Listen to the Earth's hum for imaging and monitoring

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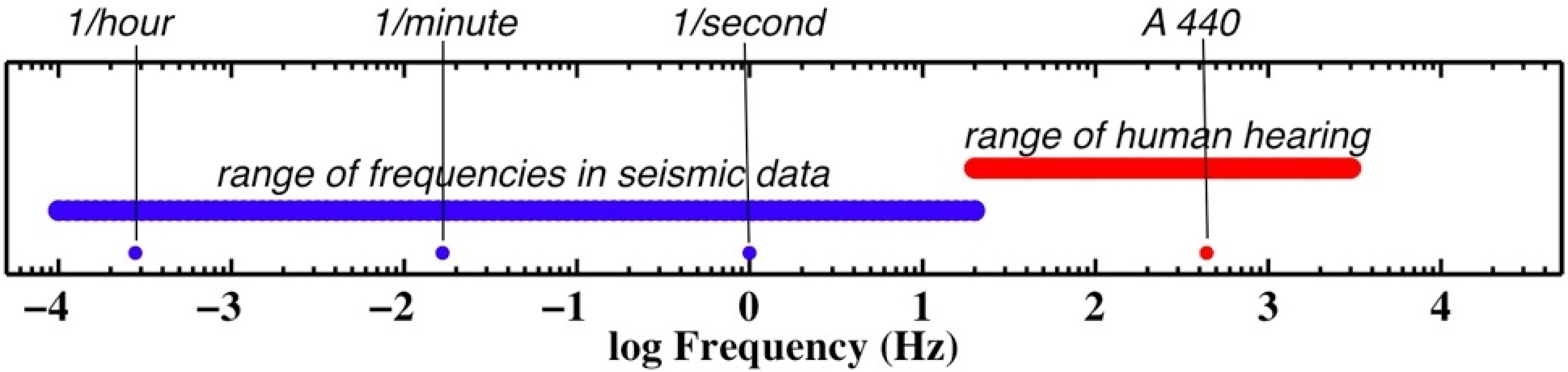
Listen to the (seismic) Earth's hum

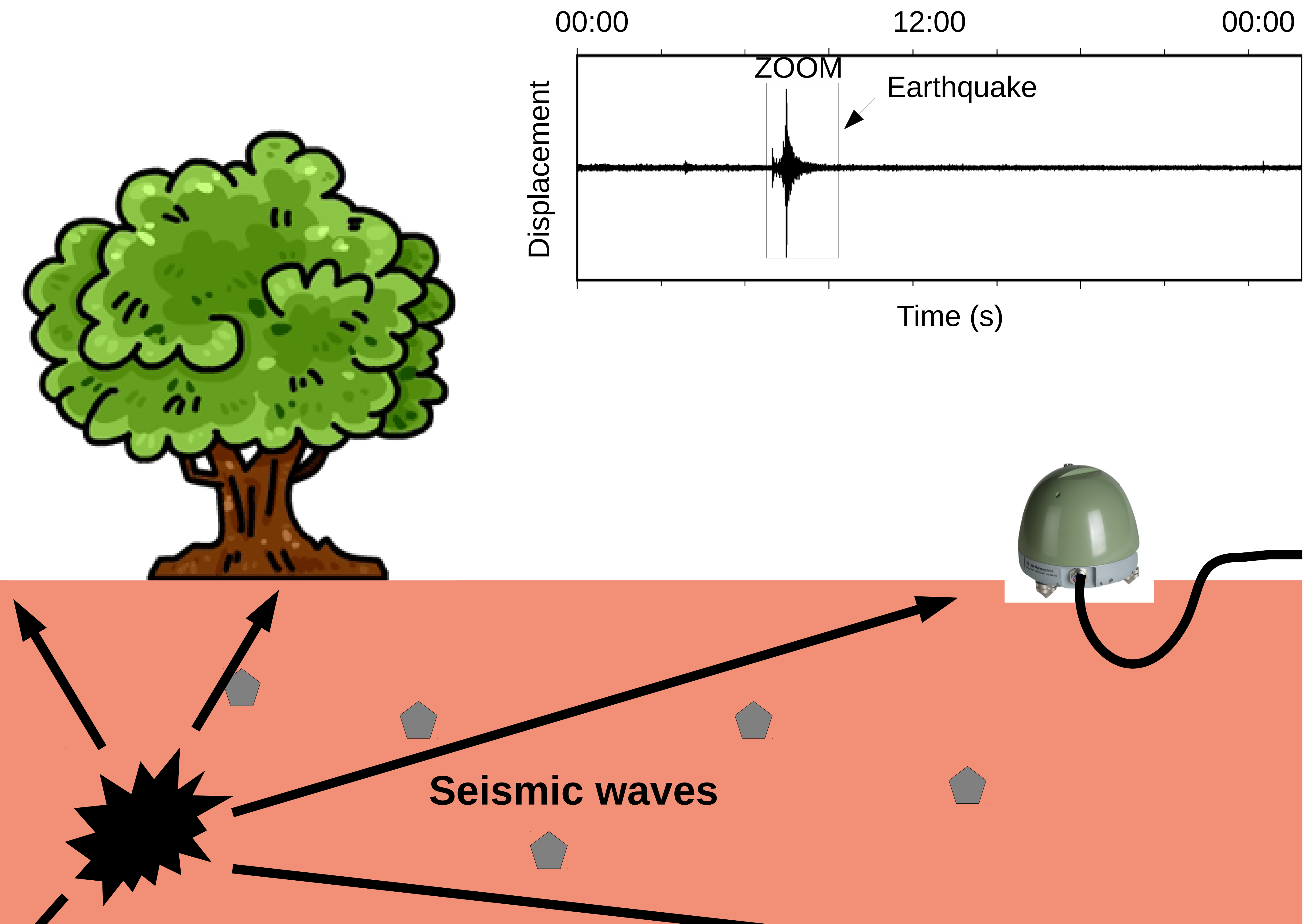


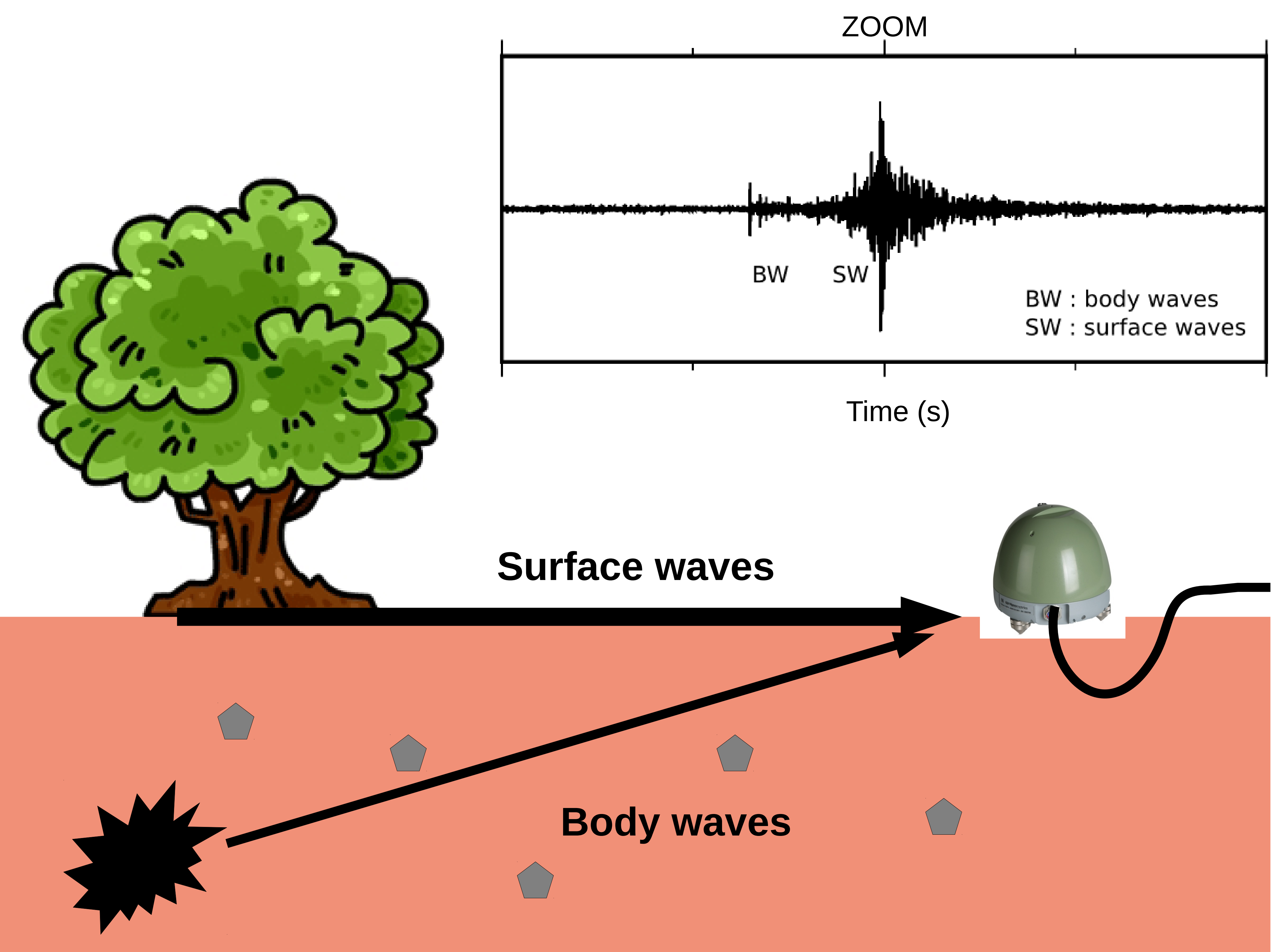
http://www.nanometrics.ca

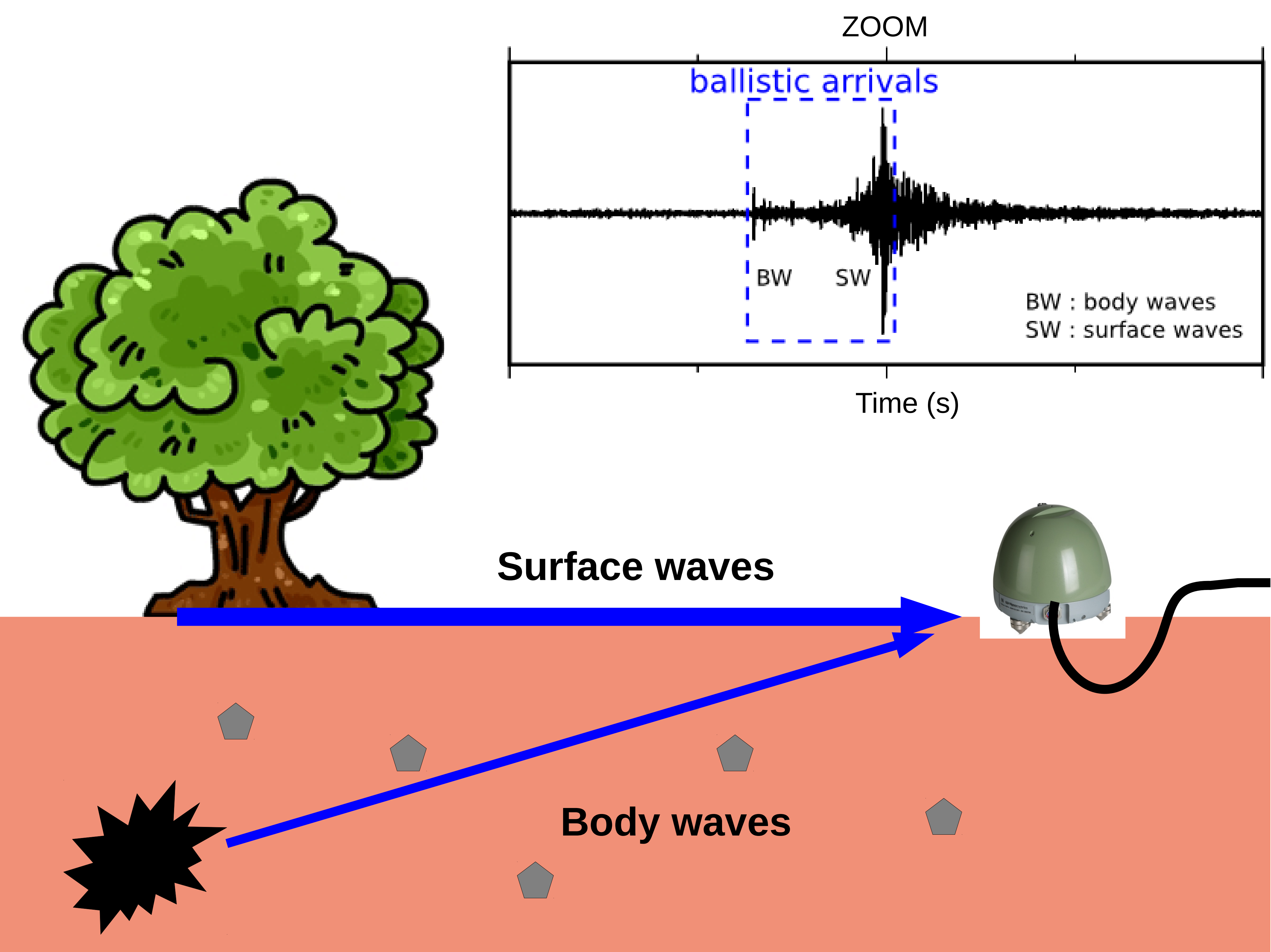
seismometer

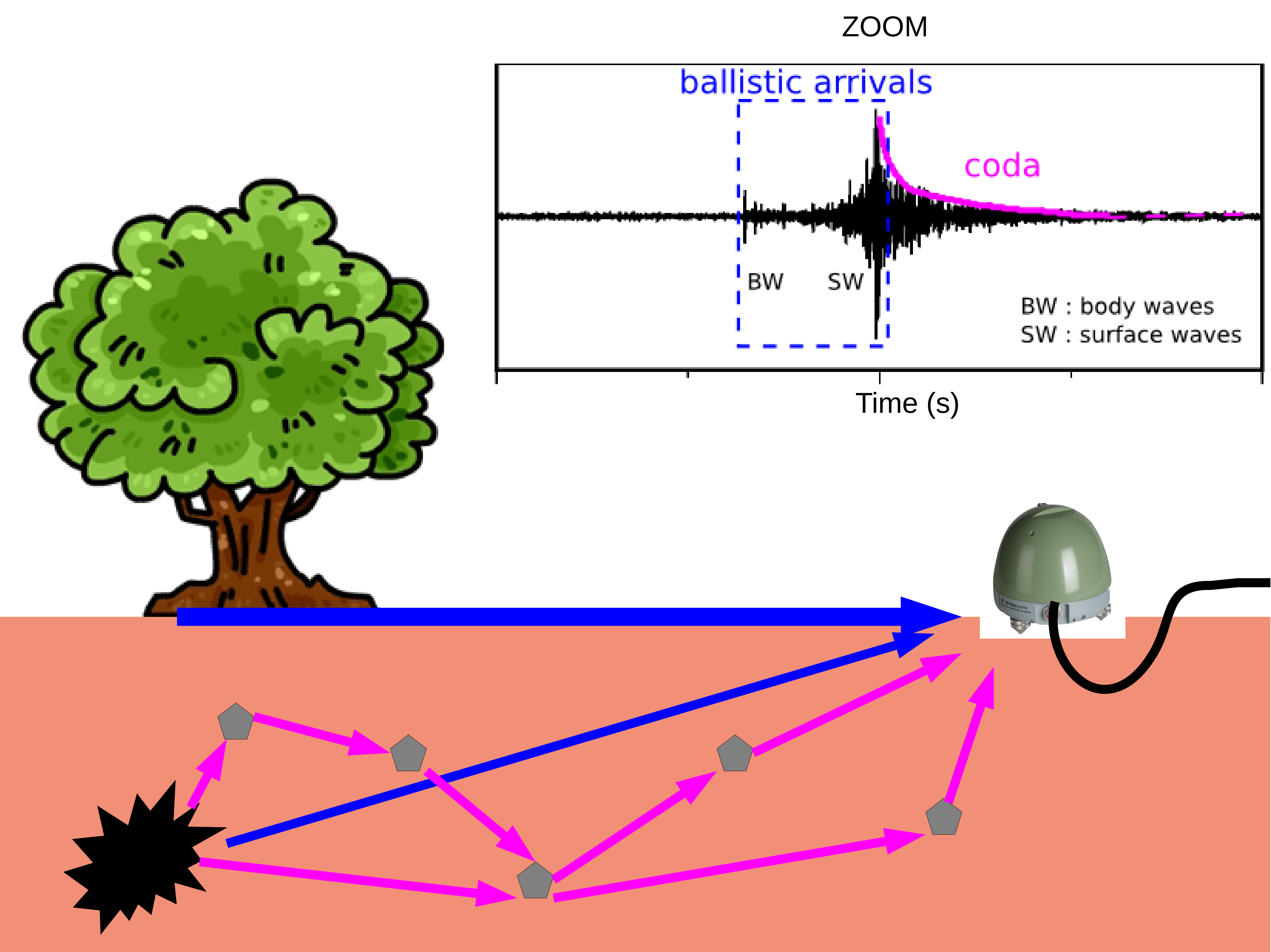
http://www.shure.fr/

microphone

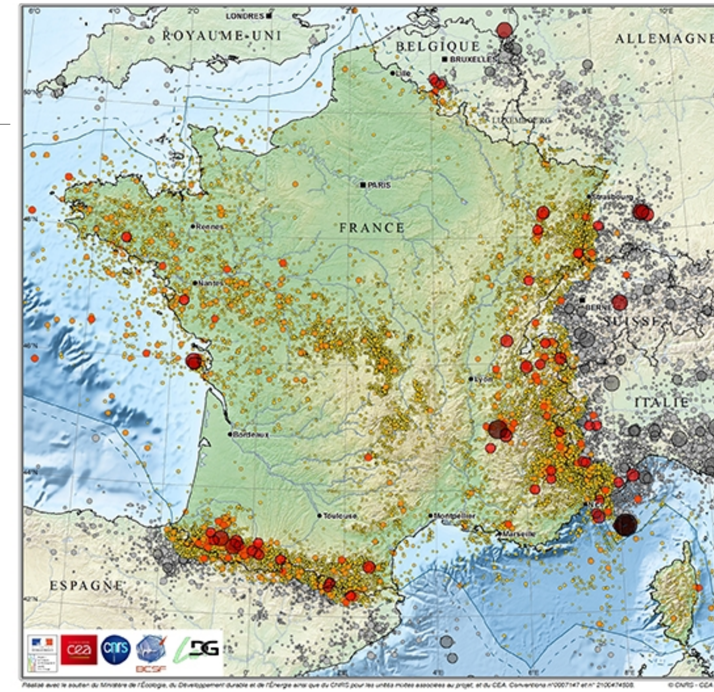

00:00
12:00
00:00
ZOOM
Earthquake
Displacement
Time (s)
Seismic waves


ZOOM
BW
SW
BW : body waves
SW : surface waves
Time (s)
Surface waves
Body waves


ZOOM
ballistic arrivals
BW
SW
BW : body waves
SW : surface waves
Time (s)
Surface waves
Body waves


ZOOM
ballistic arrivals
coda
BW
SW
BW : body waves
SW : surface waves
Time (s)

Why do we record seismic waves ?

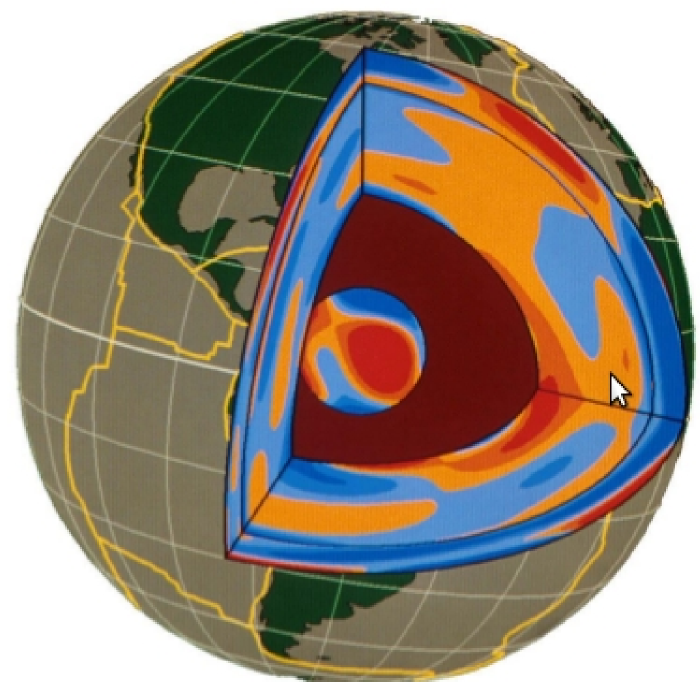


Cara et al., 2015

1) to understand the seismic source properties (location, magnitude)

crucial for seismic hazard assessment

2) for imaging and monitoring (Earth's) structures



https://science.rpi.edu/earth

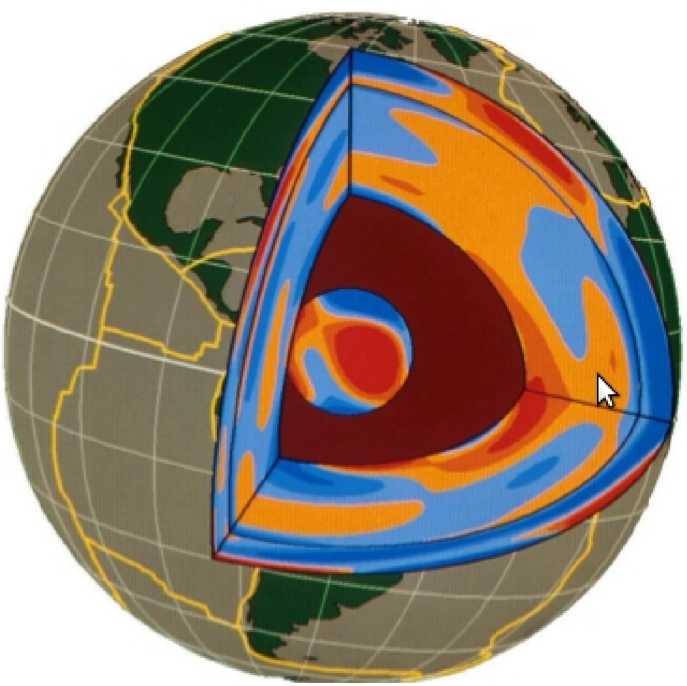
understand geodynamics
exploration (petroleum, etc...)
geotechnical engineering

Why do we record seismic waves ?

Imaging (Earth's) structures

understand geodynamics, exploration (petroleum, etc...) , geotechnical engineering

Seismic imaging



https://science.rpi.edu/earth

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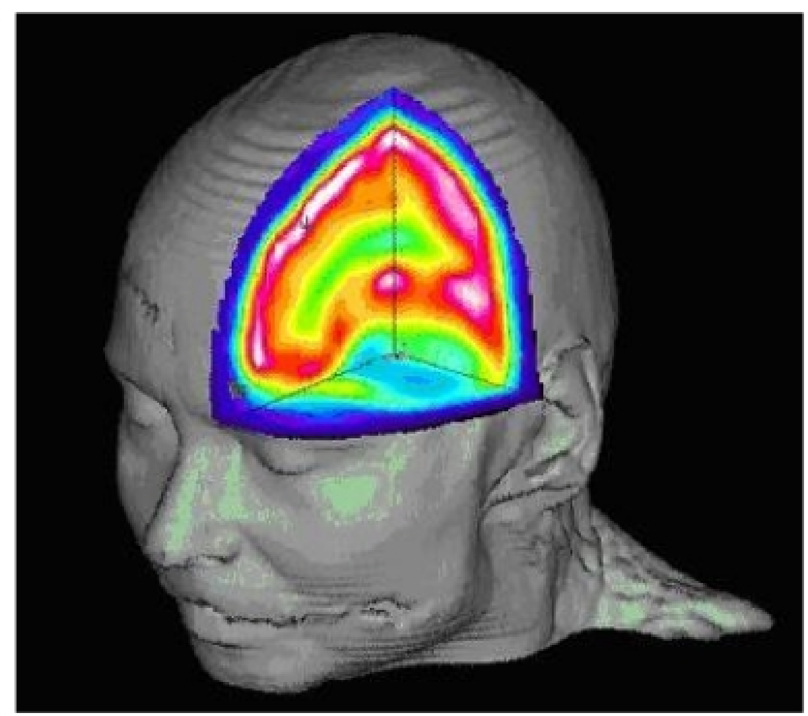
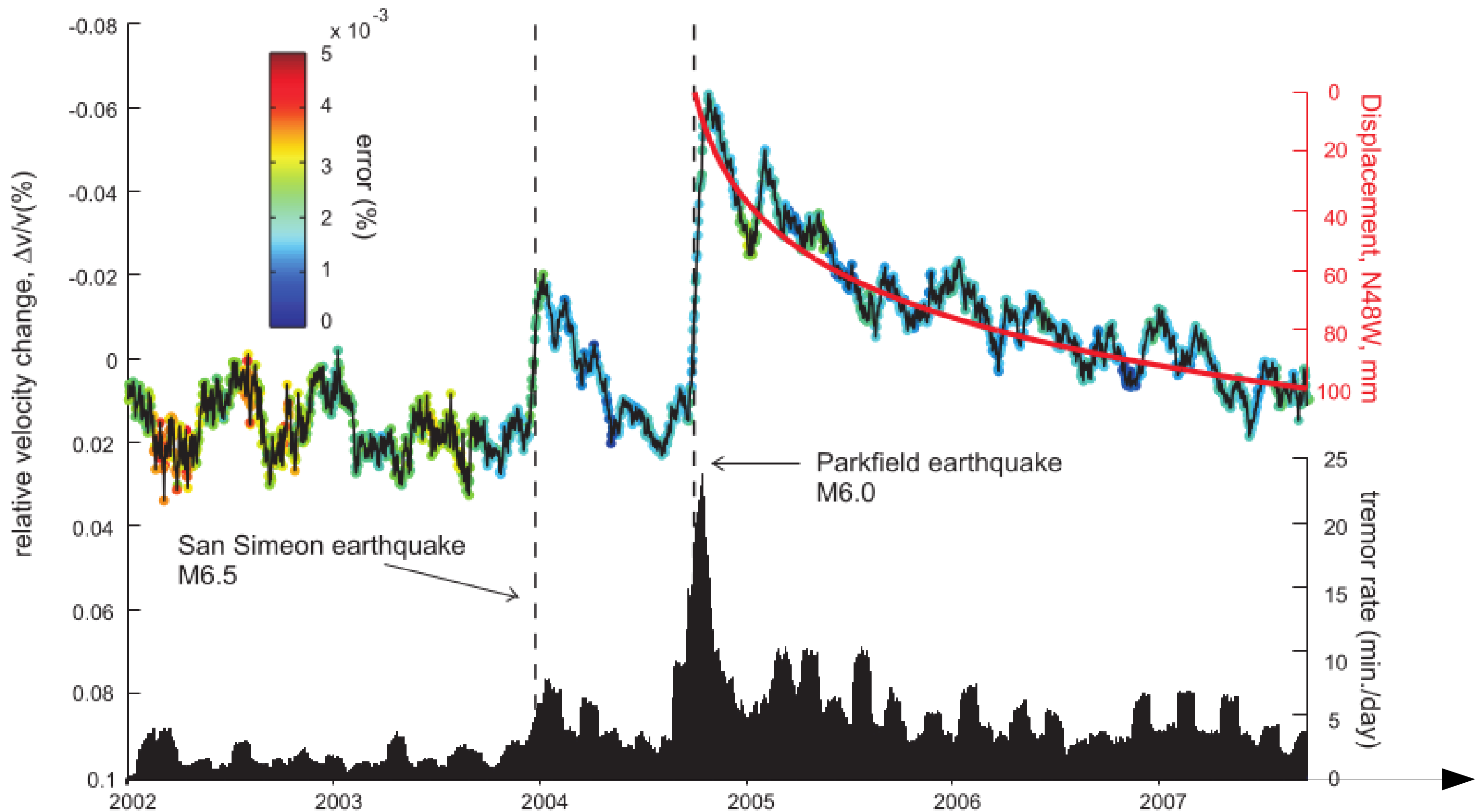
Medical imaging



Why do we record seismic waves ?

Monitoring (Earth's) structures (4D imaging, temporal variations)

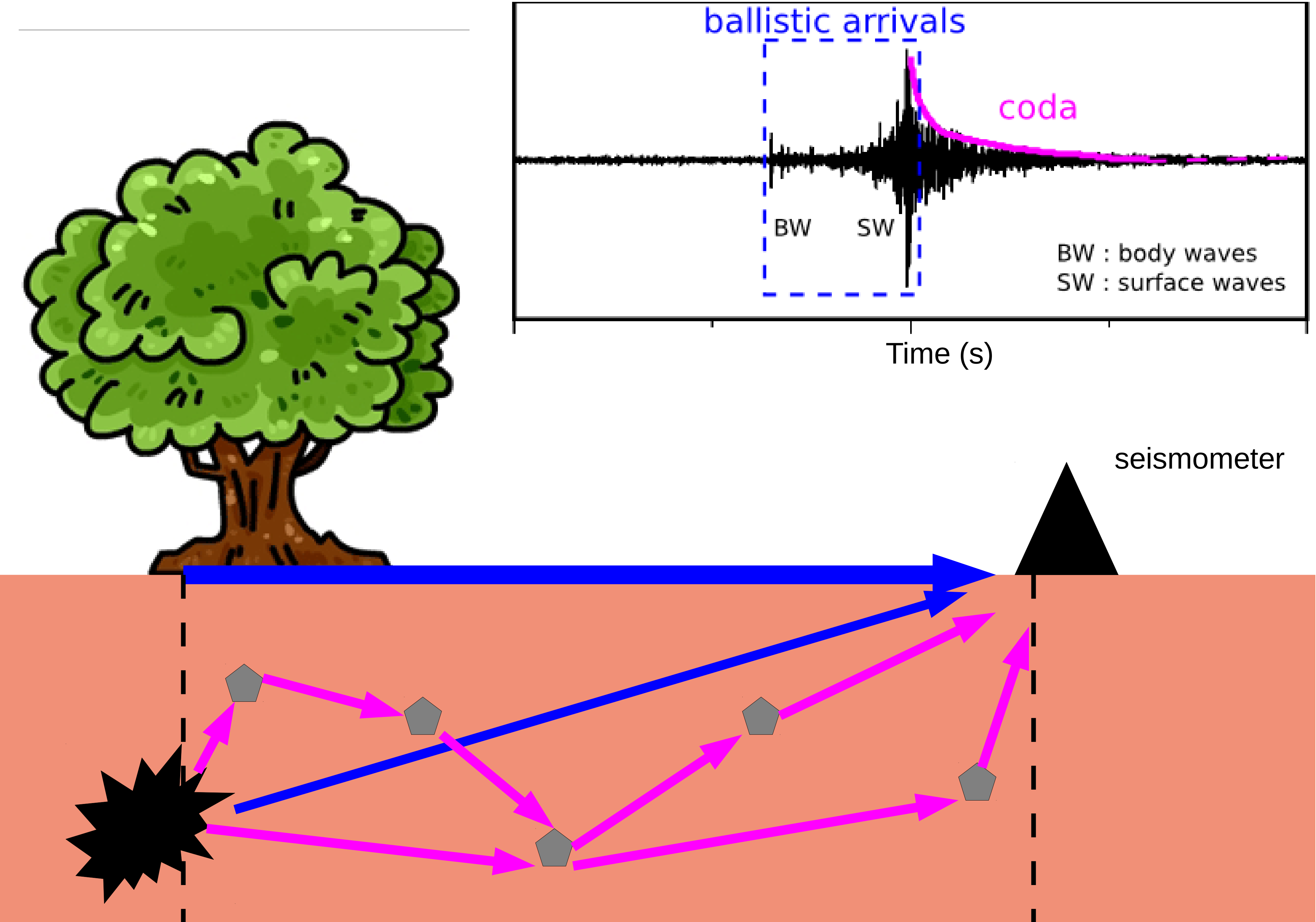
understand geodynamics, exploration (petroleum, etc...) , geotechnical engineering



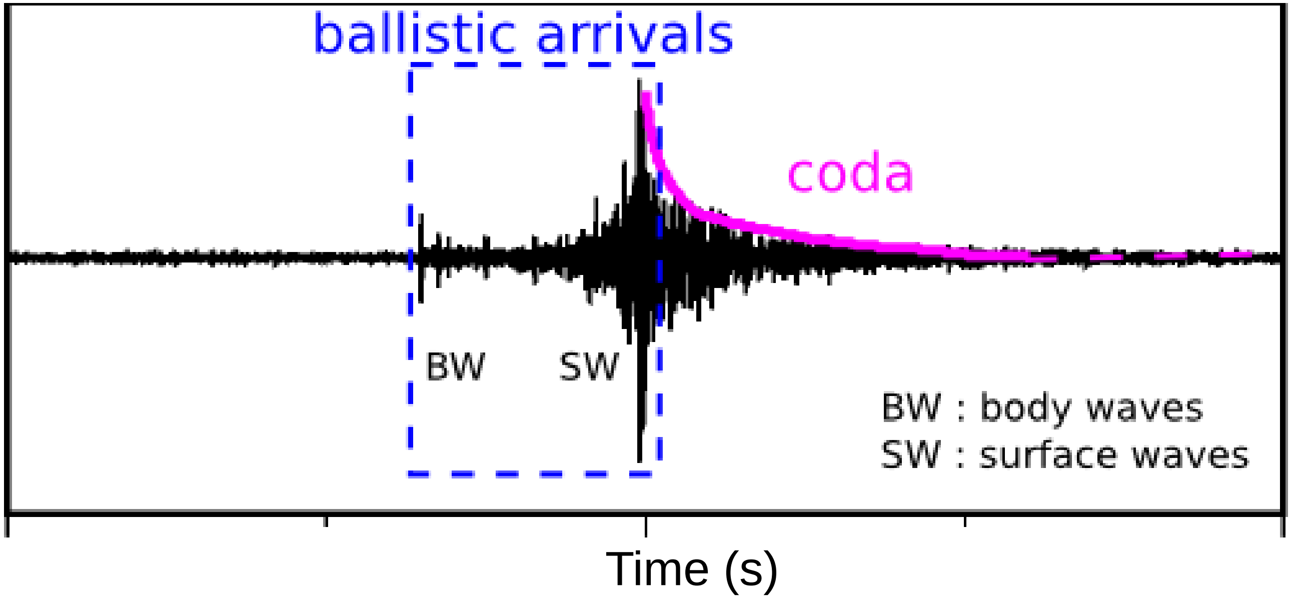
From Brenguier et al., 2008

Time (year)

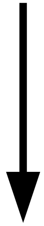
The Green's function



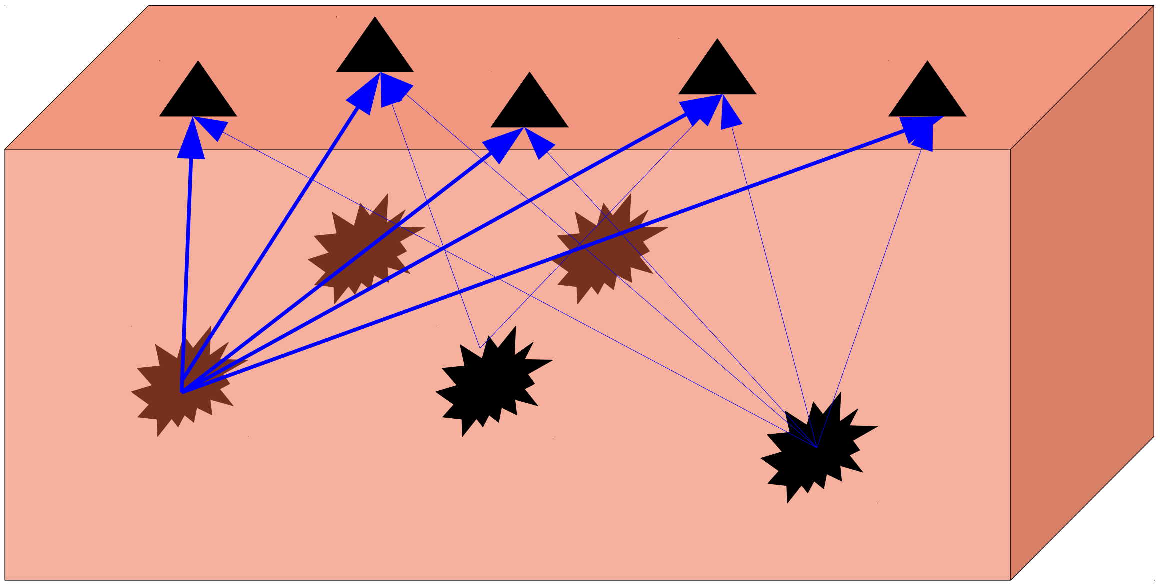
The Green's function

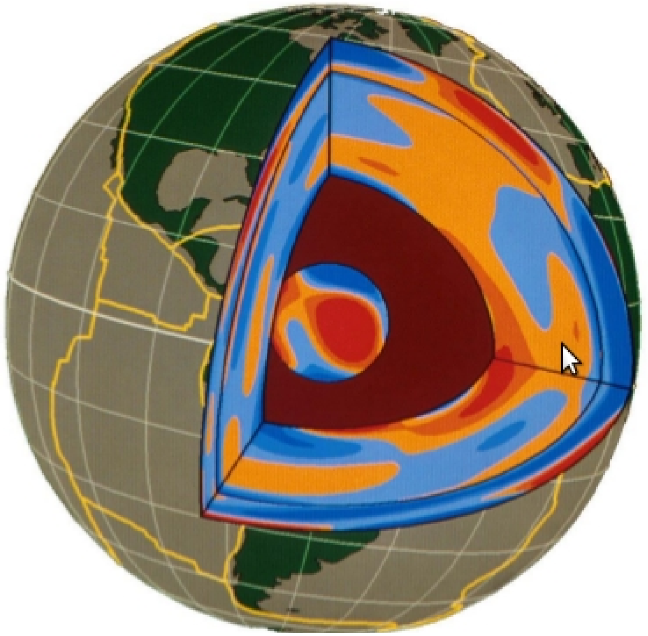


Compilation of
Green's functions



3D seismic imaging

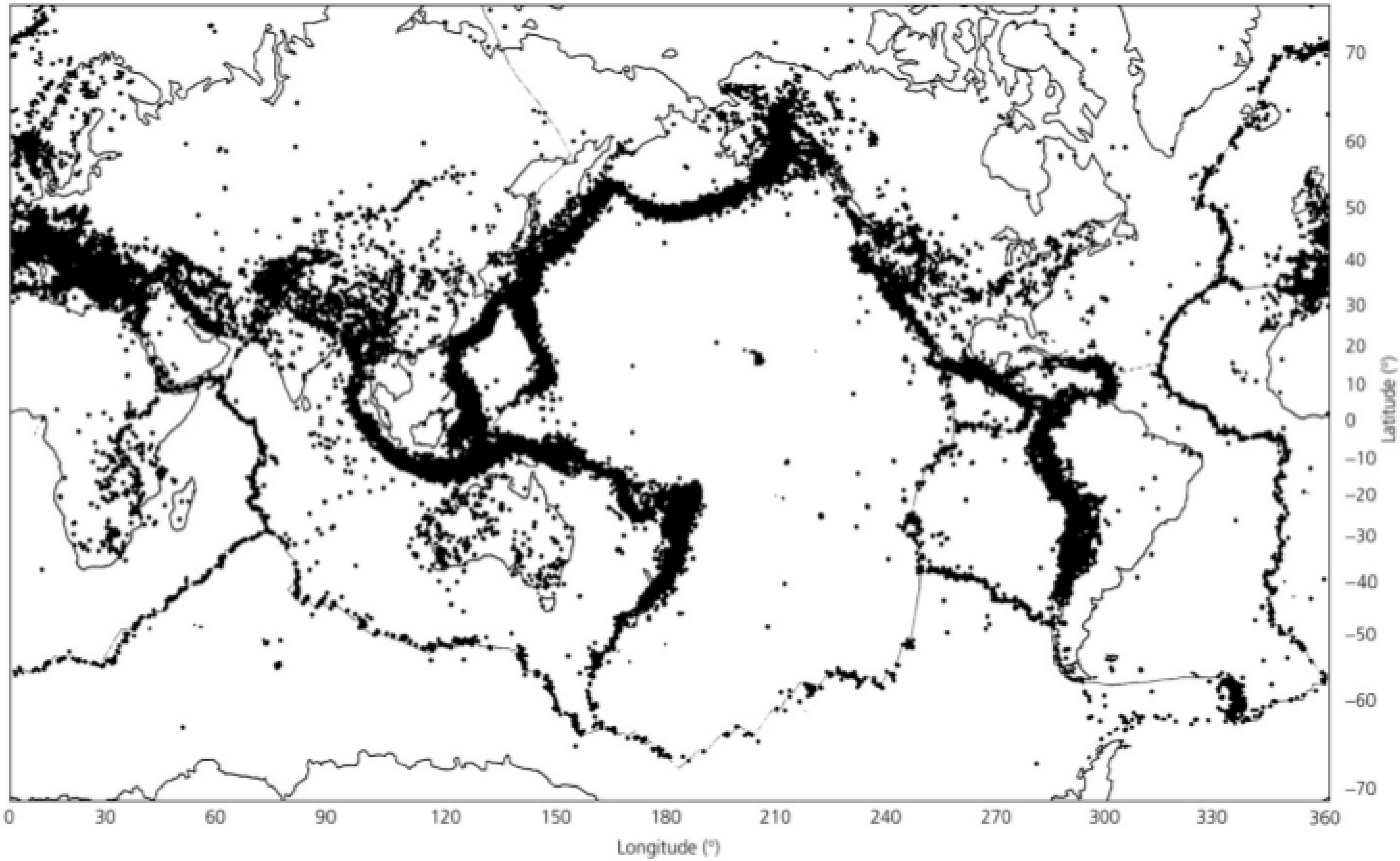




https://science.rpi.edu/earth

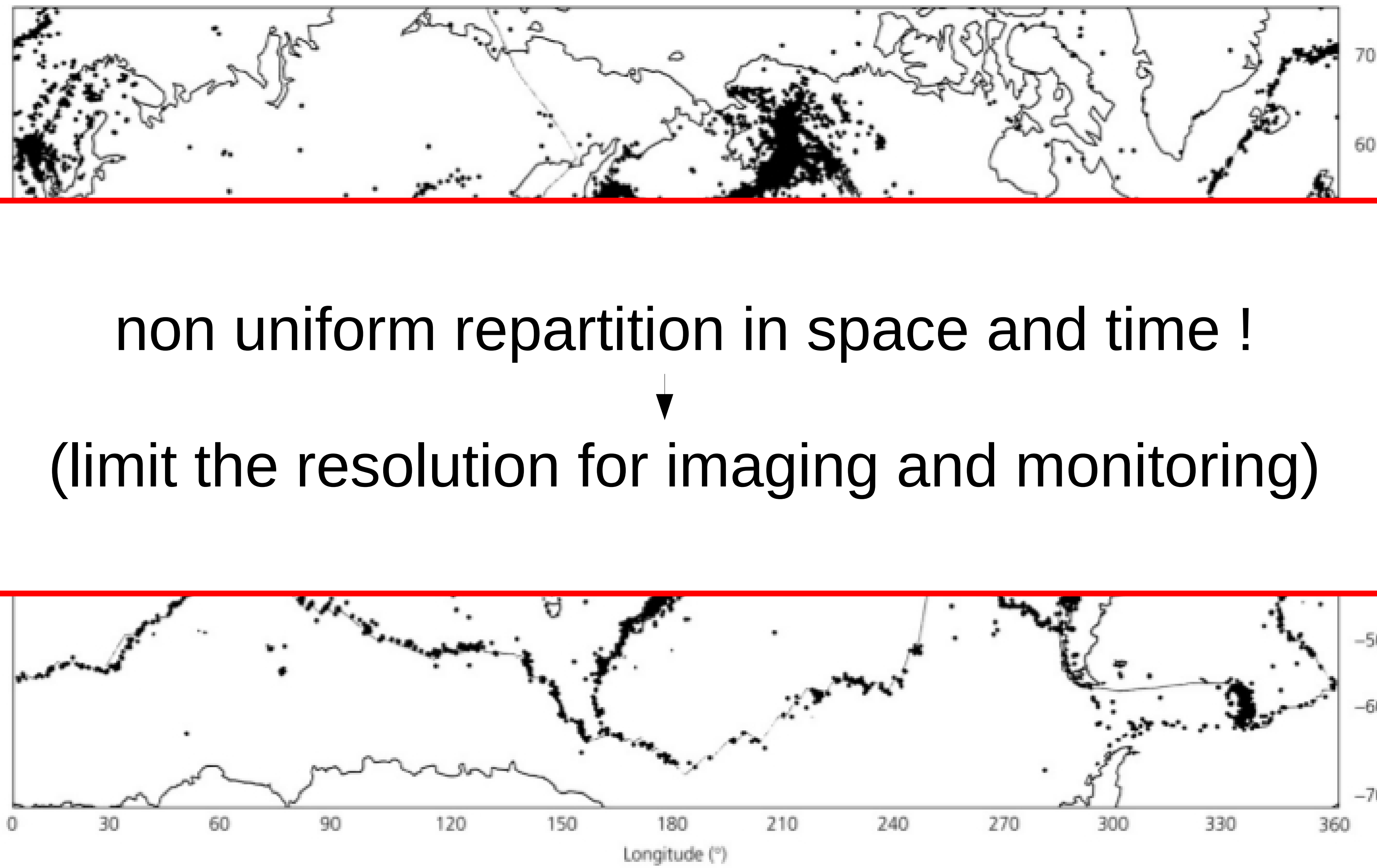
Limitations of the technique

Global seismicity 1963-1995



Limitations of the technique

Global seismicity 1963-1995



non uniform repartition in space and time !

