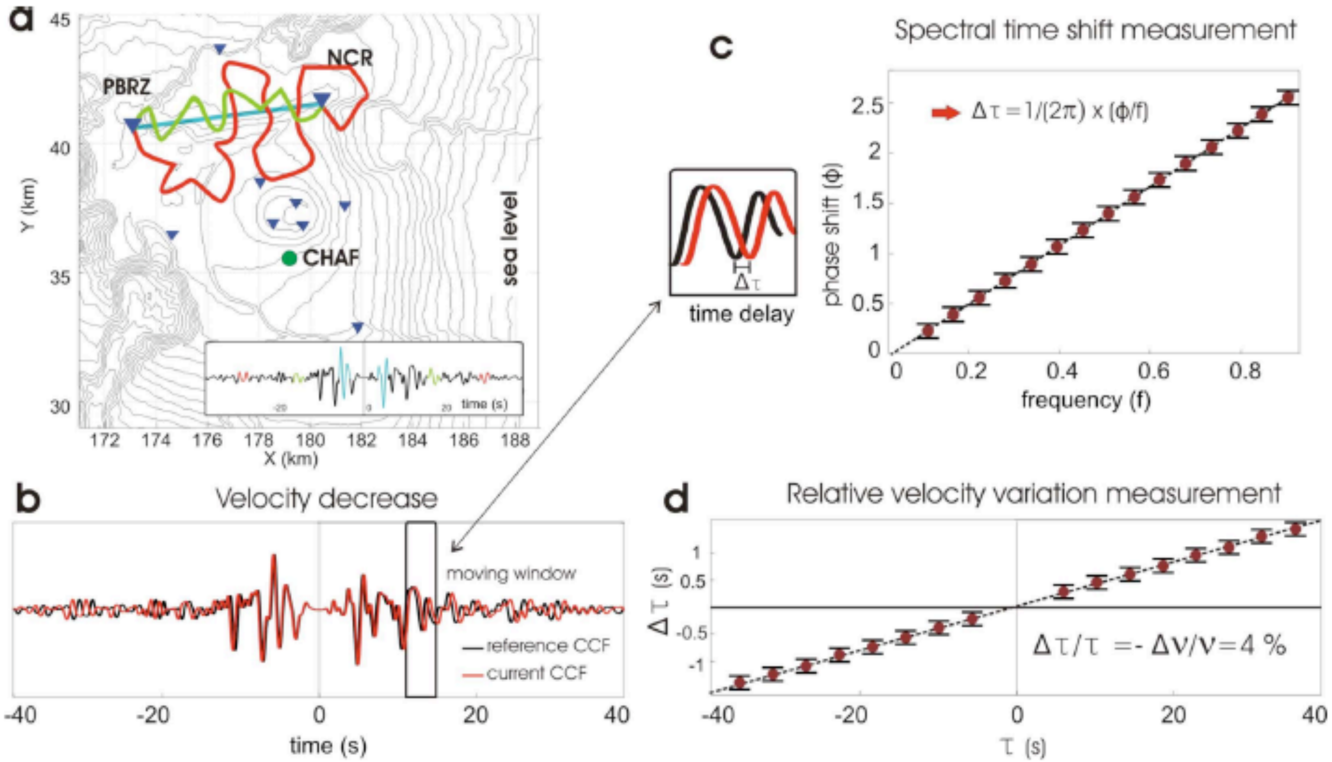
The correlation is equivalent to the record during an *active* experiment

This operation can be repeated at different dates and the virtual Earth responses analyzed to detect seismic velocity changes

Measure of temporal variations : the coda again

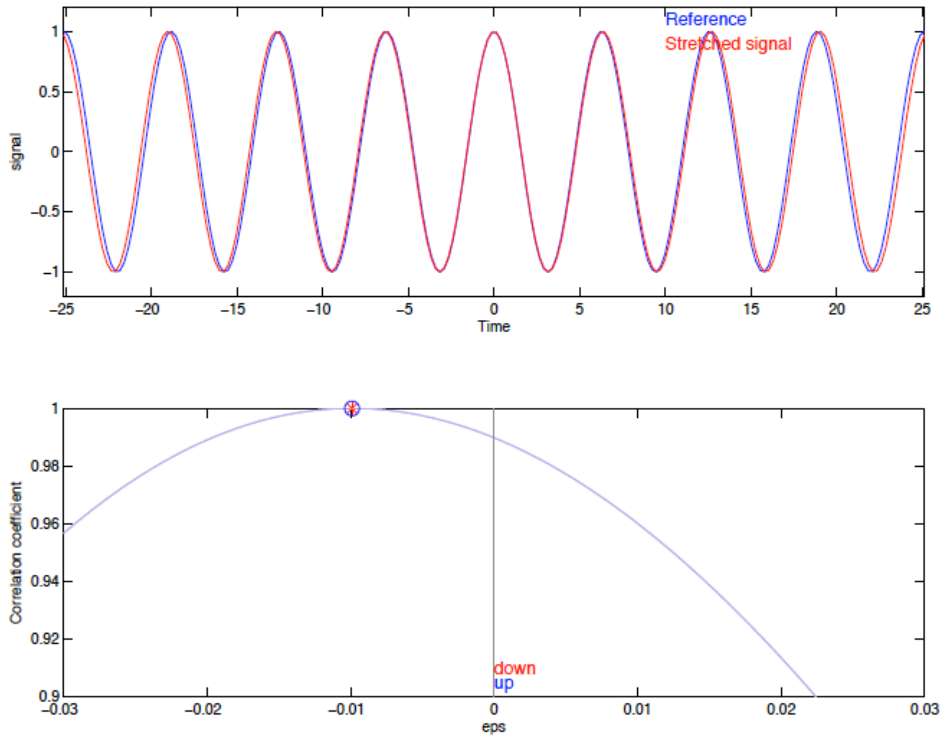
Hypothesis: homogeneous (or large scale) variation of velocity

