Non fully diffuse wavefields and the noise cross-correlations in seismology

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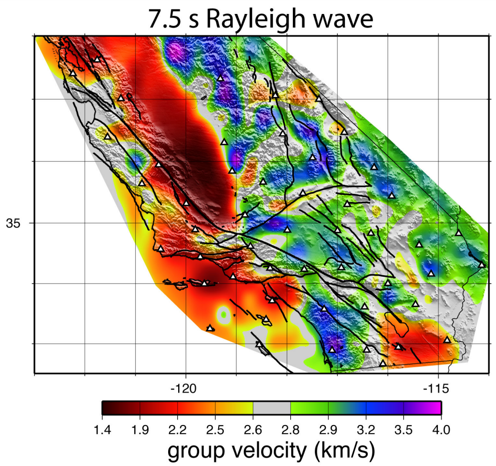
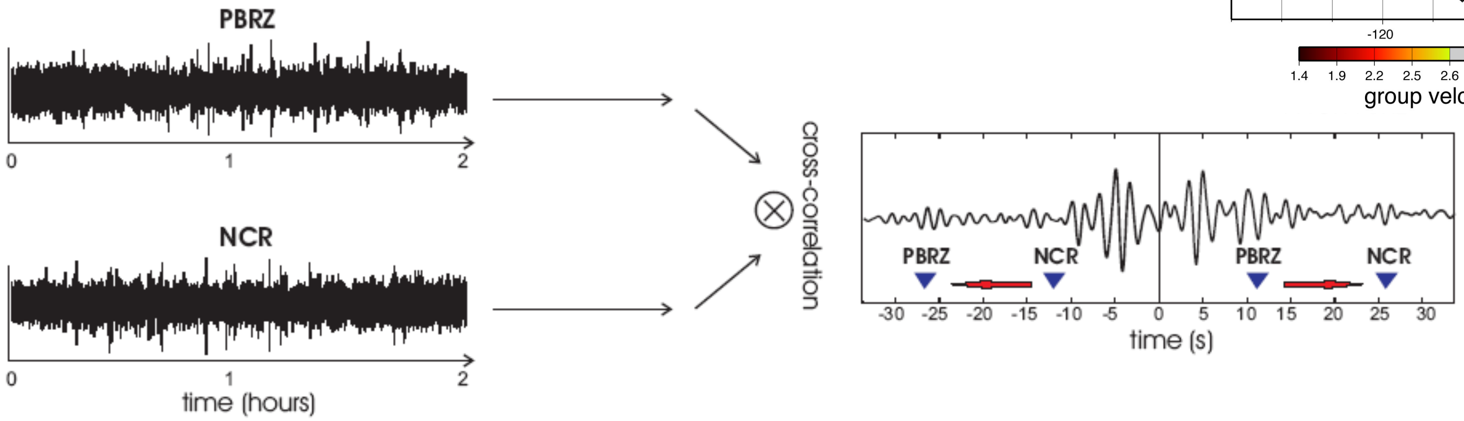
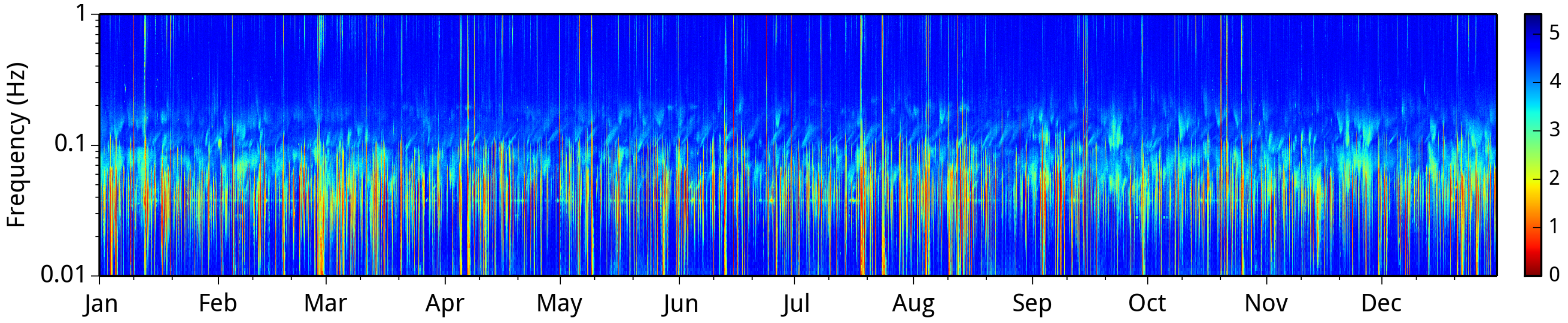
with contributions from: Léonard Seydoux, Lise Retailleau,
Julien de Rosny, Kairly Jaxybulatov, Aurelien Mordret,
Dmitry Droznin, Florent Brenguier, Michel Campillo, …





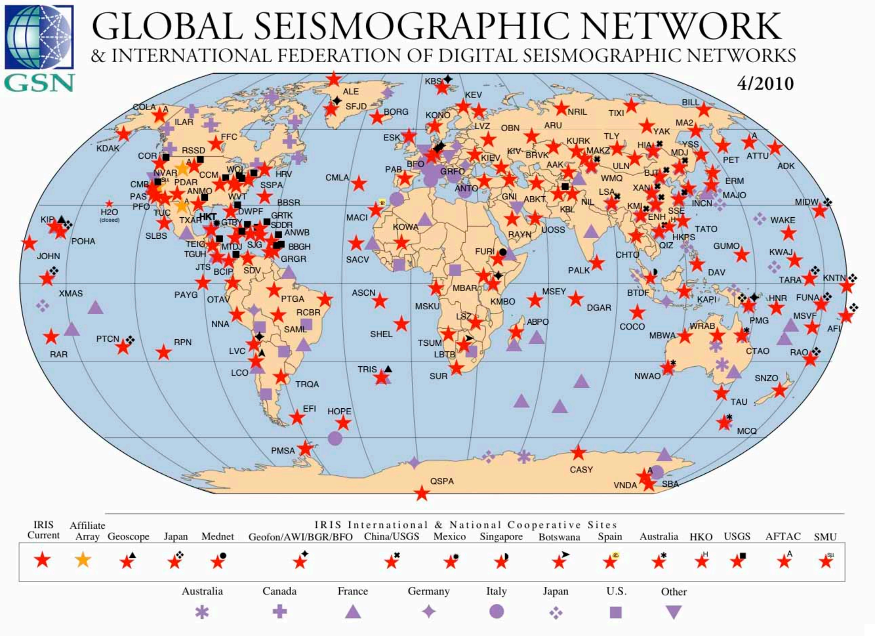


Outline

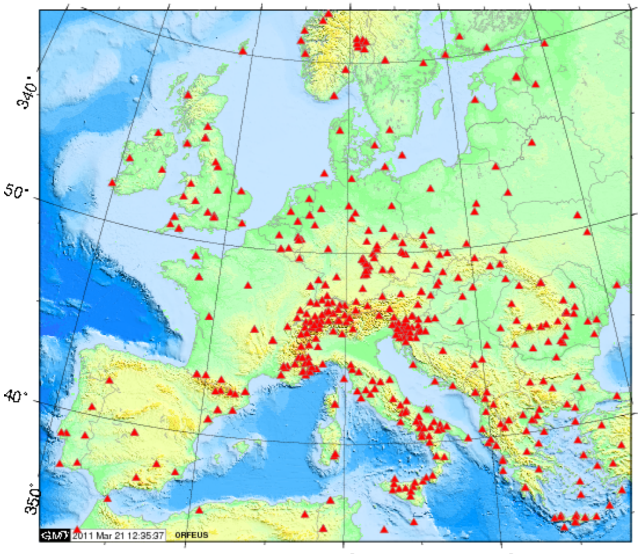
- Brief overview of passive seismic imaging
- “Noise correlation theorem” and the seismic imaging
- Signal pre-processing to correct for inhomogeneity of the wavefield
- Using seismic arrays to characterize the wavefield spatial coherence
- A large-scale example: seismic wavefield seen by USArray

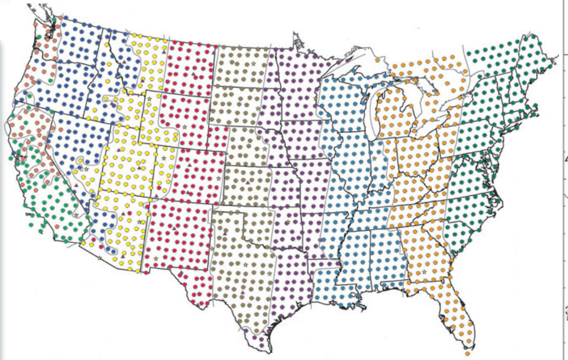
Seismological observations

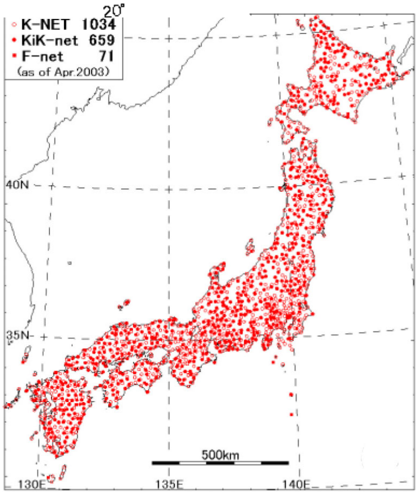
records of ground motion (displacement, velocity, or accelerations) by seismographs



dense regional networks







- **Thousands of permanent seismometers are operating continuously**

- **Some temporary networks regroup tens and hundreds of thousands of instruments**

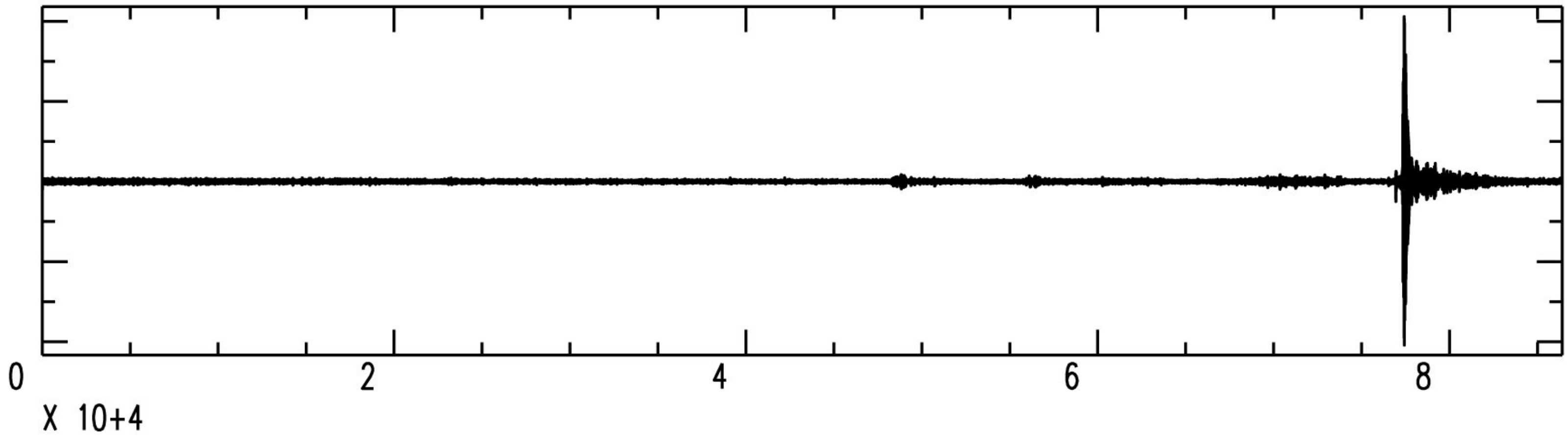
- **Installed on or close to the Earth's surface**

- **Recorded frequencies: 0.001 – 100 Hz**

Seismological observations

records of ground motion (displacement, velocity, or accelerations) by seismographs

one day of seismic record



Seismological observations

records of ground motion (displacement, velocity, or accelerations) by seismographs

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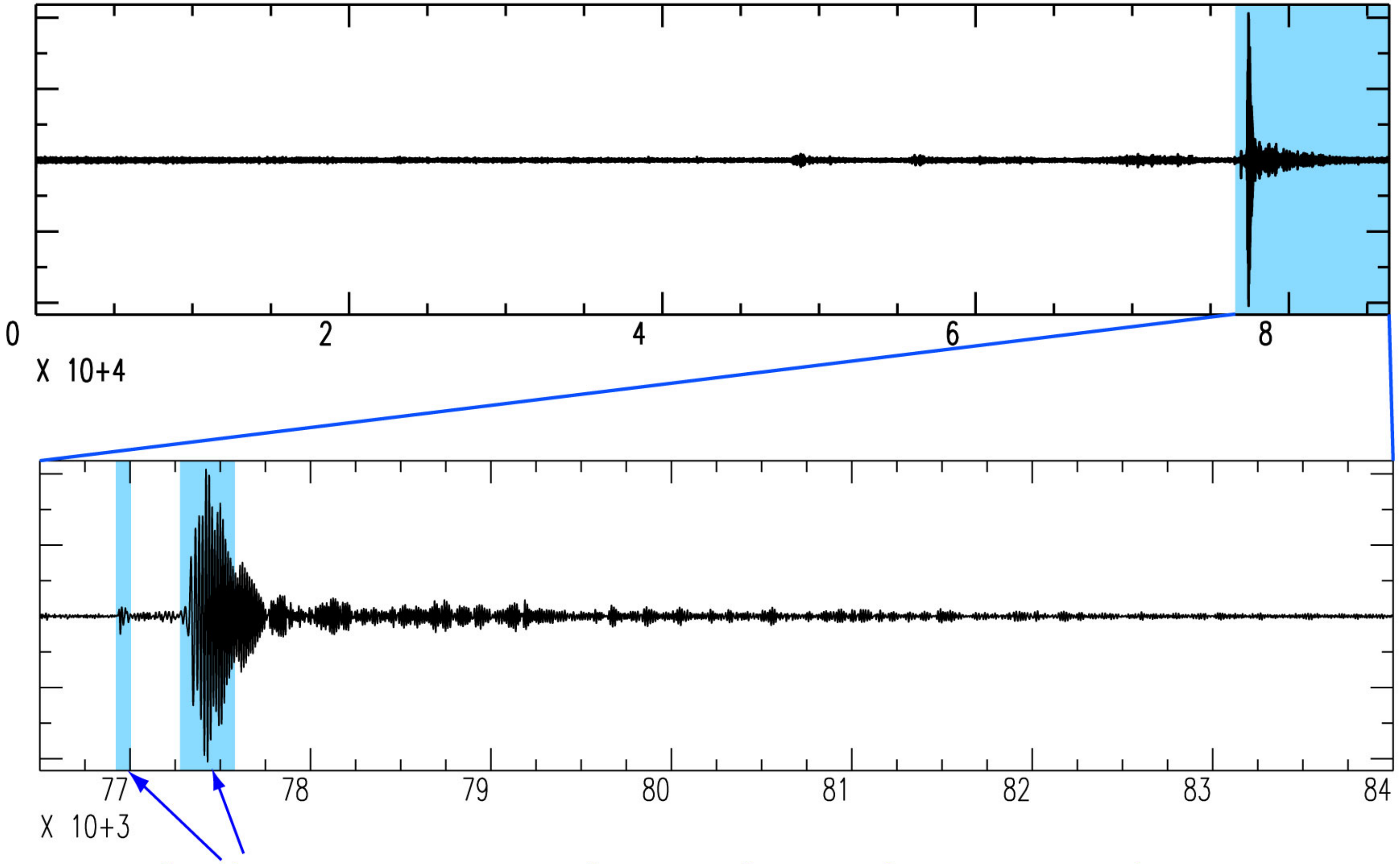
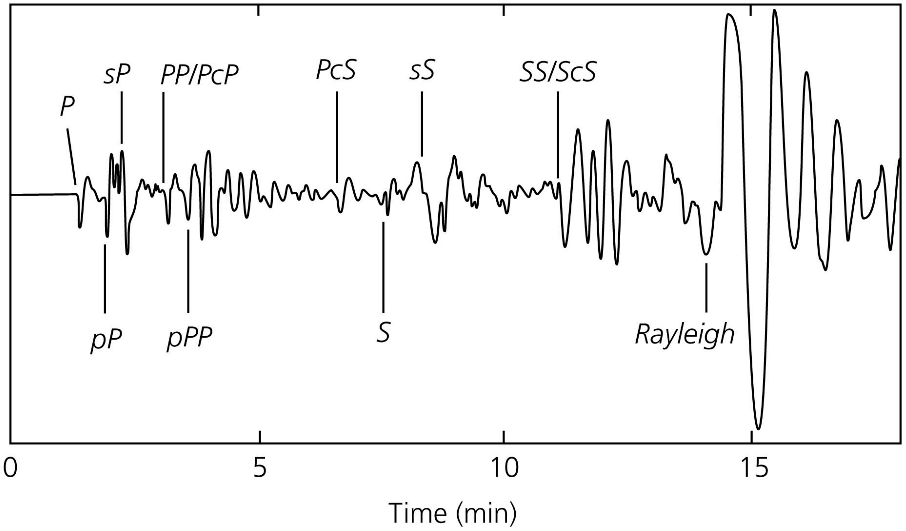
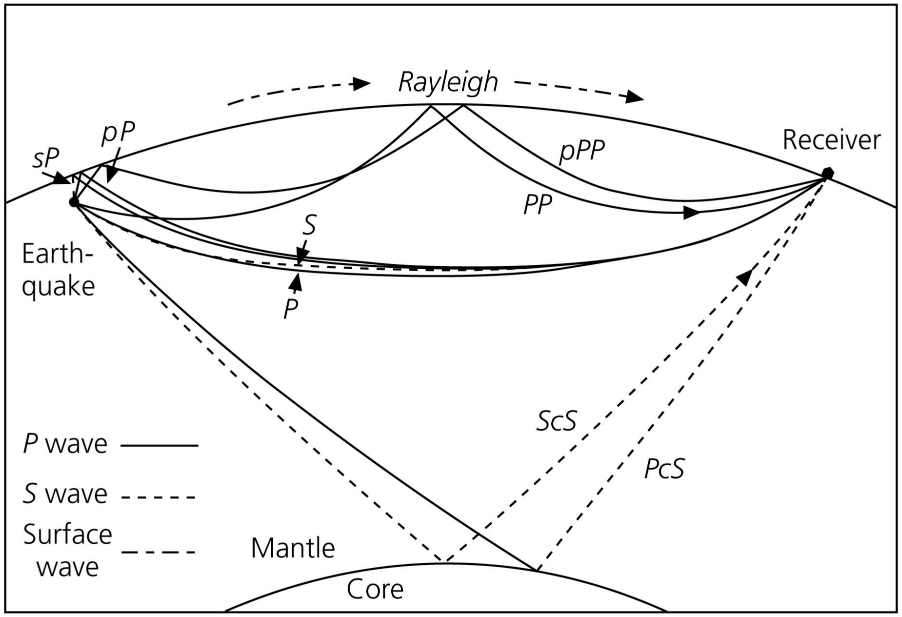


ballistic waves used in traditional tomography

Seismic waves emitted by an earthquake





Body waves

sample deep parts of the Earth

P and S

multiplicity of phases because of internal reflections

Surface waves

sample the crust and upper mantle

Rayleigh and Love

Traditional passive seismic imaging uses earthquakes

Strong signals

Sources localized in space and time

Many methods developed since 2-nd half of the 20th century

Inversion of:

- **travel times**
- **amplitudes**
- **full waveforms**

For:

- **Vp**
- **Vs**
- **Q (attenuation)**
- **ρ**
- **anisotropy**

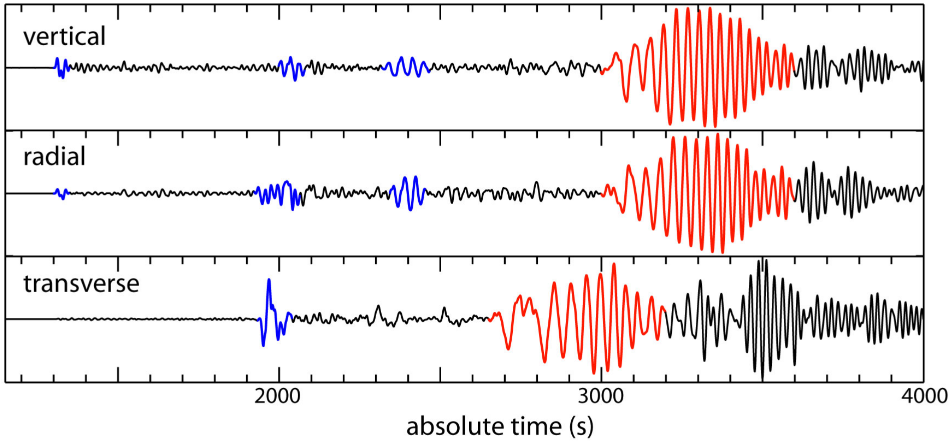
Body-wave tomography

Surface-wave tomography

…

Seismological Inverse problem

earthquake record



$$\mathbf{D} = \mathbf{S} \otimes \mathbf{M}$$

D - seismic data
S - seismic source
M - media (Earth)

imaging, monitoring

we need to know **S** to find **M**

earthquakes

S - location, focal mechanism, time function

Shortcomings of the earthquakes-based methods

- earthquakes do not occur everywhere: limited resolution of resulted images
- earthquakes do not occur continuously: no continuous monitoring possible
- earthquakes rarely occur at the same place: difficult to make repeatable measurements

