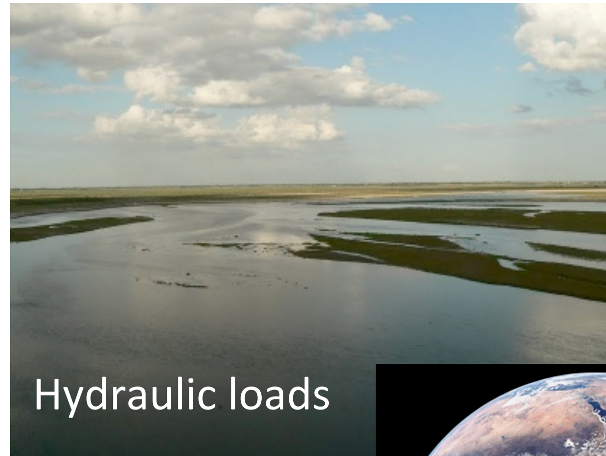
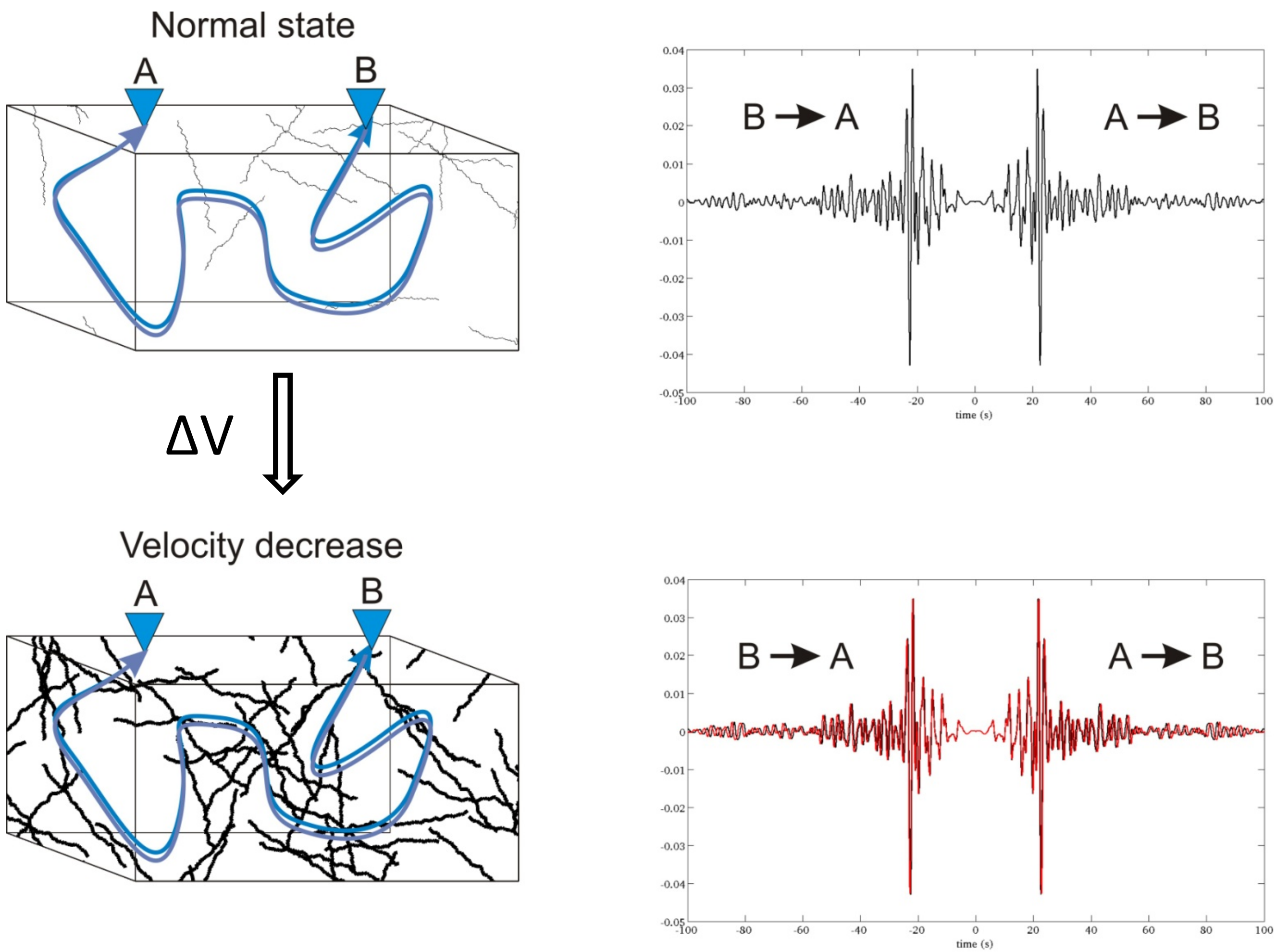


Monitoring temporal changes in the solid Earth with seismic velocities

`ICTP 2016 Michel Campillo`

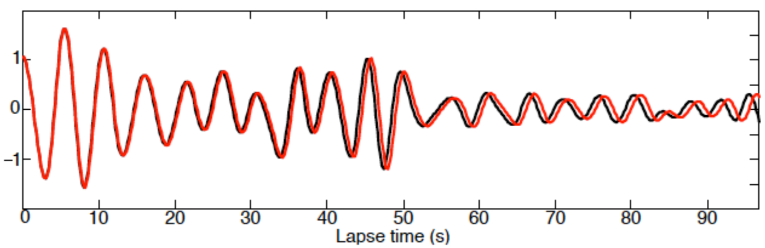
Noise based seismic velocity temporal changes

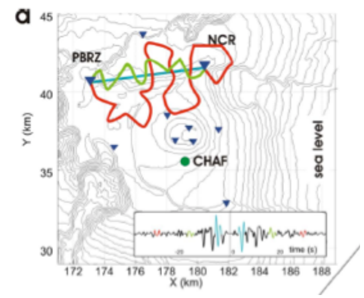
Because seismic noise is continuous in time, it is possible to reconstruct **repeating virtual seismic sources** and perform **continuous monitoring of seismic velocities**.



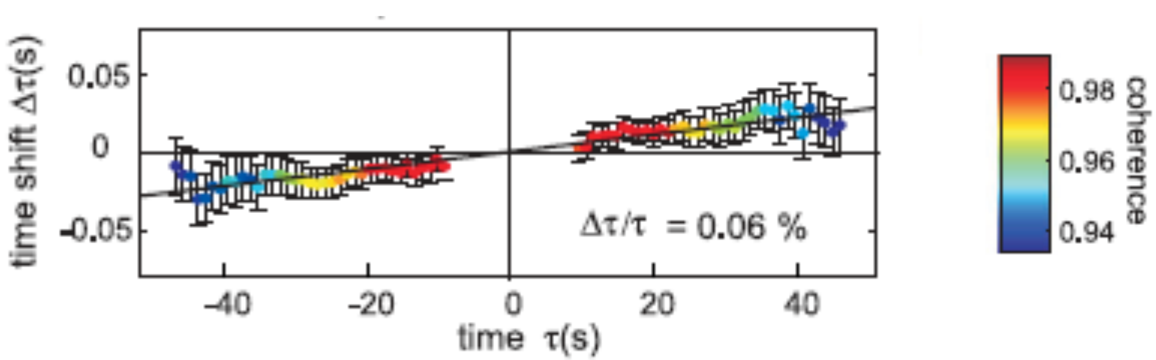
Detecting a slight change of seismic speed with coda waves

Comparing a trace with a reference under the assumption of an homogeneous change





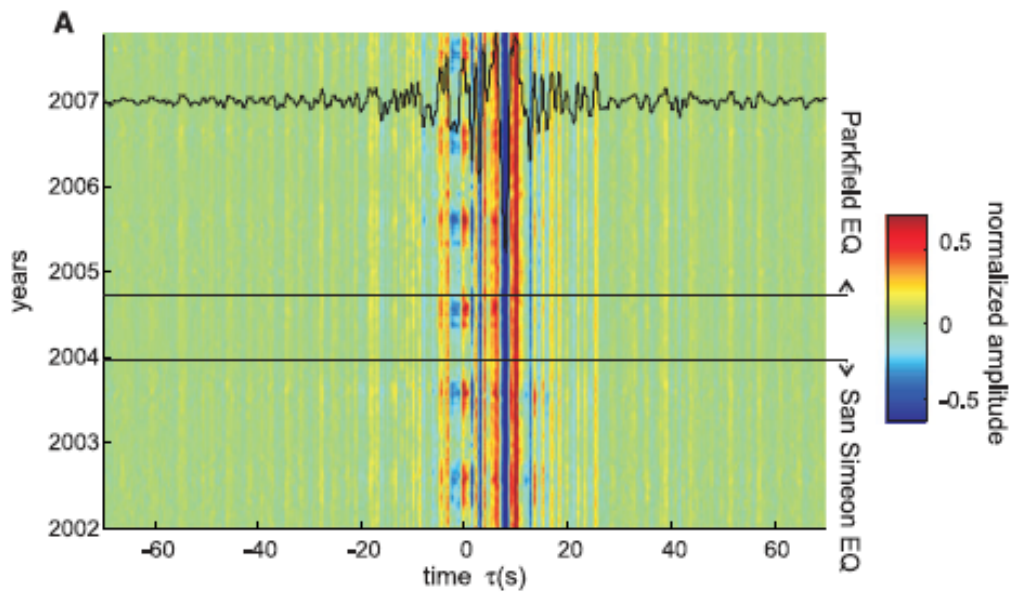
The ‘doublet’ method: moving window cross spectral analysis (phase measurements)



➔ Extreme sensitivity

Monitoring with noise correlation functions as approximate Green functions

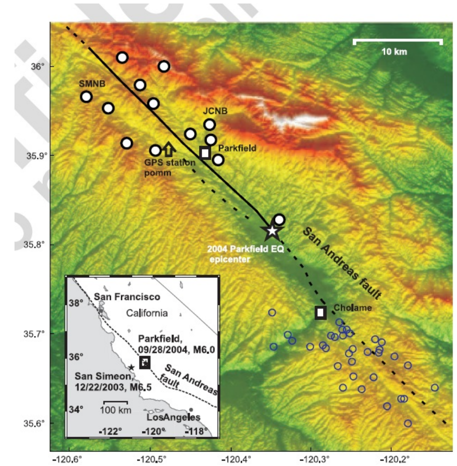
(Sens-Schönfelder and Wegler, 2006; Stehly et al., 2007; Brenguier et al., 2008;…)



