Listen to the Noise: understanding the message of ambient vibrations

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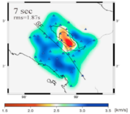
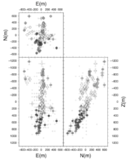
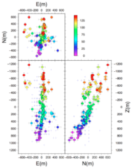
May 20, 2013

Seismological Investigations

	structure	sources
distribution		
dynamics	?	

Seismological Investigations

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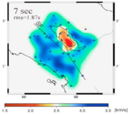
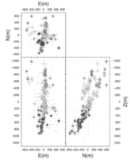
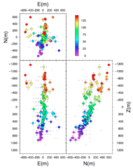
distribution		
dynamics	?	

Why is there so little activity related to dynamics of Earth's material?

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Monitoring of Earth's properties

Earth's material is not stationary!

major difficulties

- Impulsive sources are badly distributed in space and time

  $\Rightarrow$ listen to ambient noise
- temporal variations are very weak
  - well below the spatial variations
  - usually below the error of spatial estimates

  $\Rightarrow$ understand the complete noise correlation, including its coda

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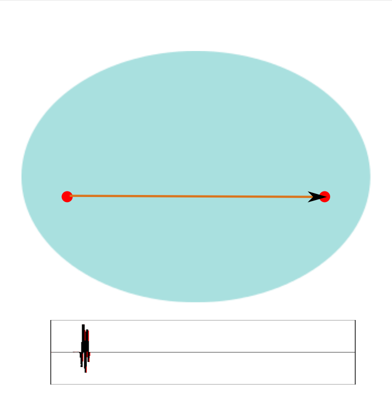
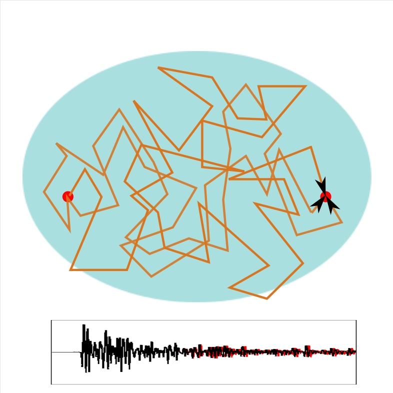
Why to monitor with scattered waves?

weak extended velocity change



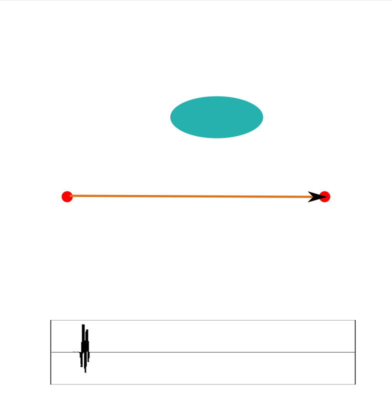


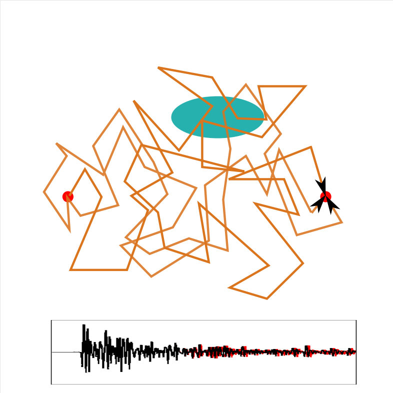
⇒ Increased precision

Monitoring with Scattered Waves

Why to monitor with scattered waves?