↓

(limit the resolution for imaging and monitoring)

Limitations of the technique

Lac Nègre, french Alps, 1966

http://www.ecpad.fr

Explosives
Seismic Vibrator trucks
etc....

Limitations of the technique

Lac Nègre, french Alps, 1966

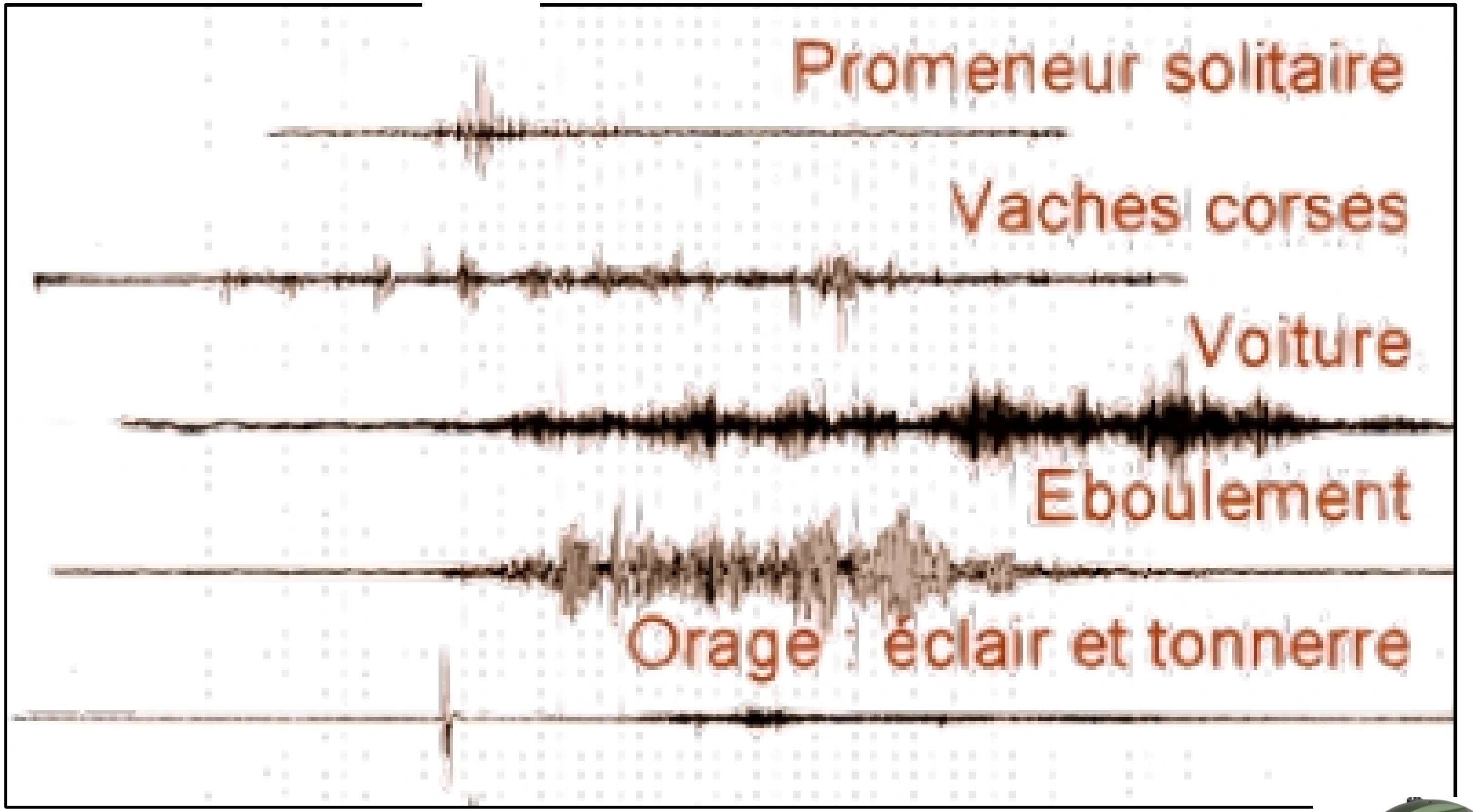
http://www.ecpad.fr

high costs, challenging field conditions !

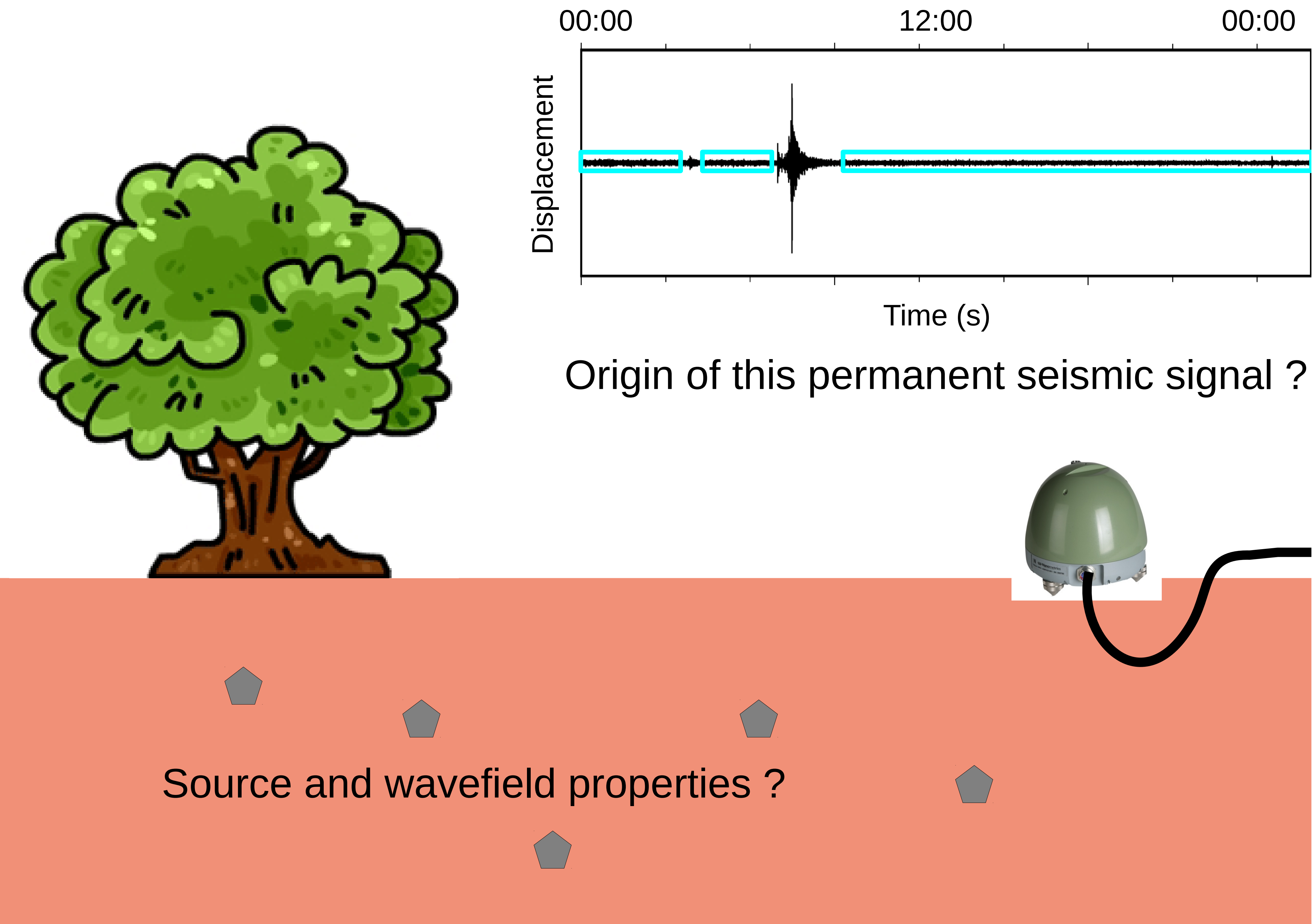
↓

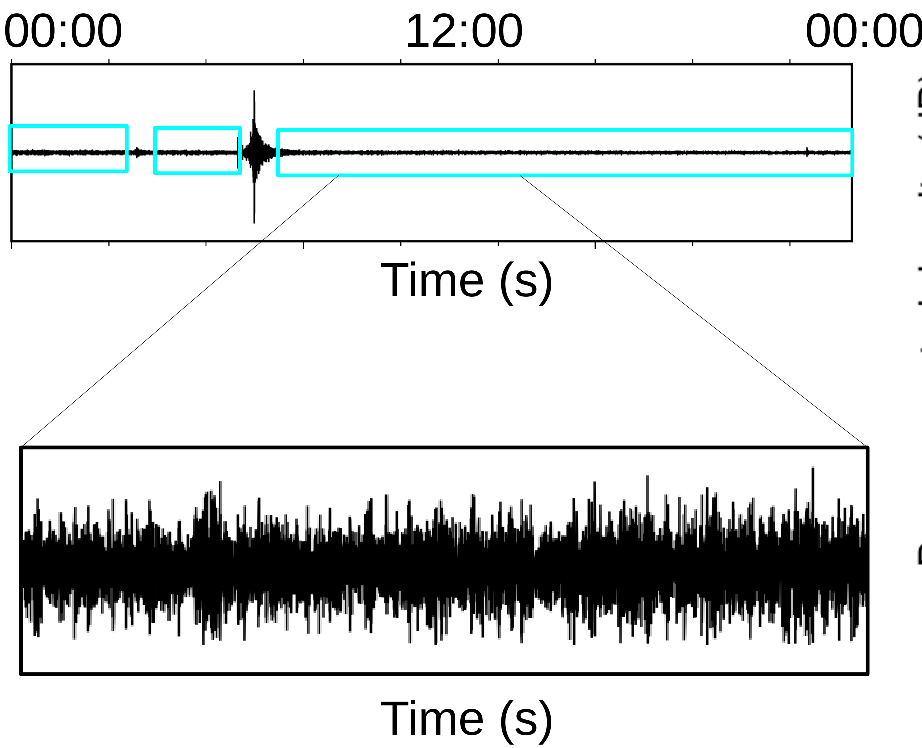
limit the resolution for imaging and monitoring

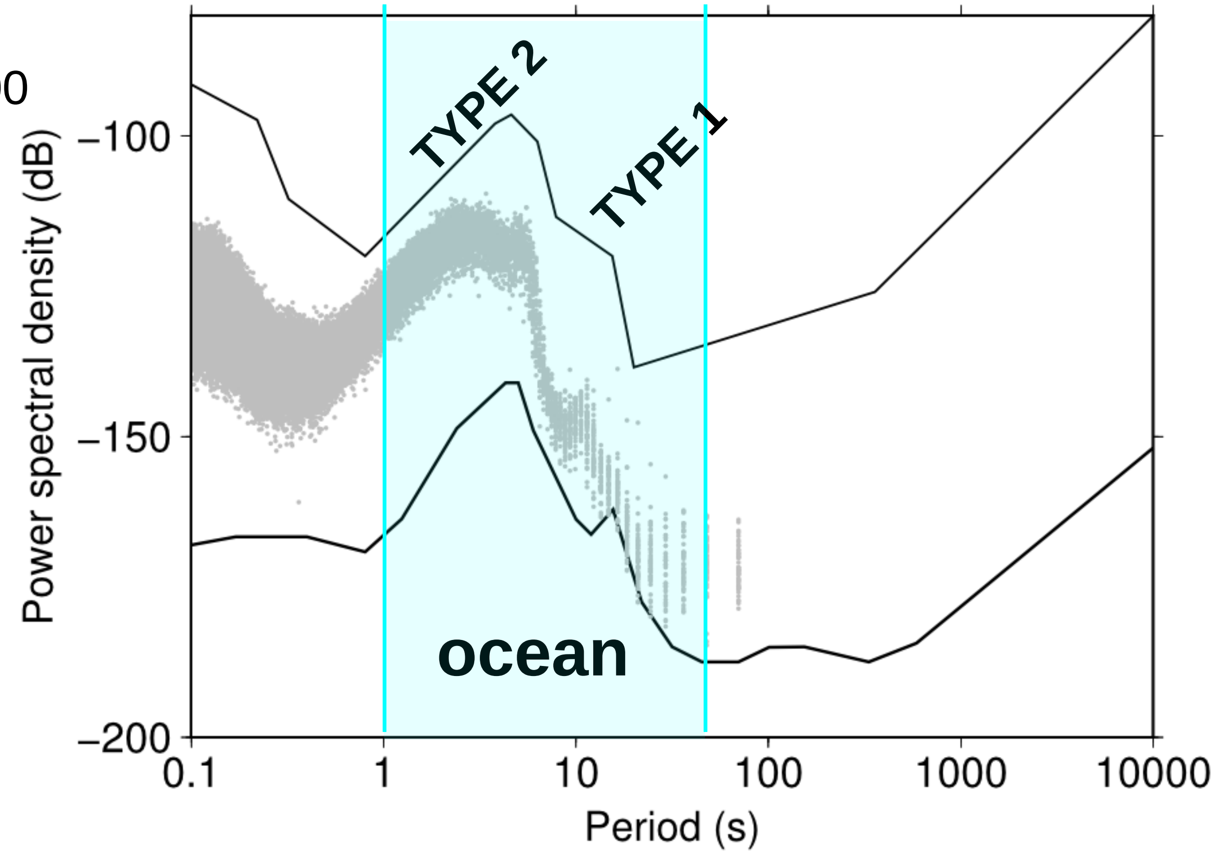
Continuous seismic records contain a lot of different signal of various origins

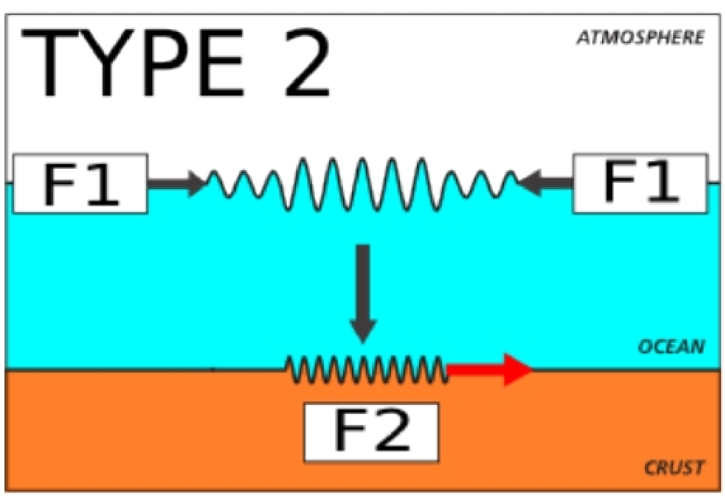


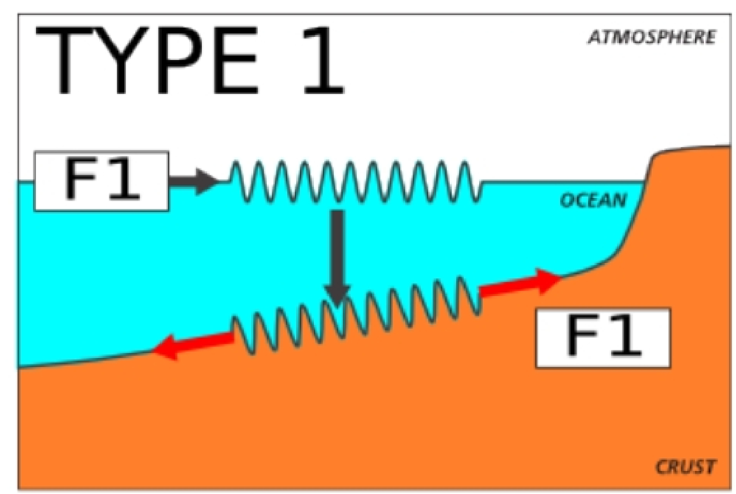
F. Thouvenot, pers. comm.


00:00
12:00
00:00
Displacement
Time (s)
Origin of this permanent seismic signal ?
Source and wavefield properties ?

