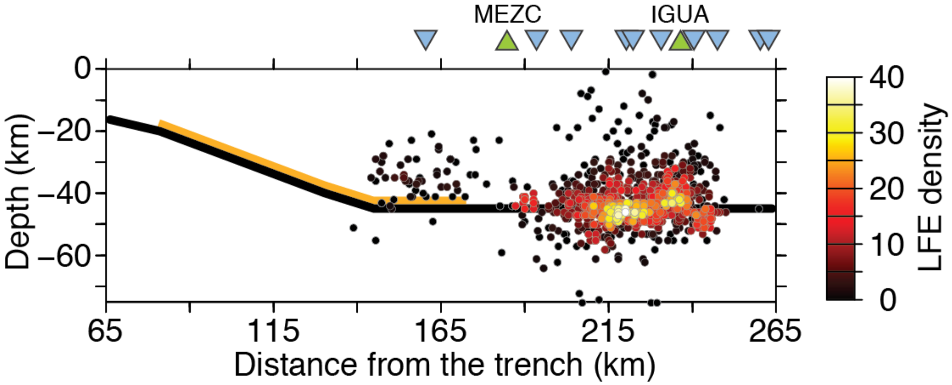
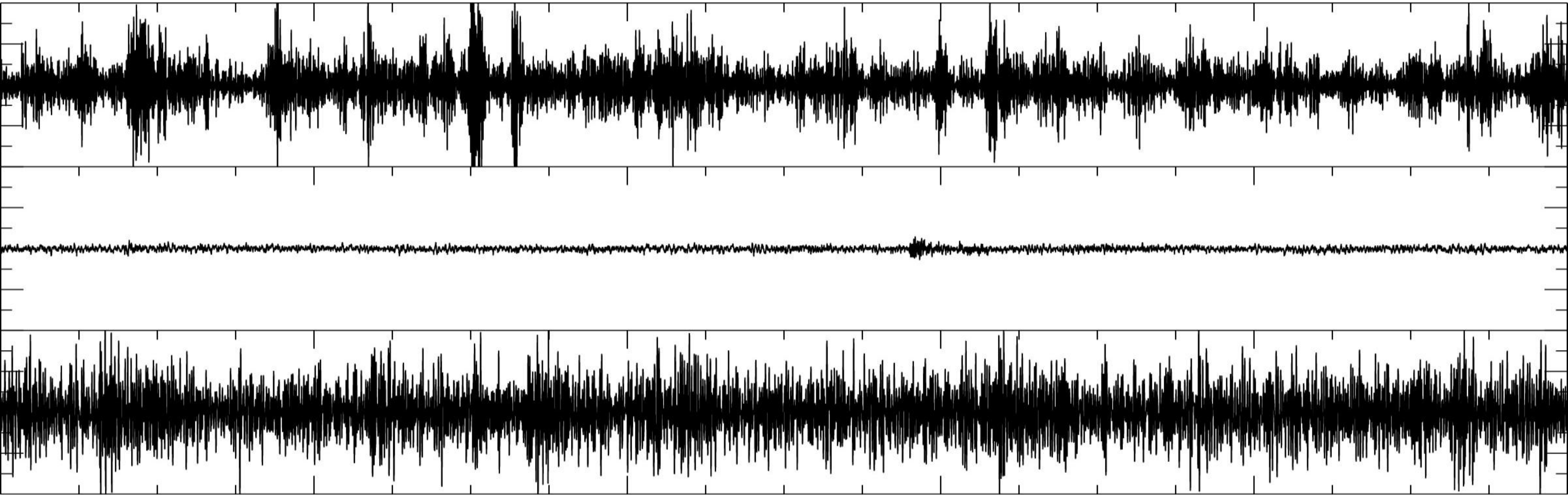
Internal sources of “seismic noise” (volcanic and tectonic low-frequency tremors)

Nikolai Shapiro, Jean Soubestre, Dmitry Droznin, Svetlana Droznina, Leonard Seydoux, Julien de Rosny, William Frank

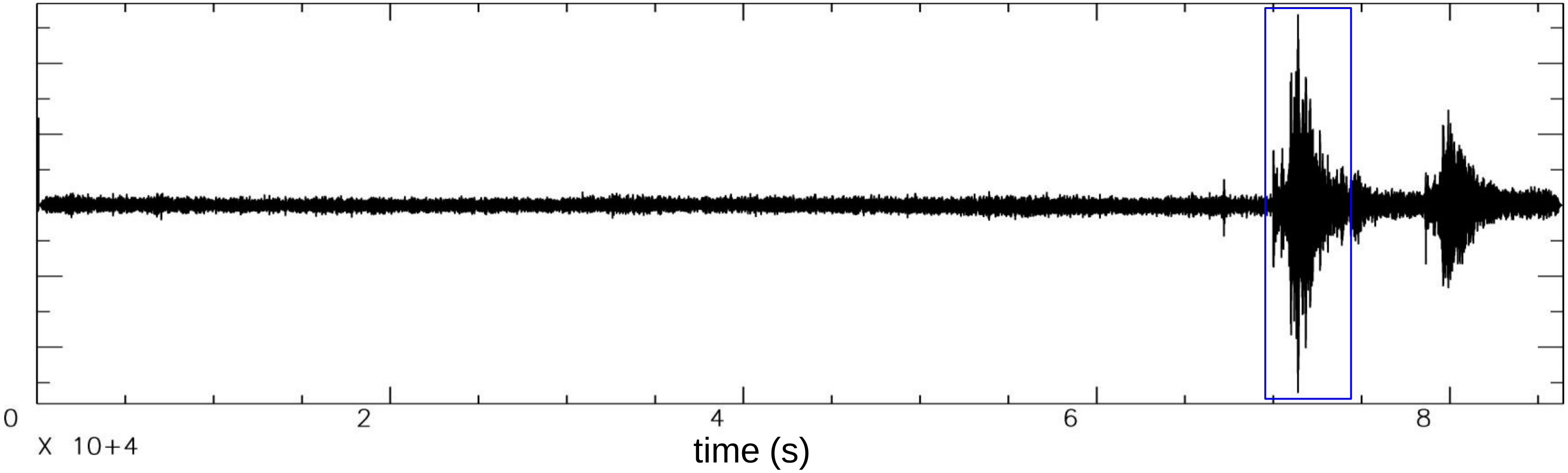


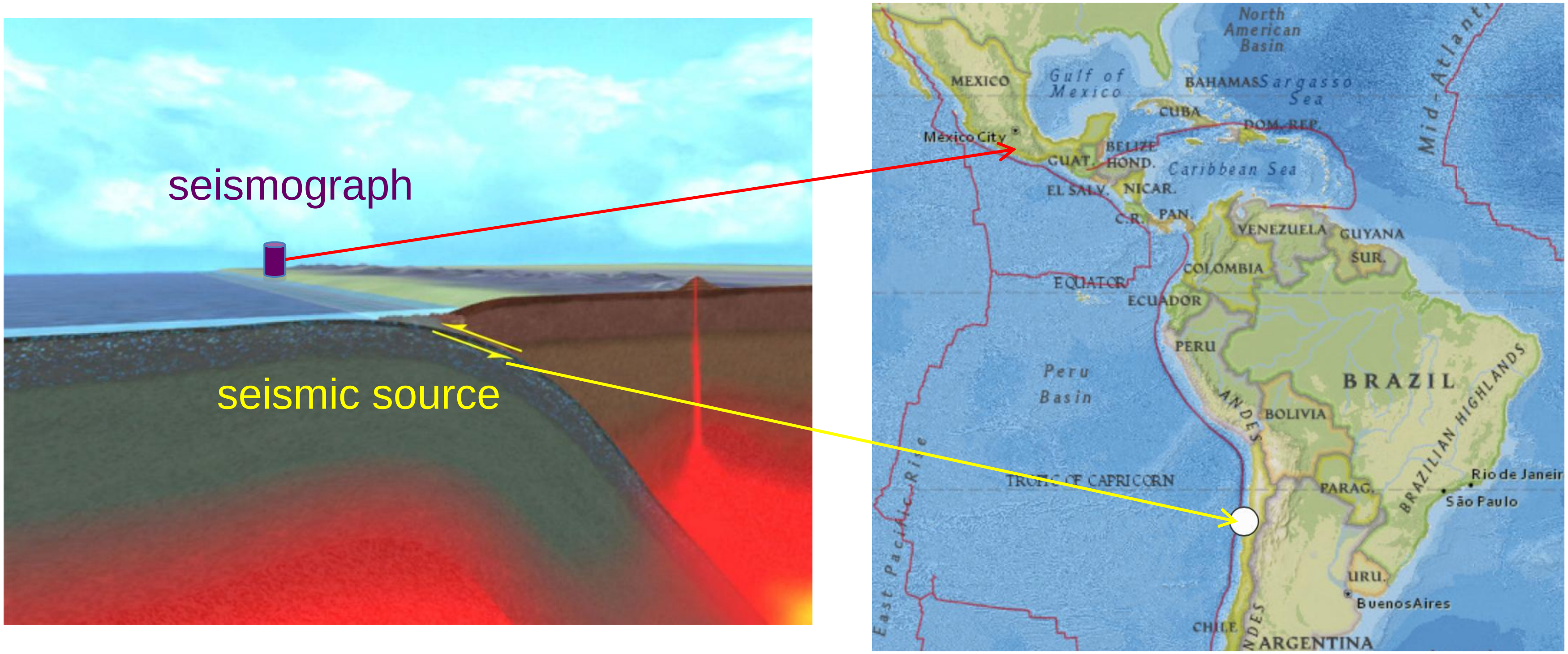


Outline

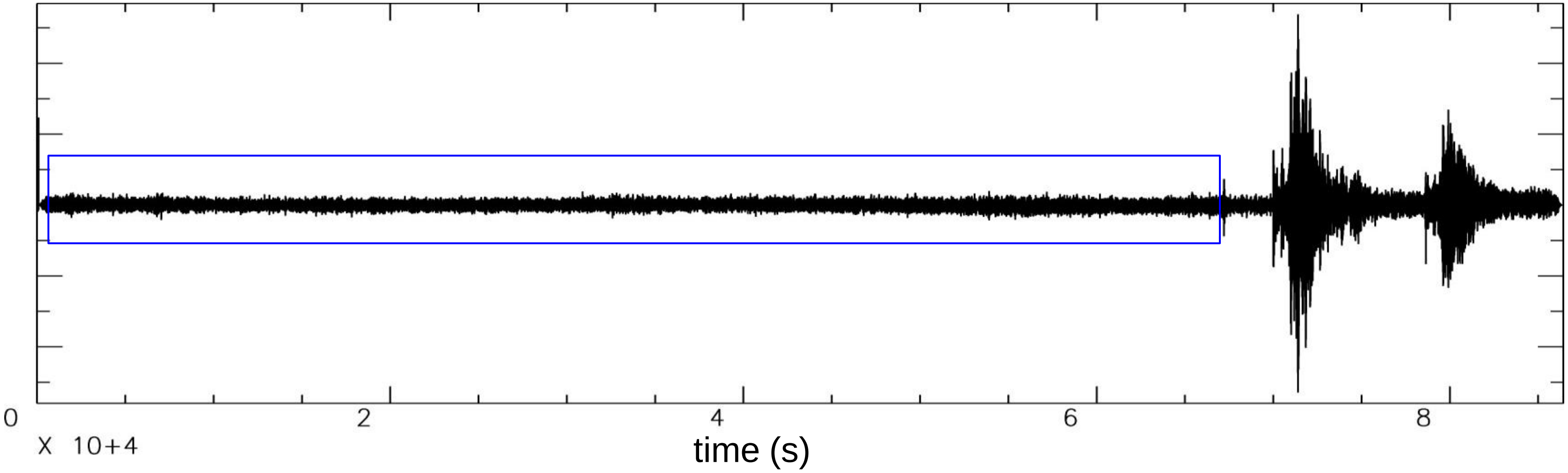
- Main types of observed Earth’s seismic signals
- Volcanic tremors
- Tectonic tremors
- Challenges with the interpretation