1)Doublet method (Poupinet et al., 1984)=MWCSA=CWI=…



See Pacheco and Snieder 2005

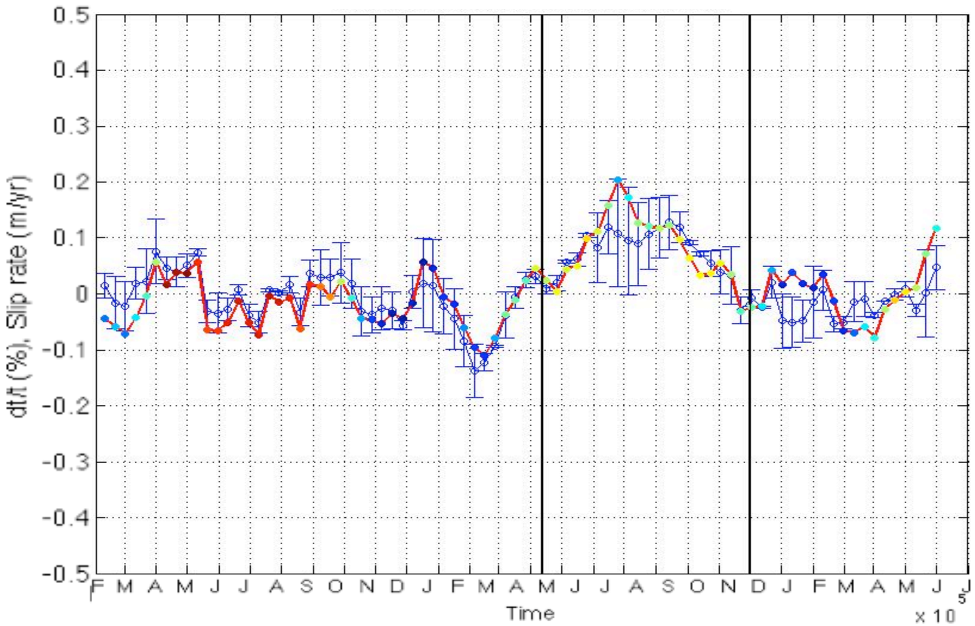
Stretching method: optimizing the coherence of two signal by stretching



Stretching vs. Doublet

Stretching: global measurement

Doublet: local measurement



Rivet et al, 2011

Variance of the measure of velocity change as a function of coherence, central frequency, bandwidth and time window:

$$\frac{\sqrt{1-X^2}}{2X}\sqrt{\frac{6\sqrt{\frac{\pi}{2}}T}{\omega_c^2\ (t_2^3-t_1^3)}}$$

Weaver, RL, C Hadziioannou, E Larose, and M Campillo On the precision of noise correlation interferometry in press Geophys. J. Int. 2011.

(In the example above, the change is 5 times the variance)

Noise correlations and Green function

. Ambient noise correlations ⟶ Green Function?

Main <u>limitation</u>: uneven source distribution $\Rightarrow$ noise correlation does not reconstruct the **exact** Green function

⟶ Source signature in correlations
Convergence

For monitoring we rely on the coda waves ⟶ Nature of the tail of the CCF?

Correlation of Coda of Correlations : C3 (Stehly et al. 2008)

C3 method

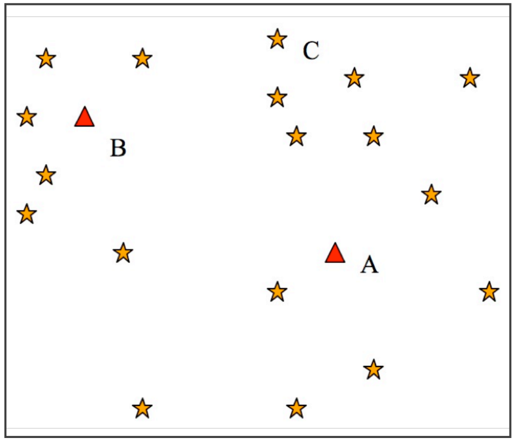
Repeating the processing of codas of EQ data but for noise CCFs:

Considering the station pair AB:

. Consider a third station C and the coda of correlations AC (s_{AC}) and BC (s_{BC}). C is a virtual source

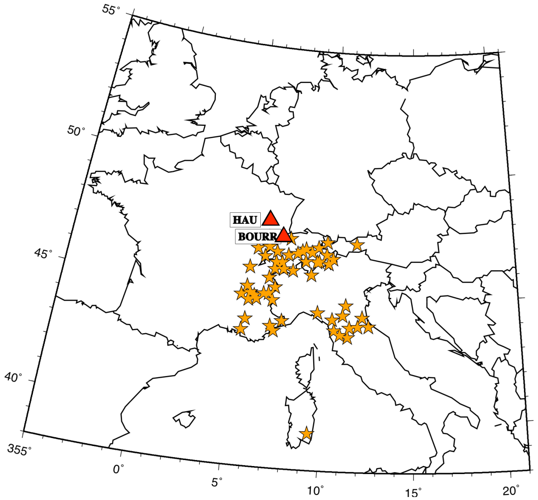
. Correlate s_{AC} and s_{BC}

. Average over all the N stations (Cs) of the Network

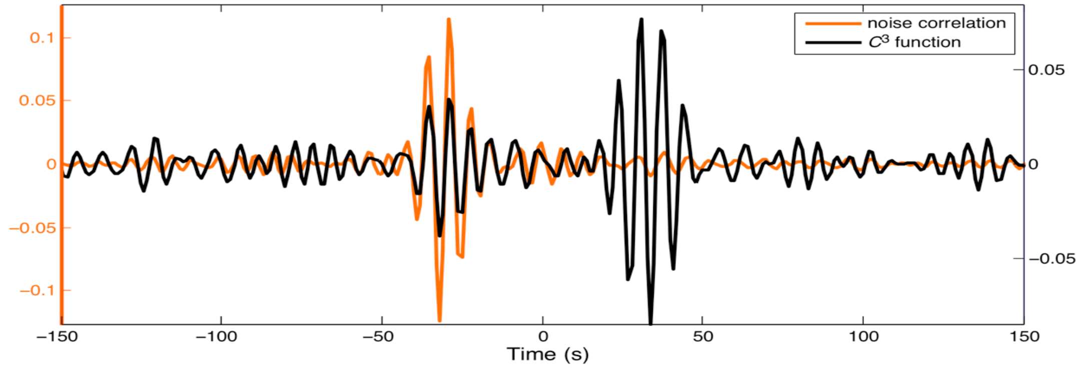


Stations of the network ⟷ Virtual sources

Time-symmetry of the C3 function: example



Example: station pair BOURR-HAU

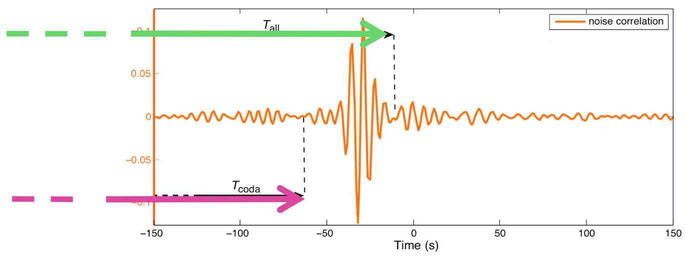


N S

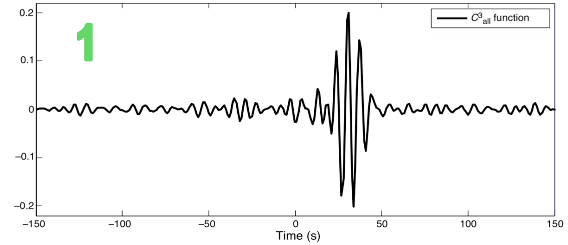
S N

The later part of the noise correlations is meaningful = coda part of the Green function)