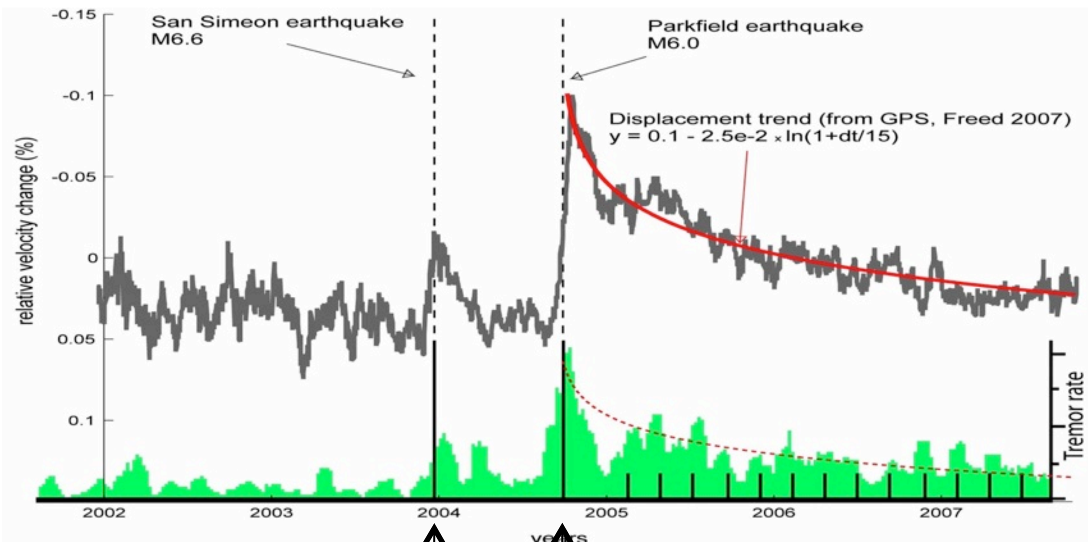
Direct waves are sensitive to noise source distribution (errors small enough for tomography (≤1%) but too large for monitoring (goal ≈ 10^{-4})

Stability of the 'coda' of the noise correlations

Application to Parkfield *(Brenguier et al. 2008)*
Short period sensors / Processing in the period 1-10s



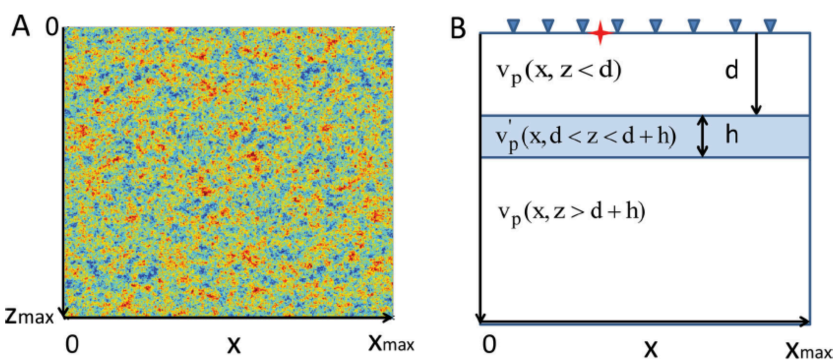
HRSN network

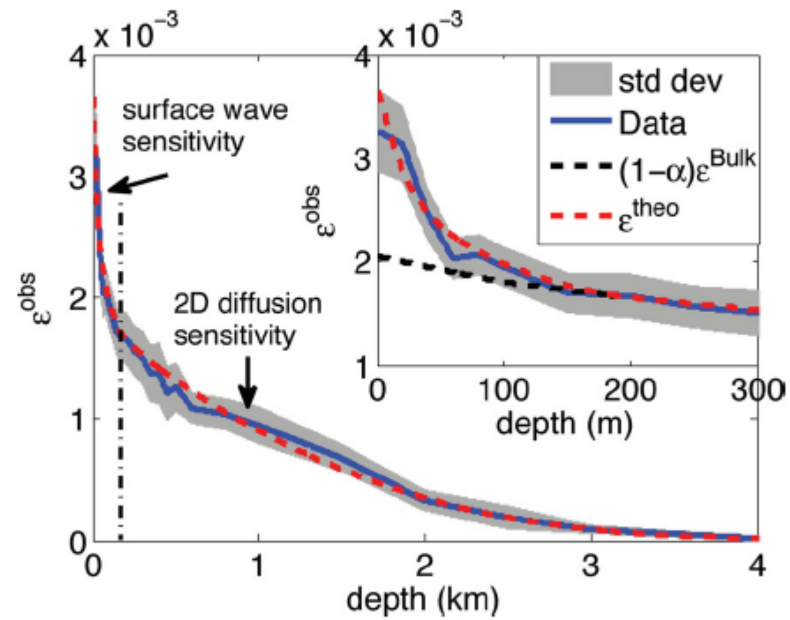


Distant event **Local event**

➔ GPS trend
➔ tremor activity
➔ but ambiguity with non-linear effect of strong ground motion on surficial materials

Sensitivity of coda to a change in the medium 1: wave type and depth sensitivity





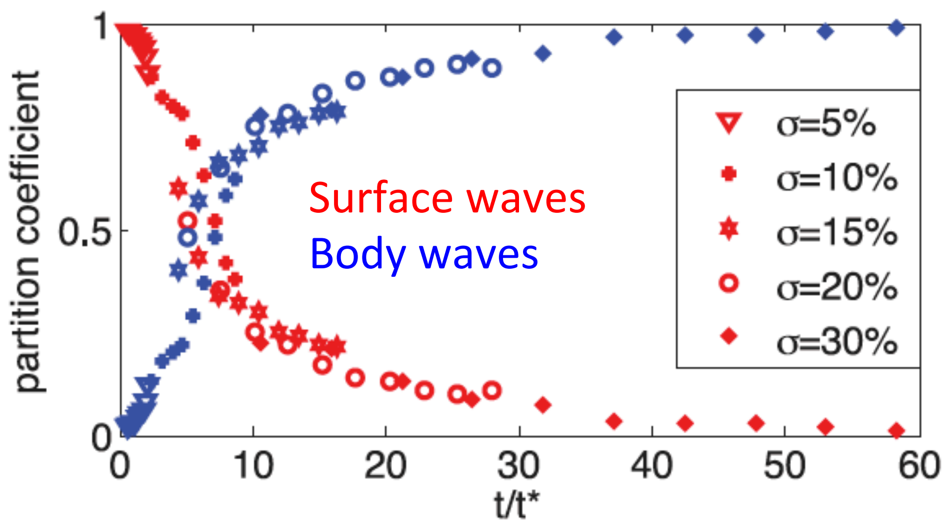
$$\varepsilon^{theo}(d,t) = \alpha(t)\varepsilon^{Surf}(d) + (1-\alpha(t))\varepsilon^{Bulk}(d,t)$$

Partition coefficient

Obermann et al., 2013a

Sensitivity of coda to a change in the medium 1: wave type and depth sensitivity

$$\varepsilon^{\text{theo}}(d,t) = \alpha(t)\varepsilon^{\text{Surf}}(d) + (1-\alpha(t))\varepsilon^{\text{Bulk}}(d,t)$$



Lapse time in the coda/scattering mean free time

Obermann et al., 2013a

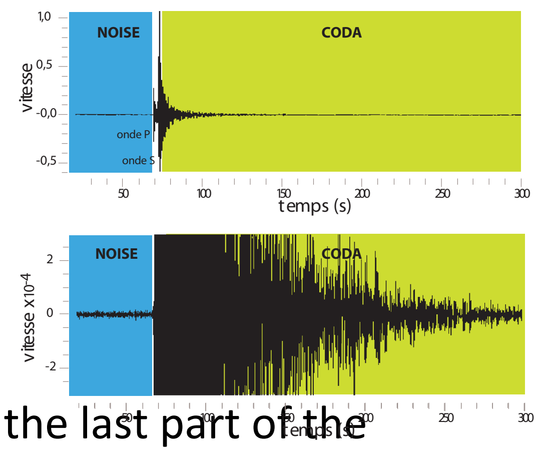
In the applications presented here, we analyze early coda (a few mean free times) so our measures concern mainly surface waves

Manipulate the seismic wavefield:

-with arrays of seismometers: beam-forming, double-beamforming, rejection of surface or body waves,…

-with distant seismometers: separate ballistic/coherent and scattered field to use scattered waves for Green function reconstruction?

Practically impossible with noise records. A strategy is to use correlations as Green functions, and separate simply in the time domain…



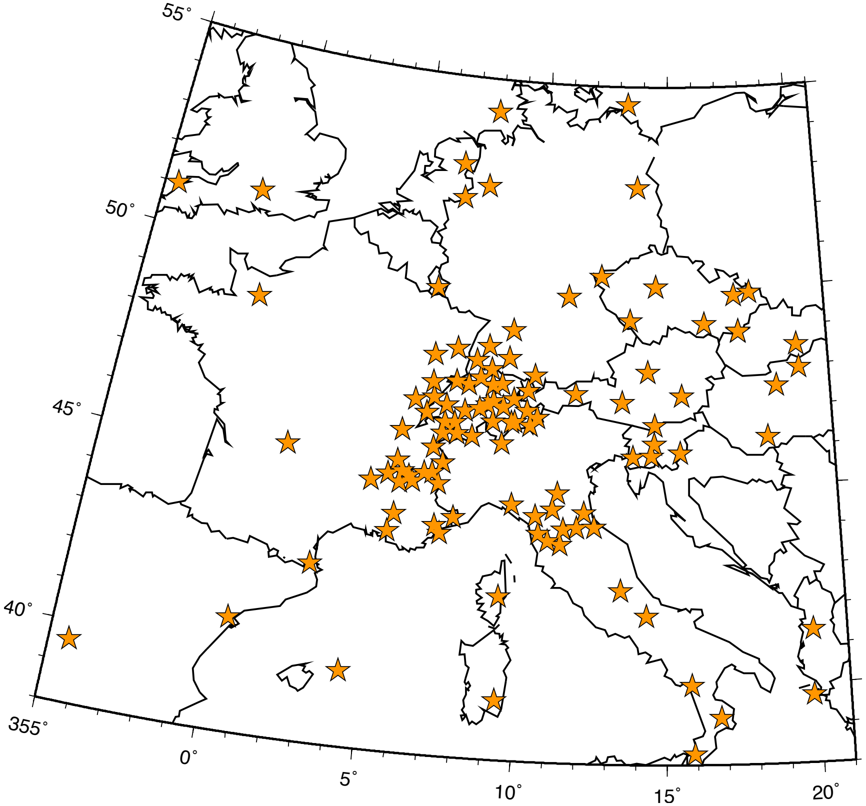
Question: How far the multiply scattered field is present in the last part of the correlation?