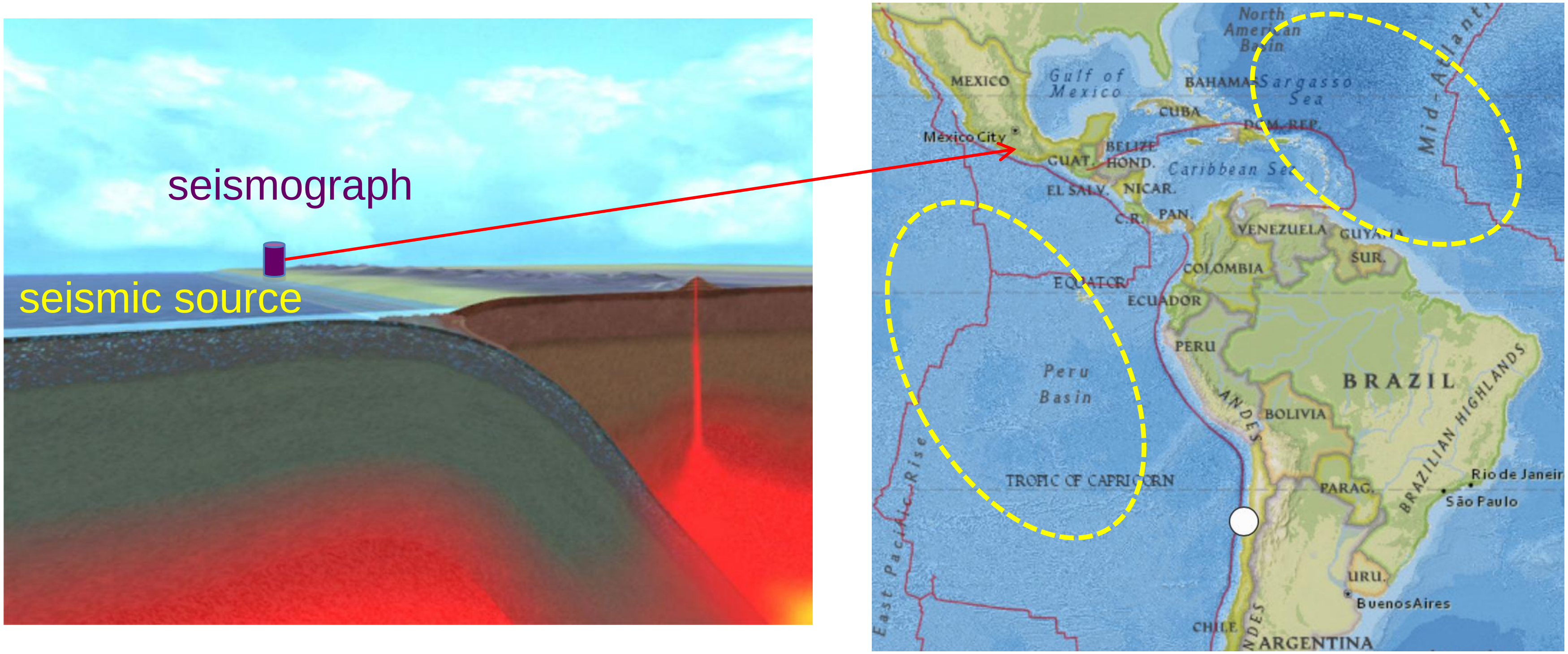
Example of seismic record: earthquake



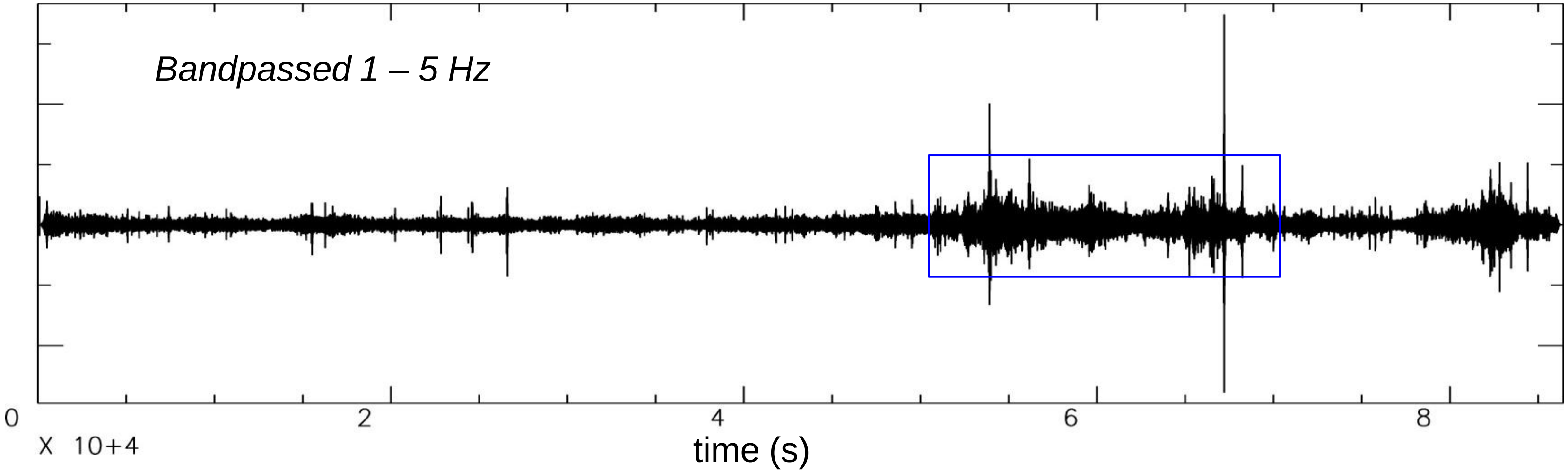


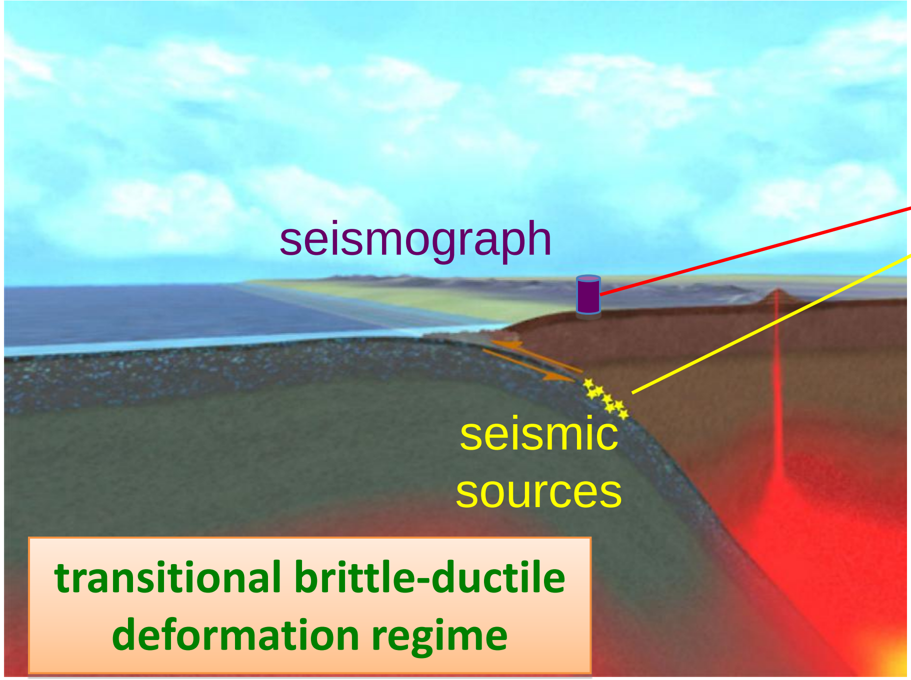
Example of seismic record: ambient noise





Example of seismic record: tectonic tremor



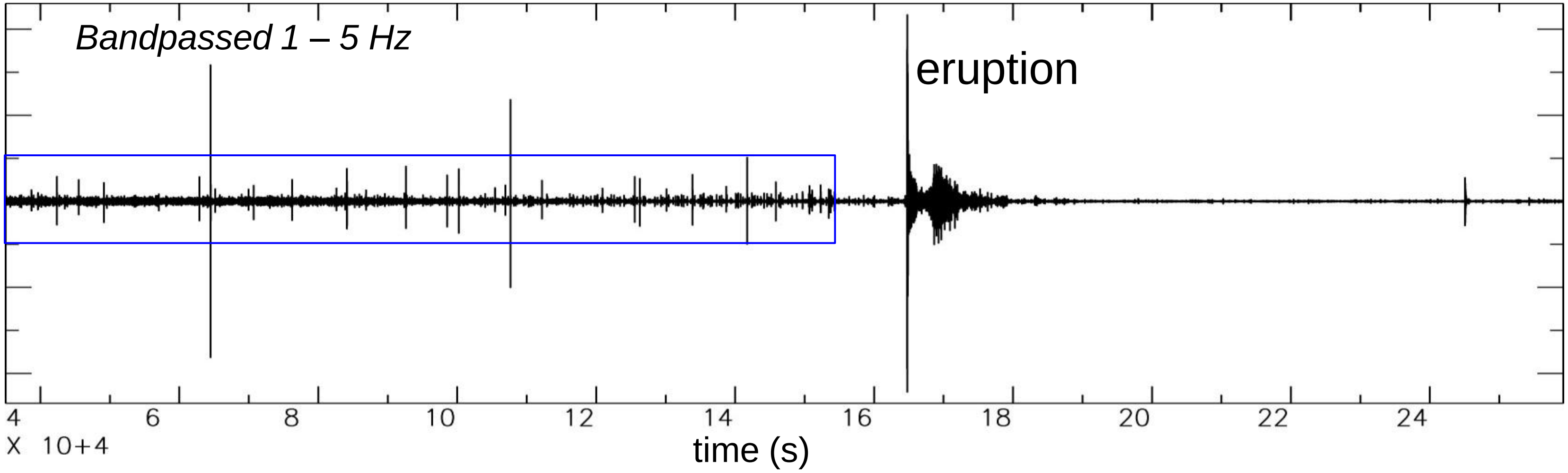


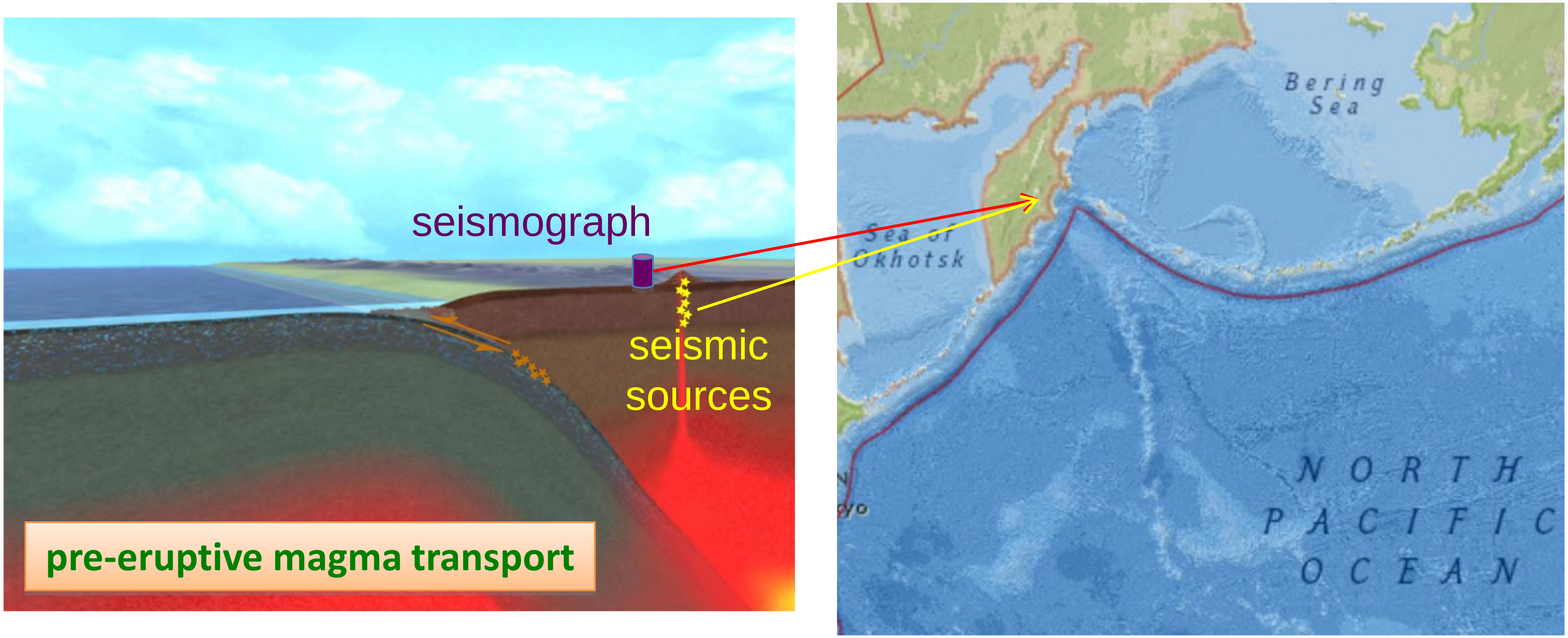
seismograph

seismic sources

transitional brittle-ductile deformation regime

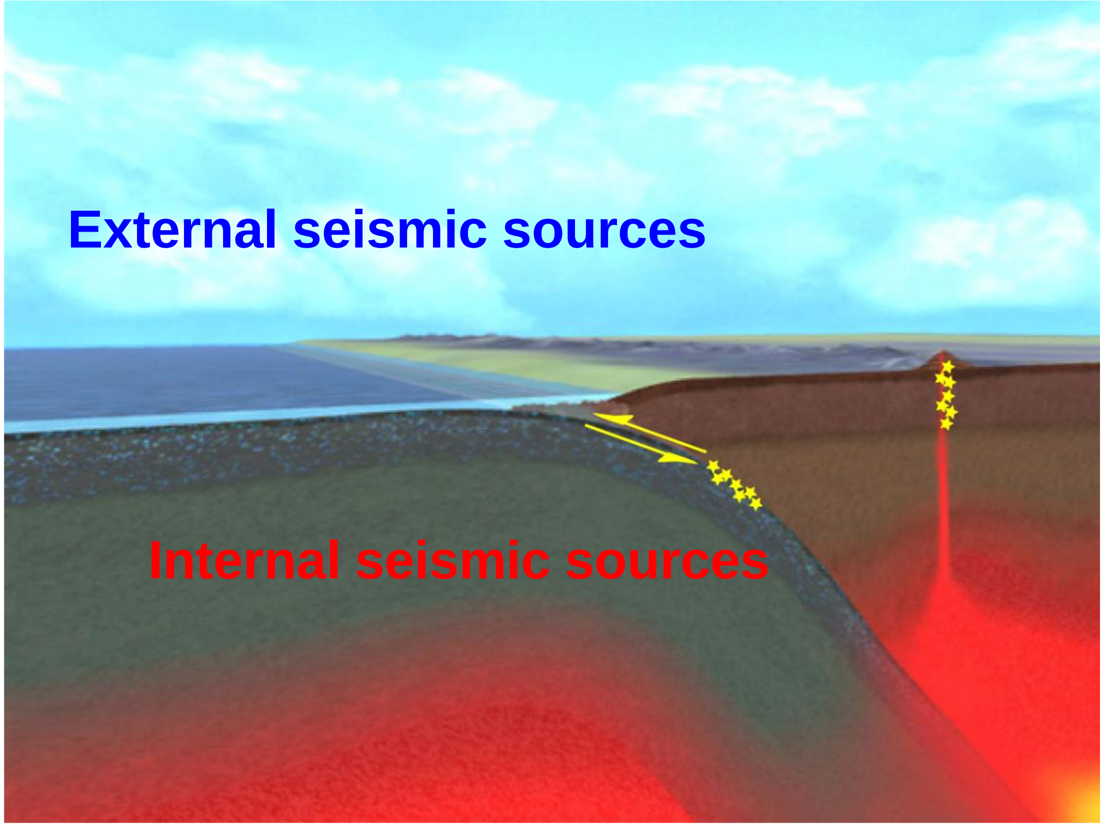
Example of seismic record: volcanic tremor