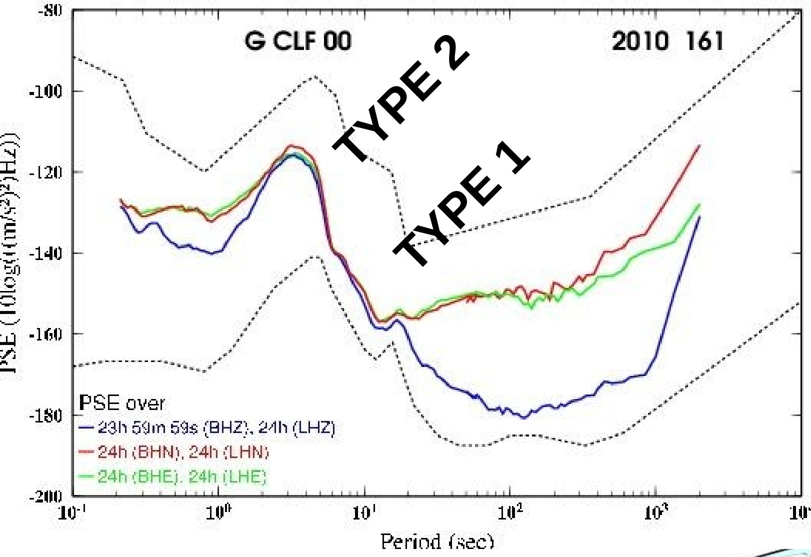




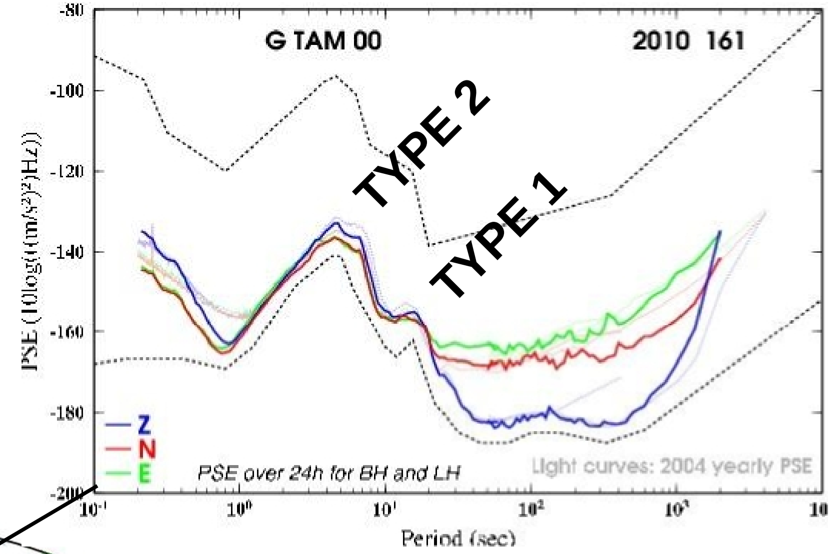


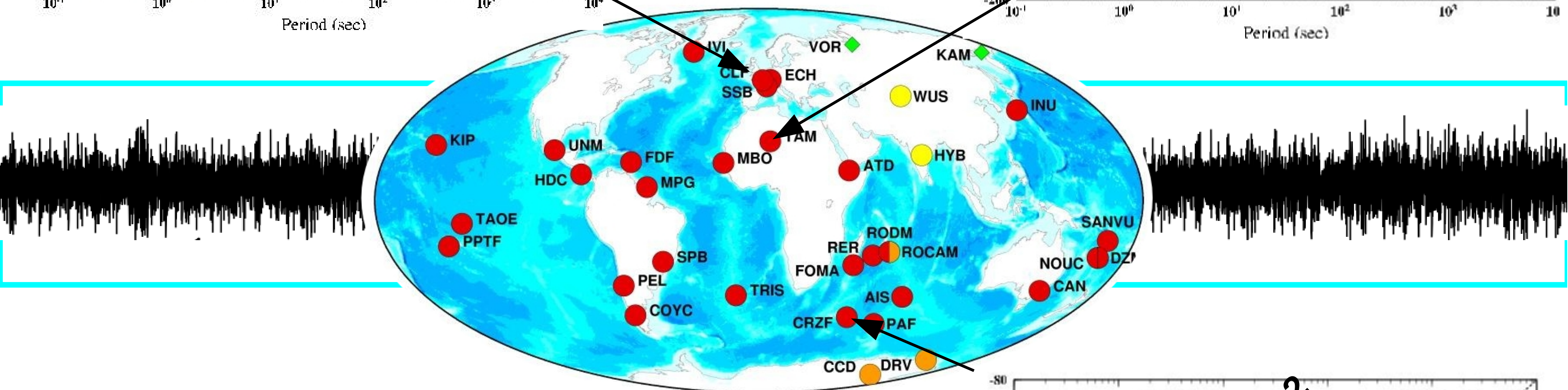


D'après Ebeling, 2012

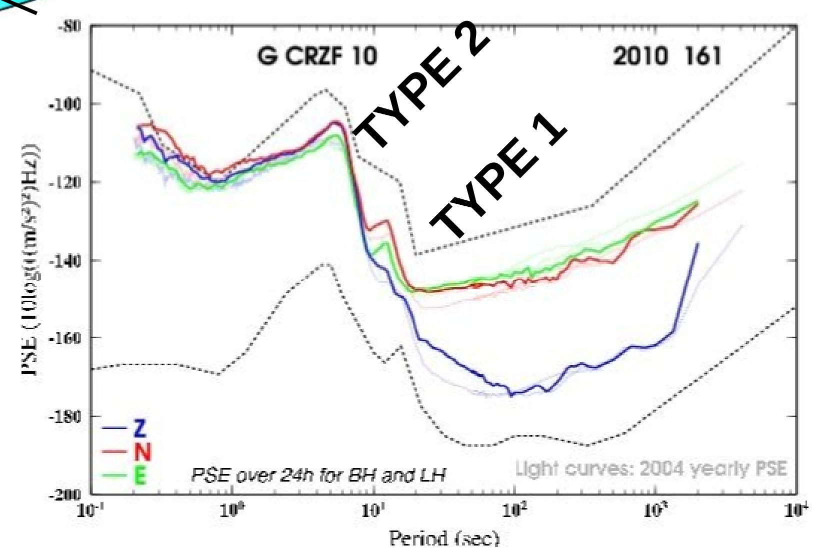


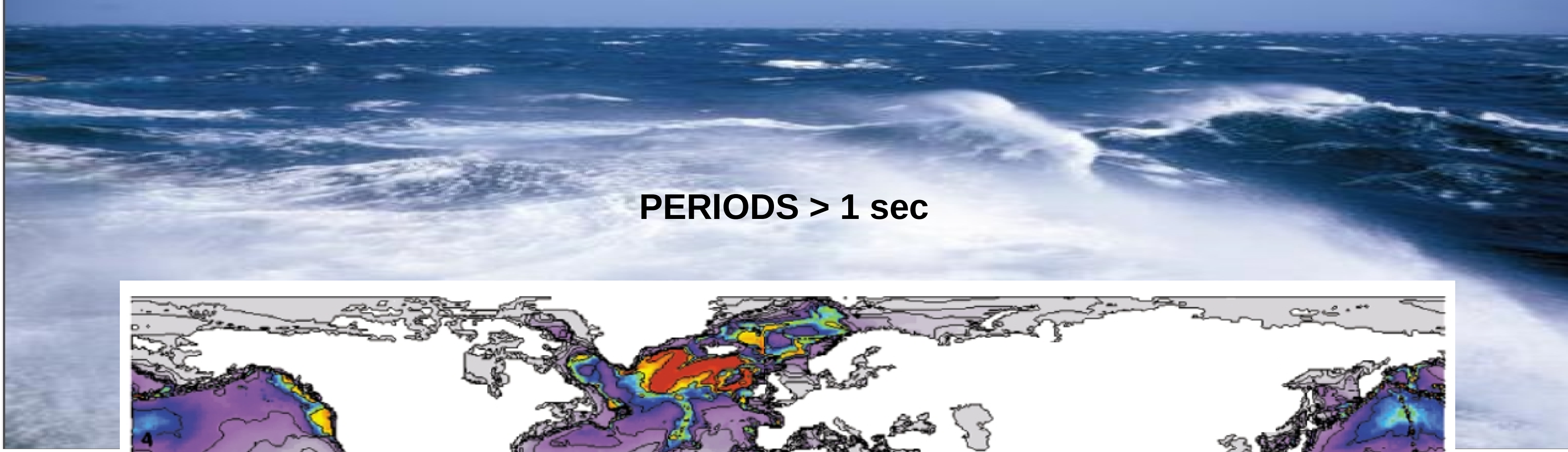
PERIODS > 1 sec

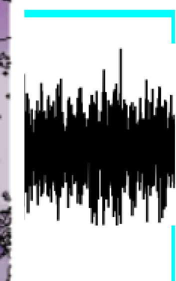


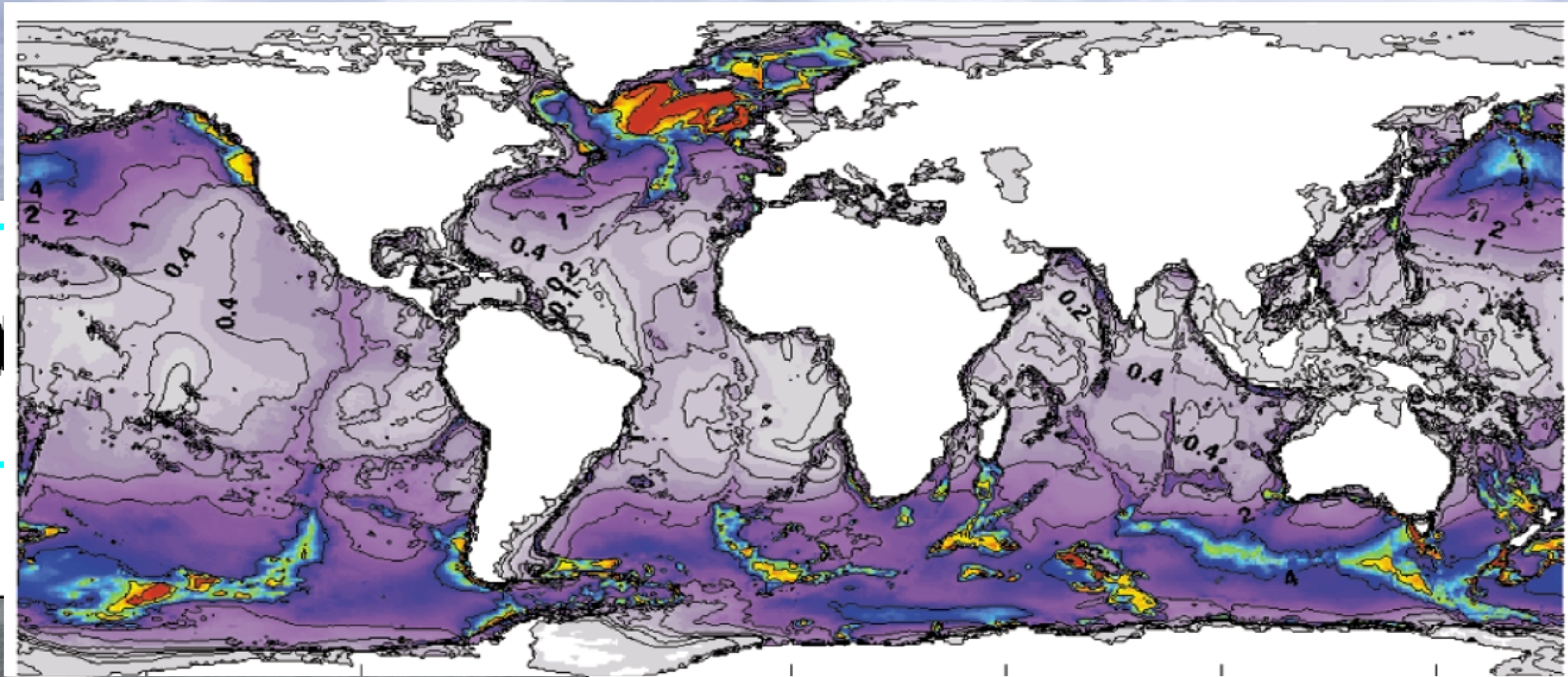


http://geoscope.ipgp.fr



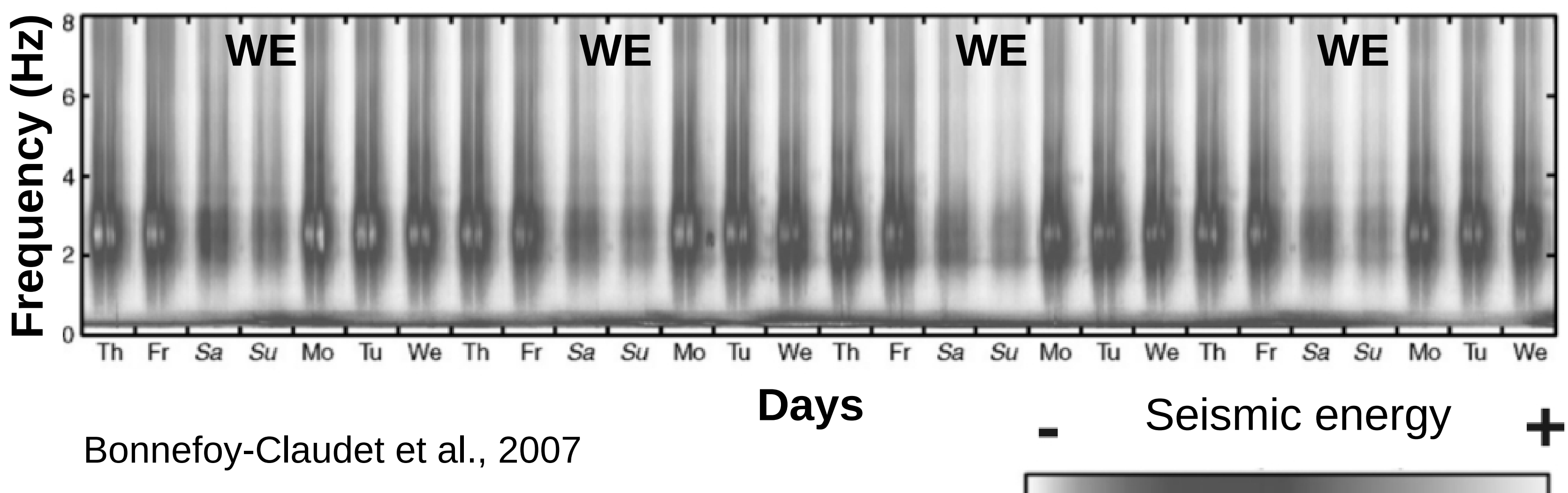






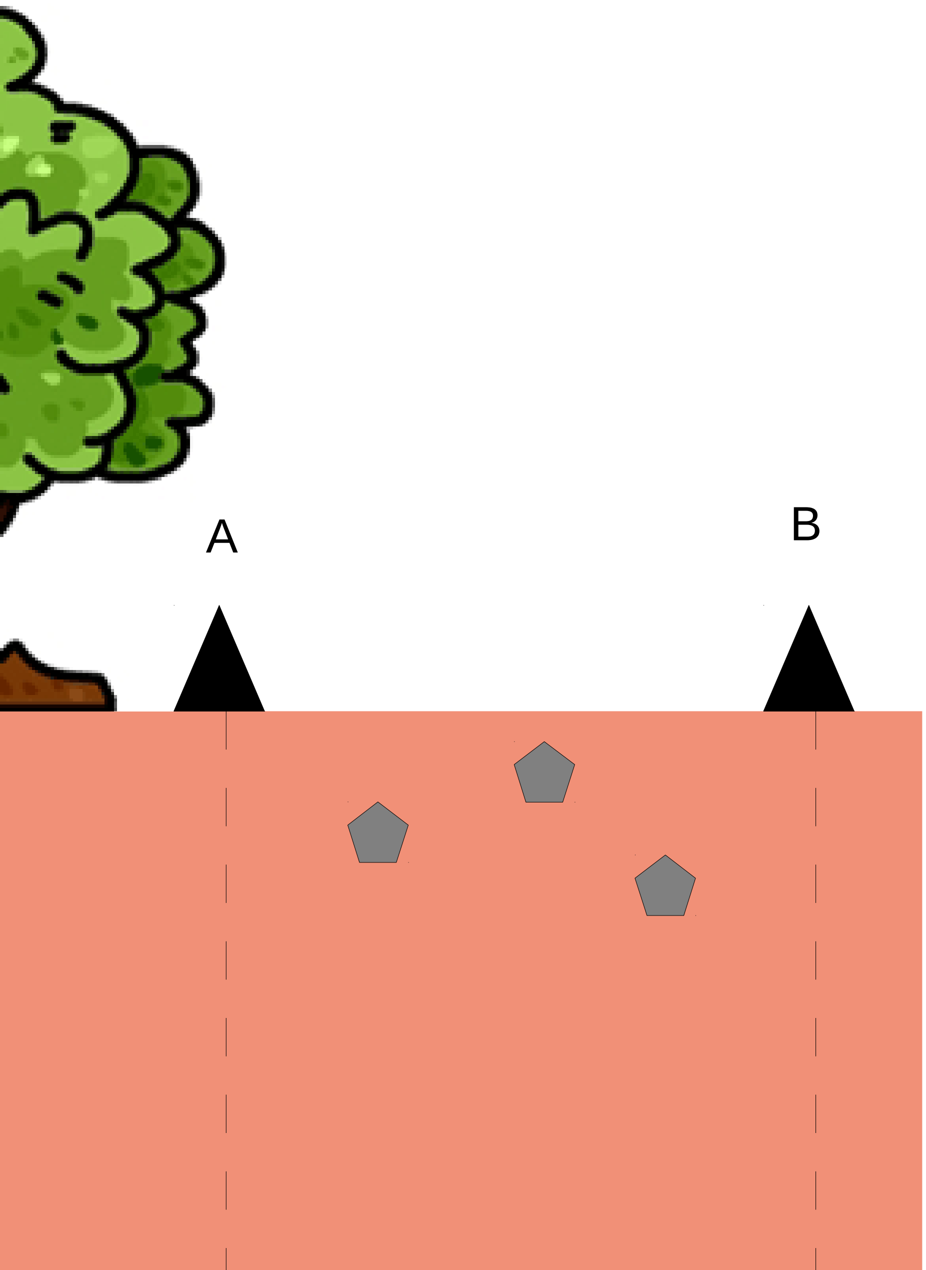
Ardhuin et al., 2009

PERIODS < 1 sec

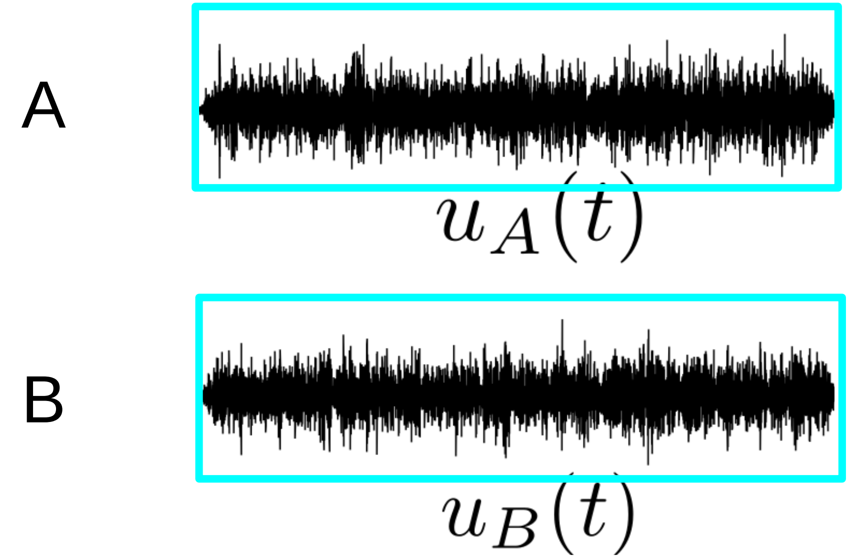


Bonnefoy-Claudet et al., 2007

Correlation and Green's function

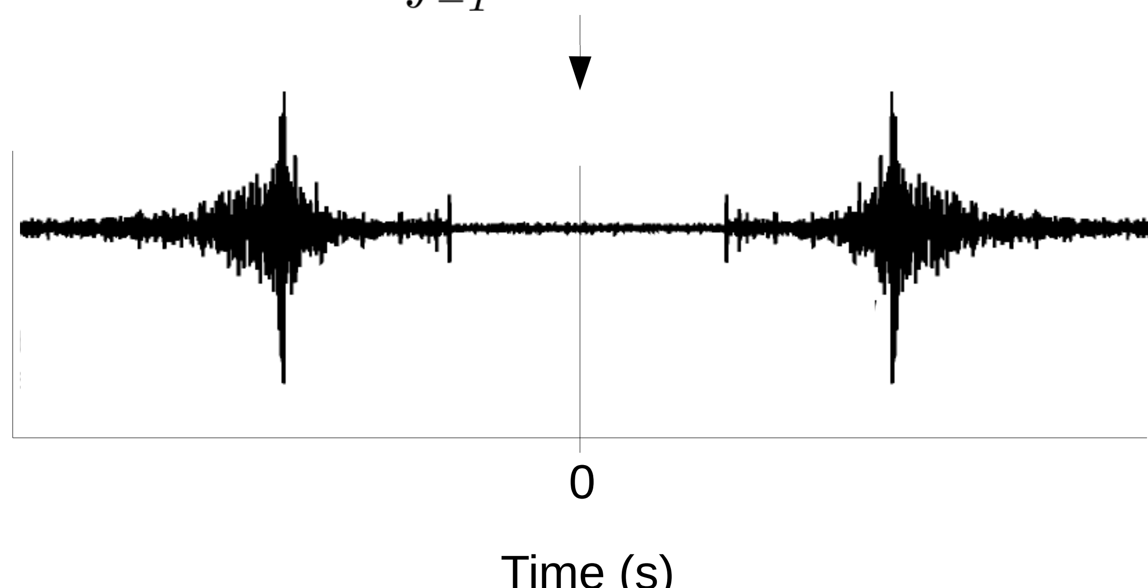


long record duration T

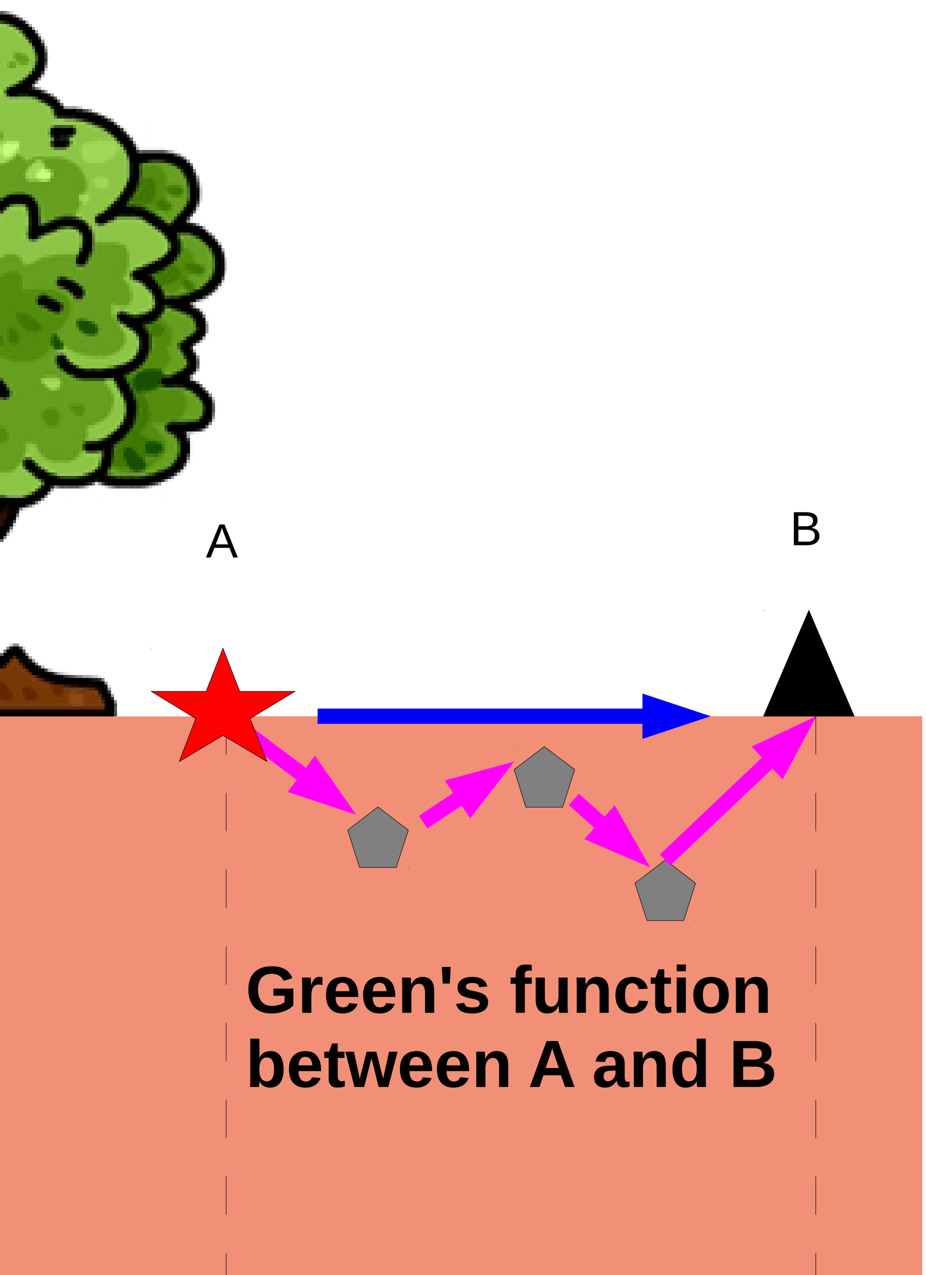


cross-correlation

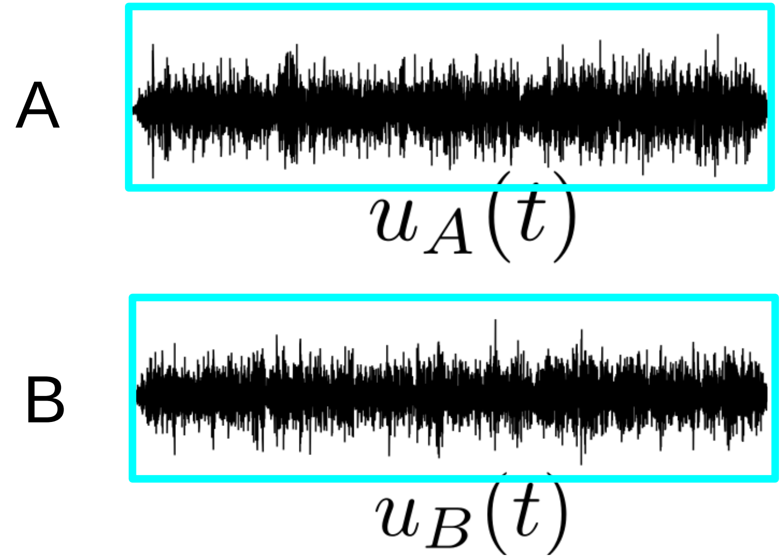
$$cc_{AB}(\tau) = \int_{-T}^{T} u_A(t) \; u_B(t+\tau)\mathrm{d}t$$



Correlation and Green's function



long record duration T



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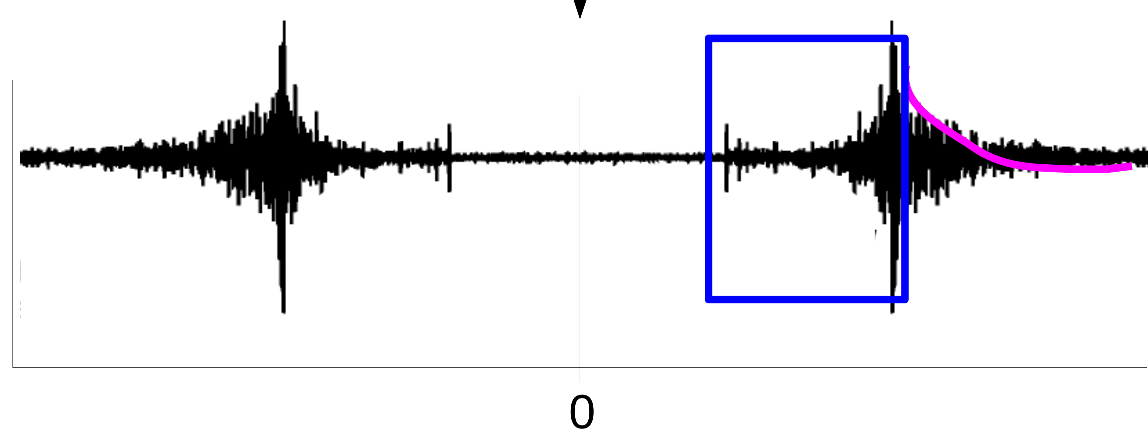
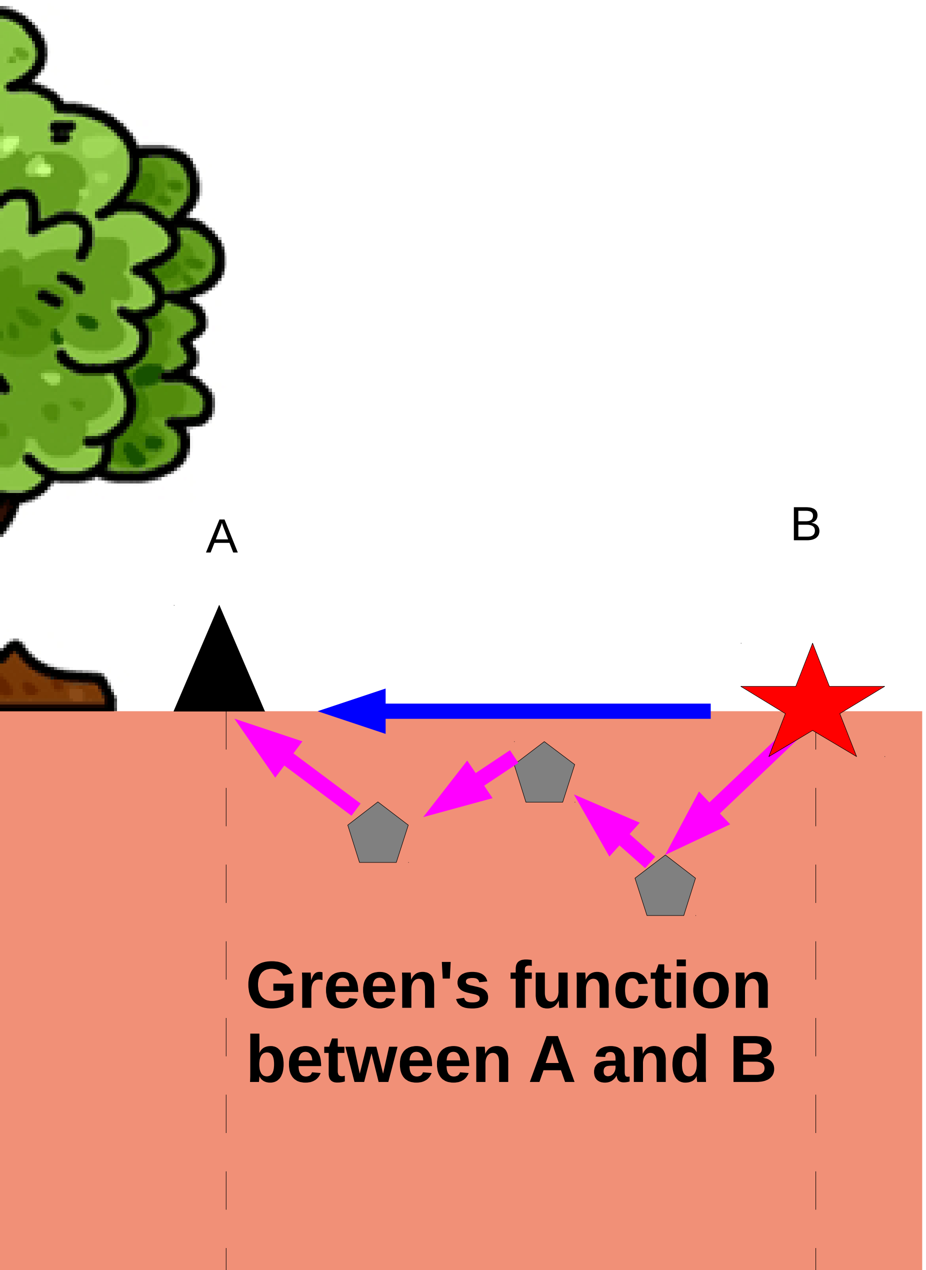
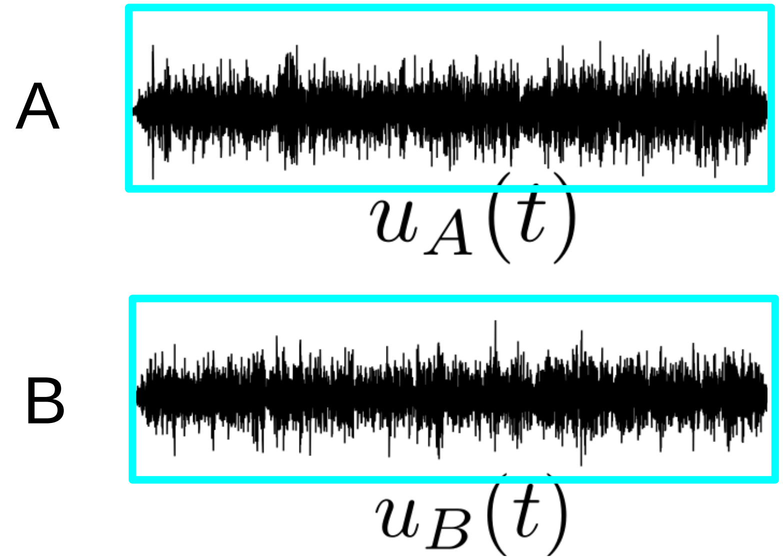


Correlation and Green's function



long record duration T



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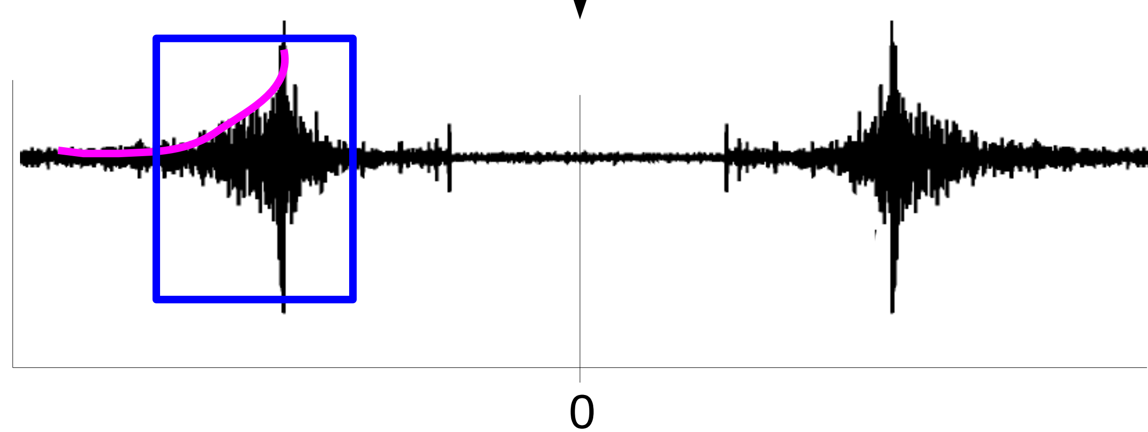


Listen to the Earth's hum

Listen to the Earth's hum : a revolution in seismology !

Earth's hum available **everywhere and at any time**

NO DETERMINISTIC SOURCES NEEDED !

revolution for **imaging** and **monitoring**

Listen to the Earth's hum for imaging and monitoring

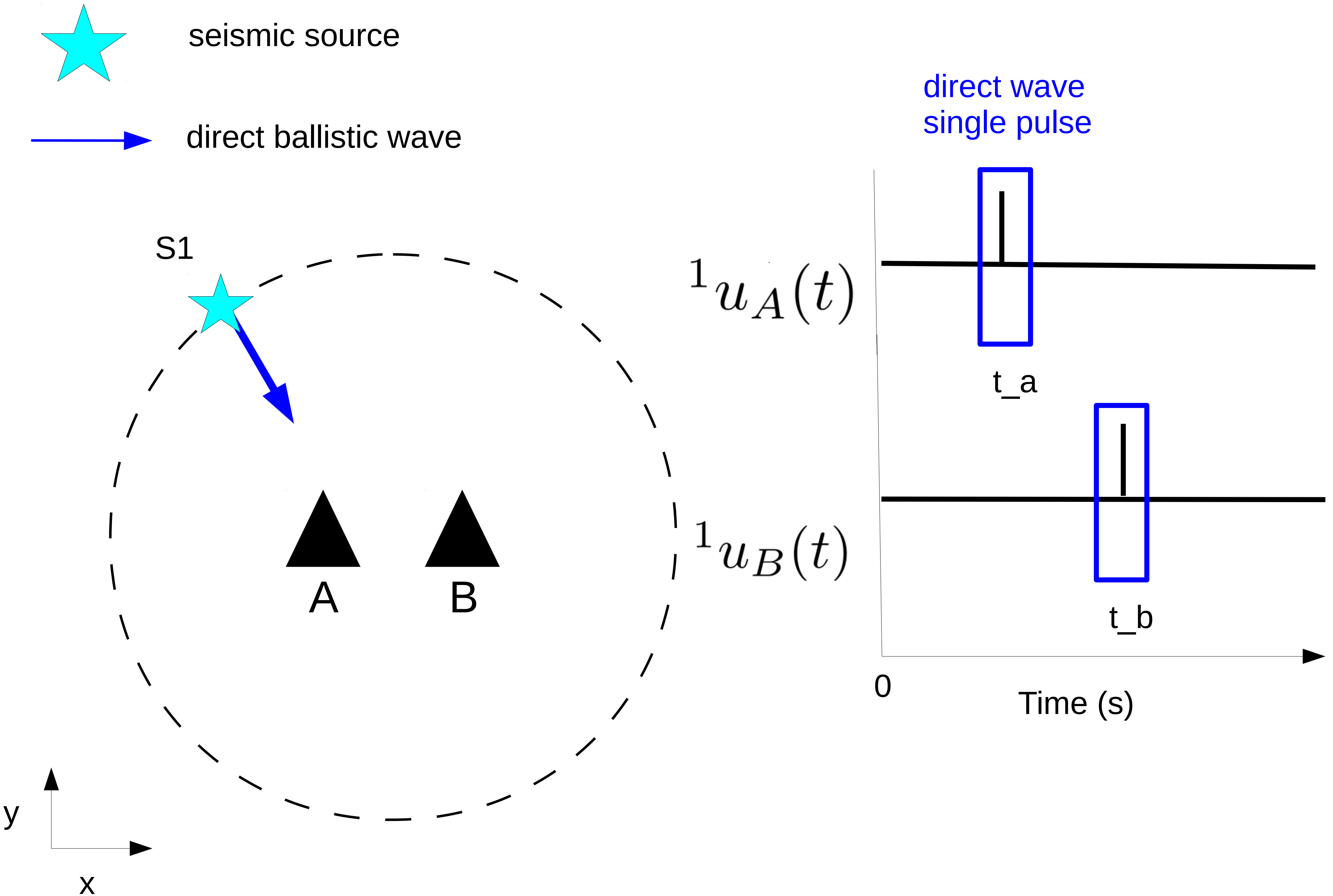
1) Why and how does it work ?

2) Earth's structure imaging

3) Earth's structure monitoring

4) Other applications on Earth, and beyond !

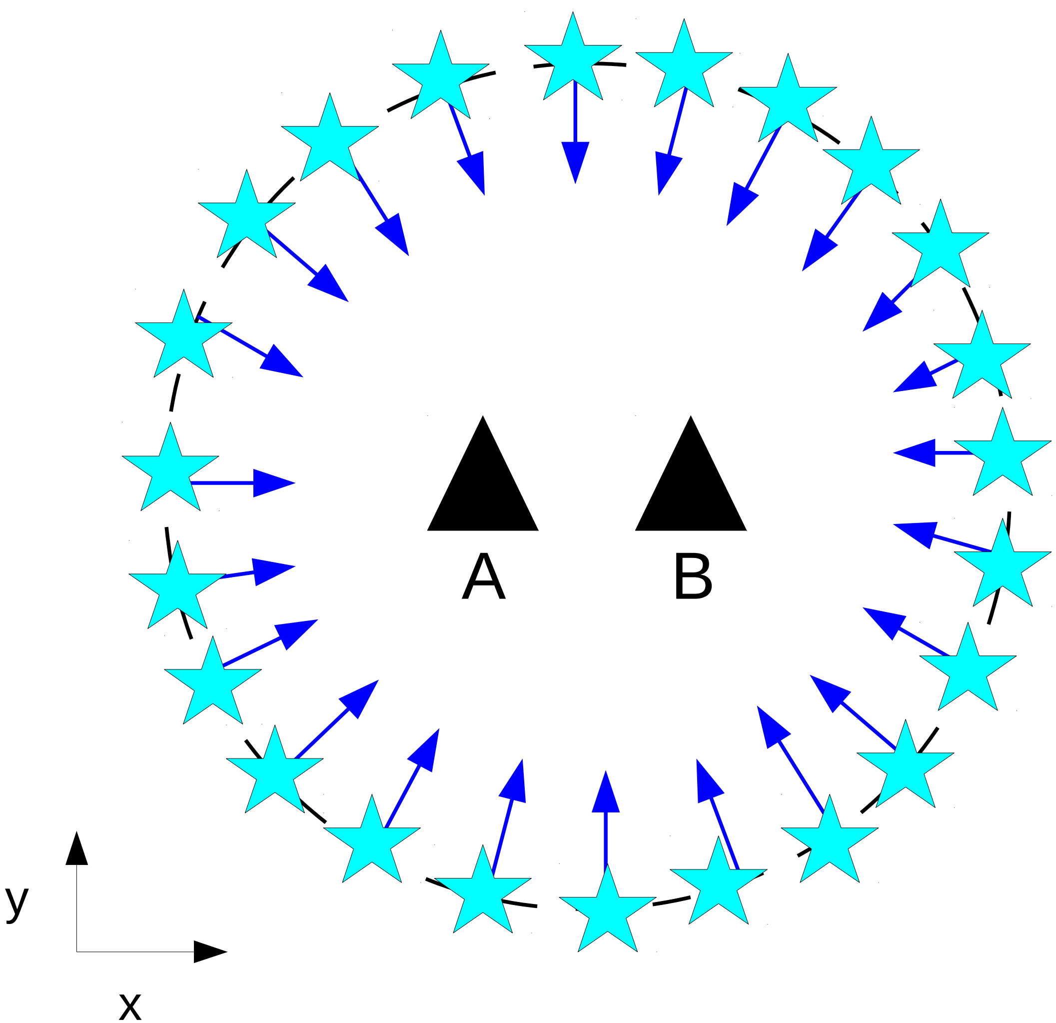
Stationary phase approach (« ballistic » case)



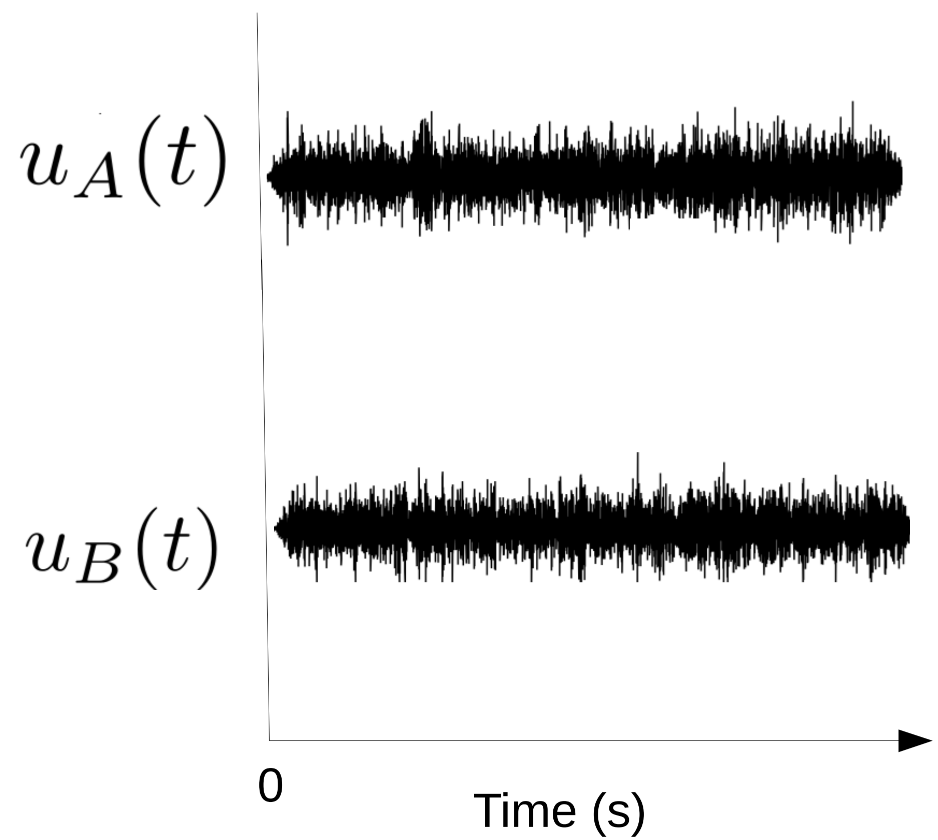
Stationary phase approach (« ballistic » case)

uncorrelated seismic sources

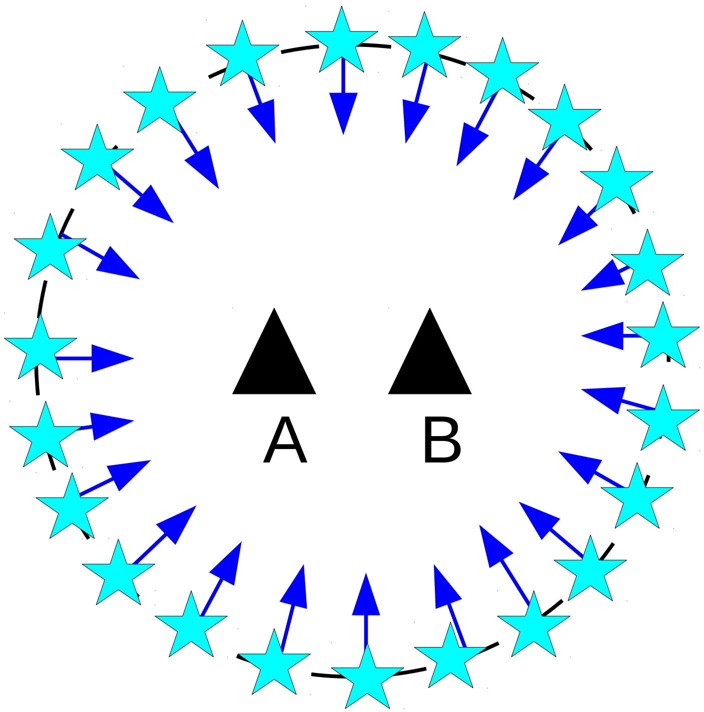
direct ballistic waves



complex seismic wavefield

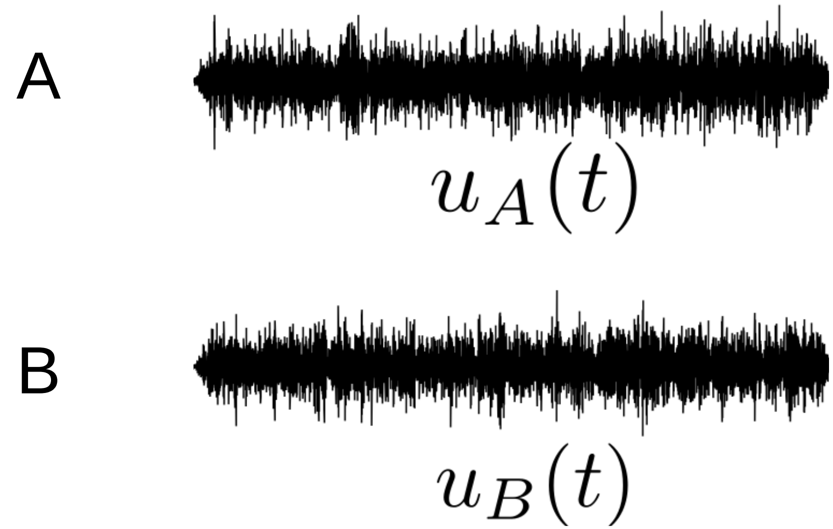


Stationary phase approach (« ballistic » case)



uniform repartition
of the sources

Green's function



cross-correlation

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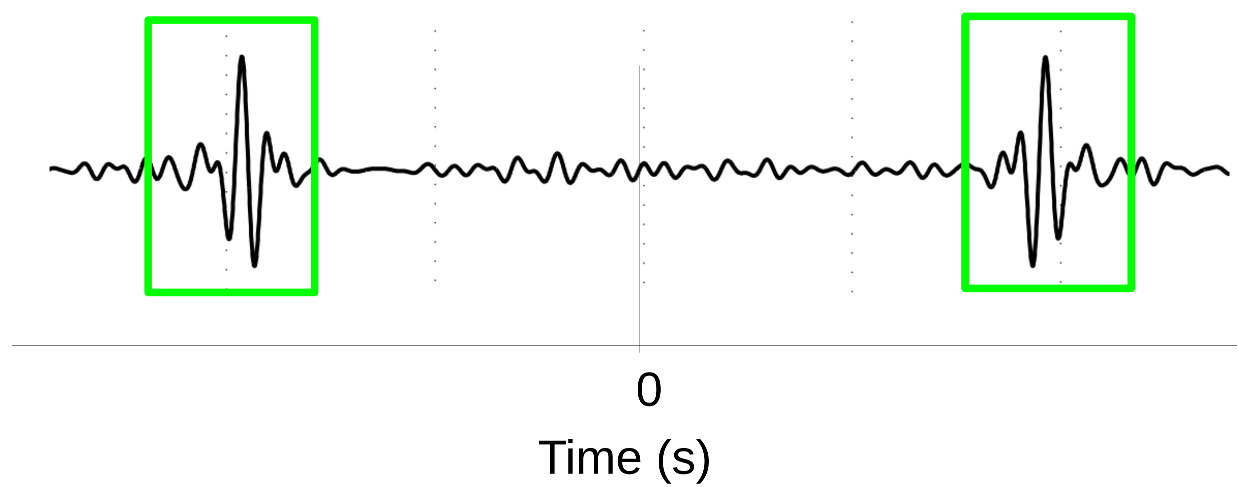
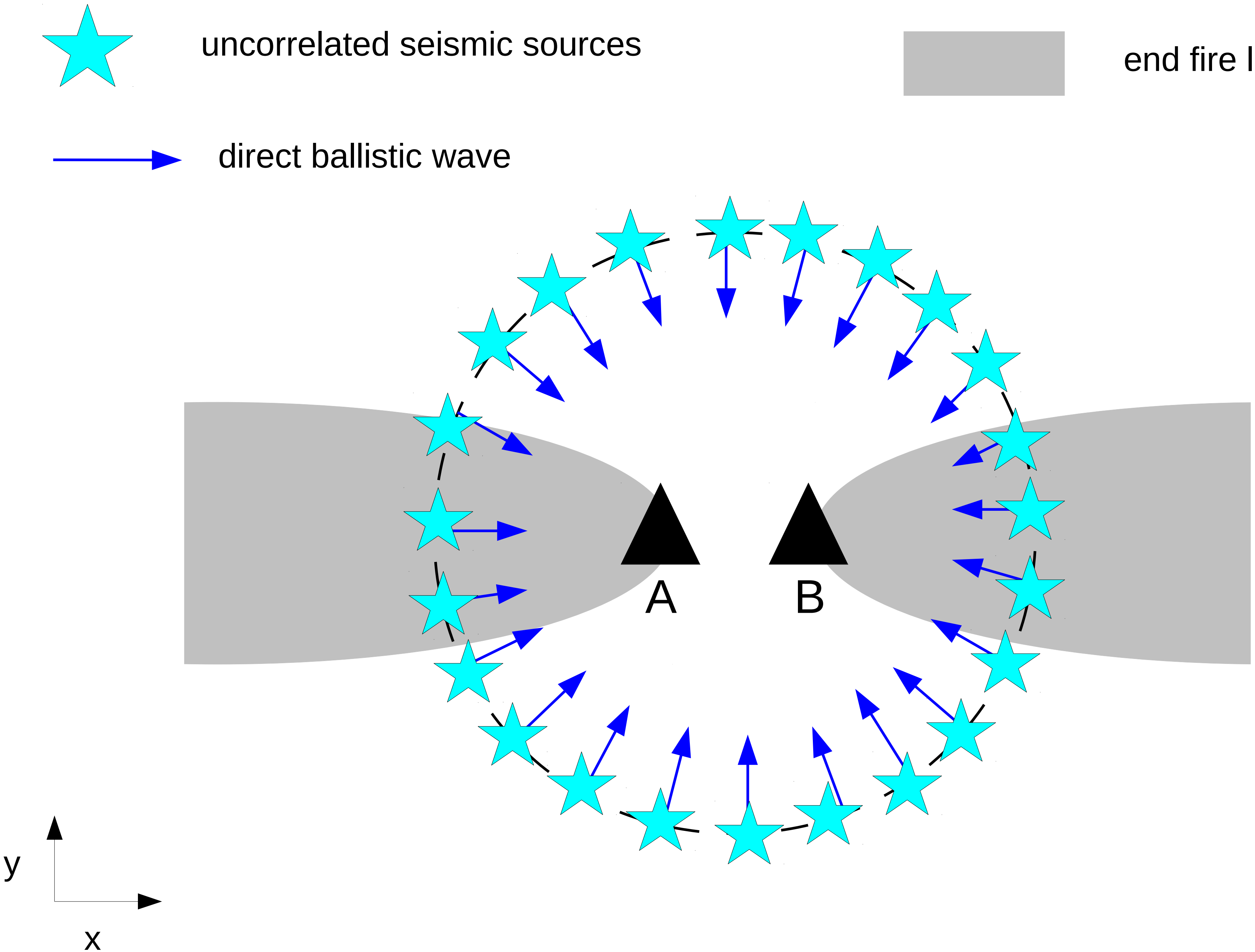
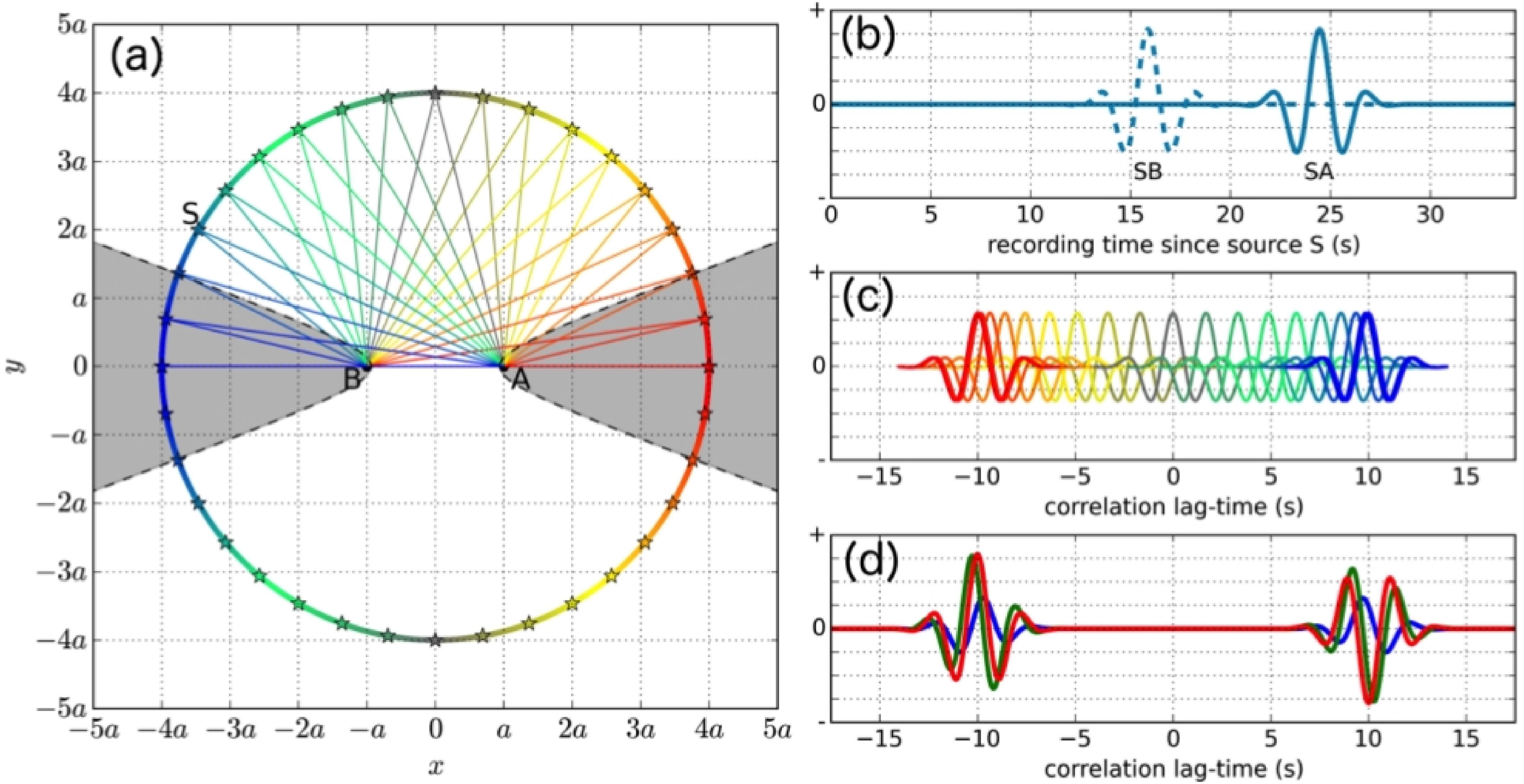


Stationary phase approach (« ballistic » case)