A signature of multiple scattering: « coherent backscattering » (or « weak localization »)

C3

Network & Data

Virtual European Network (Alps)



. 150 broadband stations

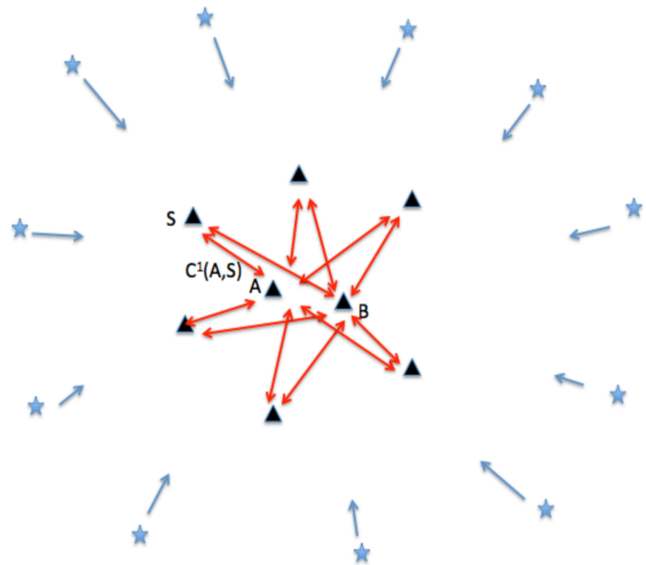
. 1 year of continuous records

. Vertical component

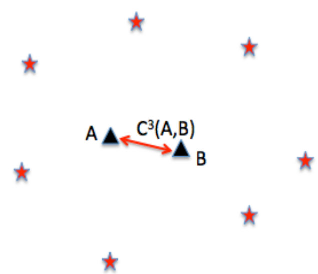
. Signals in the 5-10-s period band

Illustration of C3

(a) Computation of noise correlations (virtual seismograms)

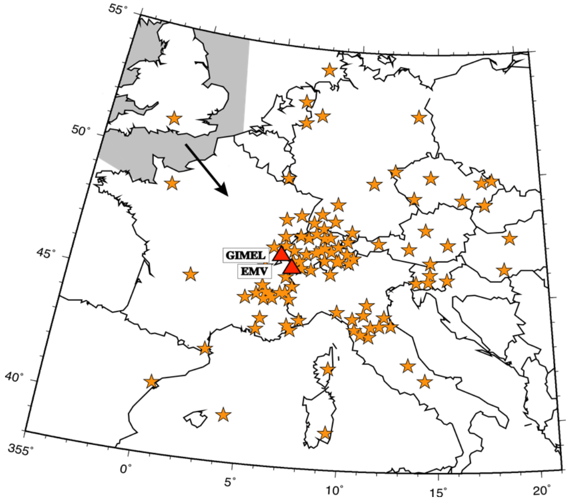


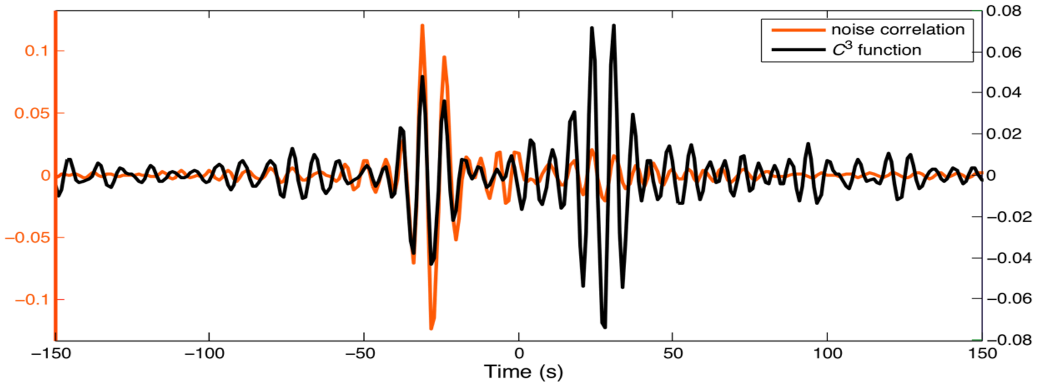
(b) Correlations of noise correlation codas (stations as virtual sources)



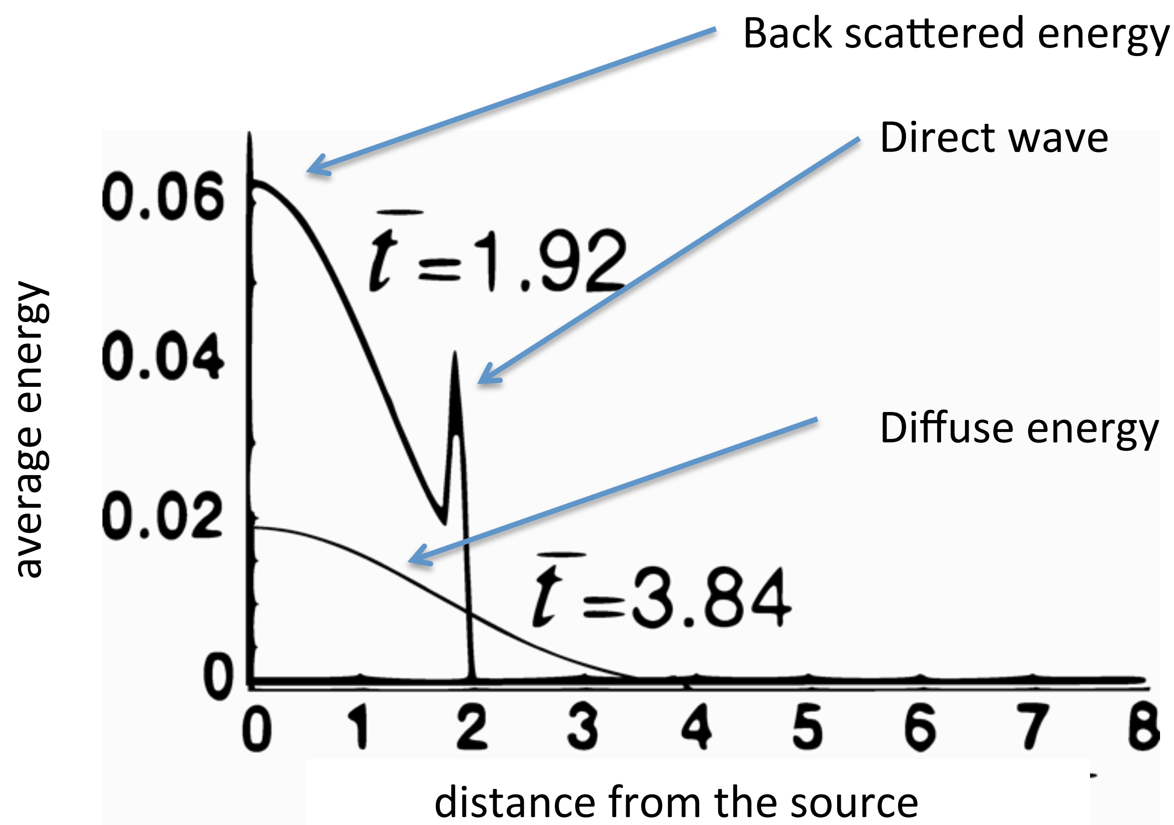
Remove the influence of actual source distribution- or extracting multiply scattered waves

C3 method: results





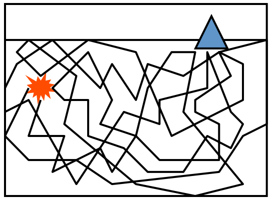
Diffusion, radiative transfert equation = model for the average energy of the scattered waves



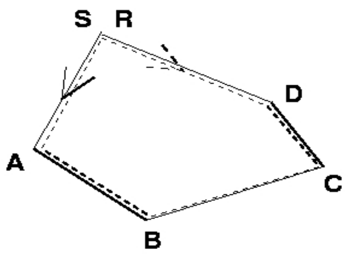
Sato & Fehler, 1998

Coherent Back Scattering (weak localization)
Reciprocal paths in the multiple scattering regime

(Akkermans et al., 1988)



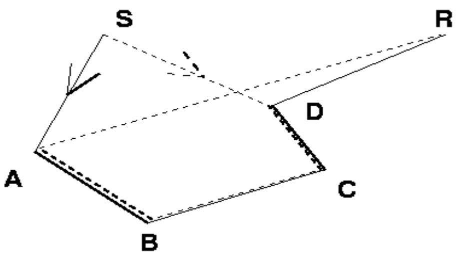
Receiver at the source



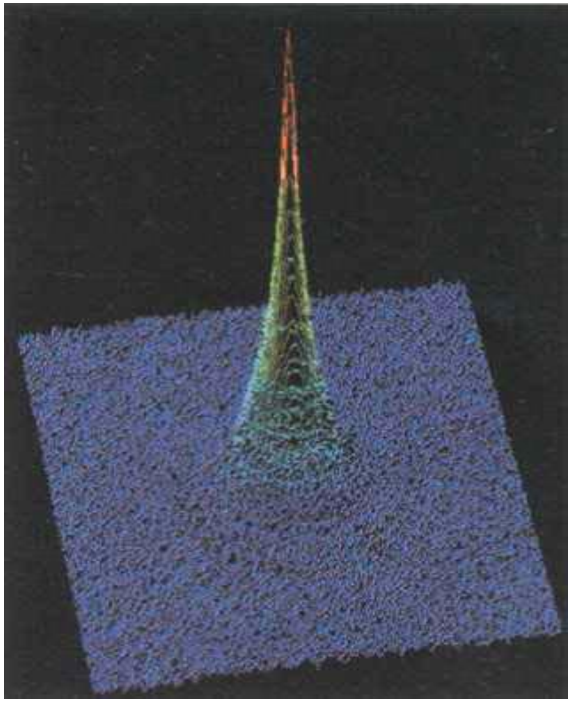
Reciprocal paths:

interference

Receiver far from the source



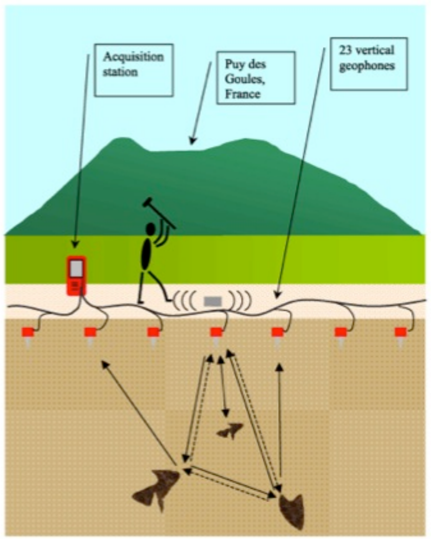
'random' phase

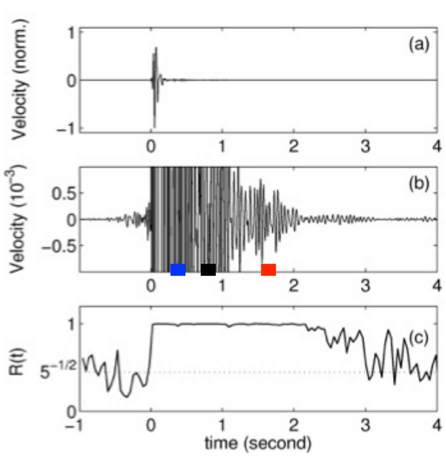


Back-scattering of light
by a cold atoms gaz
Labeyrie et al., 1999

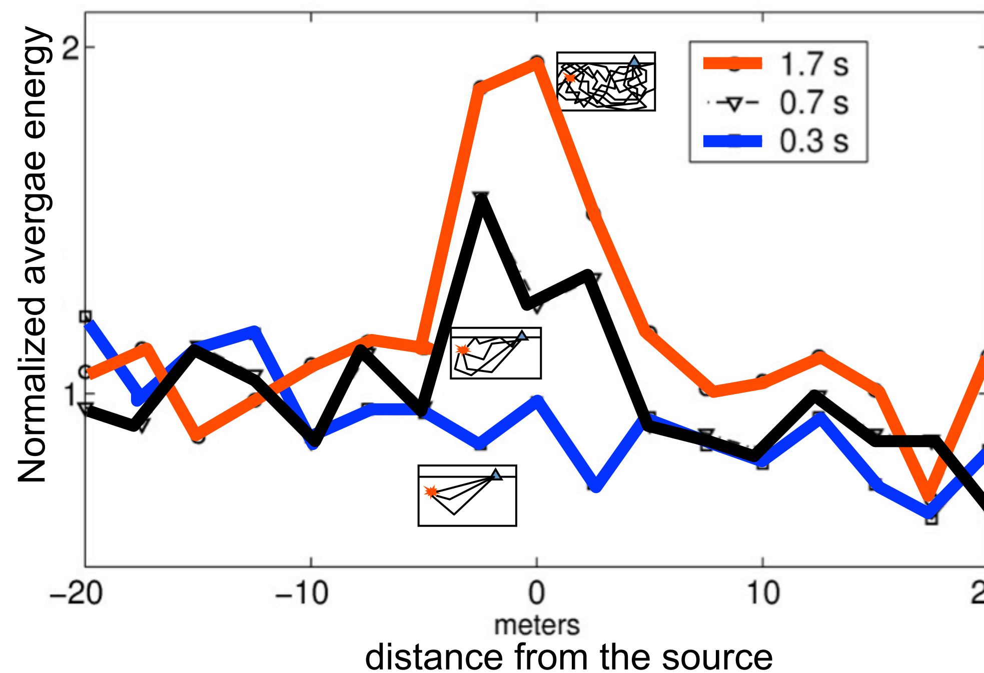
In average, enhancement of the diffuse energy at the source by a factor 2..

Weak localization: coherent backscattering of seismic waves





Average spatial energy distribution at different times



(Larose, Margerin, van Tiggelen and Campillo, PRL 2004)

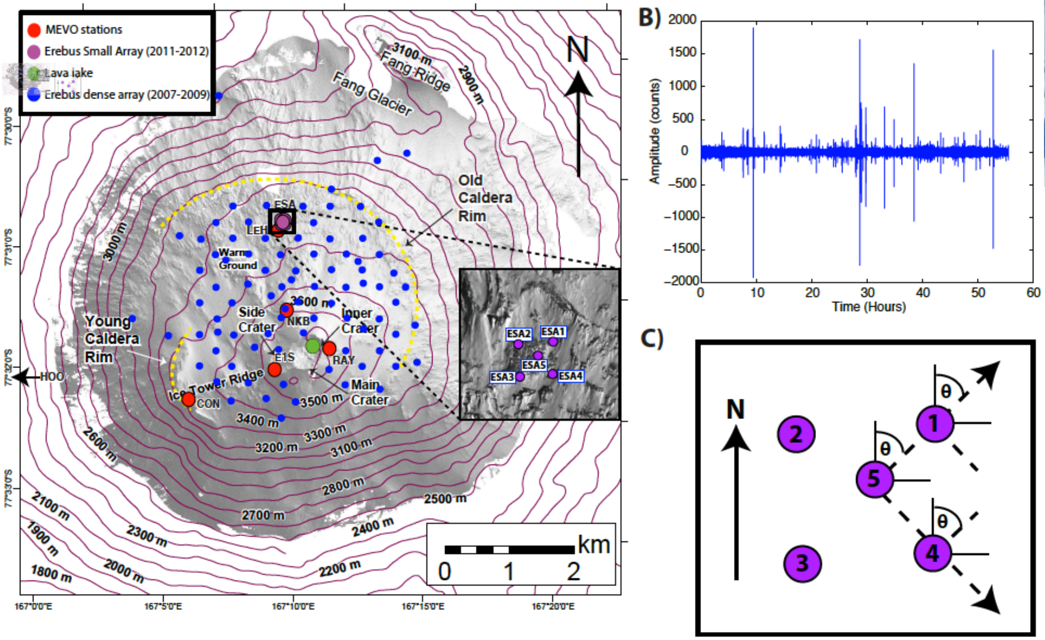
Consider now correlations as virtual Green functions.

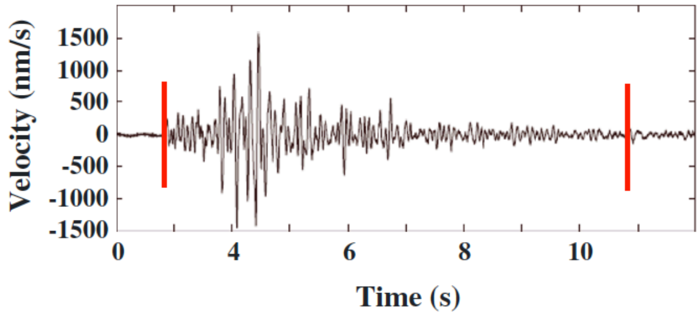
Do the correlations contain the multiply scattered waves?

Are their subtle properties present?

Such as self interferences and weak localization?