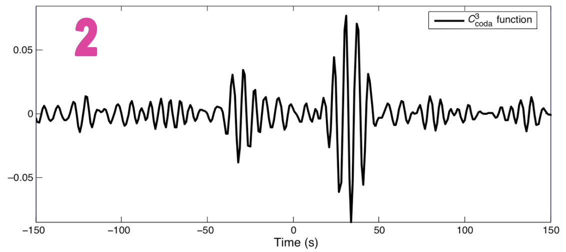
Time-symmetry of the C3 function: the role of scattering



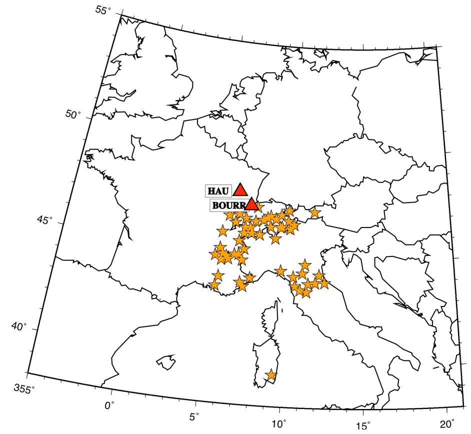
(a)



(b)



(c)



Correlation of entire noise correlation

→ **Stations location**

Direct waves are dominant

Correlation of coda of correlation (C3)

→ **Stations location + scattering**

Coda waves are more isotropic

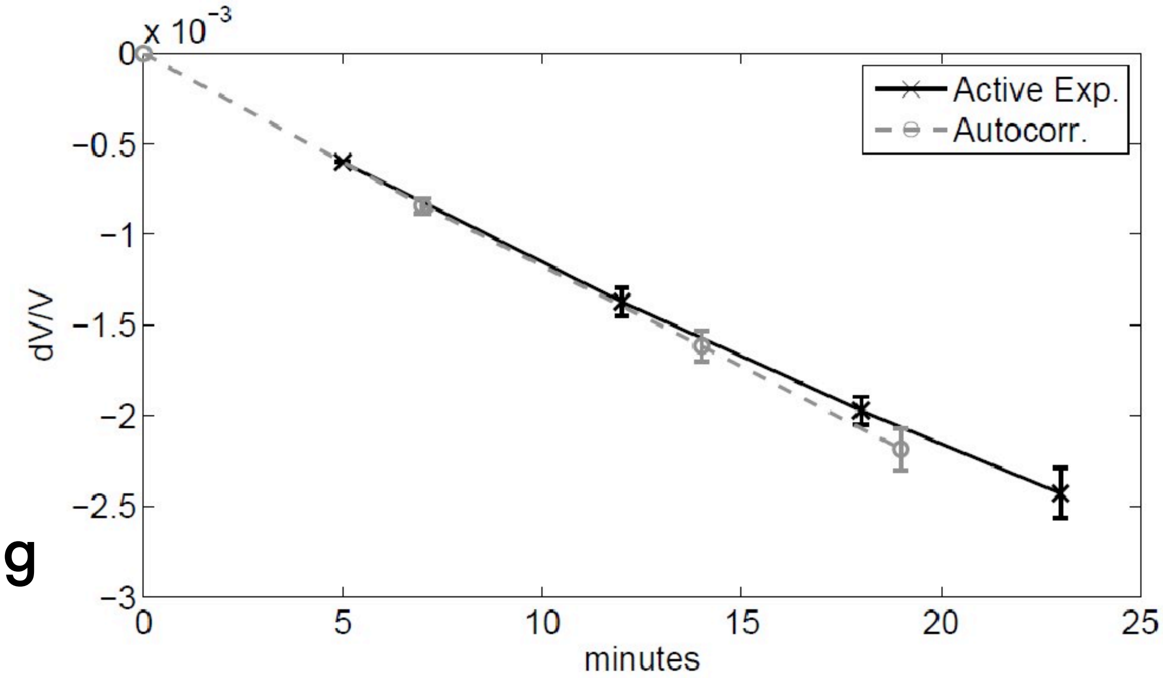
No need for the exact GF: Hadziioannou et al., 2009

Experiment

Xcorr ≠ GF

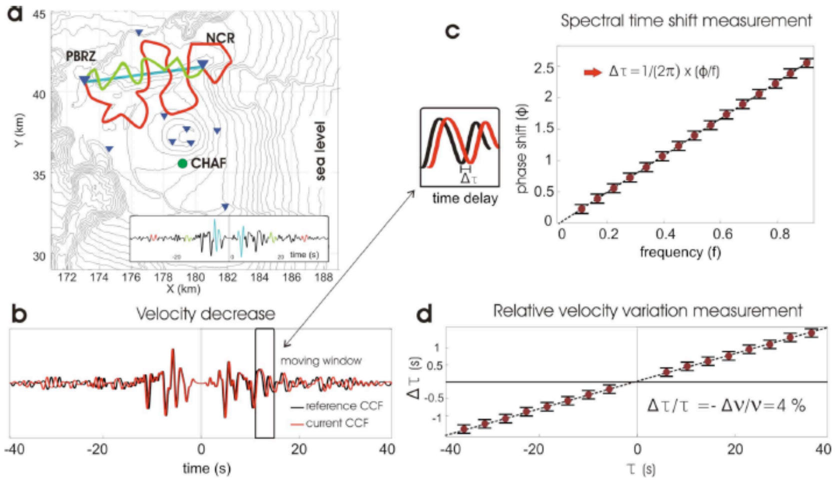
but!

active monitoring
=
passive monitoring



Time / Temperature

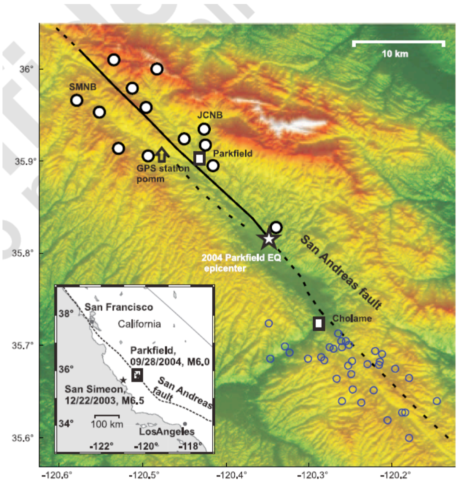
Measure of temporal variations



We use the coda of the cross correlation functions to detect small perturbations of velocity (similar to the doublet method of Poupinet et al. 1984).