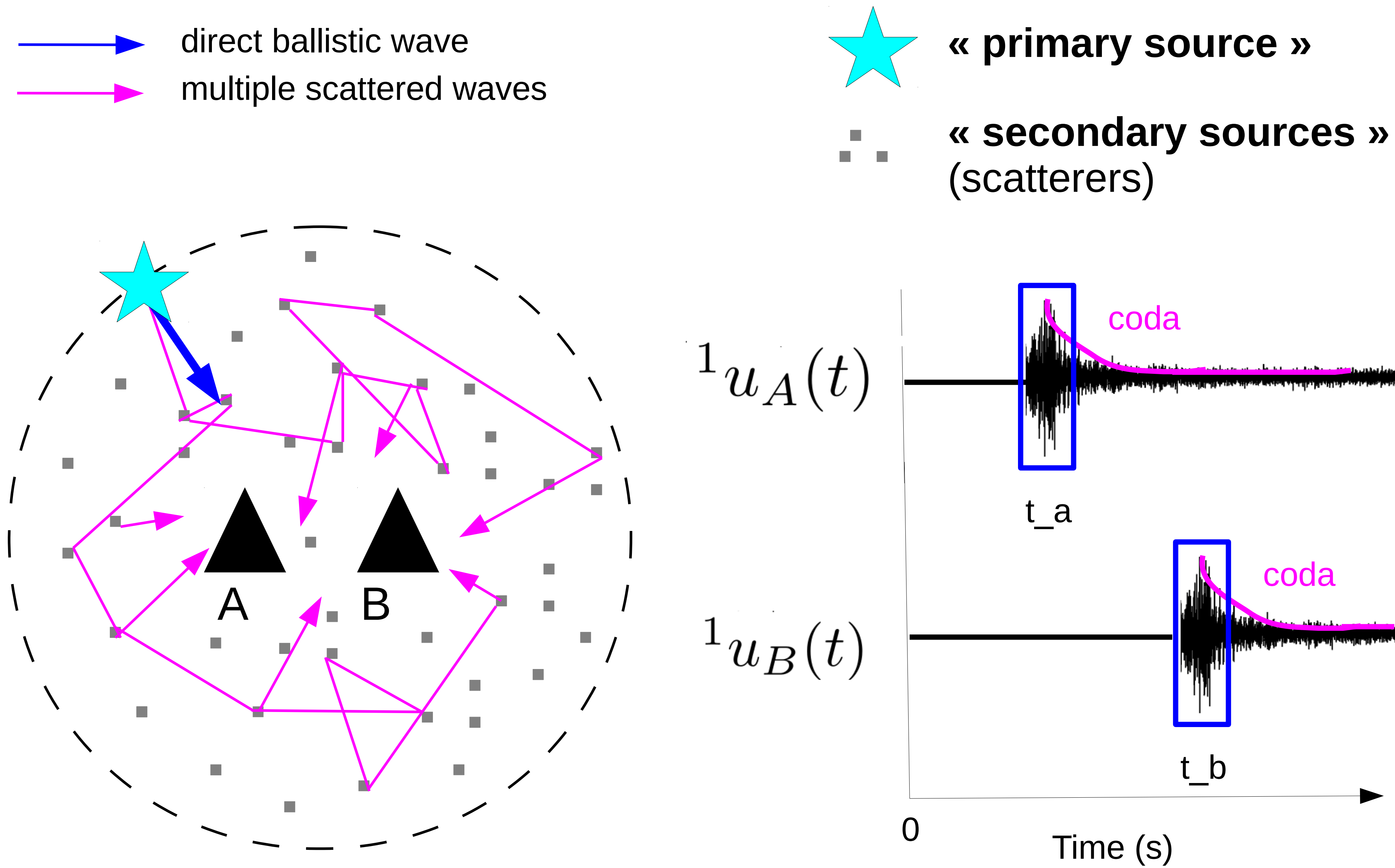
Stationary phase approach (« ballistic » case)

Source at y=0



From Lehujeur M., 2015, Ph.D thesis

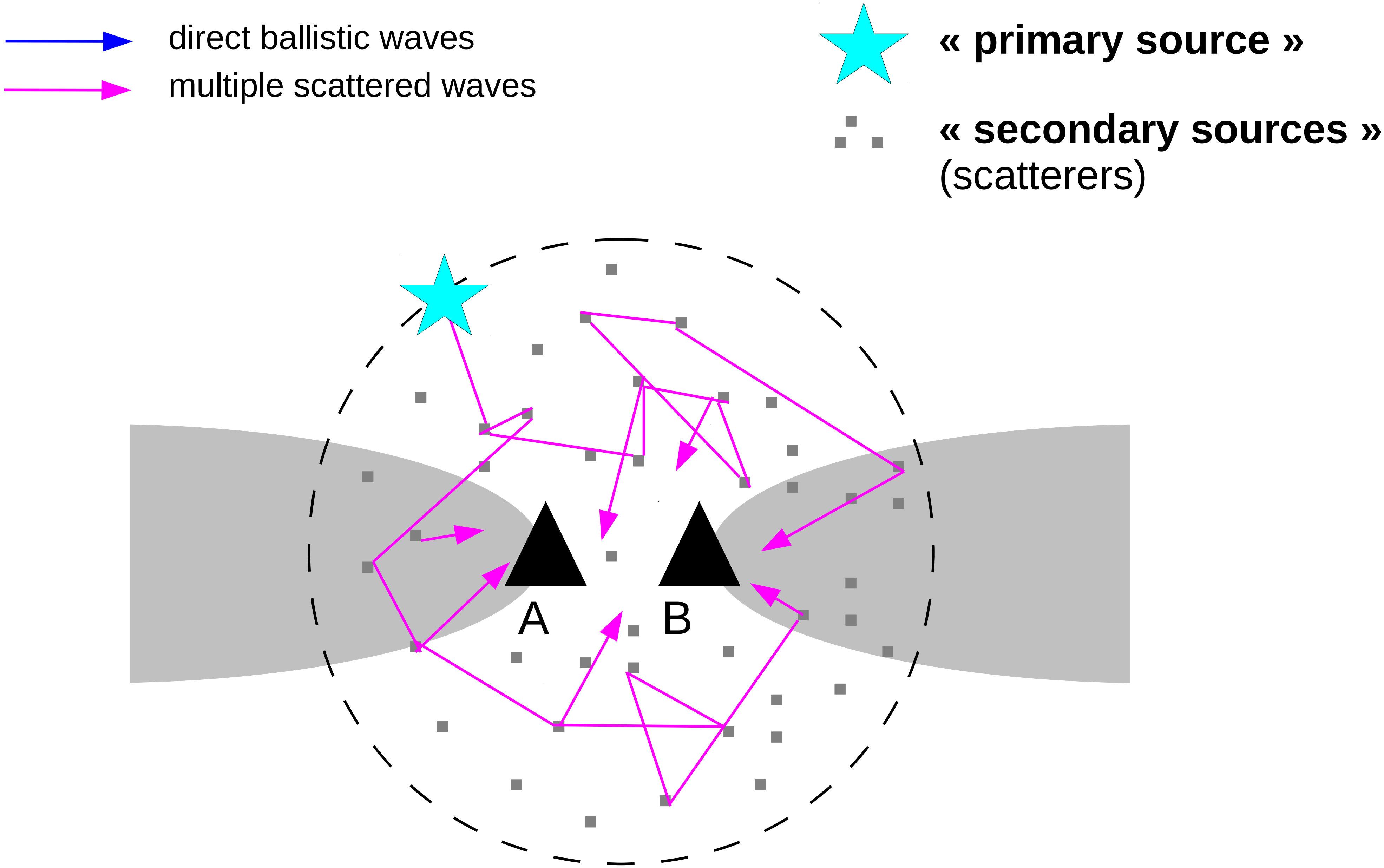
Stationary phase approach (« diffuse » case)



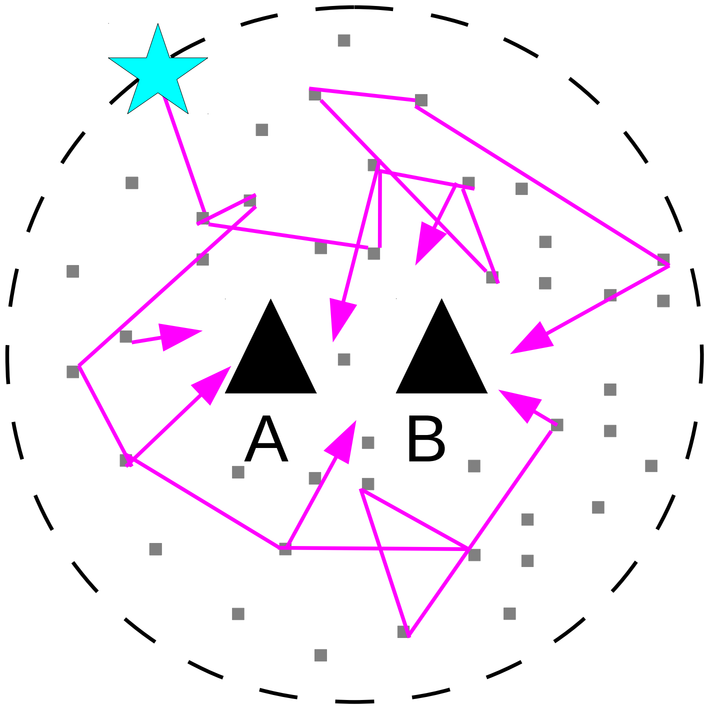
$^1u_A(t)$

$^1u_B(t)$

Stationary phase approach (« diffuse » case)

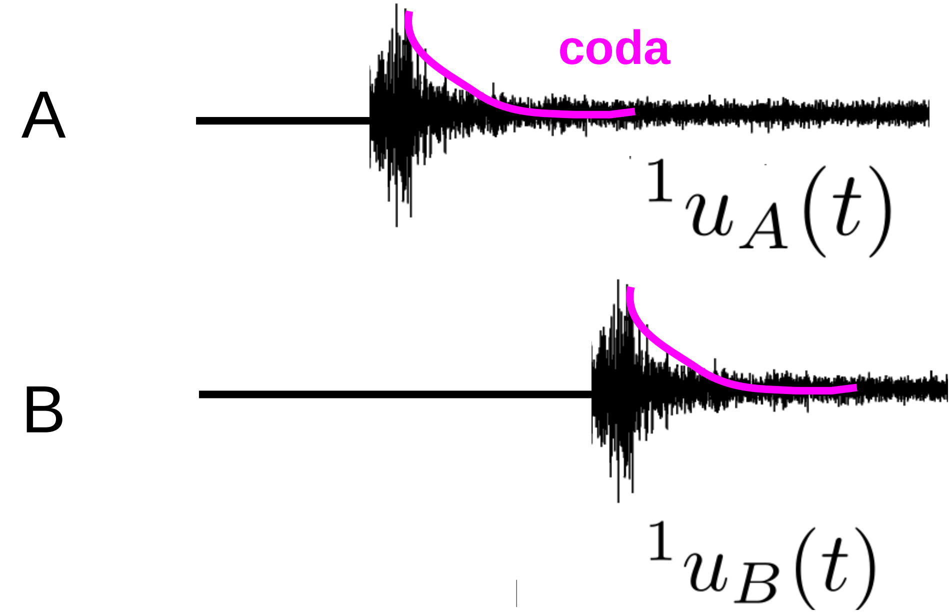


Stationary phase approach (« diffuse » case)



one single source +
heterogeneous medium

Green's function



cross-correlation

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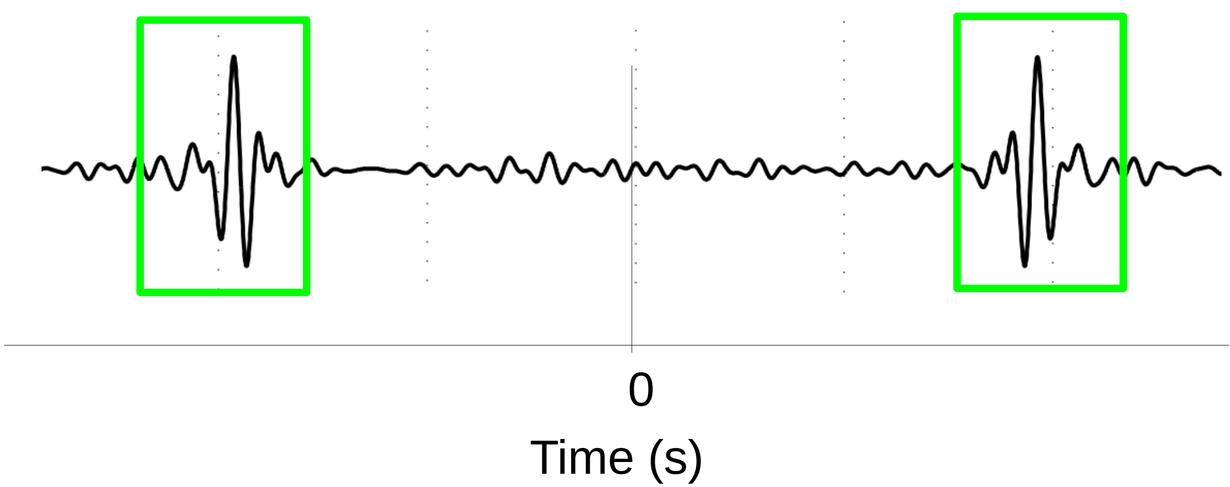
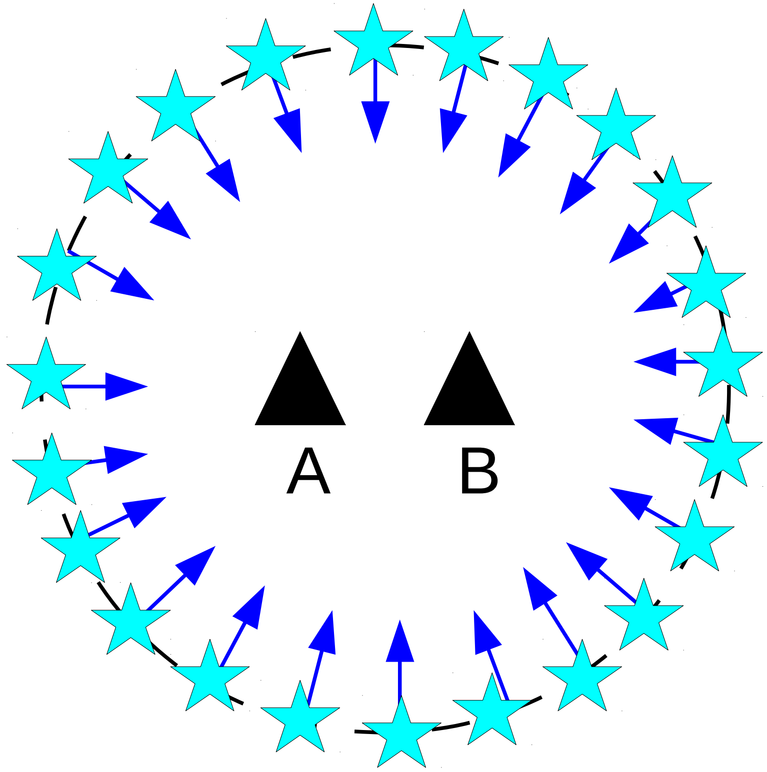


Conditions for the construction of the Green's function

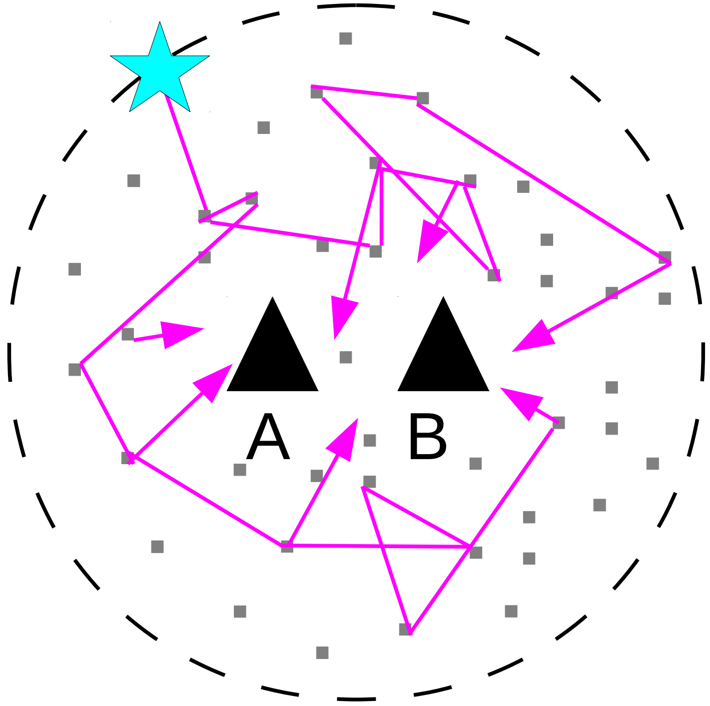
CASE 1

uniform repartition of the sources



CASE 2

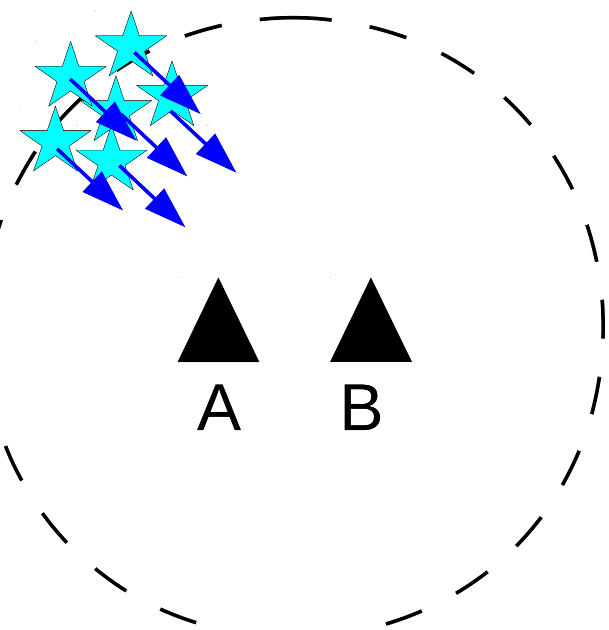
one single source + heterogeneous medium



Unfavourable conditions for the construction of the Green's function

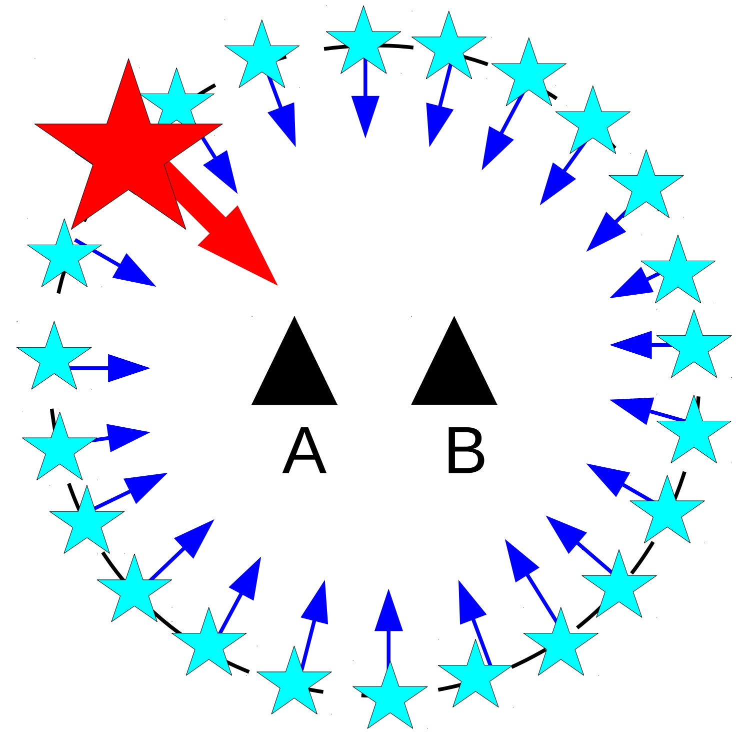
non-uniform repartition of the sources

persistent localized source



homogeneous medium

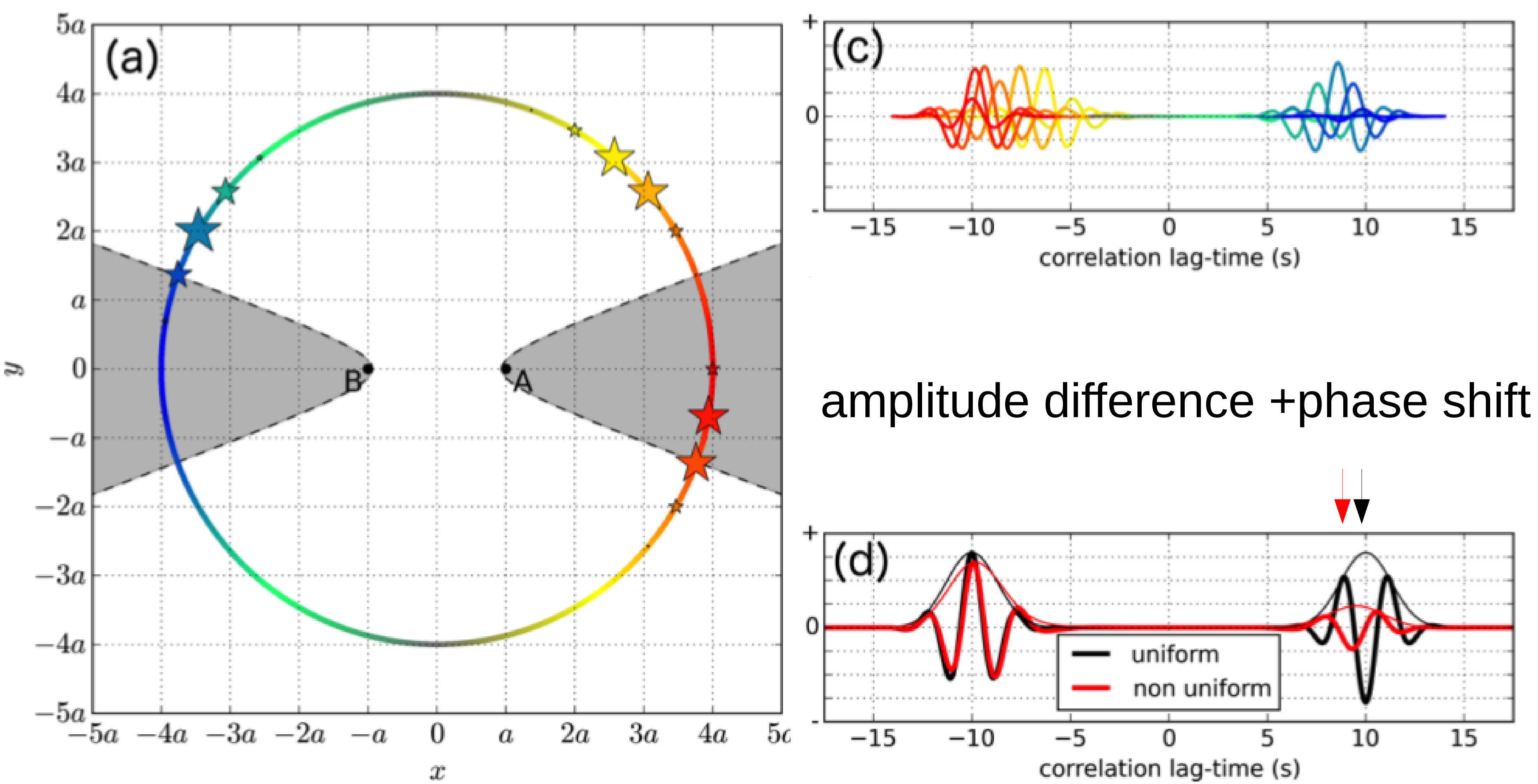
high amplitude transient source



homogeneous medium

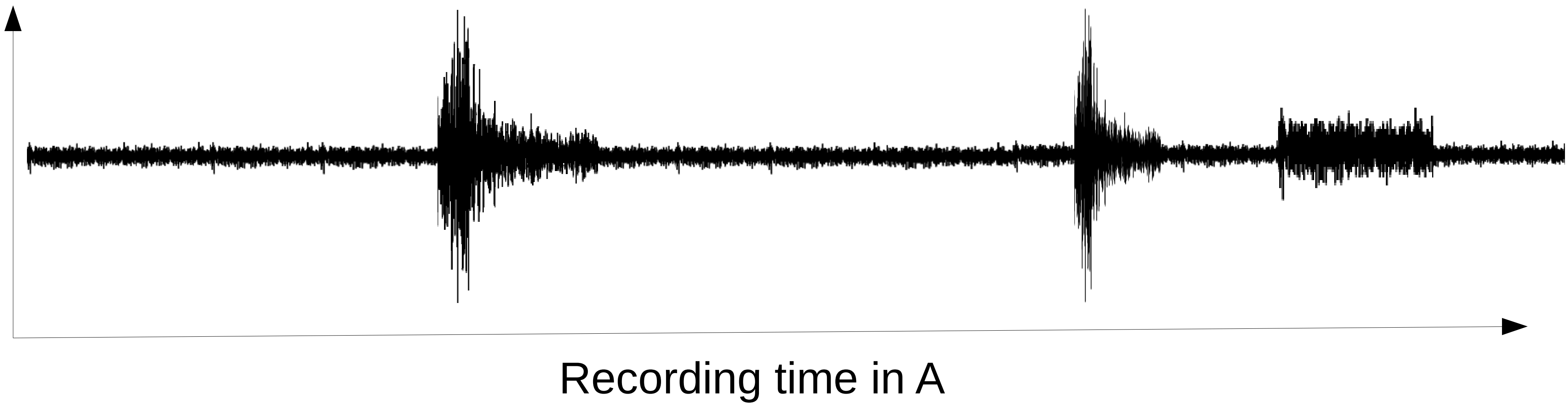
Stationary phase approach (« ballistic » case)

non-uniform repartition of the sources

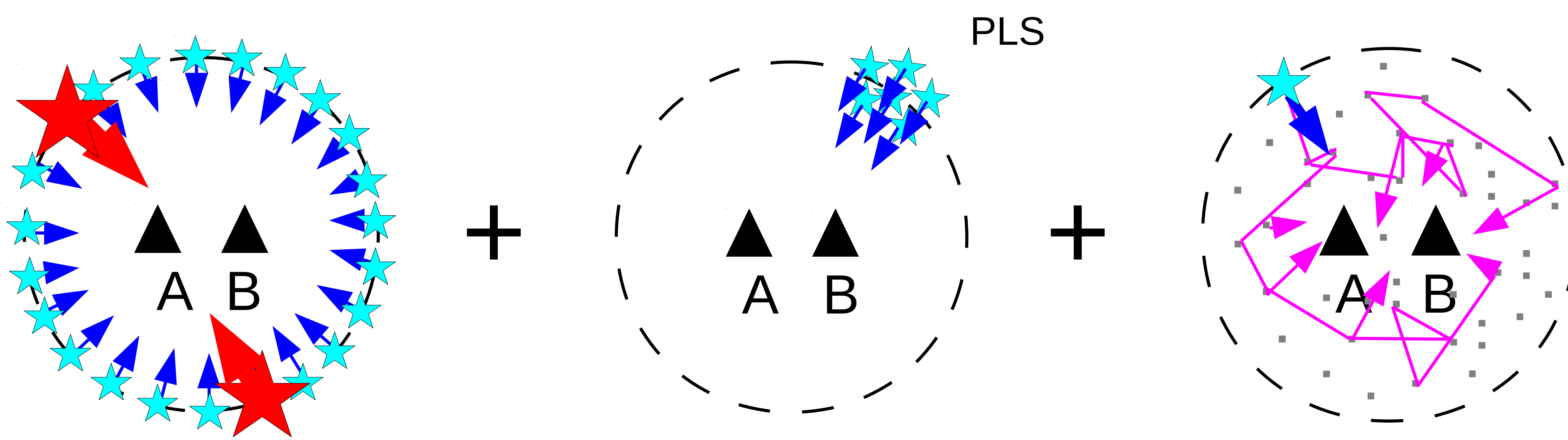


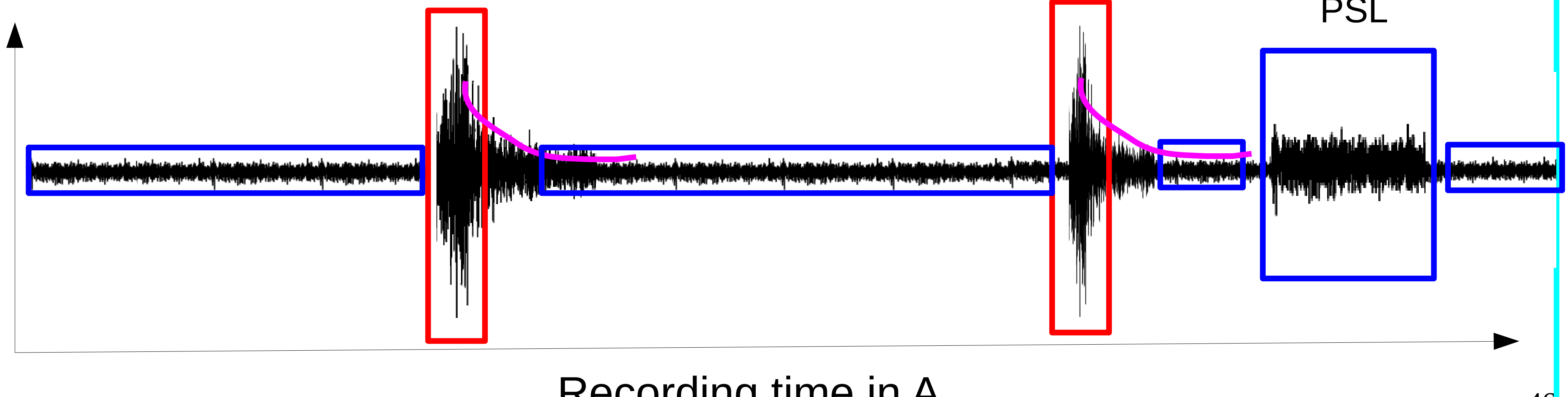
From Lehujeur M., 2015, Ph.D thesis

Earth's hum = superposition of several effects when considering long duration records

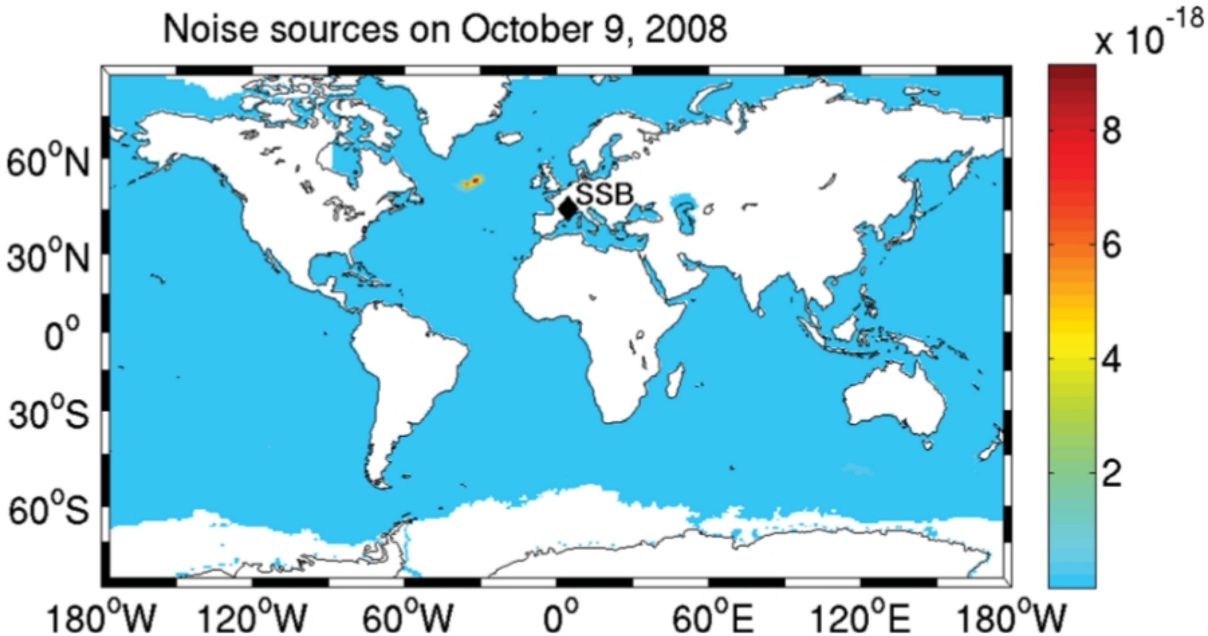


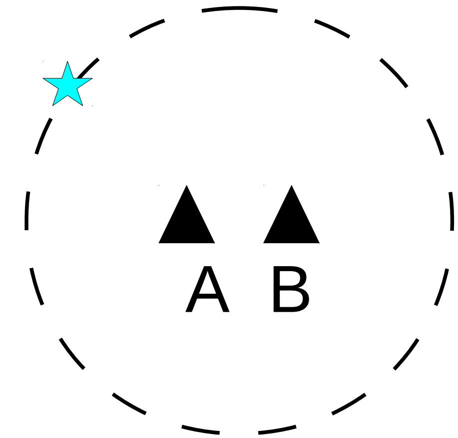
Earth's hum = superposition of several effects when considering long duration records





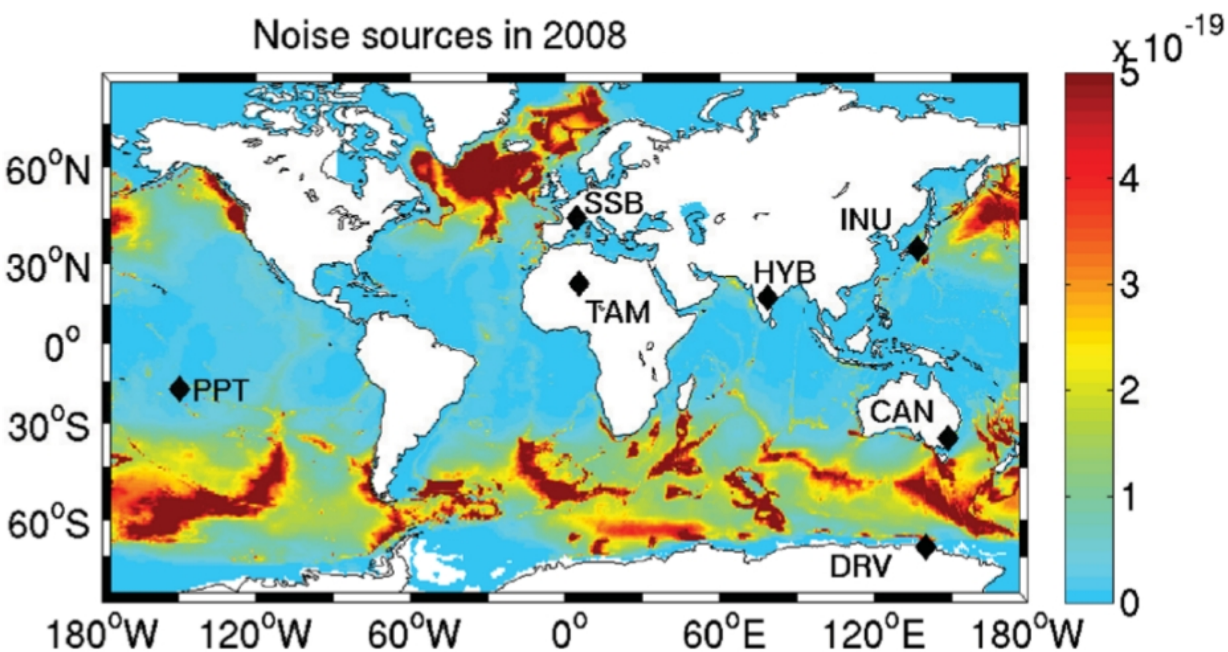
Spatio-temporal variability of the oceanic sources

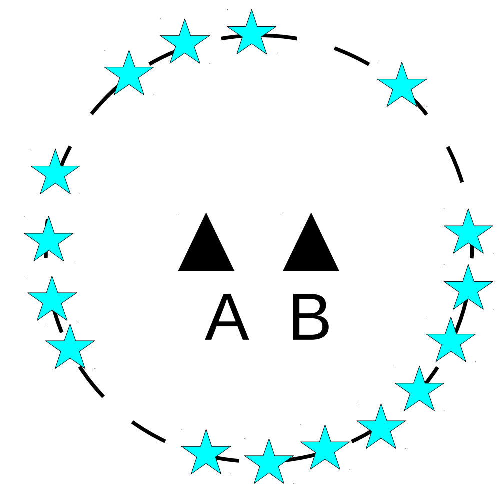




1 day

punctual source
non uniform repartition



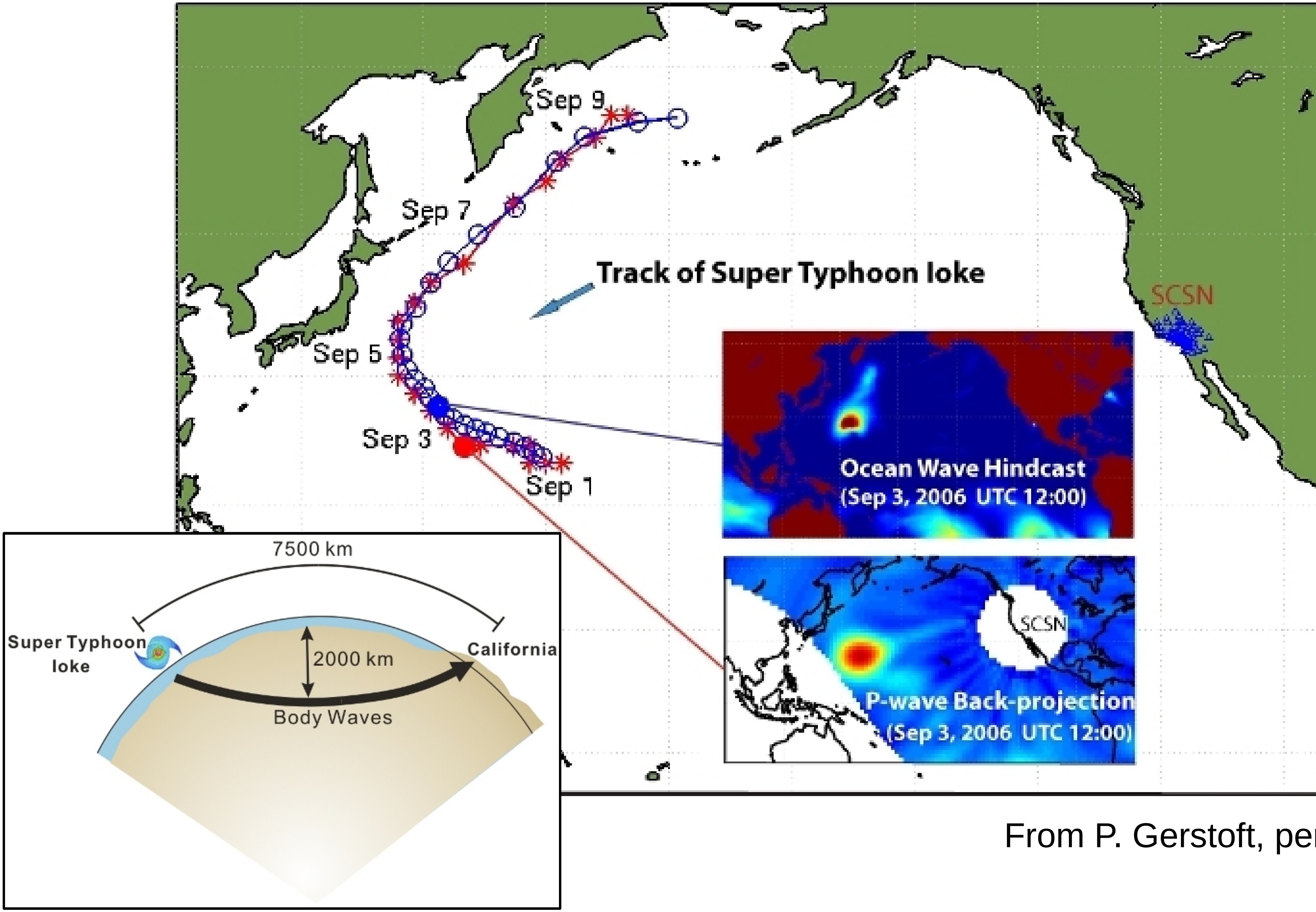


1 year

~ uniform repartition

Stutzmann et al., 2012 , modelling approach

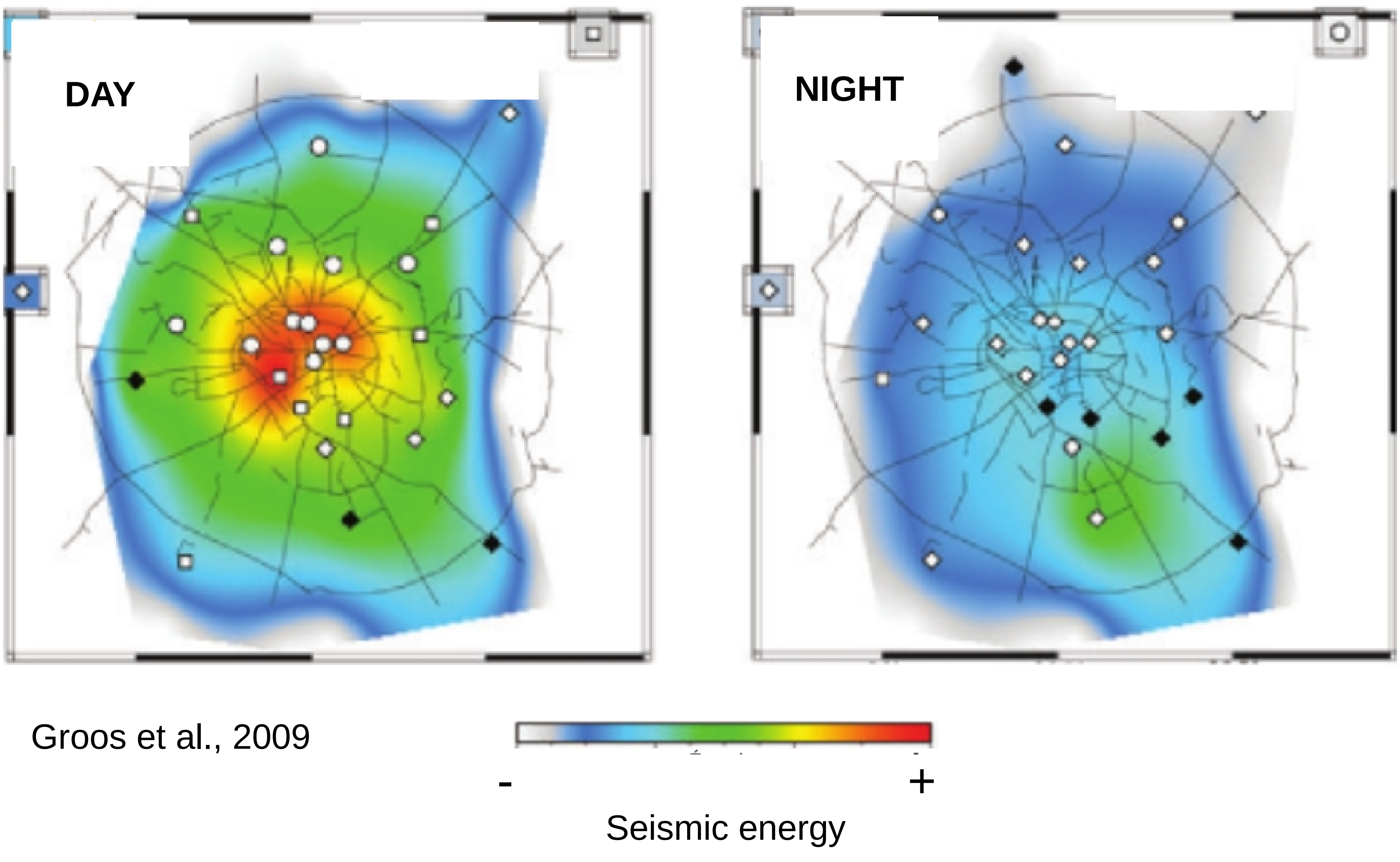
Spatio-temporal variability of the oceanic sources