Erebus volcano: icequakes

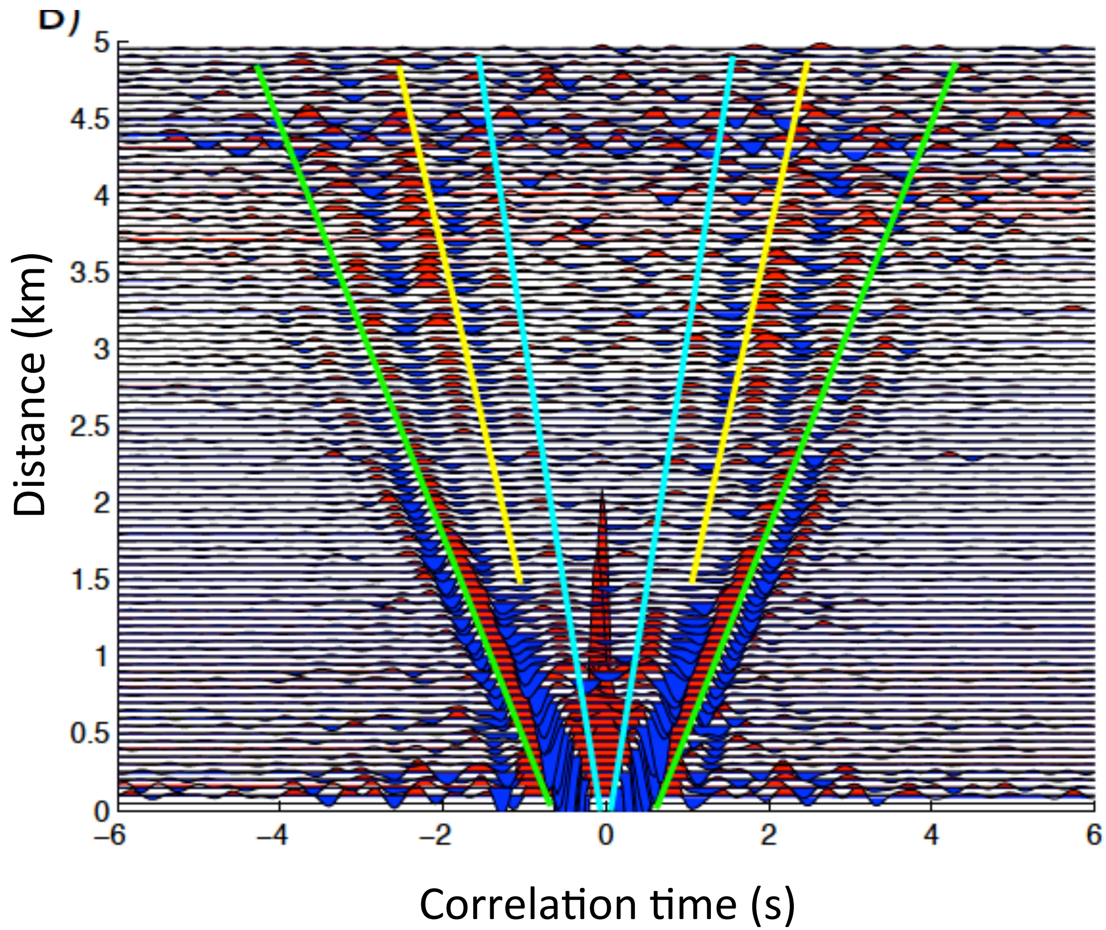




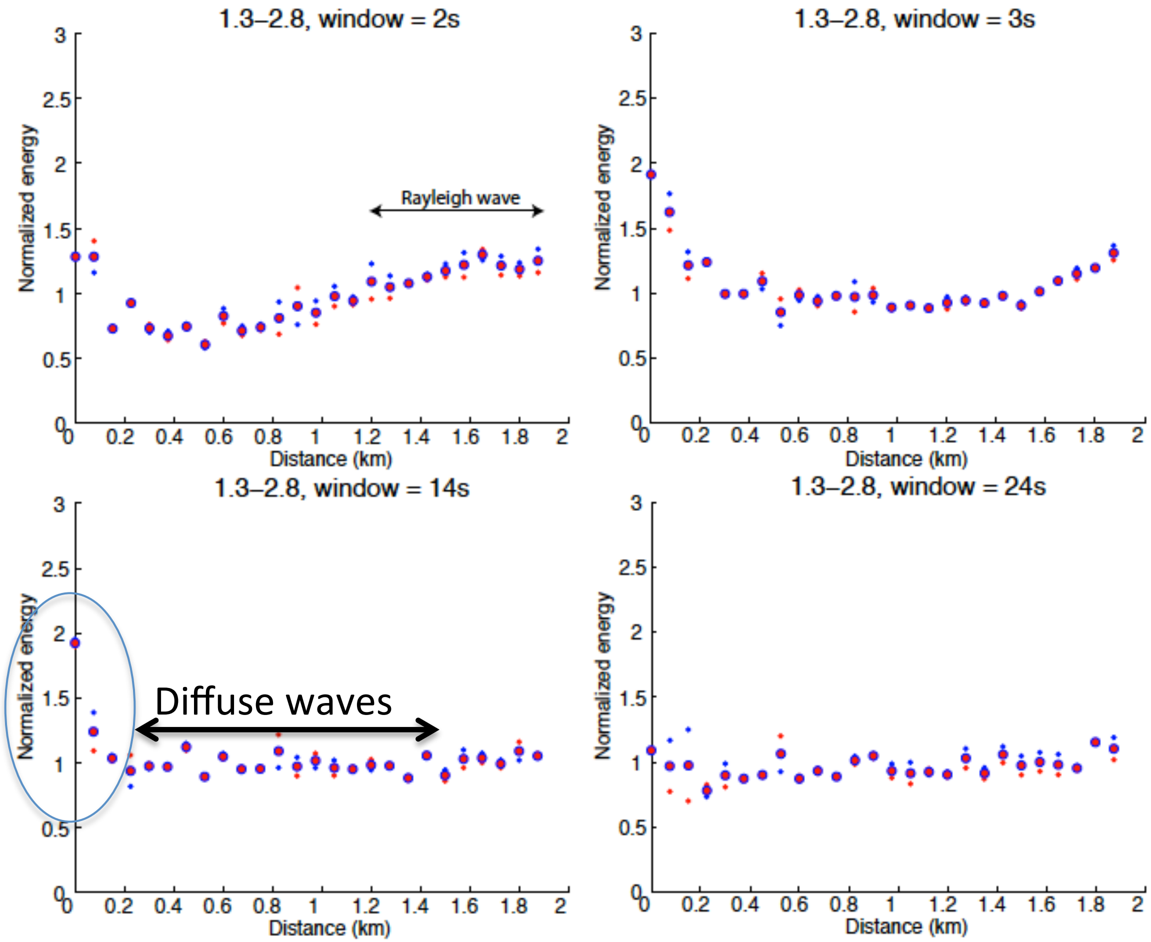
Chaput et al., JGR 2015

Coda Correlations

All 3318 events



Energy vs distance at a given time (averaged over the stations of the network)



Weak localization can be observed in correlations!
(➔mean free path…)
Not possible from earthquake data (reciprocity)

Precision of the measure of delay/velocity variations in the coda

Precision of the measure of delay/velocity variations in the coda of noise correlation functions

A key issue is related to the non-stationarity of the noise that could results in biases.

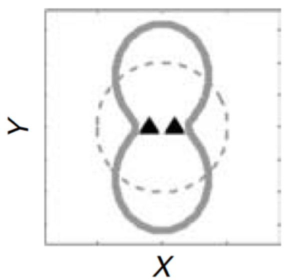
We analyze this problem for direct waves and coda waves.

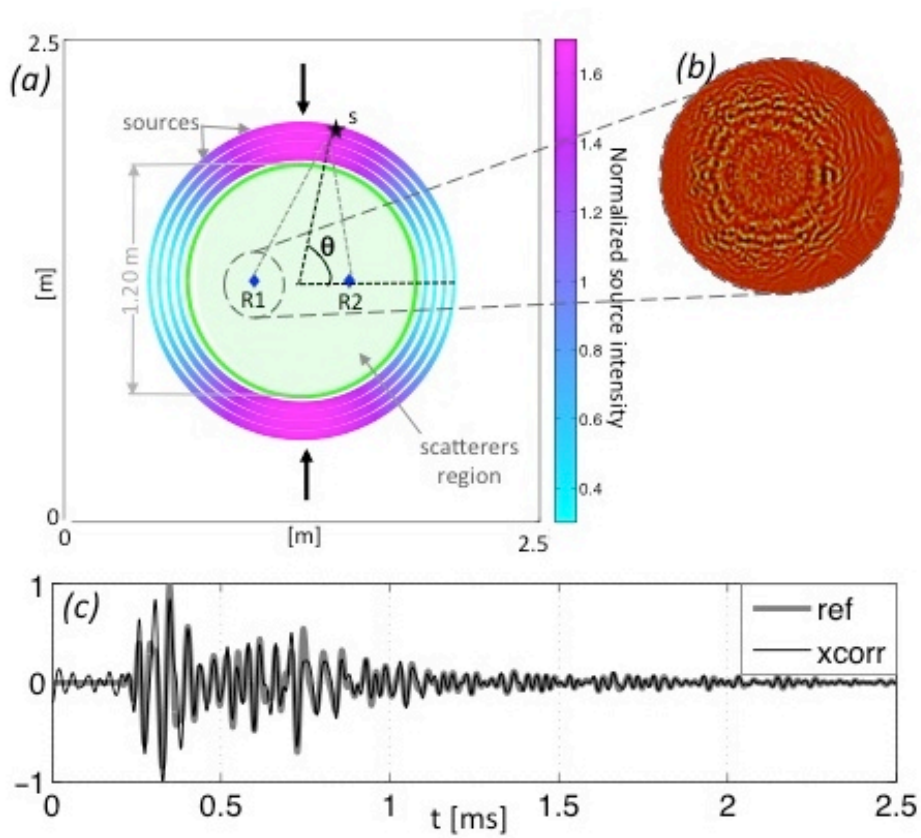
We found that the effect of a strong change of intensity anisotropy could results in errors on the delay of direct of the order of a few % while for multiply scattered waves it is of the order of 10^{-4}.

Ref: Froment et al., 2010, Colombi et al., 2014

Measuring slight changes of seismic velocity using coda waves (long travel time)
Numerical simulations in a scattering medium

2D spectral elements, anisotropic intensity of sources

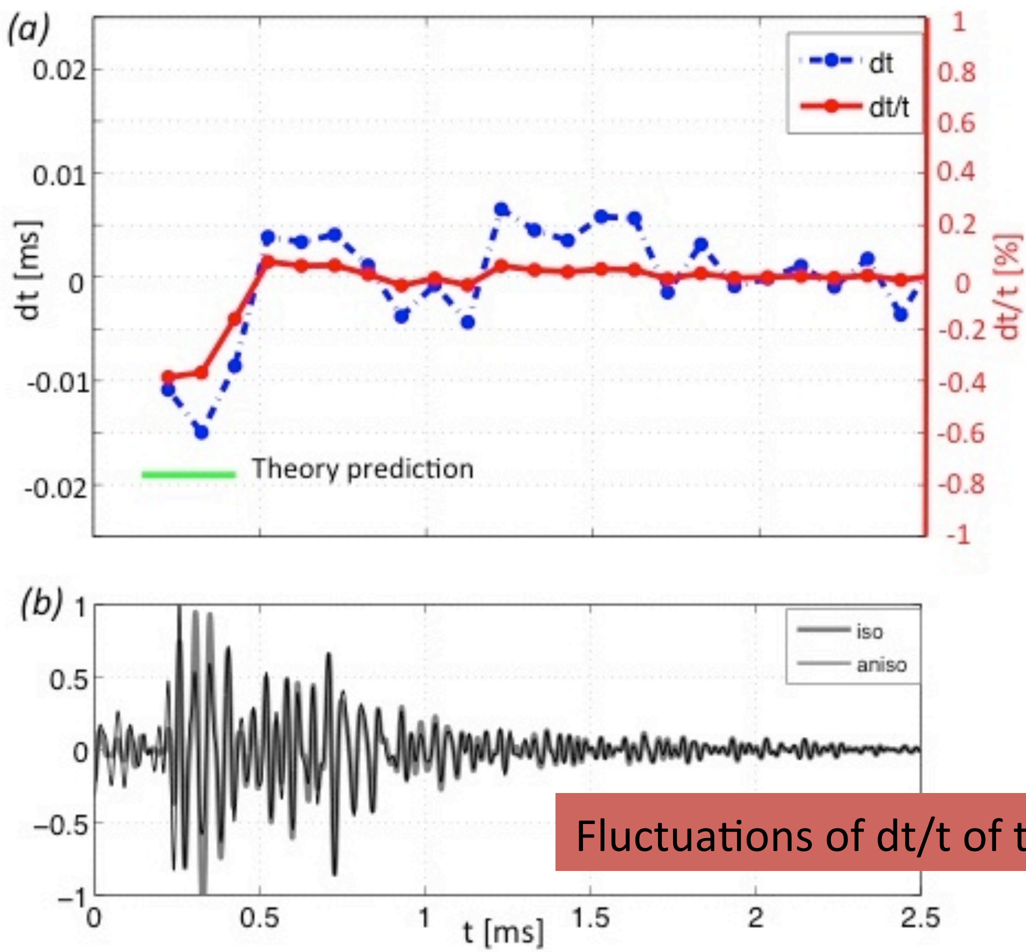




Comparison of correlations with Green function

Colombi, Chaput, Hillers et al., 2014 in press

Measure of the bias induced by a strong anisotropy of the wave field (delay with respect to the Green function)

