ISTerre

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"Seismic velocity changes and deformation of the crust: the signatures of earthquakes and transient slip events. "

Michel Campillo (with Bérénice Froment, Dimitri Zigone, Diane Rivet, Anne Obermann, Gregor Hillers, Julien Chaput, Andrea Colombi, Kentaro Emoto, Pierre Boué and colleagues from ISTerre, IPGP, USC, U. Illinois, NEID, UNAM, Tohoku U., CEA Beijing..)

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Interest in seismology for temporal changes of elastic properties since (at least) the 60s.

Laboratory experiments show that the elastic velocities are actually changing due to external sollicitations (waves, impacts e.g. TenCate and coll.) or to weak deformations (e.g. Schubnel et coll.).

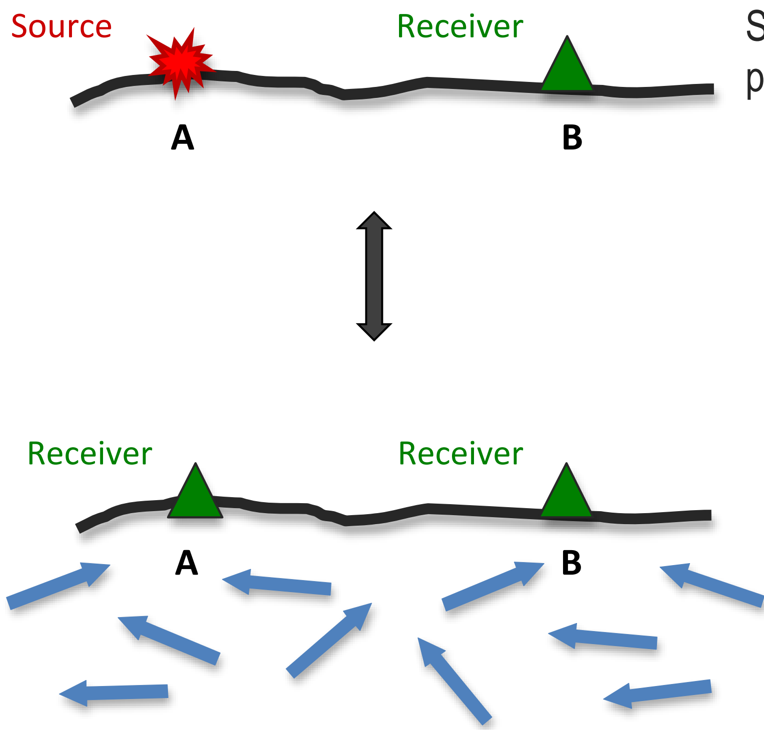
Nonlinear Mesoscopic Elasticity : fast and slow dynamics

Could we detect, and eventually image continuous temporal changes of seismic wave velocity at depth that could be used to characterize the deformation rate?

This story is about this question….

1- Introduction
2- Ambient noise correlations: what can we trust?
3- Imaging fault structures
4- Monitoring: what can we trust?
5- Parkfield ➔ possible ‘non tectonic’ signals?
6- SSE in Guerrero, Mexico ➔ deep deformations, tremors, (triggering)
7- Wenchuan imaging, delays?
8- Japan= mapping the susceptibility to non linear effects

Long range correlations



Source in A $\Rightarrow$ 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 (C_{AB}) of 'noise' from randomly distributed sources

or

« diffuse » (equipartitioned) fields recorded at A and B

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,……

Mathematical basis

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

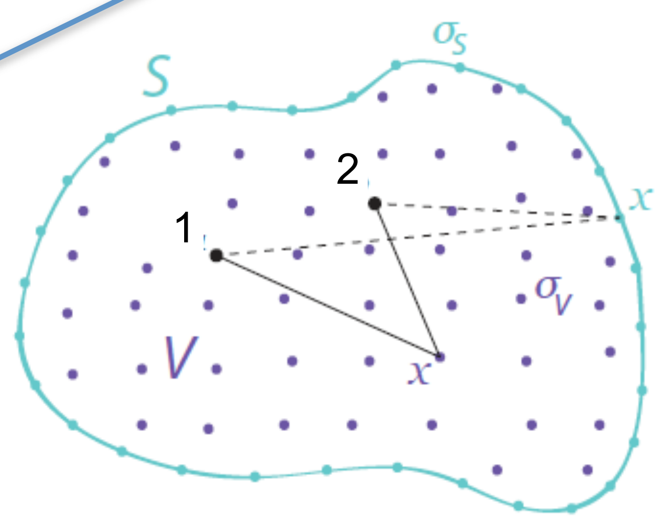
Surface term

FT of $G(-t)$

FT of $G(t)$

Absorption coefficient

Source average over « correlation terms »



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:

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

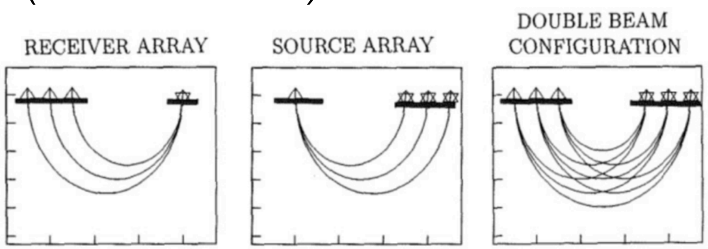
➔Derode et al., 2003: Analogy with Time reversal mirrors

➔Wapenaar 2004

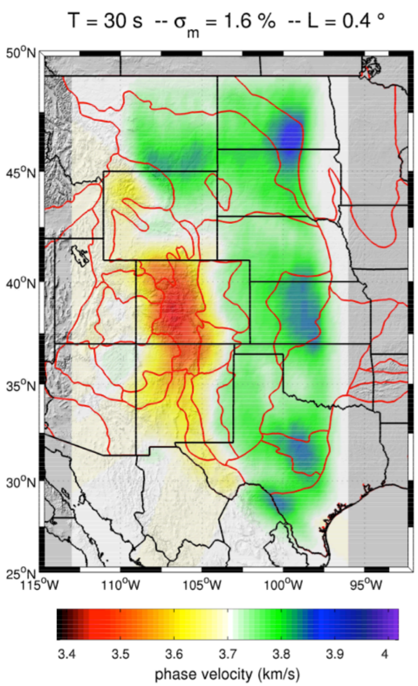
For surface waves: distant sources of noise at the surface of the sphere (2D problem)

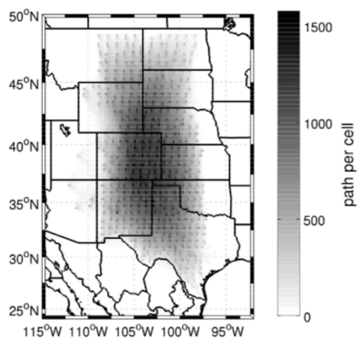
Surfave wave reconstruction within a large array

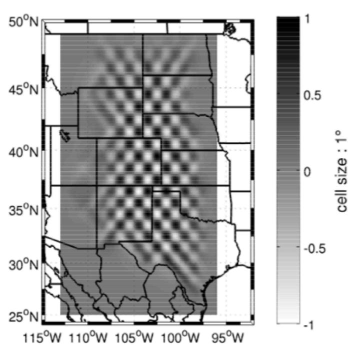
(Boué et al. 2014)



Weber et al., 1996

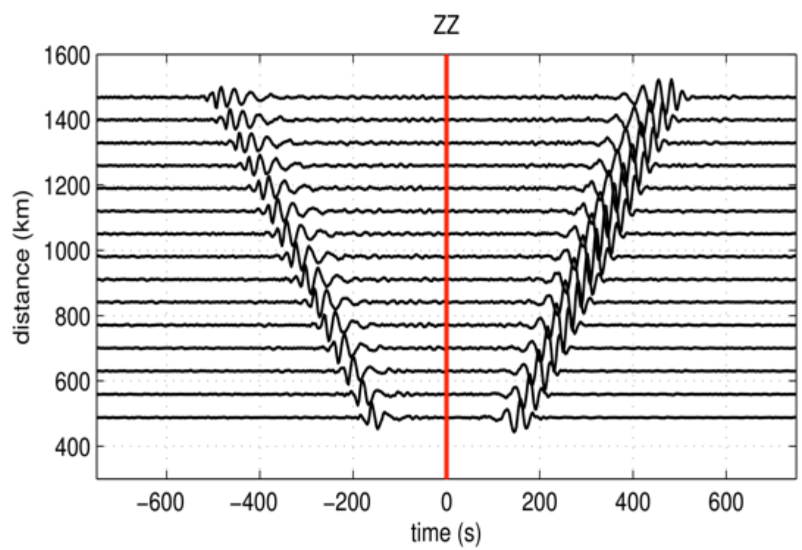






Noise correlation=GF(t)-GF(-t)

(Rayleigh waves)



Several hundreds of applications in the last 10 years!

An issue for surface wave tomography:

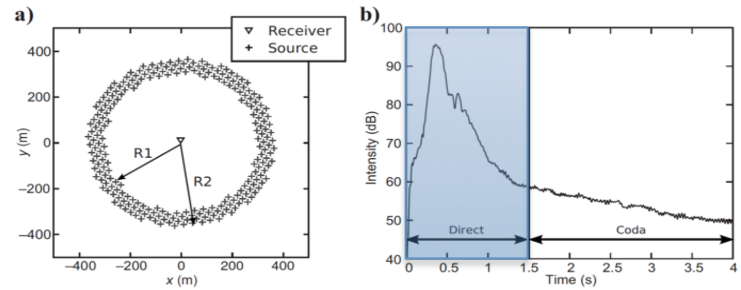
In practice, the noise sources are not evenly distributed and the field is not made fully isotropic by scattering.

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

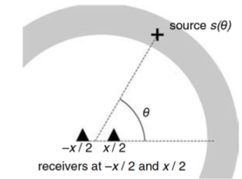
It results in a bias on the measurements of direct path travel times.

Correlation of direct waves:

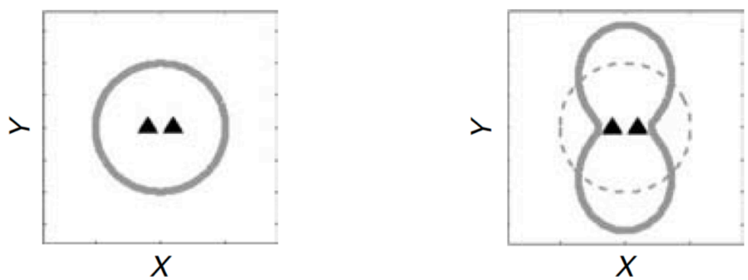
Bias in the travel time



Increasing anisotropy of the source intensity *B*

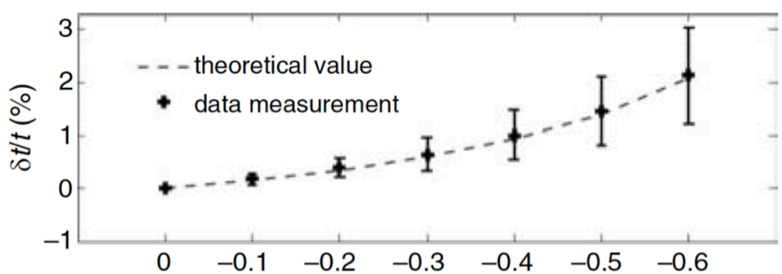


Azimuthal distribution of source intensity



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

Travel time error wrt the observed Green function

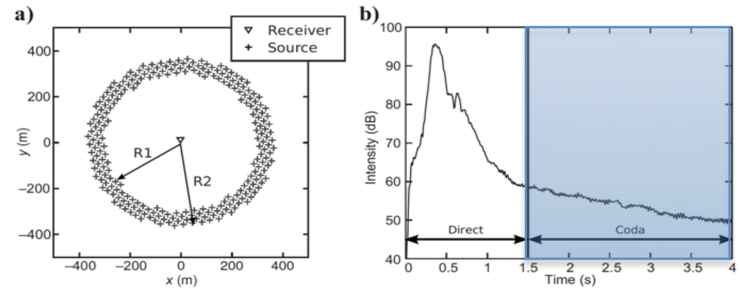


$$\delta t = \frac{1}{2t\,\omega_0^2 B(0)} \left. \frac{d^2 B(\theta)}{d\theta^2} \right|_{\theta=0}$$

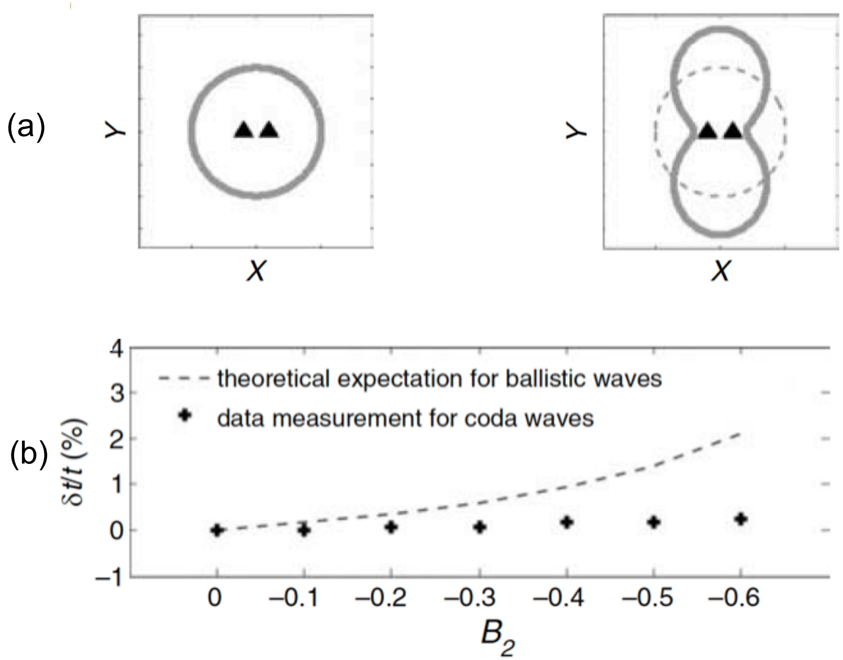
valid with t (travel time) > T (period)

From 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*



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

No bias in the correlation of coda waves!

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

An argument independant of the representation theorems
Multiple scattering and equipartition: the simplest case (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:

Compare with:

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

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

1 derivative   2 causality

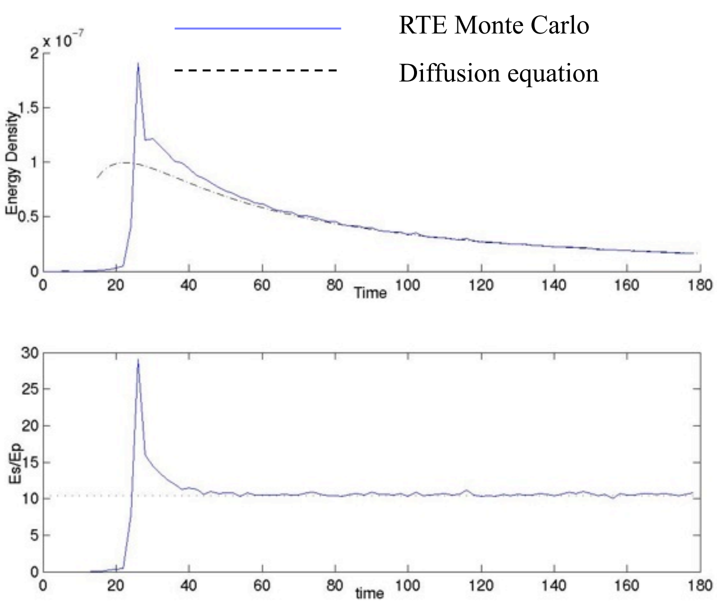
➔ Long range correlation in seismic coda= Green function (Campillo and Paul, Science 2003)

Multiple scattering and equipartition

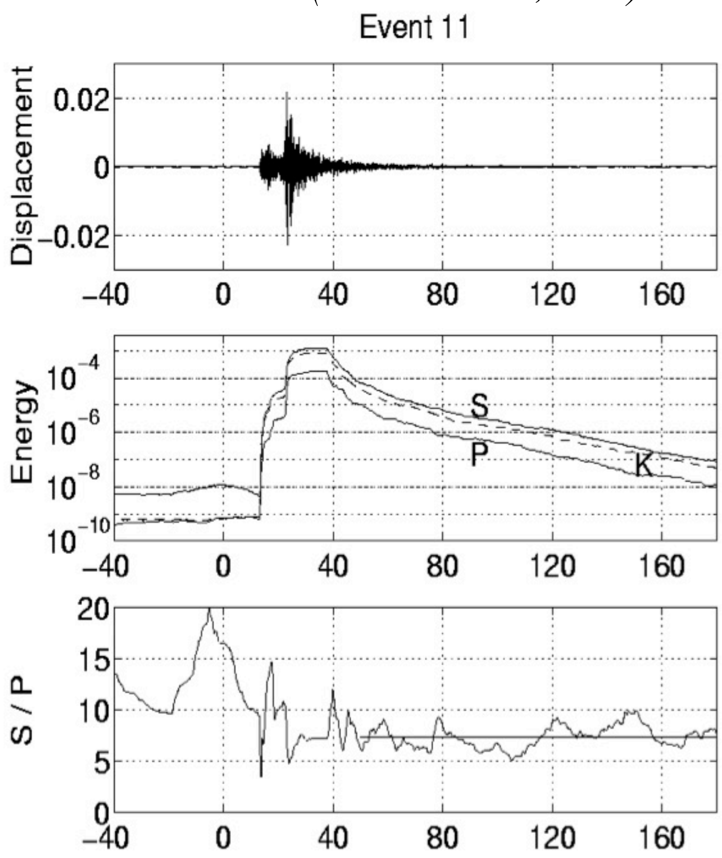
Equipartion principle for a completely randomized (diffuse) wave-field: in average, all the modes of propagation are excited to equal energy.