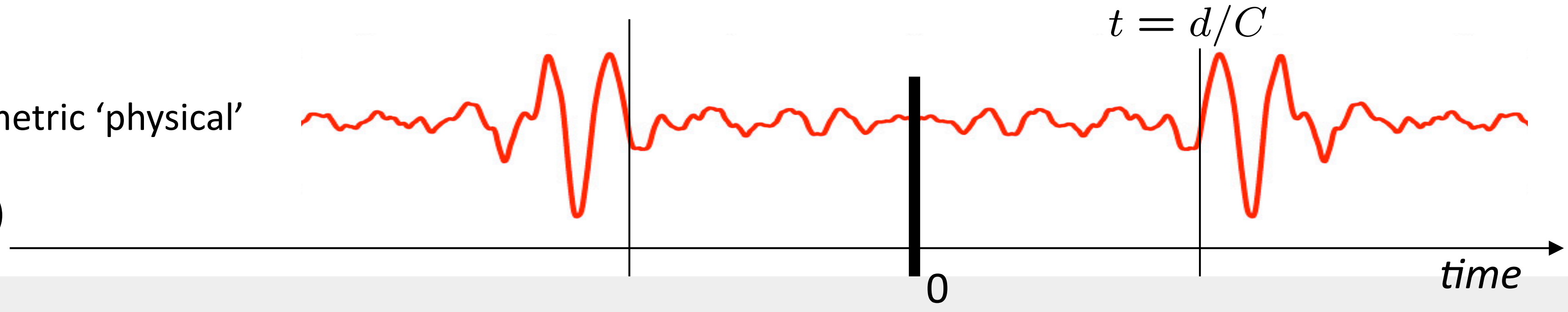
Applications to monitoring: eg. Wegler and Sens-Schonfelder (2007), Brenguier et al. (2008a,b), Hadziioannou et al. (2009), Cheng et al (2010).

Application to Parkfield *(Brenguier et al. 2008)*



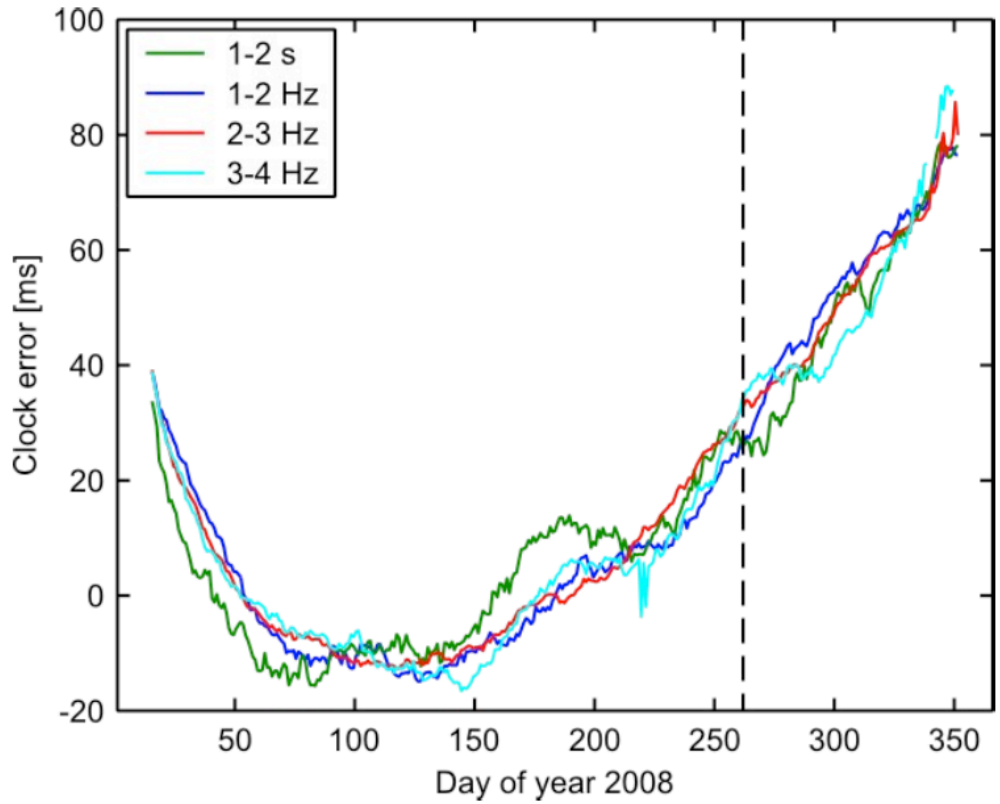
Positive-negative times

Time symmetric 'physical' signal (reference)