From P. Gerstoft, pers. website

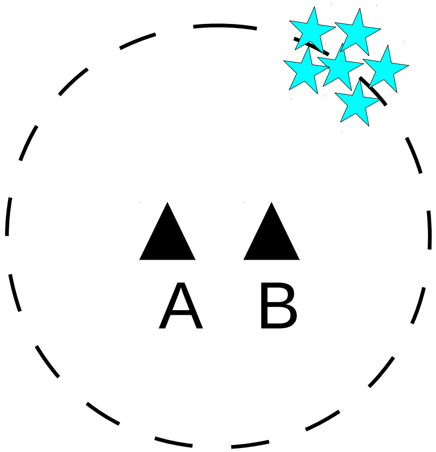
Spatio-temporal variability of the human sources

Noise level in Bucarest

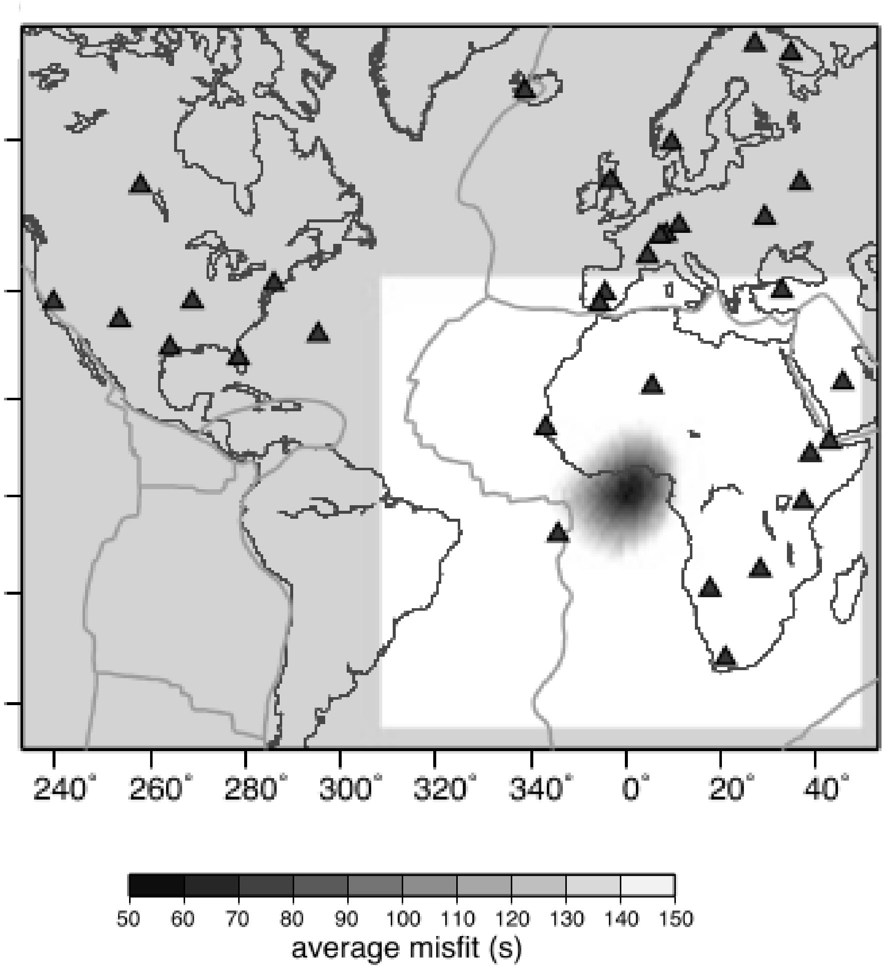


Groos et al., 2009

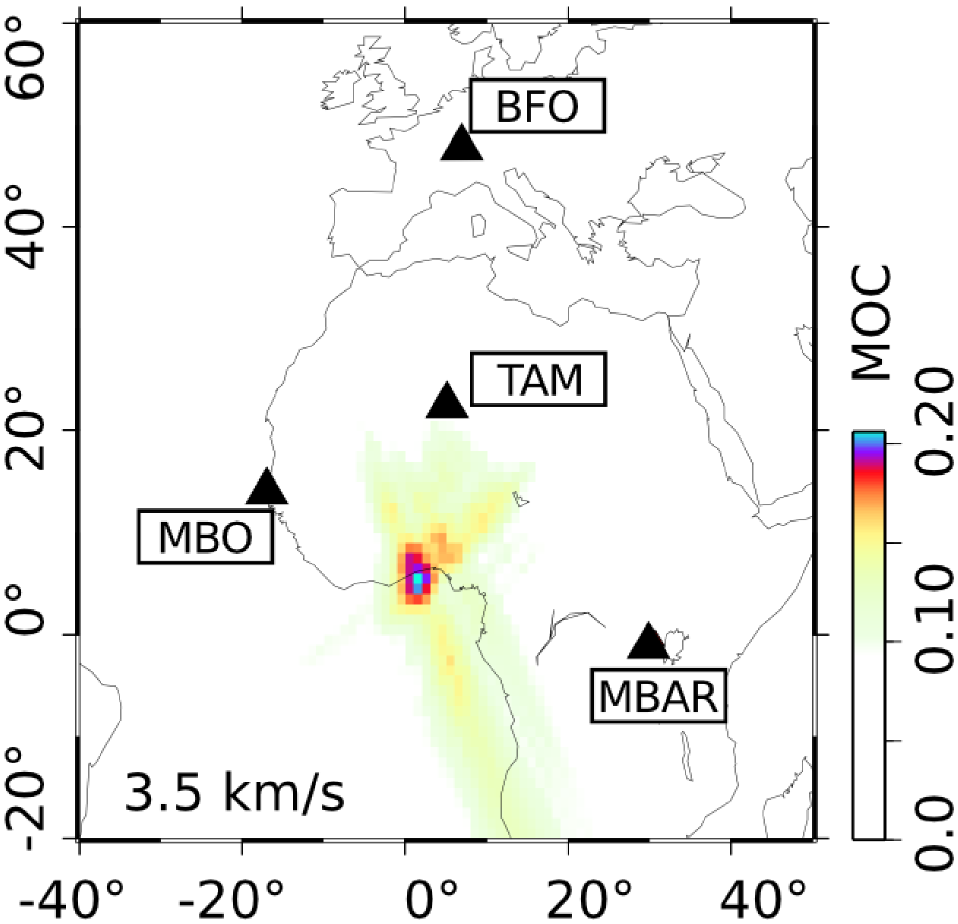
Persistent localized source (PLS)



26 s persistent localized source in the Gulf of Guinea

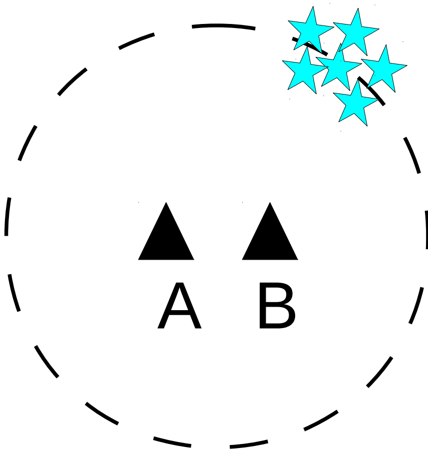


Shapiro et al., 2004

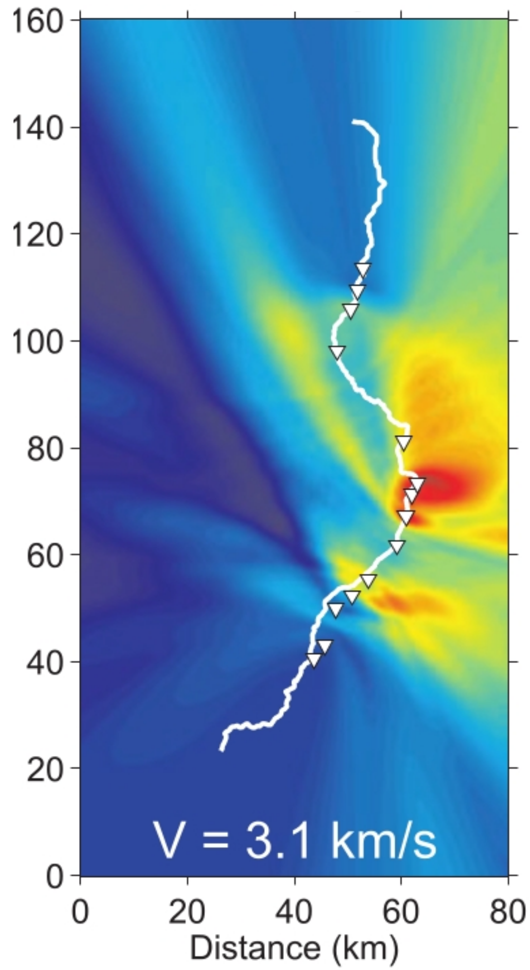


Gaudot et al., 2016

Persistent localized source (PLS)

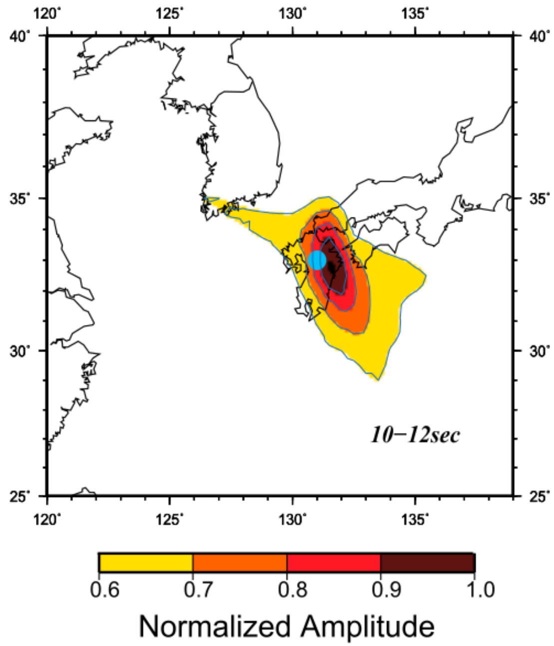


River (China)



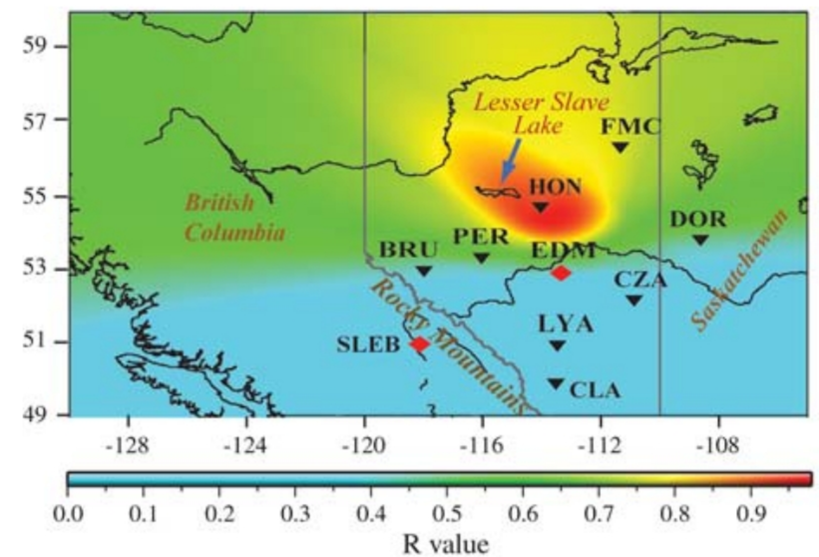
Burtin et al., 2010

Volcanoe (Japan)



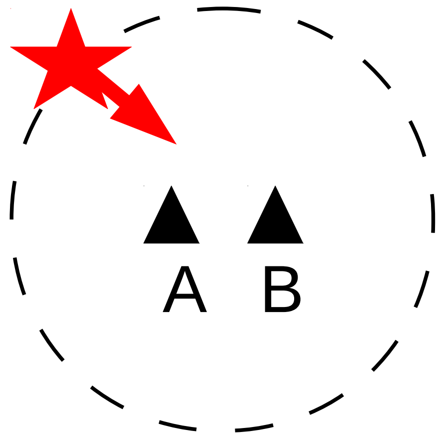
Zheng, 2011

Lake (Canada)



Gu et al., 2012

Earthquakes



Mojave Desert, California, US, 1992

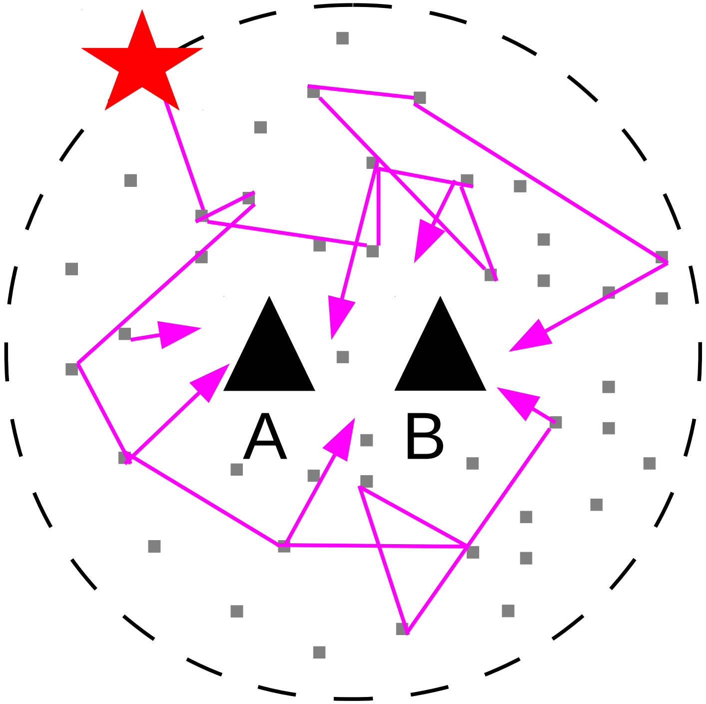
Credit : Southern California Earthquake Data Center

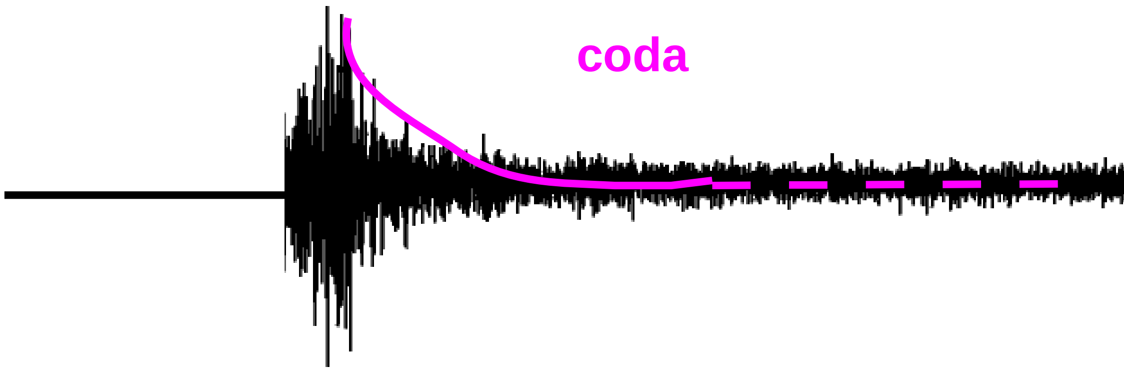
Adazapari, Turkey, 1999

Credit :http://science.nationalgeographic.com

Earthquakes

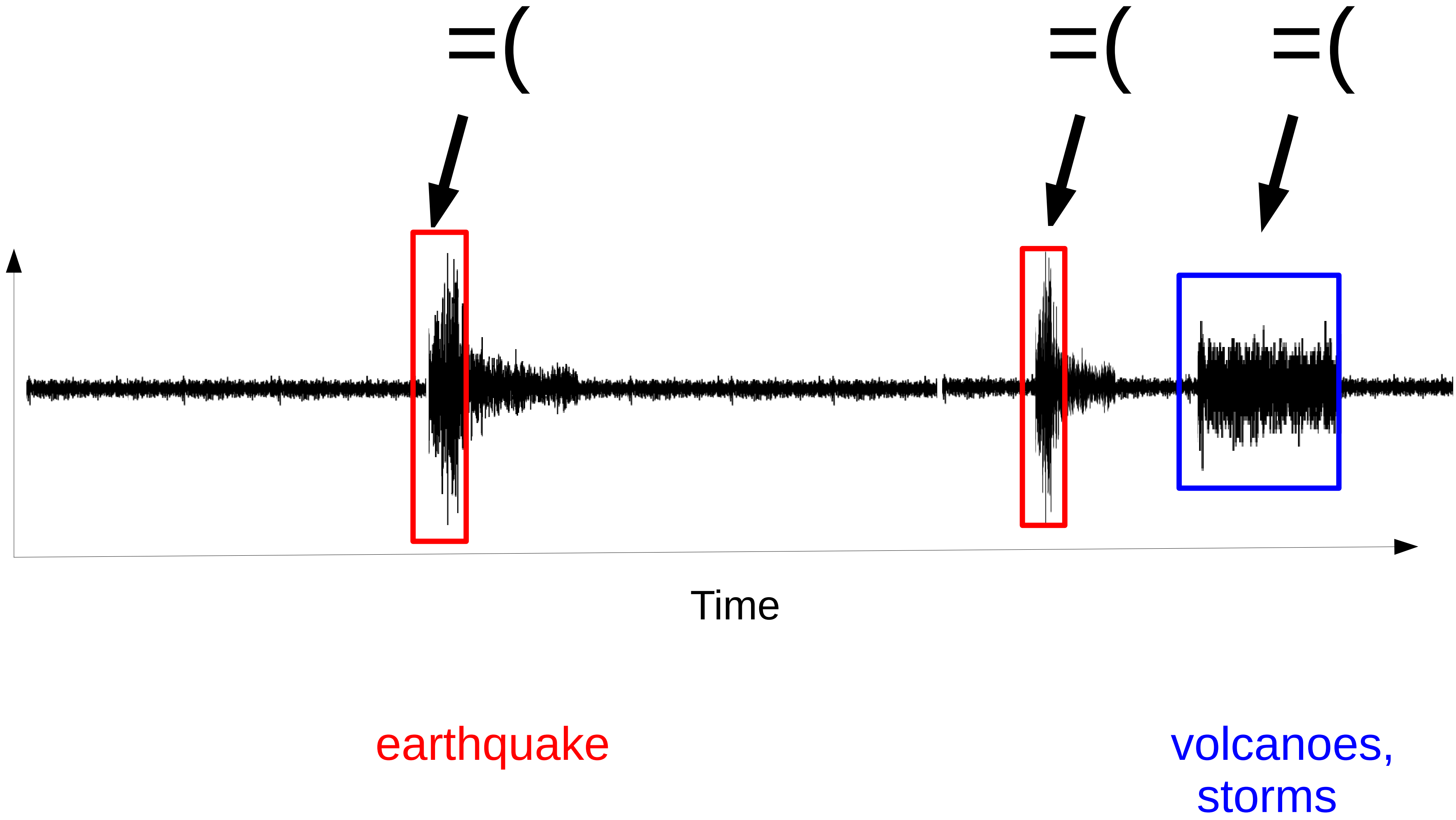
Coda signal help to construct the Green's function !



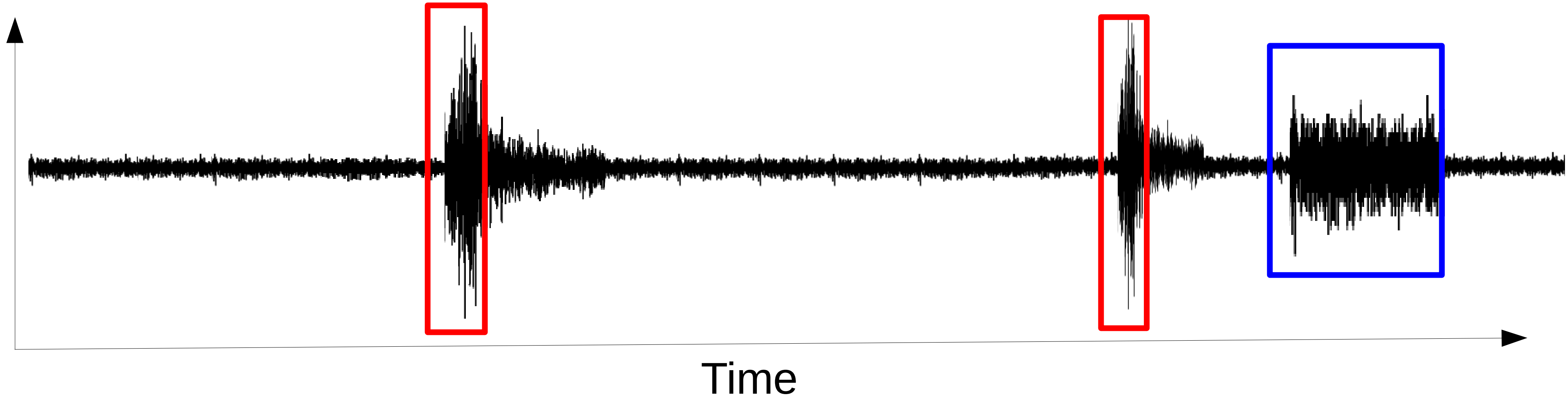


1) Also valid for the other seismic sources (oceanic, human, etc...)
2) Coda characteristics depend on the **wavelength/heterogeneities size** ratio

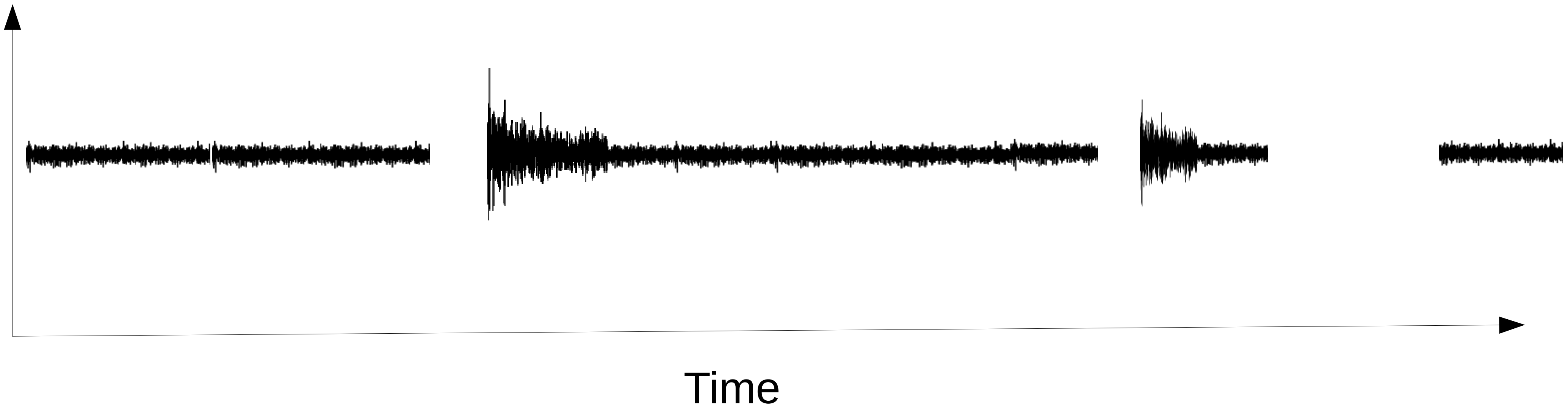
How to attenuate/remove the unwanted part of the signal ?



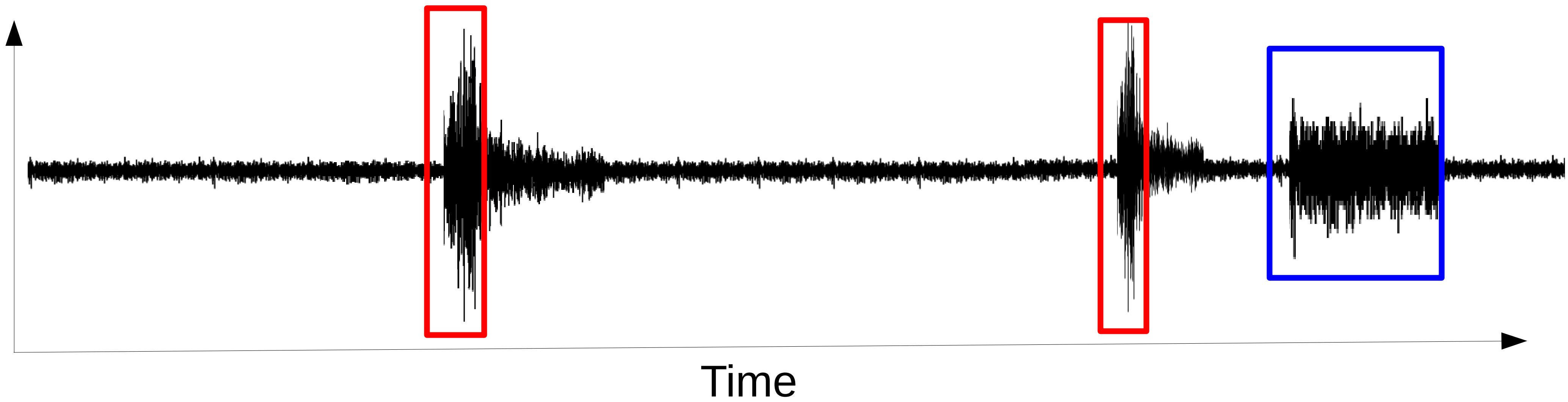
How to attenuate/remove the unwanted part of the signal ?



Solution 1 **Muting**

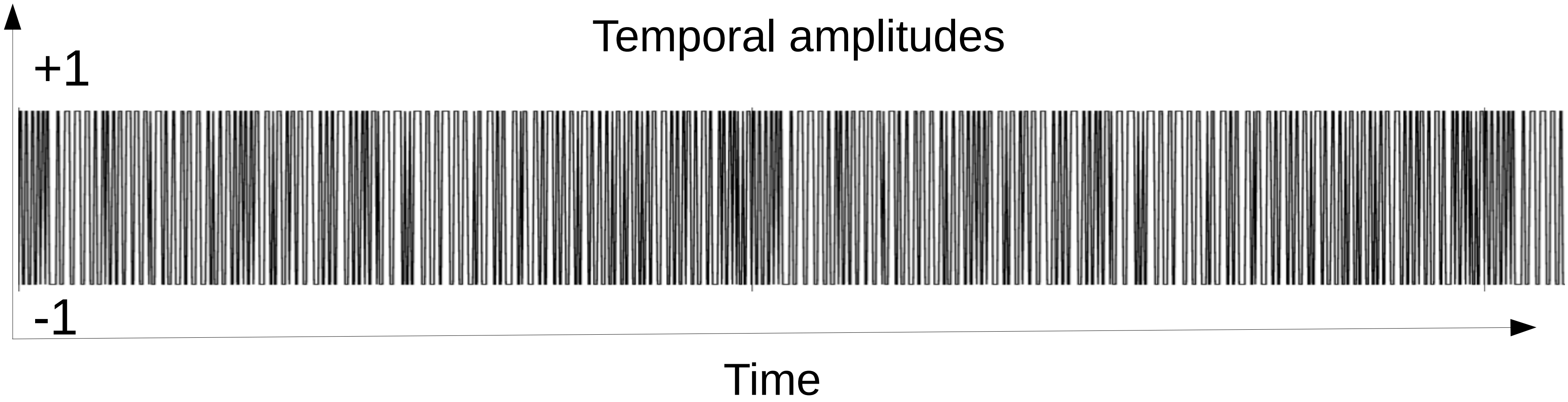


How to attenuate/remove the unwanted part of the signal ?

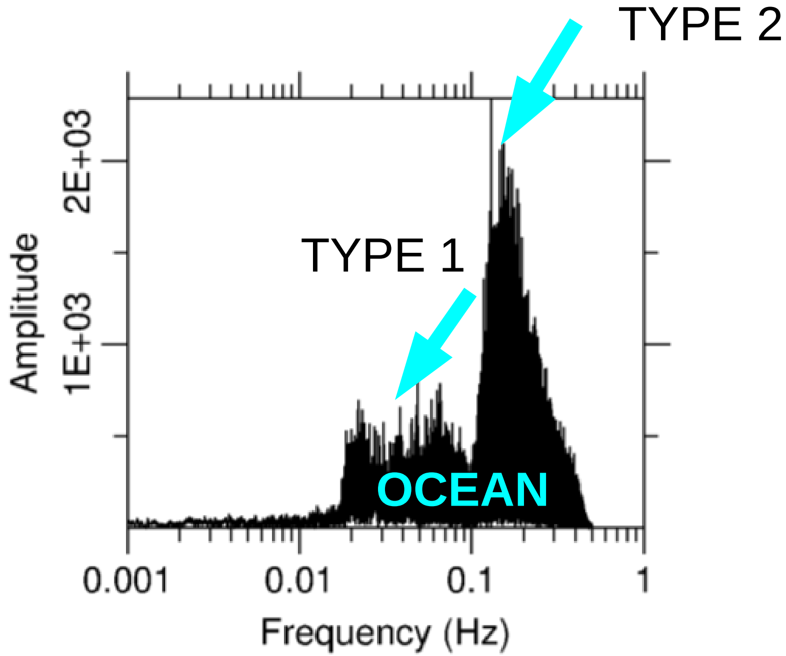


Solution 2 **Normalization (ex : 1 BIT)**

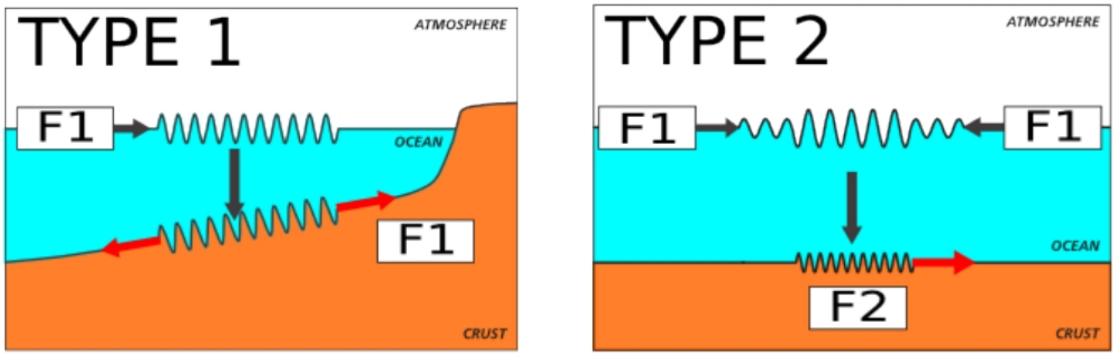
How to attenuate/remove the unwanted part of the signal ?



Spectral amplitudes

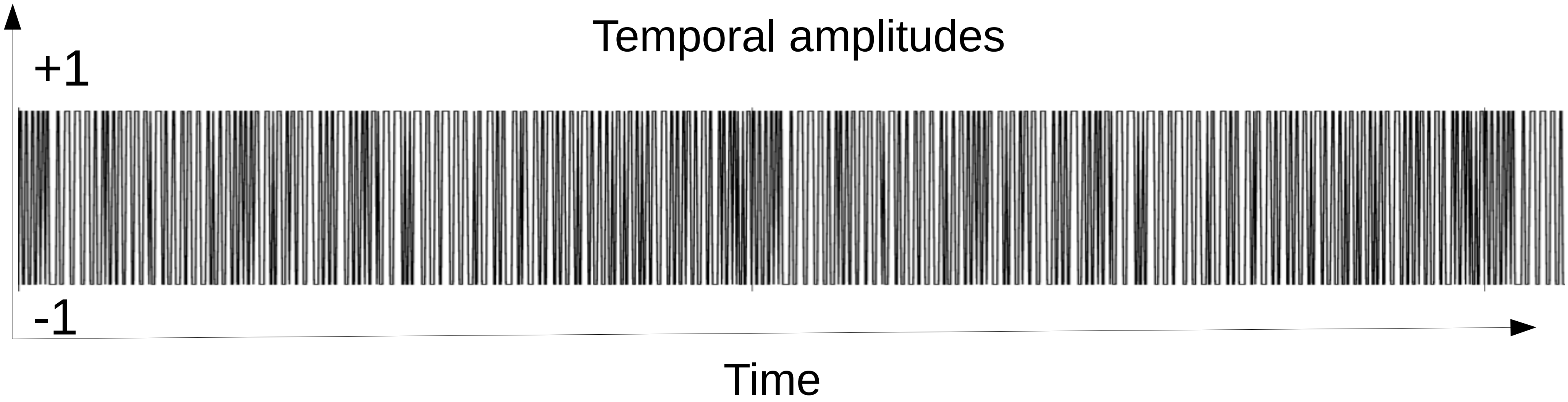


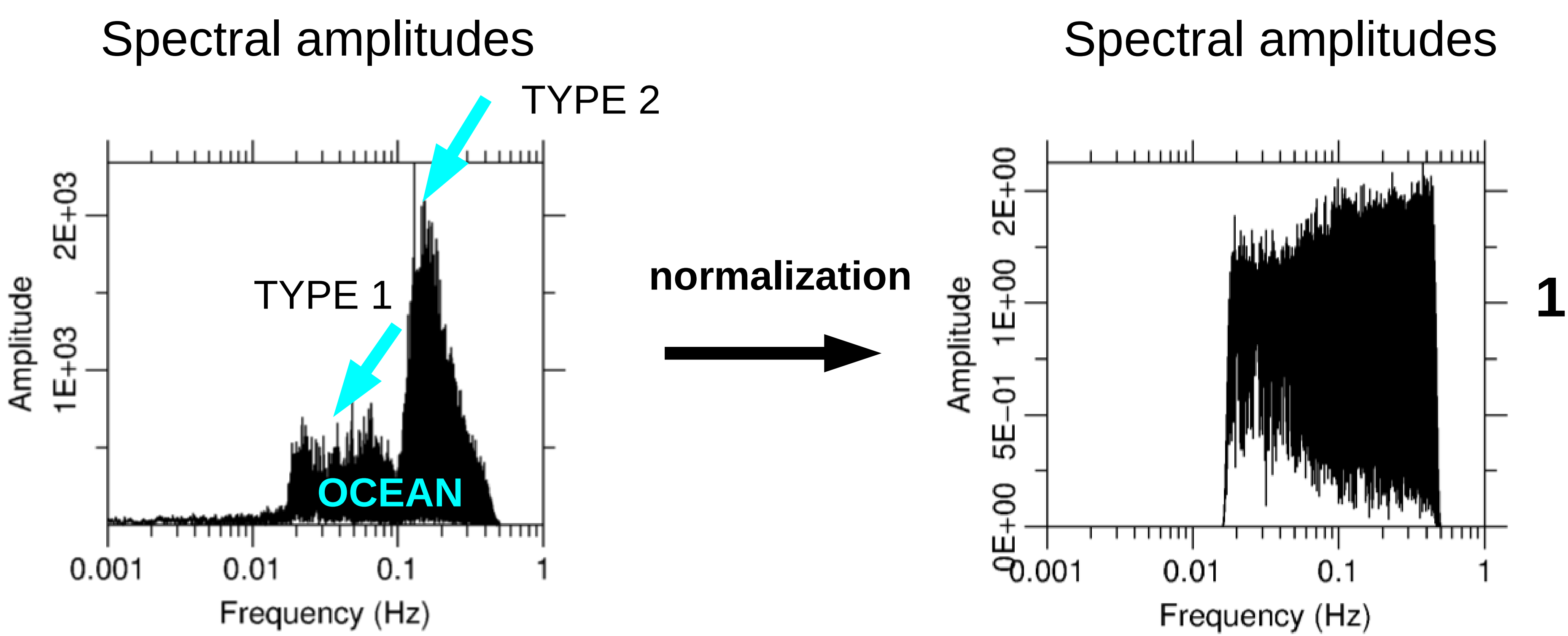
Oceanic seismic sources



After Ebeling, 2012

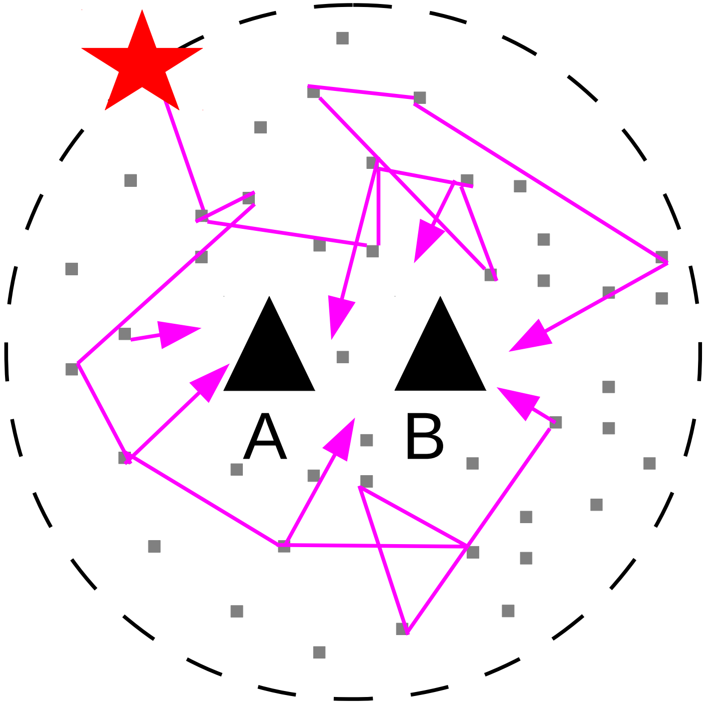
How to attenuate/remove the unwanted part of the signal ?