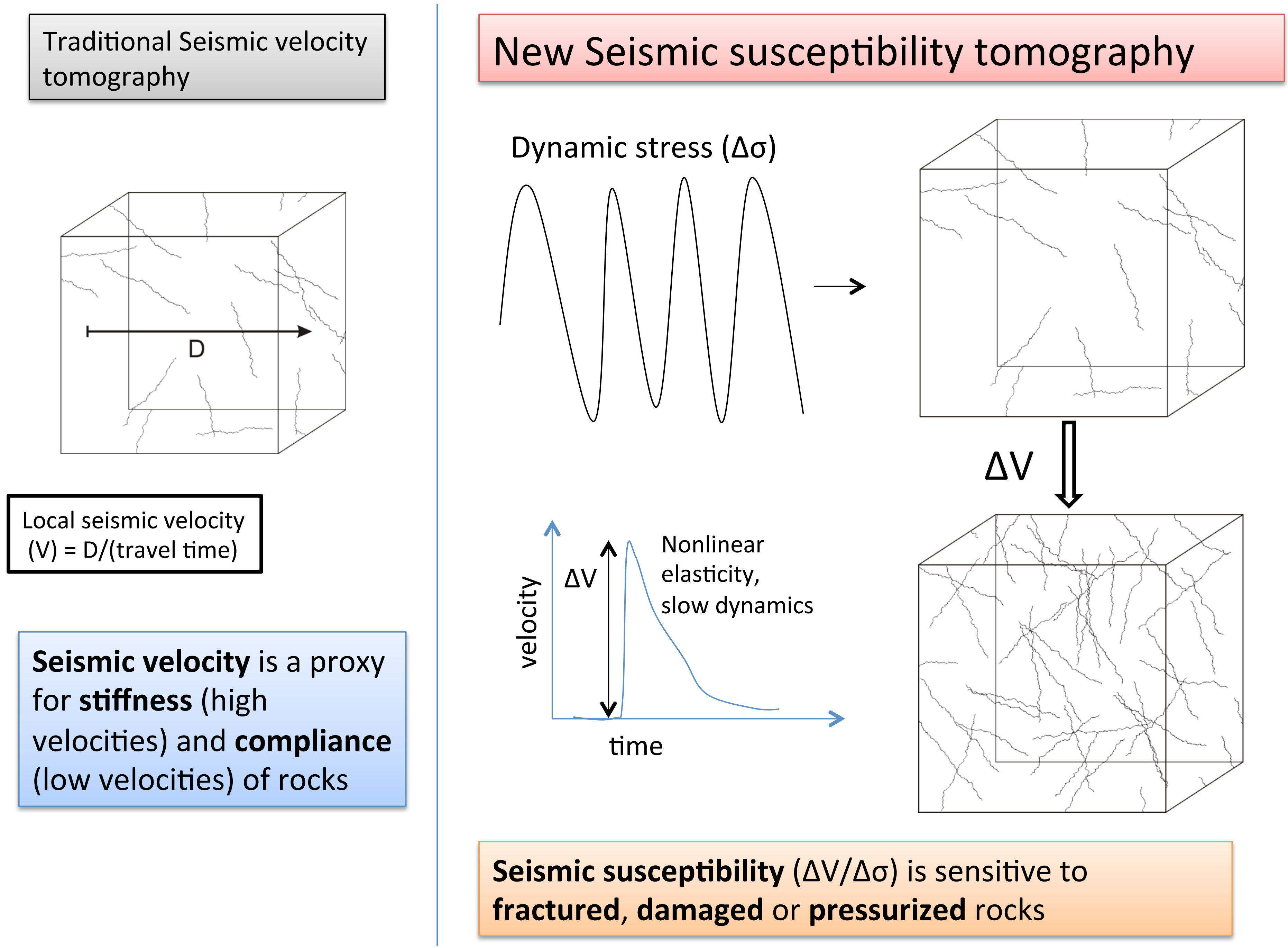


Blue: delay

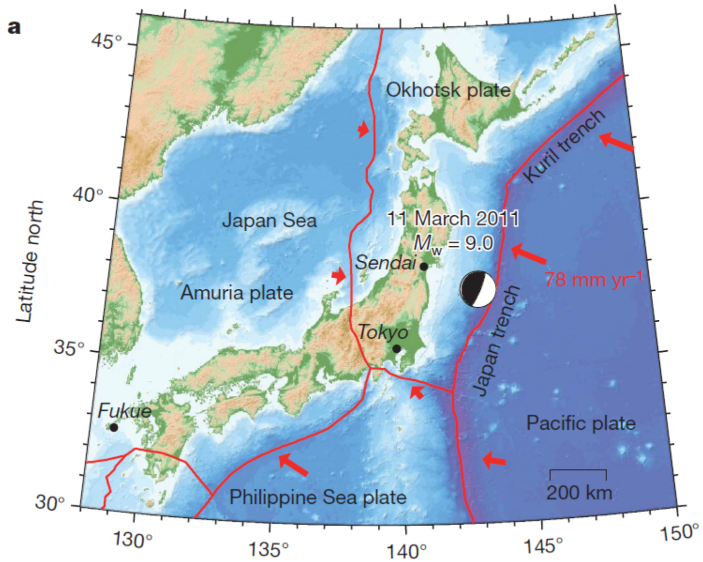
Red: relative delay

Fluctuations of dt/t of the order of 10^{-4}

Colombi, Chaput, Hillers et al., 2014

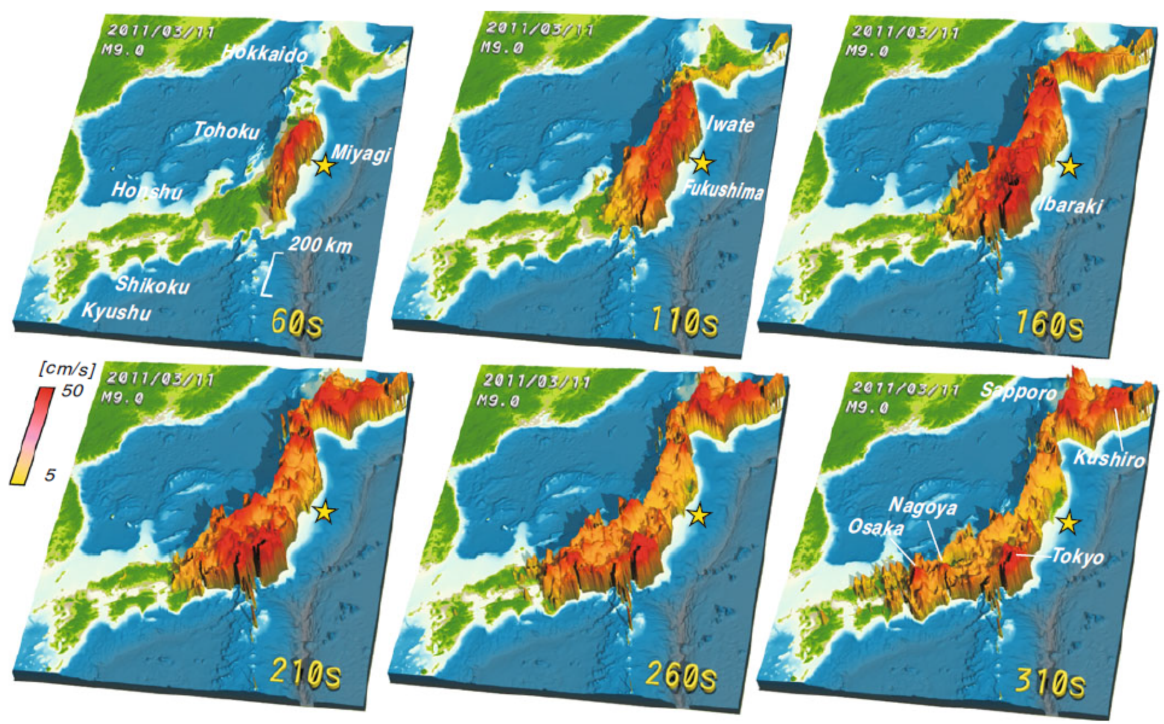

Traditional Seismic velocity tomography
D
Local seismic velocity (V) = D/(travel time)
Seismic velocity is a proxy for stiffness (high velocities) and compliance (low velocities) of rocks
New Seismic susceptibility tomography
Dynamic stress (Δσ)
ΔV
velocity
ΔV
Nonlinear elasticity, slow dynamics
time
Seismic susceptibility (ΔV/Δσ) is sensitive to fractured, damaged or pressurized rocks

Seismic susceptibility tomography of Japan



Ozawa et al. 2011

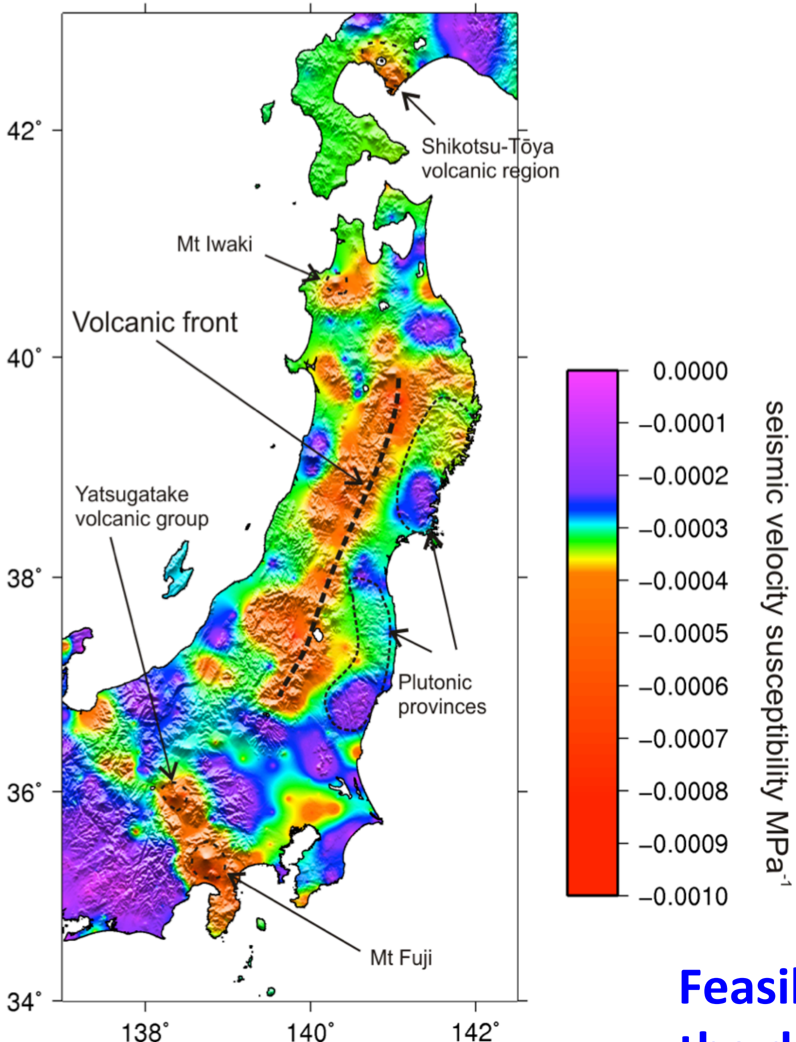
We use **seismic waves** caused by the 2011 Tohoku-oki earthquake as **dynamic stress perturbations**