Preliminary Determination of Epicenters
358,214 Events, 1963 - 1998

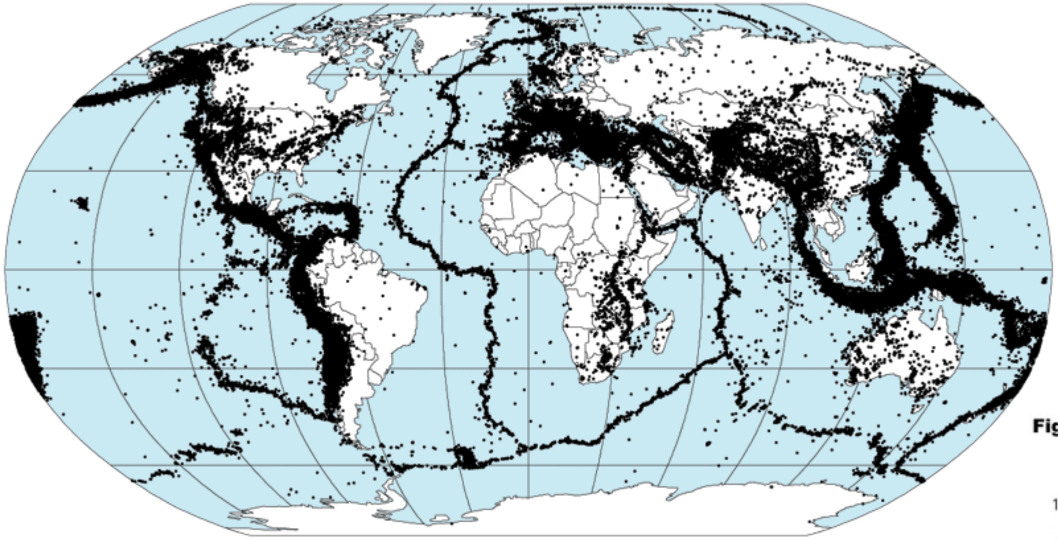
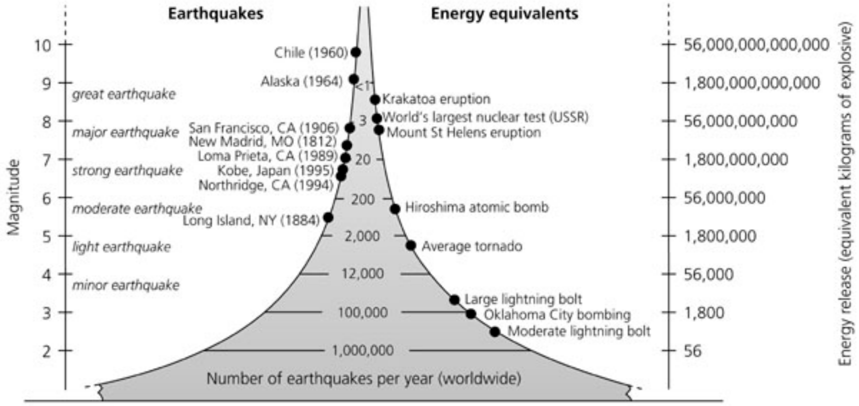


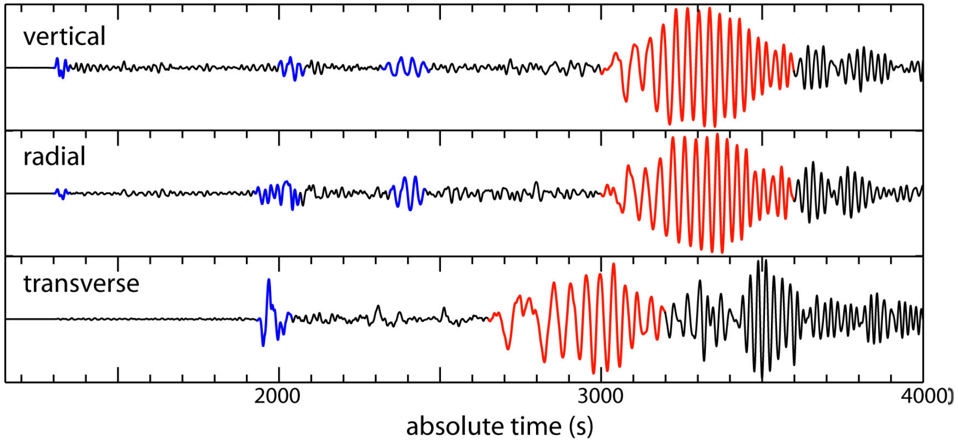
Figure 1.2-2: Comparison of frequency, magnitude, and energy release.



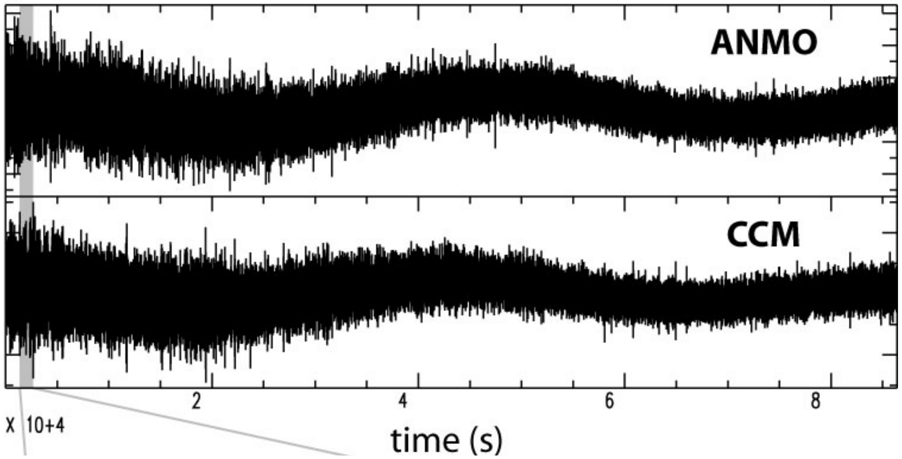
Seismological Inverse problem

Advantage of seismic noise:
Can be recorded anywhere and at any time

earthquake record



noise



$$D = S \otimes M$$

D - seismic data
S - seismic source
M - media (Earth)

imaging, monitoring

we need to know **S** to find **M**

earthquakes

- **S** - location, focal mechanism, time function

background noise

- **S** - complex function

Noise Correlation Theorem

For a **random** wavefield with sources distributed **homogeneously** everywhere in the medium it can been shown that:

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

noise cross-correlation **Green function**

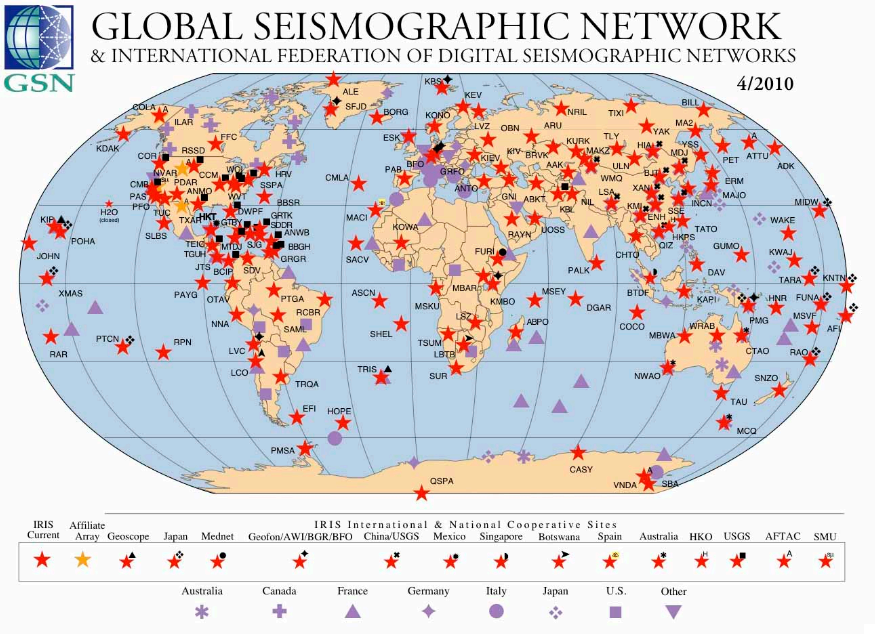
Computing noise cross-correlations between A and B is equivalent to an event occurred at A and recorded at B

$$\mathbf{D} = \mathbf{S} \otimes \mathbf{M} \Longrightarrow \mathbf{C(D)} \approx \mathbf{M}$$

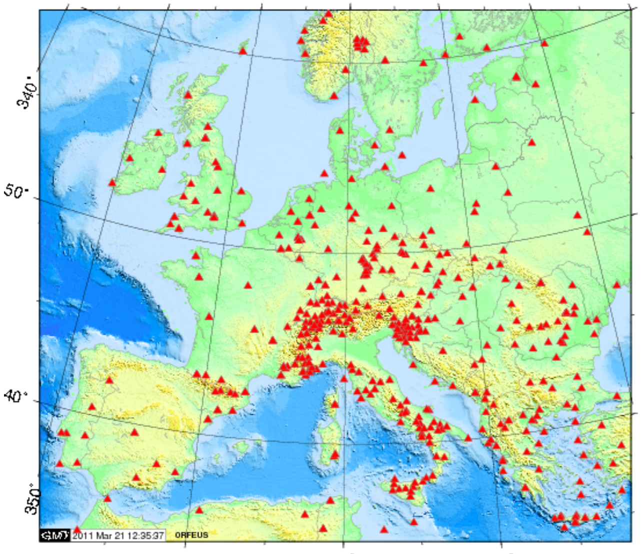
D - seismic data
S - seismic source
M - media (Earth)

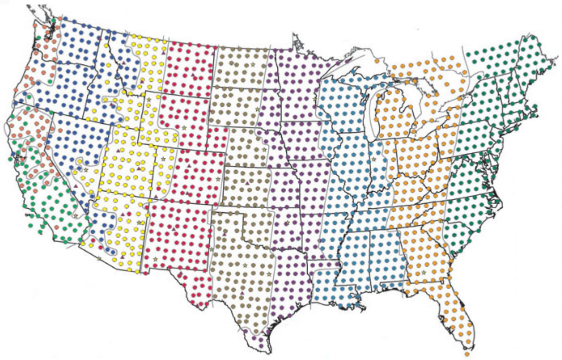
correlation eliminates source complexity

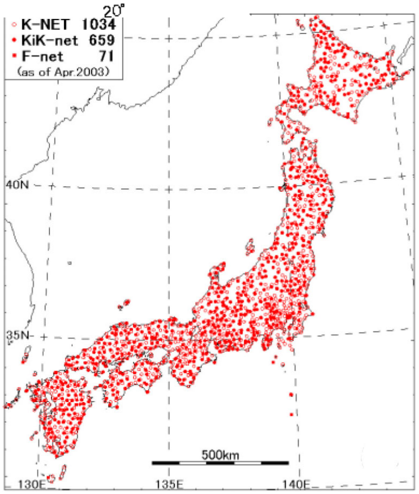
Application of the ‘noise correlation theorem’ to seismological data



dense regional networks





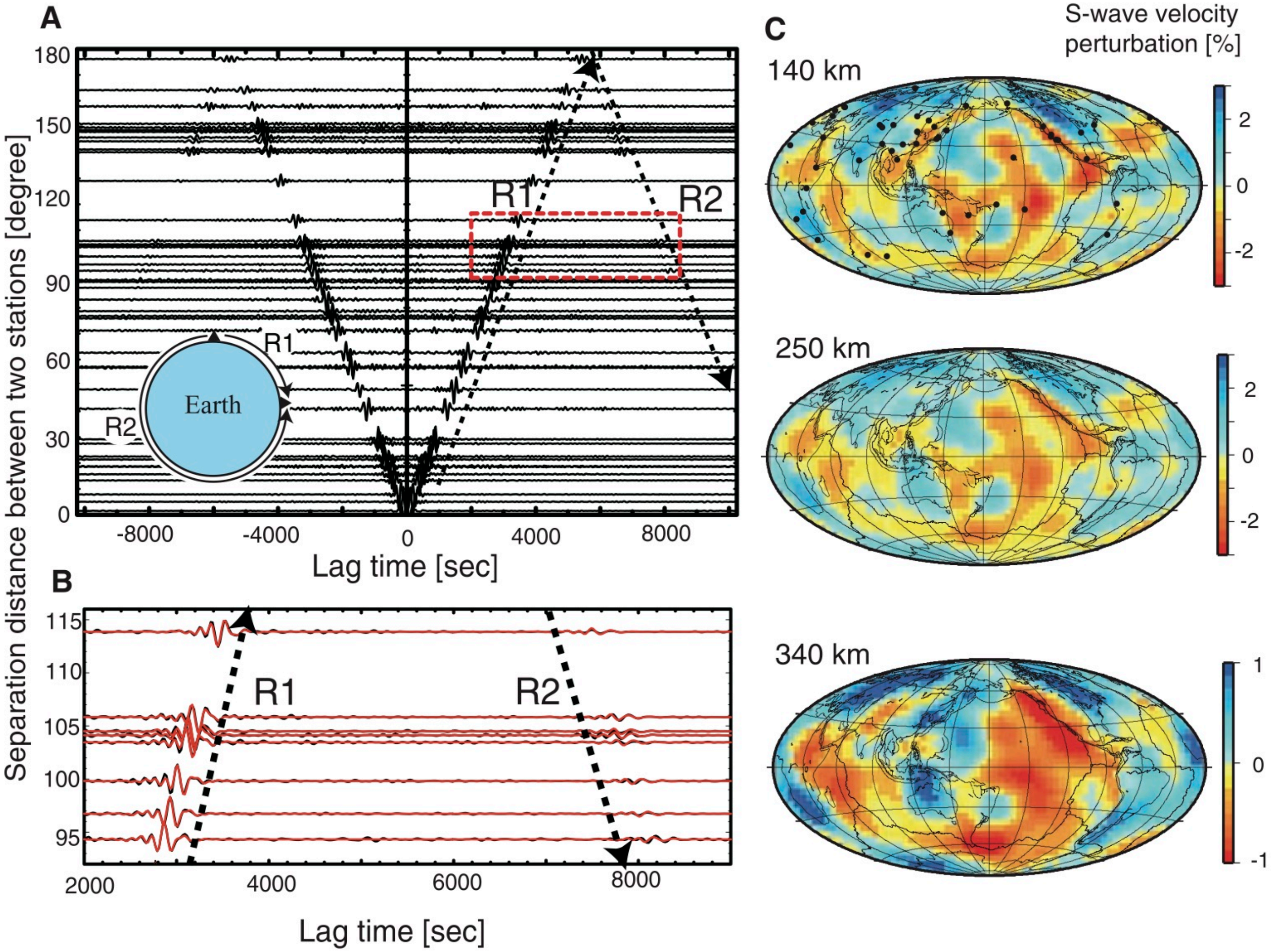


Every receiver acts as a virtual source recorded by all other receivers

N(N-1)/2 virtual seismograms

Imaging methods developed for earthquake-generated signals can be applied to virtual seismograms

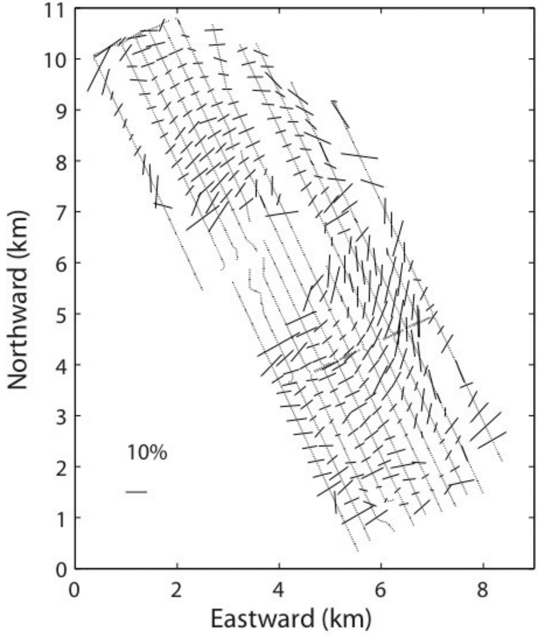
Global noise-based surface wave tomography

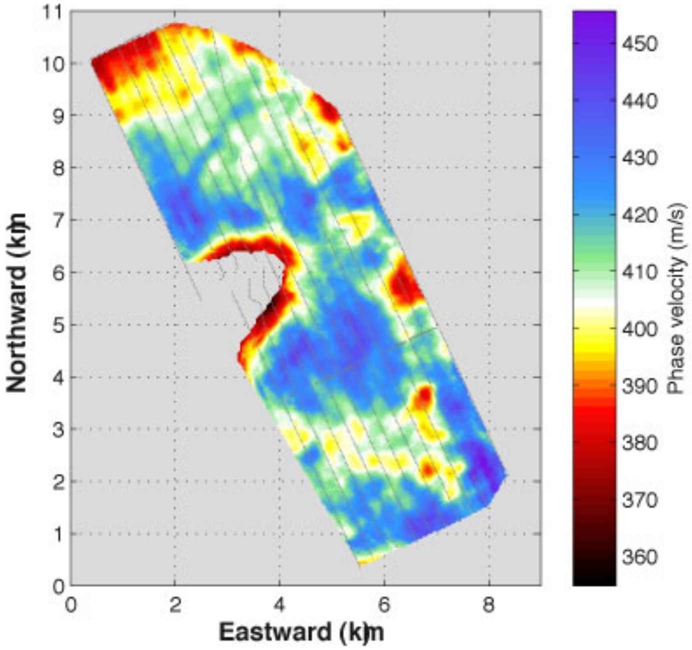


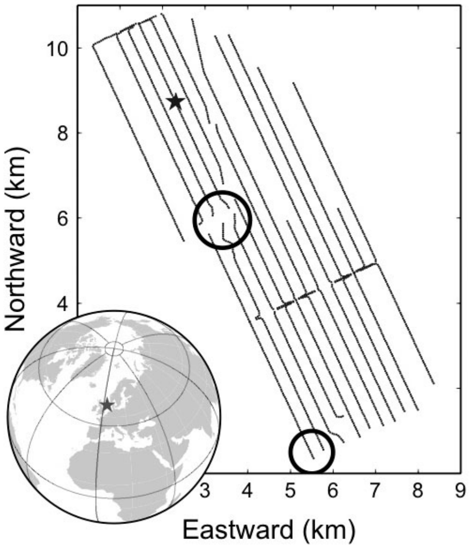
Nishida et al., 2009

Noise-based surface wave tomography of the subsurface above an oil reservoir

Seismic anisotropy



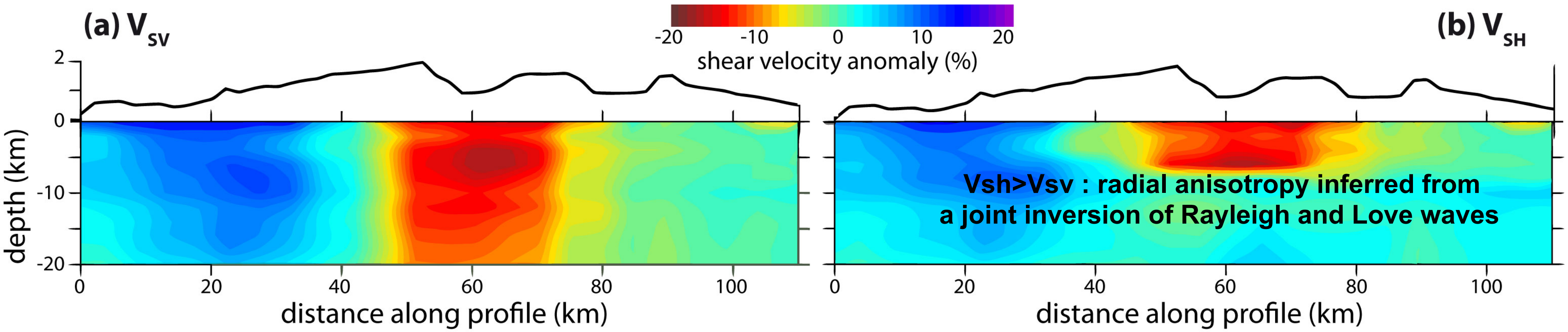




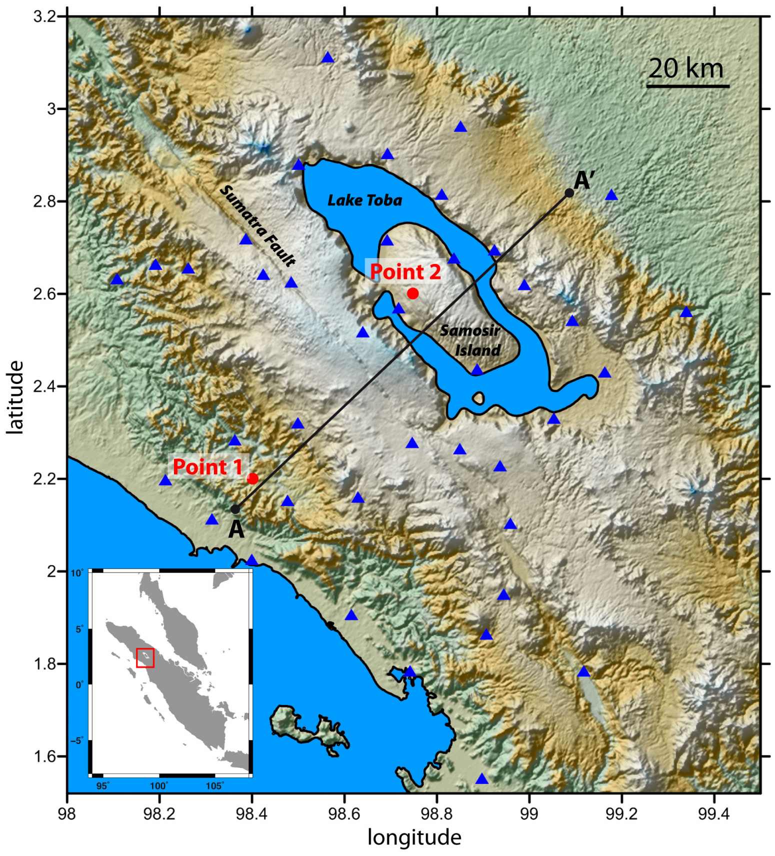
Valhall
Network
2400 receivers

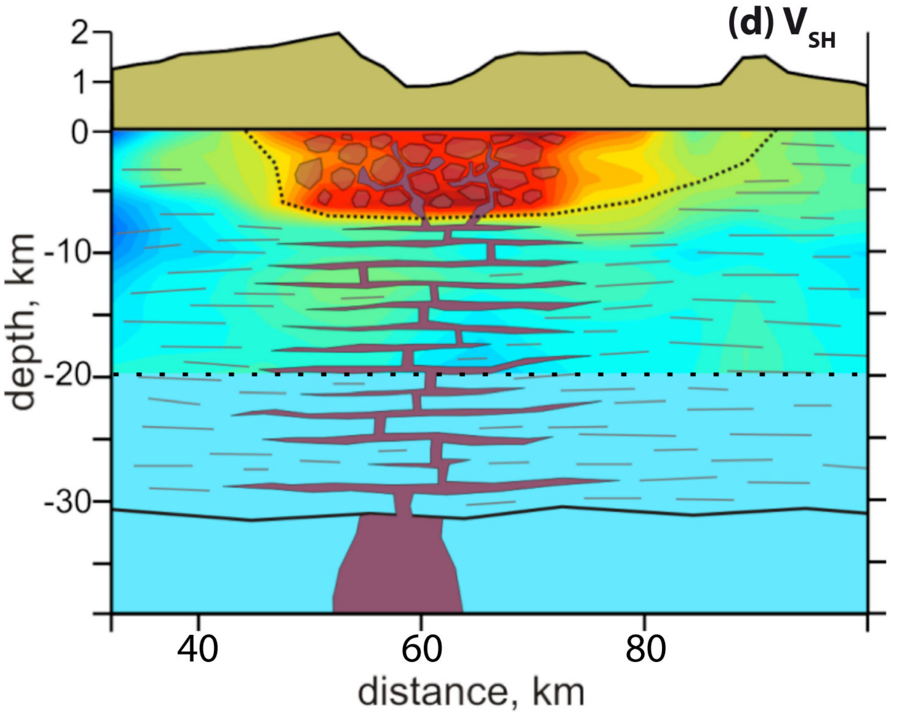
Mordret et al., 2013

Noise based anisotropic tomography of the Toba Volcano in Indonesia



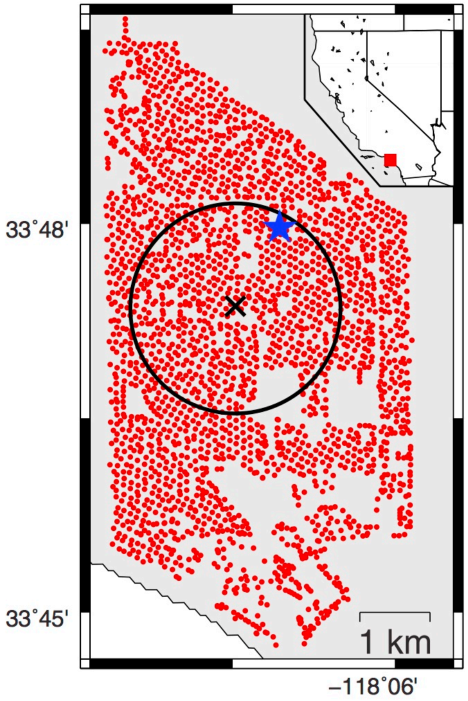
Vsh>Vsv : radial anisotropy inferred from a joint inversion of Rayleigh and Love waves