localized change



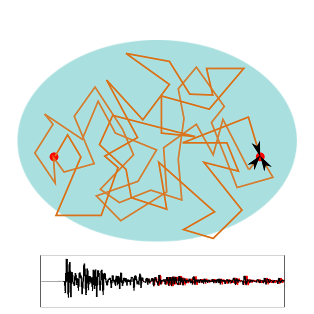


⇒ Broader sensitivity

Monitoring with Scattered Waves

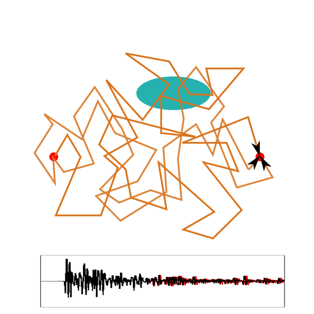
Different observables

weak extended velocity change



⇒ time shift of coda phases (Pacheco and Snieder, 2005)

localized impeadance change

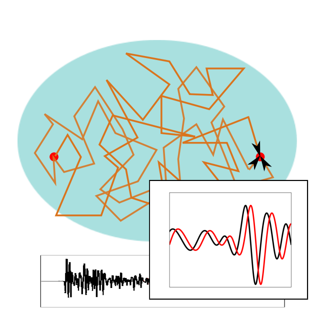


⇒ decorrelation of coda phases (Larose et al., 2010)

Monitoring with Scattered Waves

Different observables

weak extended velocity change



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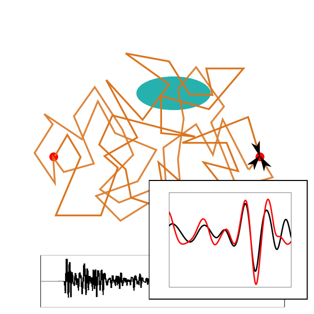
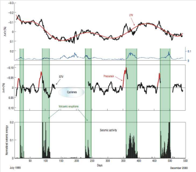


⇒ decorrelation of coda phases
(Larose et al., 2010)

Monitoring with Scattered Waves

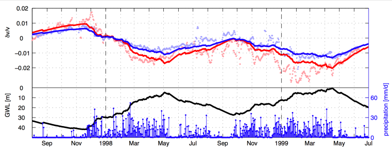
Examples

Piton de la Fournaise



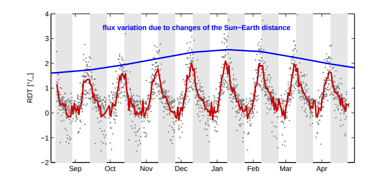
Brenguier et al. (2008)

Merapi volcano



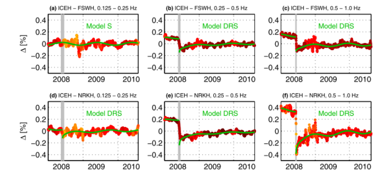
Sens-Schönfelder and Wegler (2006)

Moon



Sens-Schönfelder and Larose (2010)

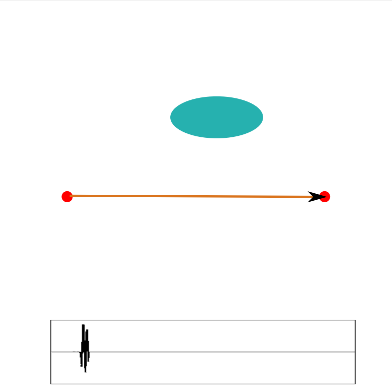
Japan



Hobiger et al. (2012)

Monitoring with Scattered Waves

Consequence for localization of changes — spatial sensitivities



deterministic path

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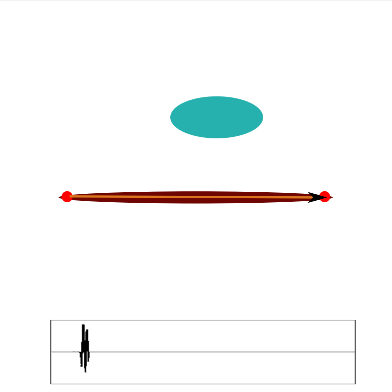