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)*



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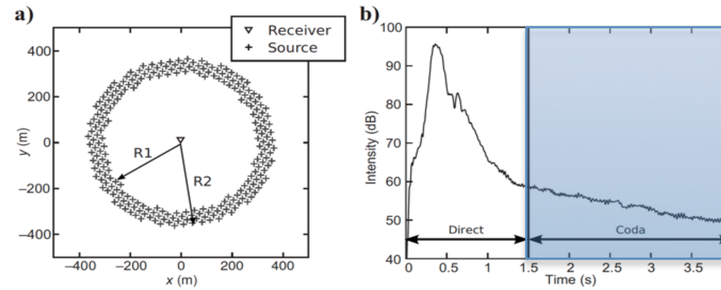

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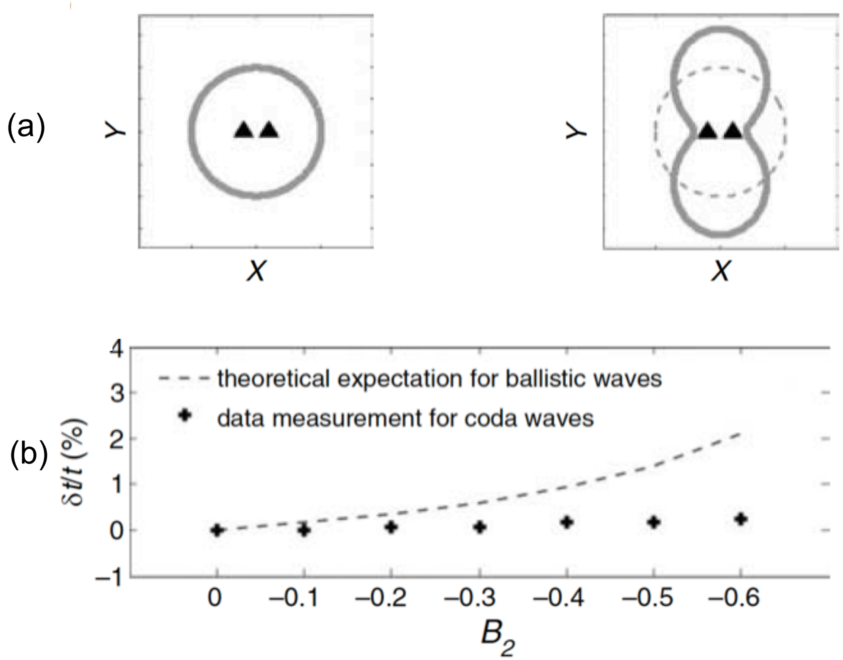


$$B(\theta) = 1 + B_2 \cos(2\theta)$$

No bias in the correlation of coda waves!

Noise records contain direct **and** scattered waves:

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

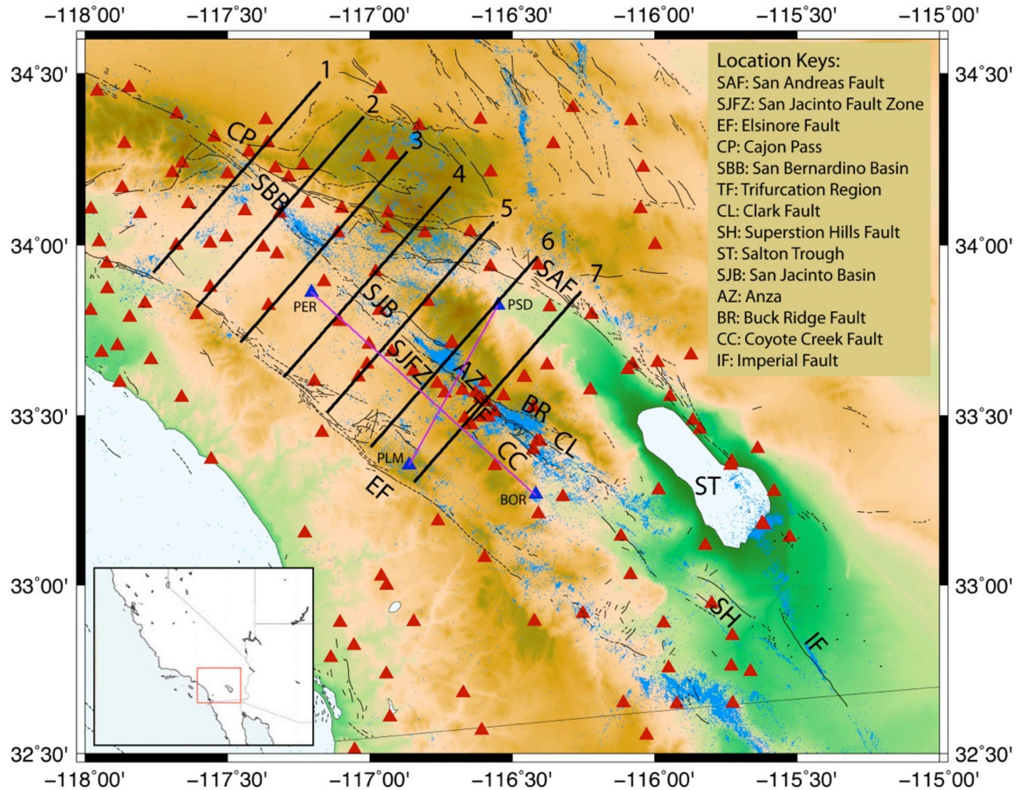
➔ Importance of processing strategies

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

Fault zone structures imaging

-fault segments, complexity (rupture speed)
-bi-material interfaces: preferential direction of rupture propagation
-amplification effects

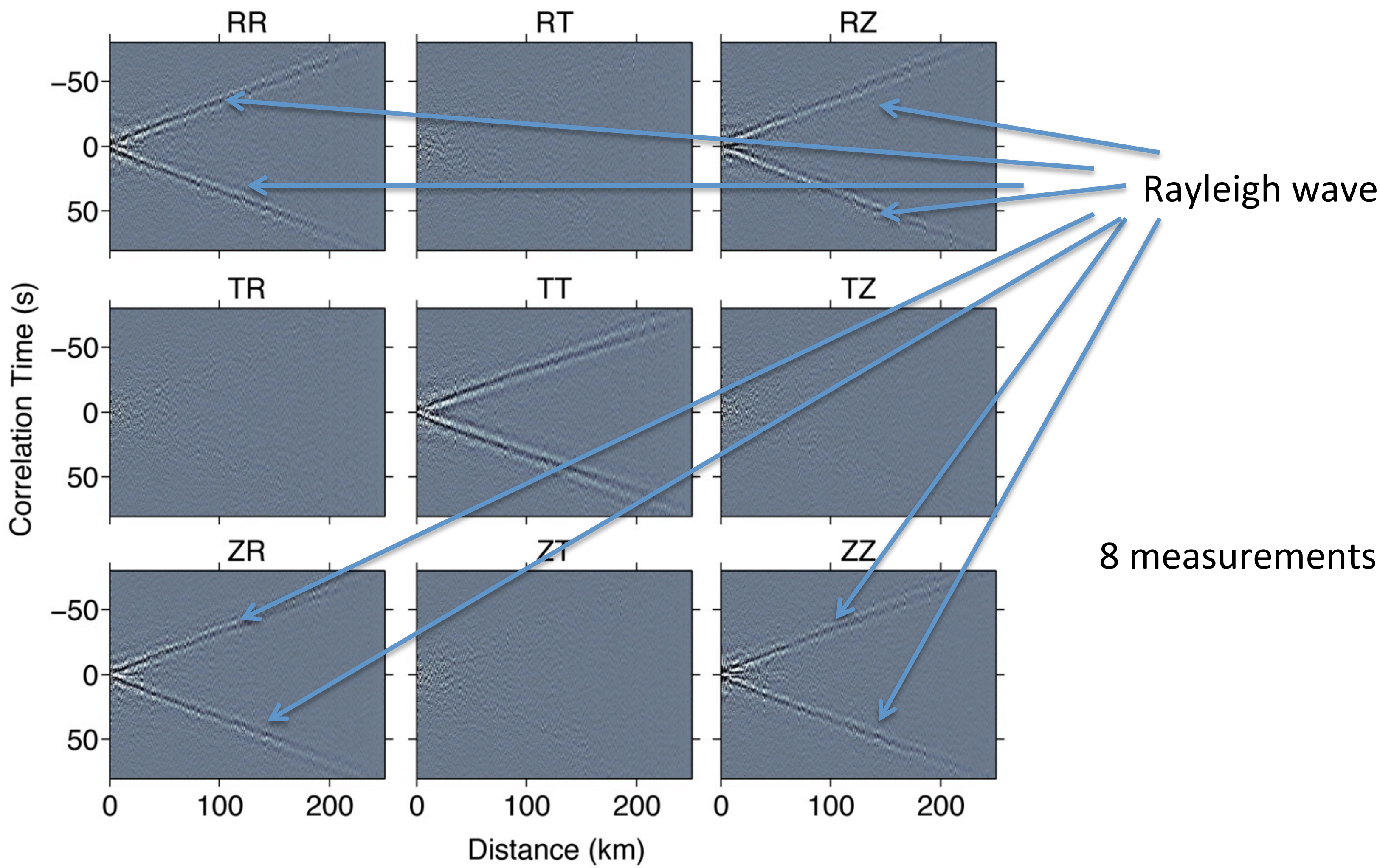
-lack of resolution for shear wave in the first kilometers for traditional tomography



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

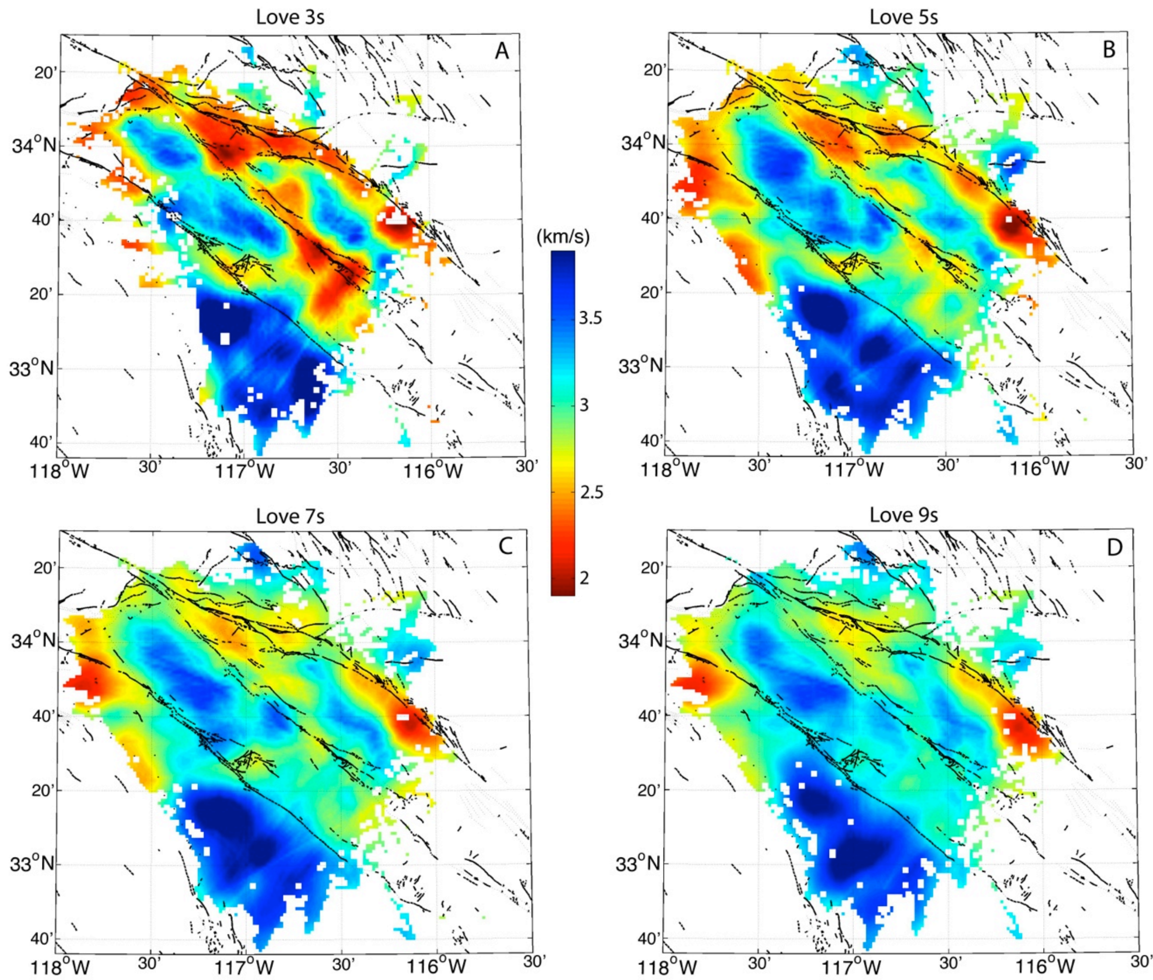
Surface wave tomography with noise correlation

9-component correlations



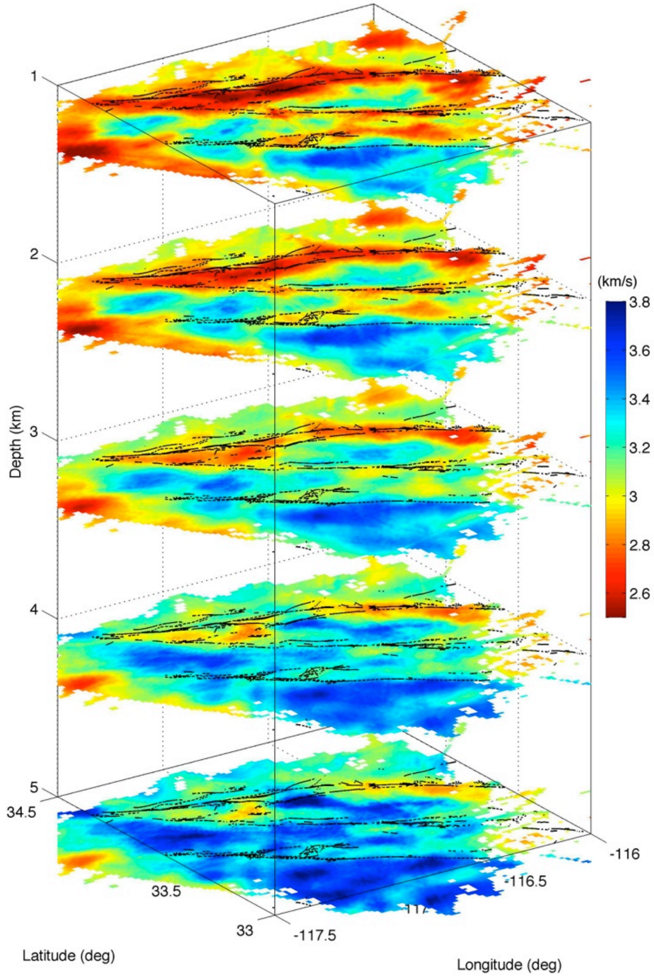
From Zigone, Ben-Zion, Campillo and Roux, 2014

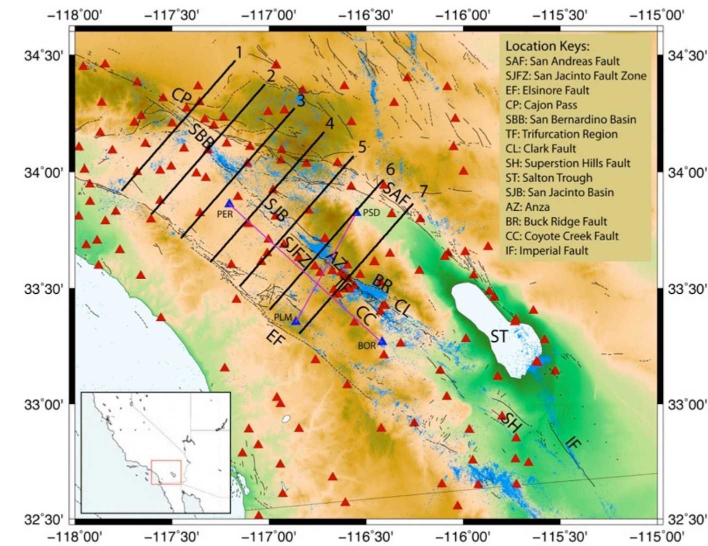
Group velocity maps at different periods



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

3D shear velocity



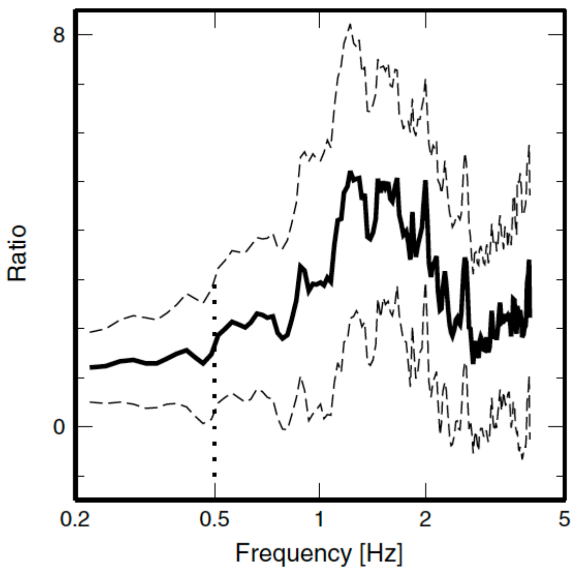


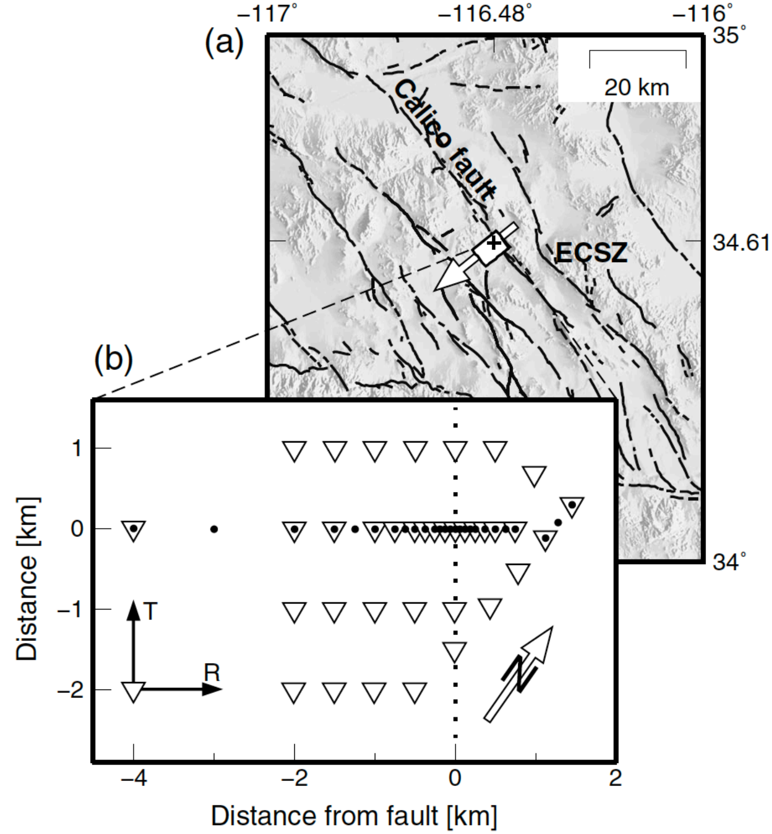
- Damaged fault zone
- Flower-like patterns
- Diffuse seismicity associated with low-velocity (damaged) area between SAF and SJFZ