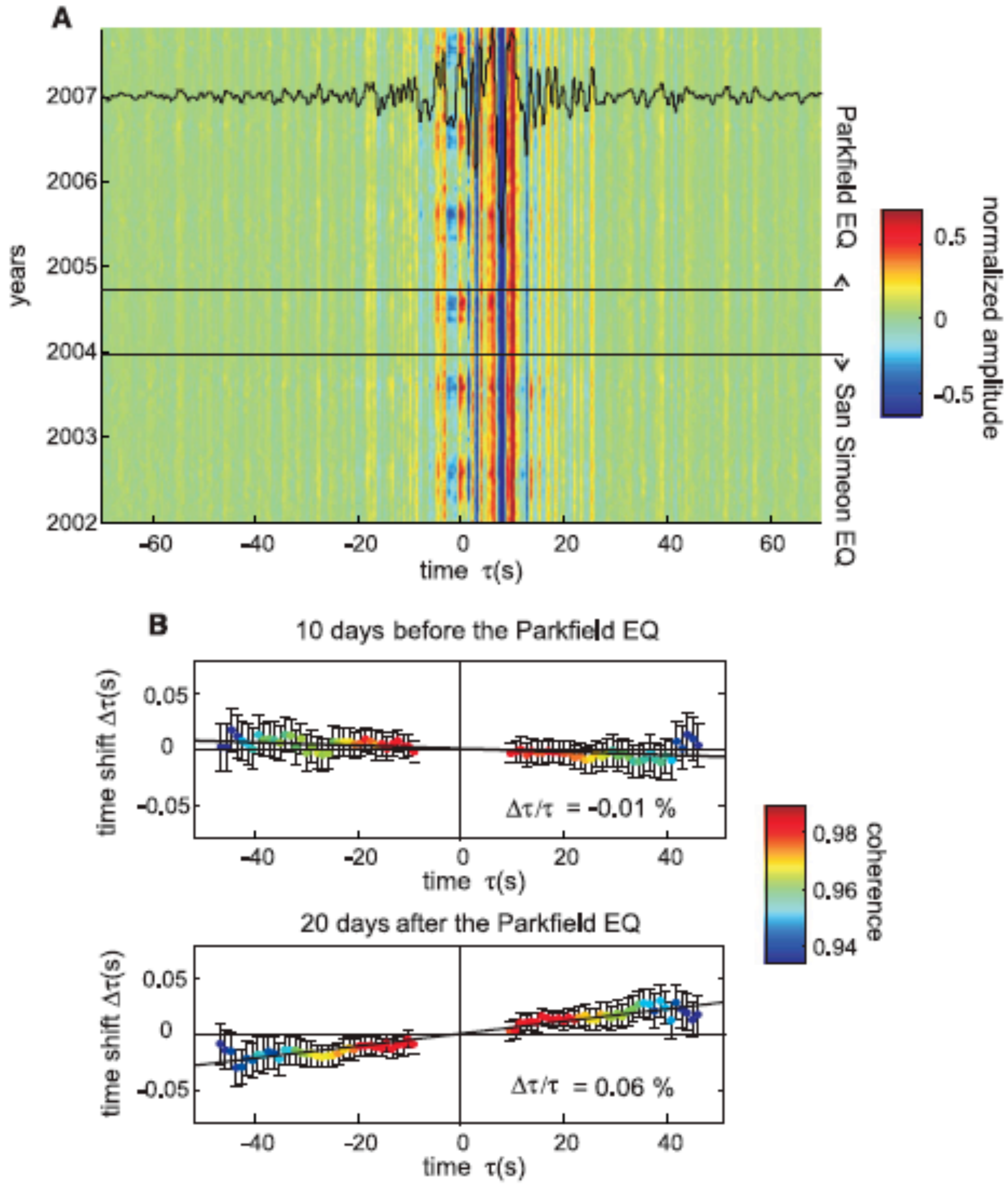
A powerful technique to detect and evaluate instrumental time errors

A careful monitoring of clocks from time symmetry (figure from Pierre Gouedard -OBS data, 2011)

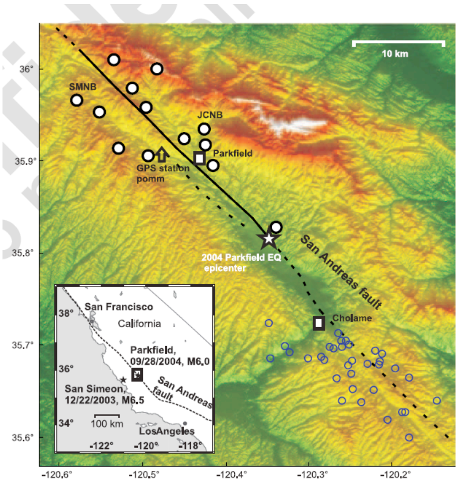


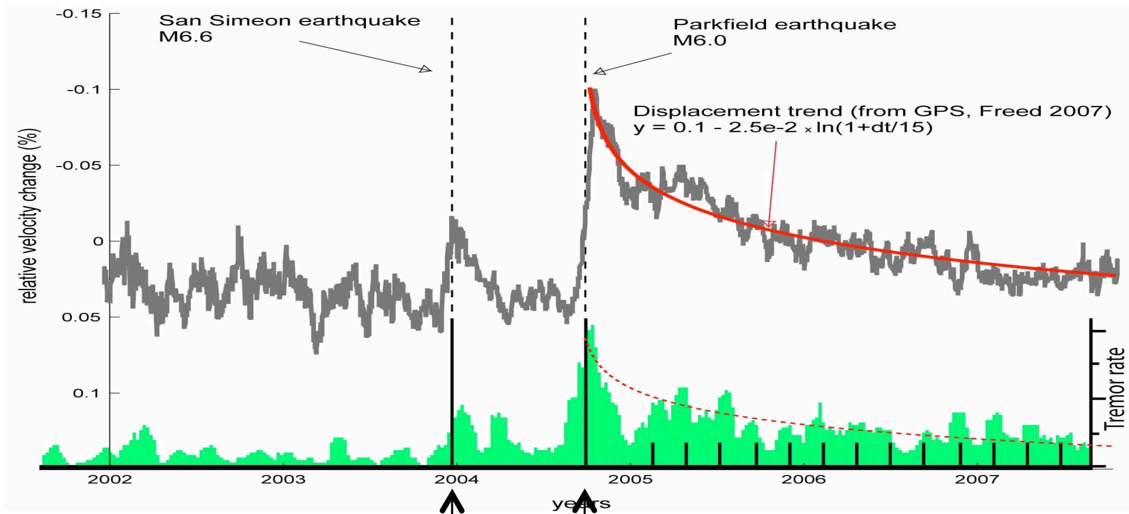
Correlation functions (period band:2-8s)

Stability of 'coda'