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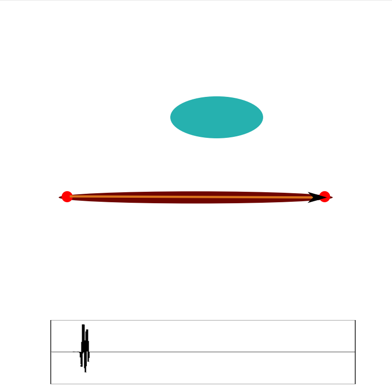

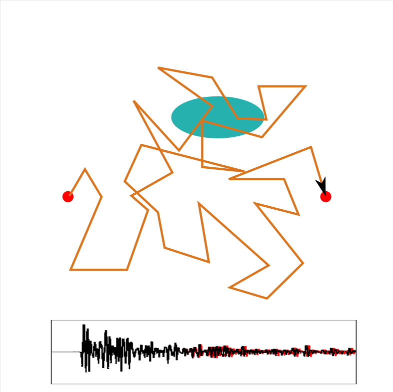

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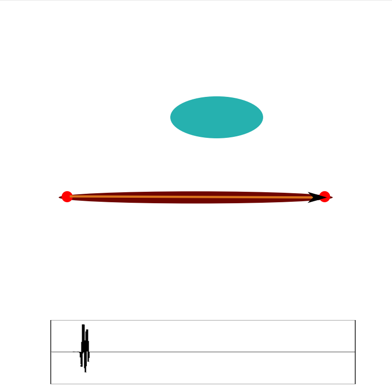

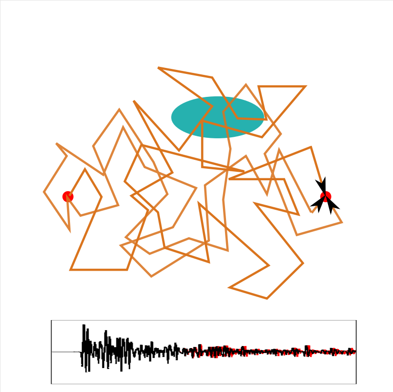

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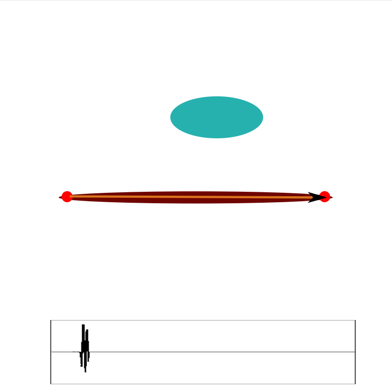

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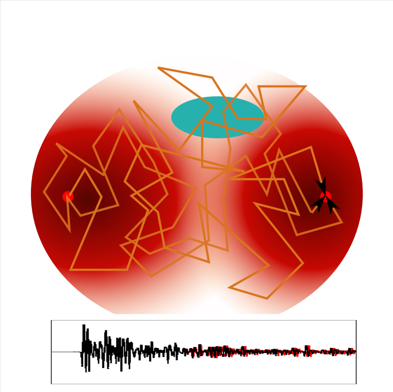
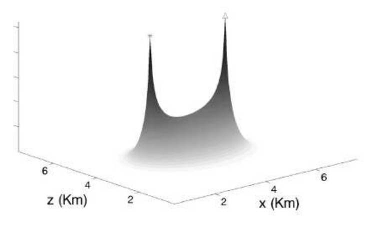


density of paths

Spatial Sensitivities of scattered bulk waves

Acoustic scattering

sensitivity $K_{\mathbf{s},\mathbf{r}}(\mathbf{x},t)$: probability of a random walker starting at $(\mathbf{s}, t'=0)$ and arriving at $(\mathbf{r}, t'=t)$ to encounter $\mathbf{x}$ on the way.



$$K_{\mathbf{s},\mathbf{r}}(\mathbf{x},t) = \frac{\int_0^t g(\mathbf{s},\mathbf{x},t-t')g(\mathbf{x},\mathbf{r},t')dt'}{g(\mathbf{s},\mathbf{r},t)}$$