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

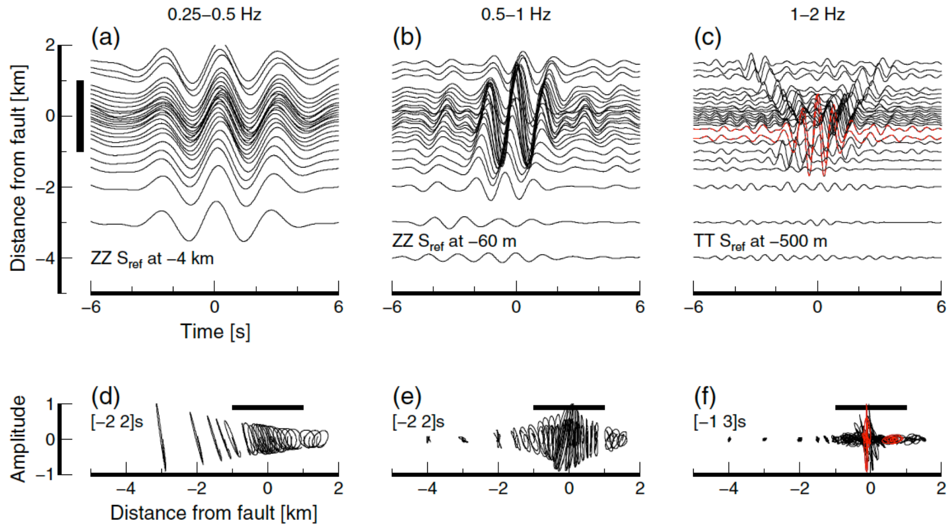
Seismic fault zone trapped noise

Spectral ratio between ZZ CC for pairs in fault and outside



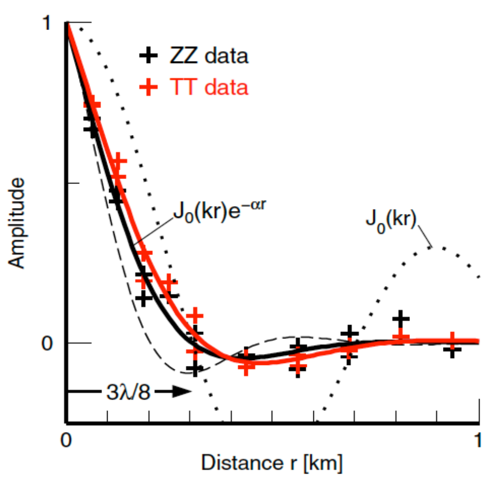


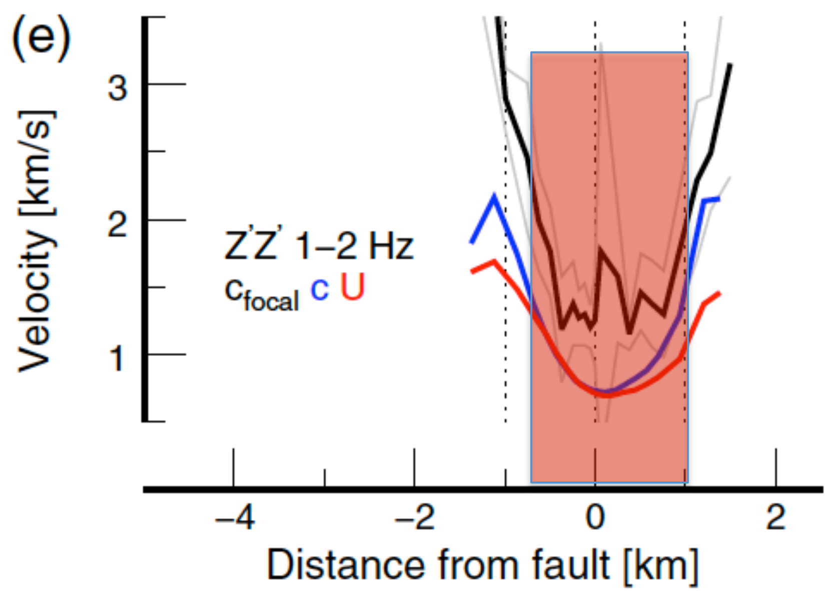
From Hillers, G., M. Campillo, Y. Ben-Zion, and P. Roux JGR 2014



Focusing

Using the width of the focal spot: a technique developped in medical imaging (elastography)

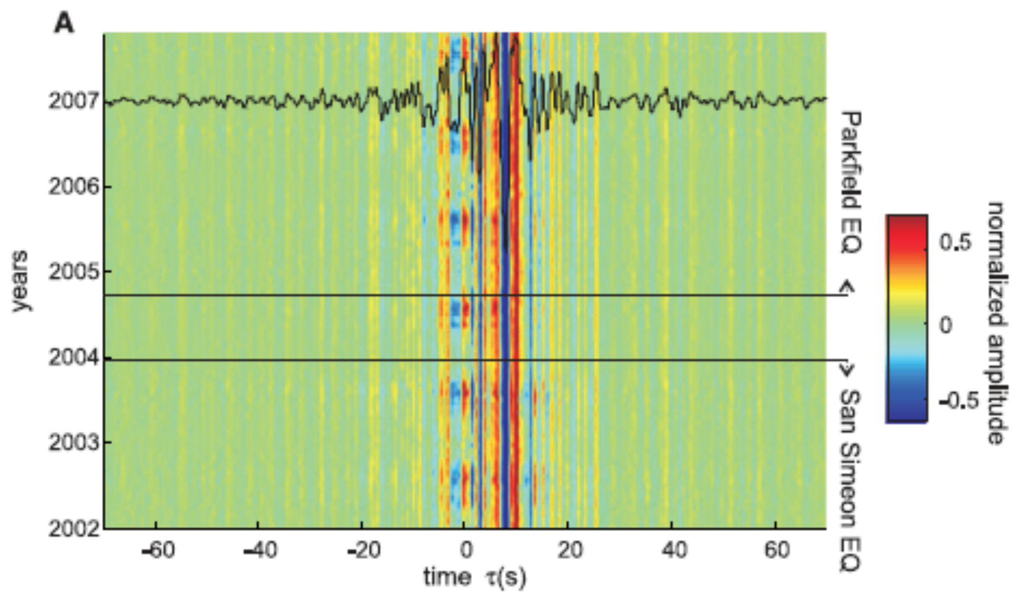




From Hillers, G., M. Campillo, Y. Ben-Zion, and P. Roux JGR 2014

Perspectives: imaging and monitoring

Correlation functions as approximate Green functions

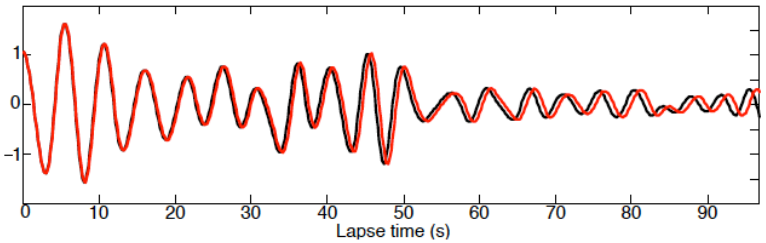


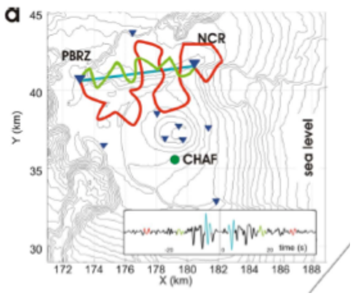
Direct waves are sensitive to noise source distribution (errors small enough for tomography (≤1%) but too large for monitoring (goal ≈ 10^{-4})

Stability of the 'coda' of the noise correlations ?

Detecting a small change of seismic speed with coda waves

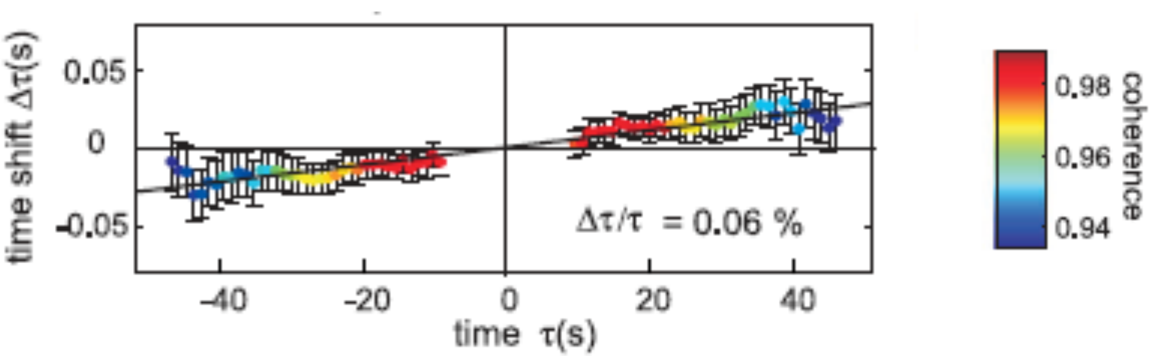
Comparing a trace with a reference under the assumption of an homogeneous change





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

(Poupinet, Ellsworth, Fréchet, 1984)

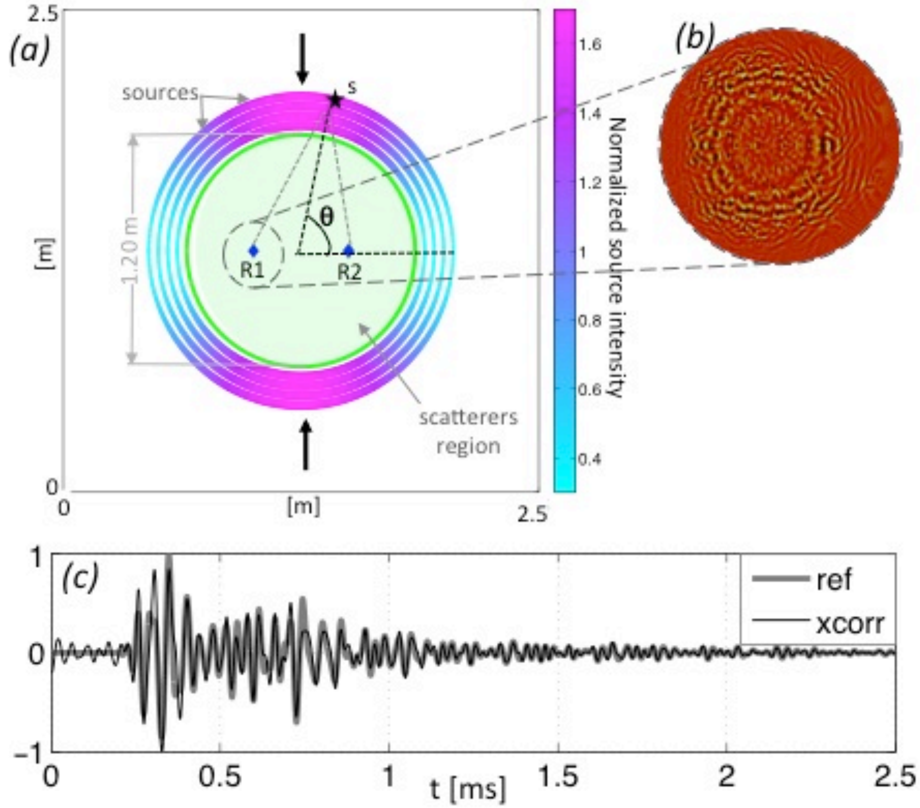


Alternative technique: stretching

Sensitivity of coda waves in cross-correlations to changes of the noise sources

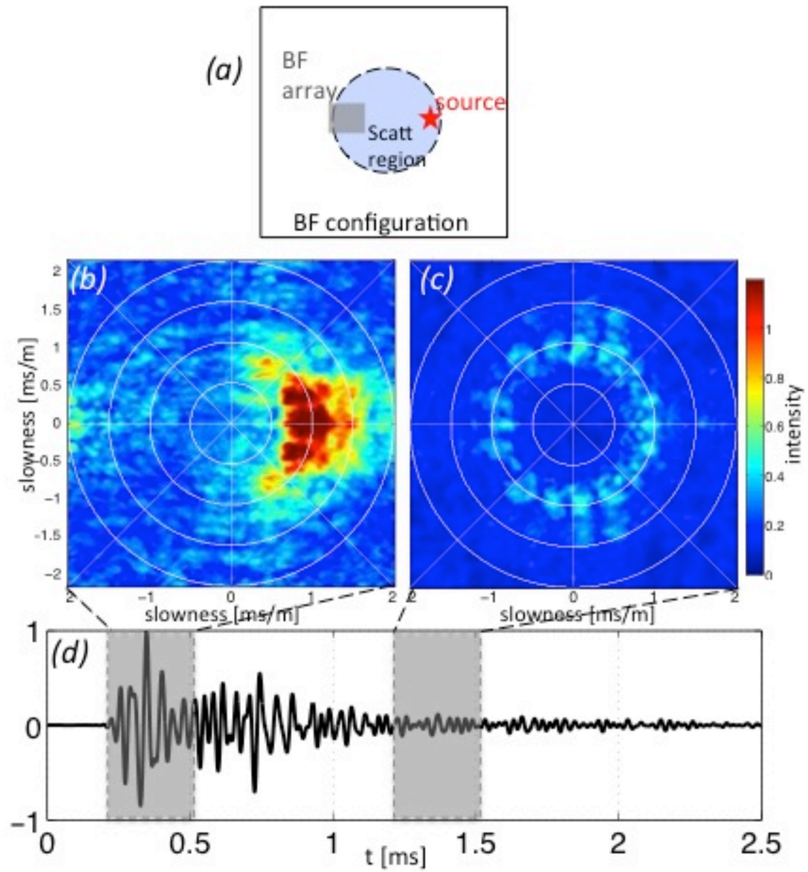
Specific to passive imaging and monitoring

Numerical simulations in a scattering medium



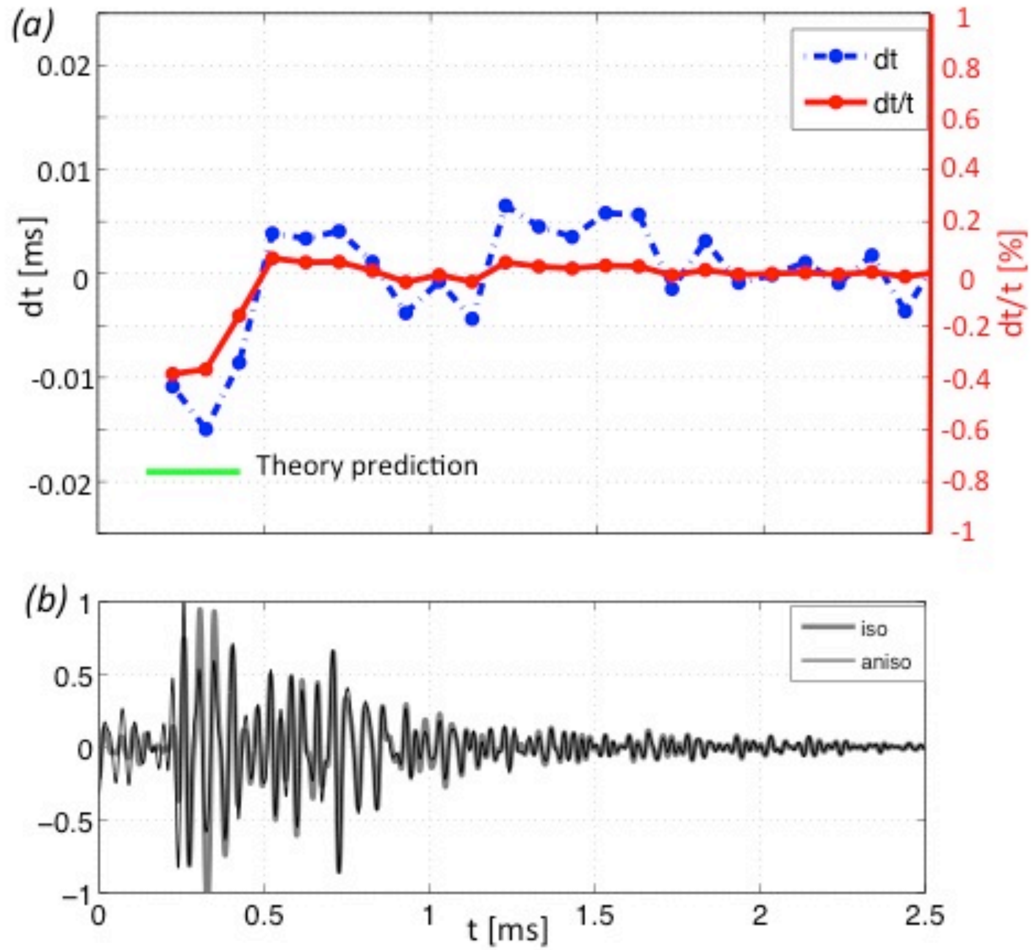
Colombi, Chaput, Hillers et al., 2014 in press