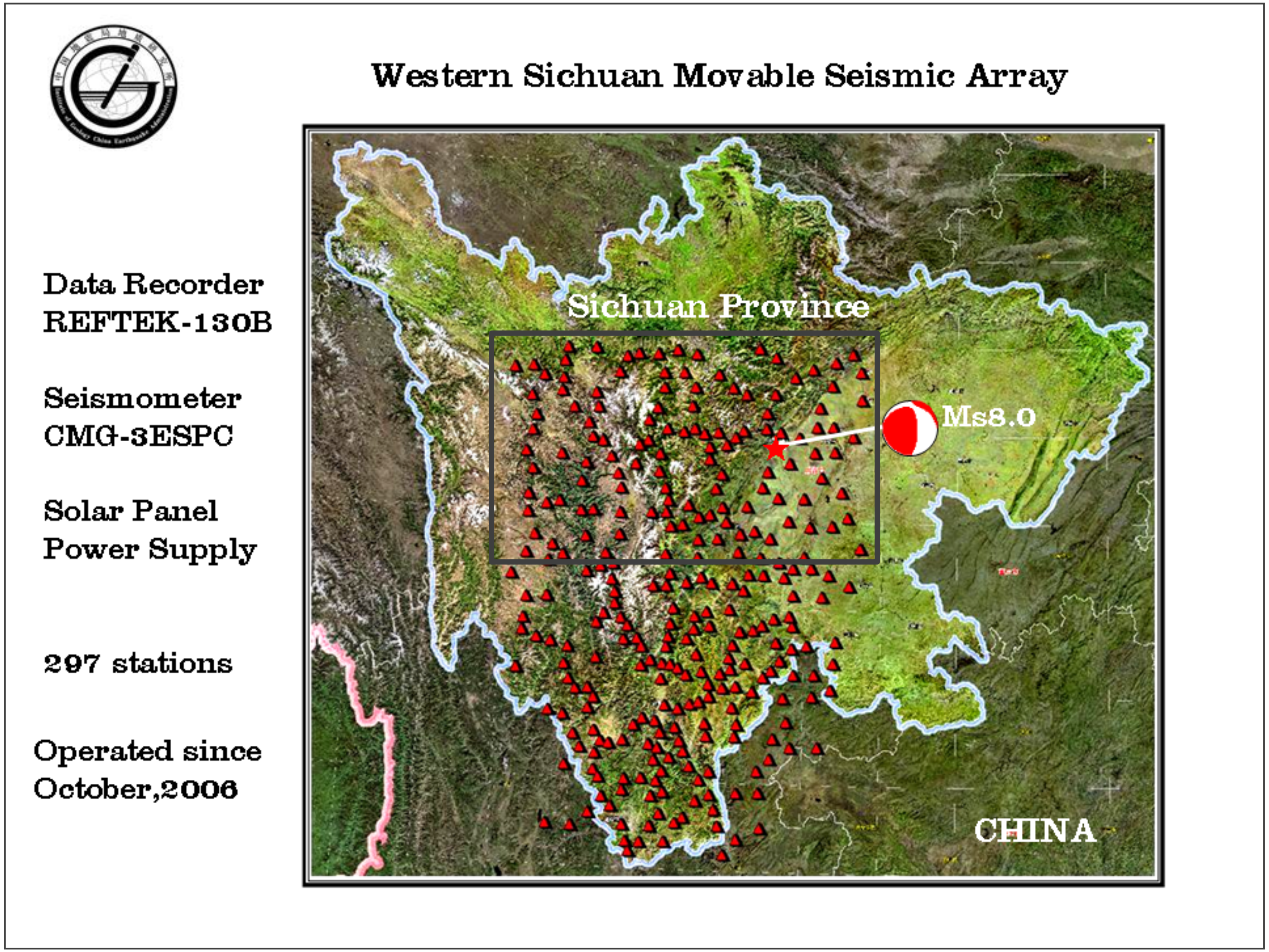
Application to Parkfield *(Brenguier et al. 2008)*