$g(\mathbf{a},\mathbf{b},t)$: probability of a random walker starting at $\mathbf{a}$ to be at $\mathbf{b}$ at time t

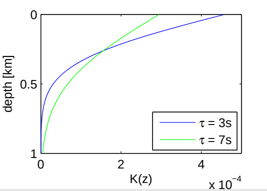
Pacheco and Snieder (2005); Larose et al. (2010)

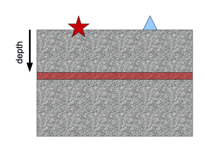
$\Rightarrow$ details depend on g but always strong peaks at stations

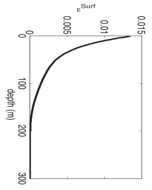
Sensitivity in the presence of the free surface

Depth distribution of sensitivity

bulk waves ⟺ surface waves







Sens-Schönfelder and Wegler (2006)

Obermann et al. (2012)

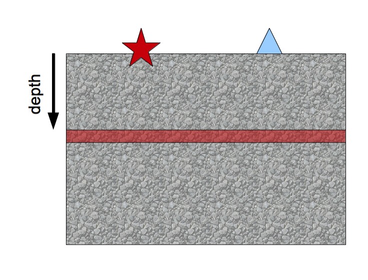
- depends on lapse time
- depends on scattering

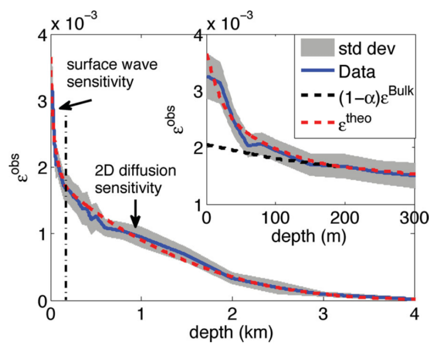
- no dependence on lapse time
- frequency dependent

Sensitivity in the presence of the free surface

Combined effect of surface and bulk waves

coda waves in numerical simulations (Obermann et al., 2012)





- transition from surface to bulk wave sensitivity with increasing lapse time

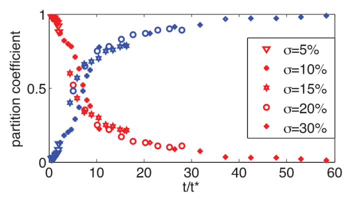
⇒ allows to infer the depth of the perturbation

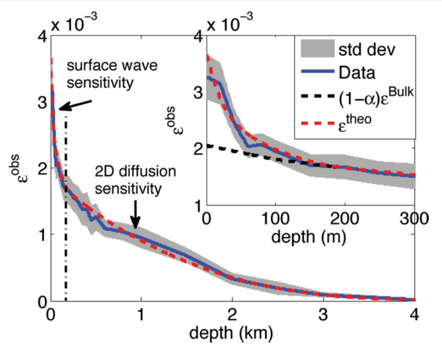
Sensitivity in the presence of the free surface

Combined effect of surface and bulk waves

coda waves in numerical simulations (Obermann et al., 2012)

surface - body waves





- transition from surface to bulk wave sensitivity with increasing lapse time

⇒ allows to infer the depth of the perturbation

Contents

Piton de la Fournaise

La Reunion Island

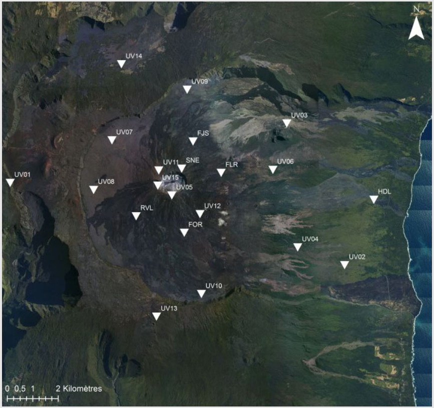
Piton de la Fournaise

Data

UNDERVOLC
(UNDERstanding VOLCanic processes, an international project led by IPGP)
15 stations