pre-eruptive magma transport

Main classes of natural seismic sources



Ambient seismic noise
broadband, recorded continuously

Earthquakes
broadband, less than 1% of records

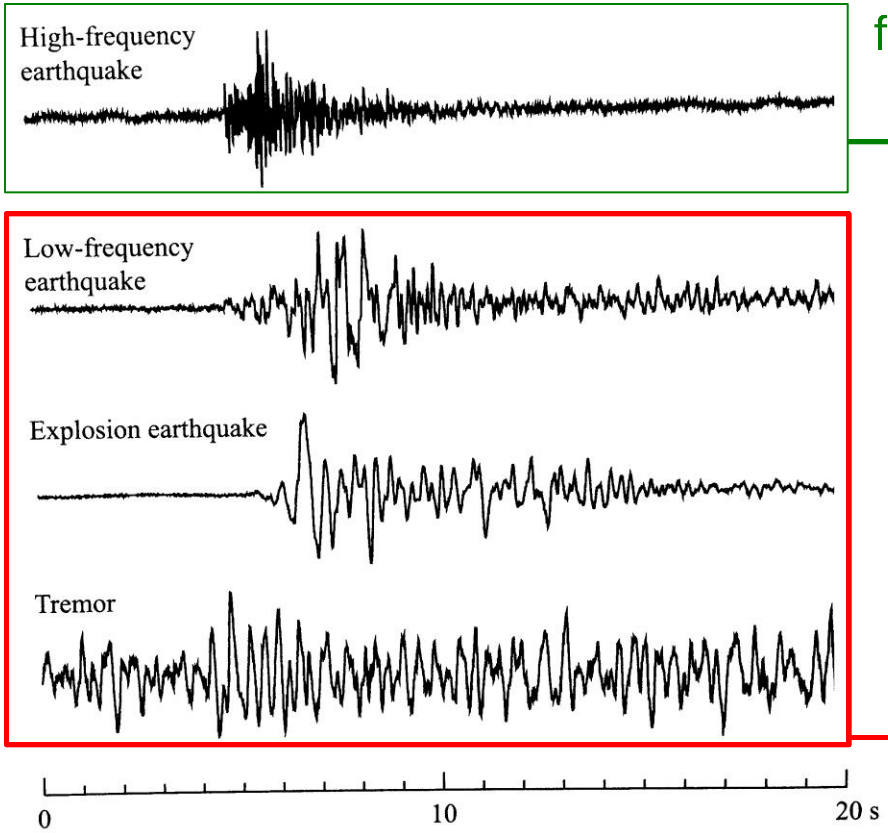
Tectonic tremors
Volcanic tremors
high-frequency (> 1 Hz)
up to 50% of records
near faults and volcanoes

Low-frequency tremors – unique source of information about slow transient processes occurring within volcanic and fault systems

Outline

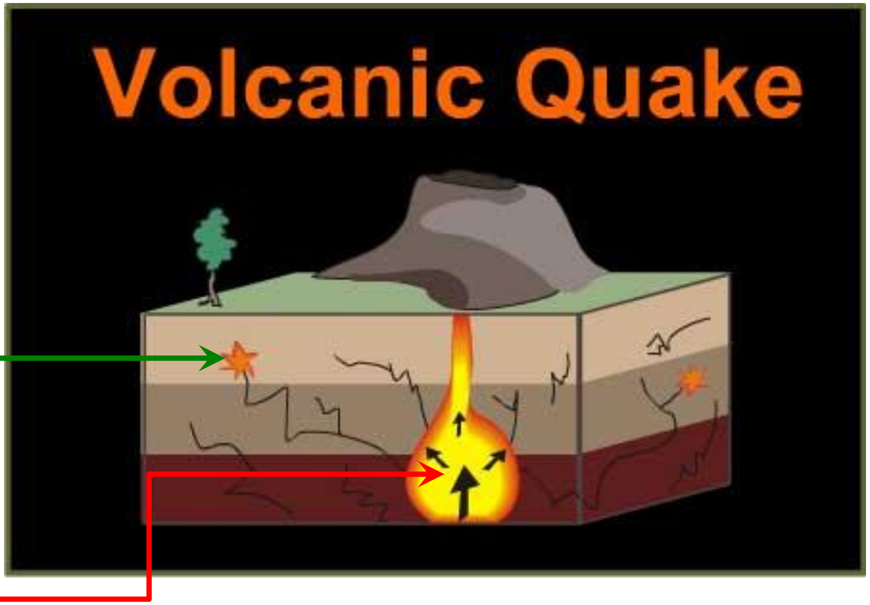
- Main types of observed Earth’s seismic signals
- Volcanic tremors
- Tectonic tremors
- Challenges with the interpretation

Two main classes of seismo-volcanic signals



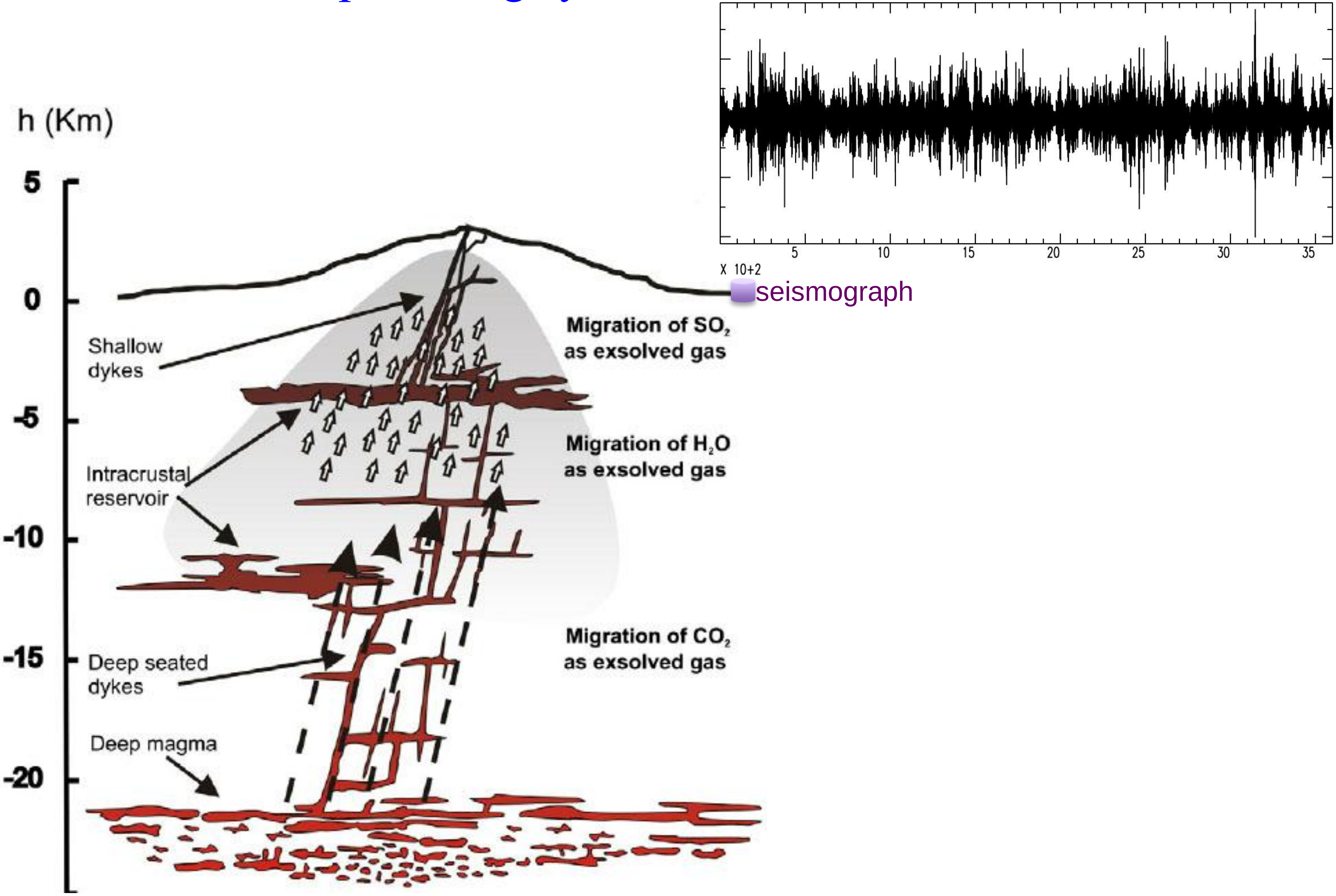
Mt. Tokachi (Japan)
From Nishimura and Iguchi, 2011

Volcano-tectonic earthquakes:
faulting within the solid part of volcanic edifices