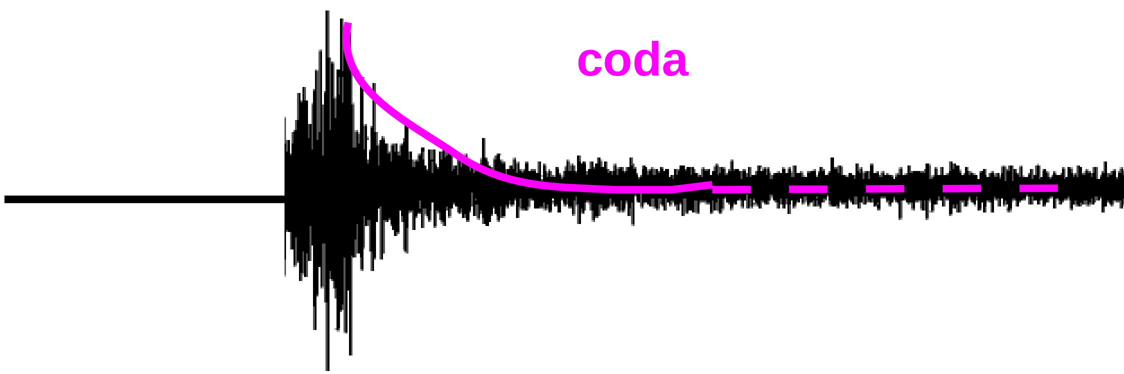




Earthquakes

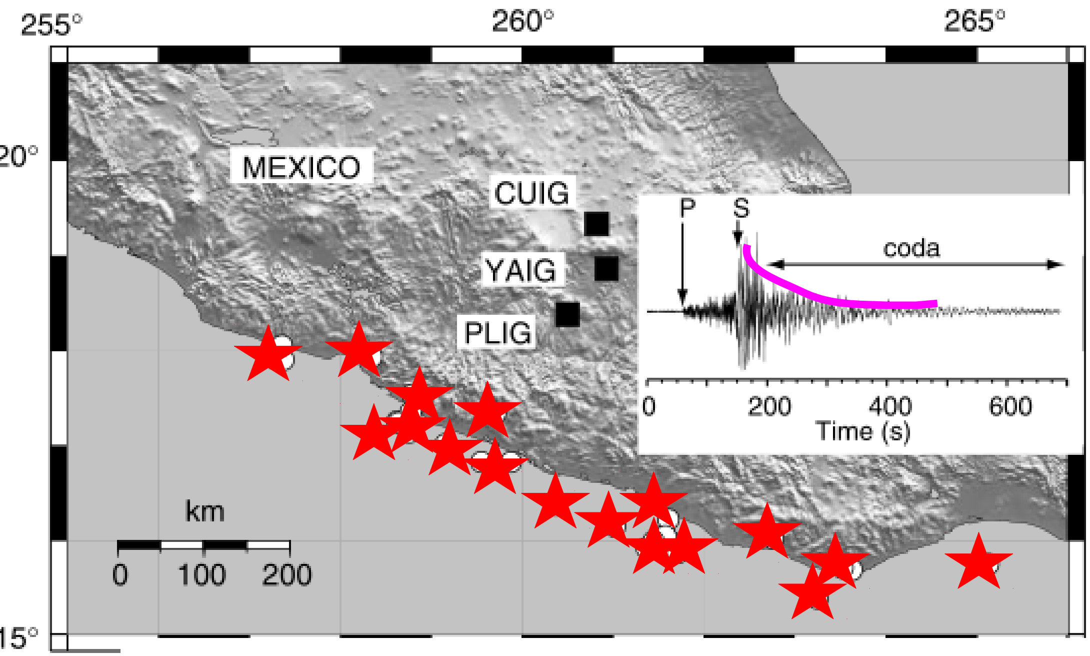
Coda signal help to construct the Green's function !





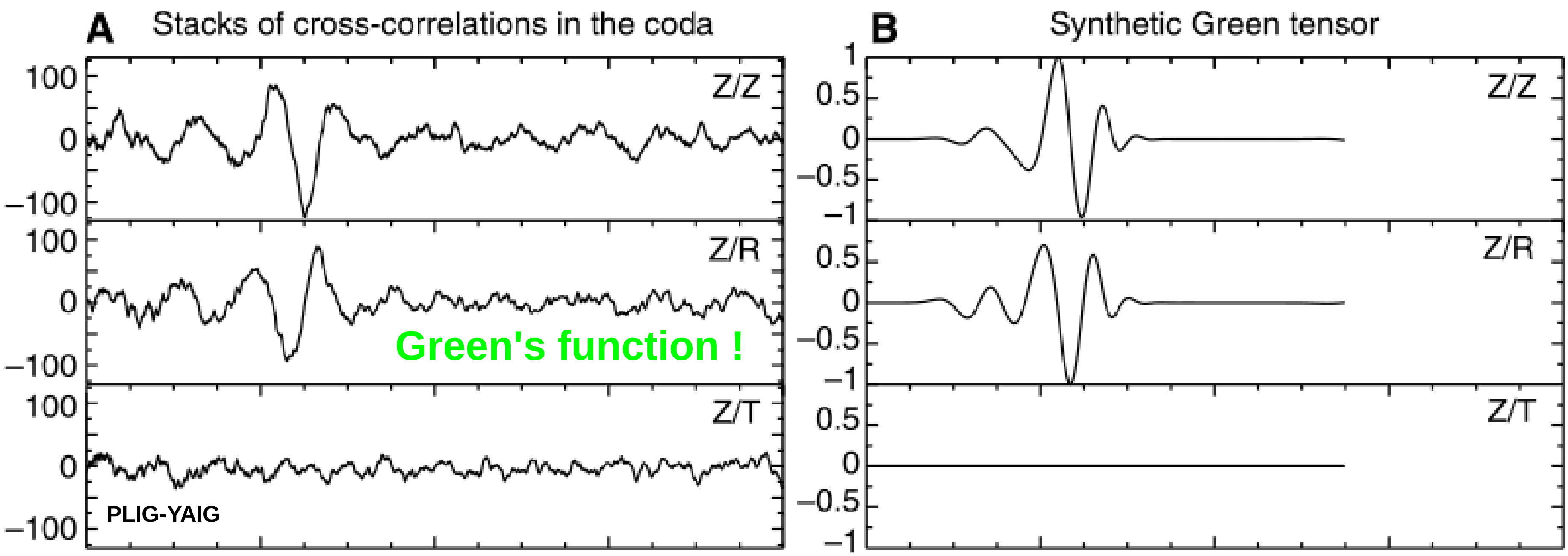
1) Also valid for the other seismic sources (oceanic, human, etc...)
2) Coda characteristics depend on the **wavelength/heterogeneities size** ratio