Effect of scattering   single source



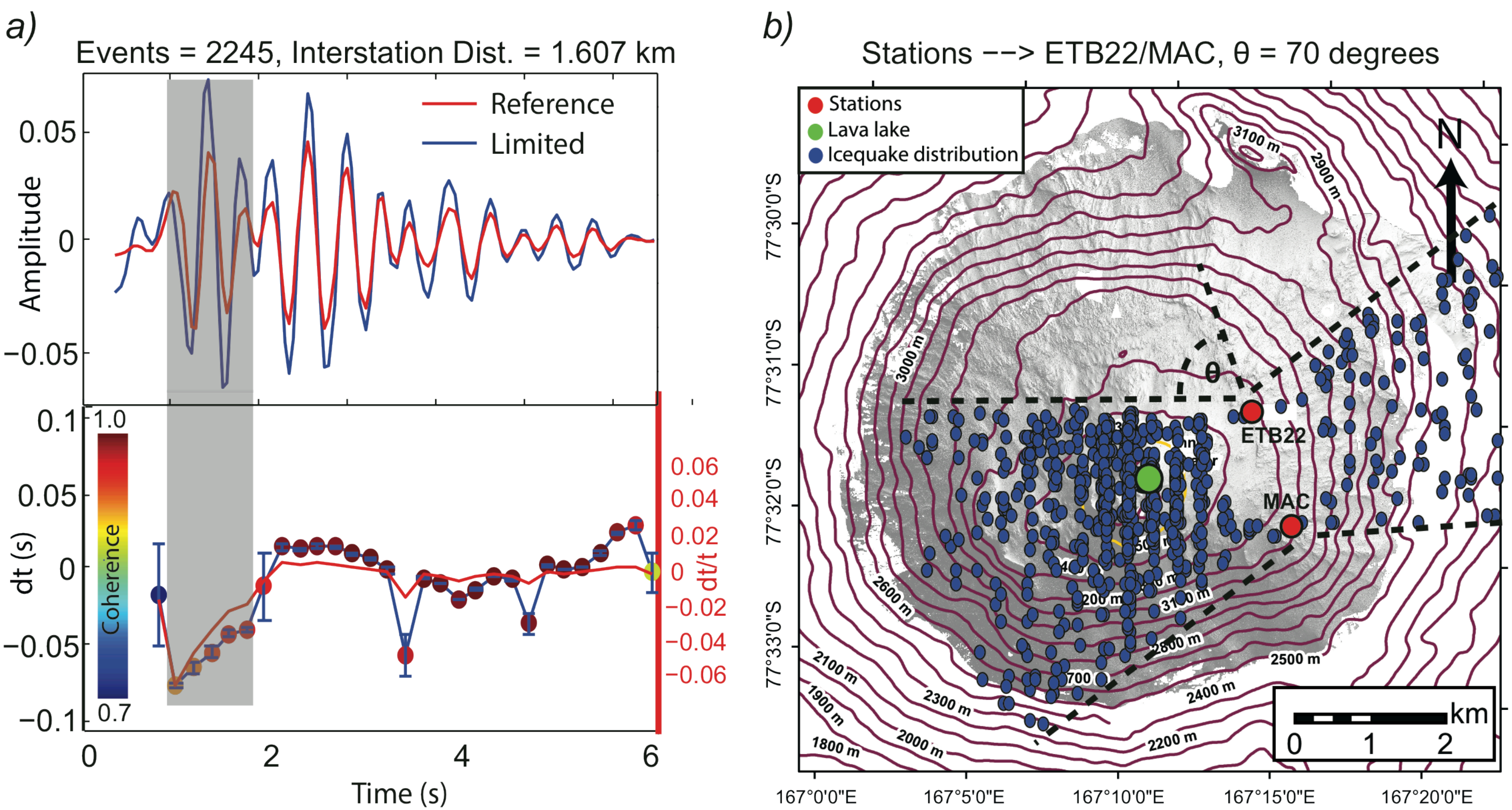
Colombi, Chaput, Hillers et al., 2014 in press

Measure of the bias induced by a strong anisotropy of the wave field



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

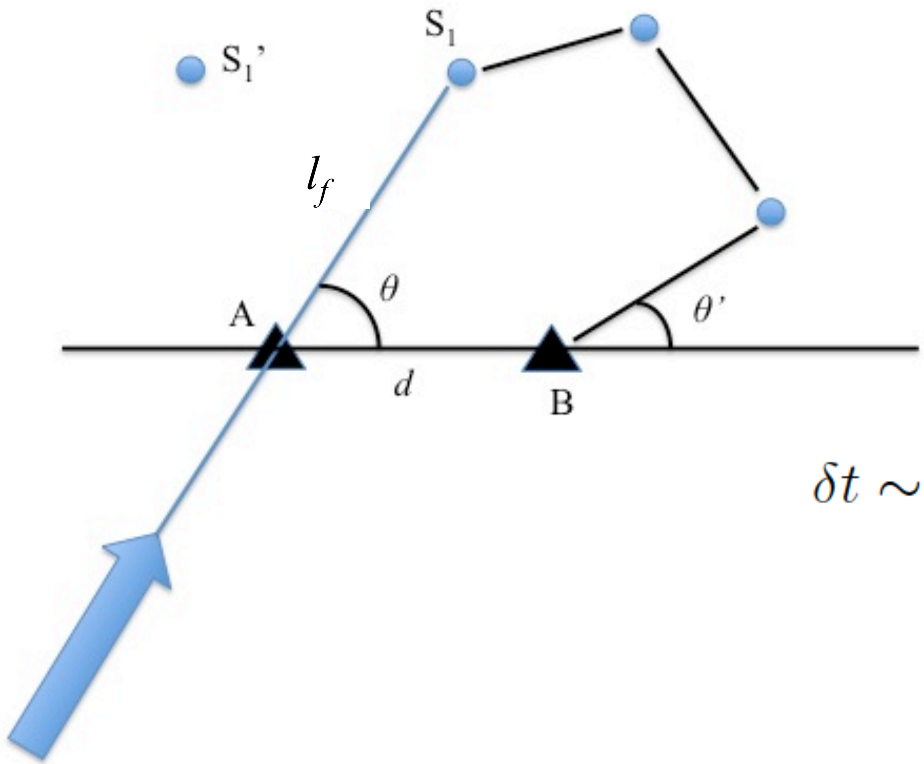
Real data: icequakes from Mount Erebus



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

Representation of coda waves as the sum of contributions of numerous paths

For a single path:



$$\delta t \sim \frac{B''(\theta)}{2\ t_f\ \omega_0^2\ B(\theta)}$$

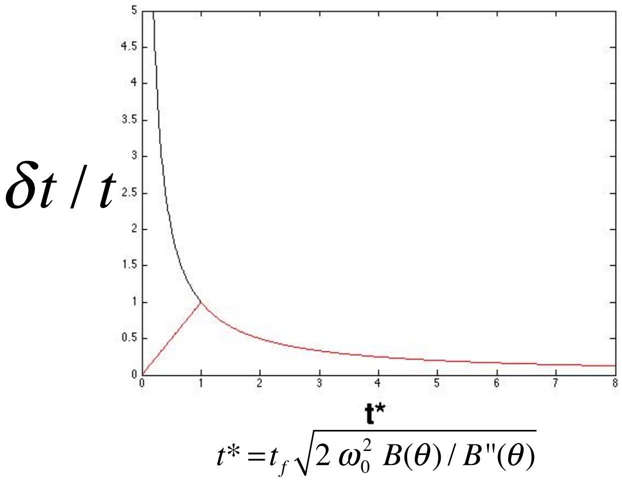
We have to compute the contributions of paths with first scatterers at all distances l_f and all azimuths θ

The distribution of distance between scattering events is exponential:

$$P(l_f) = \frac{1}{l} e^{-\frac{l_f}{l}}$$ where l is the mean free path $$< l_f > = l \qquad t_f = l_f / V$$

$$\delta t \sim \frac{B''(\theta)}{2\, t_f\, \omega_0^2\, B(\theta)}$$ valid for $l_f > \lambda$

We remove the singularity for l_f to 0 in a conservative way.



$$R = \frac{< \delta t >_{max}}{\delta t|_{t_l}}$$ ratio of max average δt over δt of the average l_f (=*l the mfp*)

Finally we consider all directions:

$$< \delta t > = \frac{R}{2\pi} \int_0^{2\pi} \delta t(\theta) d\theta = \frac{R}{4\pi t_l \omega_0^2} \int_0^{2\pi} \frac{B''(\theta)}{B(\theta)} d\theta$$

Applications

Numerical simulations

$$l = 0.5m,\ c = 2000\mathrm{m/s},$$

$$f_0 = 30000\mathrm{Hz},\ B_2 = -0.6 \text{ and } \tau_m = 0.002\mathrm{s}$$

➔ fractional error $\frac{\delta t(\tau_m)}{\tau_m}$ of 10^{-4}

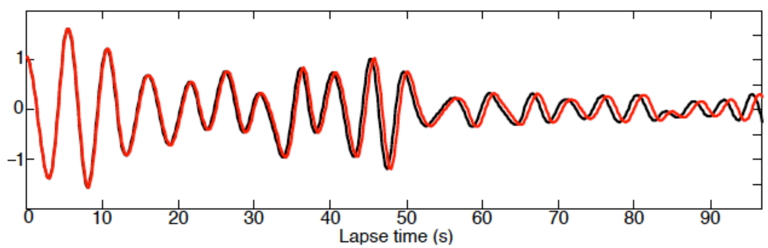
Japan (same change of anisotropy)

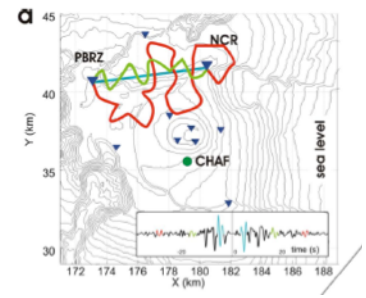
$$l = 60 \cdot 10^3 m,\ C = 3000\mathrm{m/s},\ f_0 = 0.3\mathrm{Hz} \text{ and } \tau_m = 100\mathrm{s}$$

➔ fractional error of $2 \cdot 10^{-4}$

Detecting a small change of seismic speed with coda waves

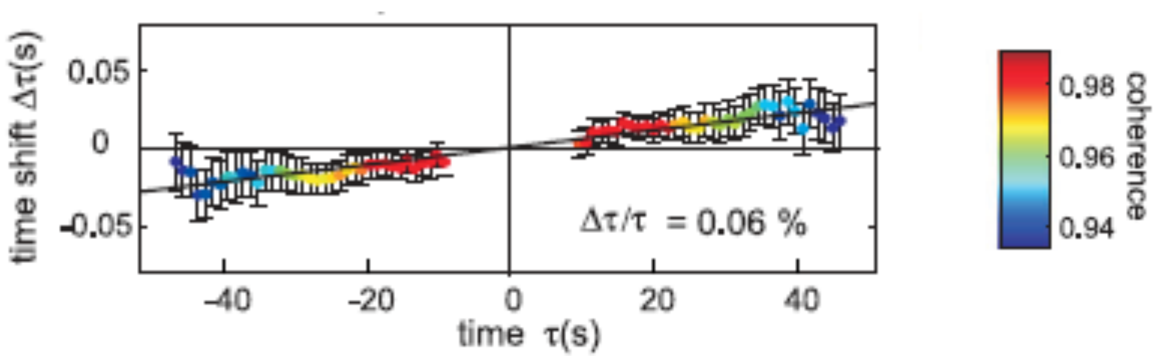
Comparing a trace with a reference under the assumption of an homogeneous change





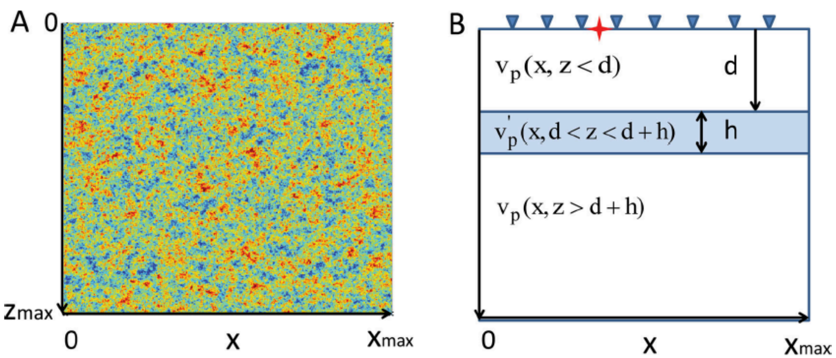
The ‘doublet’ method: moving window cross spectral analysis (phase measurements)

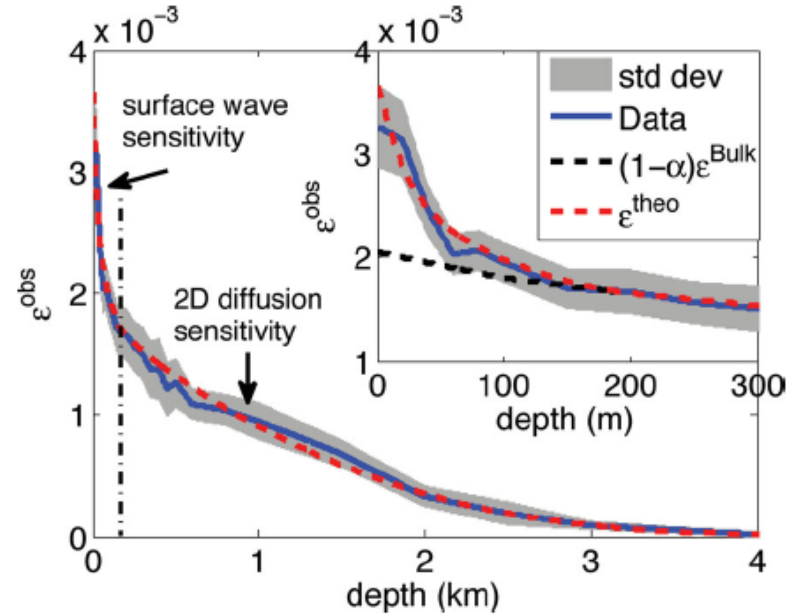
(Poupinet, Ellsworth, Fréchet, 1984)



Alternative technique: stretching

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





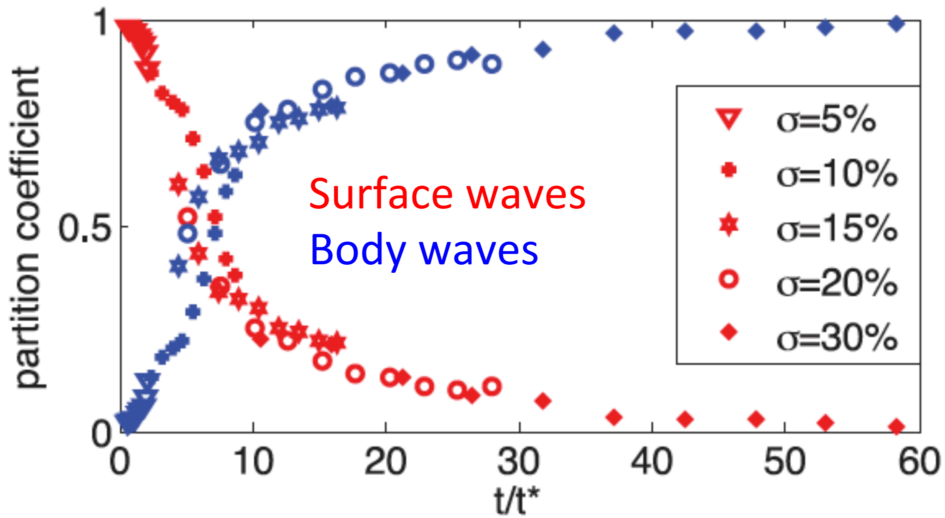
$$\varepsilon^{\text{theo}}(d,t) = \alpha(t)\varepsilon^{\text{Surf}}(d) + (1-\alpha(t))\varepsilon^{\text{Bulk}}(d,t)$$

Partition coefficient

Obermann et al., 2013a

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

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



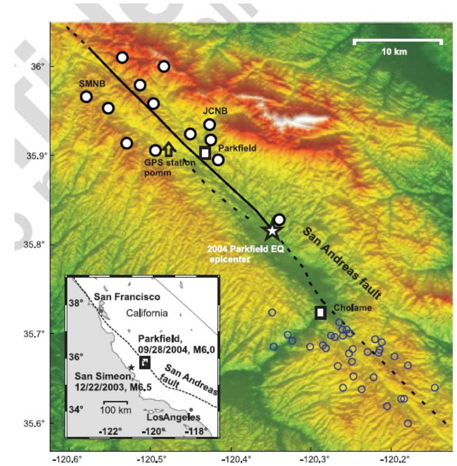
Lapse time in the coda/scattering mean free time

Obermann et al., 2013a

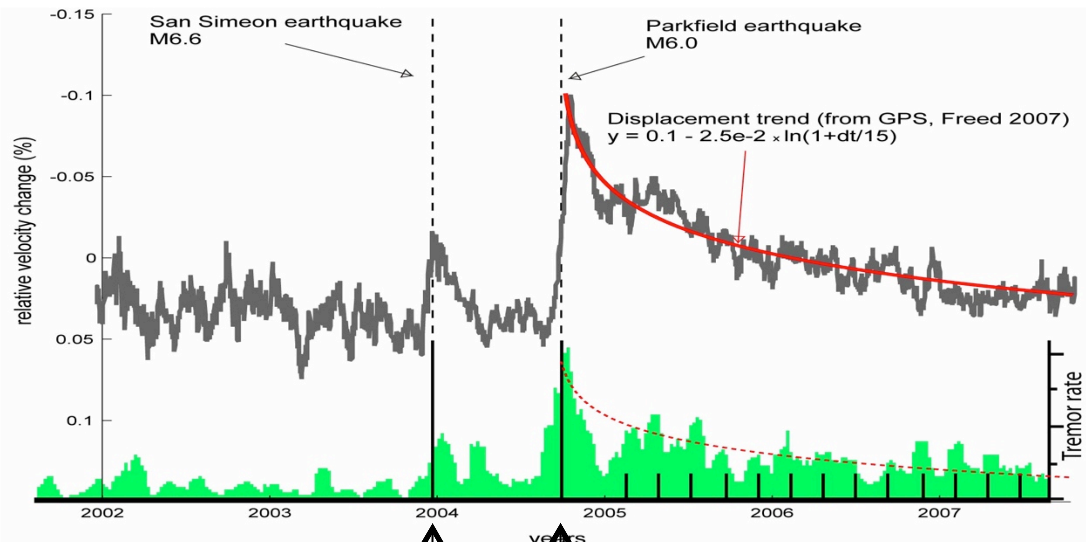
In the applications presented here, we analyze early coda (a few mean free times) so our measures concern mainly surface waves