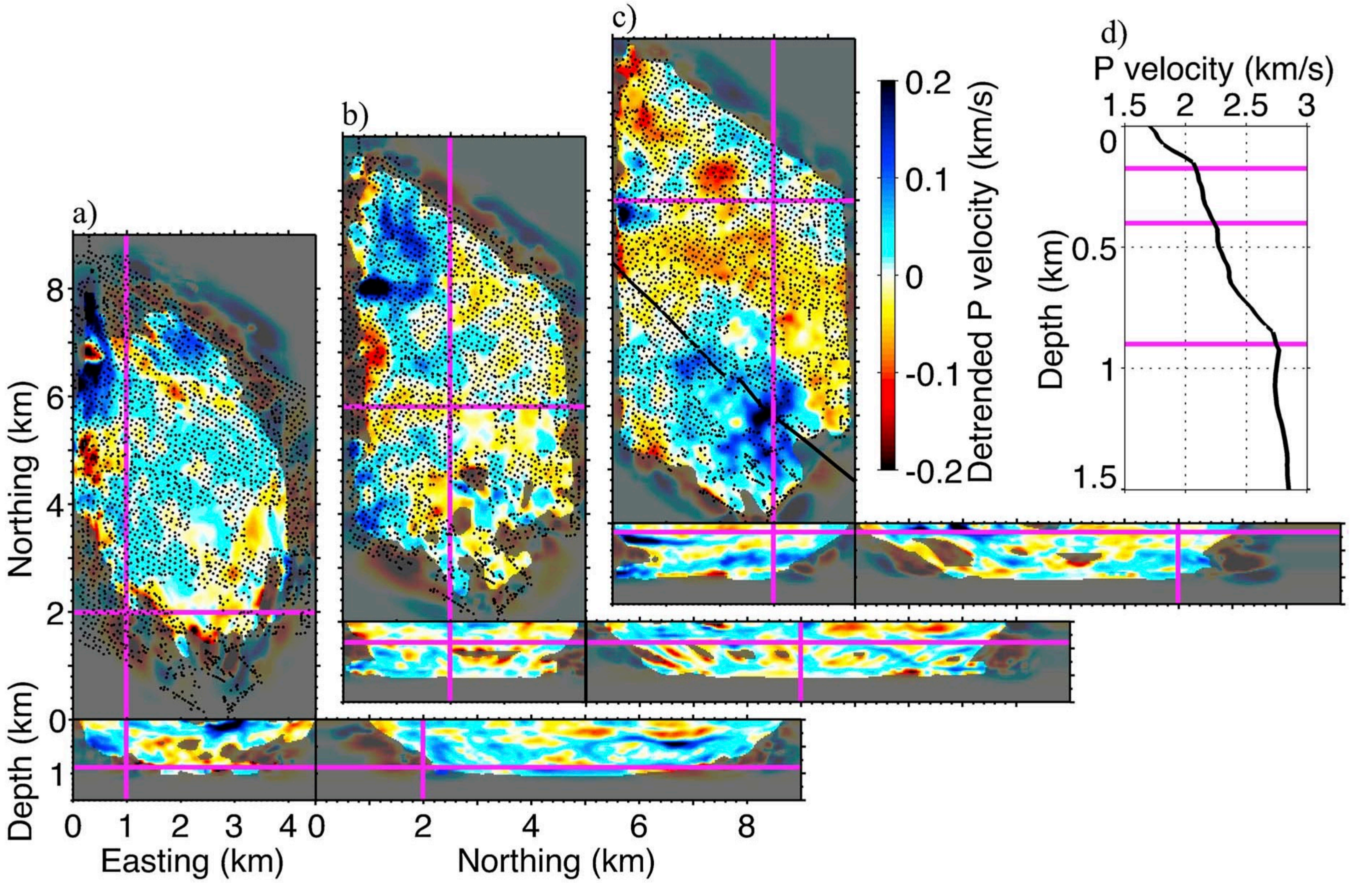




Jaxybulatov et al., 2014

Noise based P-wave tomography at Long Beach, California



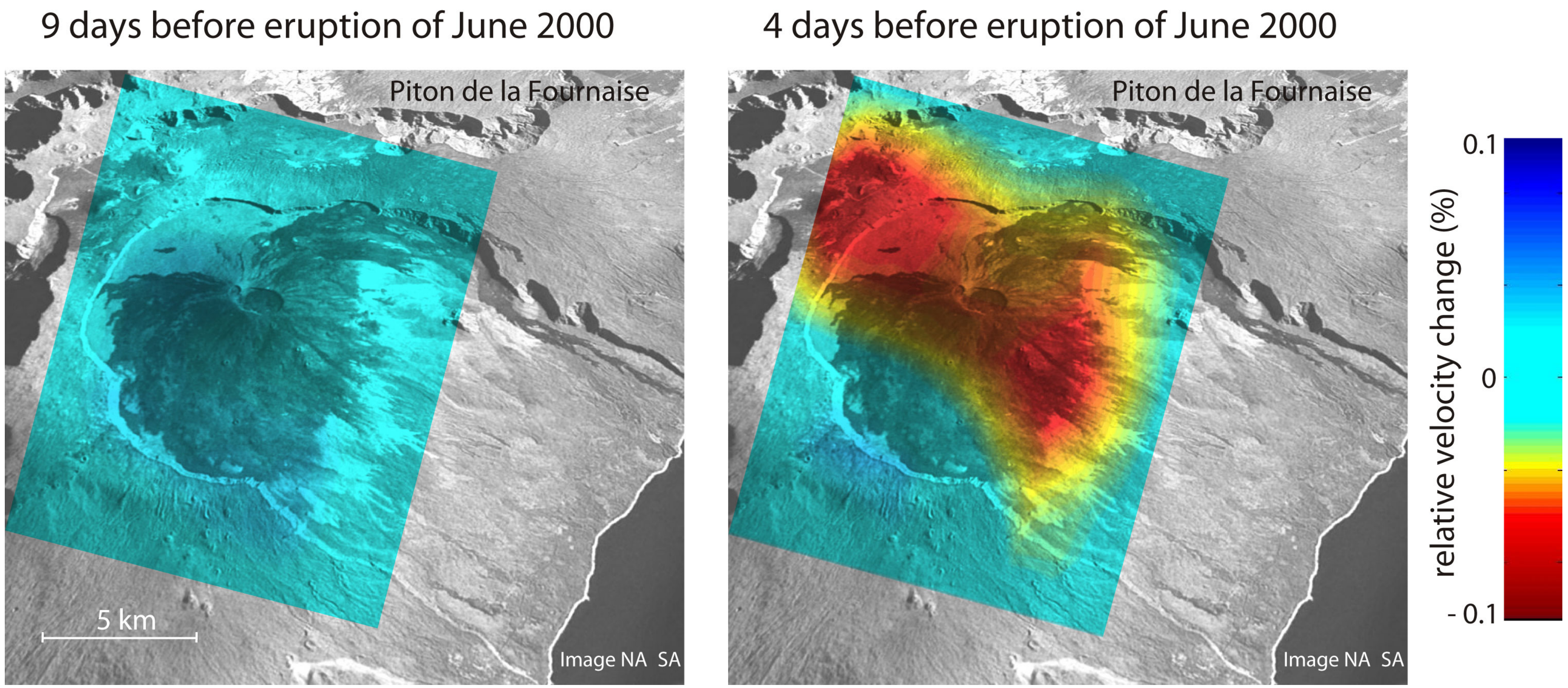


Nakata et al., 2015

Noise-based monitoring

- When media changes its Green functions change
- Green functions can be reconstructed from noise cross-correlations
- Noise cross-correlations can be computed in a nearly-continuous way providing a mean for a monitoring of the Earth’s interior

Monitoring Piton de la Fournaise volcano (La Reunion Island)



Detected velocity variations are localized in the vicinity of the main crater: consistent with a shallow source of deformation

Brenguier et al., 2008

Application of the ‘noise correlation theorem’ to seismological data

- Synthesis of virtual seismograms: ~N^2 – where N is number of used receivers

- Previously developed imaging methods applied to virtual seismograms

- Proliferation of applications at different scales since 2005

- Noise-based surface wave tomography become a ‘standard’ and very broadly used method

- Attenuation tomography

- First demonstrations of the feasibility of the noise-based body wave imaging

- Noise-based monitoring of volcanic and seismogenic areas and of industrial objects

- Empirical prediction of the ground motion from possible future earthquakes for the seismic hazard evaluation

Noise Correlation Theorem

For a **random** wavefield with sources distributed **homogeneously** everywhere in the medium it can been shown that:

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noise cross-correlation

Green function

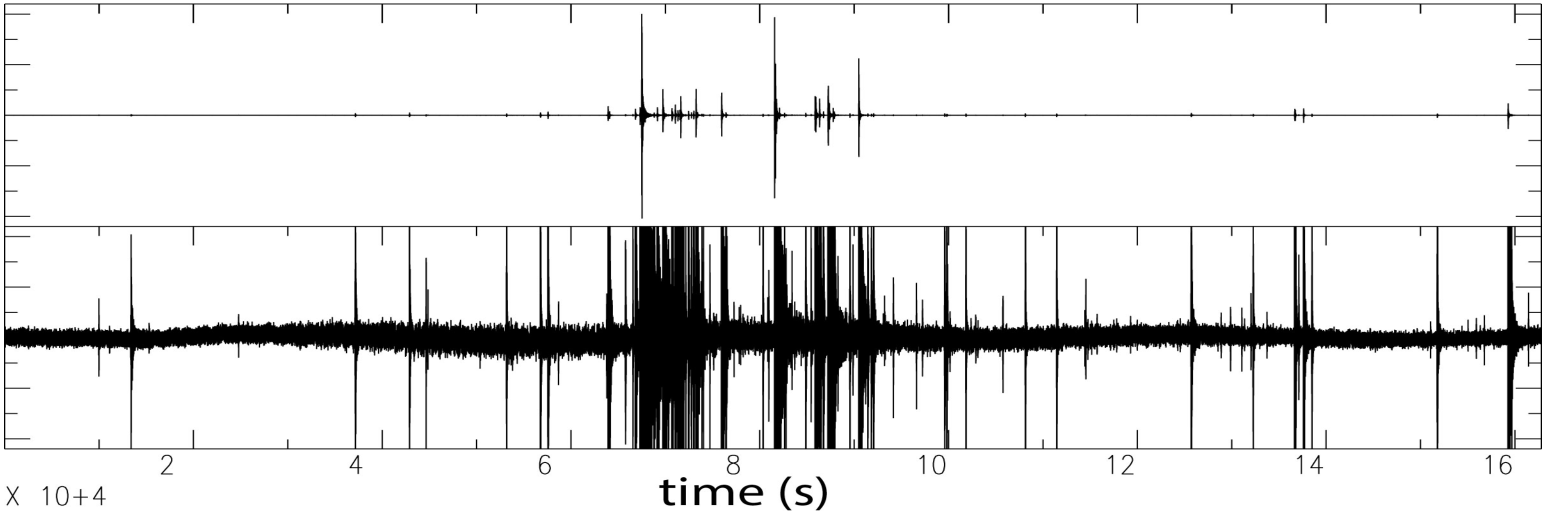
Computing noise cross-correlations between A and B is equivalent to an event occurred at A and recorded at B

To what extend the noise correlation theorem can be applied to real seismological data?

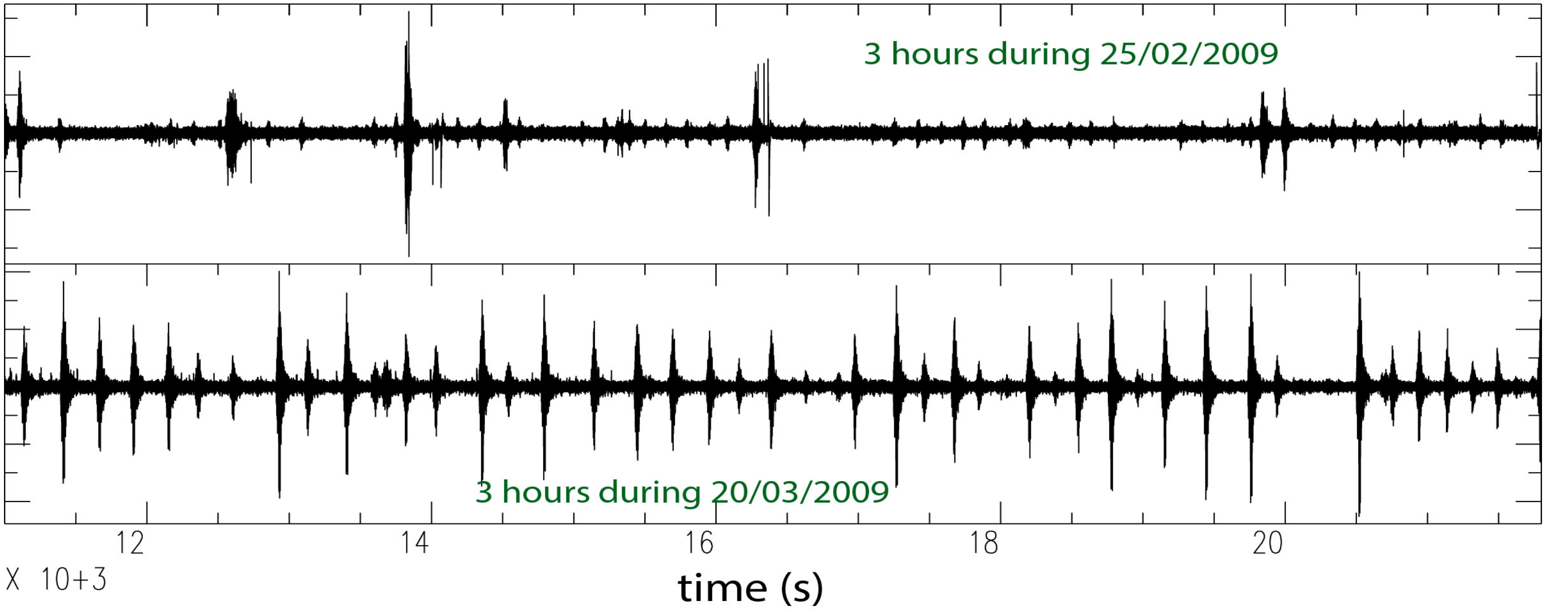
To what extend the real seismic records can be considered as a random diffuse noise?

Examples of seismic records

2 days of continuous record by a seismic station in a subduction zone



Signals recorded in vicinity of an active volcano


3 hours during 25/02/2009

3 hours during 20/03/2009

Examples of seismic records

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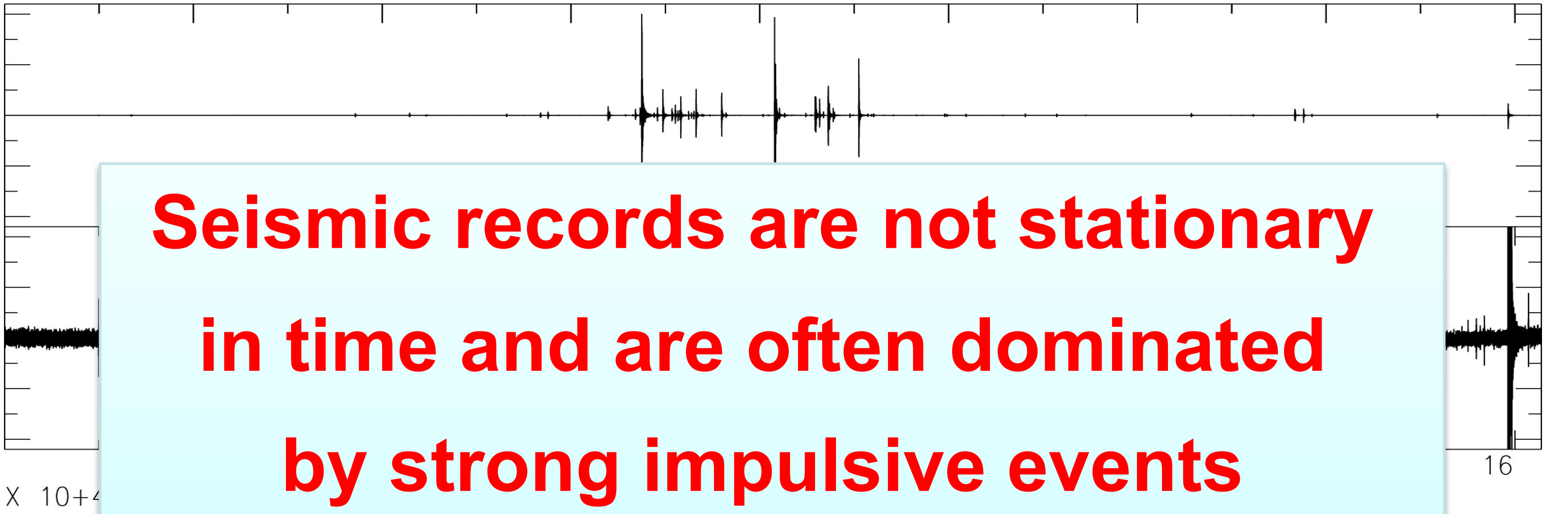
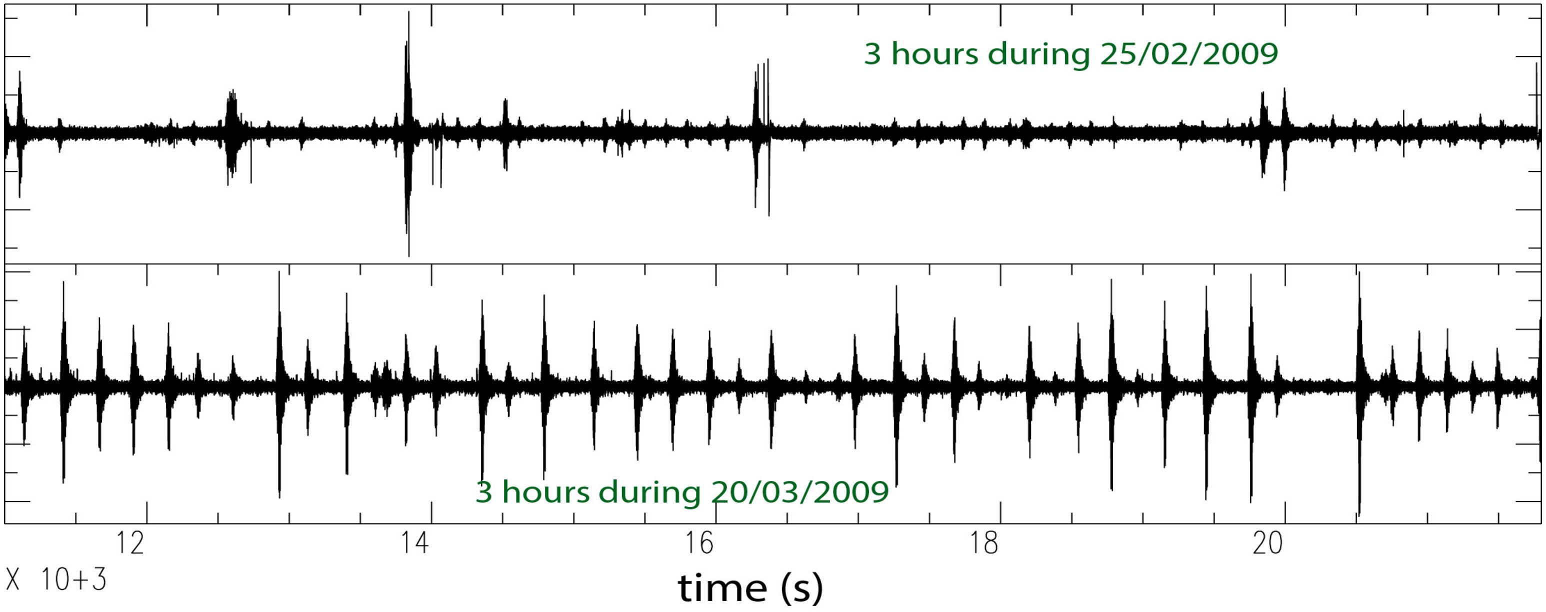