Long-Range Correlations in the Diffuse Seismic Coda



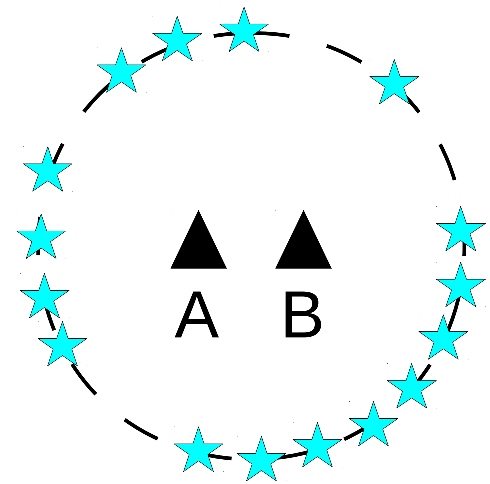
First application
in seismology

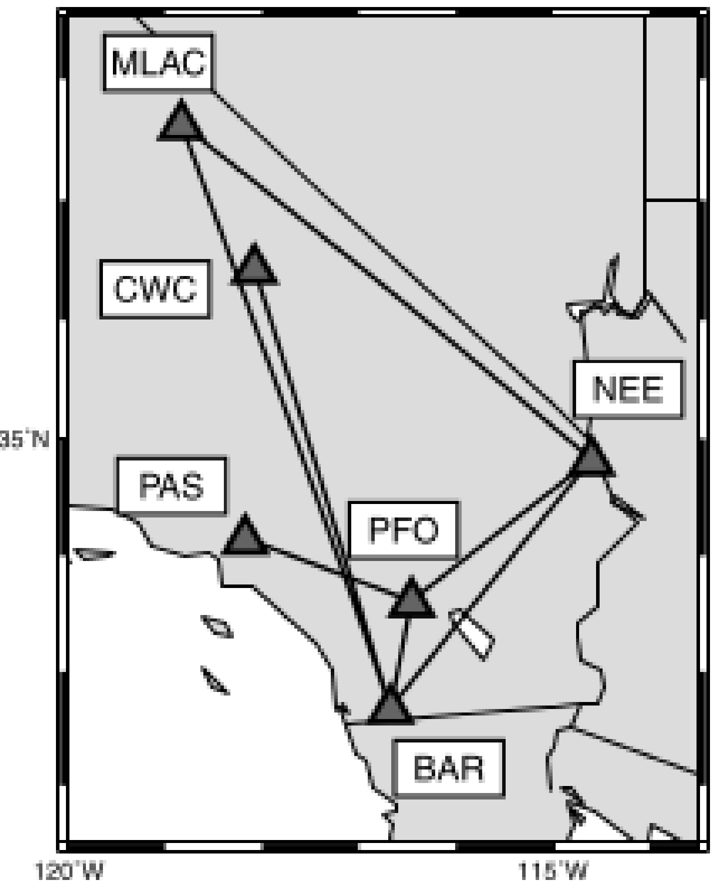
Campillo and Paul, 2003

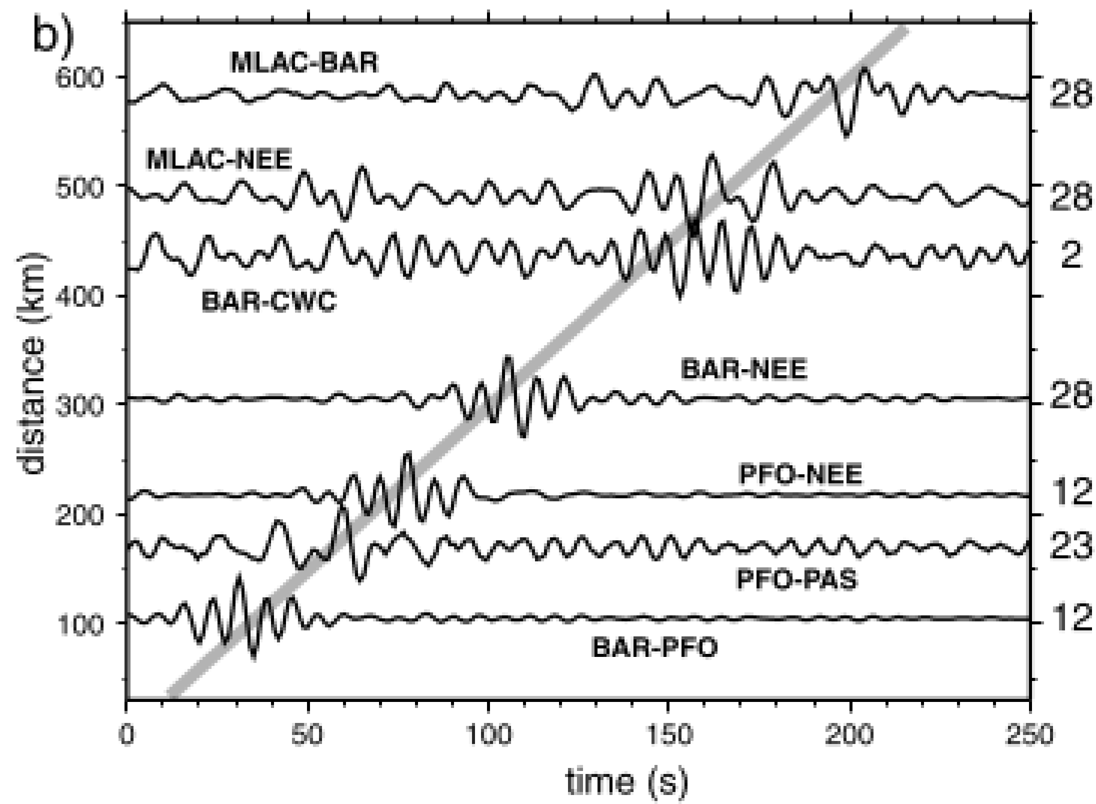


Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise

Seismic noise from oceanic sources



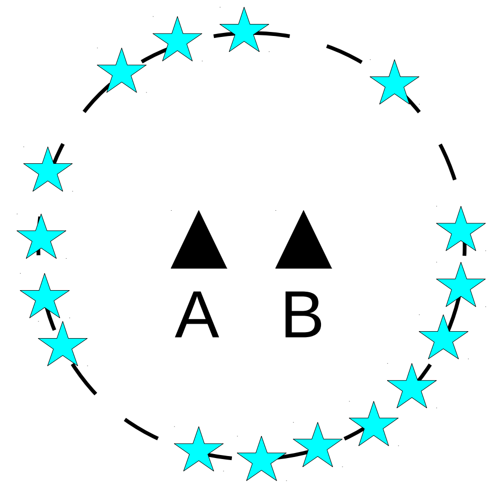


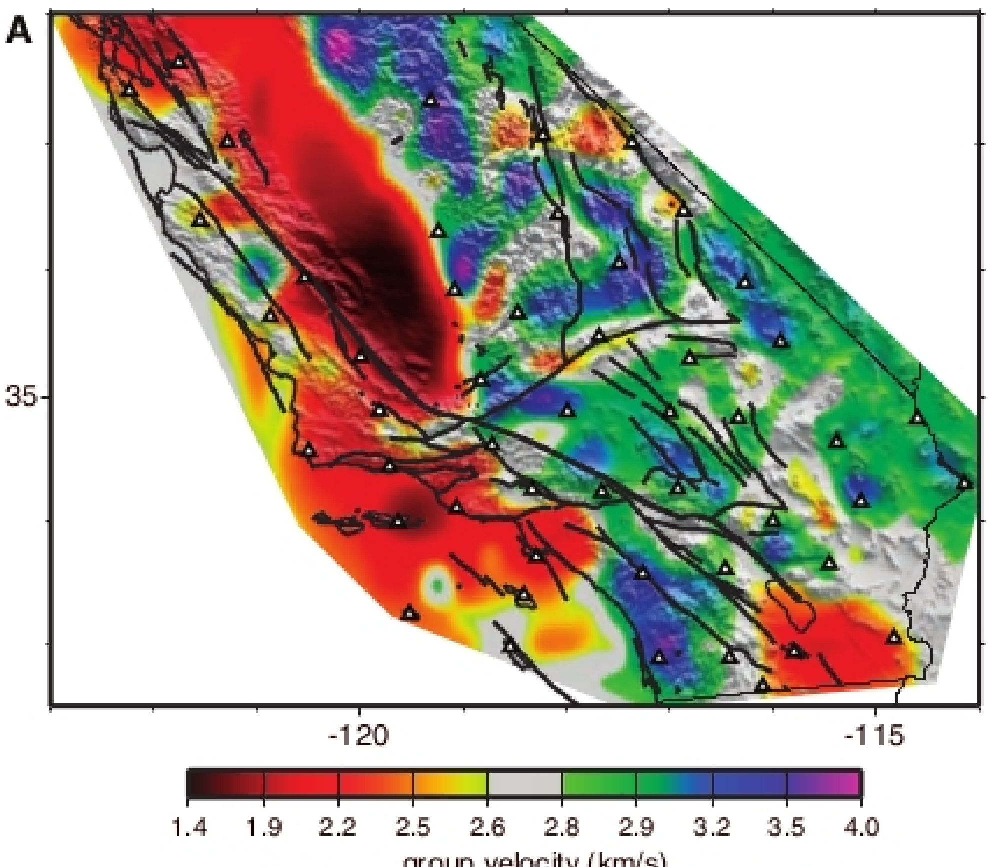


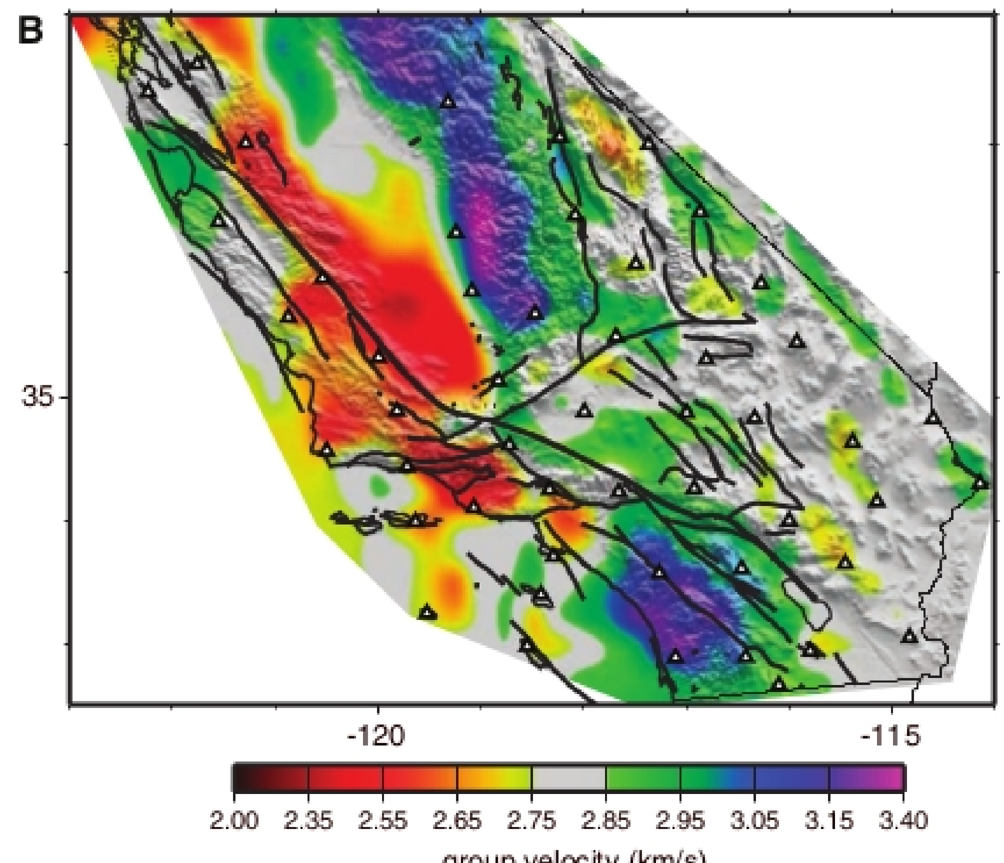
Shapiro and Campillo, 2004

High-Resolution Surface-Wave Tomography from Ambient Seismic Noise

Seismic noise from oceanic sources

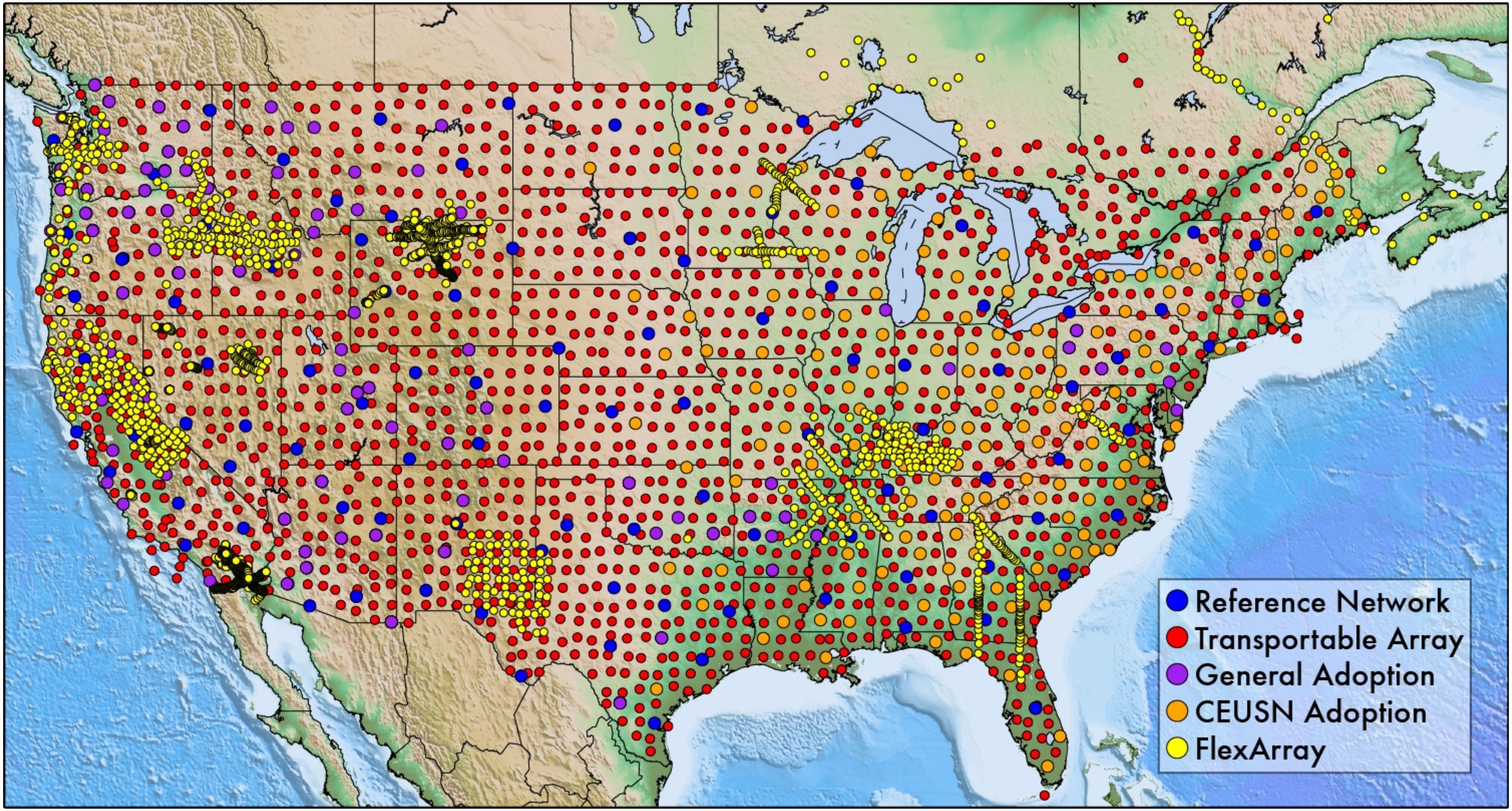






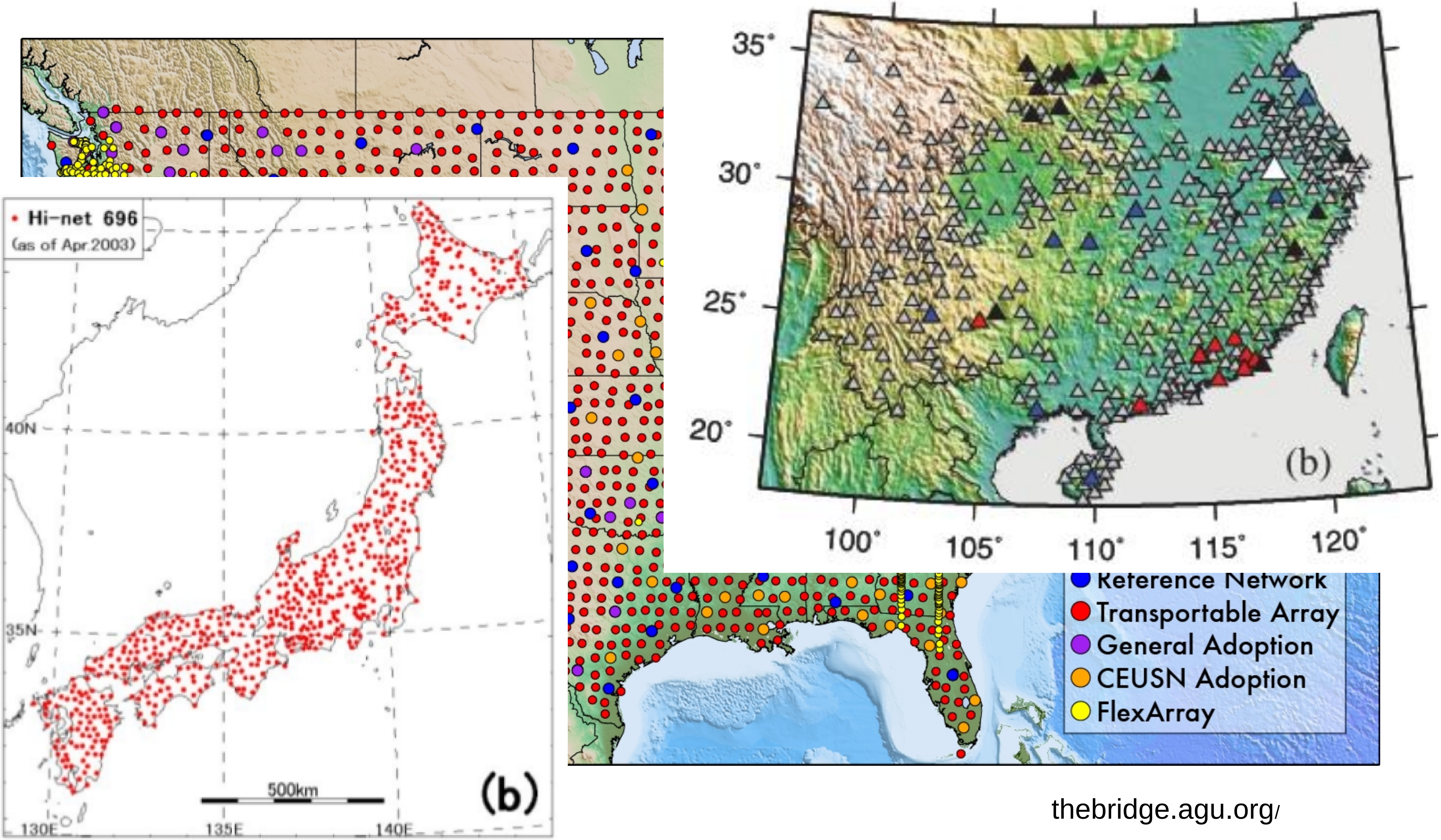
Shapiro et al., 2005

Development of dense seismic arrays



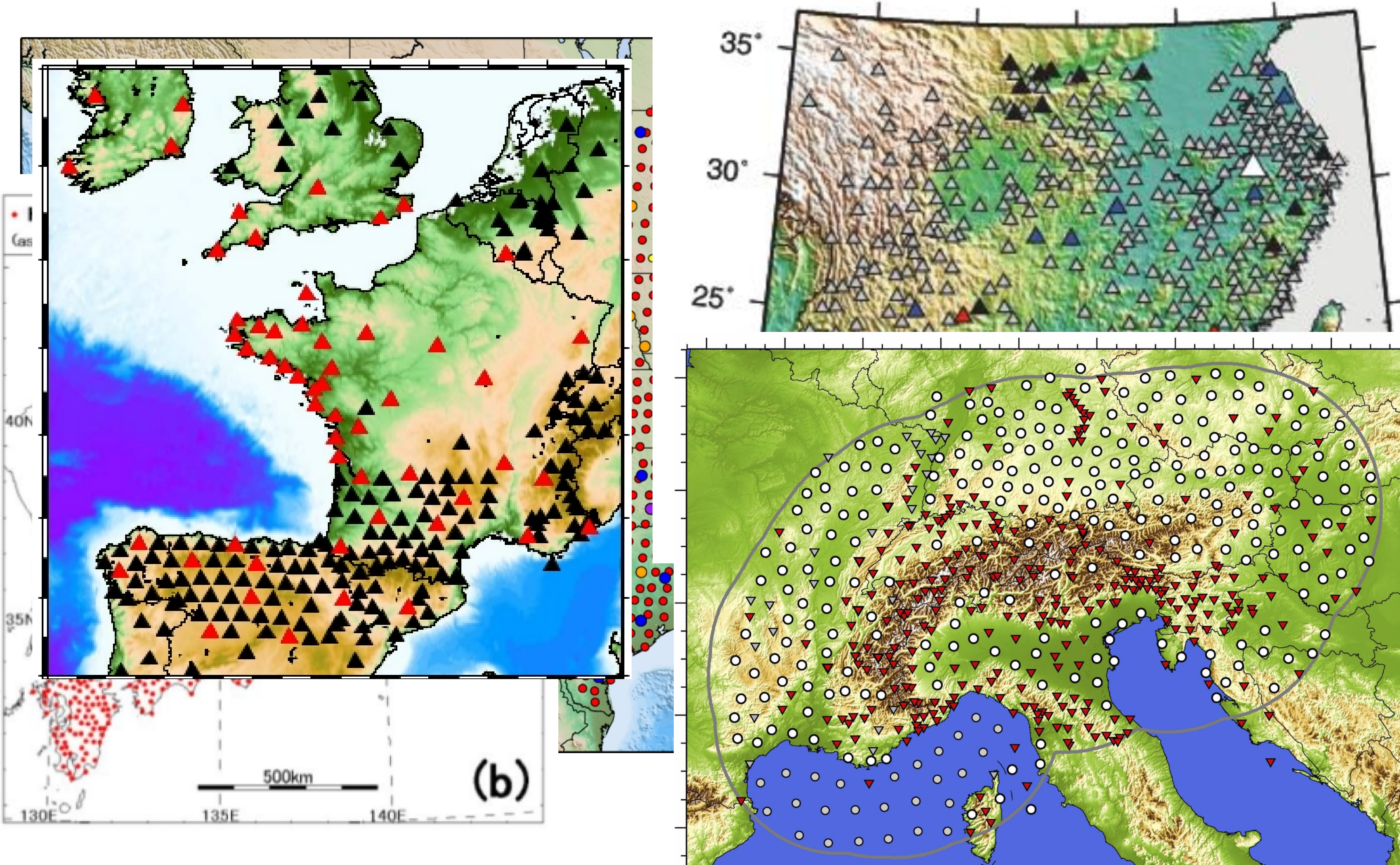
thebridge.agu.org/

Development of dense seismic arrays

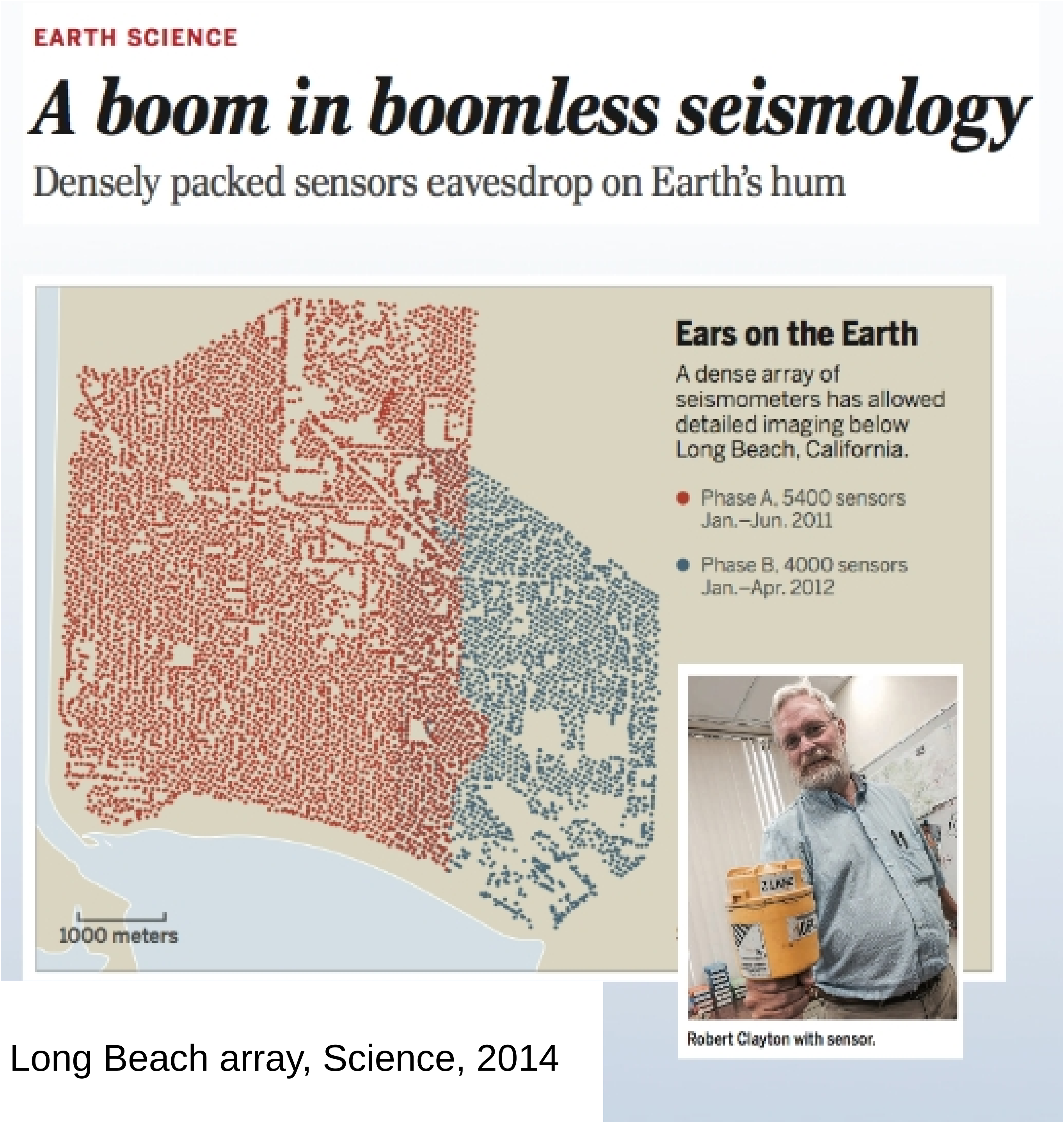


thebridge.agu.org/

Development of dense seismic arrays



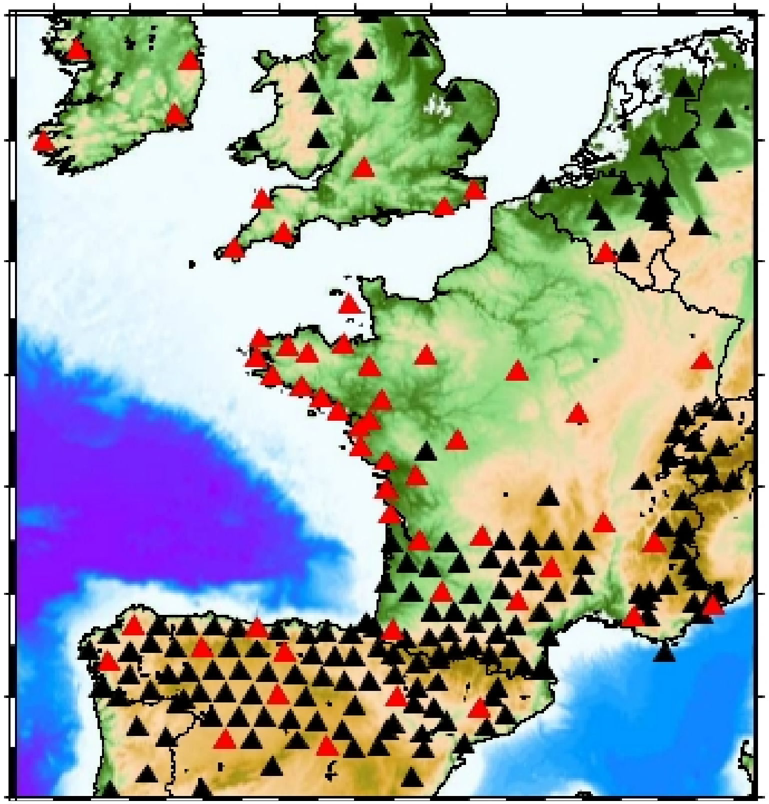
Development of dense seismic arrays



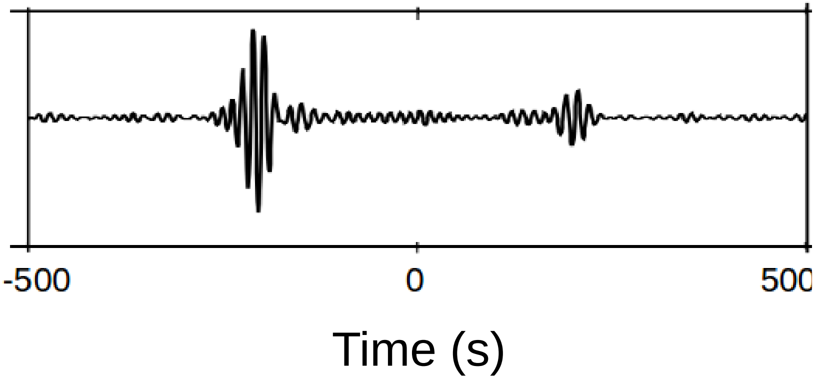
Long Beach array, Science, 2014

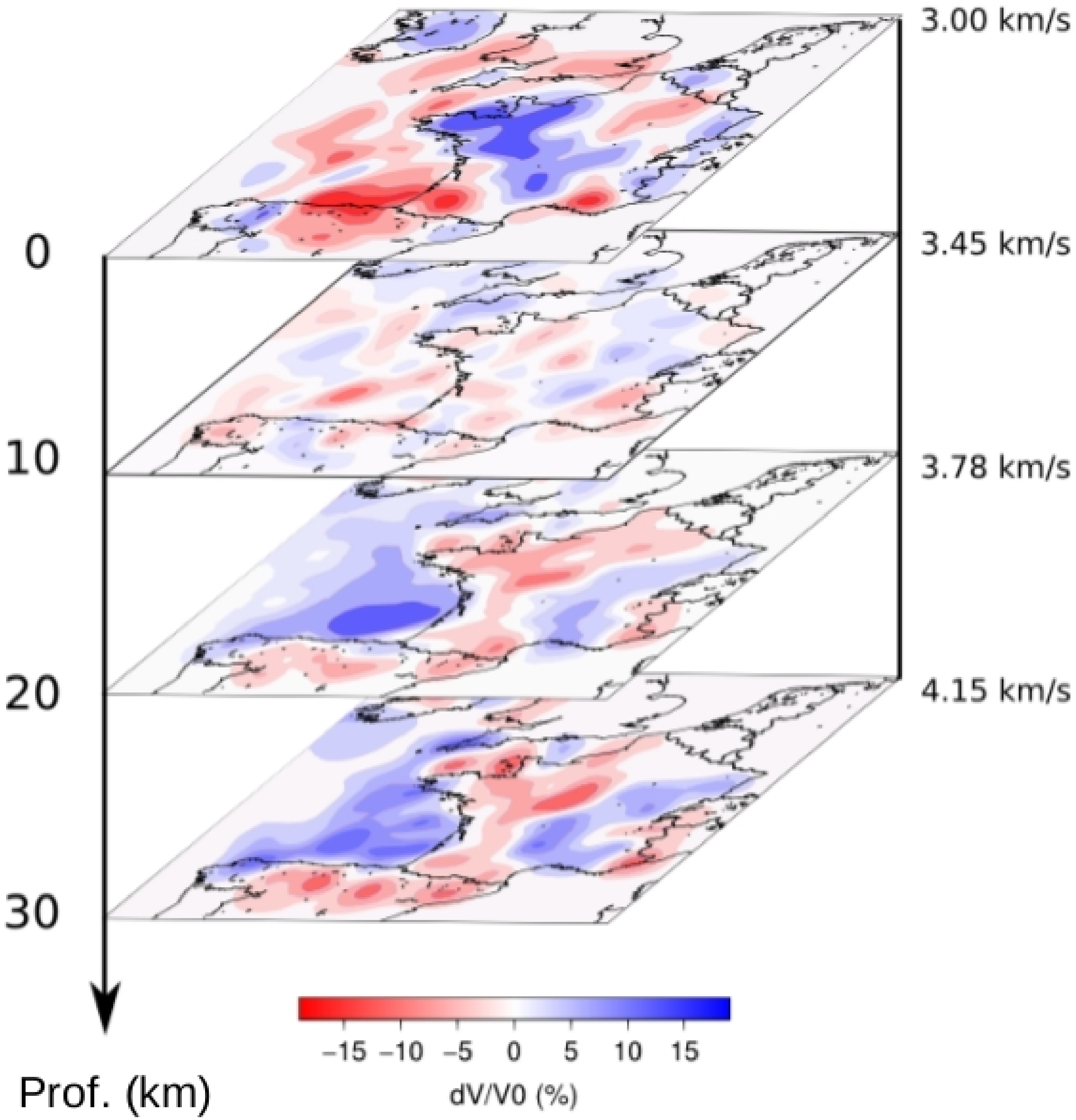
Imaging

3D velocity model of the Earth's crust



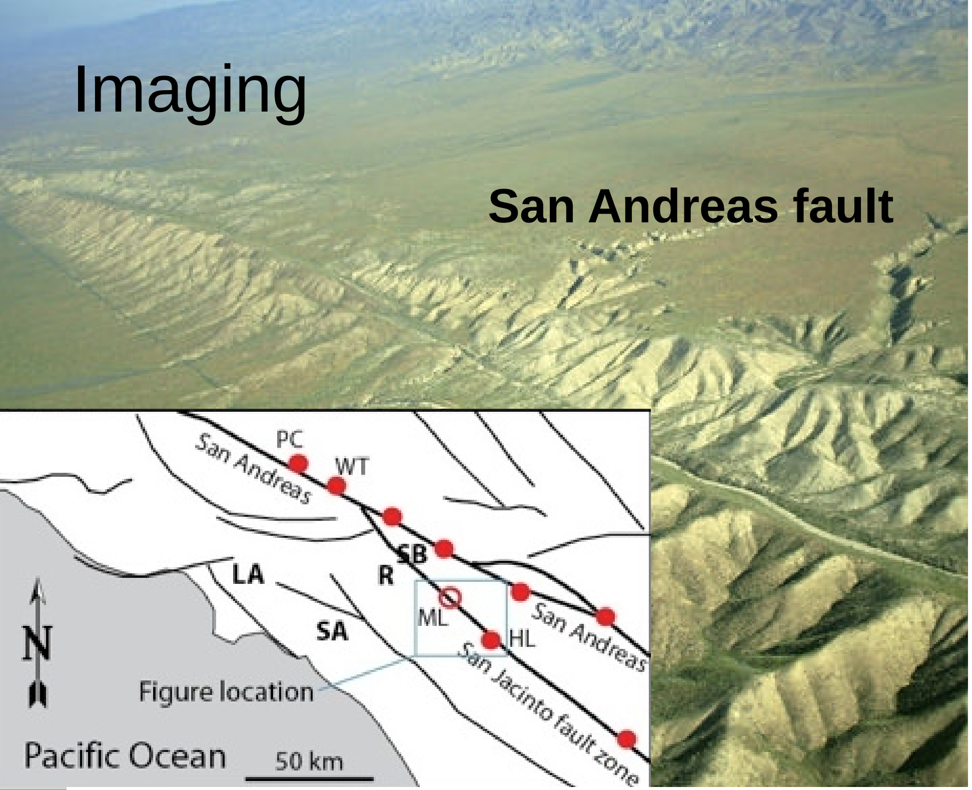
Green's function

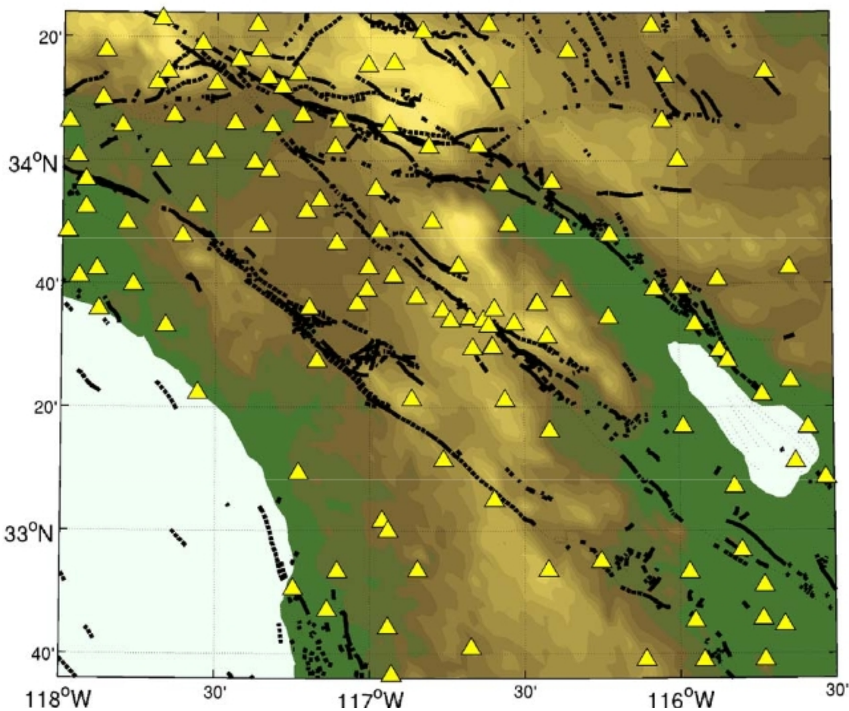


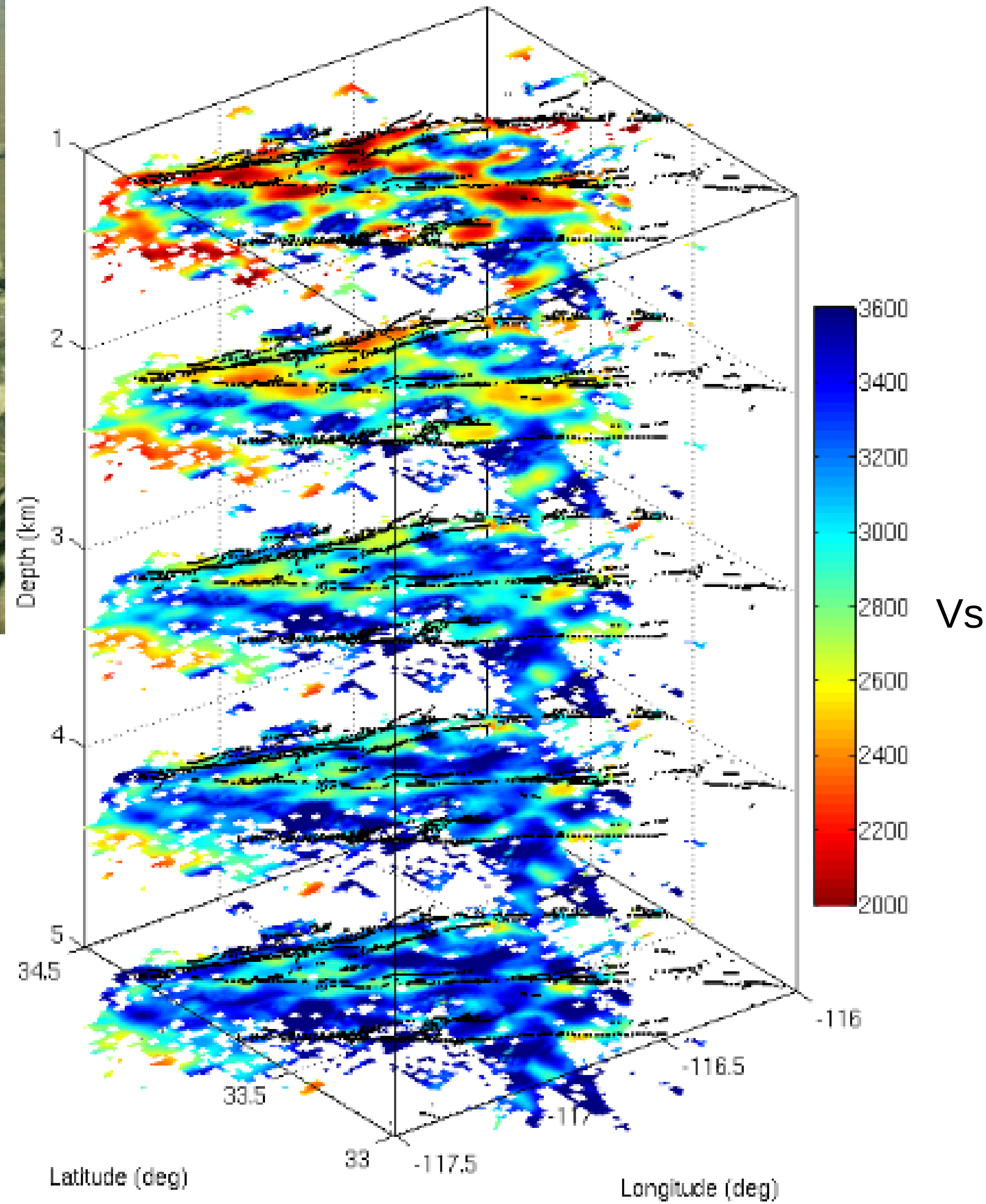


Gaudot et al., 2016, in prep.

Imaging

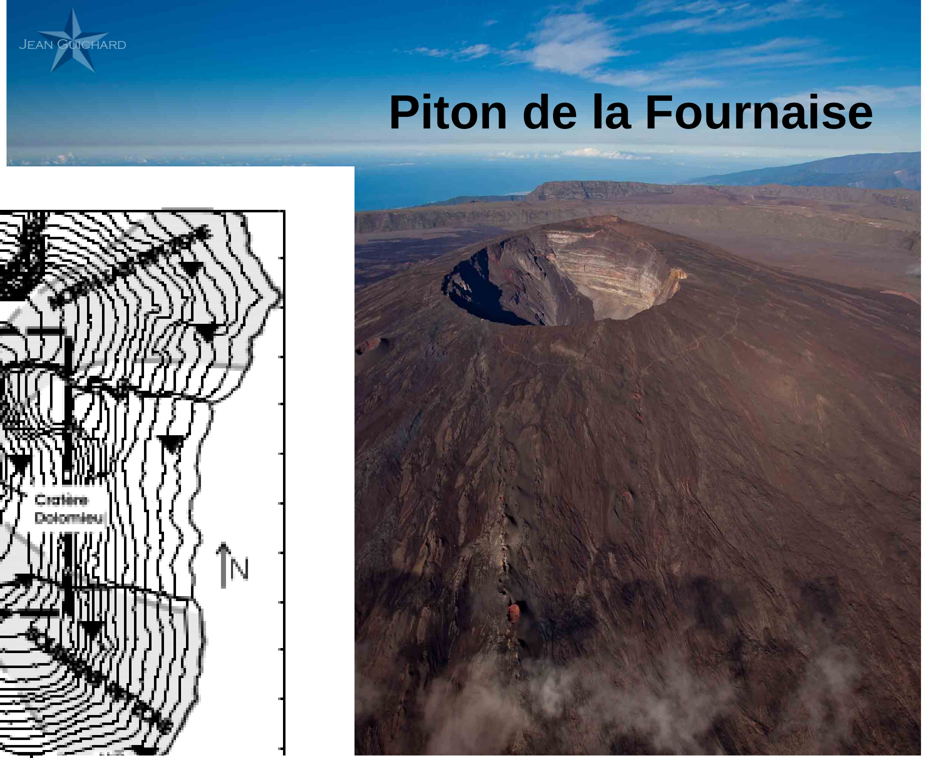


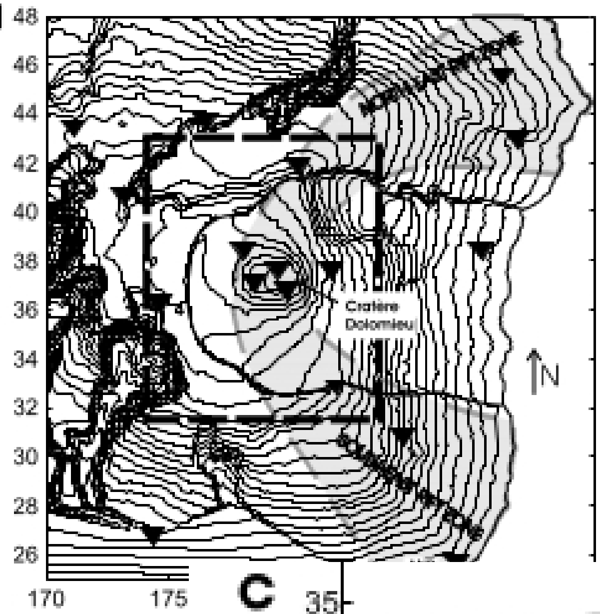


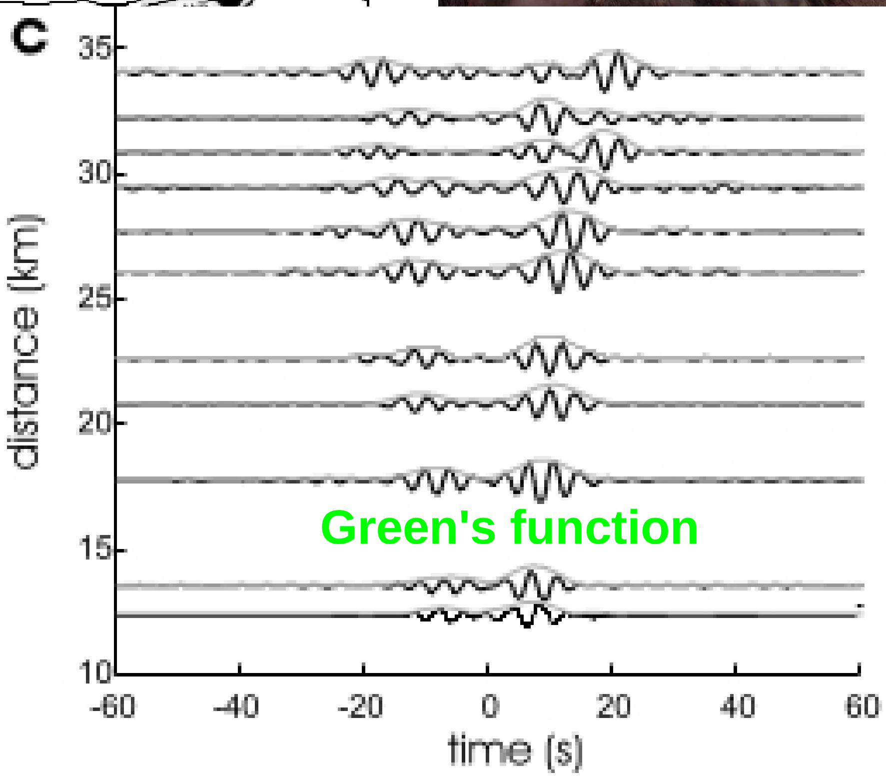


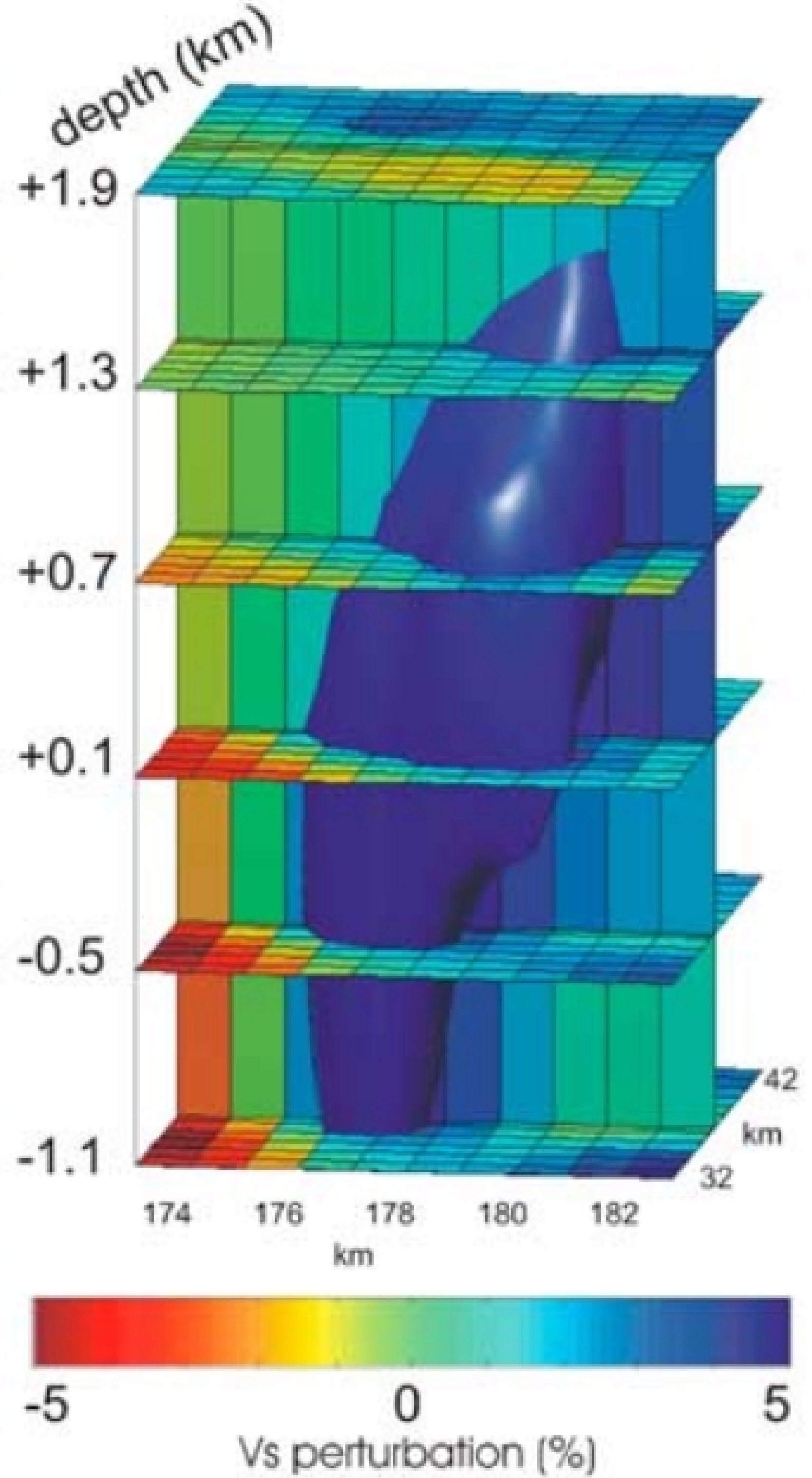
Zigone et al. , 2015

Imaging





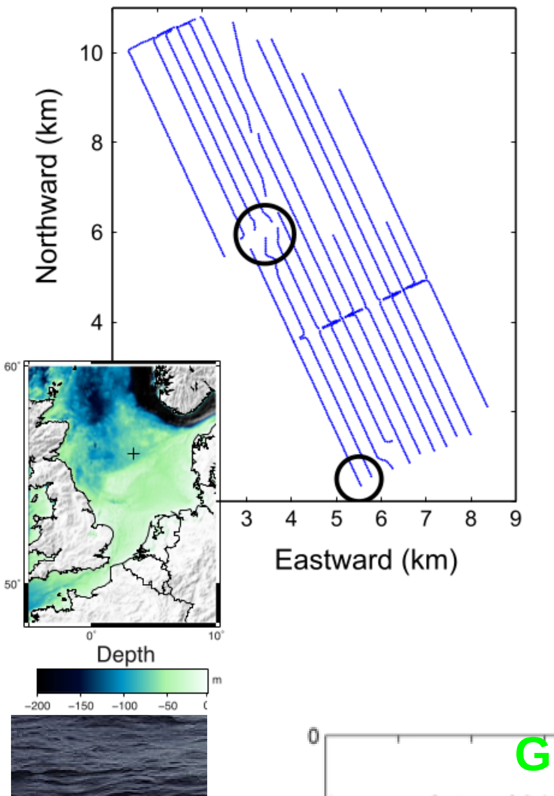




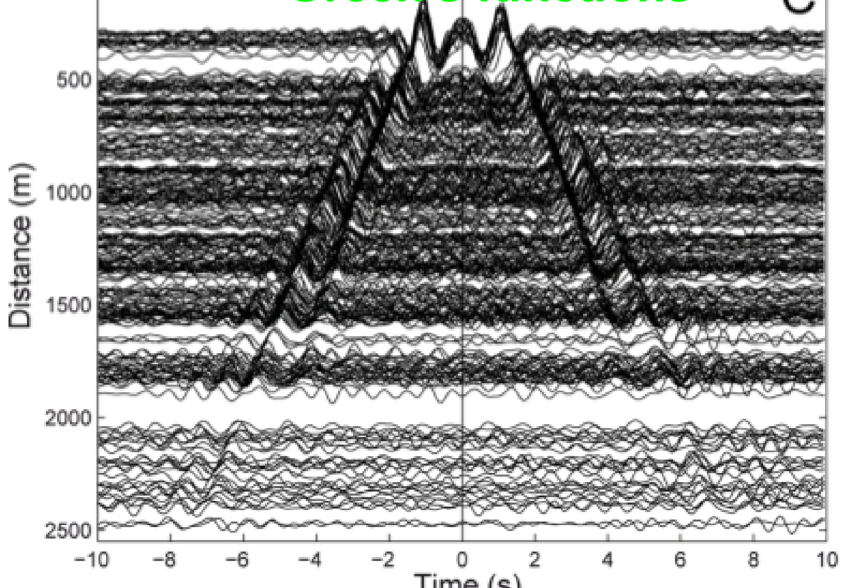
Brenguier et al., 2007

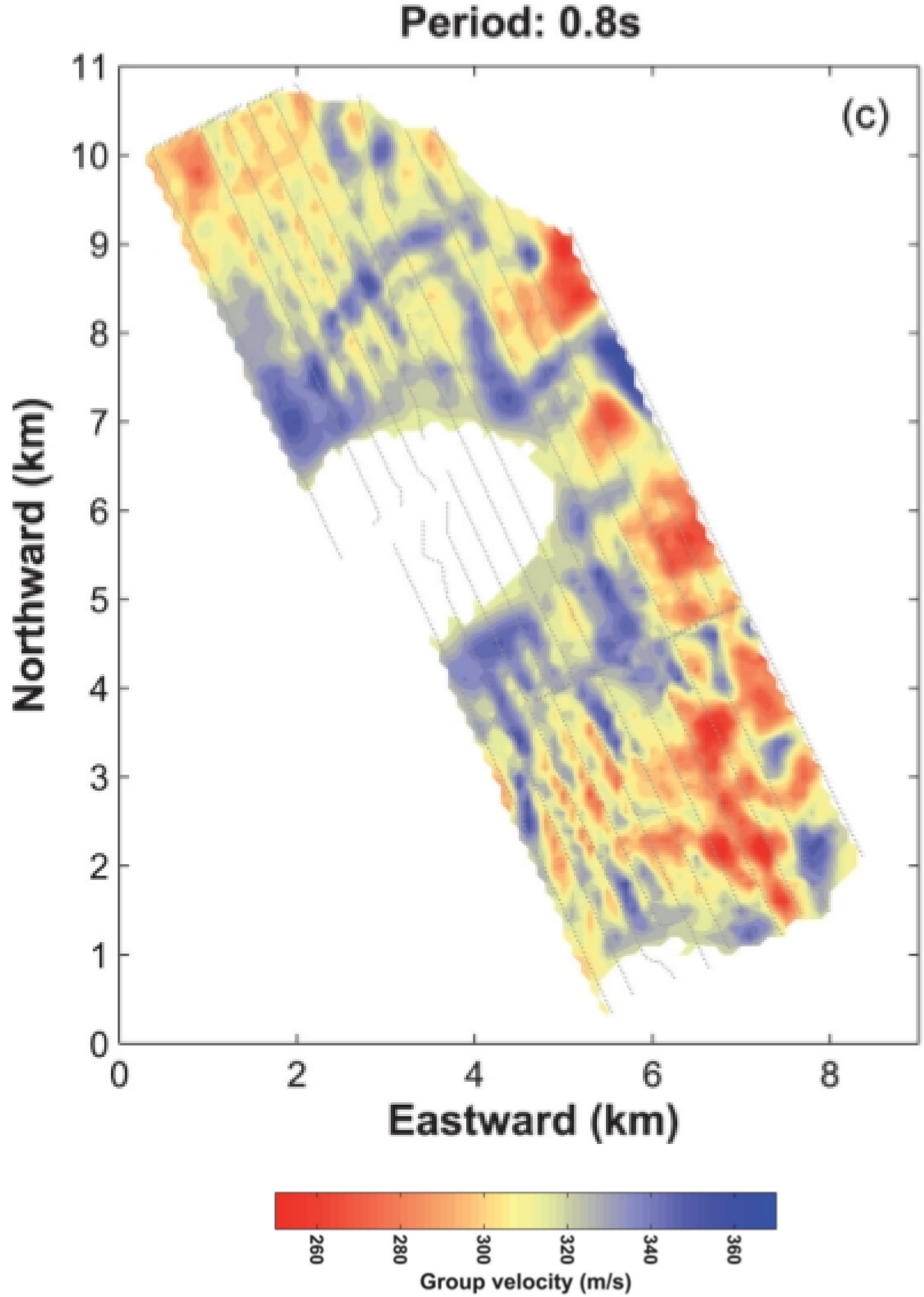
Imaging

Valhall oil field



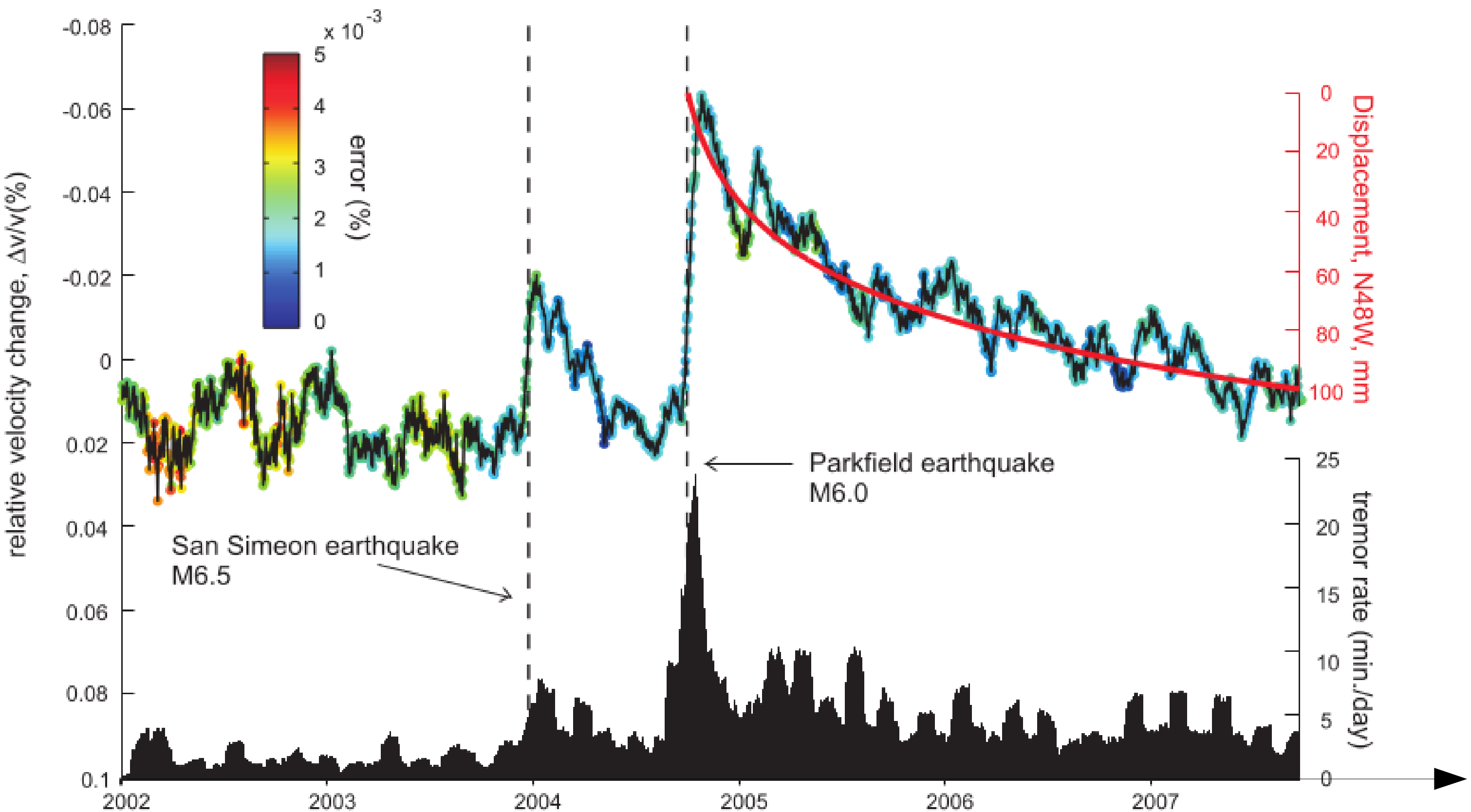
Green's functions





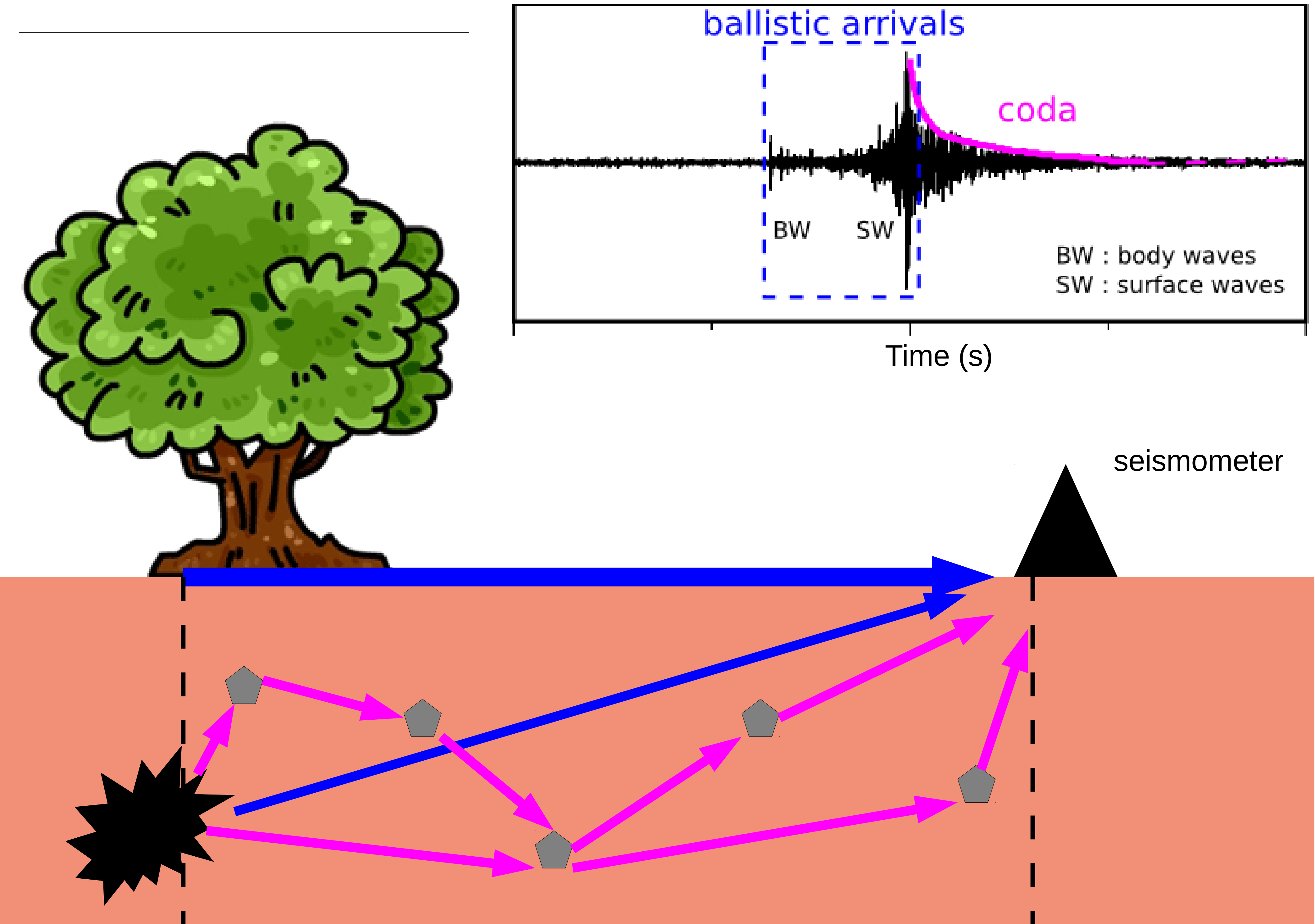
Mordret et al., 2013

Monitoring (Earth's) structures (4D imaging, temporal variations)

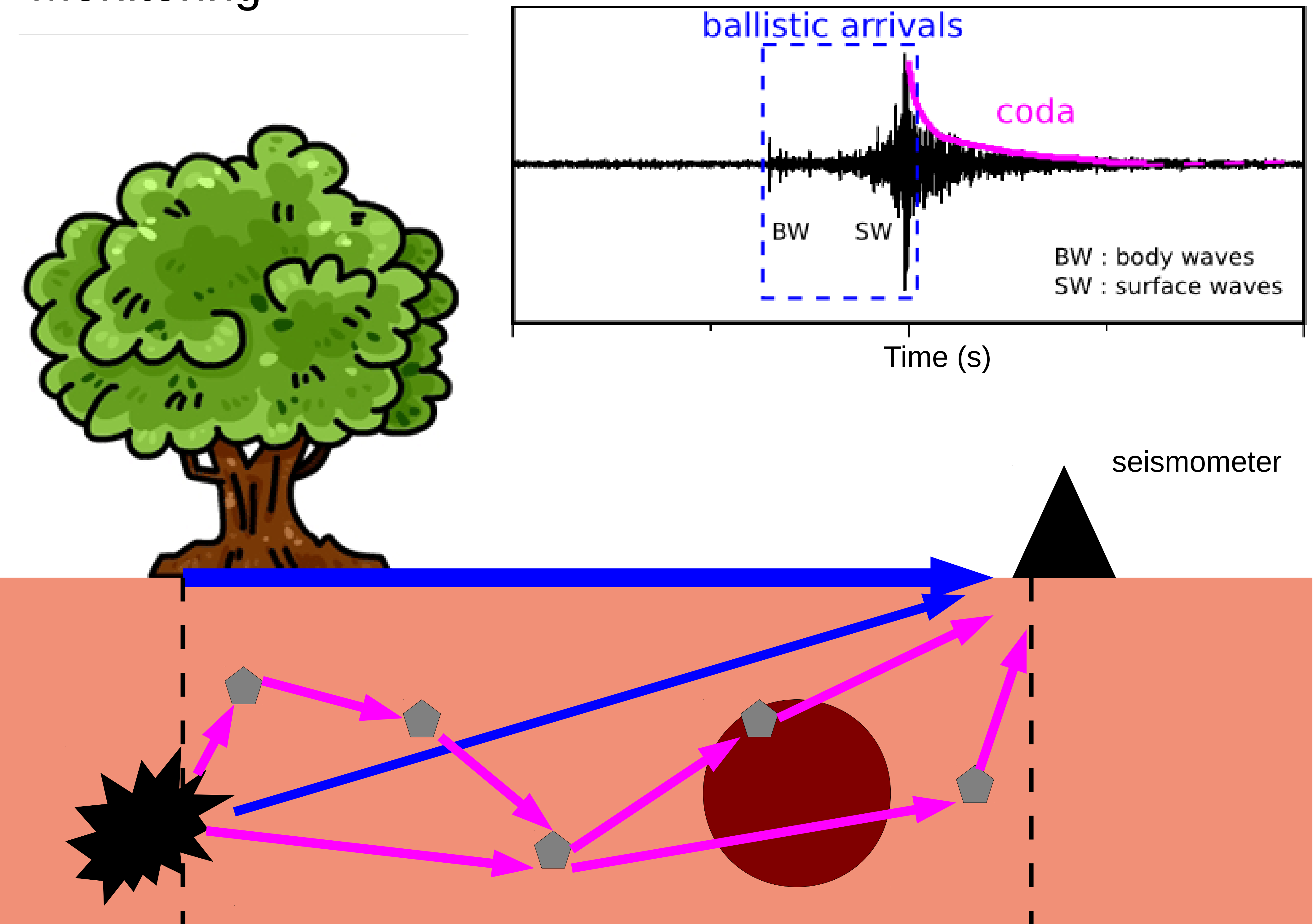


From Brenguier et al., 2008

The Green's function

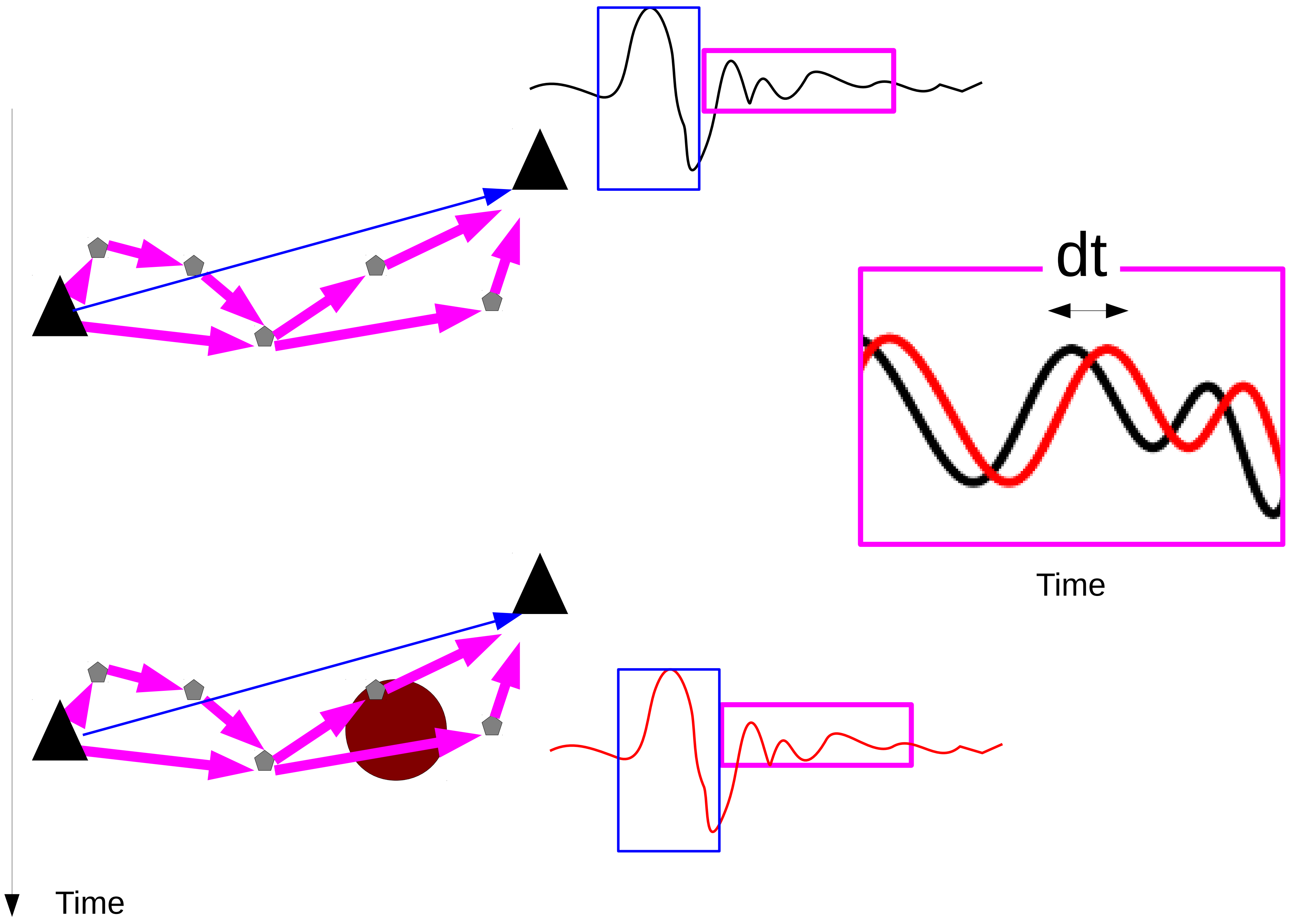


Monitoring



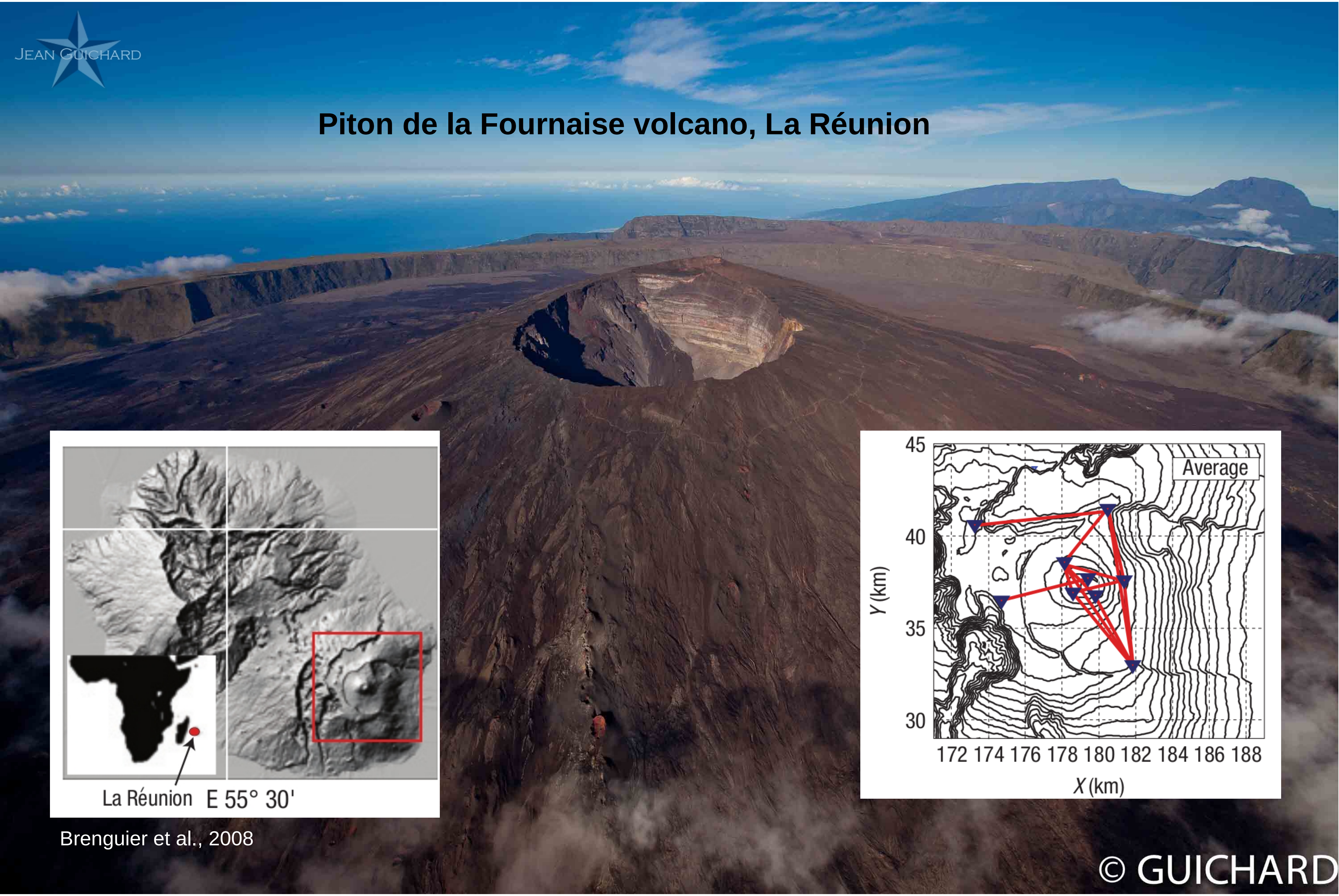
ballistic arrivals
coda
BW
SW
BW : body waves
SW : surface waves
Time (s)
seismometer