Furumura et al. 2011

Tomography of seismic susceptibility

velocity change/dynamic stress (known from strong motion records)



- Delineates volcanic regions characterized by **high volcanic fluid pressure** (low effective pressure) and sedimentary basins

- **Maximizes** below **Mt Fuji volcano** where a **M6 earthquake** occurred 4 days after the Tohoku-oki earthquake

- **Minimizes** in **stiff** old plutonic regions

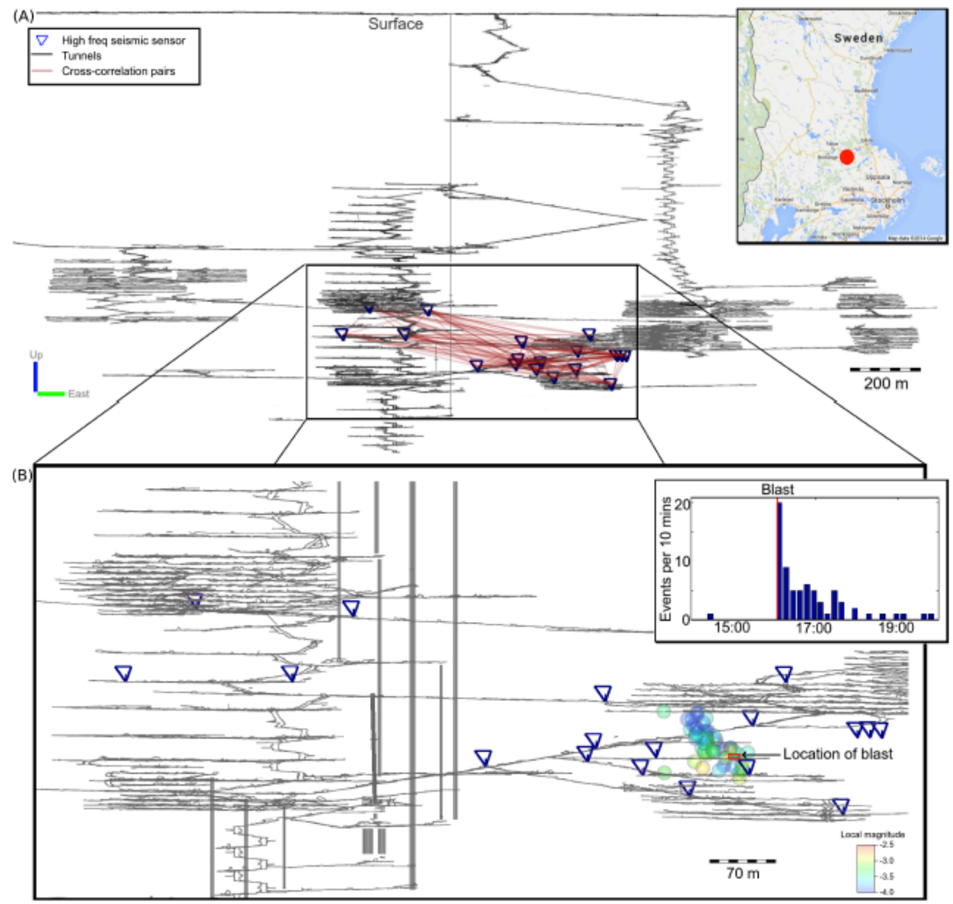
Also, it illustrates the large spatial variability of the seismic susceptibility.

Feasibility of imaging new parameters relevant for the dynamics of eruptions and earthquakes

From Brenguier, Campillo, Takeda, Aoki, Shapiro, Briand, Emoto and Miyake Science 2014

Local scale

Velocity change due to blast and excavation in a mine



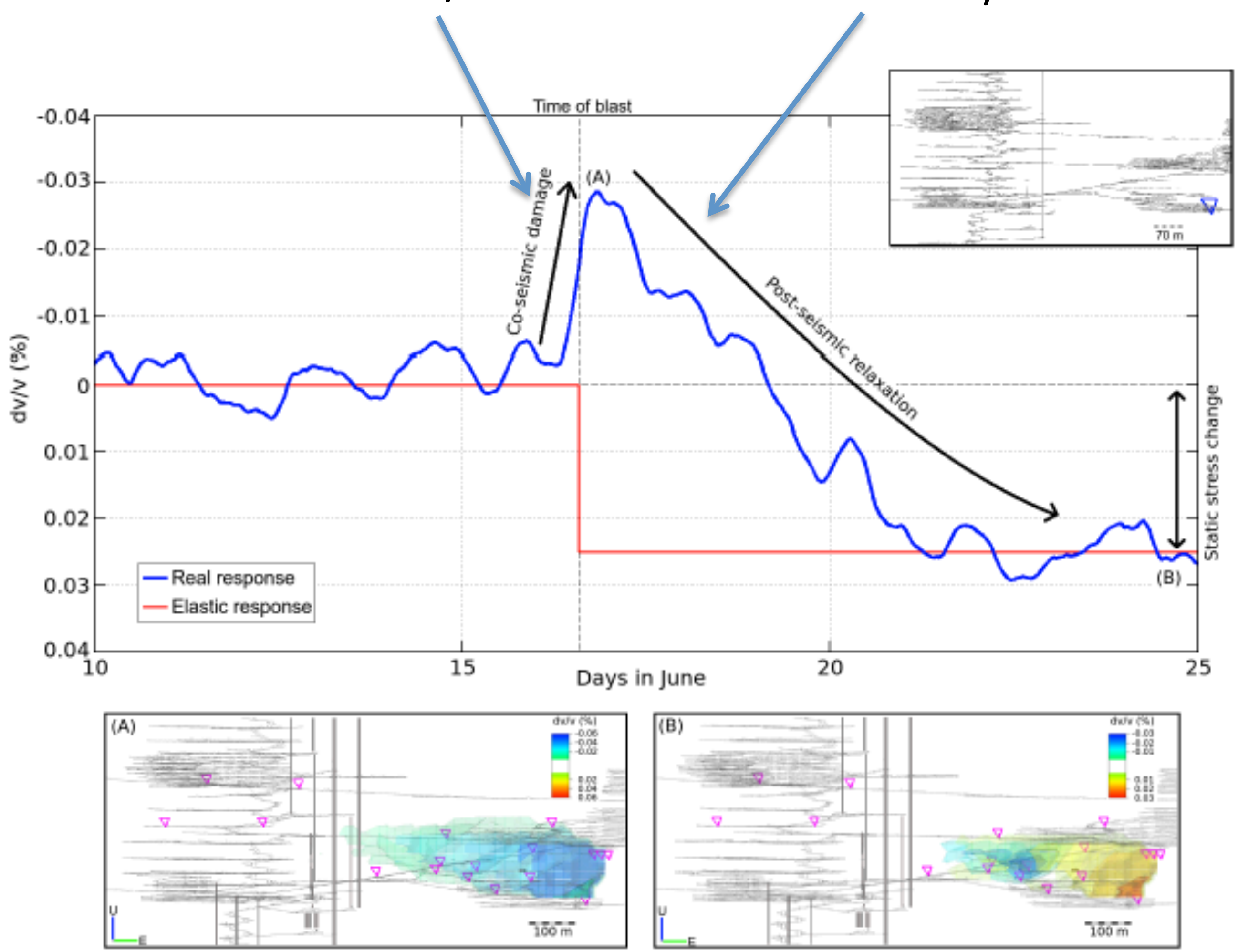
Use of the strong industrial noise in the mine.
Note the intense scattering associated with the tunnels.

Olivier et al., 2014

Velocity change due to blast and excavation in a mine

Fast dynamics

Slow dynamics



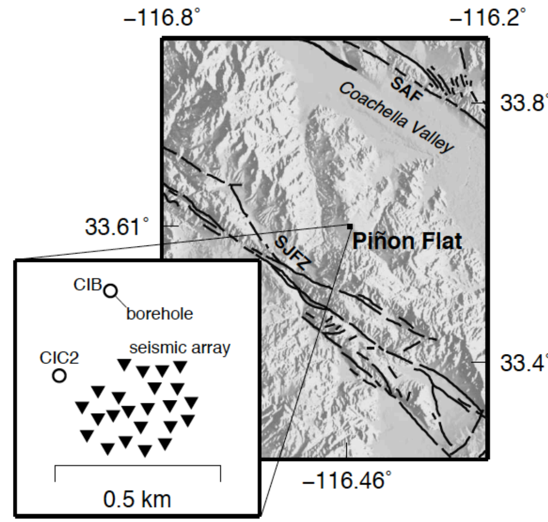
Change of baseline due to static stress change

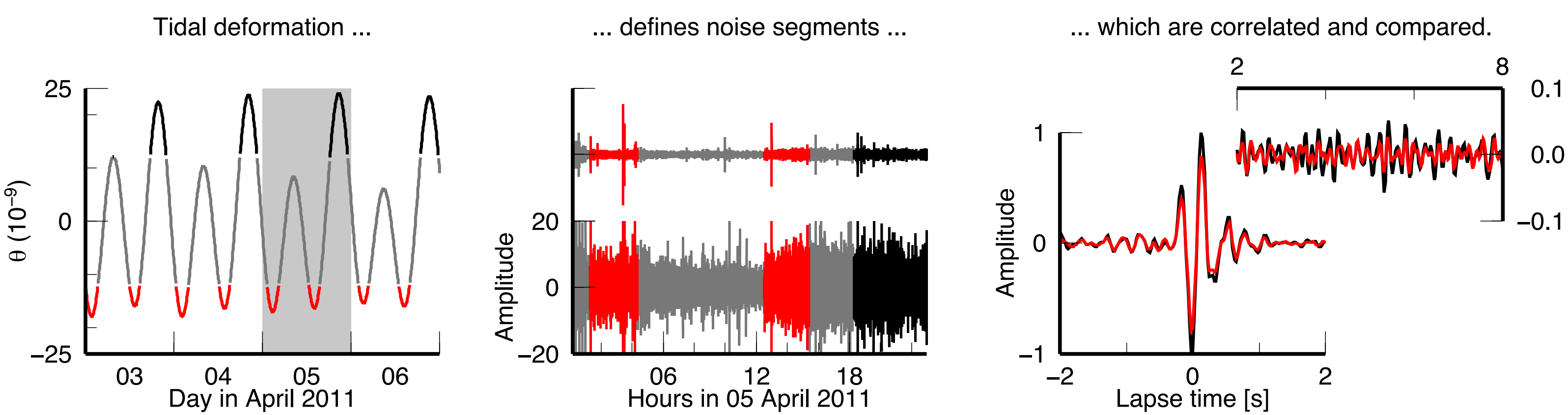
Instantaneous change

Static change

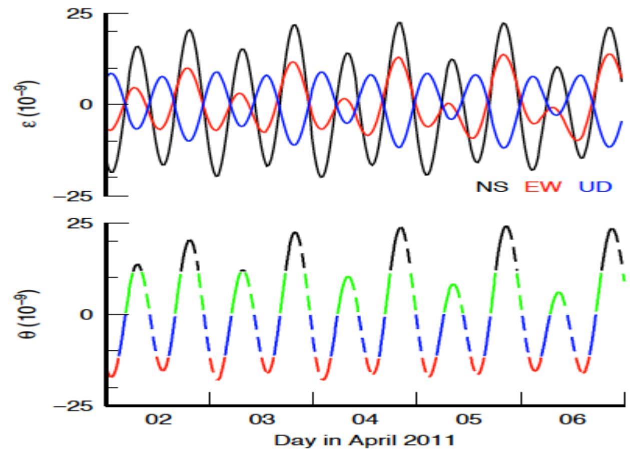
From Gerrit Olivier and co-authors (2015)