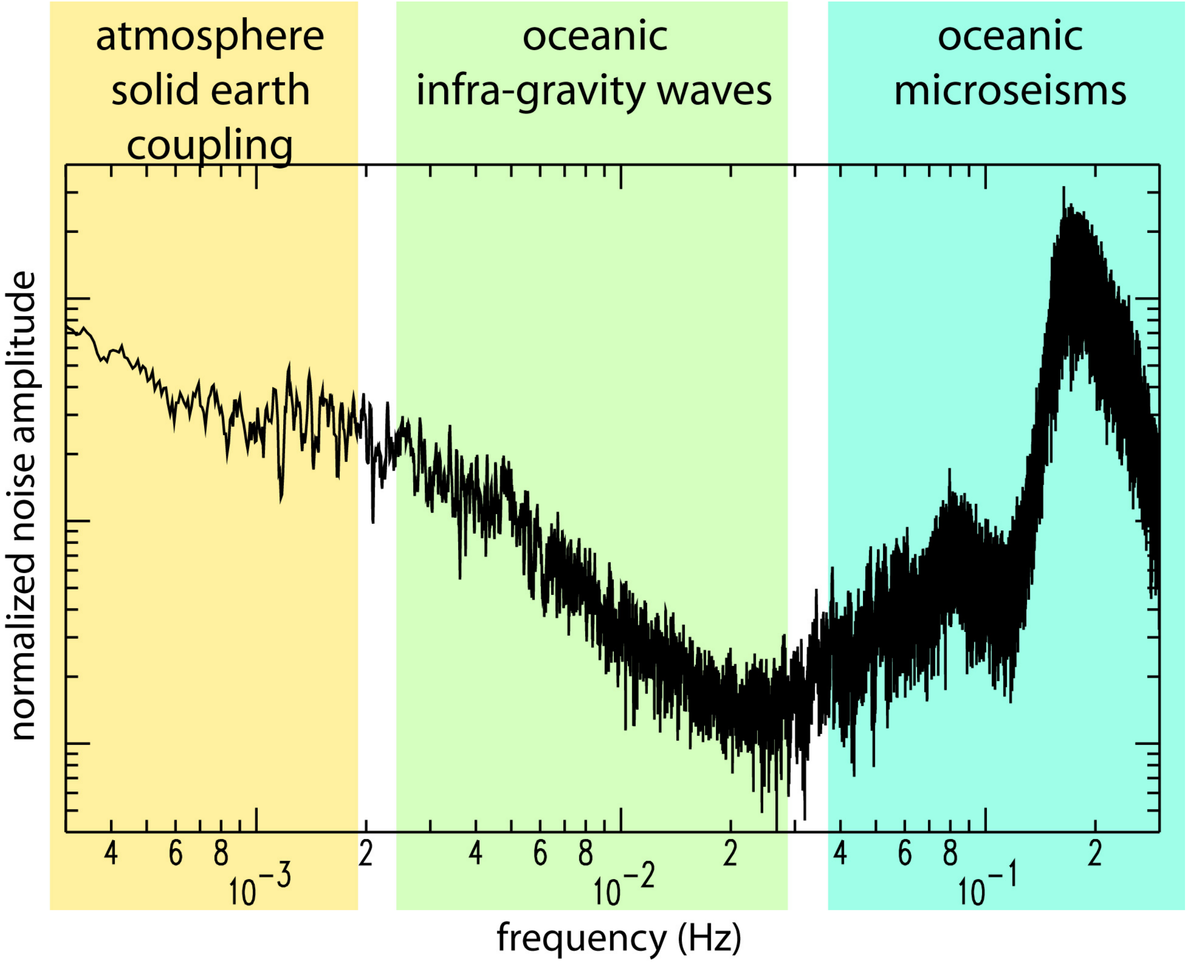
Seismic records are not stationary in time and are often dominated by strong impulsive events

Signals recorded in vicinity of an active volcano



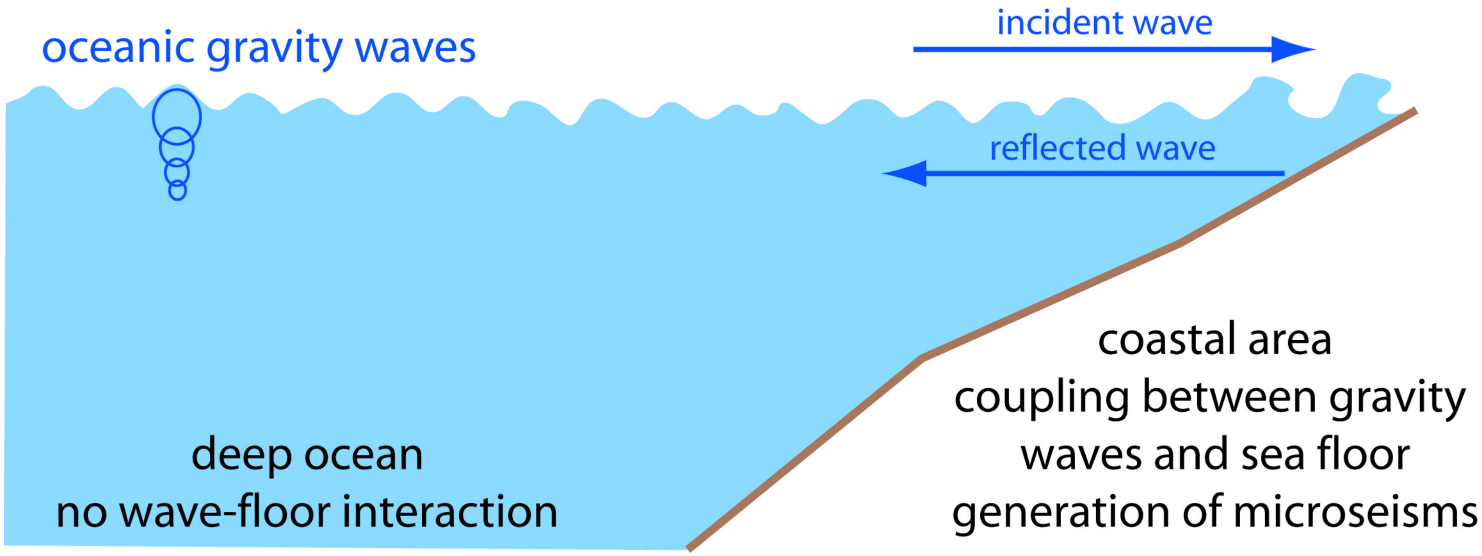
Spectrum of the seismic noise

Fourier spectrum from one day of seismic noise (August 21, 2003; station OBN)



Generation of microseisms

theory from Longuet-Higgins (1950)



primary microseism is excited at frequencies corresponding to the spectrum of incoming oceanic gravity waves (periods of **10-20 s**)

secondary microseism is exited at doubled frequencies due to the nonlinear interaction between incident and reflected waves (periods of **5-10 s**)

Need for the seismic records preprocessing

Seismic records are not stationary in time

Seismic noise is dominated by strong spectral peaks

Before computing cross-correlations individual seismic records must be preprocessed

- **identification of windows containing strong events**
- **rejection of strong events**
- **equalization of amplitudes in time and spectral domains**

Preprocessing is a complex and often nonlinear set of operations

Examples of seismic records

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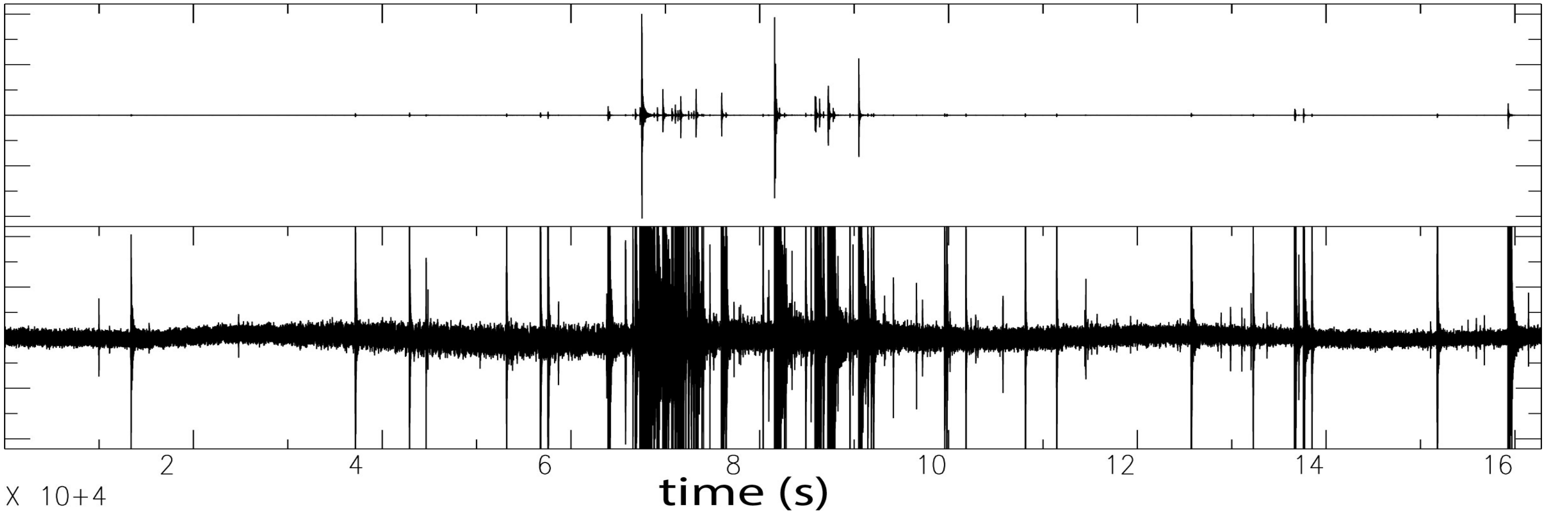

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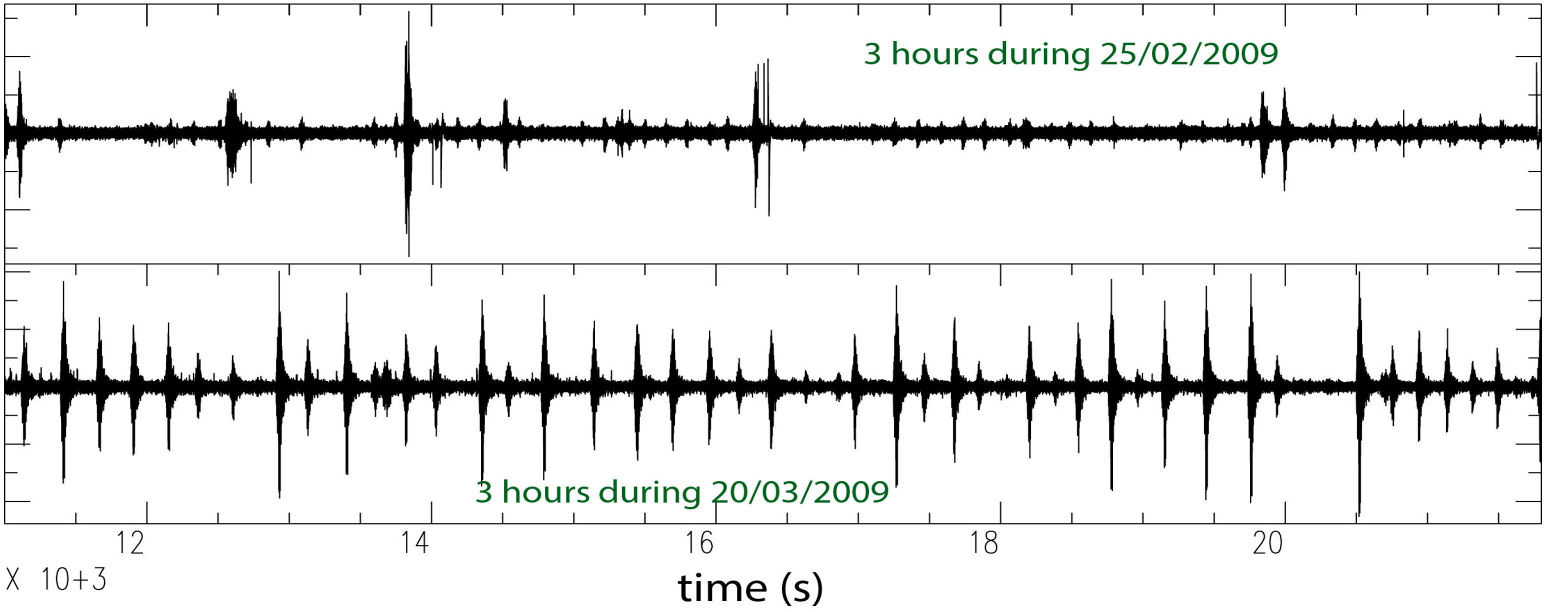
3 hours during 25/02/2009

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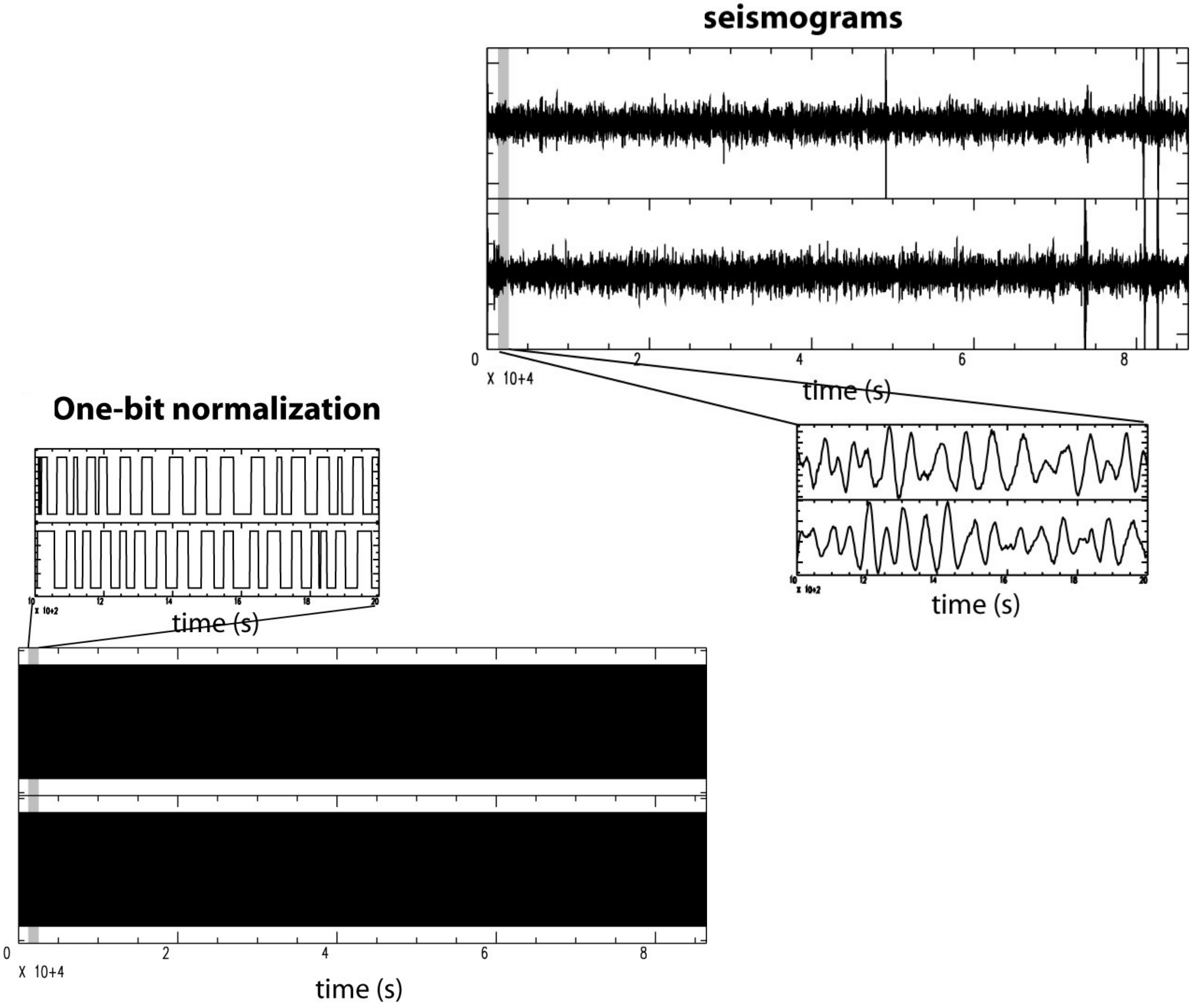
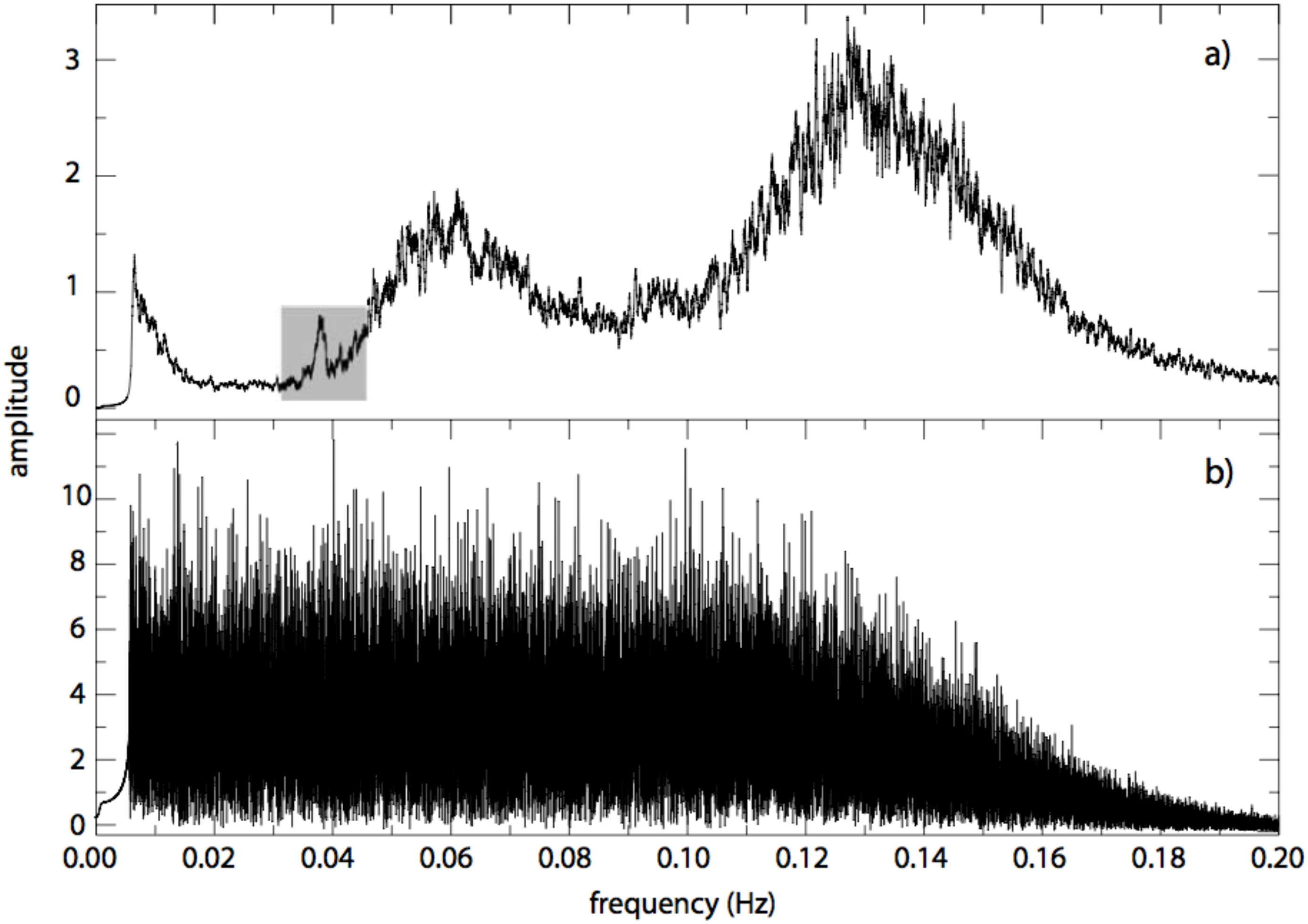
Noise records pre-processing: time normalization



Noise records pre-processing: spectral normalization (whitening)



Noise Correlation Theorem

For a **random** wavefield with sources distributed **homogeneously** everywhere in the medium it can been shown that:

$$\text{correlation of preprocessed records} \overset{?}{=} \frac{-\sigma^2}{4\,a}\left(G_a(\tau,\vec{r}_A,\vec{r}_B)-G_a(-\tau,\vec{r}_A,\vec{r}_B)\right)$$

Green function

Computing noise cross-correlations between A and B is equivalent to an event occurred at A and recorded at B

To what extend the preprocessing corrects for the noise time and spectral inhomogeneity?

How can we characterize the structure of the correlated wavefield?