Observatoire Volcanologique du Piton de la Fournaise
6 stations

21 broadband stations

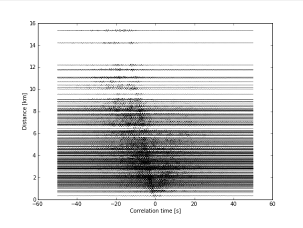


Courtesy Florent Brenguier

Data Processing

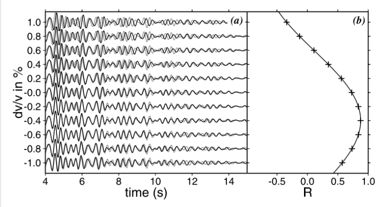
Noise correlation

- 1 hour pieces, spectral whitening, 1-bit, 24 hour stacking
- three diagonal components of the GT



Monitoring

- estimation of velocity change
- averaging of different GT results
- three days running average



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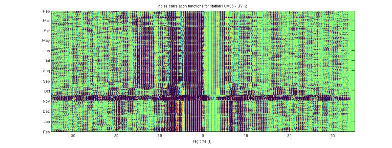

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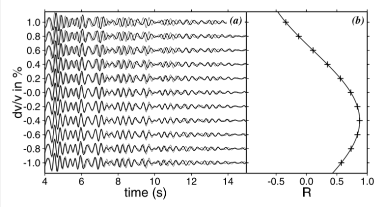

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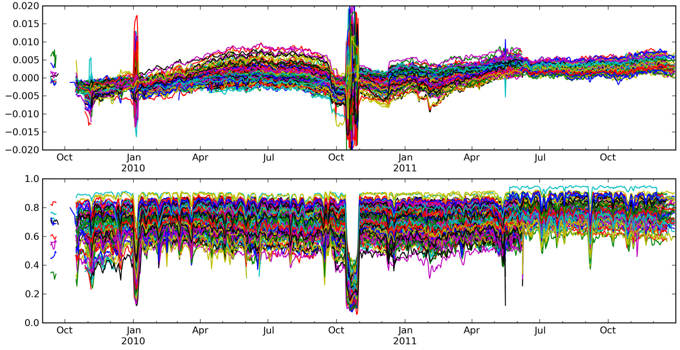
Temporal variations

Pairwise changes



common long term variation + complex short term changes

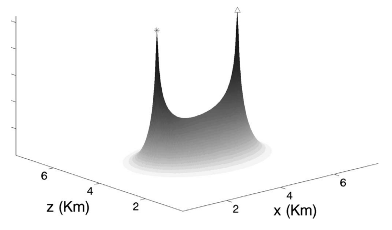
Temporal variations

Sensitivity kernel

⇒ approximate the kernel with $\delta(\mathbf{x}-\mathbf{x_s})+\delta(\mathbf{x}-\mathbf{x_r})$

⇒ $\Delta v_p(a,b)=\Delta v_s(a)+\Delta v_s(b)$

$$\mathbf{\Delta v}_p=\mathbf{G}\mathbf{\Delta v}_s$$

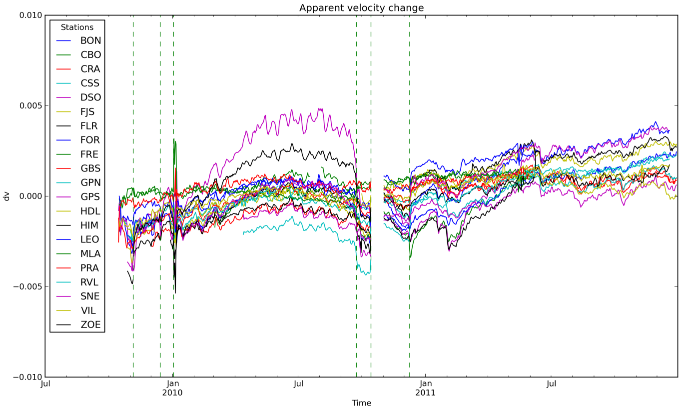


Pacheco and Snieder (2005)