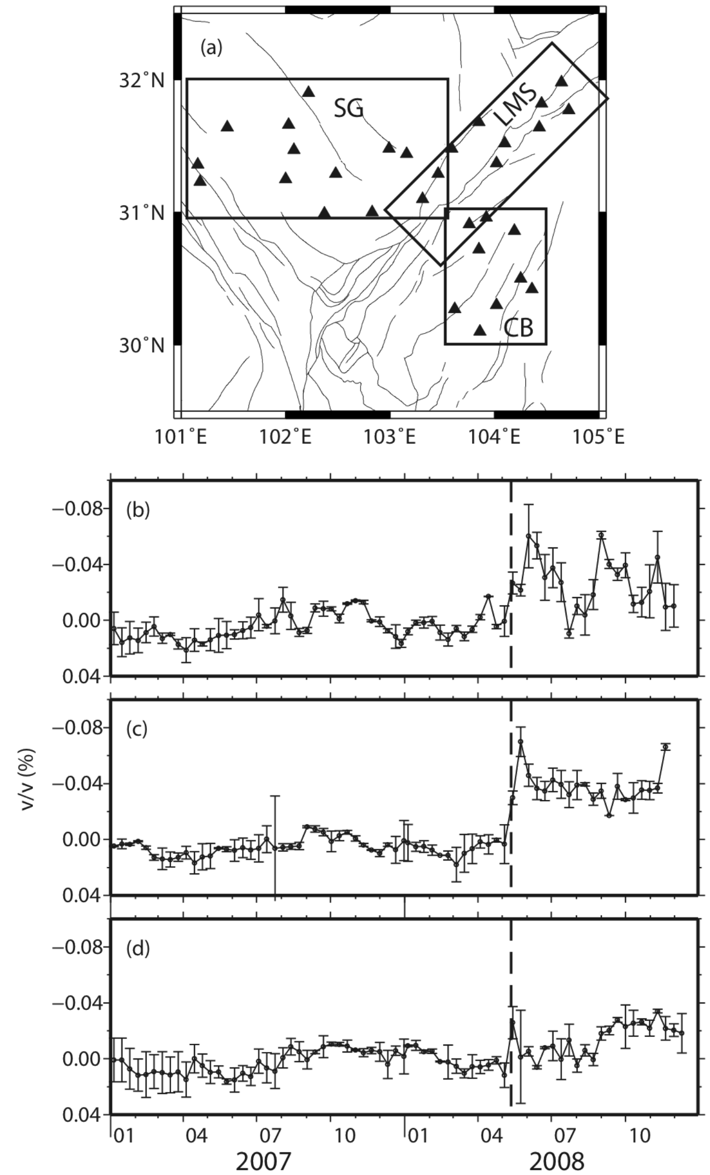


Distant event **Local event**

NETWORK and DATA



1-3s period



Sichuan Basin

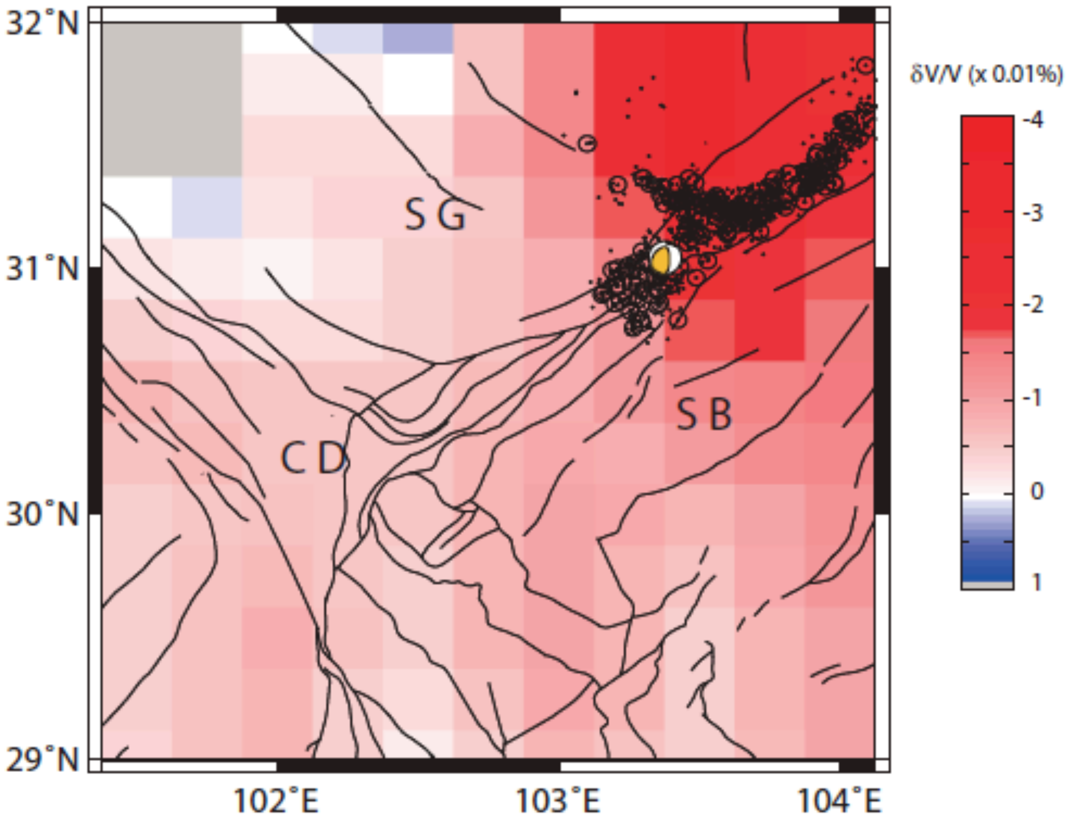
Longmen-Shan

Songpan-Ganzi

Chen, Froment, Liu and Campillo 2010

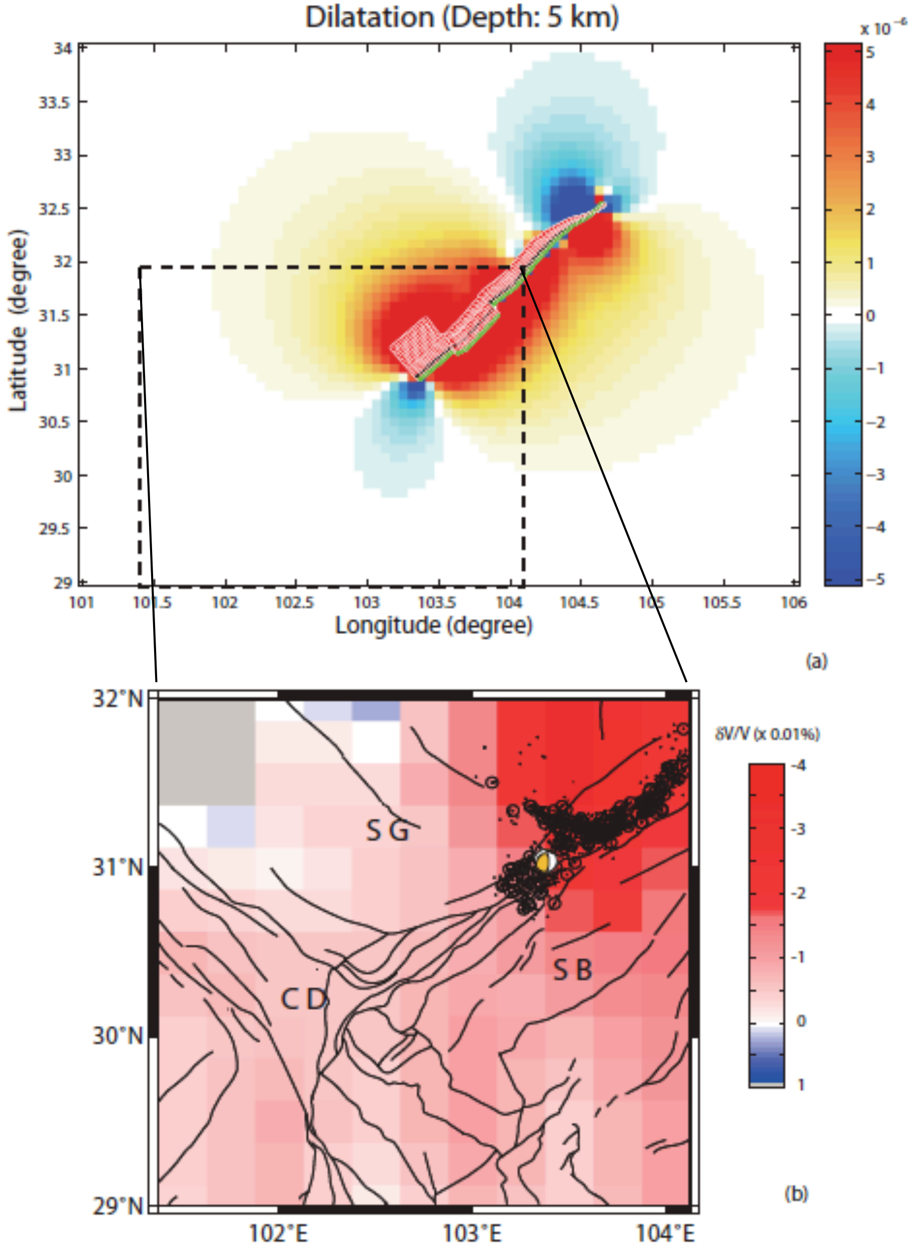
- Co and Post-seismic velocity temporal change associated with the Wenchuan earthquake -