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

Short period sensors / Processing in the period 1-10s



HRSN network



Distant event

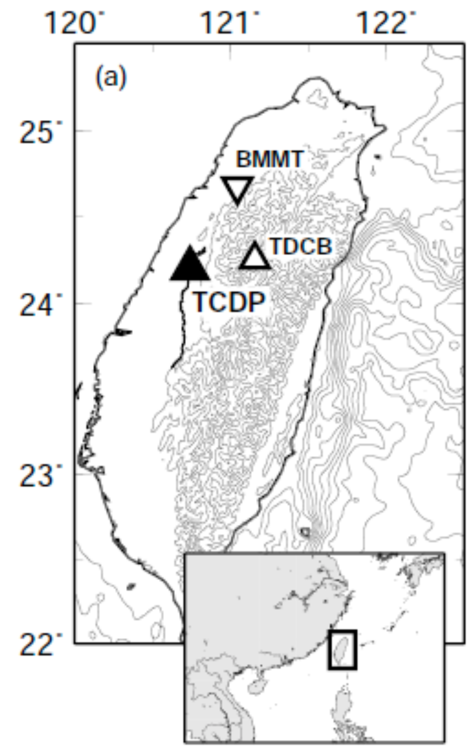
Local event

➔ GPS trend

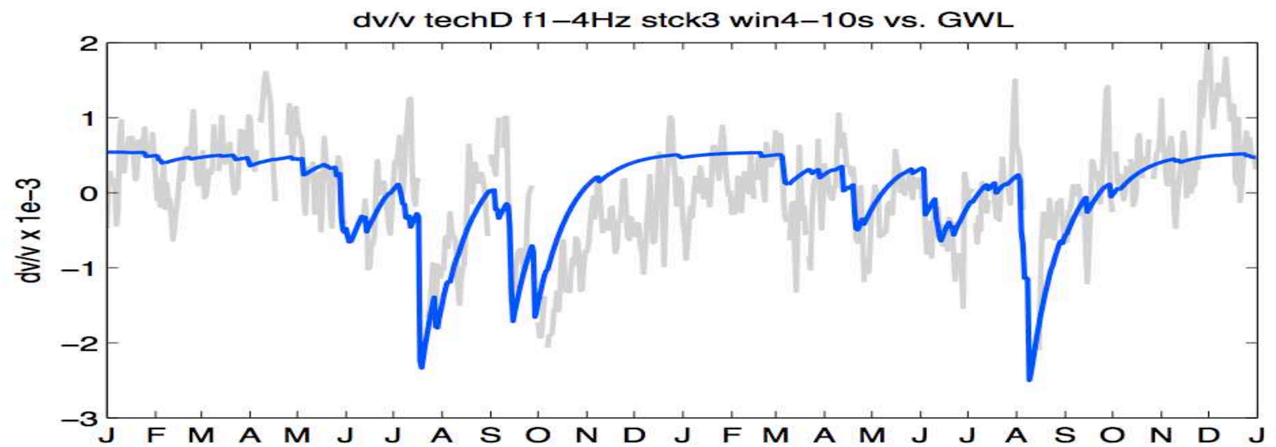
➔ tremor activity

➔ dynamic response of shallow layers

Evidence of hydro-meteorological effects



High frequency measurements at depth ≈ 1 km



grey: variations of seismic speed

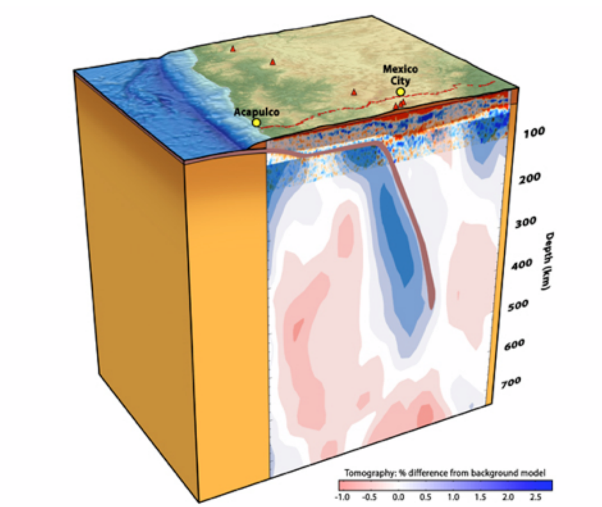
blue: model of the effet to the level of water table deduced from meteorological data

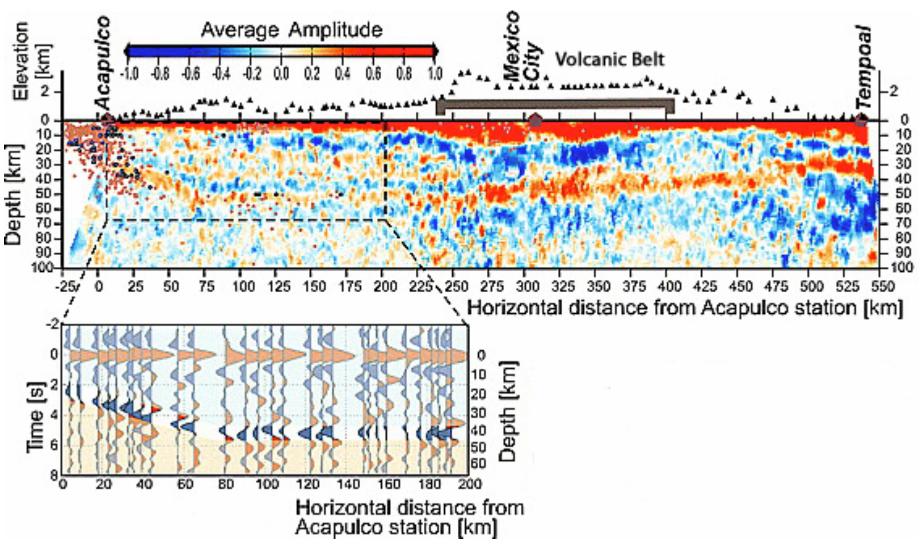
Gregor Hillers et al. EPSL 2014

Slow slip events in Guerrero, Mexico

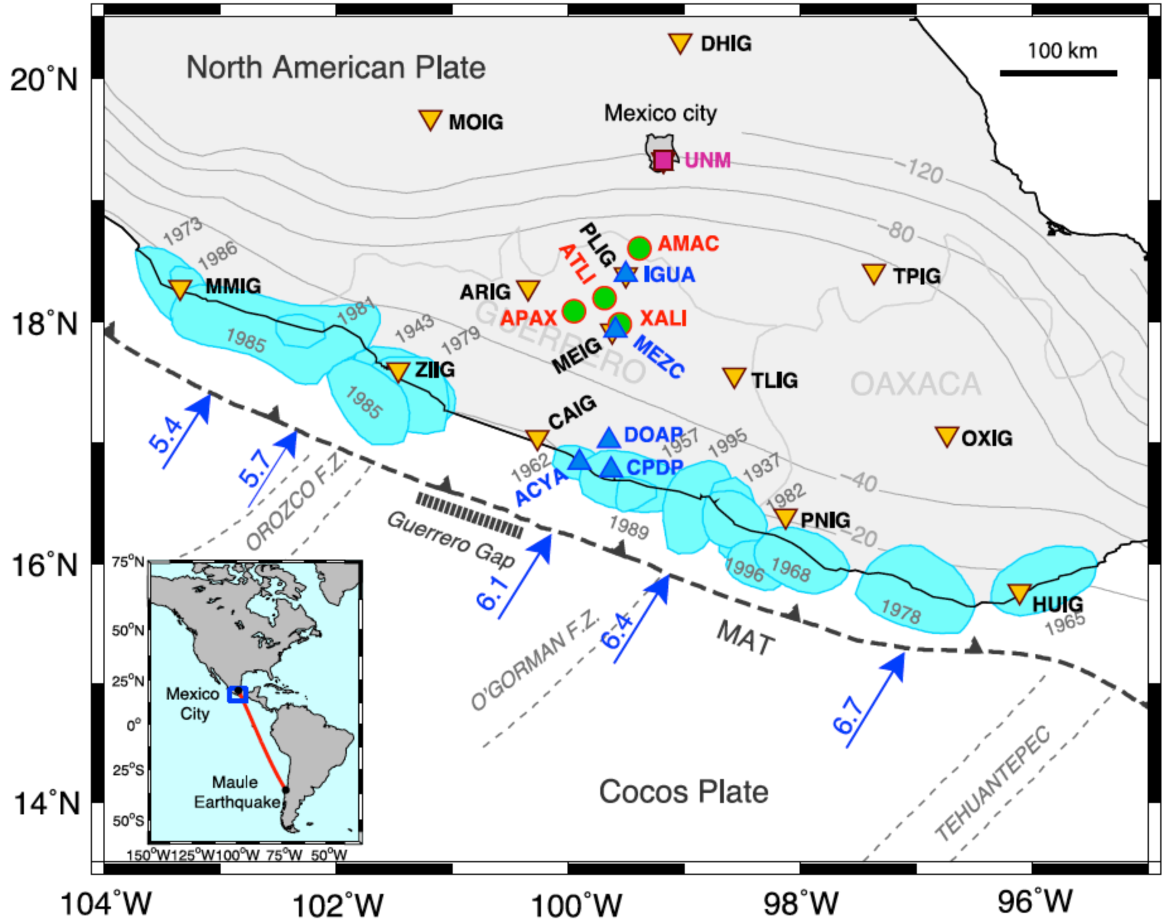
[Modified from Chen and Clayton, JGR 2009]

MASE project (US-Mexico)



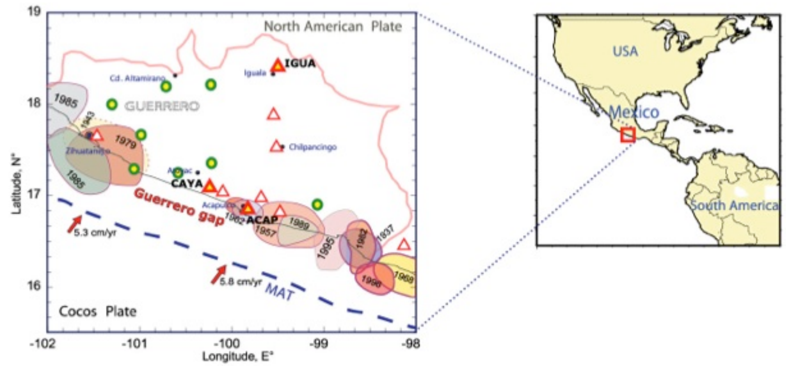


[From Perez-Campos et al., GRL 2008]



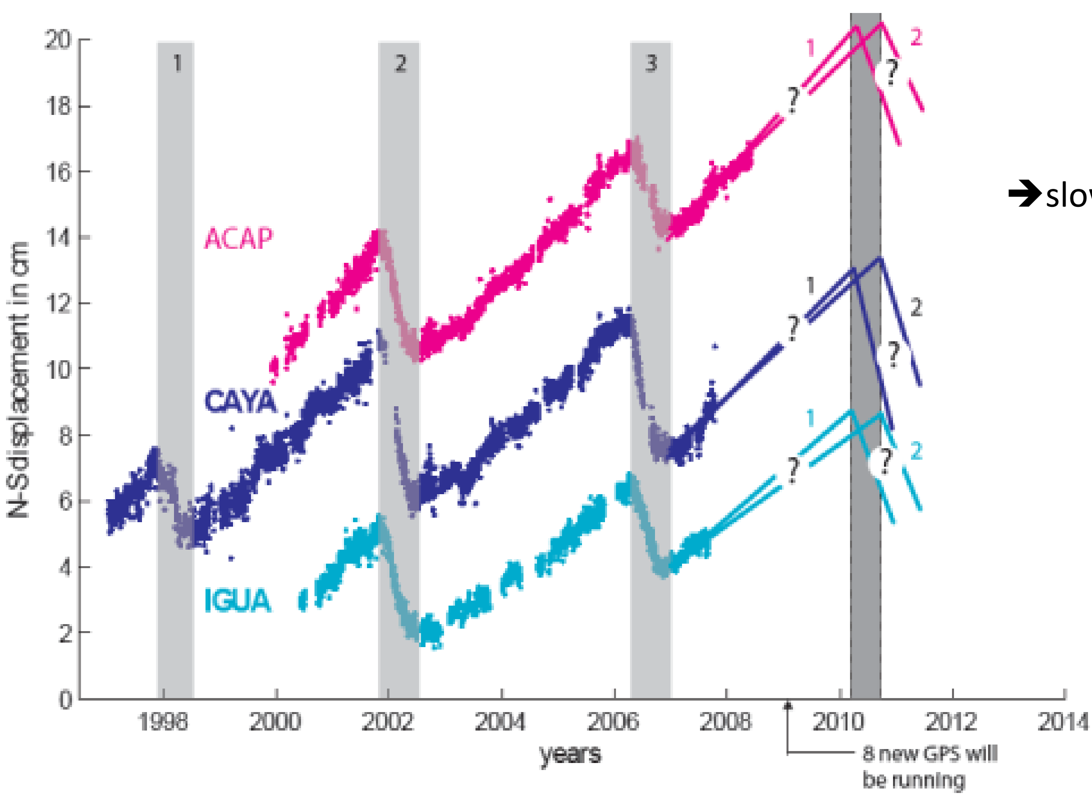
North American Plate
Mexico city
UNM
DHIG
MOIG
100 km
AMAC
PLIG
ATLI
IGUA
ARIG
APAX
XALI
MEIG
MEZC
GUERRERO
OAXACA
TPIG
TLIG
OXIG
MMIG
ZIIG
CAIG
DOAP
CPDP
ACYA
PNIG
HUIG
1973
1986
1981
1985
1943
1979
1962
1957
1995
1937
1982
1989
1996
1968
1978
1965
-120
-80
-40
-20
5.4
5.7
6.1
6.4
6.7
OROZCO F.Z.
Guerrero Gap
O'GORMAN F.Z.
MAT
TEHUANTEPEC
Cocos Plate
20°N
18°N
16°N
14°N
104°W
102°W
100°W
98°W
96°W
Mexico City
Maule Earthquake
75°N
50°N
25°N
0°
25°S
50°S
150°W
125°W
100°W
75°W
50°W

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



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

Mw7.6

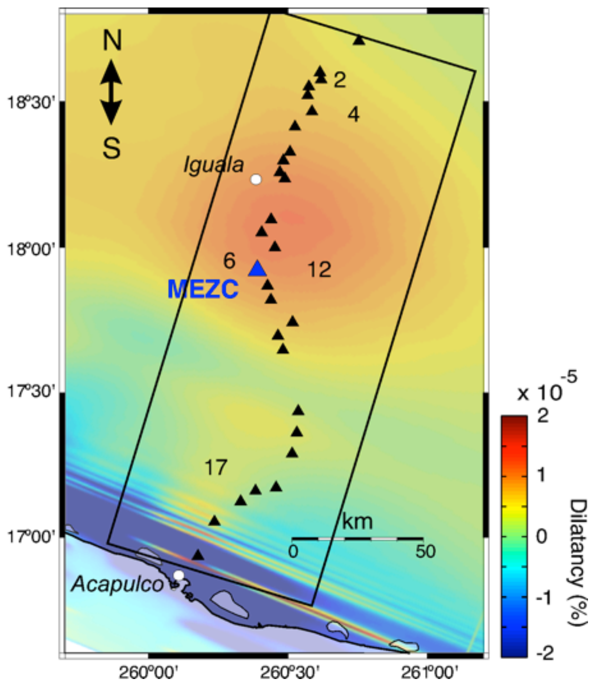


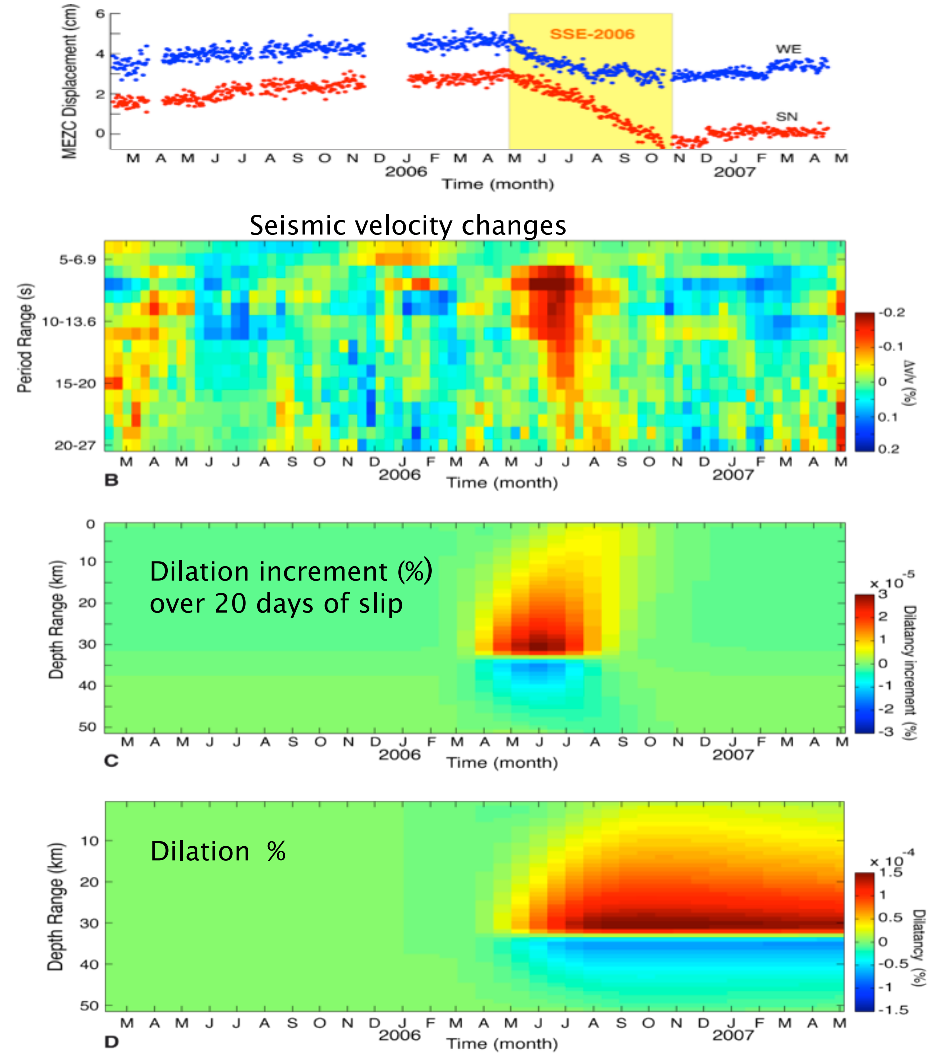
➔slow slip events (SSEs)

(Cotte et al., 2009)

Temporal relation between velocity change and dilatation

Dilation at 15km depth





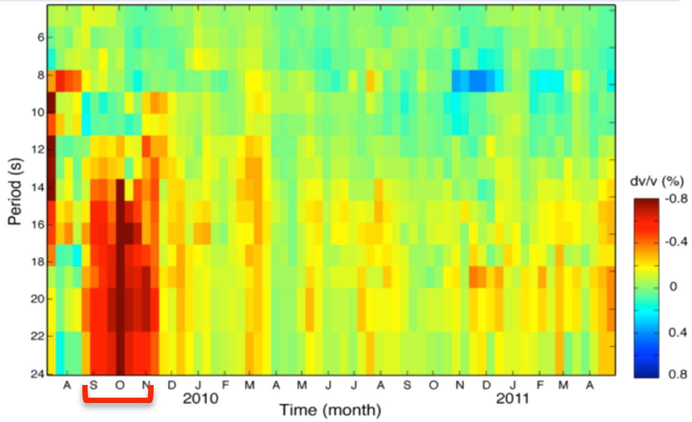
Rivet et al., 2011:

Deep velocity drop

Depth sensitivity (Obermann et al;, 2013)

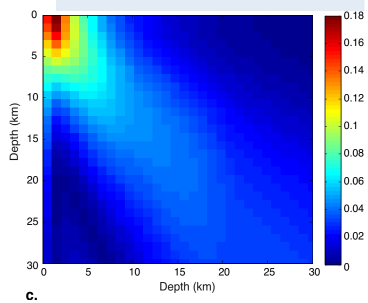
2009-2010 Slow Slip Event

Apparent temporal change of velocity (t,T)