Network Covariance Matrix

Cross-correlation between records $u_i(t)$ and $u_j(t)$ at receivers *i* and *j*:

$$CC_{ij}(t) = \int_{-\infty}^{\infty} u_i(t)u_j(t+\tau)d\tau = iFFT\left[U_i(\omega)U_j^*(\omega)\right]$$

t – time, ω - frequency, $U_i(\omega)$ and $U_j(\omega)$ – Fourier transforms of $u_i(t)$ and $u_j(t)$

Covariance matrix:

$$CM_{ij}(\omega) = \left\langle U_i(\omega)U_j(\omega)\right\rangle$$

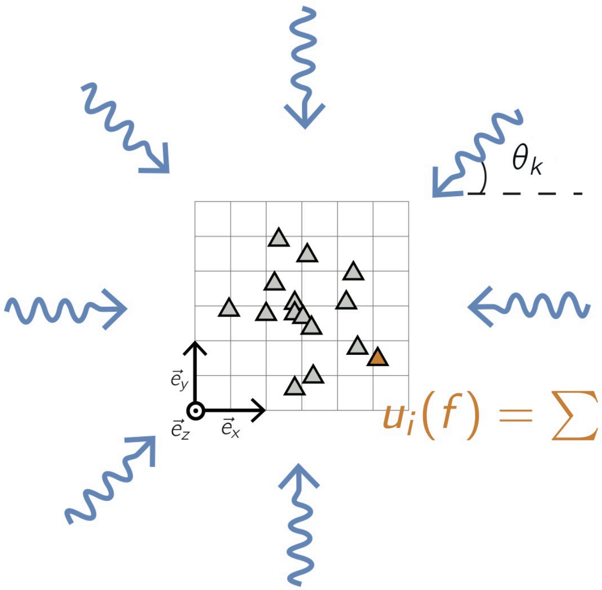
$\langle\ \rangle$ - time average

more details in poster by Léonard Seydoux

Network Covariance Matrix

Synthetic wavefield: sum of plane waves

$$\Phi_k(\mathbf{r}, f) = e^{-2i\pi f \gamma_k \cdot \mathbf{r} - 2i\pi\varphi_k}$$

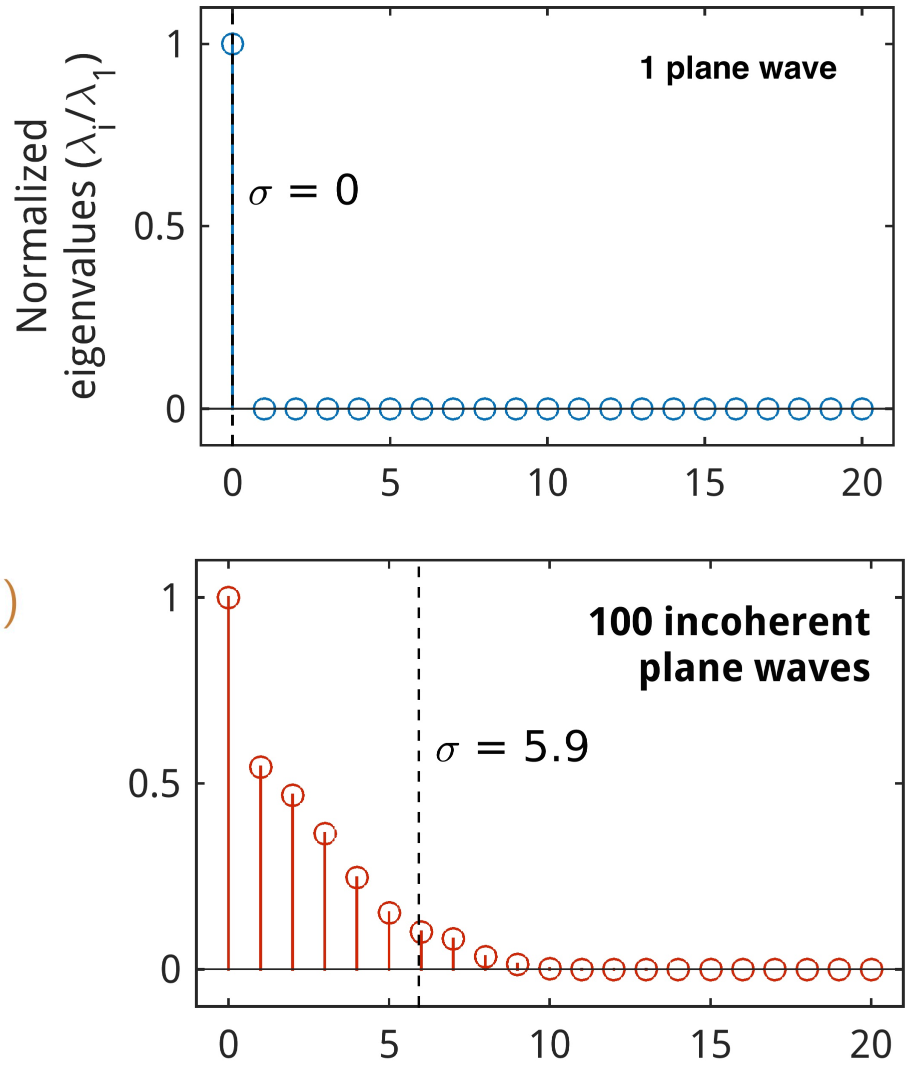


$$u_i(f) = \sum_k \Phi_k(\mathbf{r}_i, f)$$

$$\boxed{\sigma(f) = \frac{\sum_{i=1}^{N}(i-1)\lambda_i(f)}{\sum_{i=1}^{N}\lambda_i(f)}}$$

Covariance Matrix spectral width

Distribution of eigenvalues



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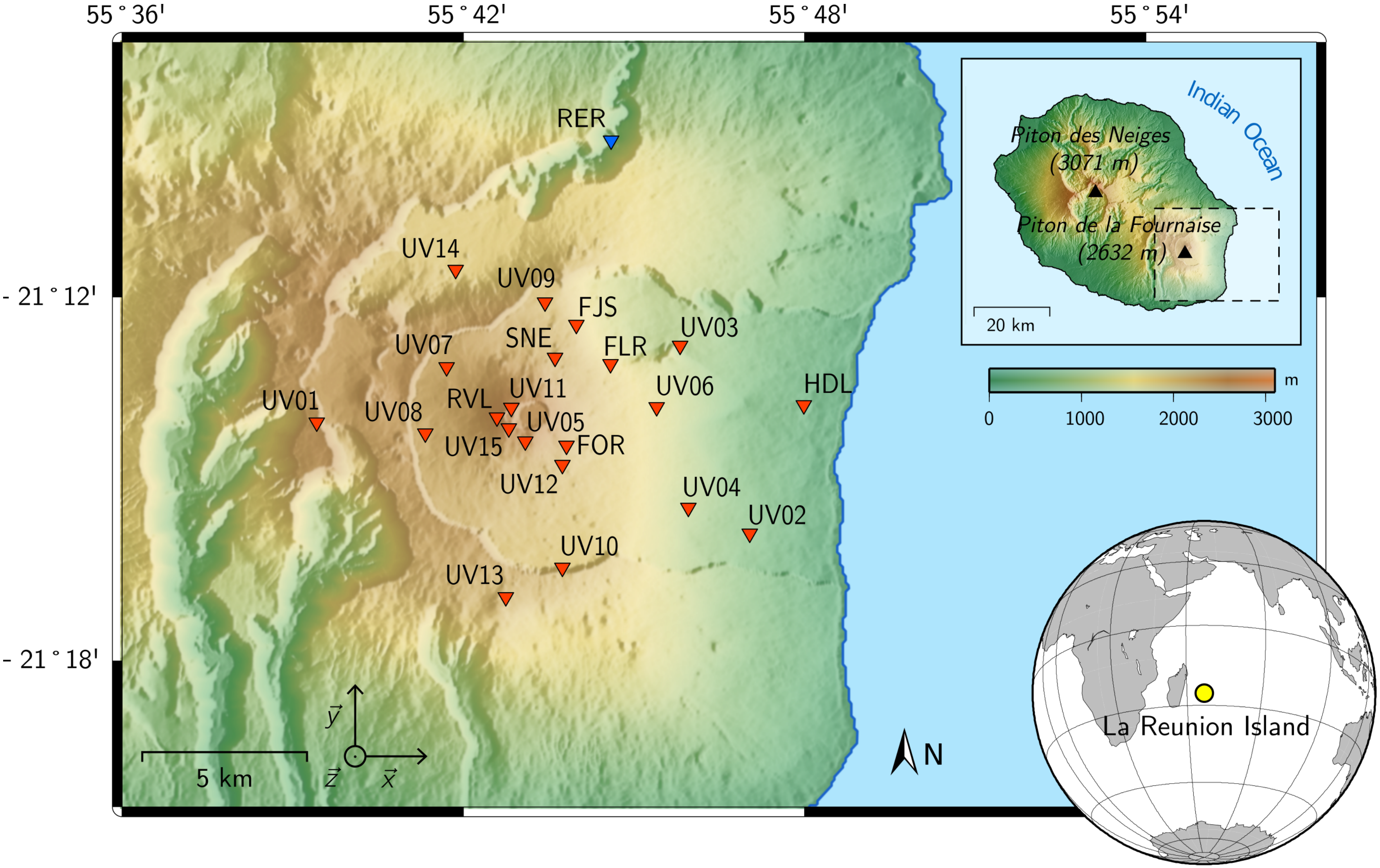
Network Covariance Matrix

Example with real data: records of an earthquake by a network of 21 seismometers



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Network Covariance Matrix

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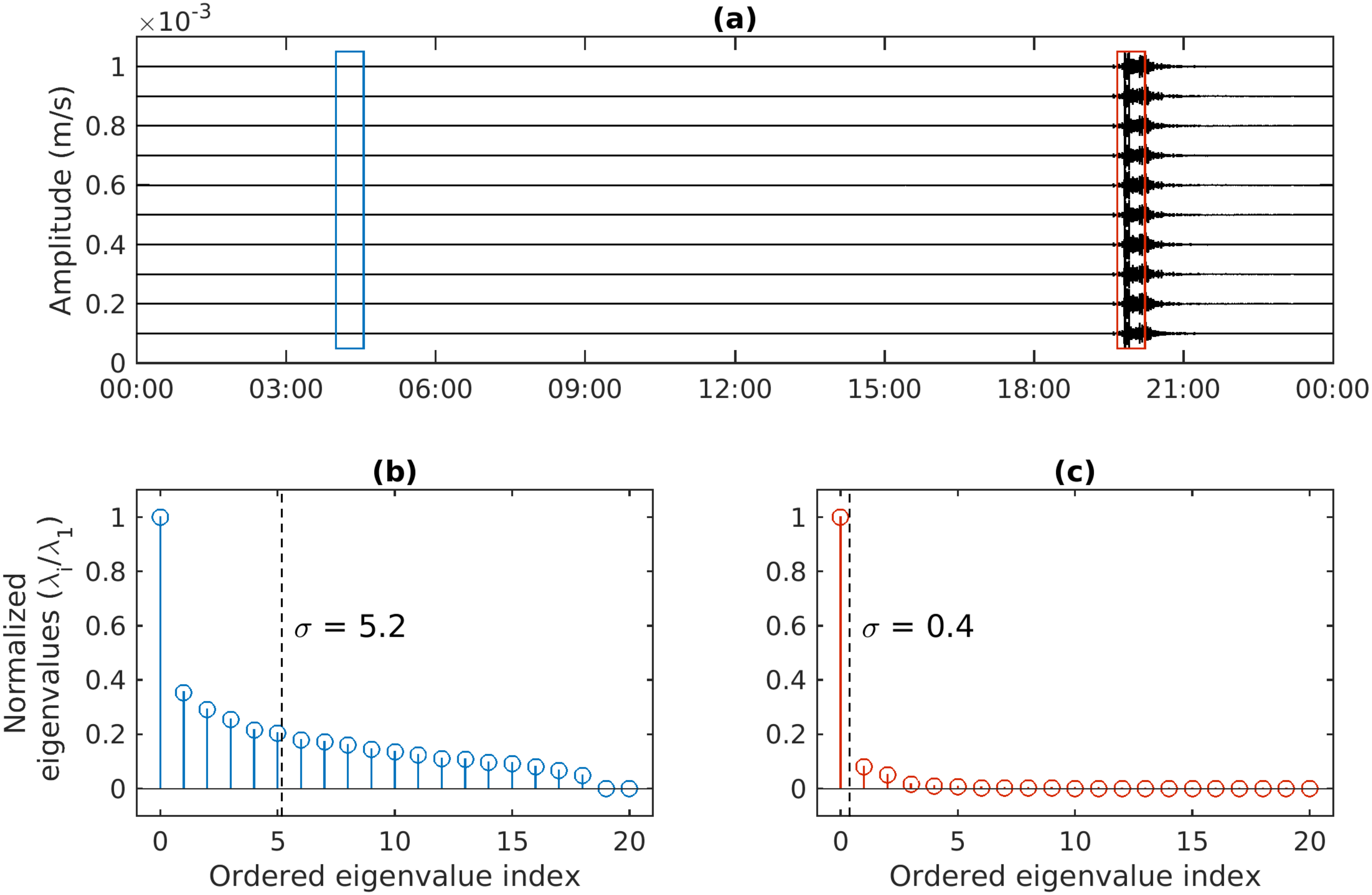

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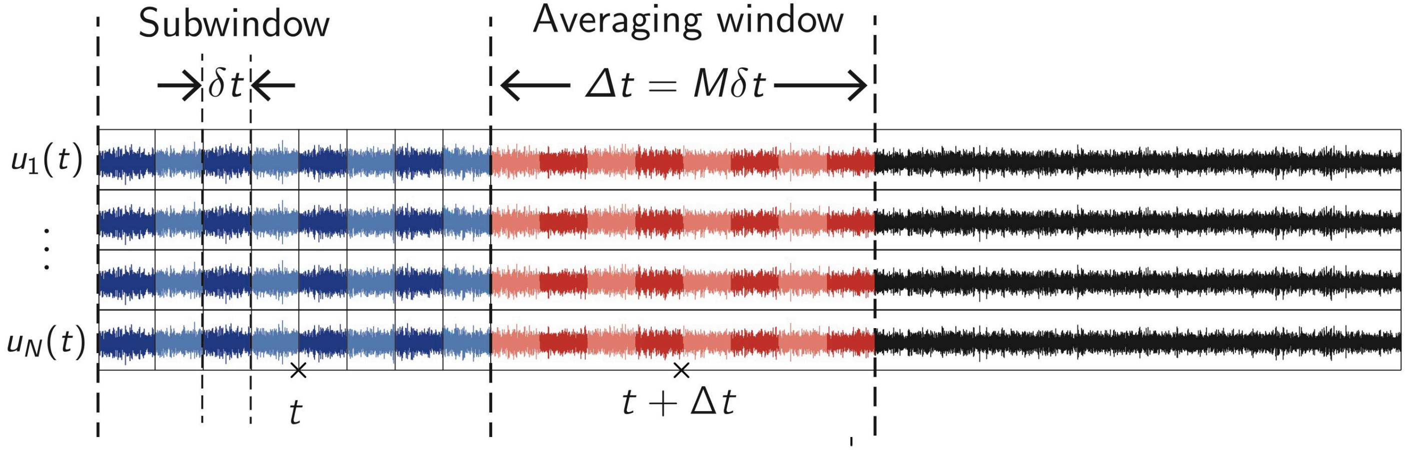
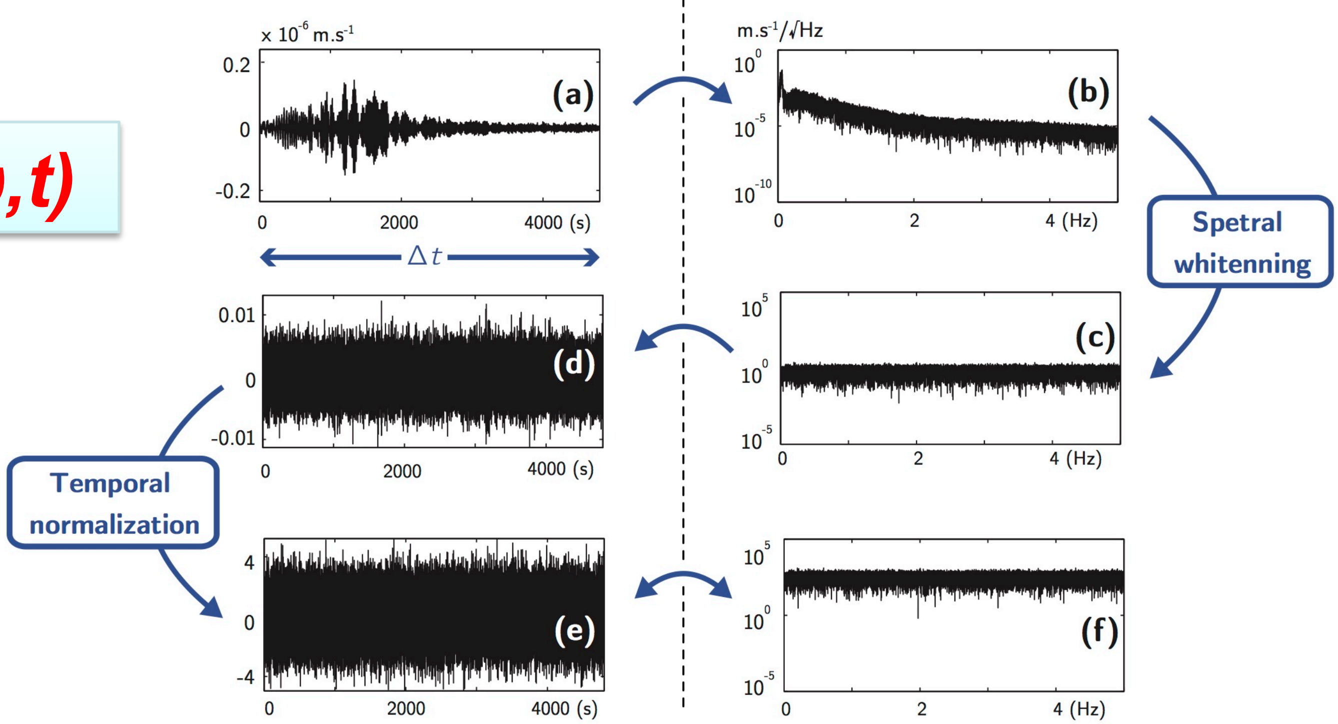