In-situ observations of velocity changes in response to tidal deformation from analysis of the high-frequency ambient wavefield

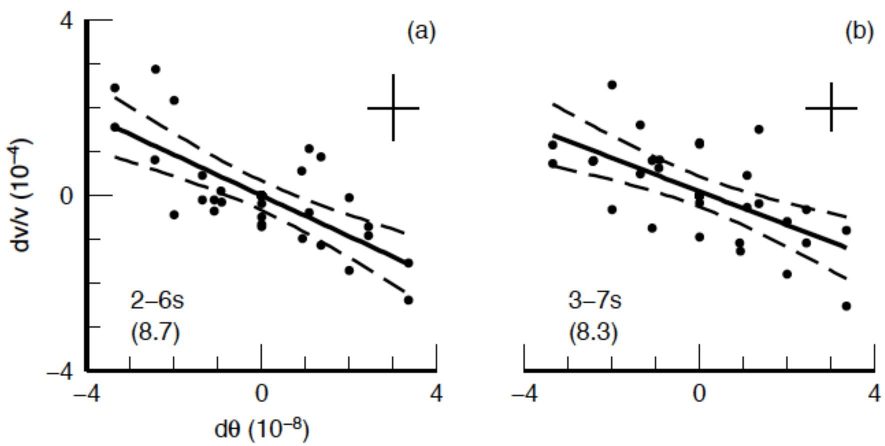




Hillers et al. 2014 (JGR)



Define time windows for multiple deformation intervals



Dependance of shear wave speed with deformation

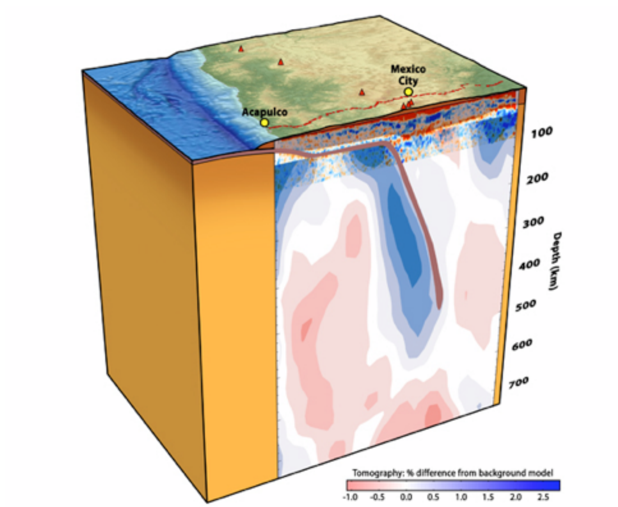
passive in-situ acoustoelastic testing= characterization of mechanical state

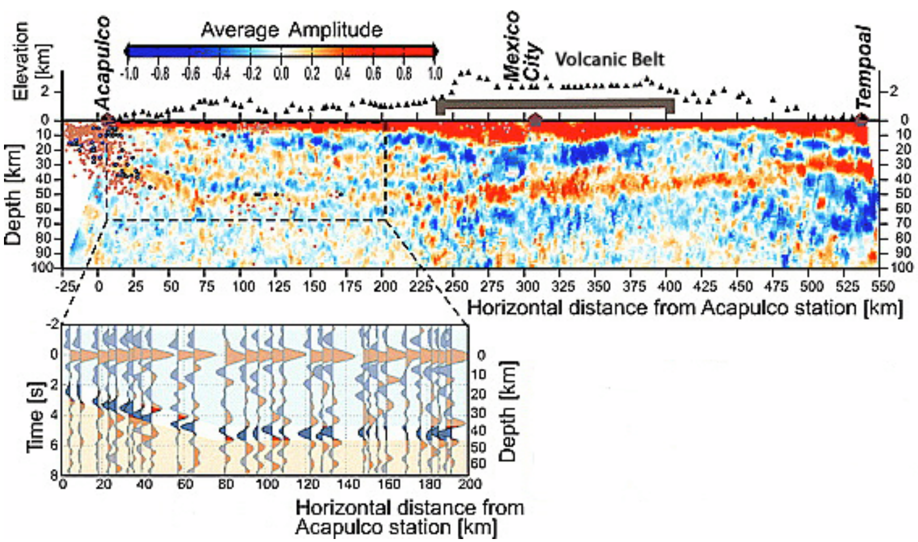
Hillers et al. 2014 (JGR)

Slow slip events in Guerrero, Mexico

[Modified from Chen and Clayton, JGR 2009]

MASE project (US-Mexico)

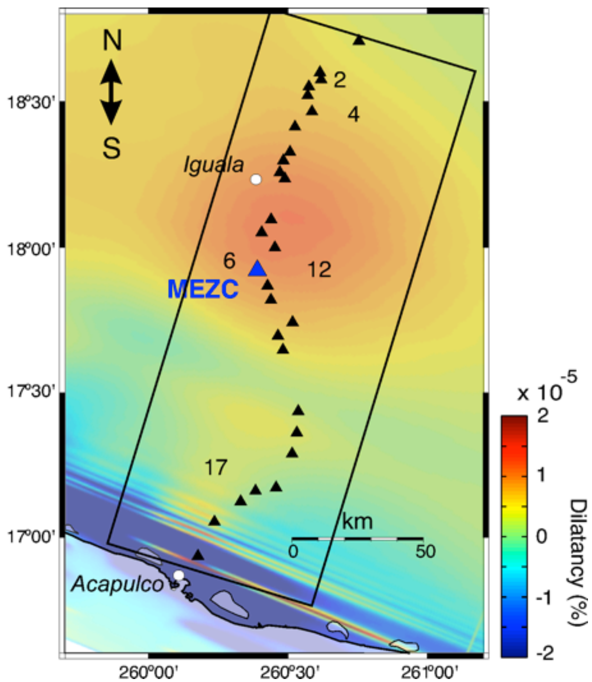


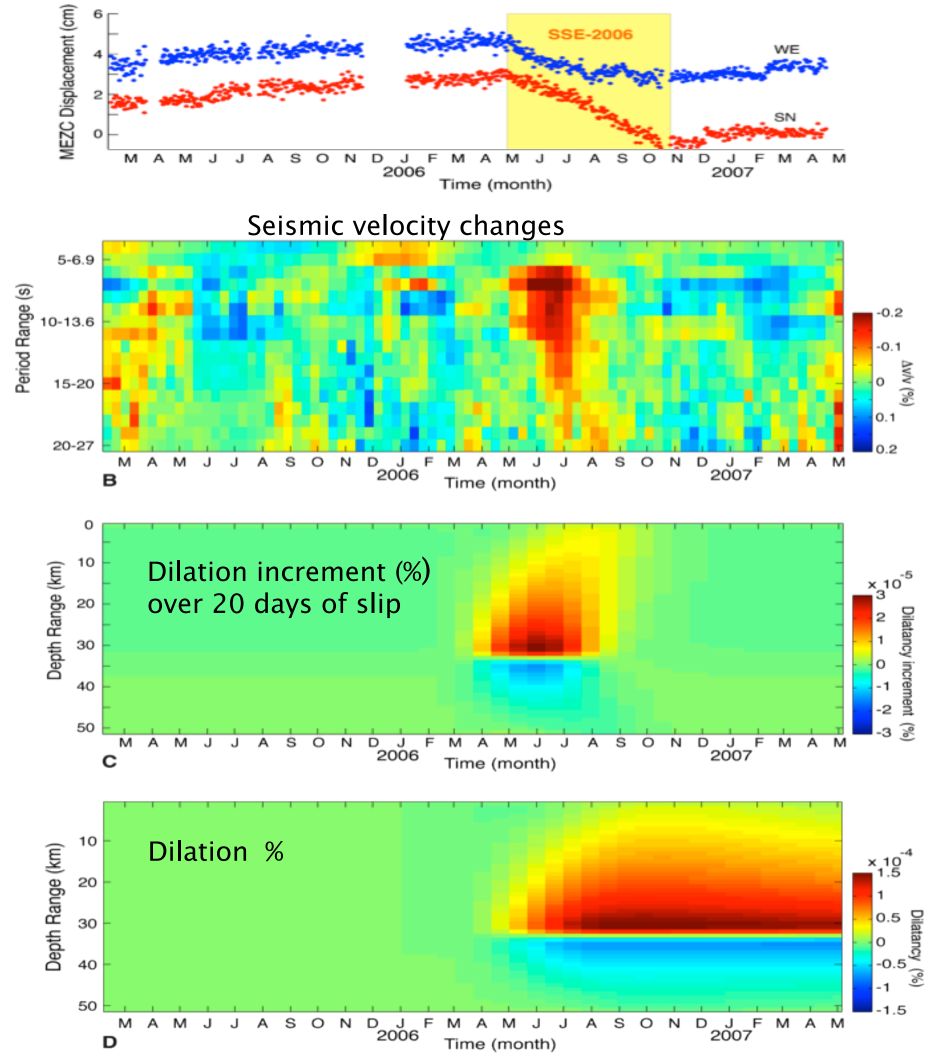


[From Perez-Campos et al., GRL 2008]

Temporal relation between velocity change and dilatation

Dilation at 15km depth





Rivet et al., 2011:

Deep velocity drop.

Depth sensitivity (Obermann et al;, 2013)