Monitoring



Monitoring

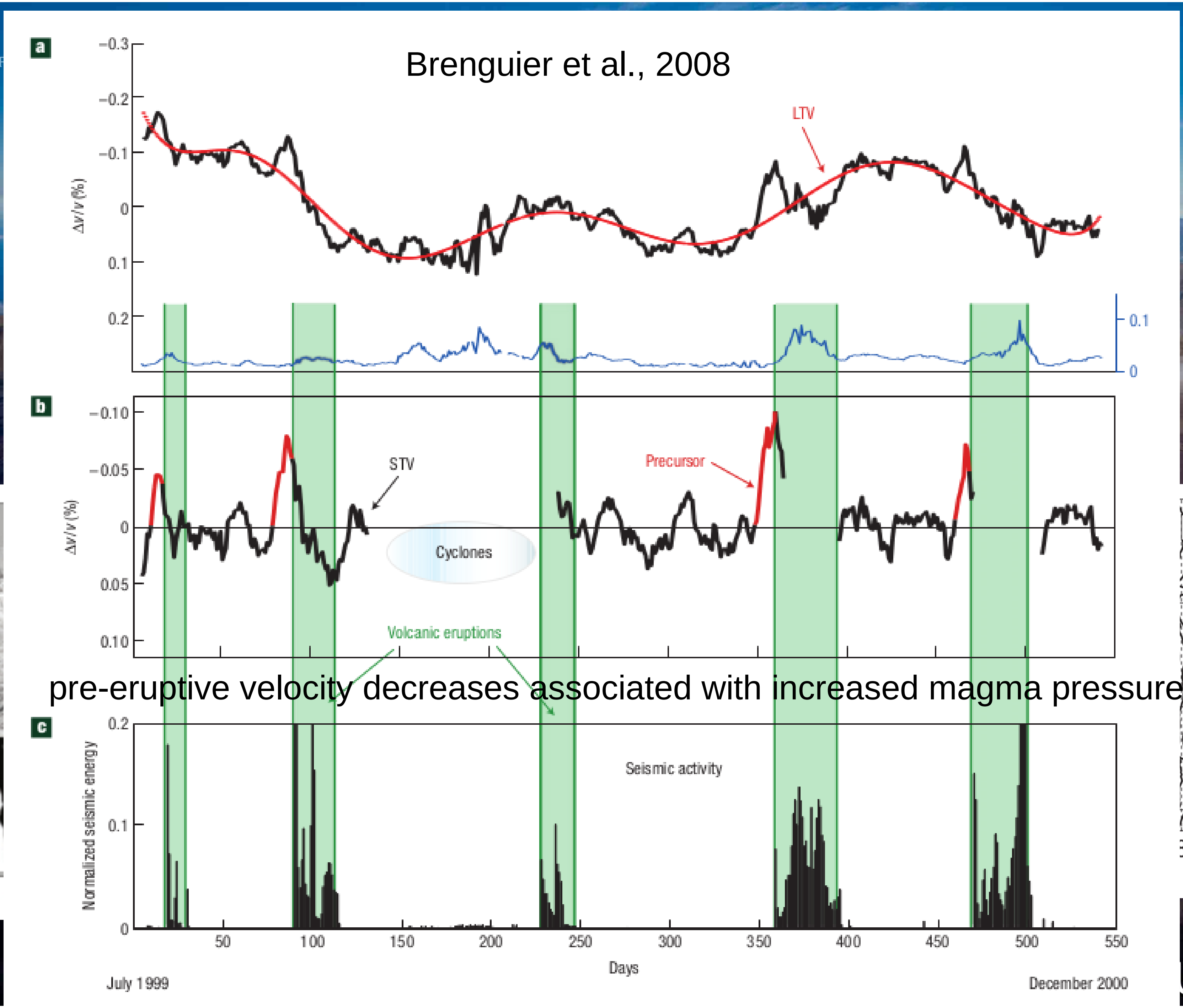
Piton de la Fournaise volcano, La Réunion



Brenguier et al., 2008

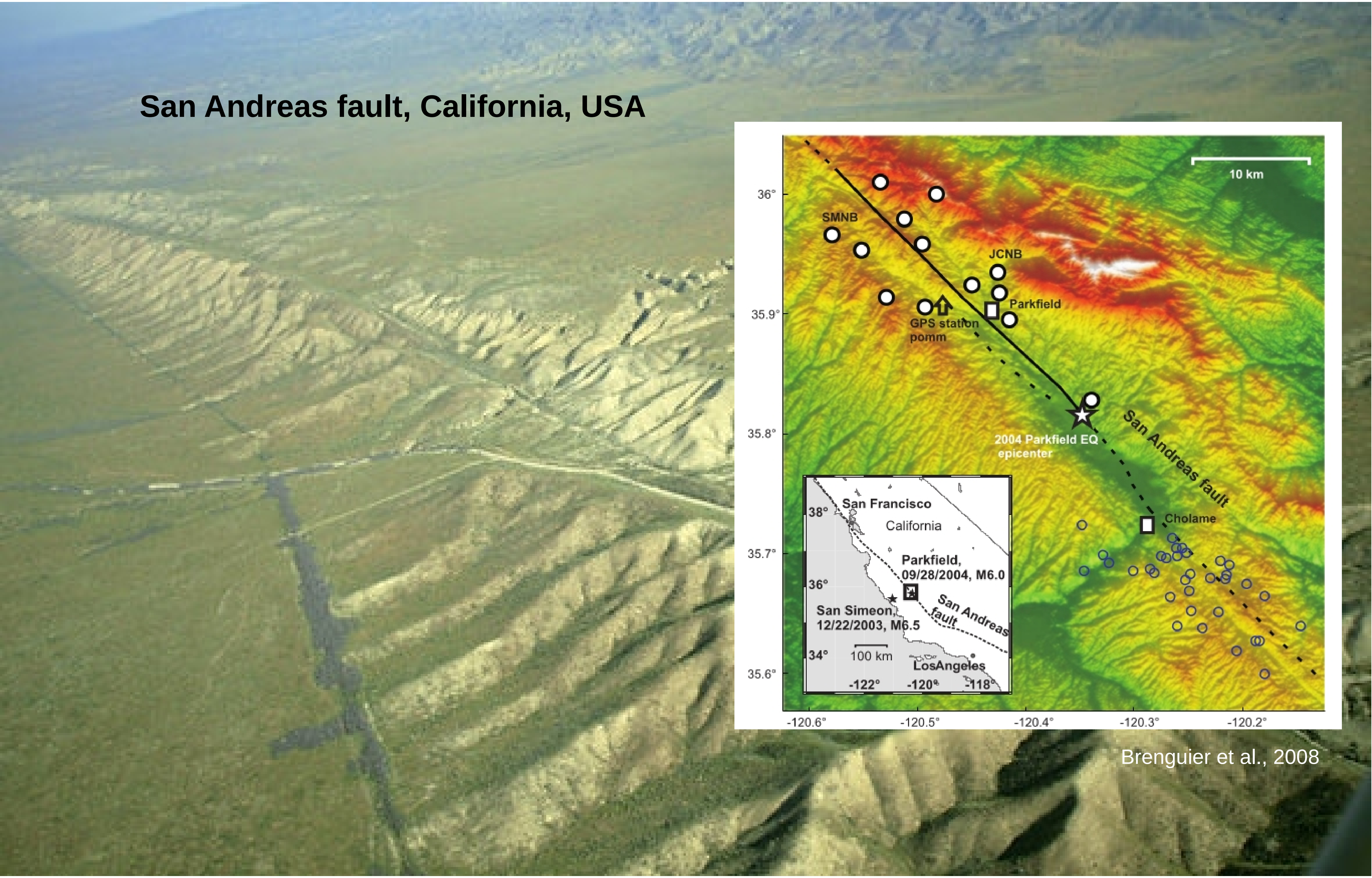
Monitoring

Brenguier et al., 2008

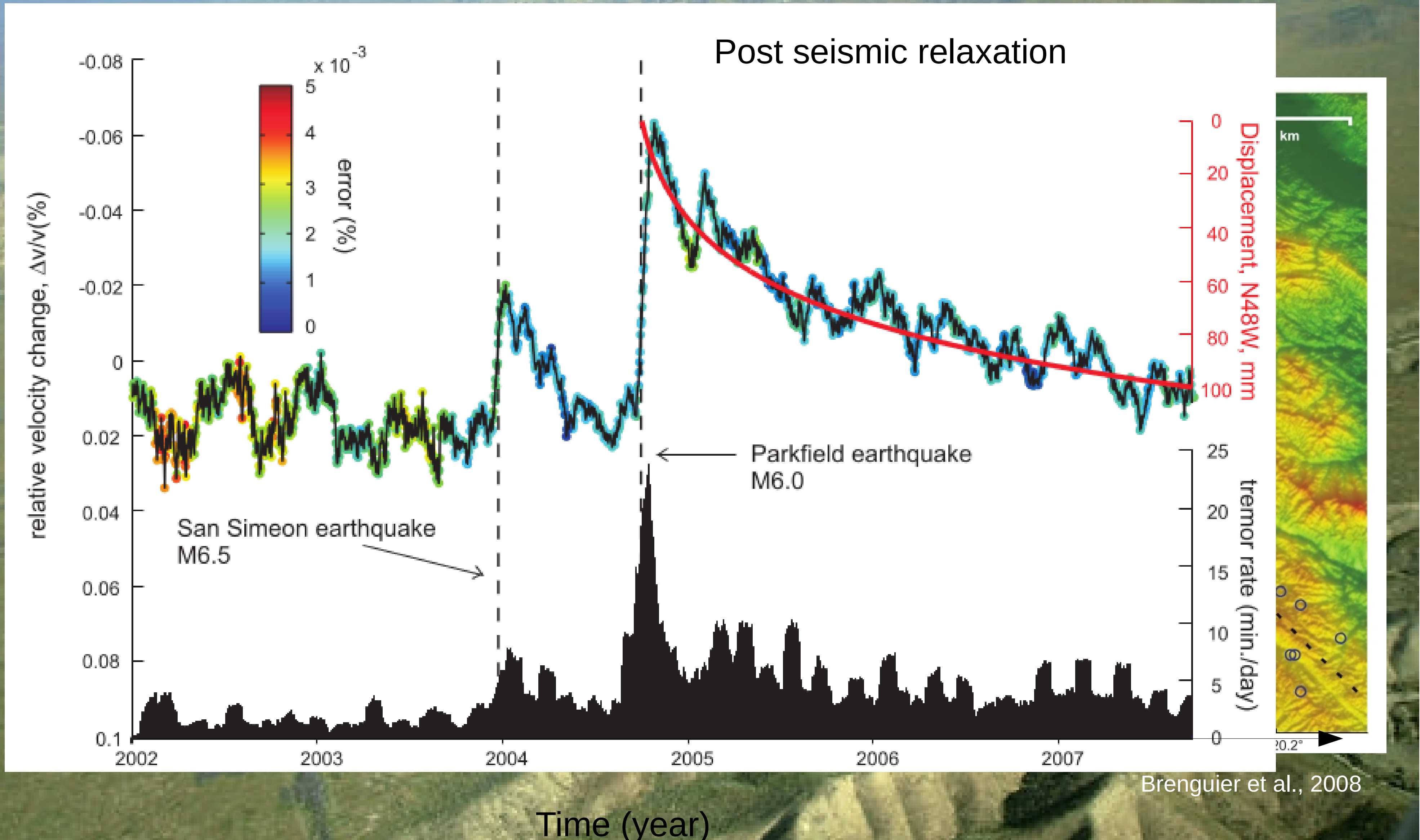


pre-eruptive velocity decreases associated with increased magma pressure

Monitoring


San Andreas fault, California, USA
10 km
36°
35.9°
35.8°
35.7°
35.6°
SMNB
JCNB
Parkfield
GPS station
pomm
2004 Parkfield EQ
epicenter
San Andreas fault
Cholame
San Francisco
California
38°
36°
34°
Parkfield,
09/28/2004, M6.0
San Andreas
fault
San Simeon,
12/22/2003, M6.5
100 km
LosAngeles
-122°
-120°
-118°
-120.6°
-120.5°
-120.4°
-120.3°
-120.2°
Brenguier et al., 2008

Monitoring

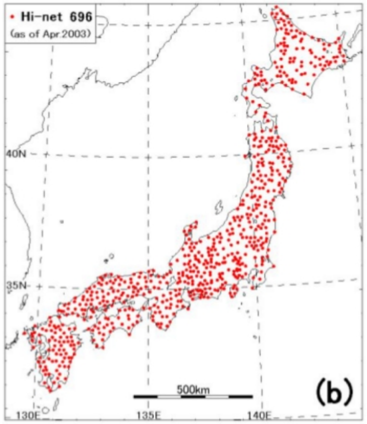


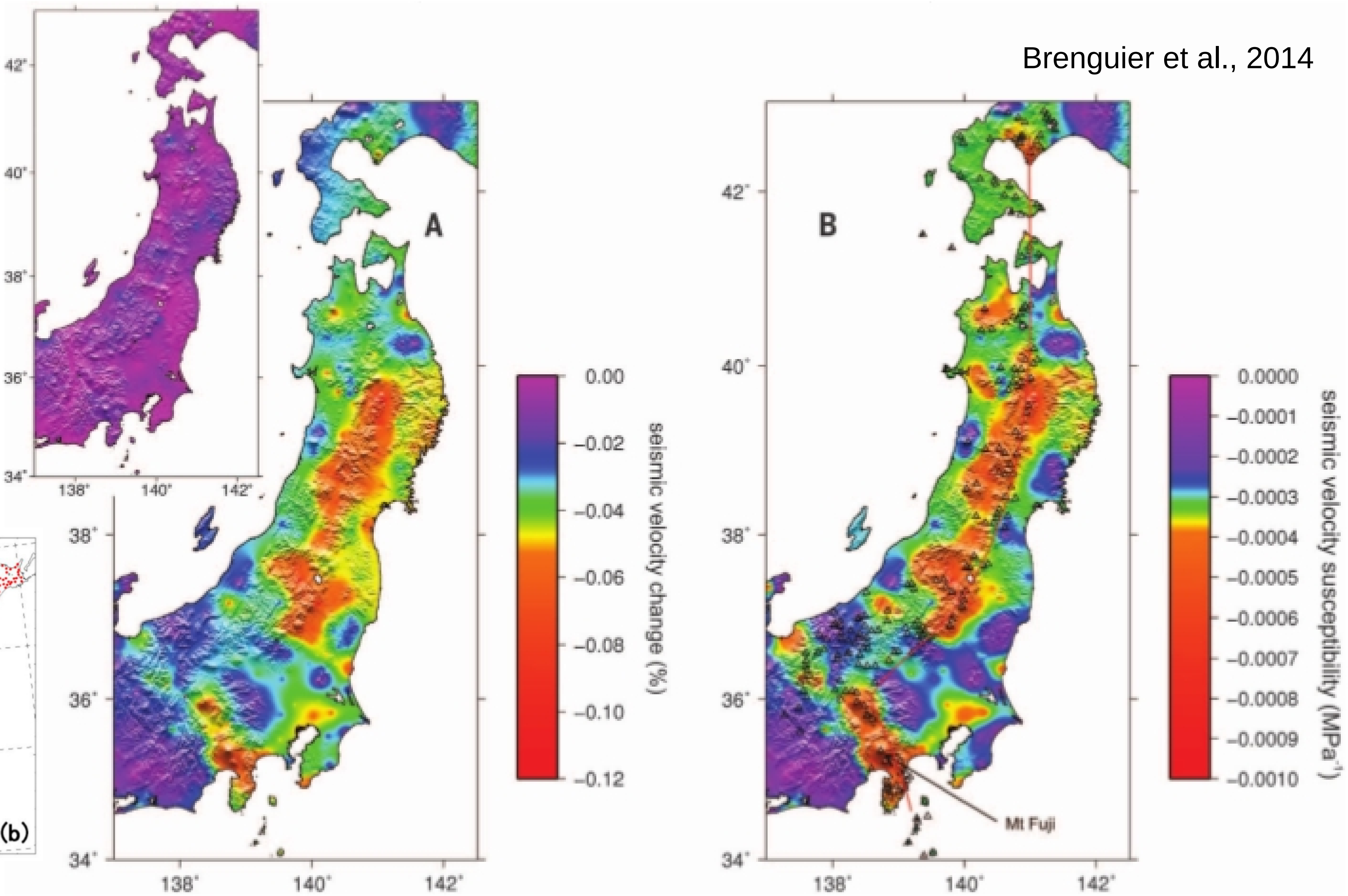
From Brenguier et al., 2008

Monitoring

Japan crust monitoring after the Tohuku-Oki earthquake, 2011

Brenguier et al., 2014

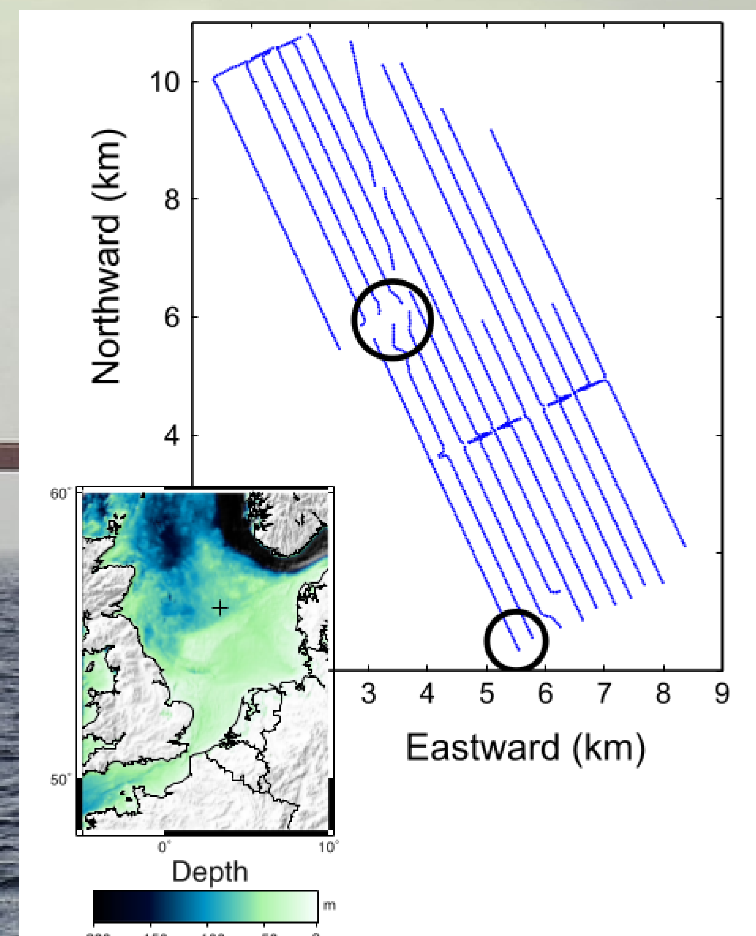




Coseismic velocity reductions highlight pressurized **volcanic fluids** in the upper crust

Monitoring

Valhall oil field , North sea, Norway

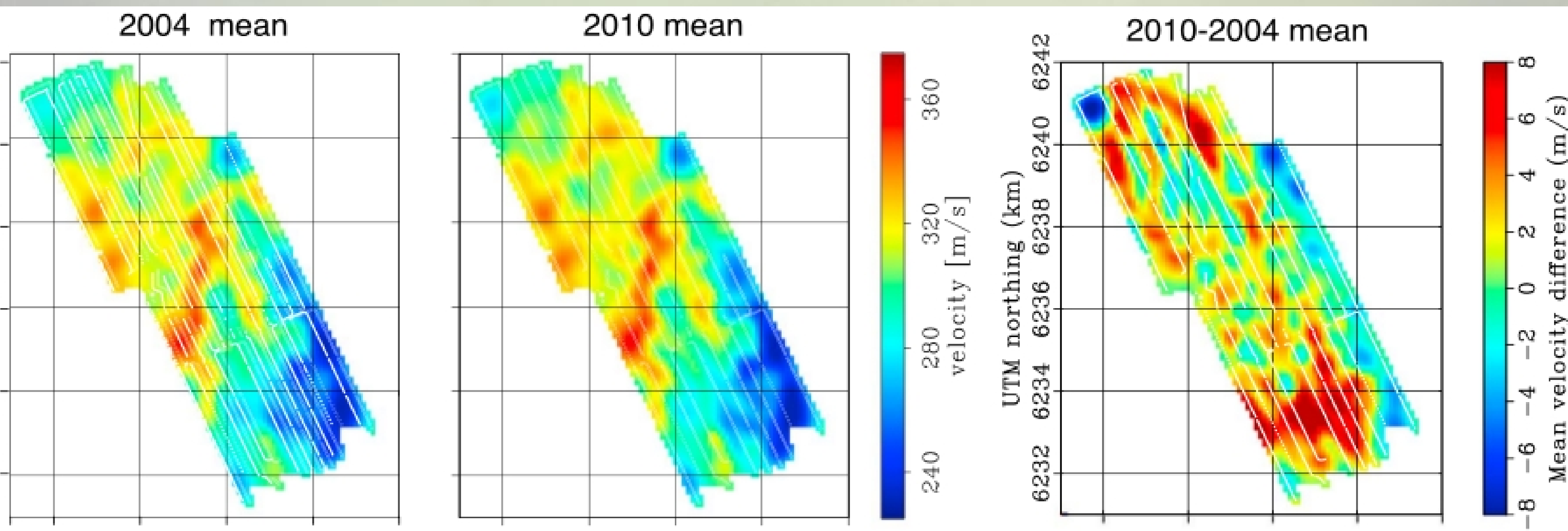


Monitoring

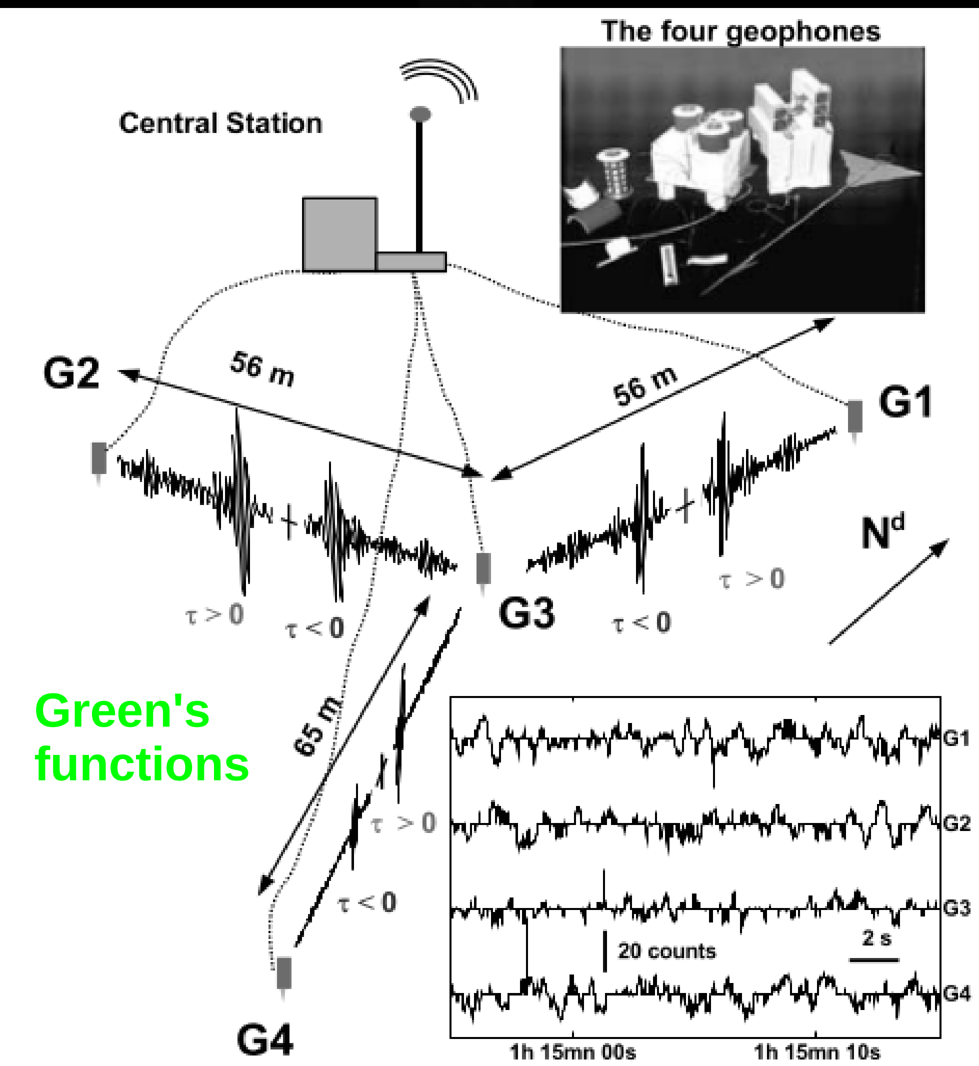
Valhall oil field , North sea, Norway

Time (year)

TIME LAPSE IMAGING

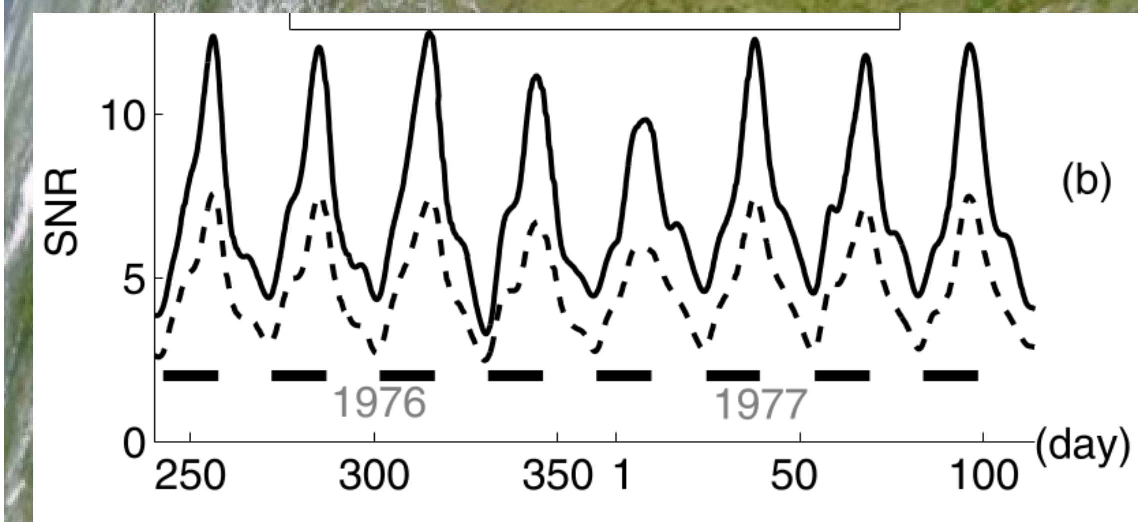


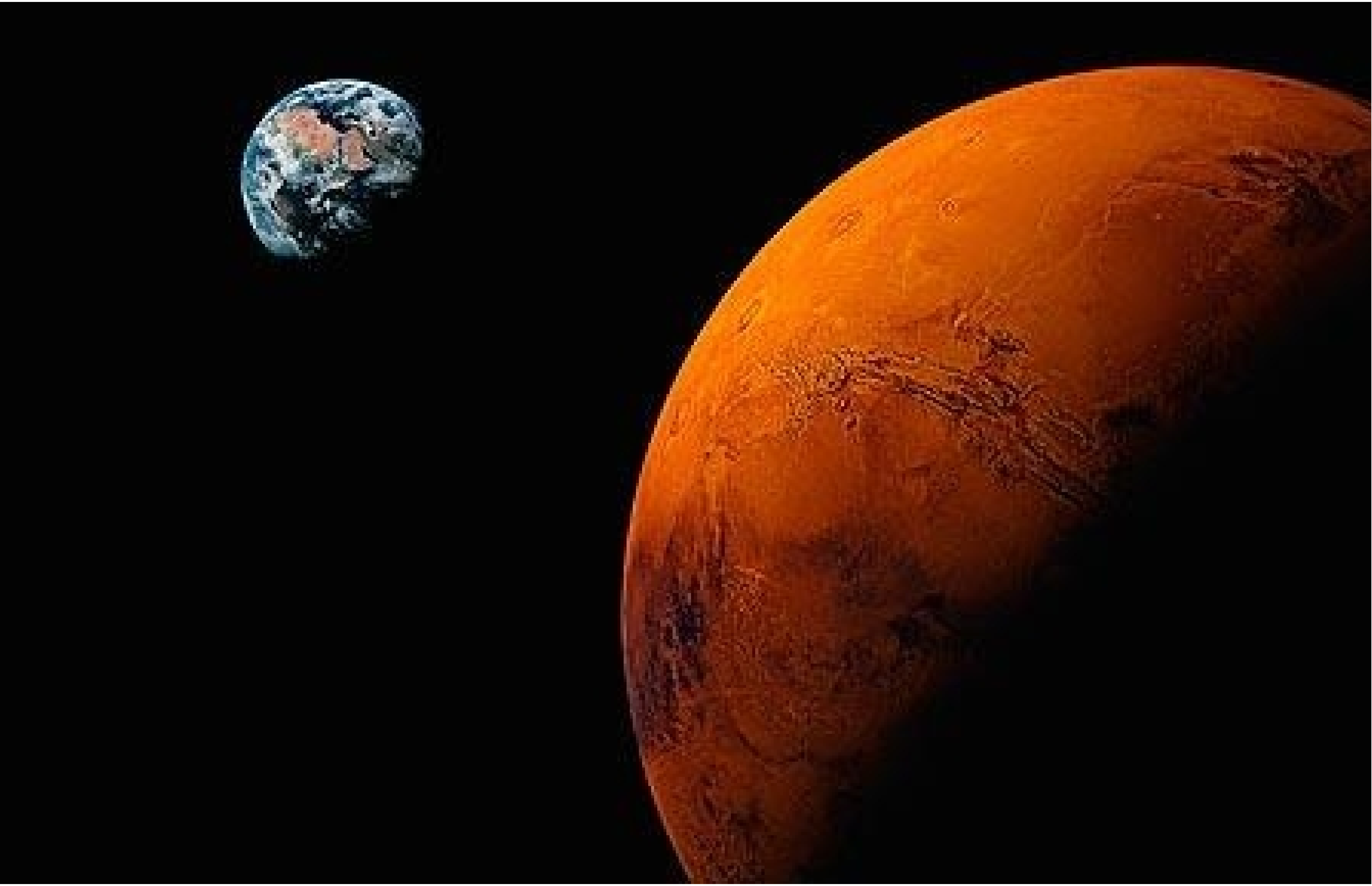
Velocity increase associated with compaction and subsidence as a result of **reservoir productio**



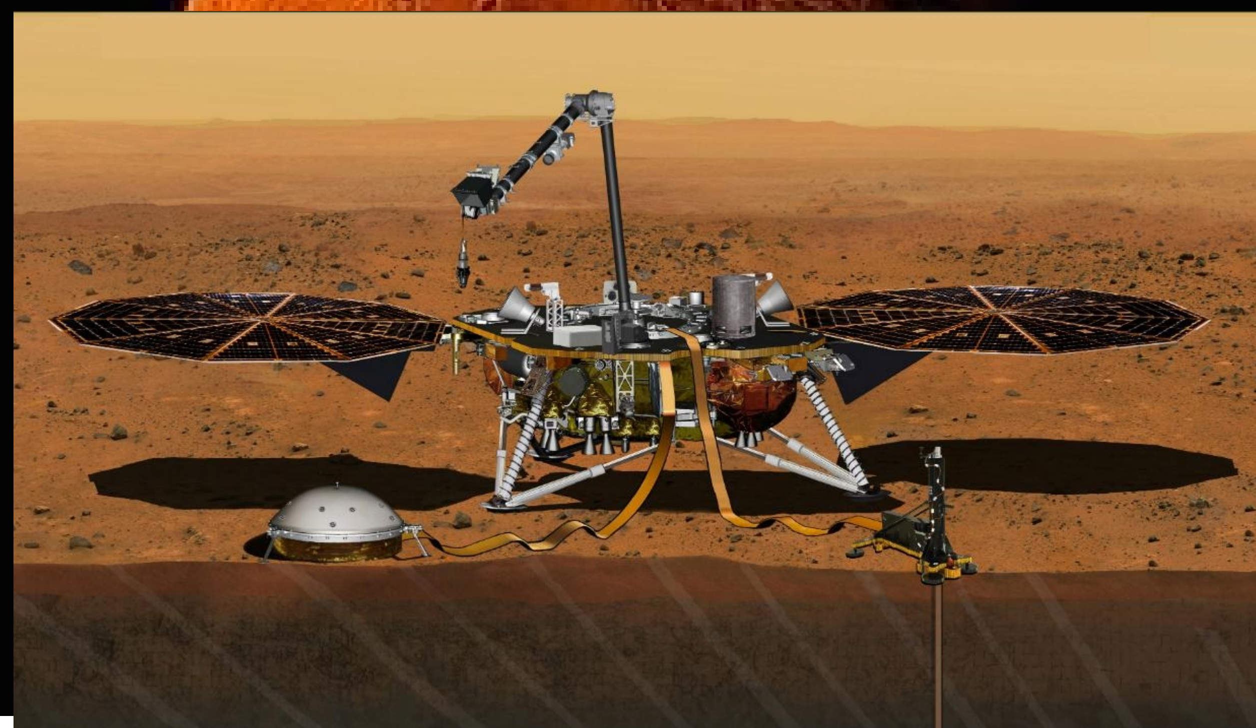
Green's functions

cracking of the lunar surface material due to high temperature during the day = seismic noise !!





Listen to Mars' hum (?) may help if « marsquake » are not frequent



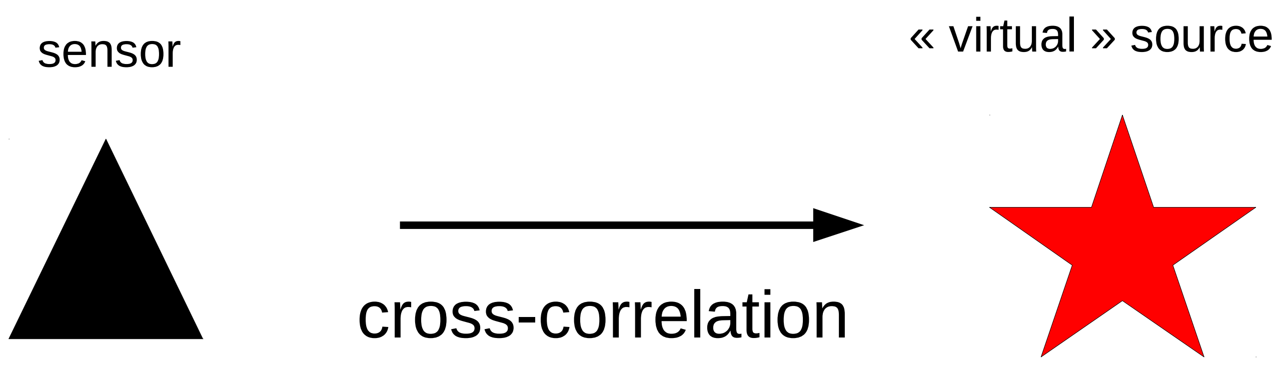
Others application

- acoustic waves in ocean
- structural engineering (concrete, etc...)
- human body
- helioseismology
- Etc ...

Applications exist in a wide range of environments and frequency bandwidths because the physics driving **cross-correlation process of « diffuse wavefield »** remains similar.

Conclusion

Listening to continuous complex wavefields provide a new way to image and monitor structures in a wide range of applications



Listen to the Earth's hum for imaging and monitoring

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