$\mathbf{\Delta v}_p$: observed pairwise velocity changes
$\mathbf{\Delta v}_s$: modeled velocity changes at the stations
$\mathbf{G}$: Sensitivity matrix containing 0 and 1 (Hobiger et al., 2012)

Temporal variations

Variations at stations



Temporal variations

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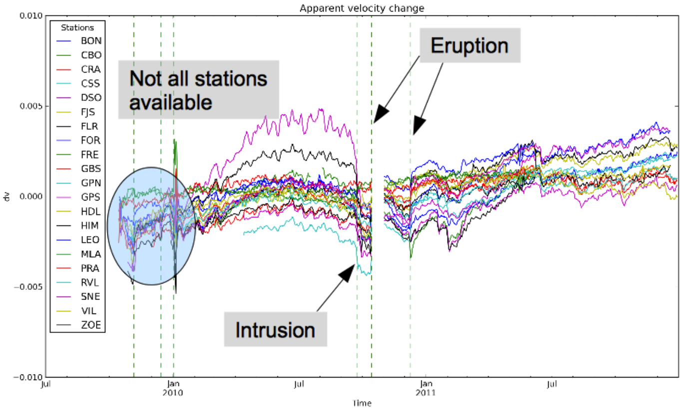
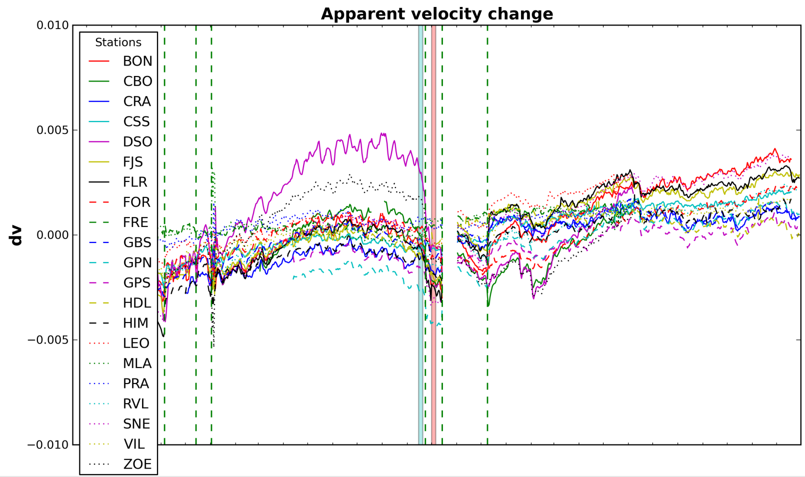