Linearized Rayleigh wave inversion

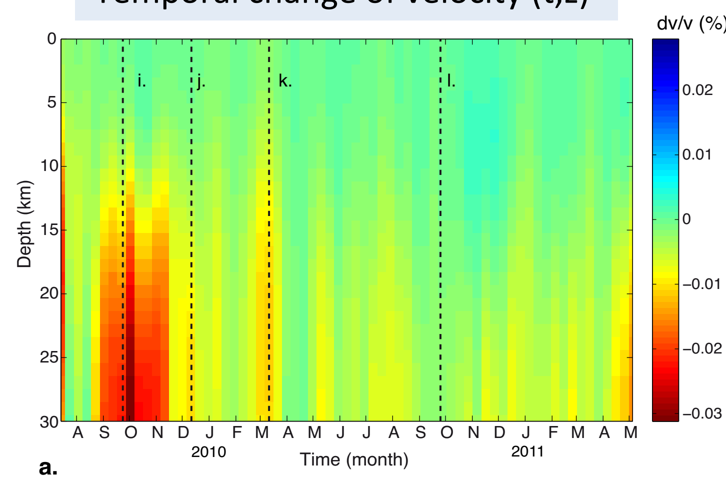
Resolution matrix



Monte Carlo inversion

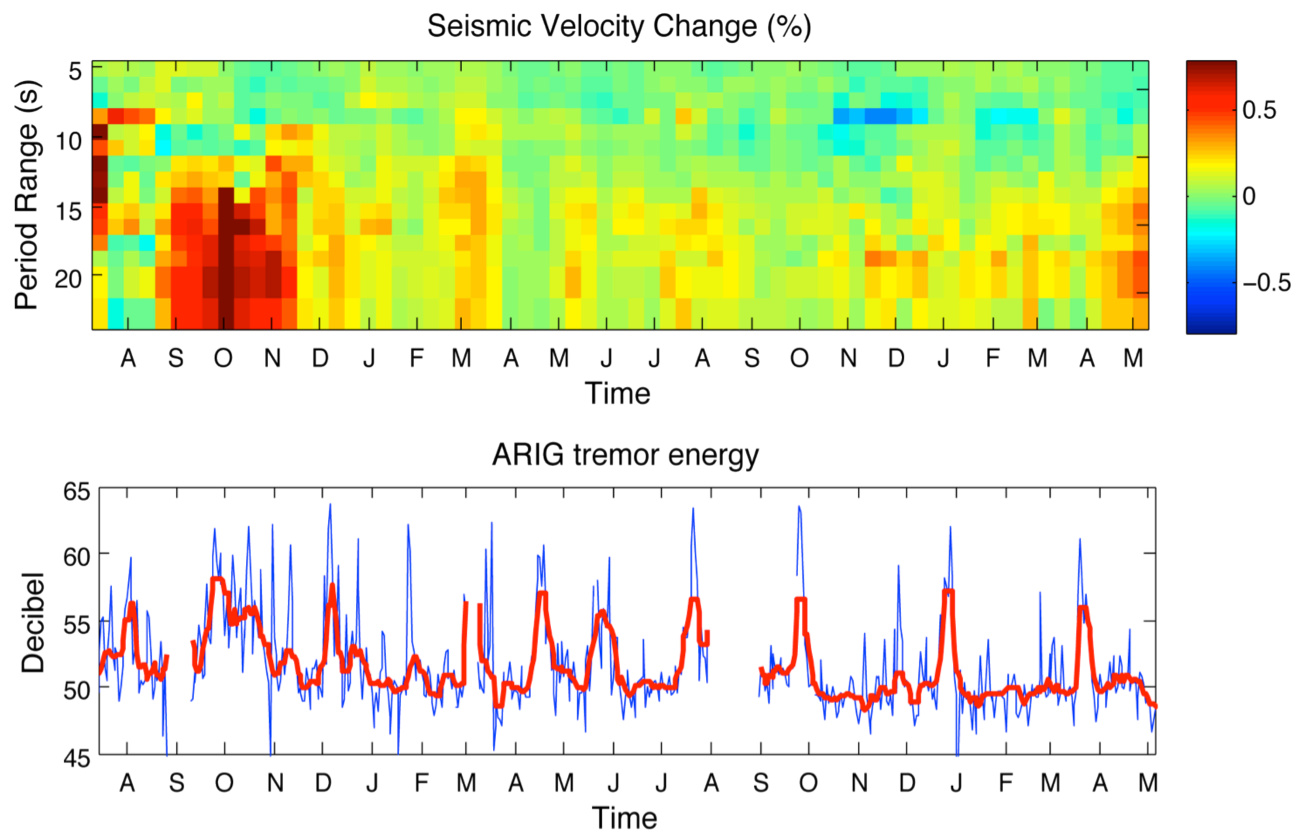
With the period band available, we conclude that the change occurs in the lower crust or below.

Temporal change of velocity (t,z)



Rivet et al., 2012

Velocity change and Tremors



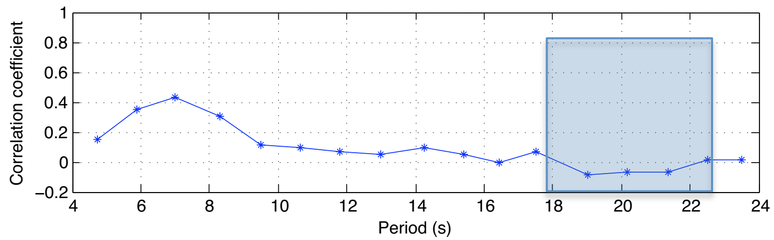
Rivet et al., 2012

Is there a measurement bias between Δv/v and NVT activity?

Different frequency ranges (10-20s vs 0.12 -0.2s)

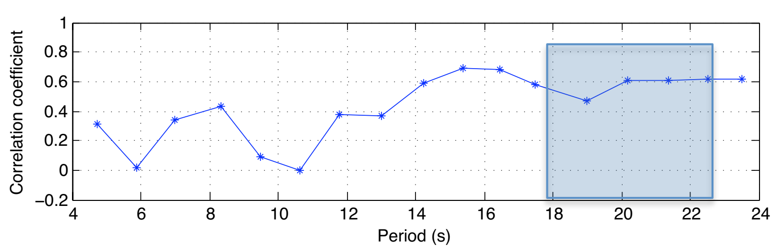
Comparison between temporal variations of velocity measured at period T and of spectral energy in the band 10-20s :

Temporal correlation



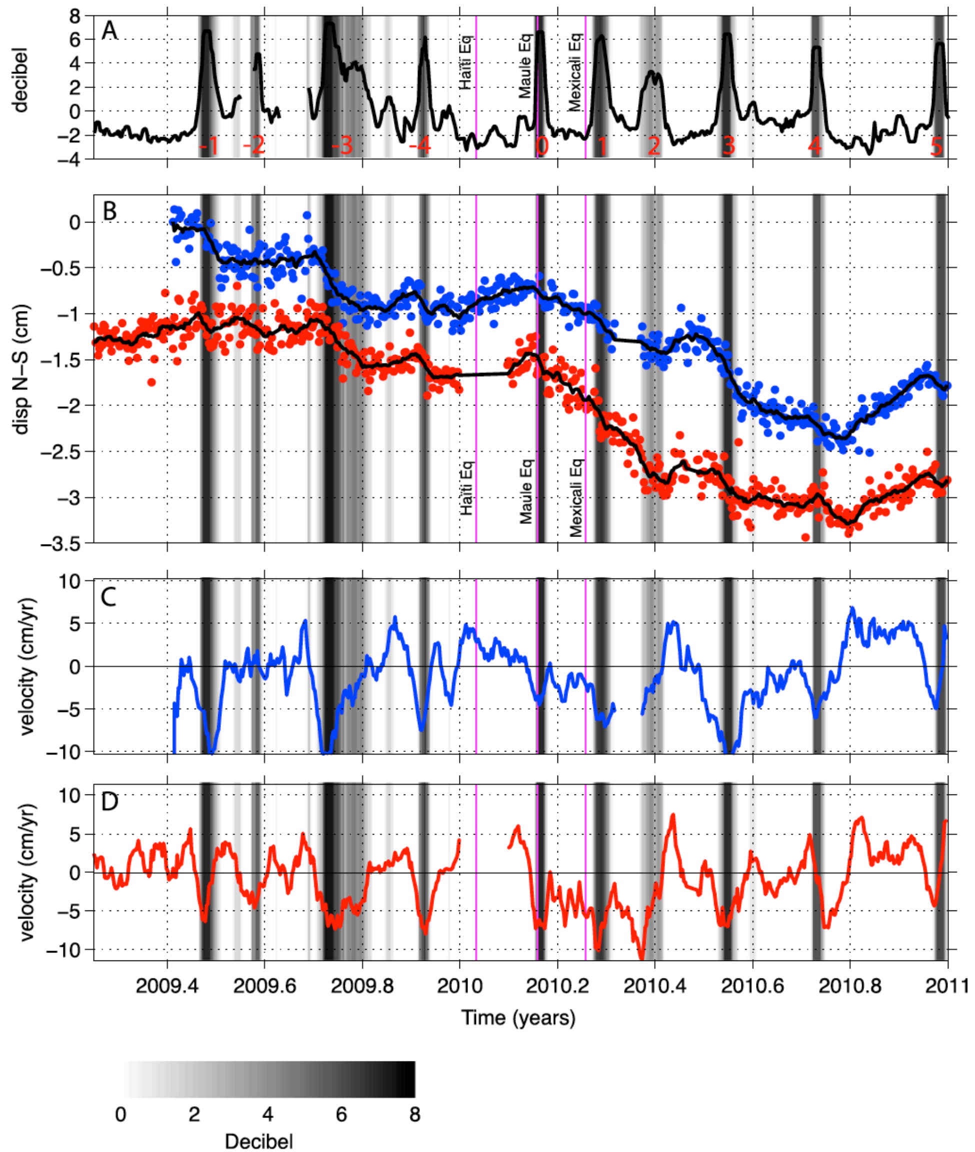
Comparison between temporal variations of velocity measured at period T and of spectral energy in the band 0.2-0.12s (non-volcanic tremors)

Temporal correlation



Low frequency dv/v measurements correlates with NVTs (not a bias)➔low Mw SSE?

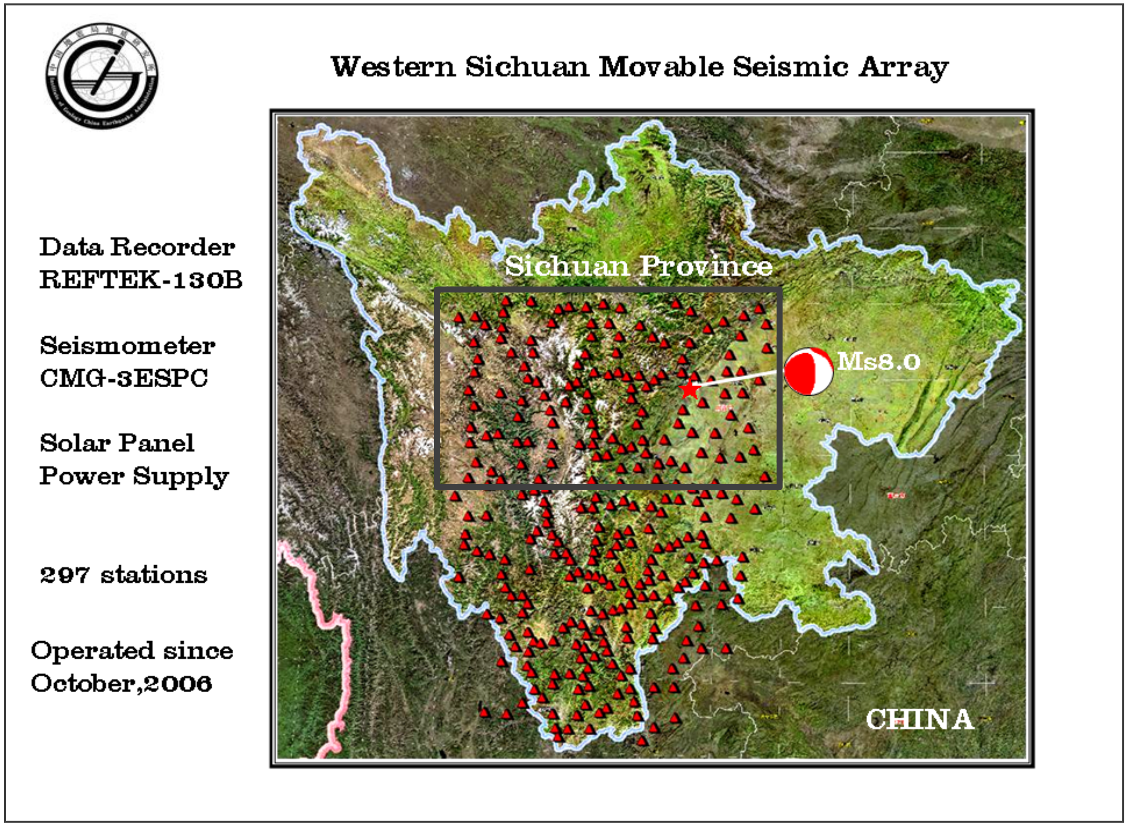
GPS positions and Tremors



Zigone et al., JGR 2012

Application to Wenchuan *(Chen et al. 2010, Froment et al., 2013)*

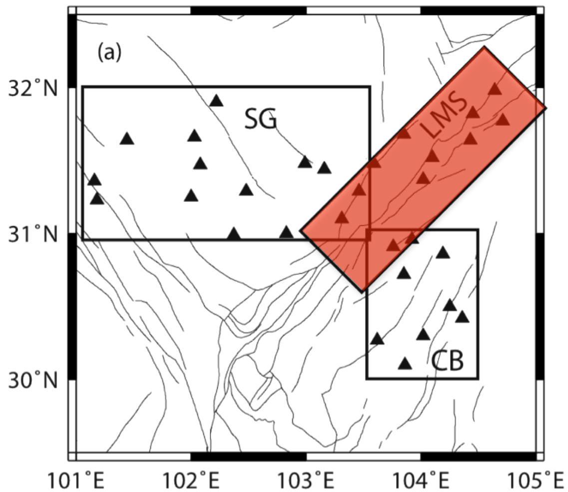
A magnitude 7.9 event occuring within a temporary (2 years) broad band network



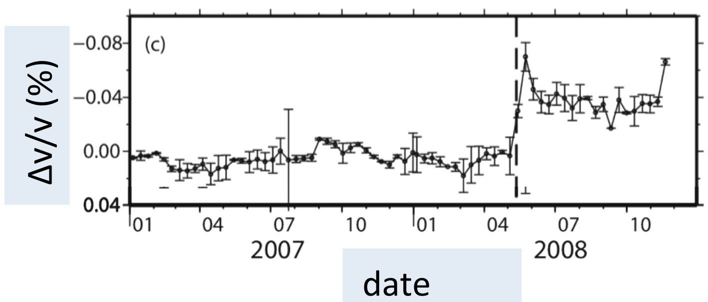
with: Bérénice Froment, Anne Obermann, Jiuhui Chen, Qiyuan Liu, Laurent Stehly,..

Short period band (1-3s)

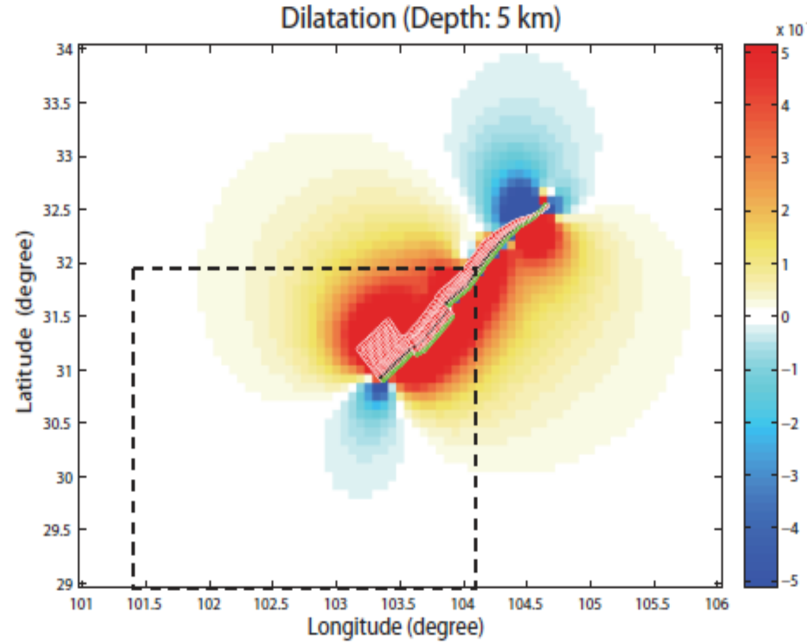
(Chen et al., 2010, Zhao et al, 2012)



Longmen-Shan (LMS)

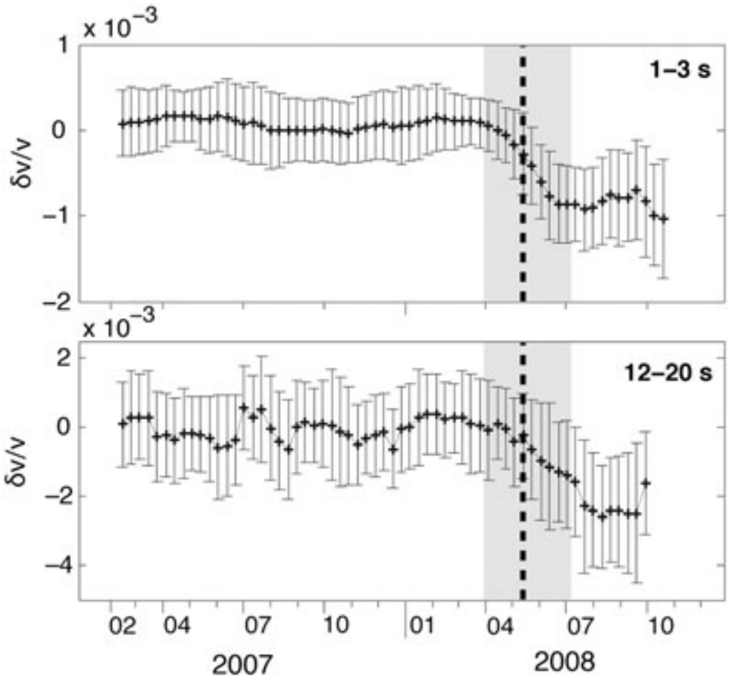


-amplitude of the velocity change is similar to Parkfield



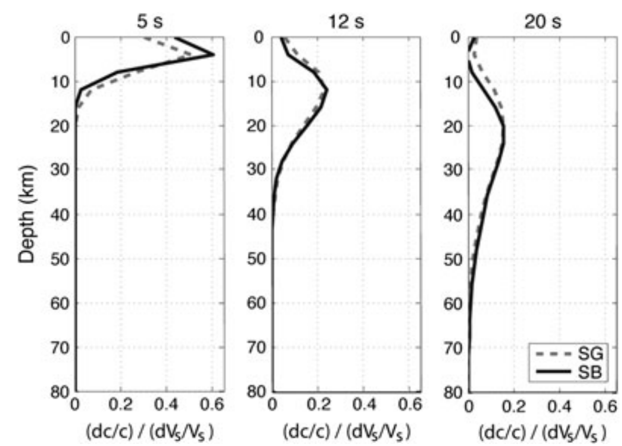
- no strong mark of the sedimentary basin
- regional effect
- correlation with deformation