$CM_{ij}(\omega,t)$



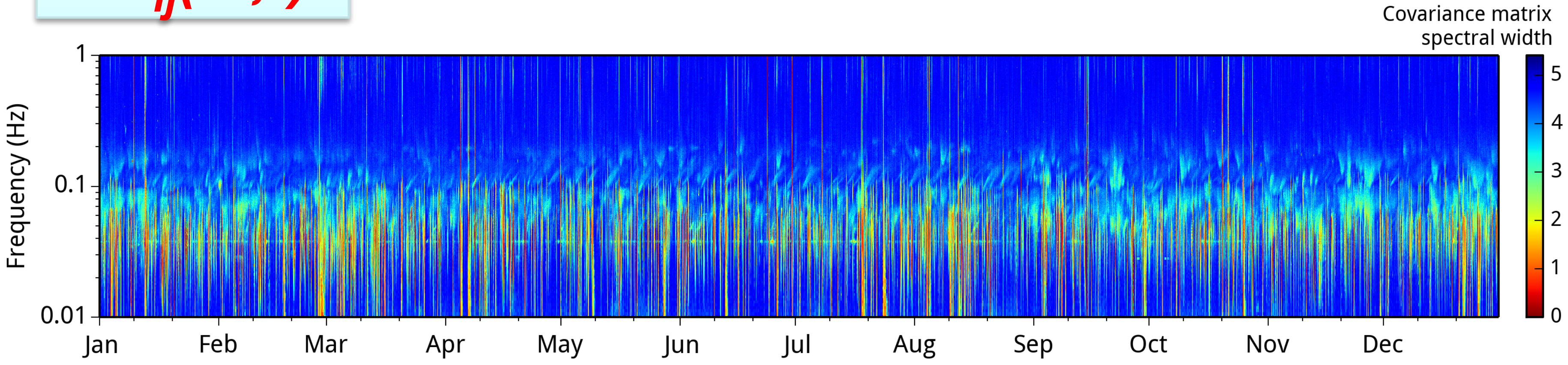
Spetral whitenning

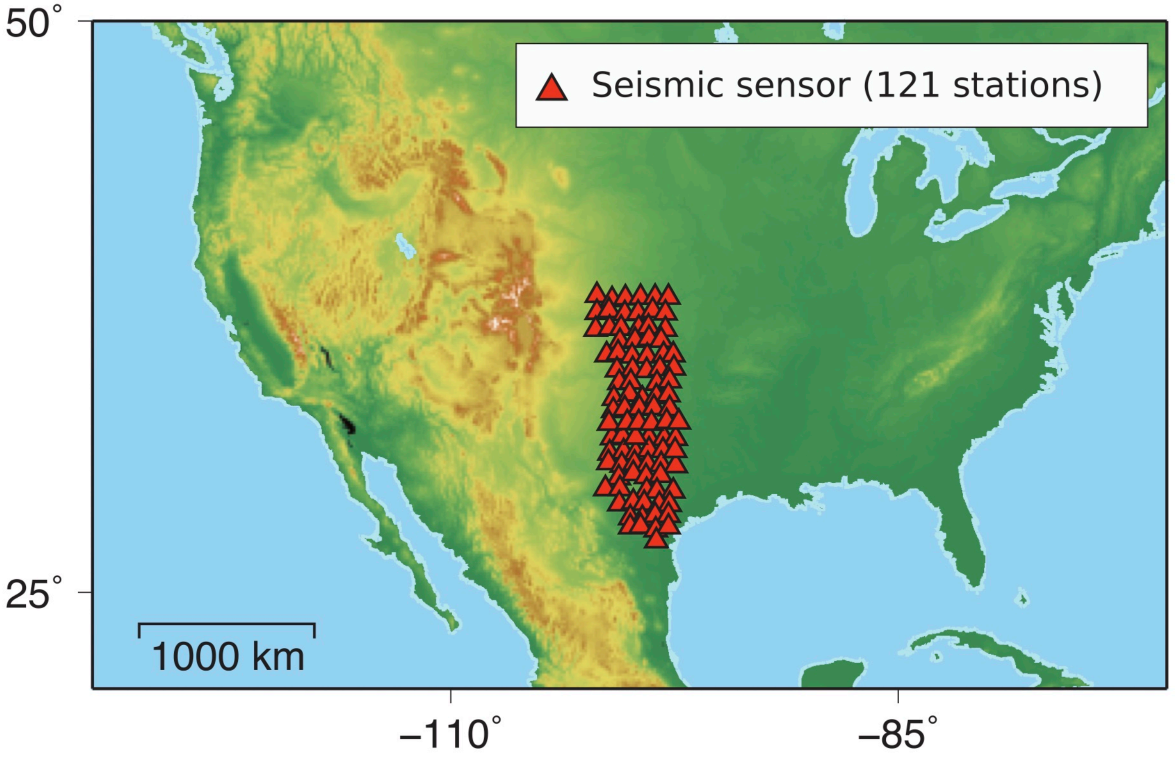
Temporal normalization

more details in poster by Léonard Seydoux

$CM_{ij}(\omega,t)$

Network Covariance Matrix





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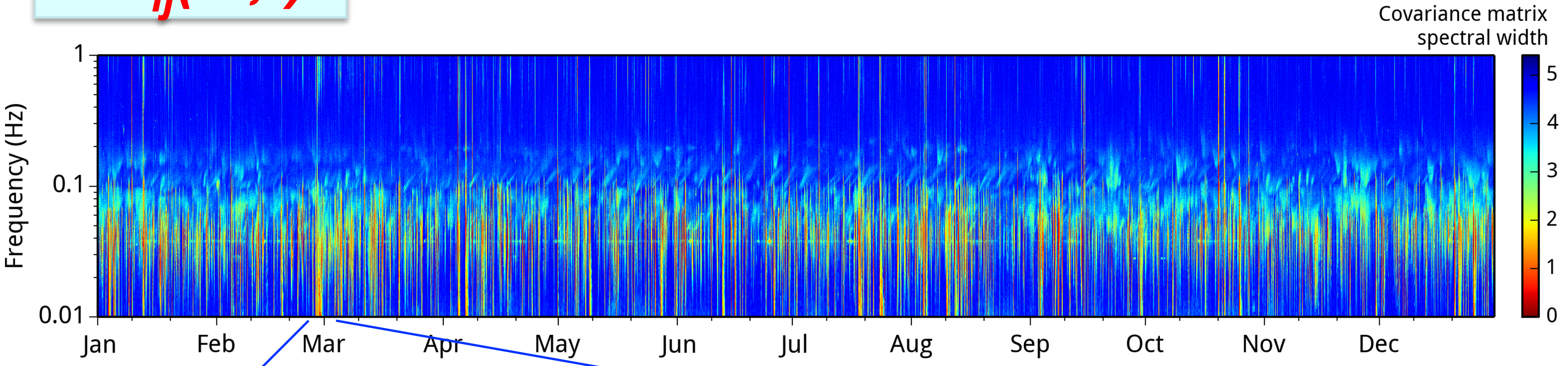
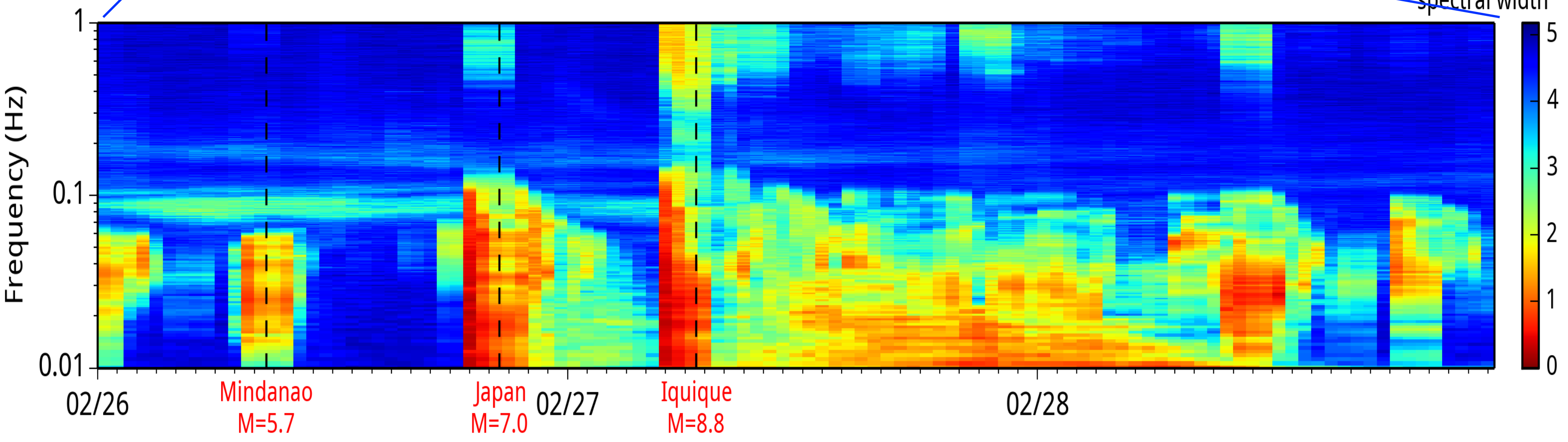


zoom on earthquakes



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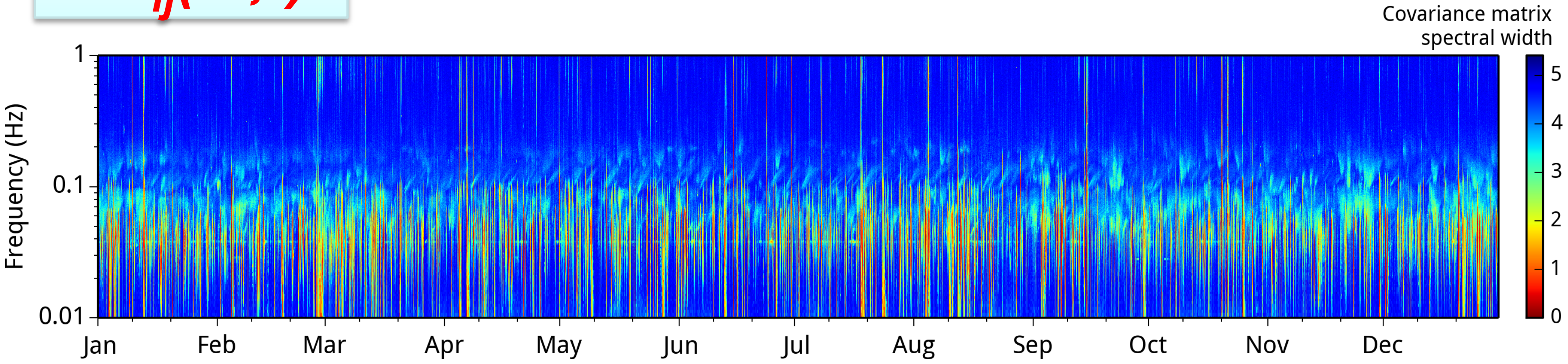
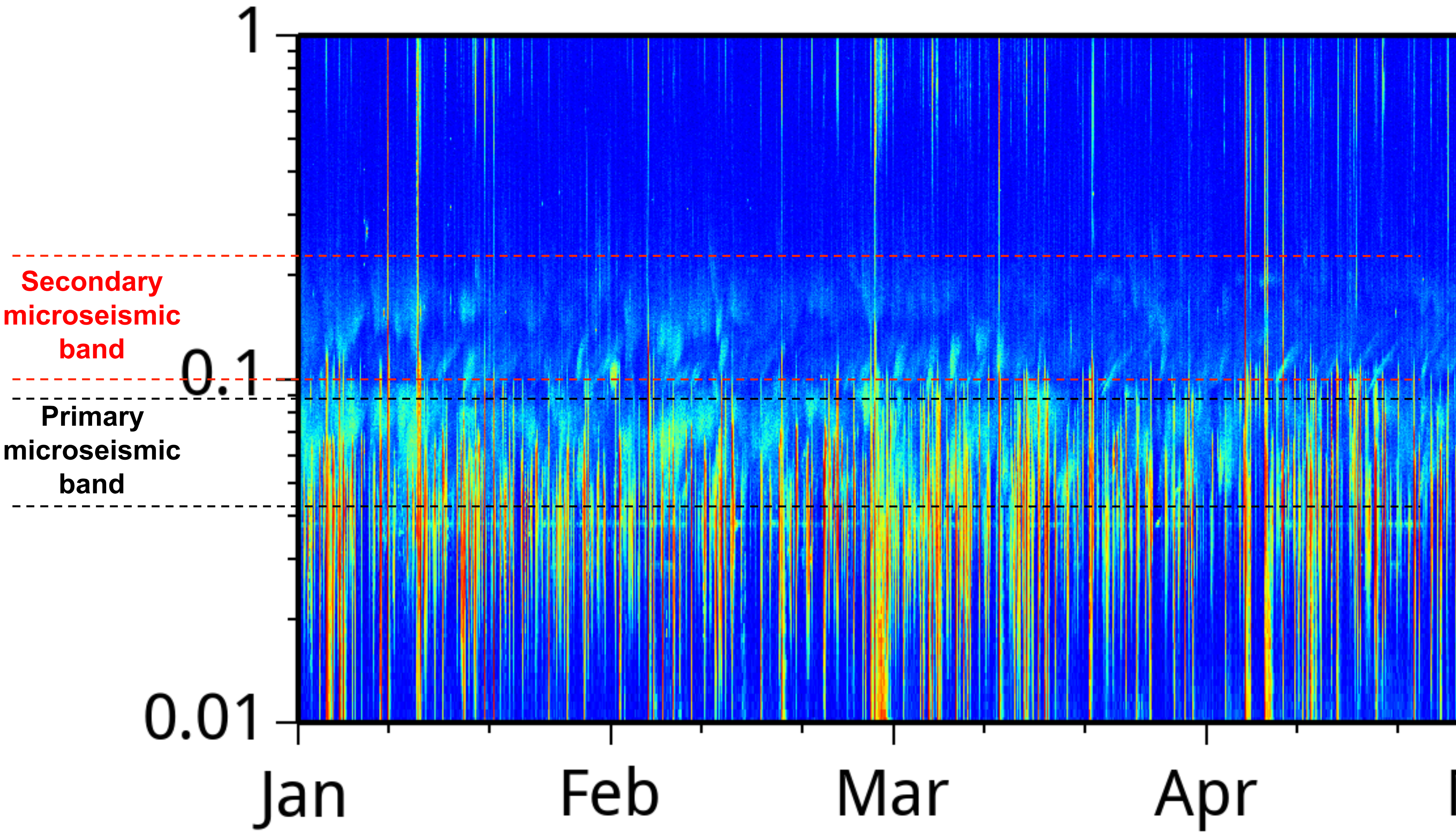


$CM_{ij}(\omega,t)$

Network Covariance Matrix

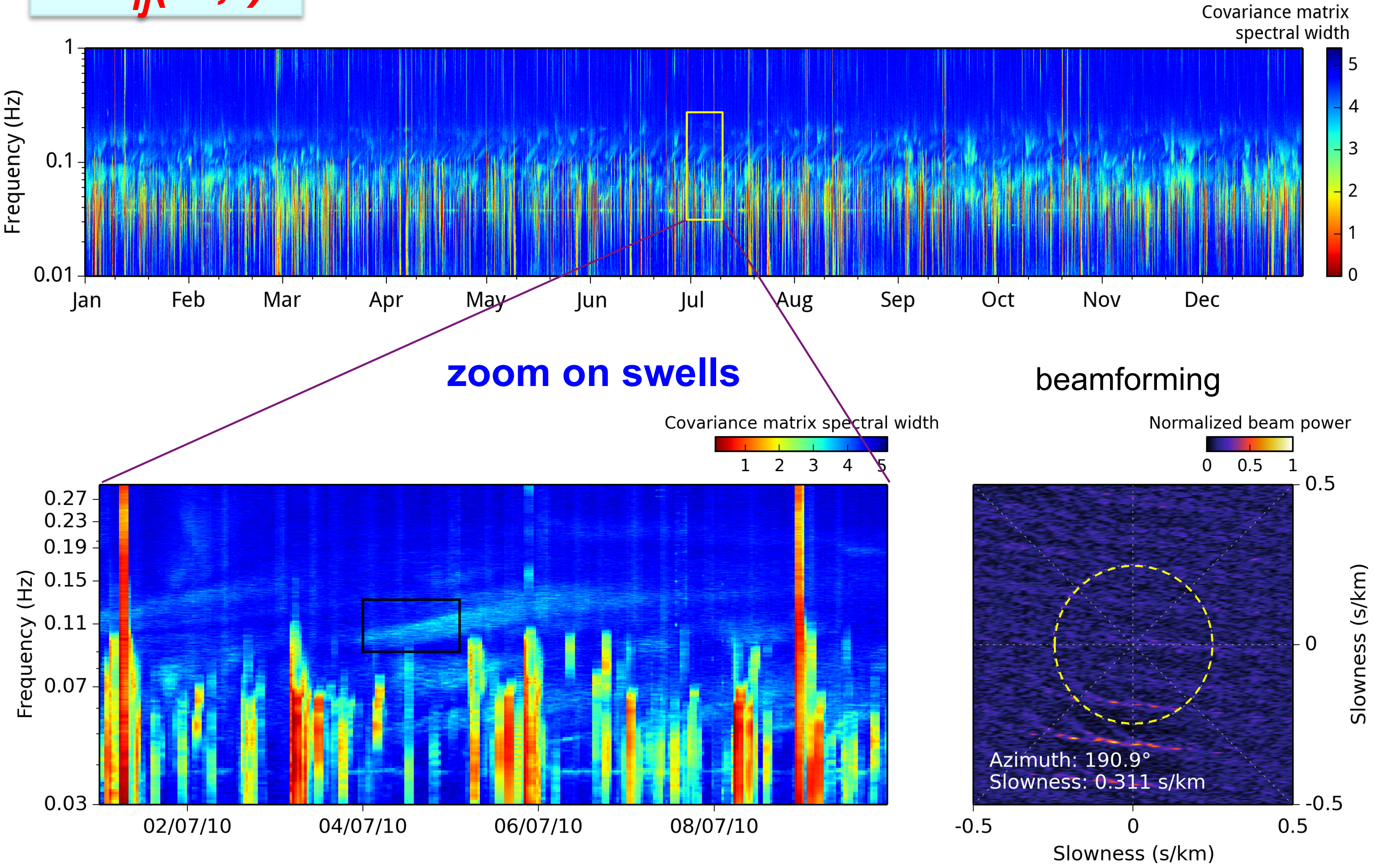
Dispersive signals : long-range propagating swells interacting with shores