Location of changes

Dike intrusion November 23, 2010



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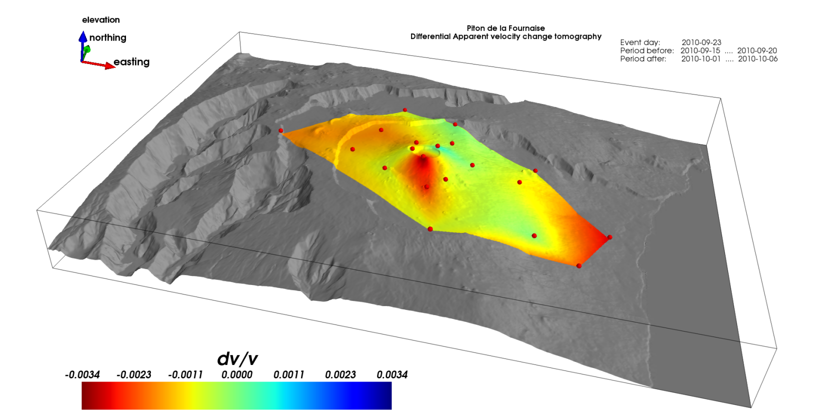
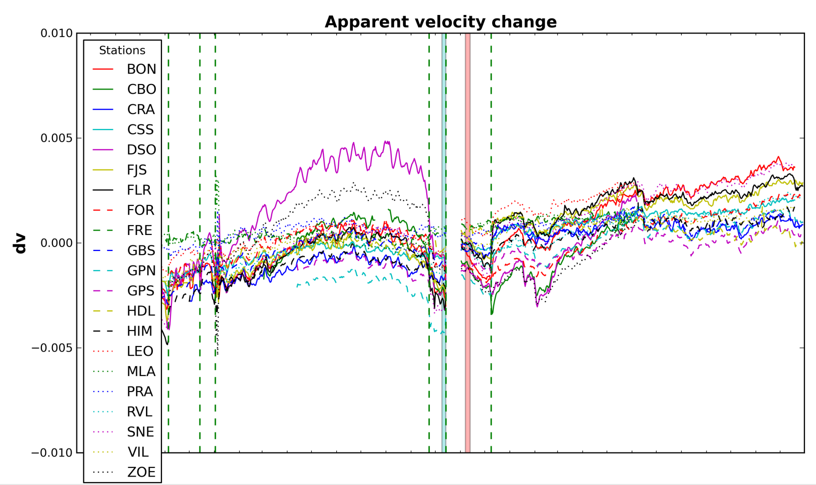


Location of changes

Eruption October 14, 2010



Location of changes

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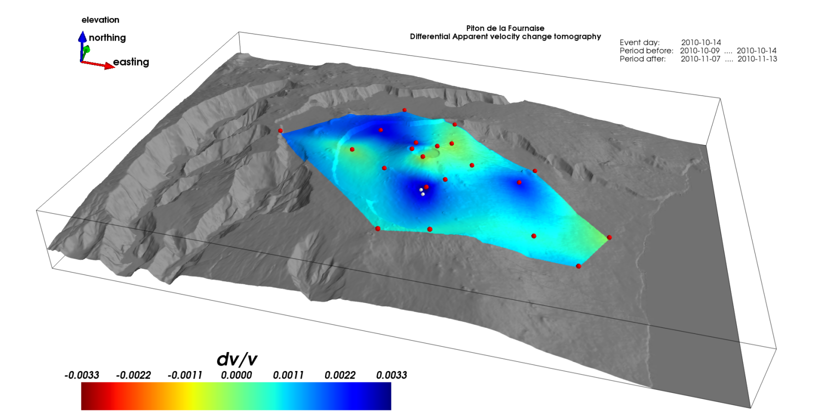
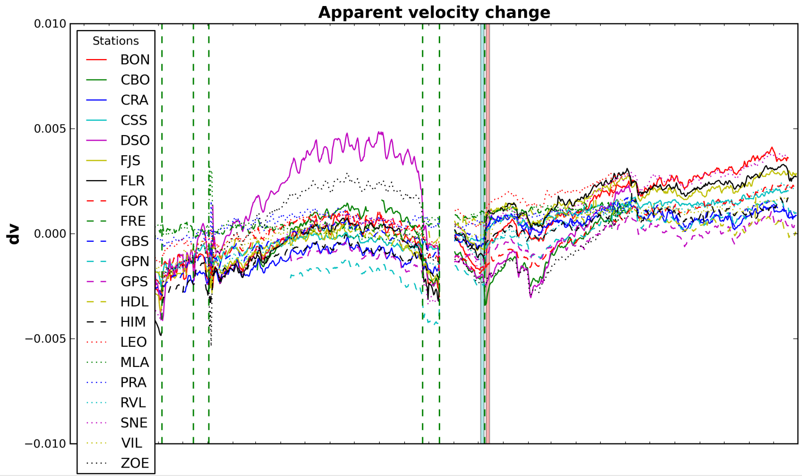