Deep origin of the temporal change (Froment et al., 2013)



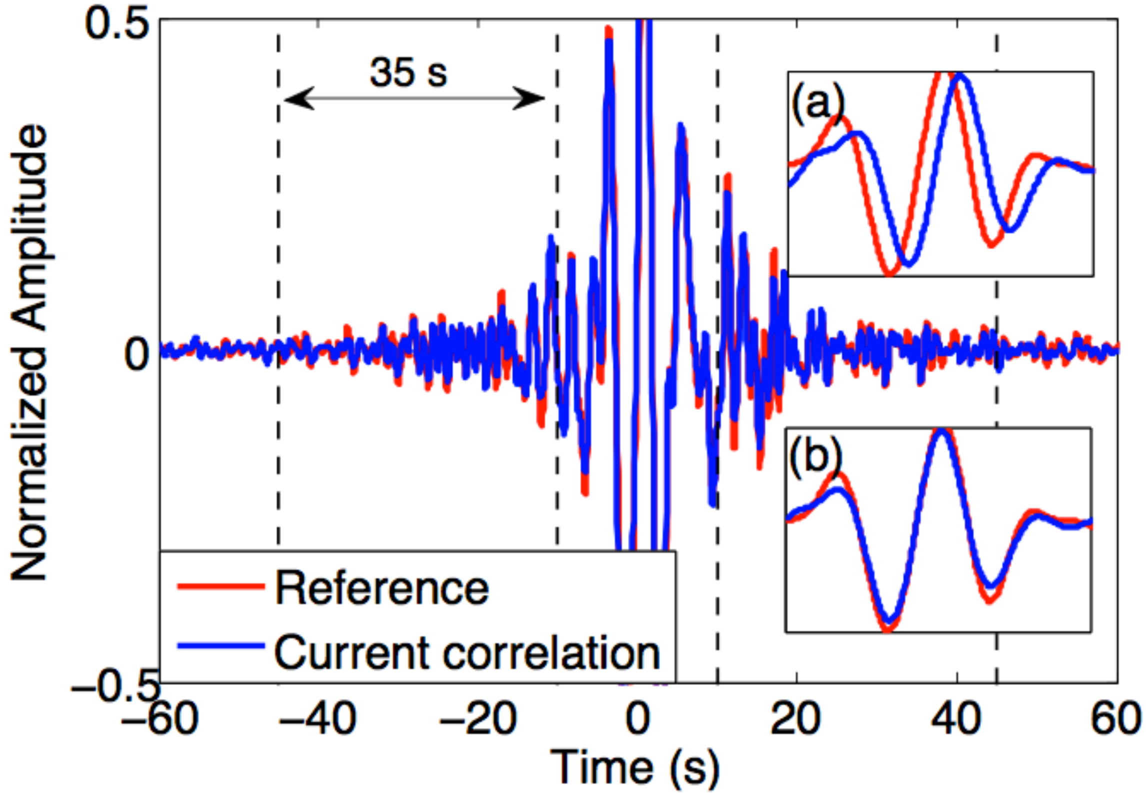
Measures in different period bands
-large amplitude at long period
-delay at long period

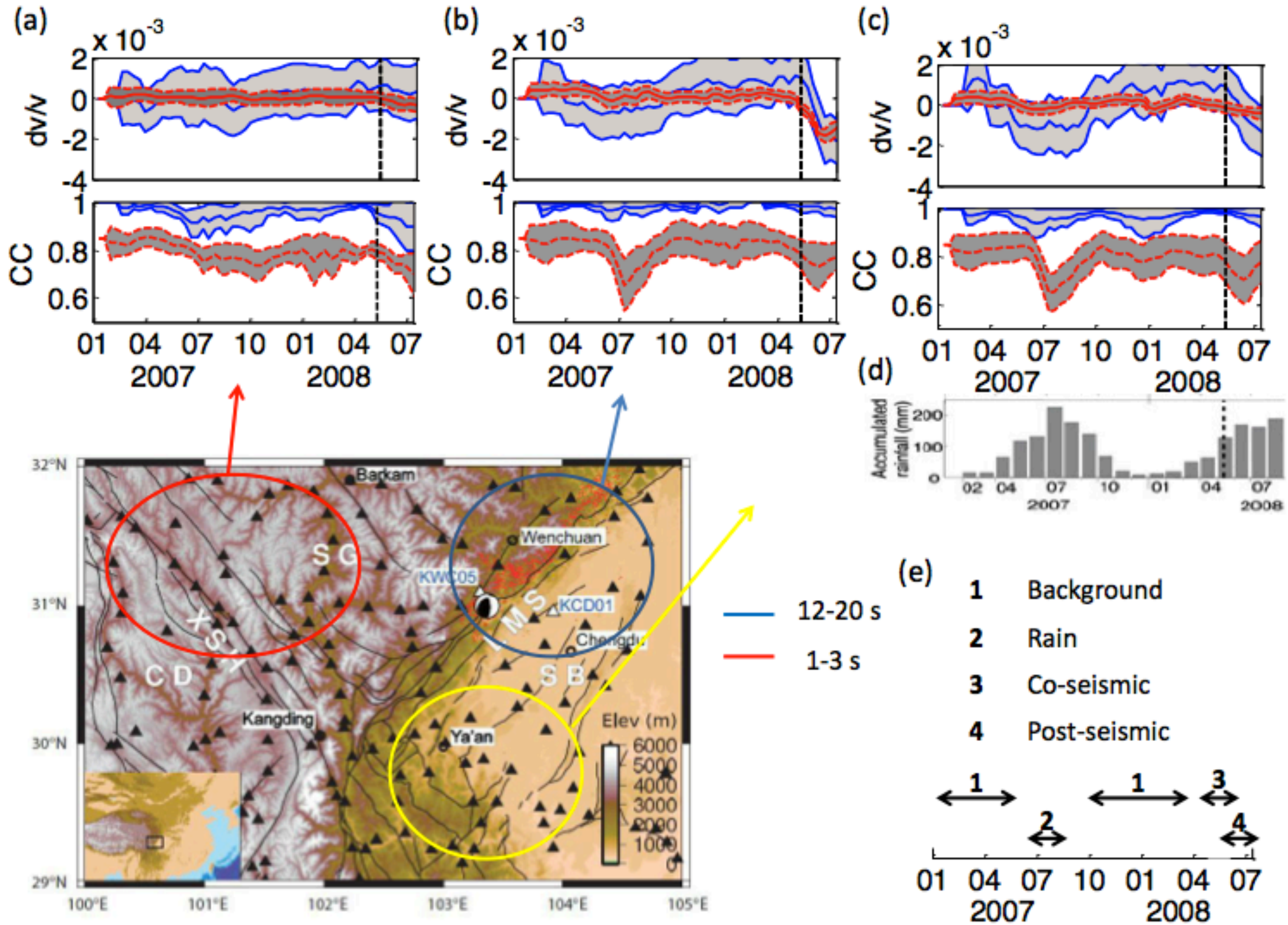
Depth sensitivity for Rayleigh waves



Changes in the mid or lower crust, with short time scale post seismic evolution

Two different measures of the temporal changes: delay and decorrelation





Need for spatial characterization

Sensitivity of coda to a change in the medium 2: lateral distribution of the changes

Mapping the change in the medium from the delays $\delta t(\tau, r_1, r_2)$ or the decorrelation

Kernels from transport equations (probabilities of presence)

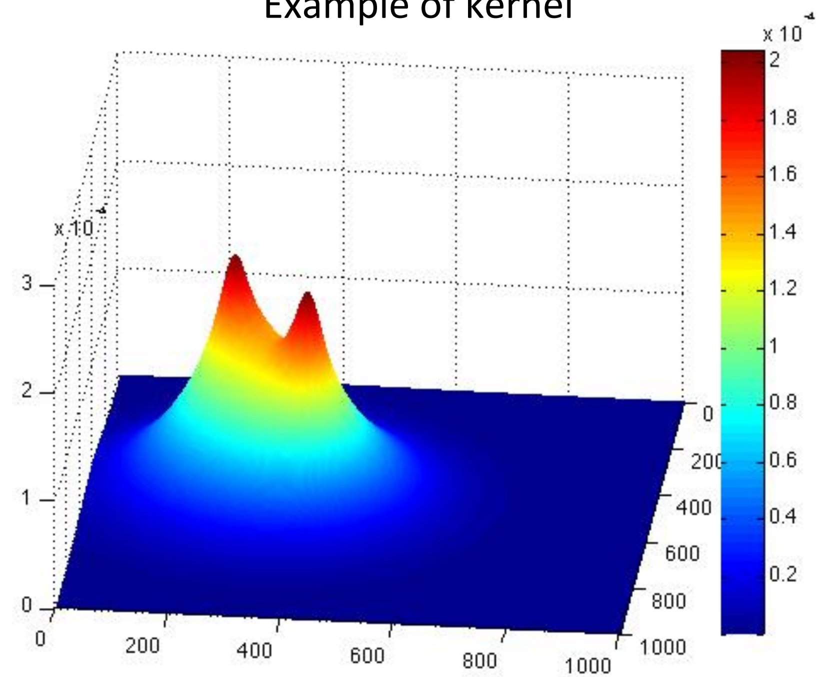
$$K(x,r_1,r_2,\tau) = \frac{1}{P(r_1,r_2,\tau)} \int_0^{\tau} P(r_1,x,\tau - t')\, P(x,r_2,t')\, dt'$$

Linear formulation

$$\delta t(\tau,r_1,r_2) = -\int_V K(x,r_1,r_2,\tau) \frac{\delta v}{v}(x)\, dV(x)$$

unknown

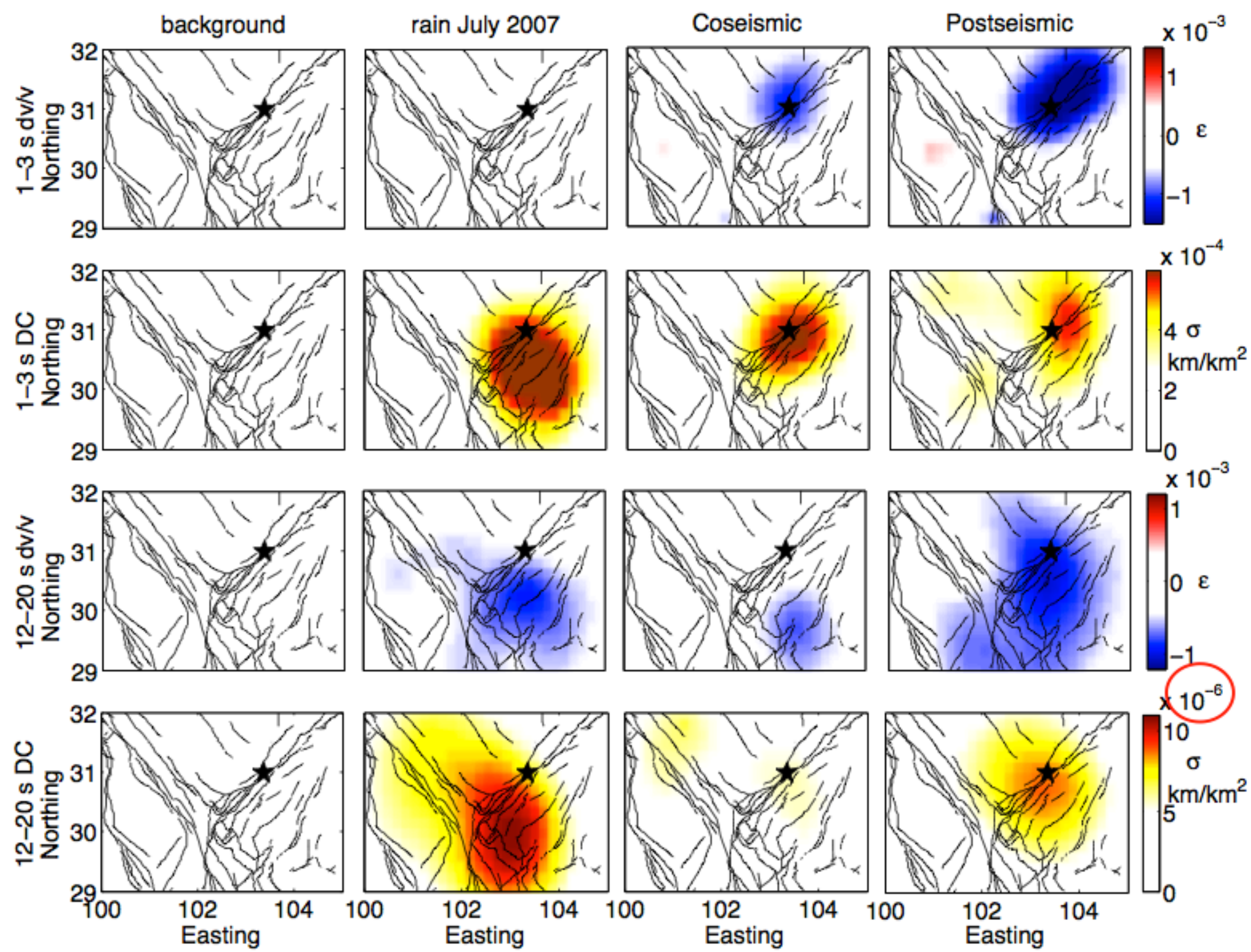
Example of kernel



P from diffusion approximation (late coda?) or radiative transfer equation

Need for realistic modelling

Pacheco and Snieder 2005, Larose et al., 2010, Froment 2011, Obermann et al., 2013…

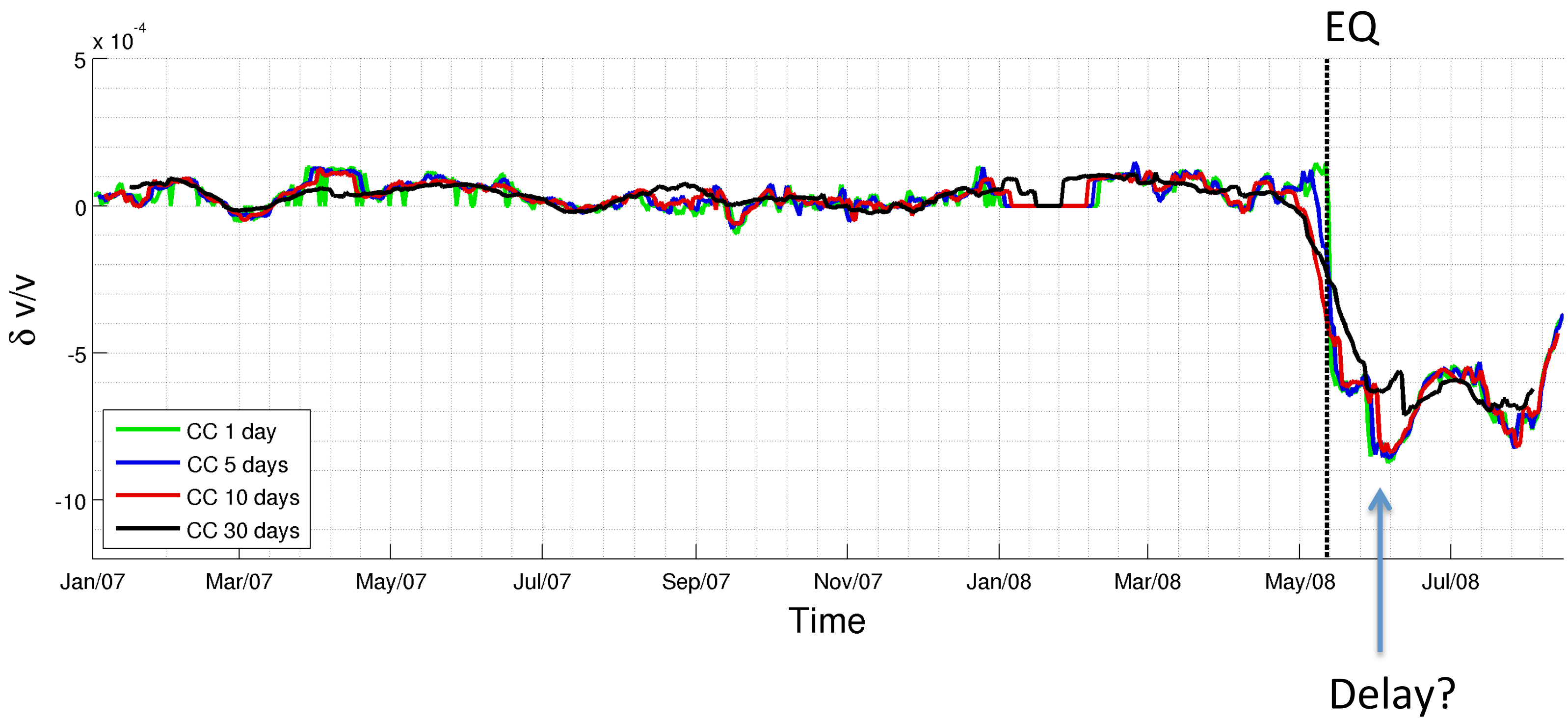


Postseismic response

Instantaneous response to hydraulic load at depth

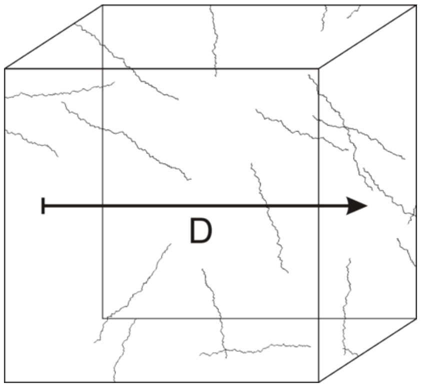
Improving the time resolution with curvelet processing (L. Stehly)

Short period (1-3s)



Superposition of the effect of waves (main shock+aftershocks) and of bulk deformation?