Non-dispersive signals : deep oceanic sources



$CM_{ij}(\omega,t)$

Network Covariance Matrix

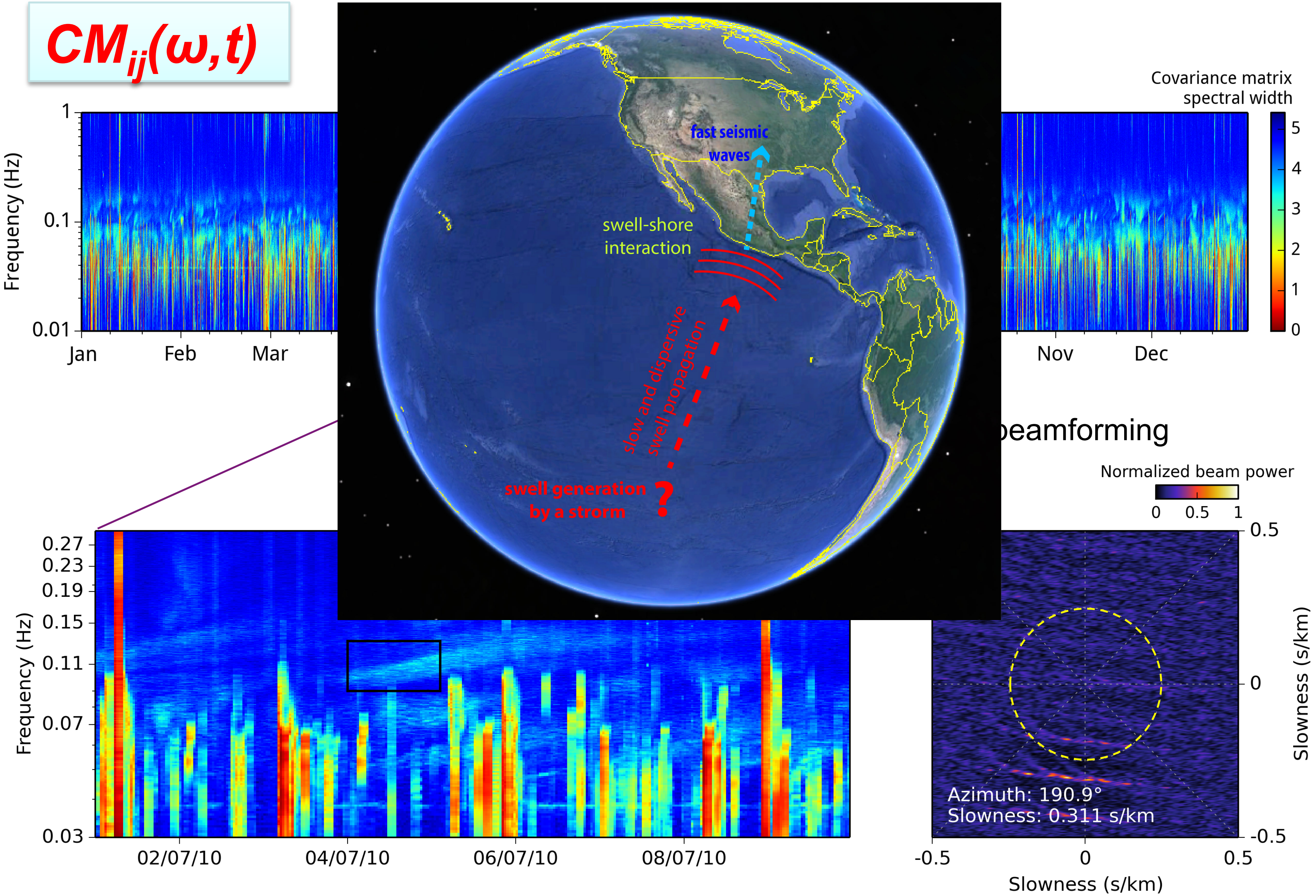


zoom on swells

beamforming

surface waves

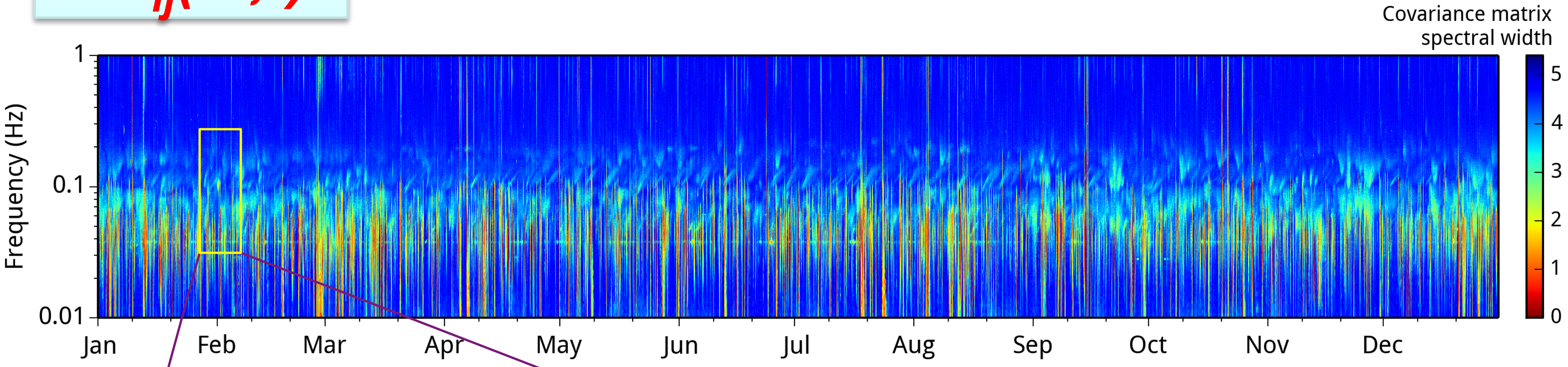
$CM_{ij}(\omega,t)$



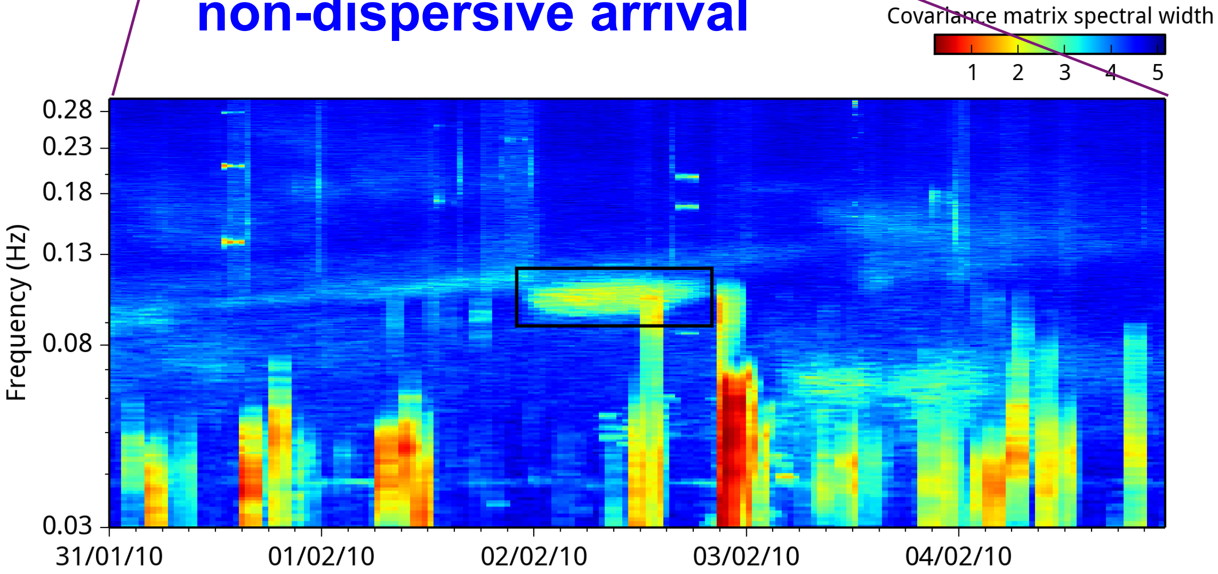
surface waves

$CM_{ij}(\omega,t)$

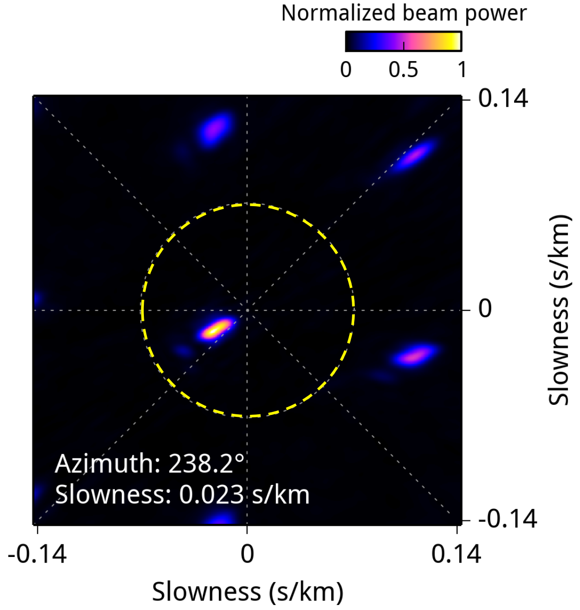
Network Covariance Matrix



zoom on a non-dispersive arrival



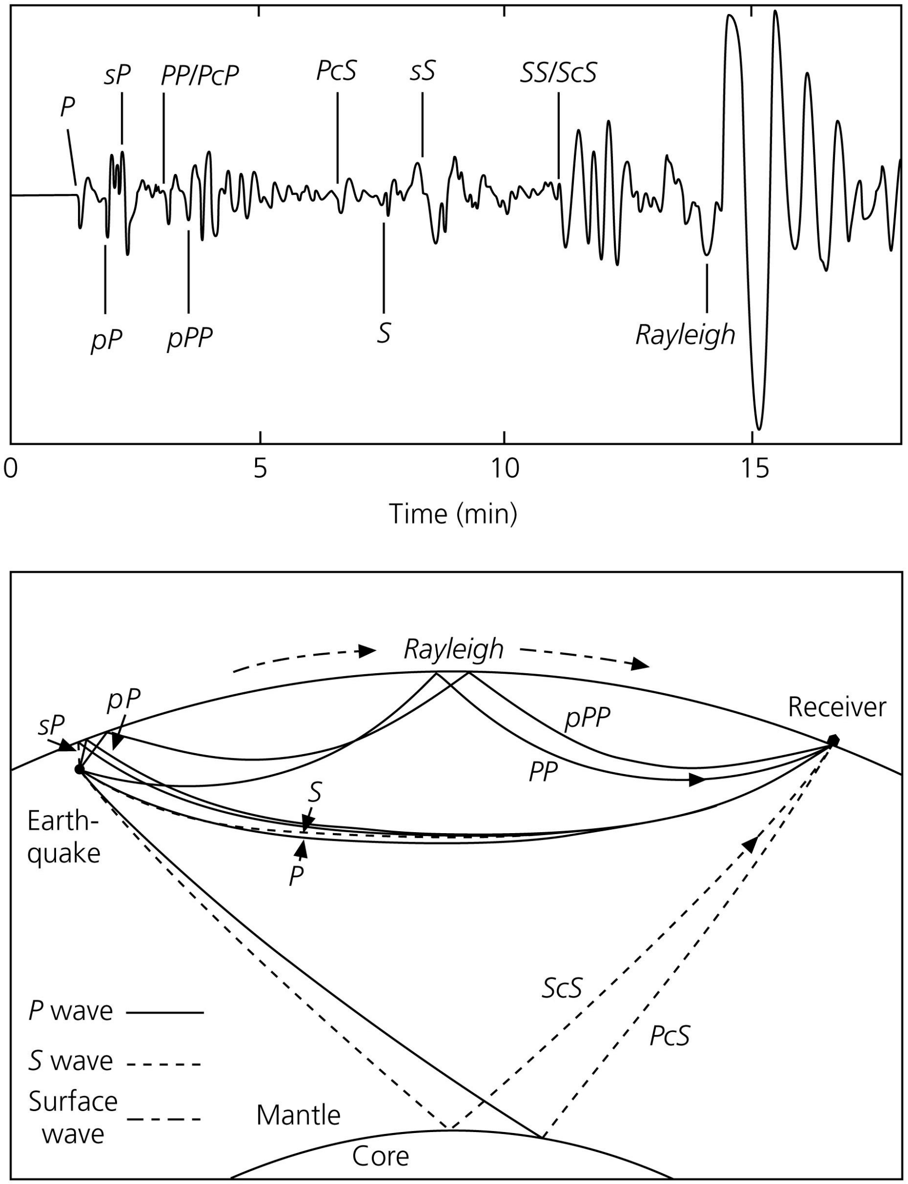
beamforming



body waves

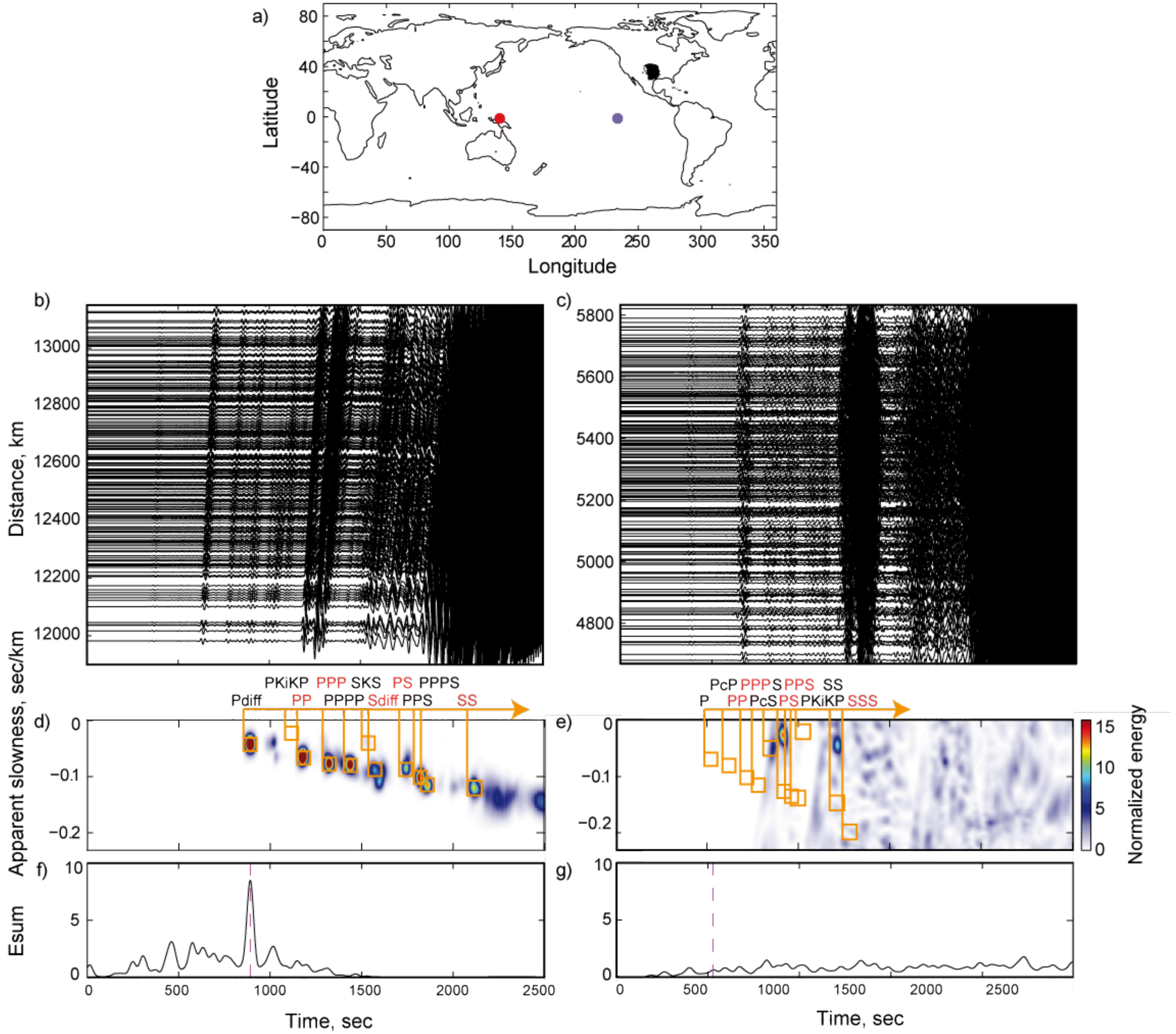
Beamforming of multiple body wave phases with USArray

Figure 3.5-2: Selection of body phases and their ray paths.



more details in poster by Lise Retailleau

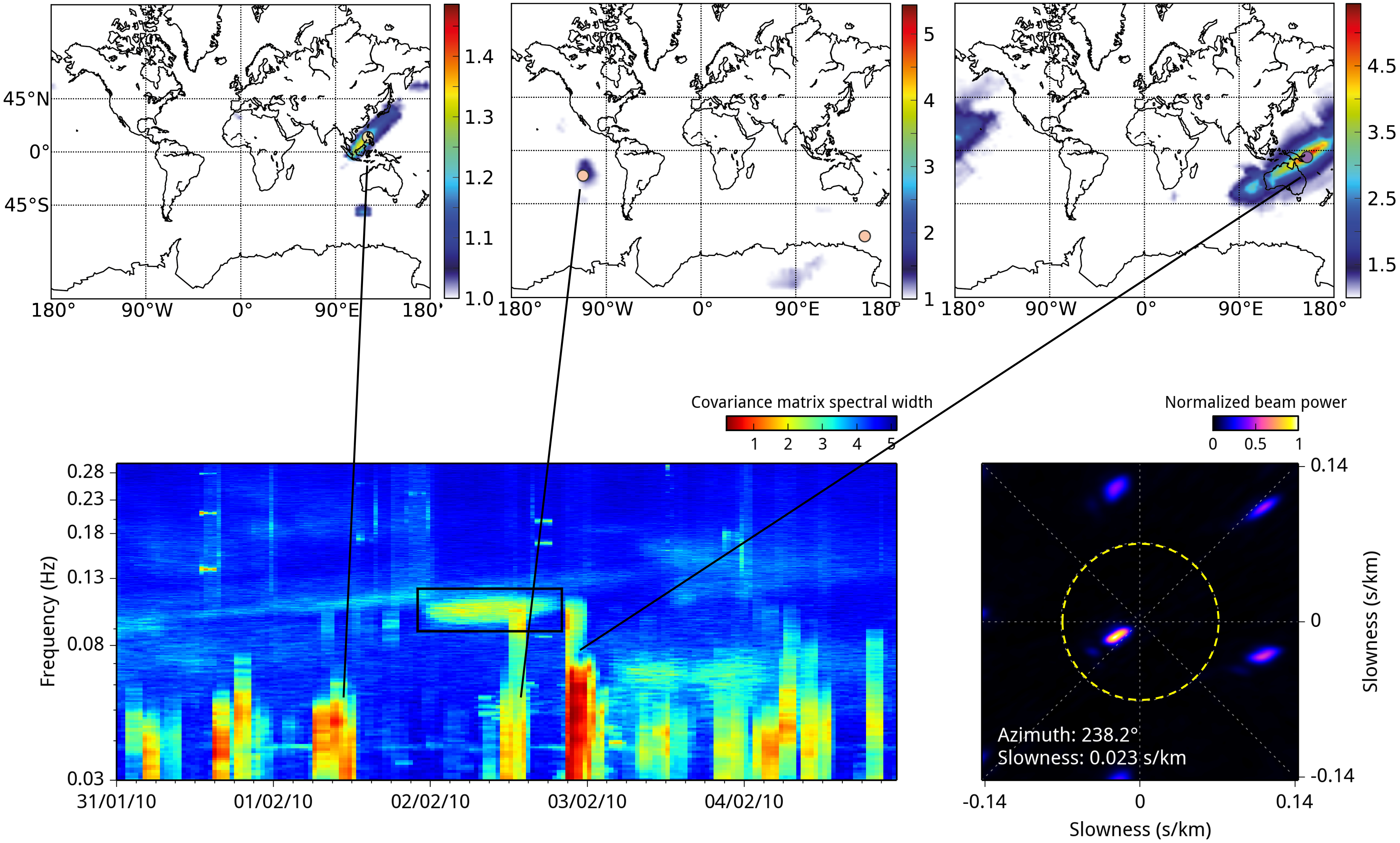
Beamforming of multiple body wave phases with USArray