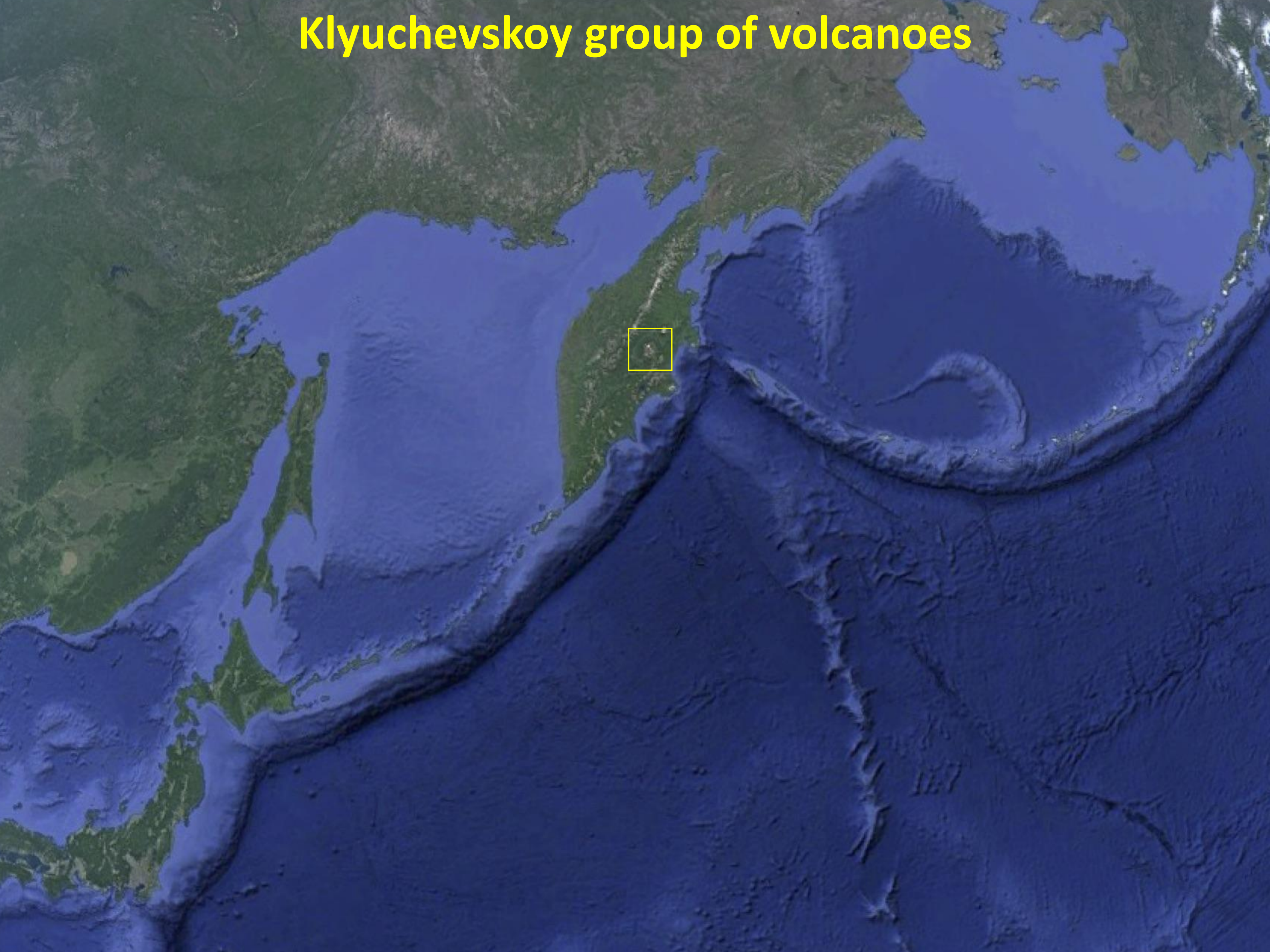


Low-frequency (0.5-5 Hz) seismicity:
processes within the plumbing system

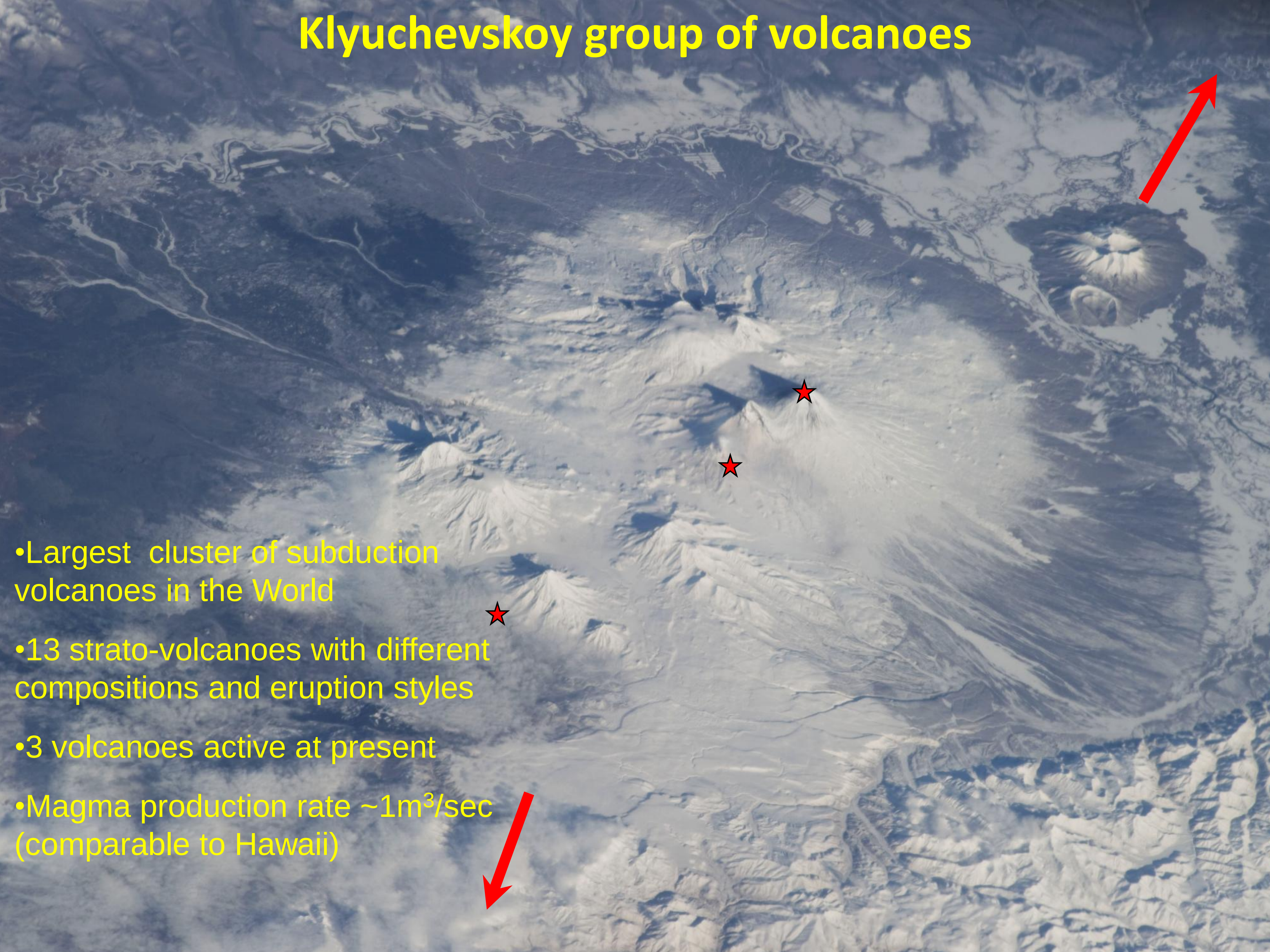
Volcanic tremors reflect slow processes within plumbing systems of volcanoes



Klyuchevskoy group of volcanoes

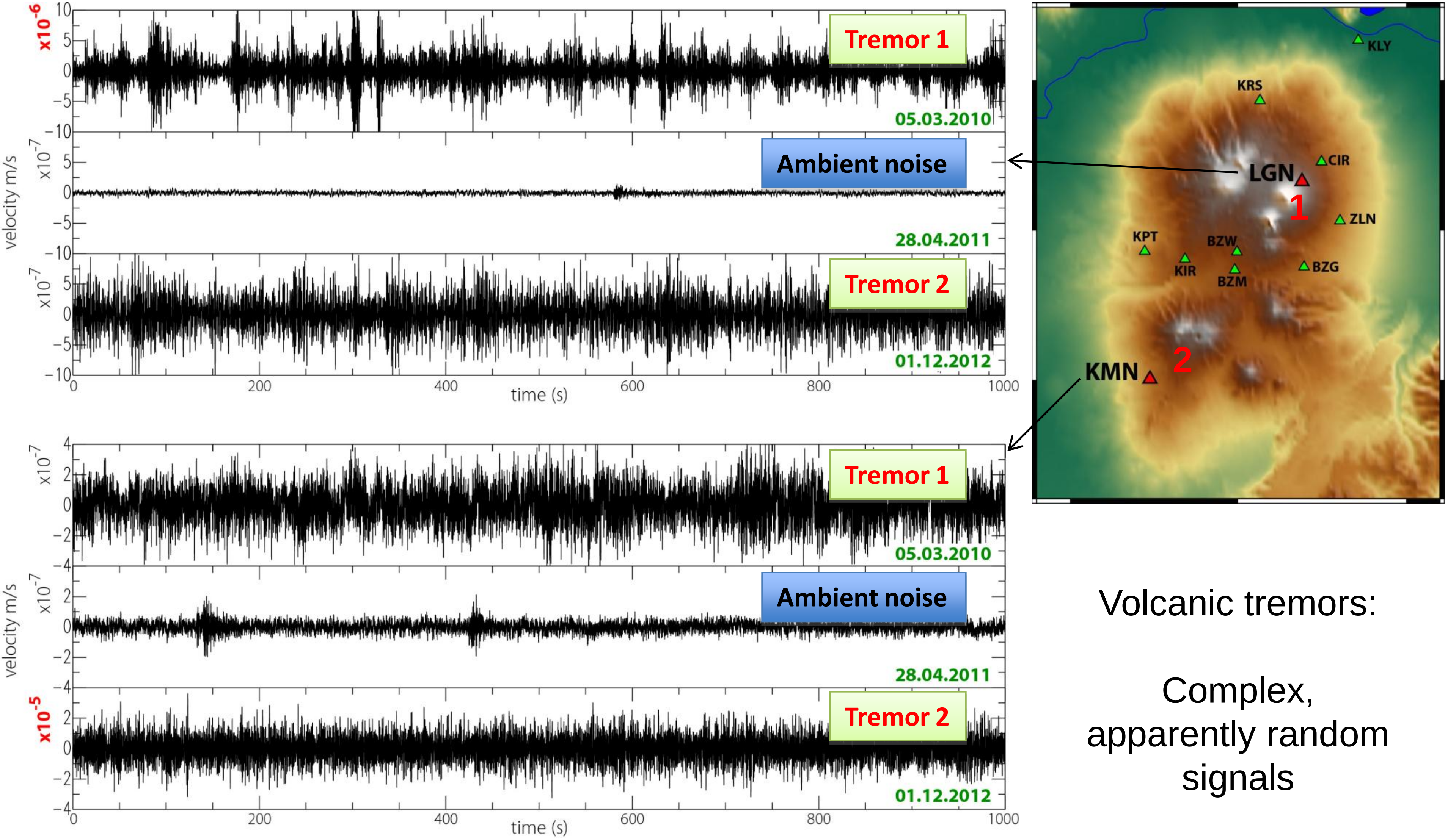


Klyuchevskoy group of volcanoes



- Largest cluster of subduction volcanoes in the World
- 13 strato-volcanoes with different compositions and eruption styles
- 3 volcanoes active at present
- Magma production rate ~1m^3/sec (comparable to Hawaii)

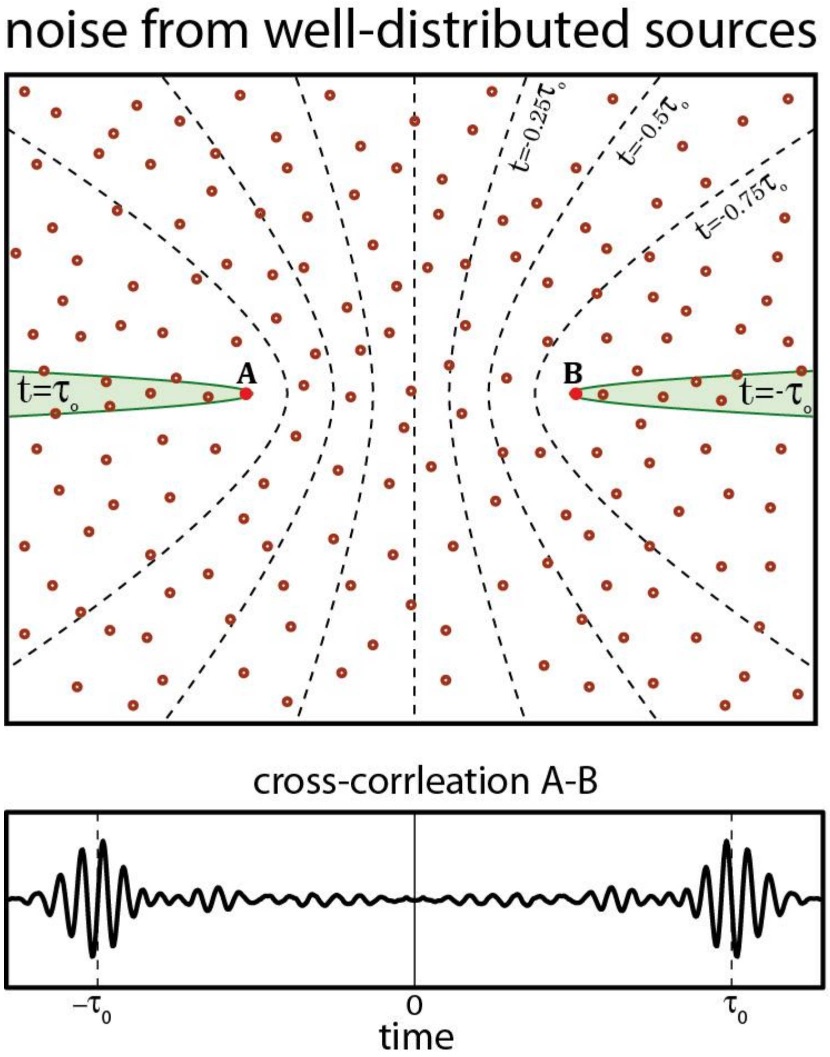
Volcanic tremors: examples of records



Volcanic tremors:

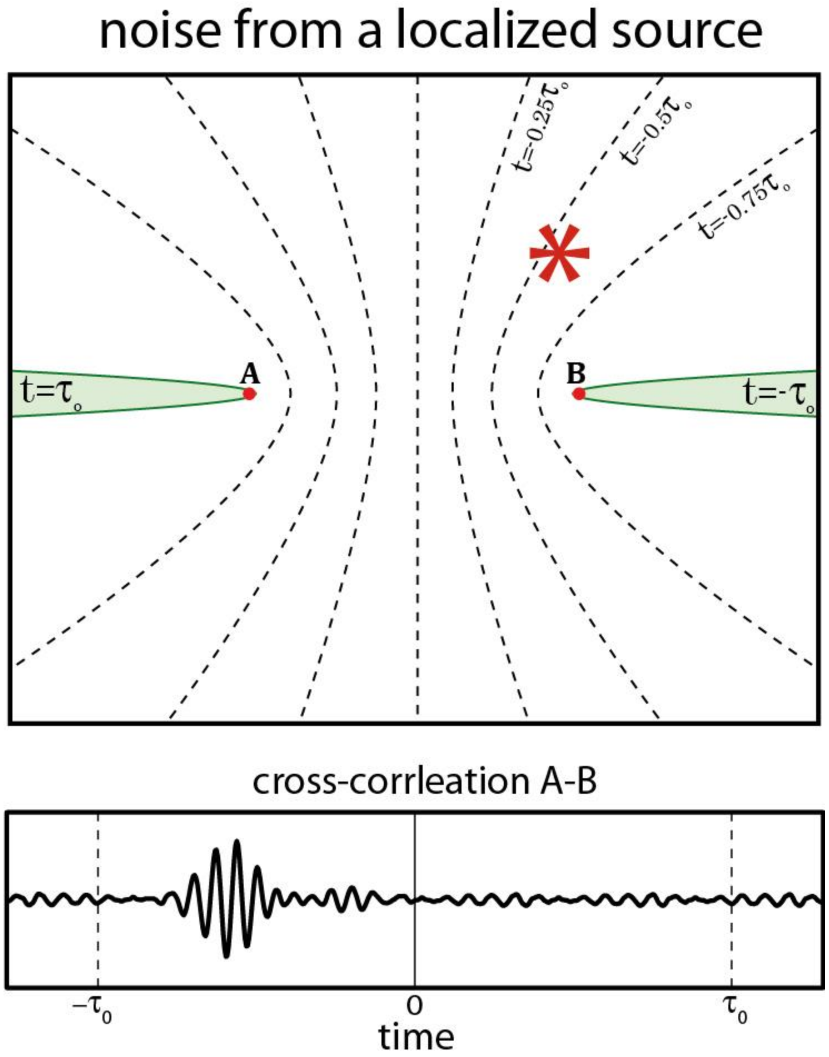
Complex,
apparently random
signals

Difference between tremors and ambient noise



noise from well-distributed sources

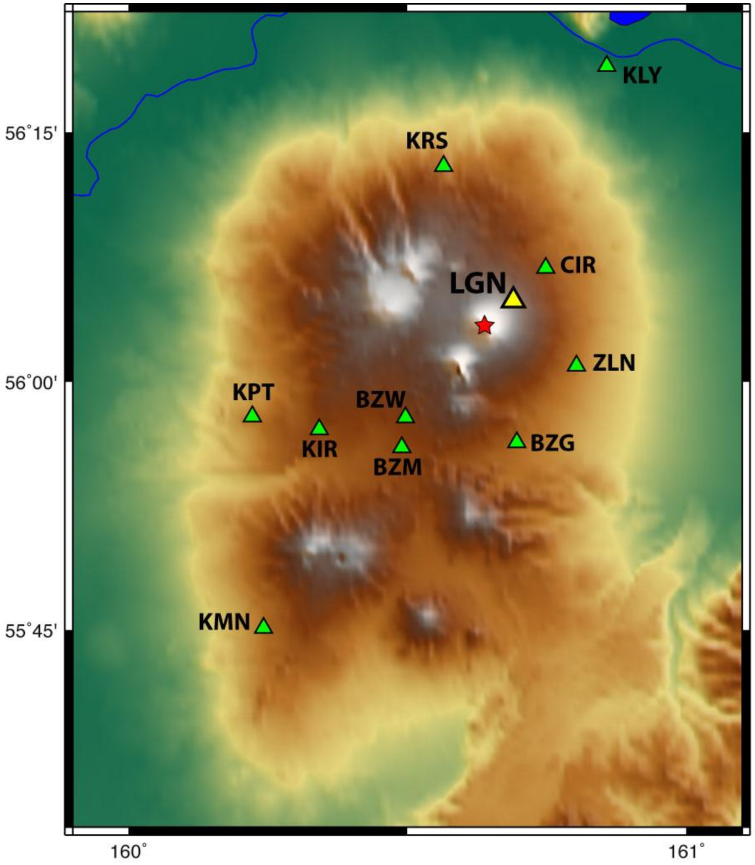
cross-correlation A-B

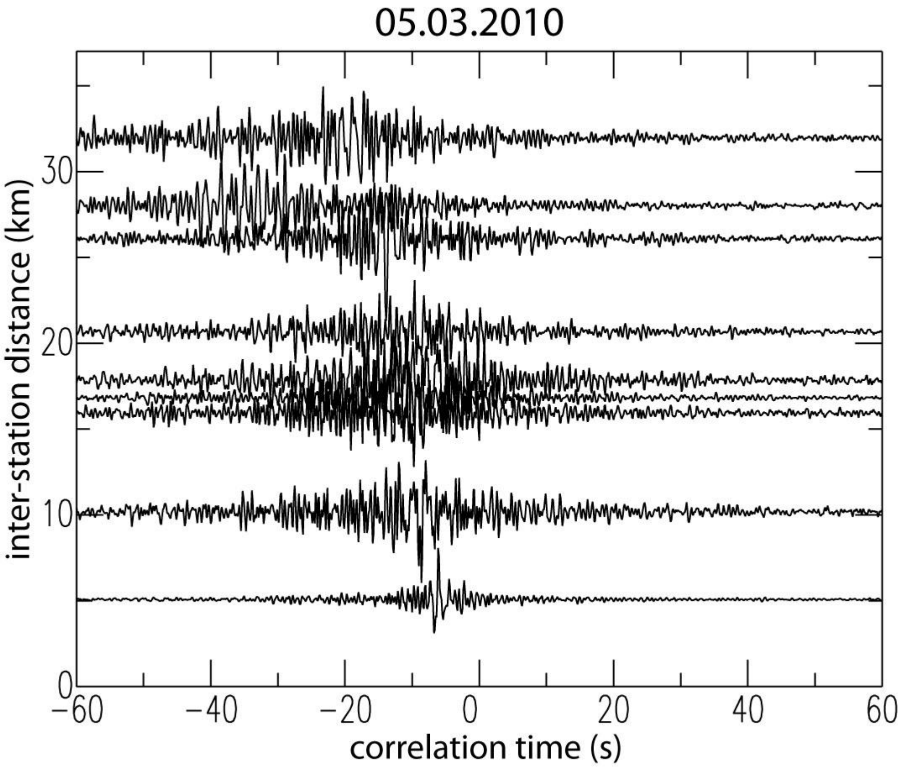


noise from a localized source

cross-correlation A-B

Cross-correlations of volcanic tremors





Arrivals appearing on cross-correlations are controlled by the travel times between the tremor source and the stations

from Droznin et al, 2015

Cross-correlations of volcanic tremors

01.12.2012

Location of tremor sources:

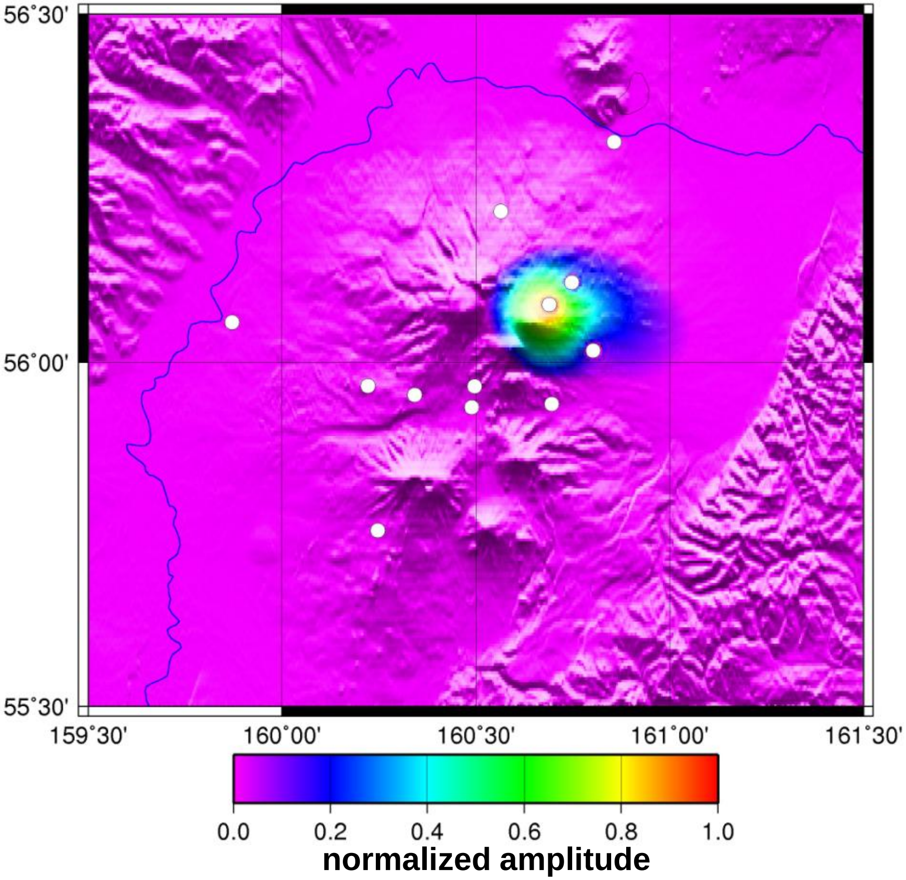
1. Computing envelopes of cross-correlations
2. Introducing time shifts based on tested source location
3. Computing network response function by adding shifted envelops
4. Repeating steps 2 and 3 for all source positions
5. Finding the position maximazing the network response function

Arrivals appearing on cross-correlations are controlled by the travel times between the tremor source and the stations

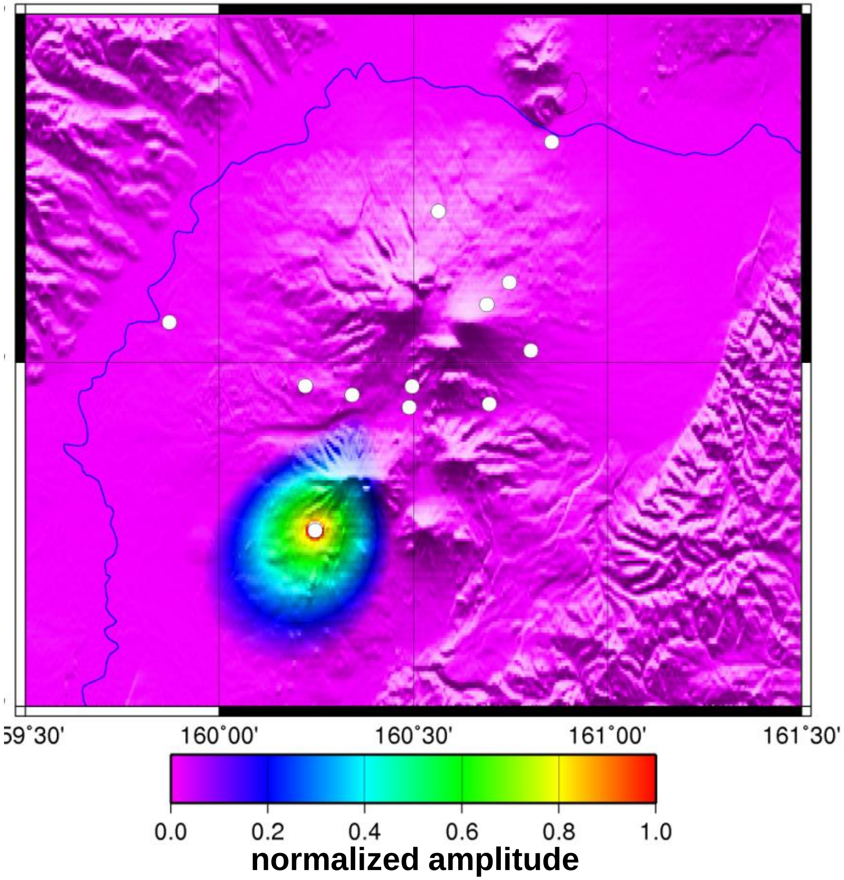
from Droznin et al, 2015

Cross-correlation network response function

Klyuchevskoy erupting
(March 5, 2010)



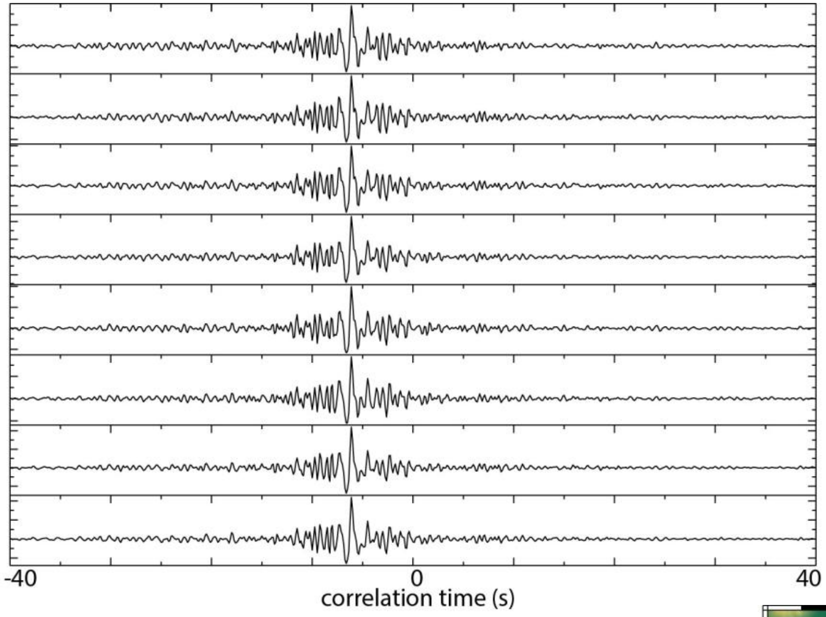
Tolbachik erupting
(December 1, 2012)



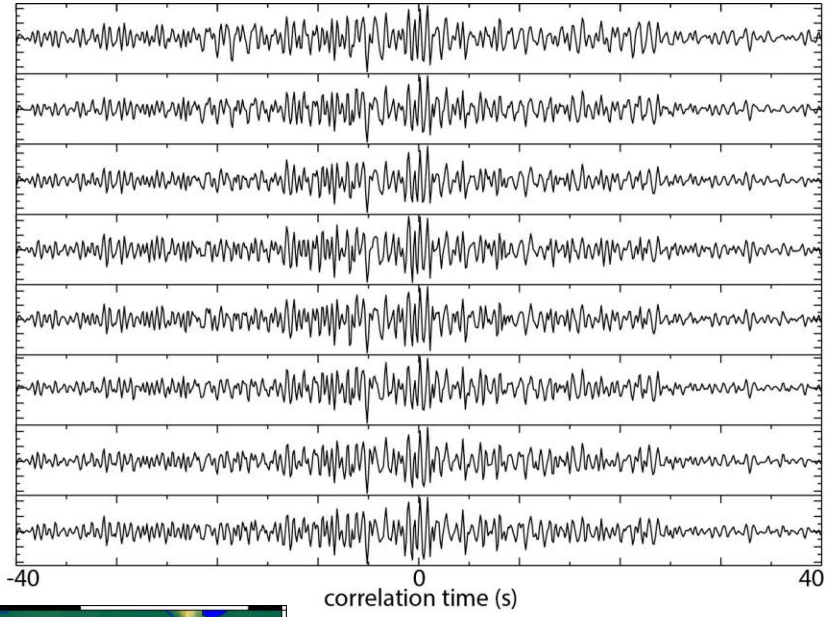
from Droznin et al, 2015

Exploring the repetitivity of the seismic correlations: “tremor fingerprinting”