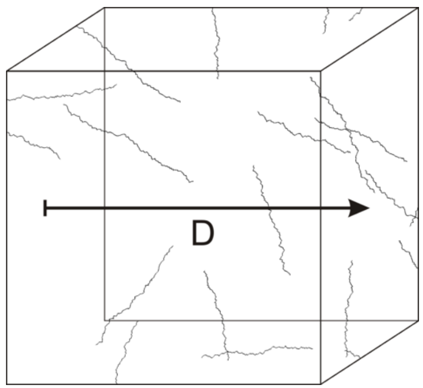
Traditional Seismic velocity tomography



Local seismic velocity (V) = D/(travel time)

Seismic velocity is a proxy for **stiffness** (high velocities) and **compliance** (low velocities) of rocks

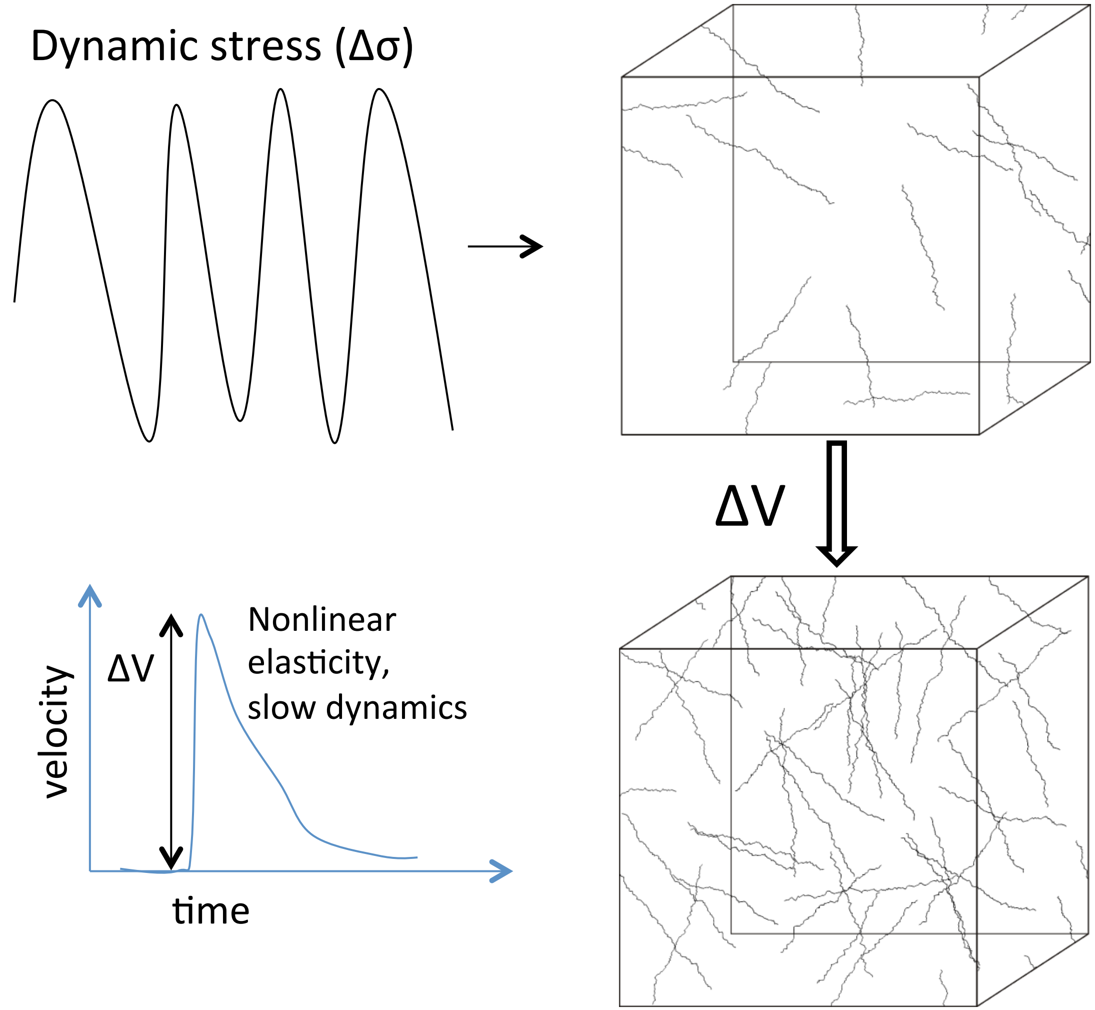
Traditional Seismic velocity tomography



Local seismic velocity (V) = D/(travel time)

Seismic velocity is a proxy for **stiffness** (high velocities) and **compliance** (low velocities) of rocks

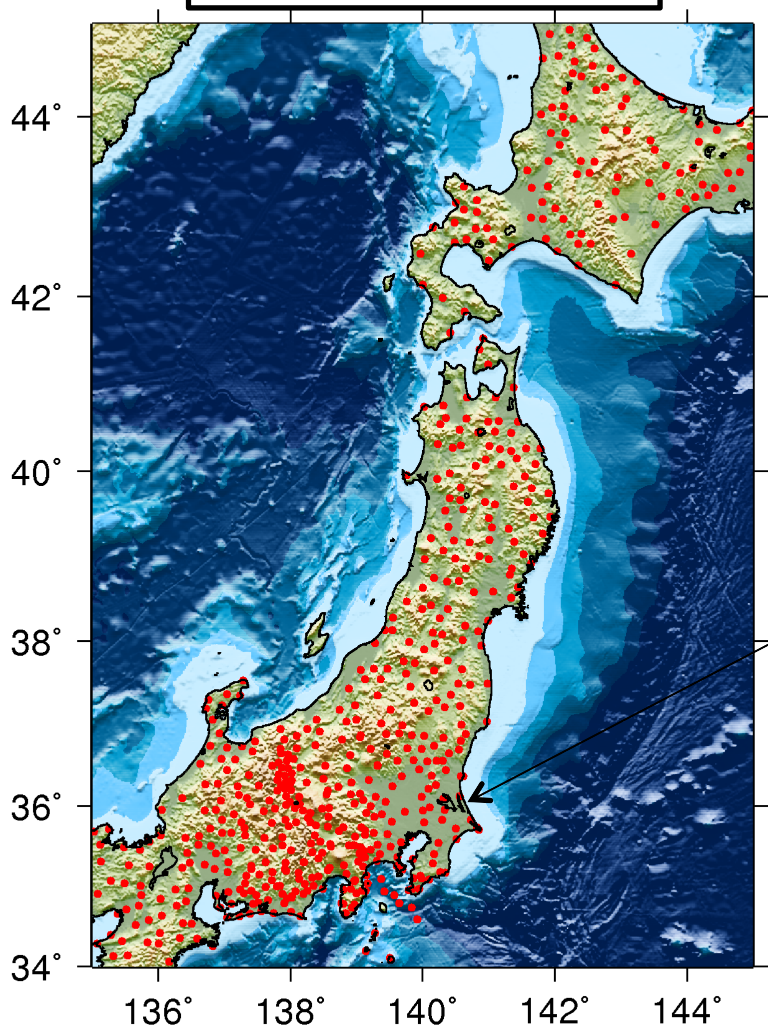
New Seismic susceptibility tomography



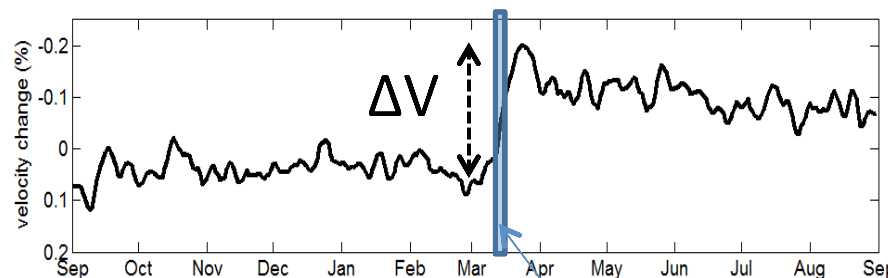
Seismic susceptibility (ΔV/Δσ) is sensitive to **fractured**, **damaged** or **pressurized** rocks

Monitoring seismic velocities before and after the M9 Tohoku-oki earthquake

600 seismic stations (Hi-net)



For each seismic station, we obtain a **continuous seismic velocity change time series**

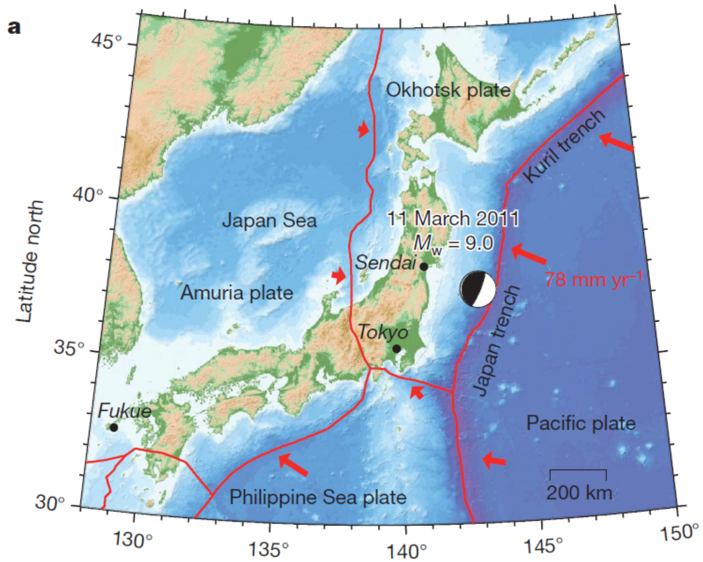


Tohoku-oki earthquake

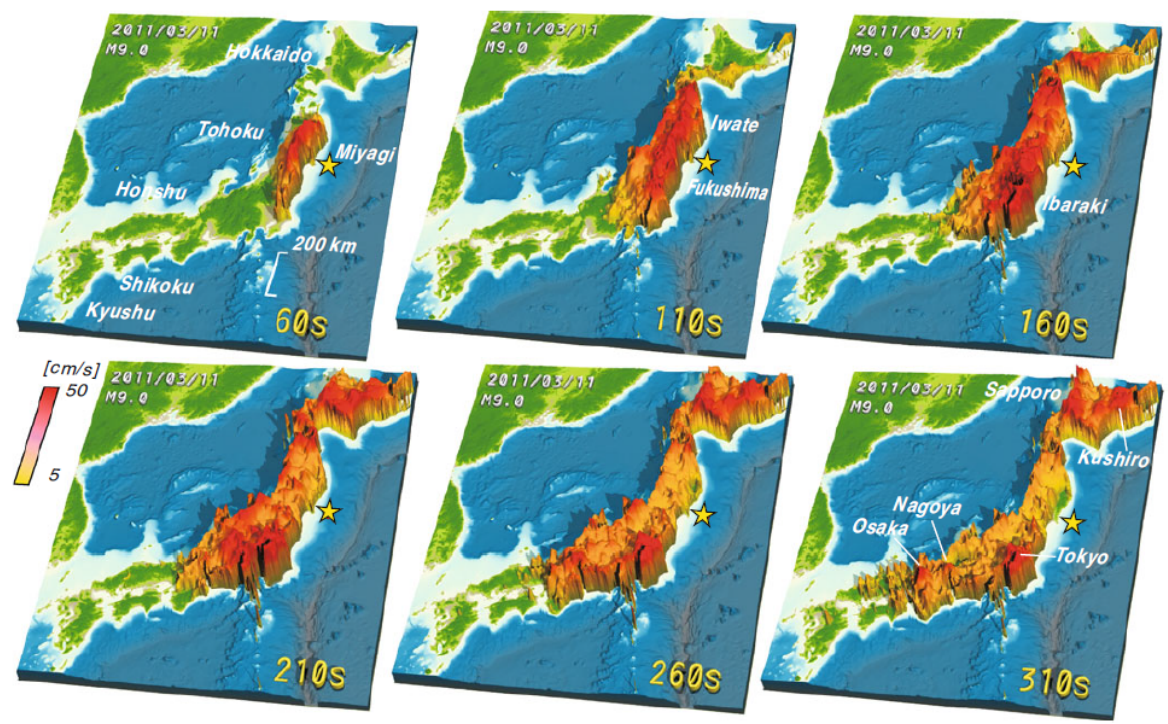
From Brenguier, Campillo, Takeda, Aoki, Shapiro, Briand, Emoto and Miyake 2014

Seismic susceptibility tomography of Japan

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

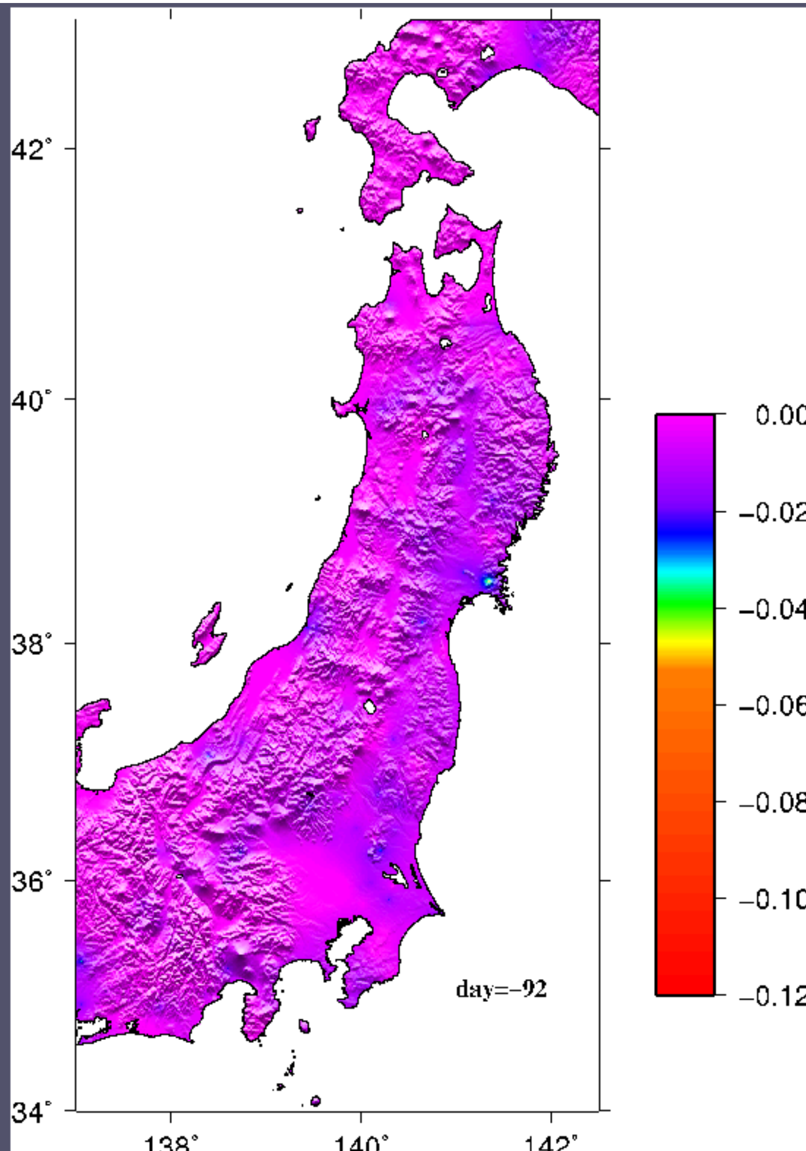


Ozawa et al. 2011



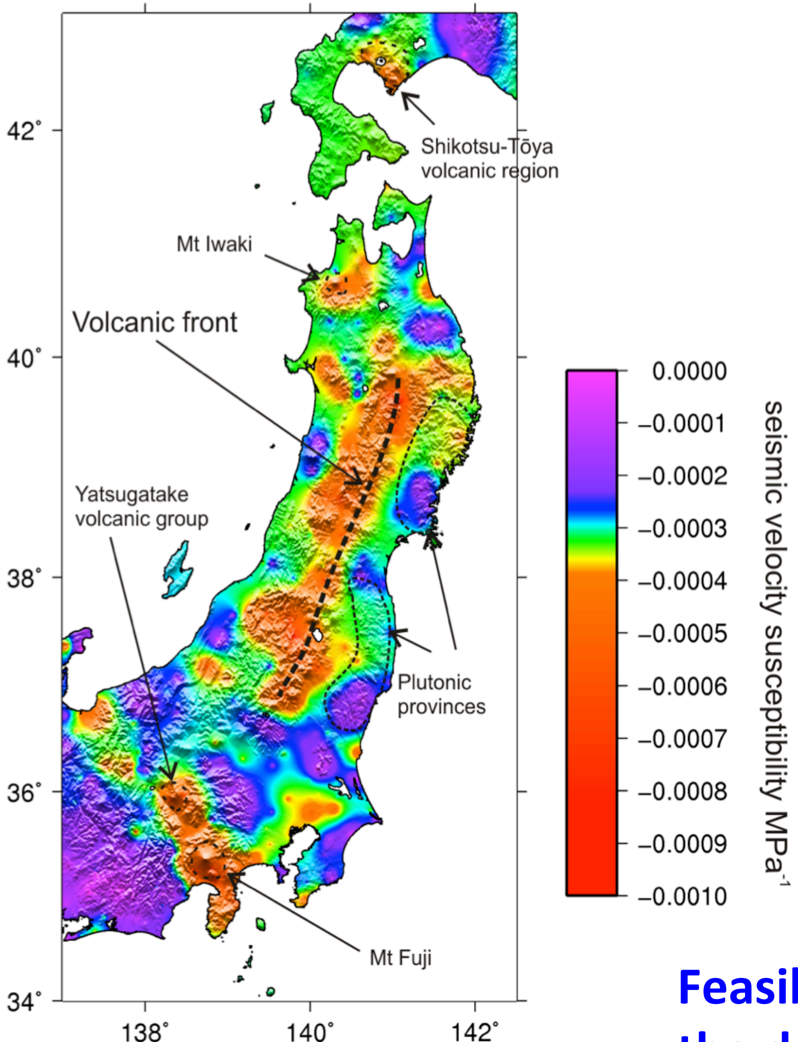
Furumura et al. 2011

Relative velocity change (in %) measured in the band 0.1-0.9 Hz



Calendar time measured in days with respect to March 11 (M9 Tohoku EQ)
(a movie provided by F. Brenguier)

Tomography of seismic susceptibility (velocity change/dynamic stress)



- 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

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

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

Tentative interpretation for dv/v at depth:

-

1) Associated with 'high' deformation rate (SSE)

2) Strong change in middle/deep crust (SSE, Eqs)

3) Post seismic, maximum is delayed, spatially extended (short time scale : 10^{-1} year)(Wenchuan, Tohoku, ..)➔ non elastic deformation at intermediate time scales

4) According to Schubnel et al. 2006, 2011, large sensitivity of seismic speed to deformation rate in cataclastic flow (with an analogous of the transition brittle/ductile)

5) Short time scale viscoelastic response of the layered crust including multiple time scales (e.g. Ivins, 1996, Hedland and Hager 2006)

6) Using external forcing (earthquake, tides,…) to probe properties related to the dynamics of the crust…

Conclusions:

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

Temporal changes occur at various depths, likely associated with various physical mechanisms.

The charm of experimental studies: the new observations are not always coherent with our prejudices.