Location of changes

Eruption December 9, 2010



Location of changes

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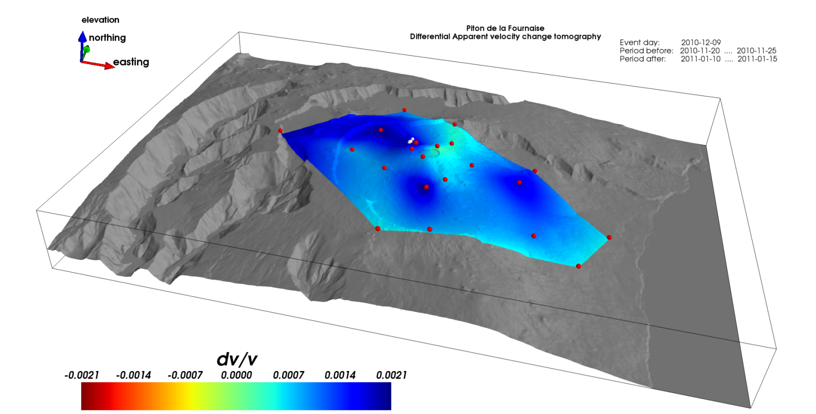
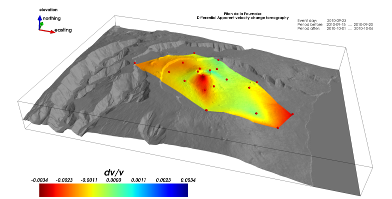
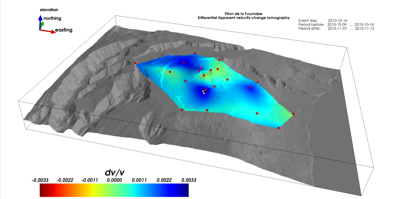


Location of changes

Interpretation





- Locations of max. changes are different and correspond to surface deformation
- Polarities of changes for the intrusion (inflation) and eruptions (deflation) are different

$\Rightarrow$ velocity changes reflect strain in the subsurface caused by magma movement

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Contents

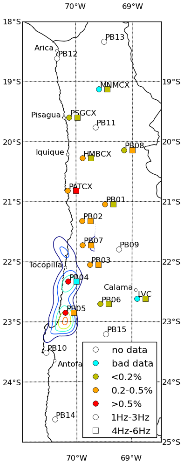
Coseismic variations in northern Chile

Tocopilla event

- Mw = 7.7, November 14 2007
- Network of the Integrated Plate boundary Observatory Chile (IPOC)
- Variations obtained with auto-correlations

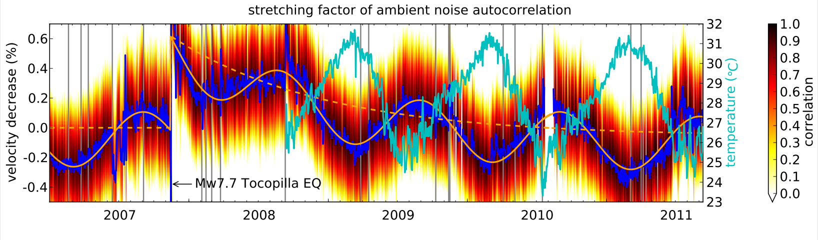
⇒ stronges velocity decrease in the fault area (0.5%)

⇒ exceptionally strong changes at Patache



Long term variations at Patache

Superimposed effects



- coseismic drop and long term recovery after Tocopilla event
- short term excursions after various local events
- seasonal variation caused most likely by thermal stresses
- seasonal change shallower than coseismic effect

⇒ exceptional sensitivity to shaking and strain related to geology (salar)

Summary

- spatial sensitivities of coda waves are different from ballistic waves
- can be described in a probabilistic sense (different approximations)
- even simple approximations can capture a significant part of the spatial variability

$\Rightarrow$ improves monitoring capabilities

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