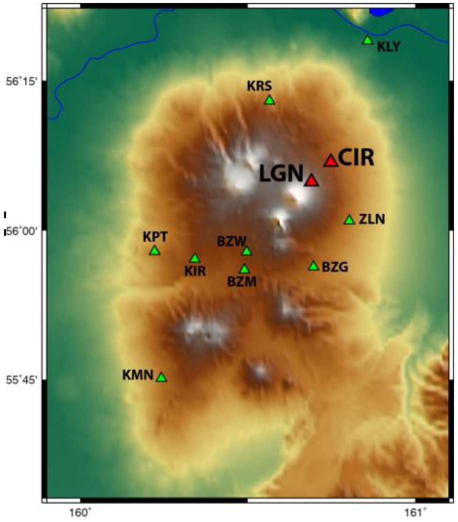
01.20.2010-08.20.2010 : Klyuchevskoy eruption



01.20.2013-08.20.2013 : Tolbachik eruption



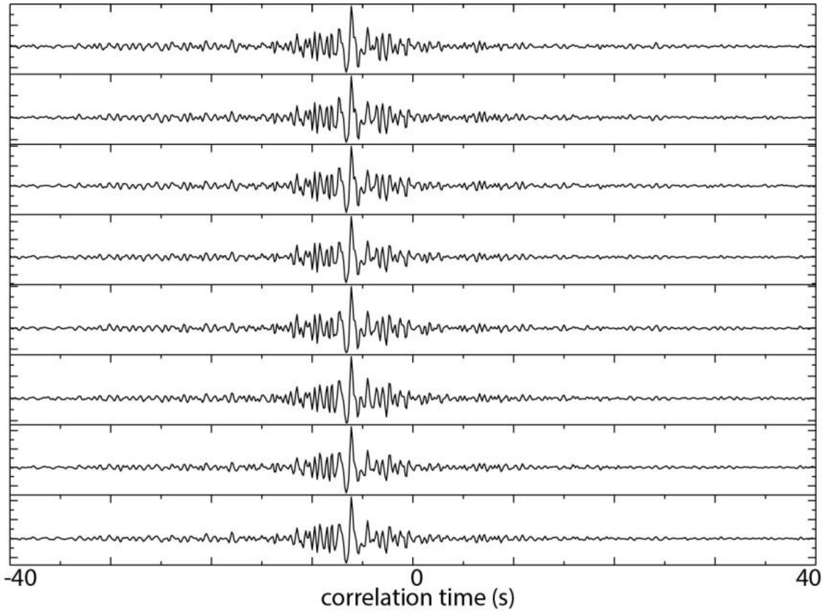
Daily cross-correlations between one pair of stations: LGN - CIR



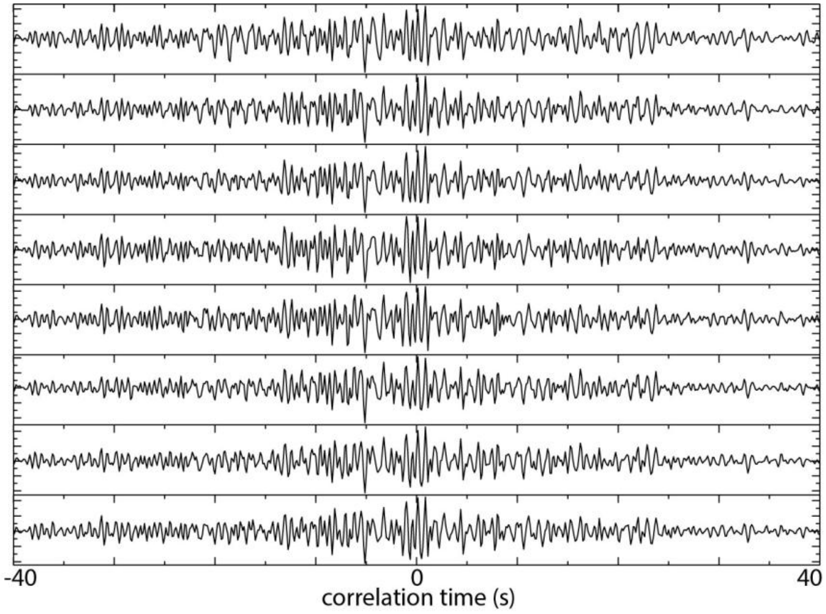
from Droznin et al, 2015

Exploring the repetitivity of the seismic correlations: “tremor fingerprinting”

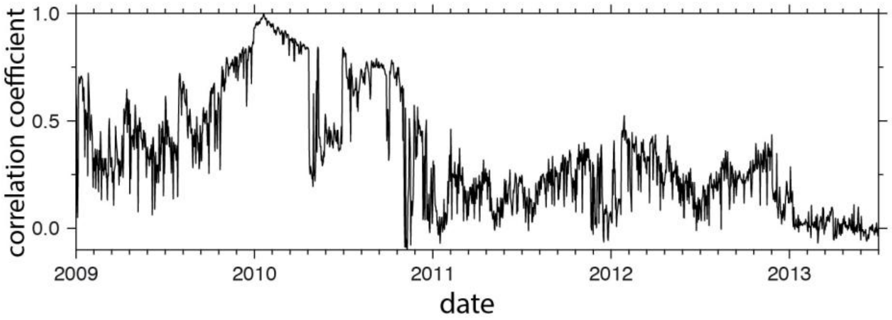
01.20.2010-01.27.2010 : Klyuchevskoy eruption



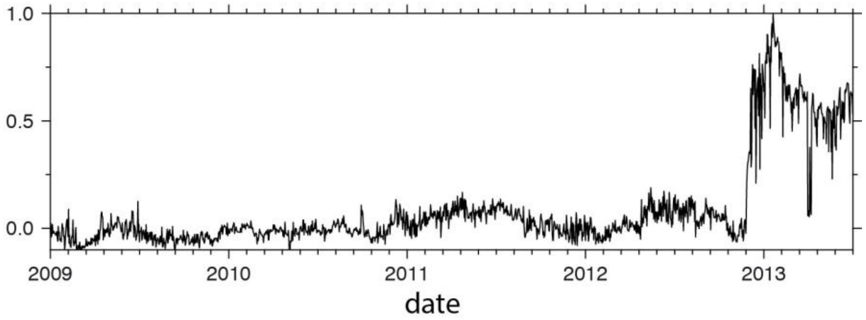
01.20.2013-01.27.2013 : Tolbachik eruption



Detection of activity: correlation coefficient with a reference CC waveform

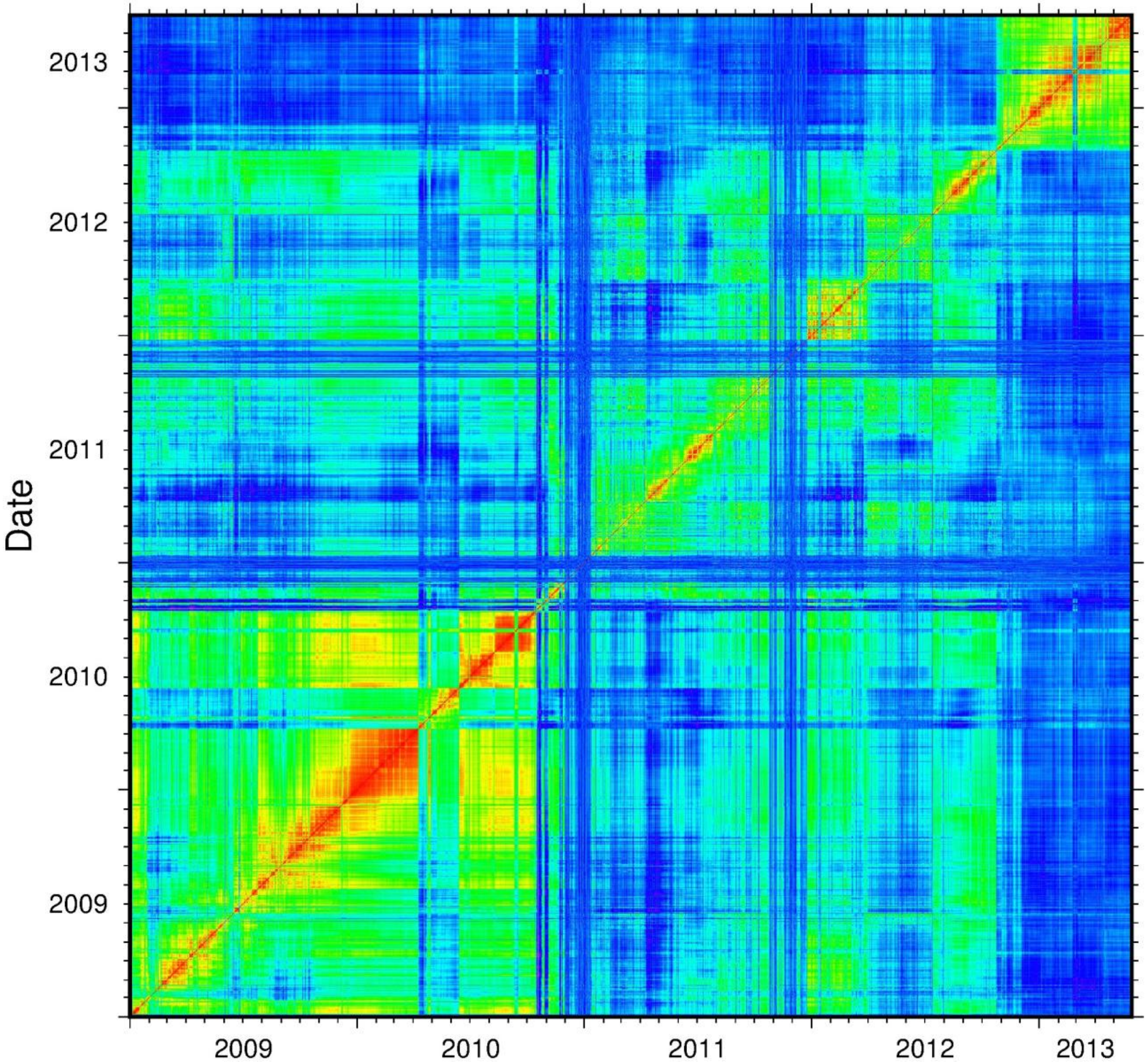


Klyuchevskoy activity



Tolbachik activity

Matrix of correlation coefficients



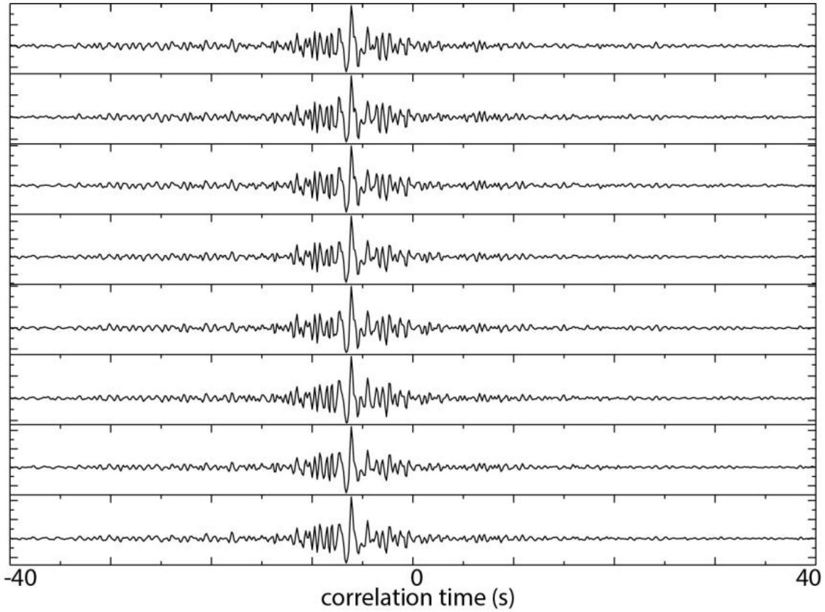
Tolbachik activity

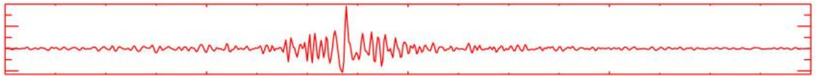
Klyuchevskoy activity

from Droznin et al, 2015

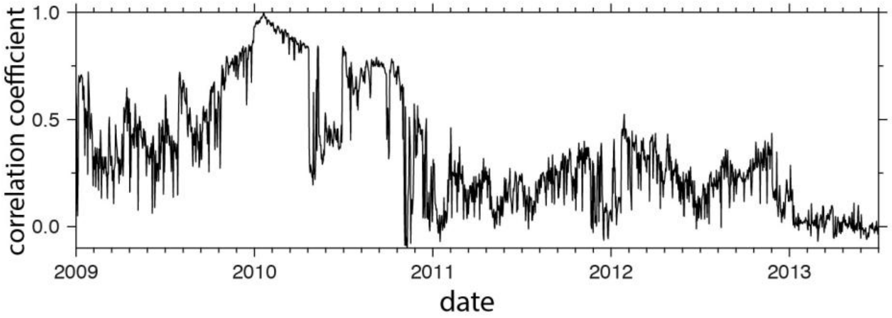
Principle component analysis of the ensemble of daily cross-correlations