more details in poster by Lise Retailleau

Beamforming of multiple body wave phases with USArray

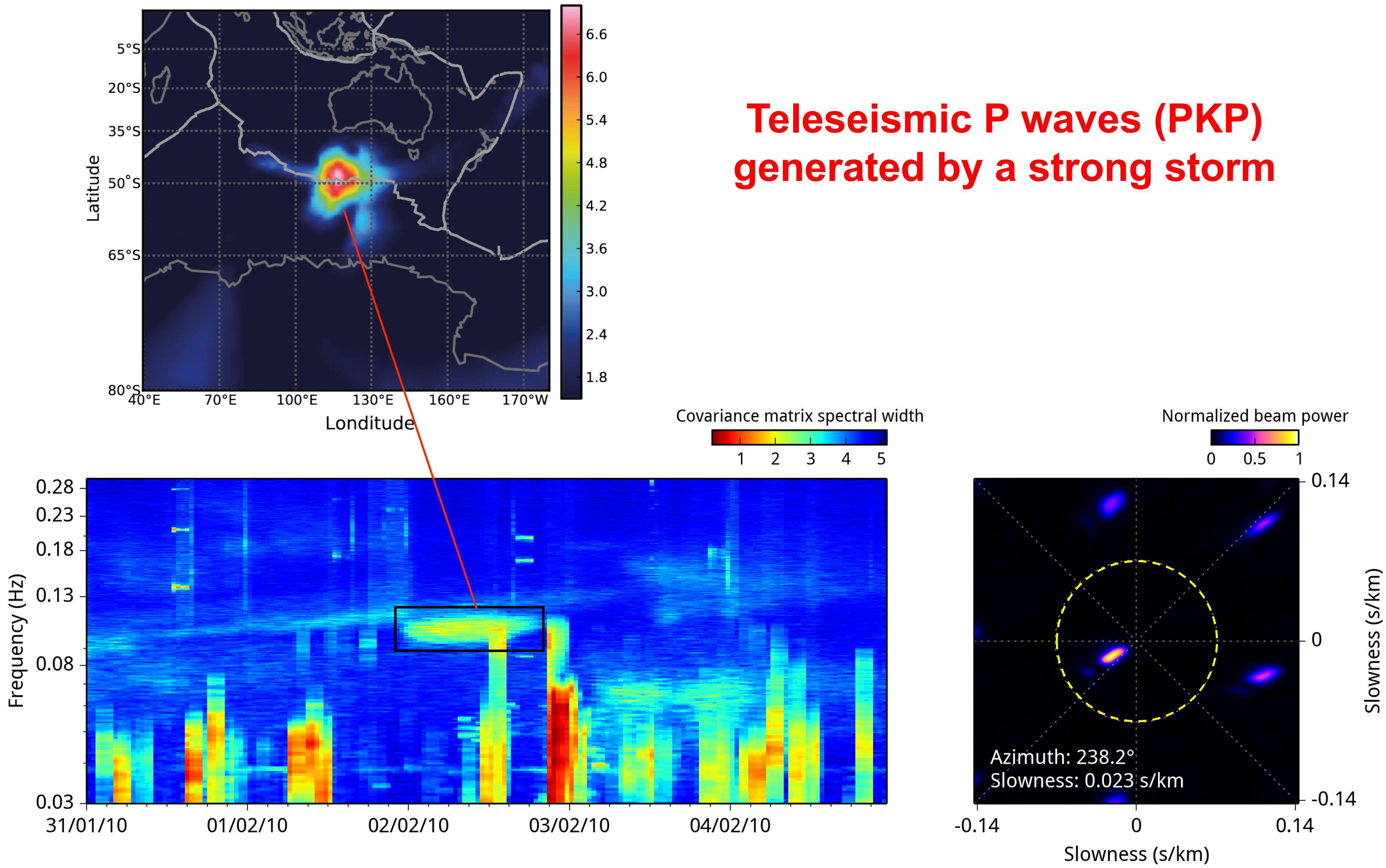
earthquakes



more details in poster by Lise Retailleau

Beamforming of multiple body wave phases with USArray

non-dispersive microseism

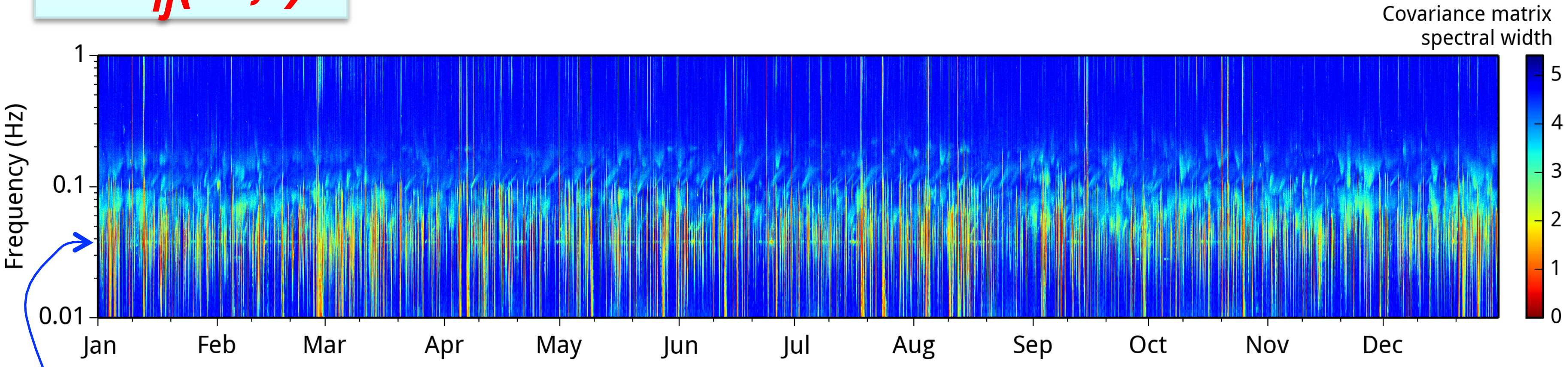


Teleseismic P waves (PKP) generated by a strong storm

more details in poster by Lise Retailleau

Network Covariance Matrix

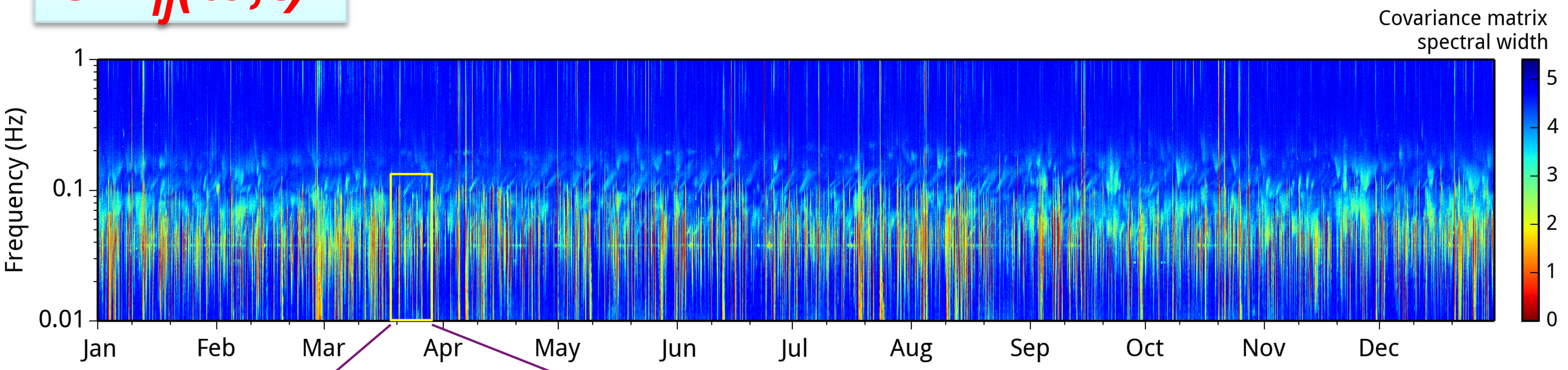
$CM_{ij}(\omega,t)$



26 s microseism

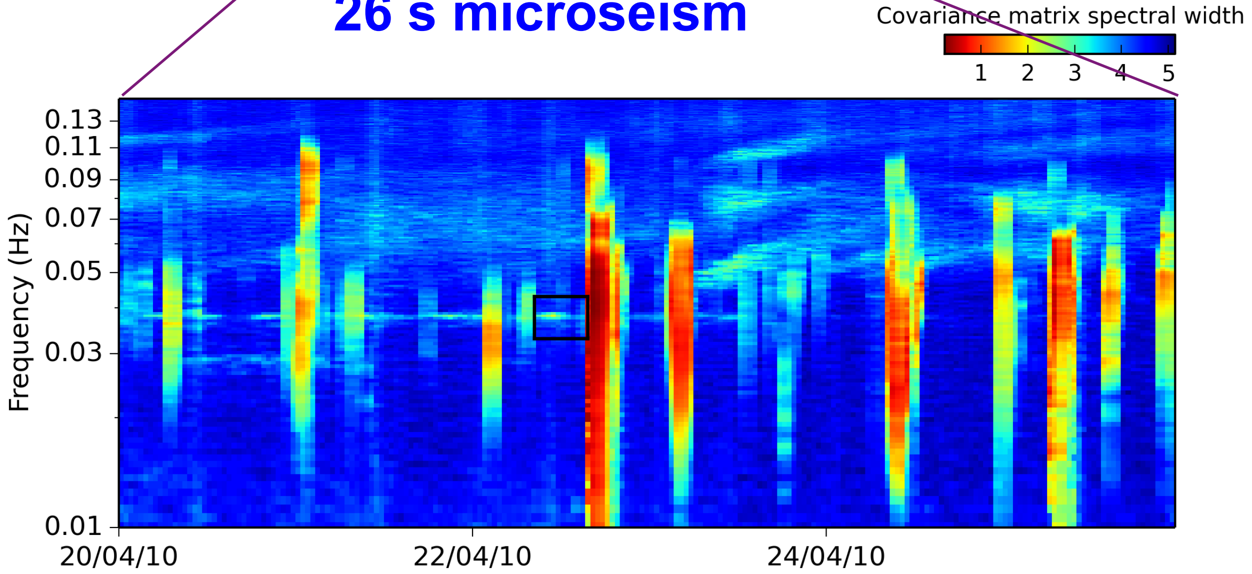
$CM_{ij}(\omega,t)$

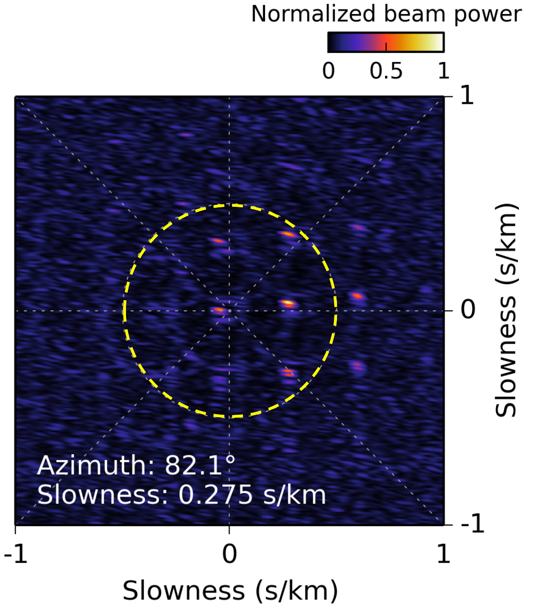
Network Covariance Matrix



beamforming

26 s microseism

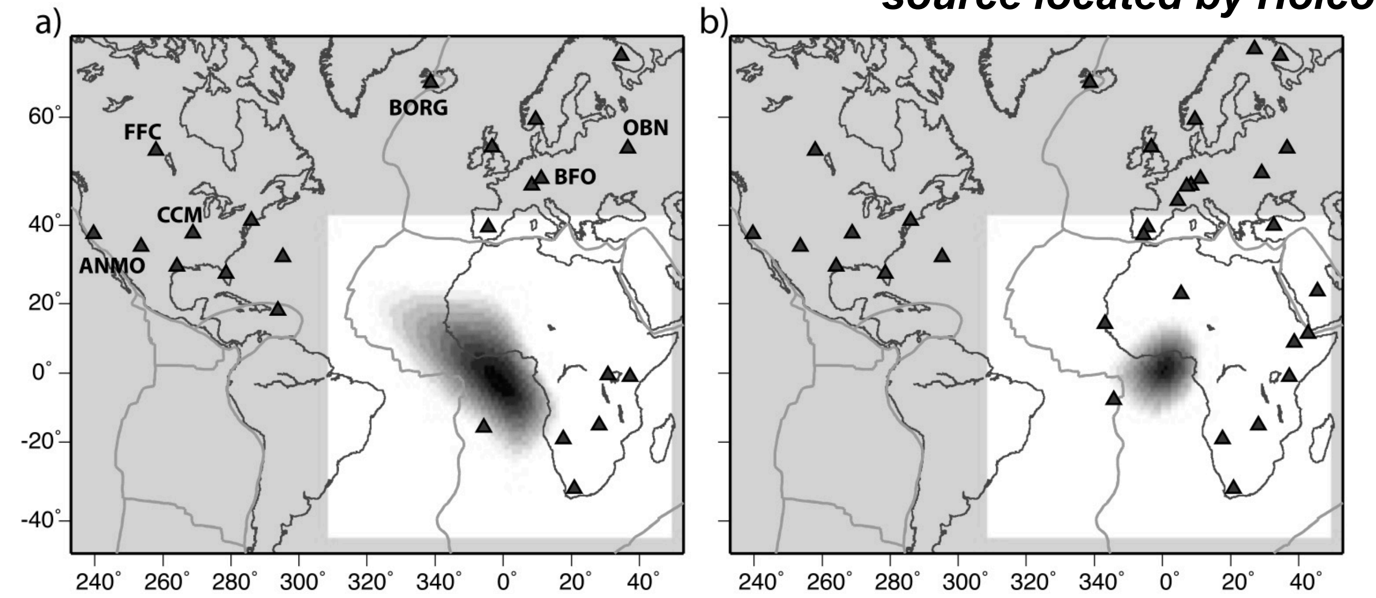


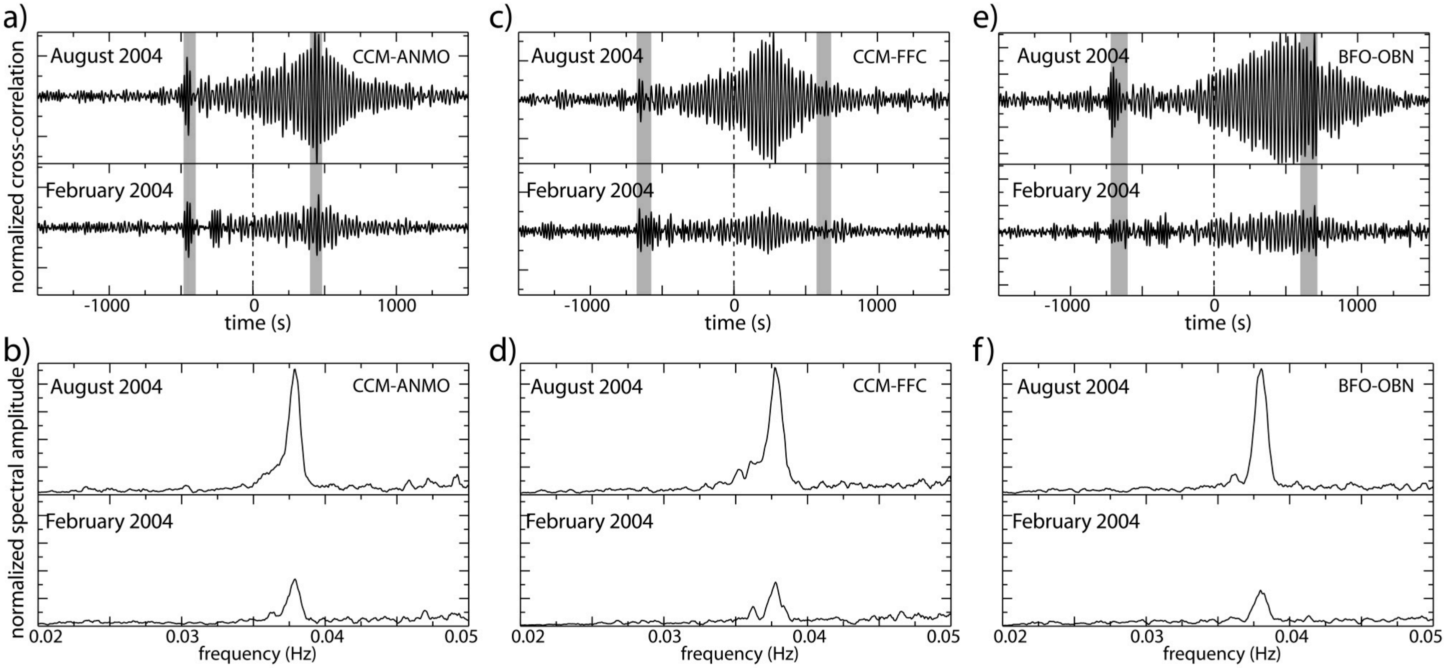


surface waves

26 s microseism

discovered by Oliver in 1962
source located by Holcomb in 1980





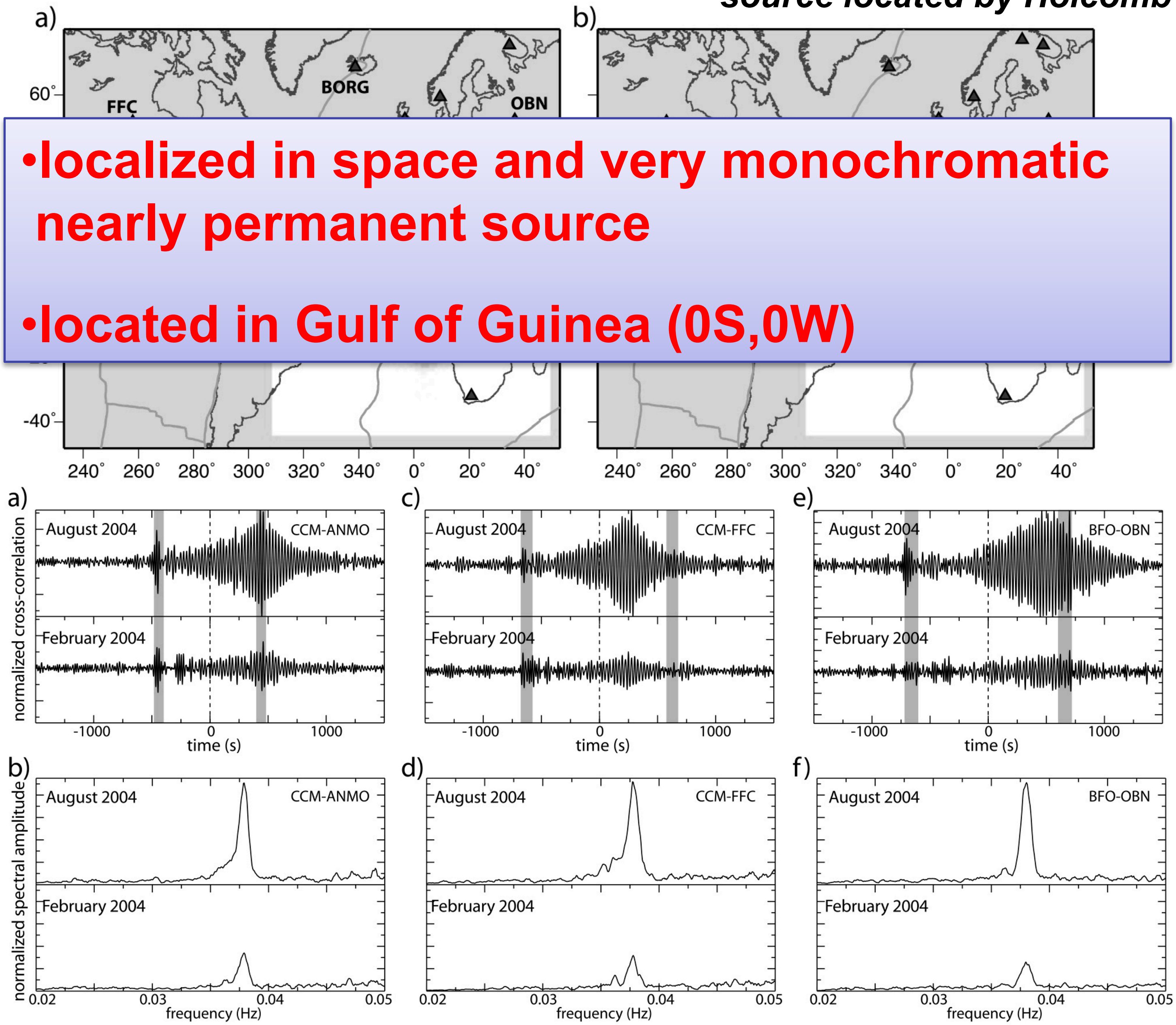
from Shapiro et al., 2006

26 s microseism

discovered by Oliver in 1962
source located by Holcomb in 1980

- **localized in space and very monochromatic nearly permanent source**

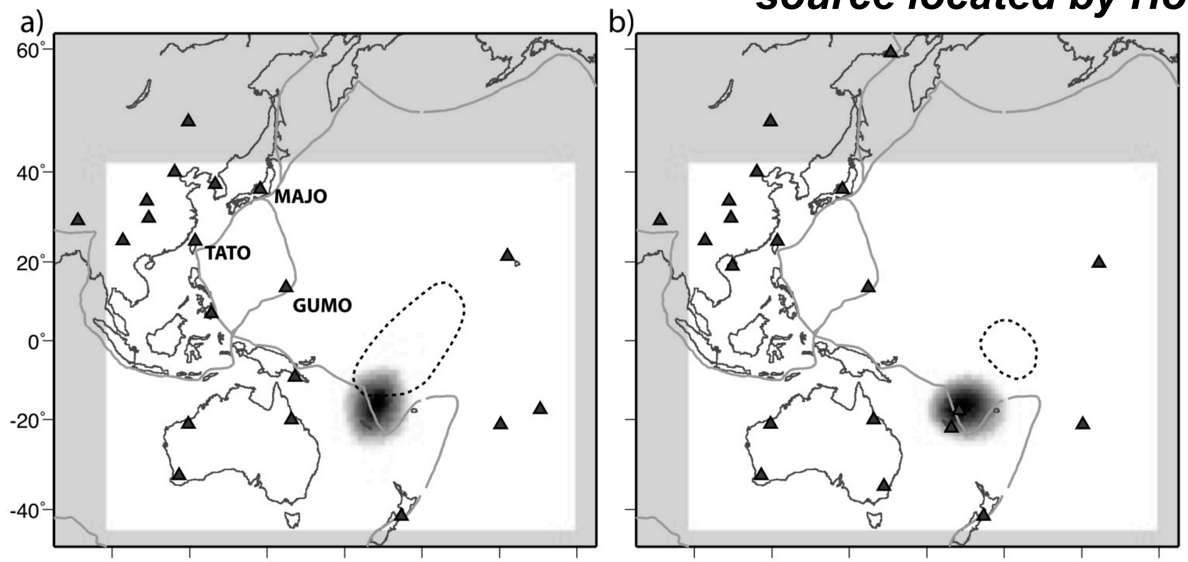
- **located in Gulf of Guinea (0S,0W)**

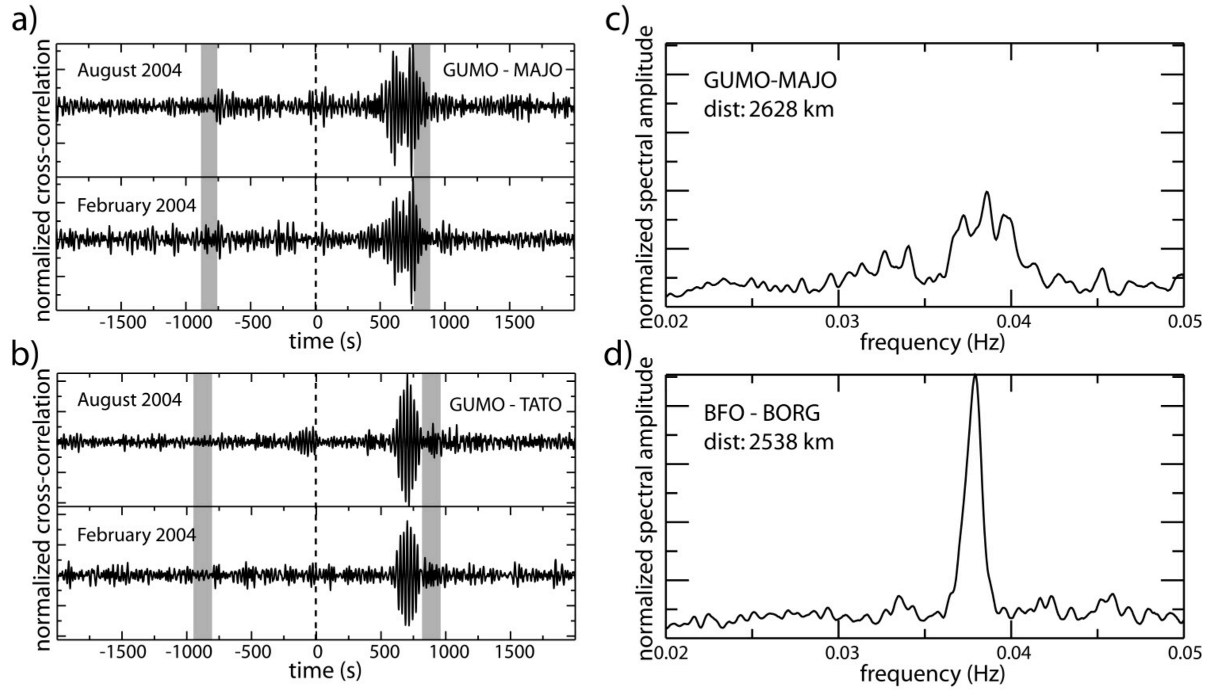


from Shapiro et al., 2006

26 s microseism

discovered by Oliver in 1962
source located by Holcomb in 1980

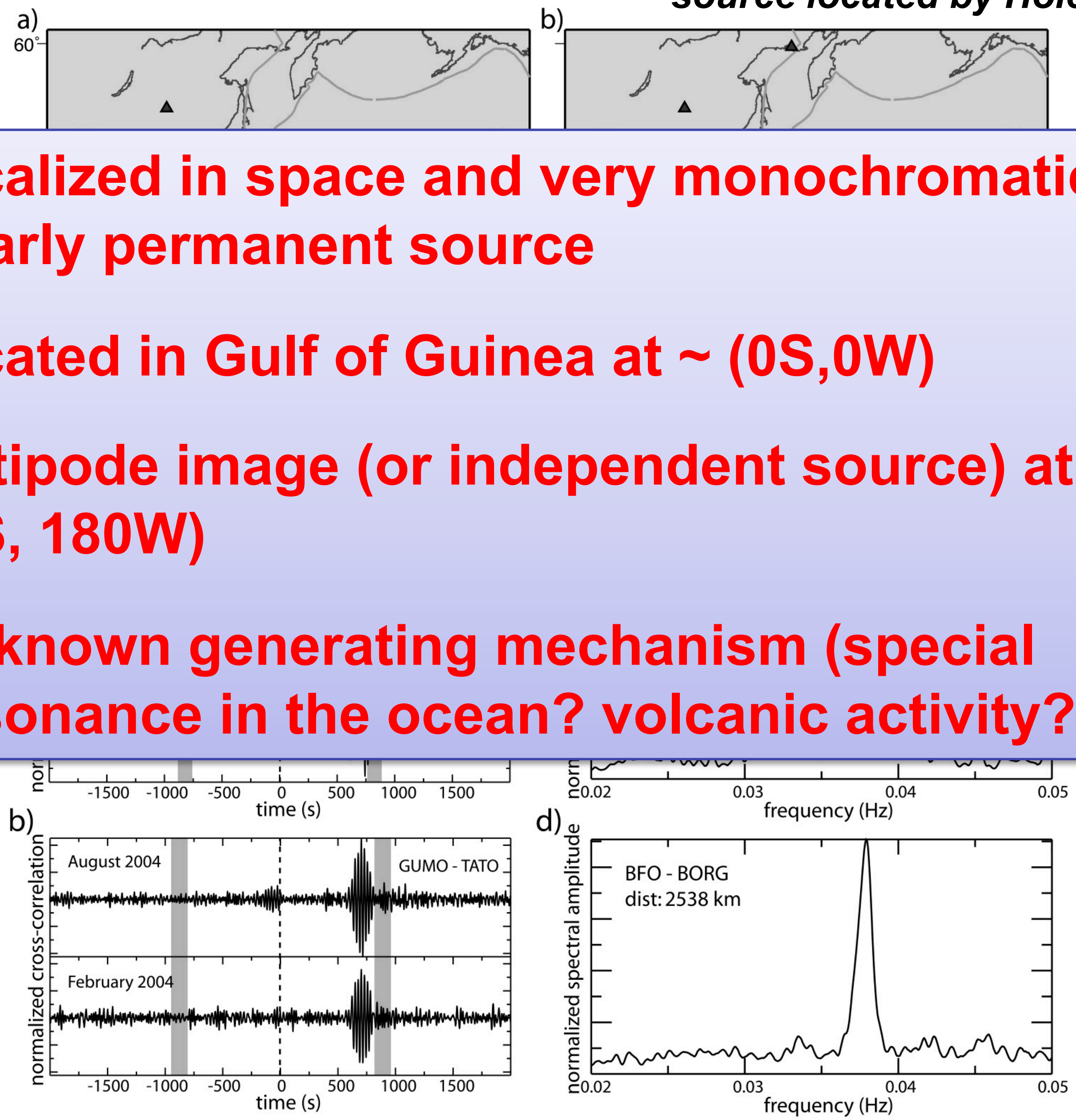




from Shapiro et al., 2006

26 s microseism

discovered by Oliver in 1962
source located by Holcomb in 1980



- **localized in space and very monochromatic nearly permanent source**
- **located in Gulf of Guinea at ~ (0S,0W)**
- **antipode image (or independent source) at ~ (0S, 180W)**
- **unknown generating mechanism (special resonance in the ocean? volcanic activity?)**

from Shapiro et al., 2006

Some conclusions

- Seismic wavefield in the Earth is not fully random and diffuse
- Seismic records must be pre-processed before cross-correlation to obtain a reasonable approximation of Green functions
- Seismic arrays can be used to characaterize the structure of the correlated wavefield
- We should think about array-based signal (wavefield) pre-processing
- Some sources of seismic noise remain enigmatic and their understanding is a strong scientific challenge

END