SPATIAL DISTRIBUTION - Results 1-3 s-



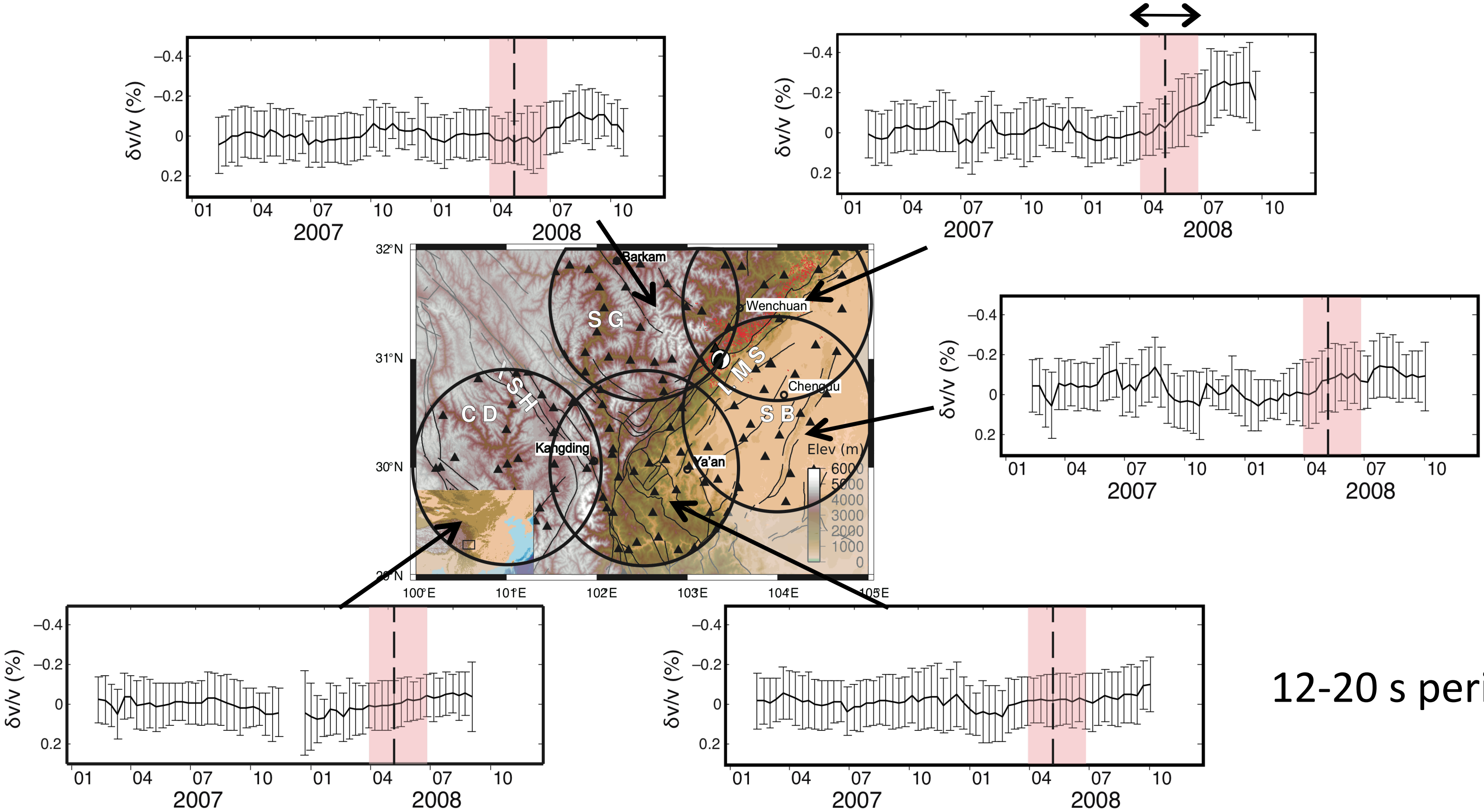
- no evidences for role played by the sedimentary basin
- regional effect

Chen, Froment, Liu and Campillo 2010



Chen, Froment, Liu and Campillo 2010

100-day stack



12-20 s period

Froment, B., M. Campillo, J. Chen, Q. Liu, 2011

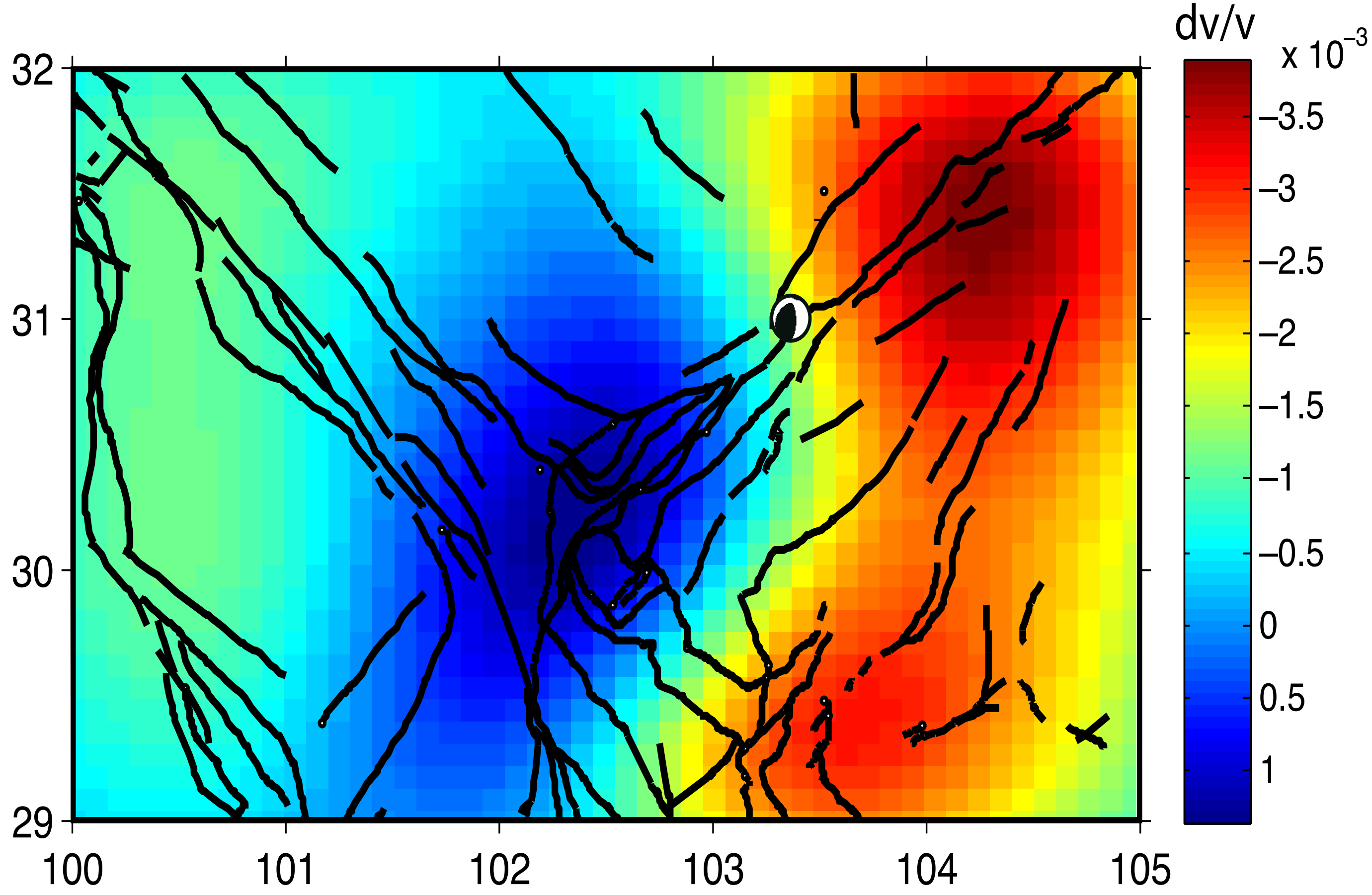


Figure from Bérénice Froment, 2011