01.20.2010-08.20.2010 : Klyuchevskoy eruption



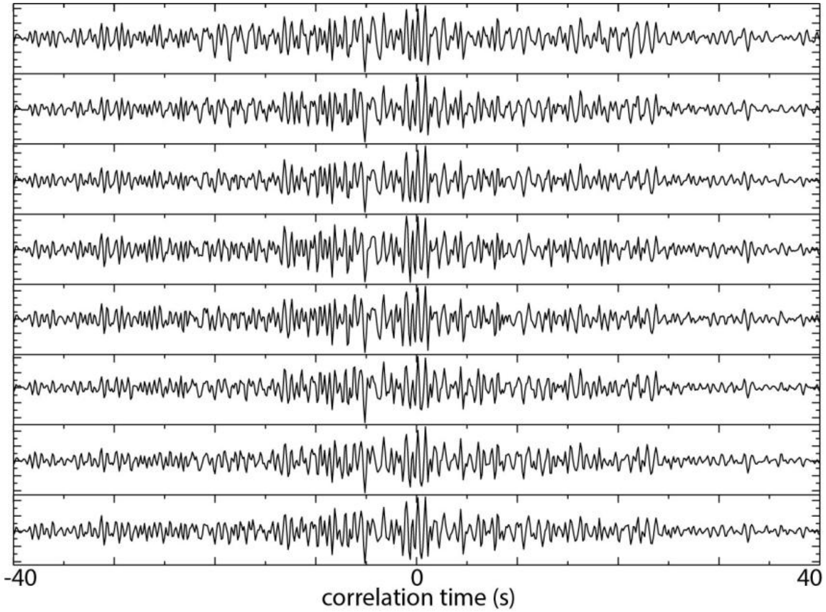


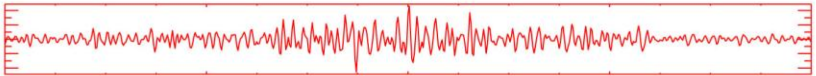
eigenvector 1



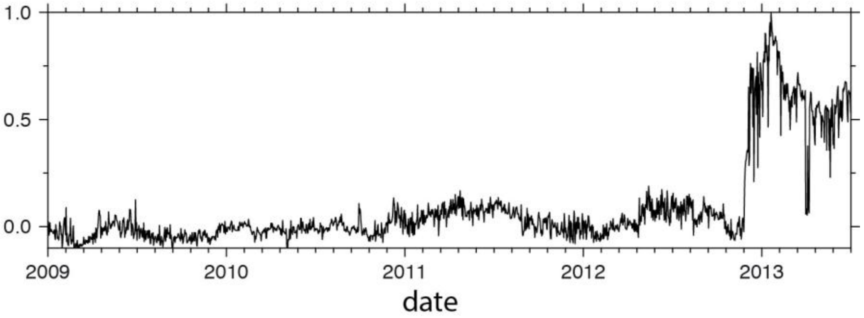
Klyuchevskoy activity

01.20.2013-08.20.2013 : Tolbachik eruption





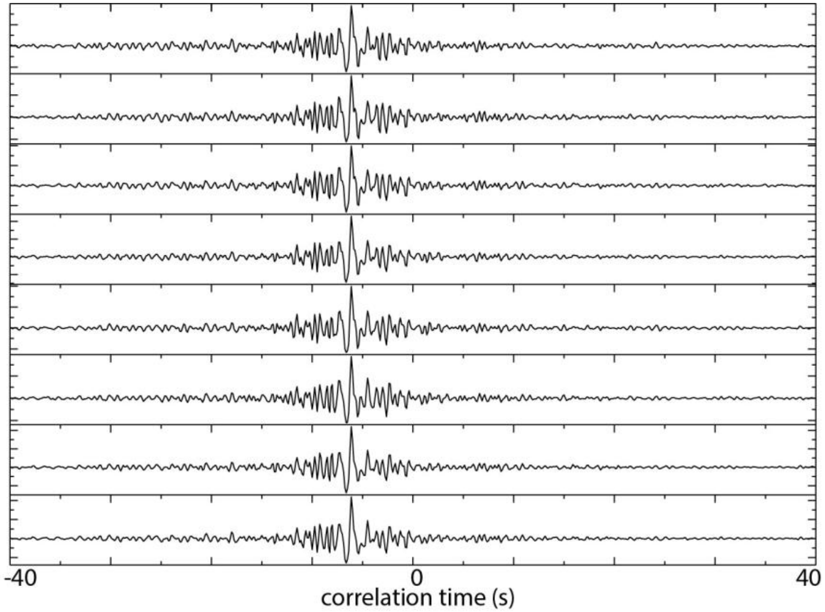
eigenvector 2

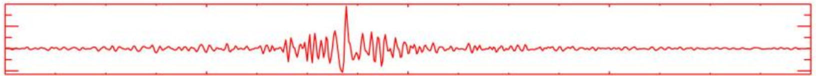


Tolbachik activity

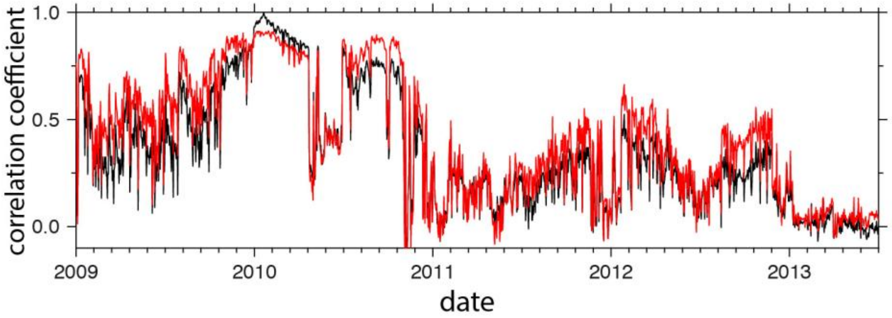
“Tremor fingerprinting” from the results of the Principle component analysis

01.20.2010-08.20.2010 : Klyuchevskoy eruption



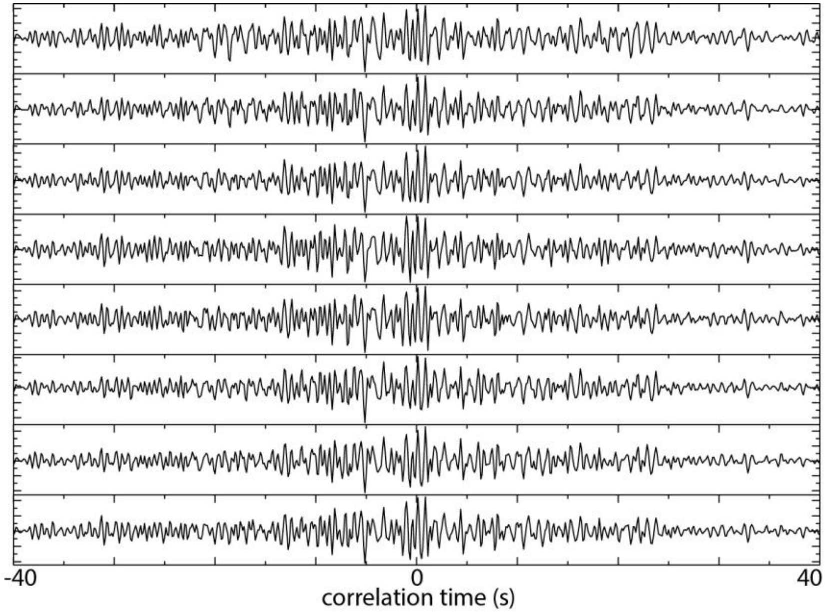


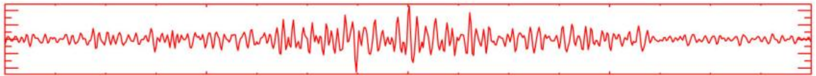
eigenvector 1



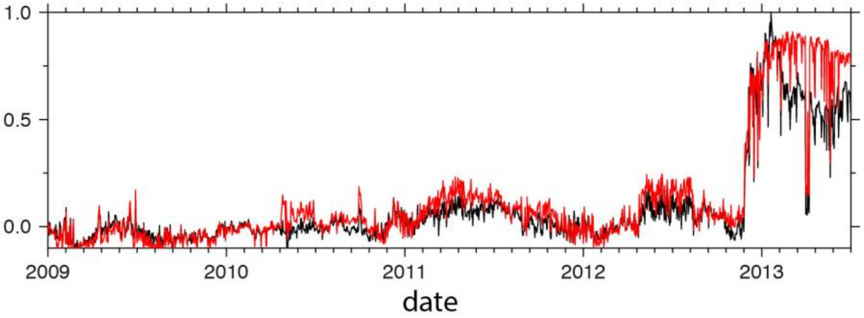
Klyuchevskoy activity

01.20.2013-08.20.2013 : Tolbachik eruption





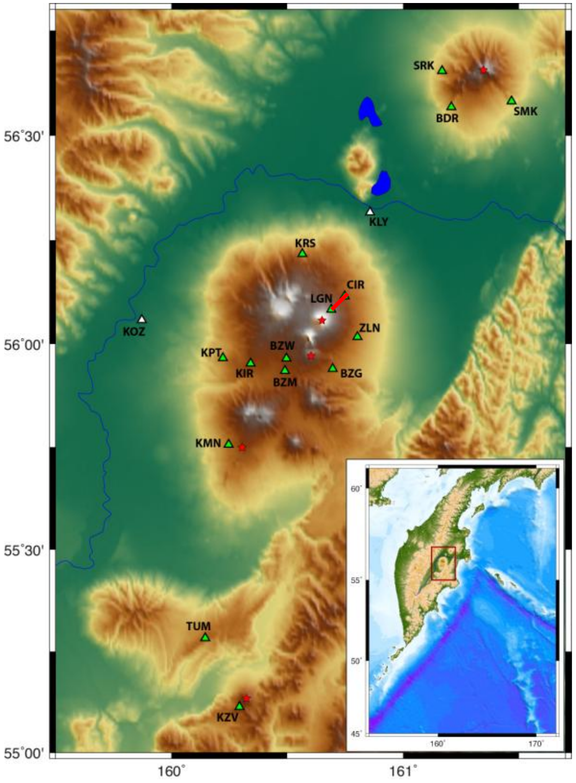
eigenvector 2

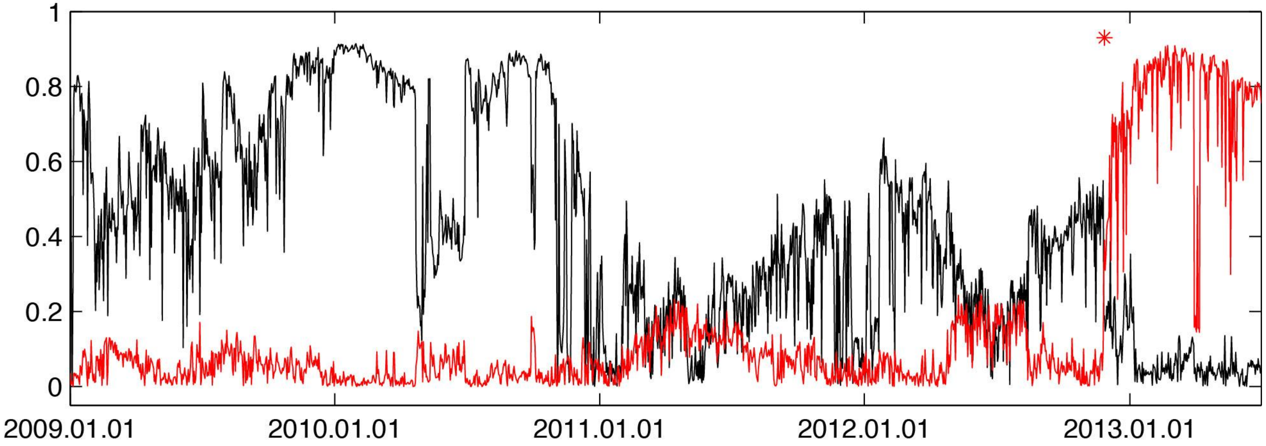


Tolbachik activity

Exploring the repetitivity of the seismic correlations:

CIR - LGN



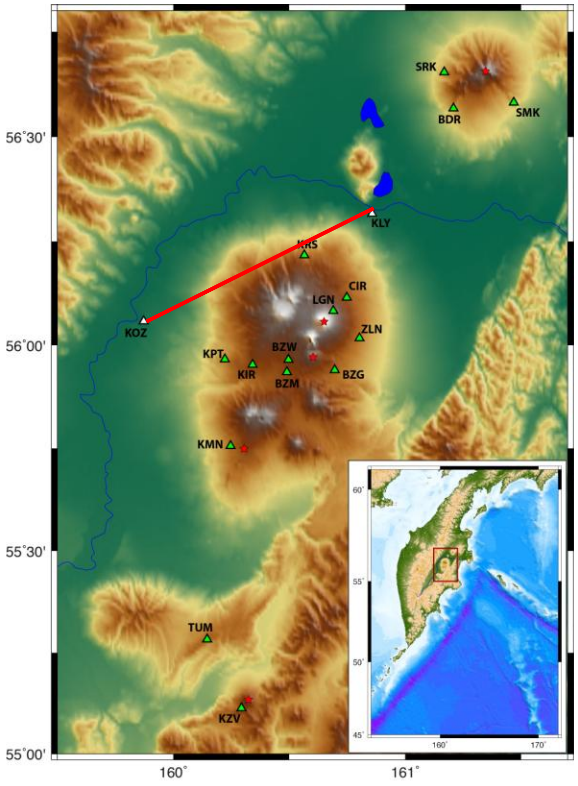


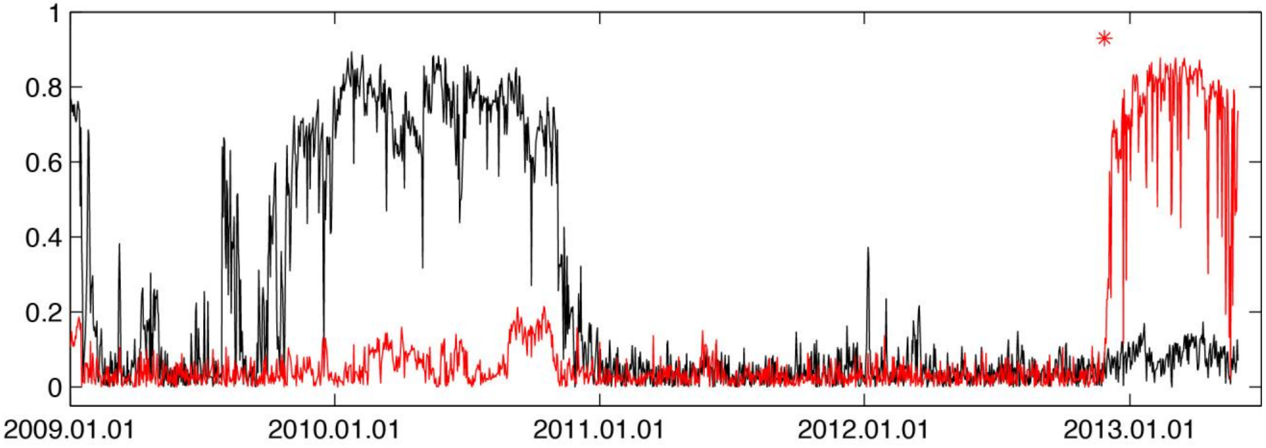
Klyuchevskoy activity

Tolbachik activity

Exploring the repetitivity of the seismic correlations:

KLY - KOZ





Klyuchevskoy activity

Tolbachik activity

Ensemble of inter-station cross-correlations: 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

Eigenvector-eigenvalue decomposition

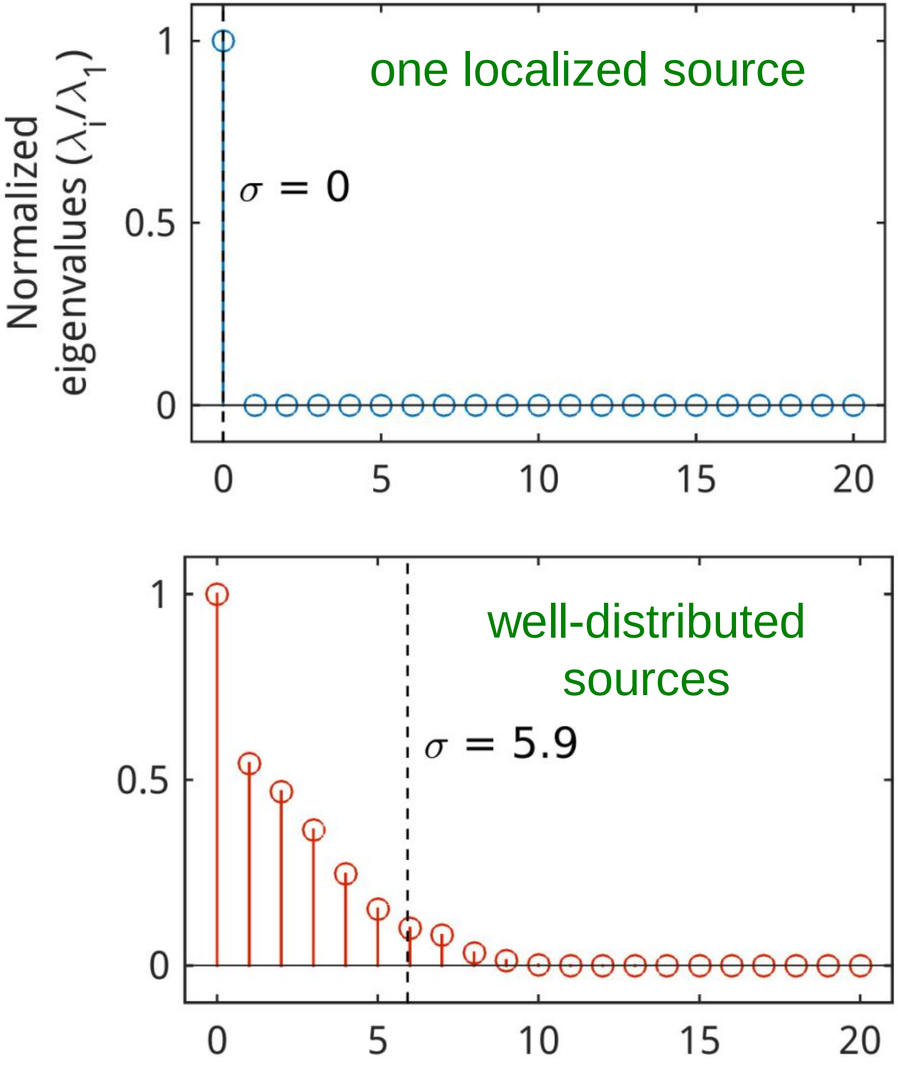
$$\mathbf{C}(f) = \sum_{n=1}^{N} \lambda_n \mathbf{v}_n \mathbf{v}_n^{\dagger}$$

Eigenvector corresponding to the **maximum eigenvalue** describes the wavefield emitted by the **dominating seismic source**

from Seydoux et al, 2016

Network Covariance Matrix: **distribution of eigenvalues** depends on **distribution of sources**

Synthetic tests

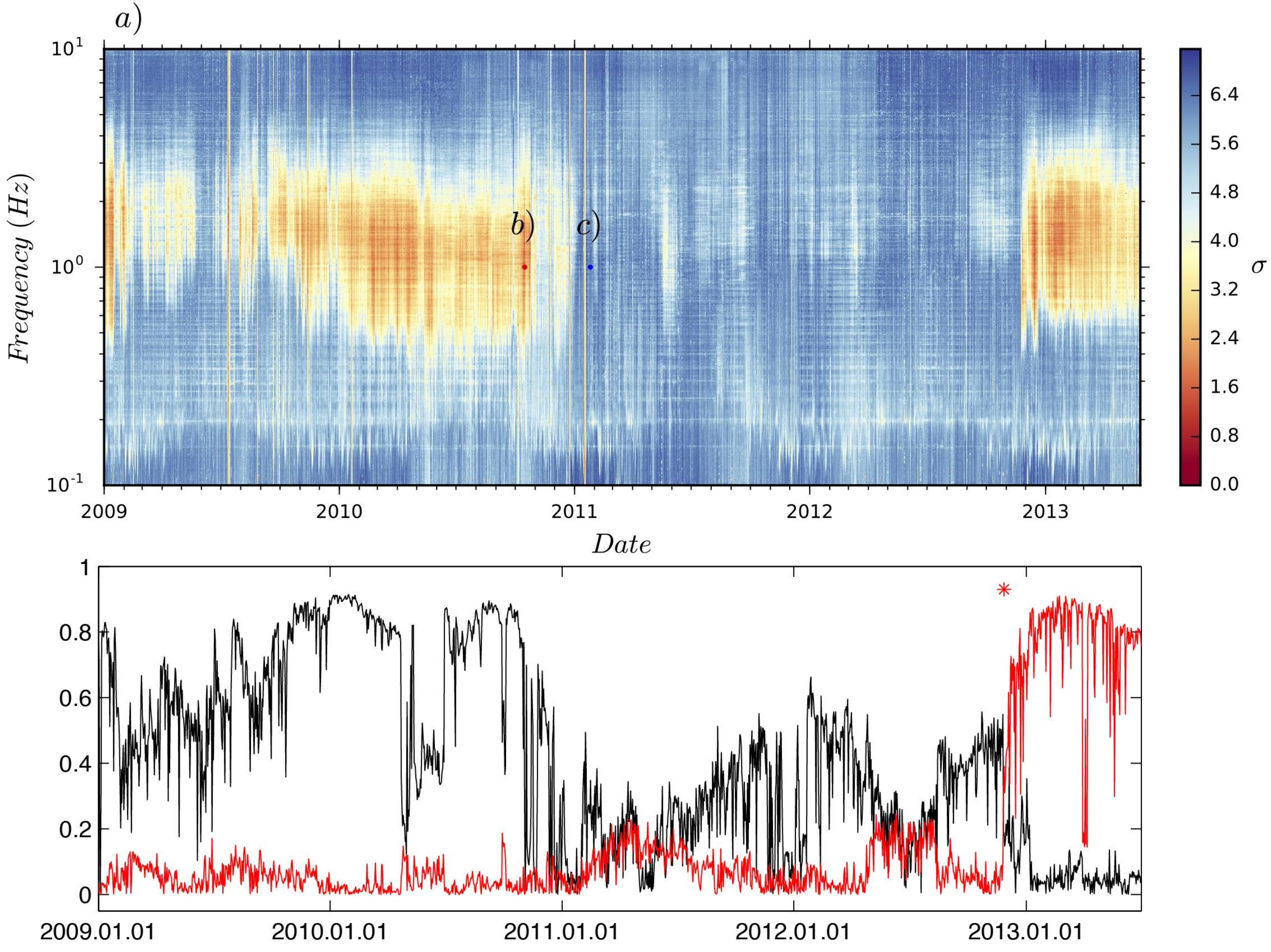


$$\sigma(f) = \frac{\sum_{i=1}^{N}(i-1)\lambda_i(f)}{\sum_{i=1}^{N}\lambda_i(f)}$$

Covariance Matrix spectral width

from Seydoux et al, 2016

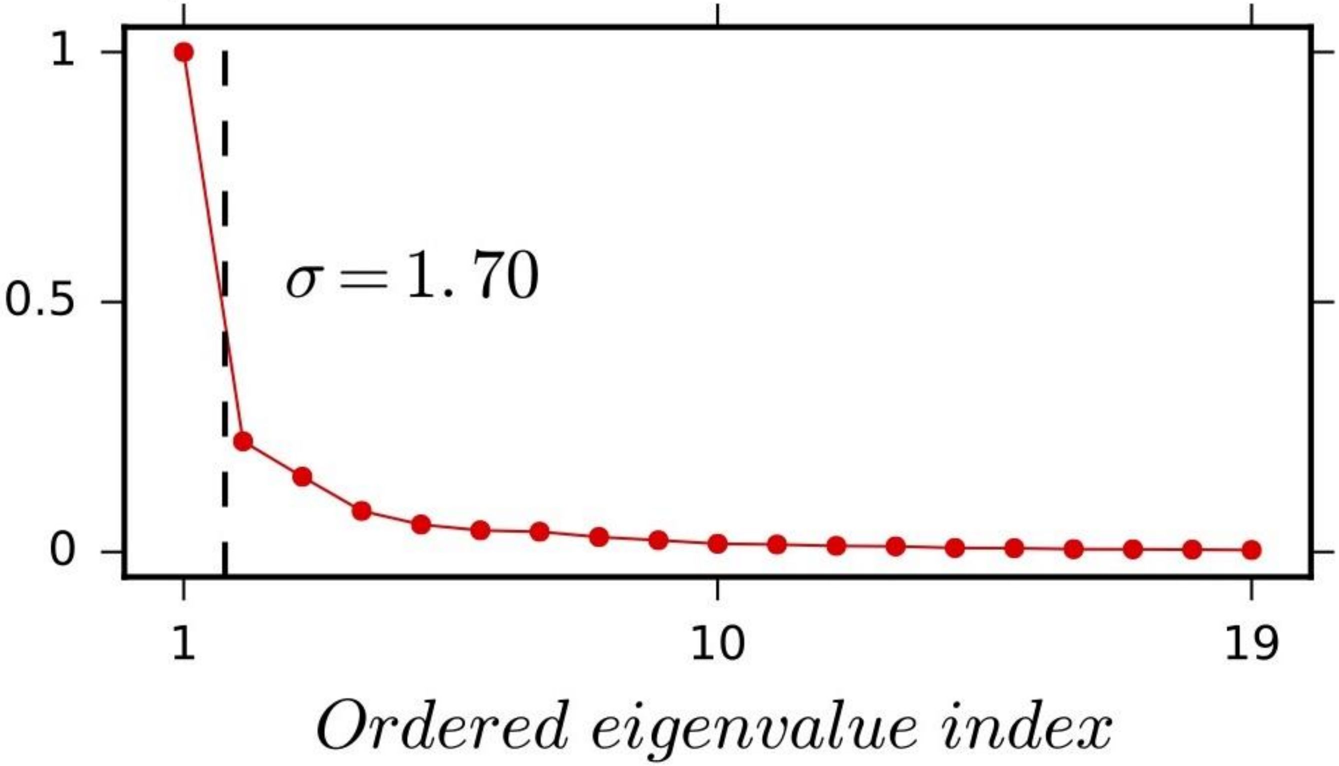
Network Covariance Matrix for the Klyuchevskoy group of volcanoes: eigenvalues



from Soubestre et al, 2017

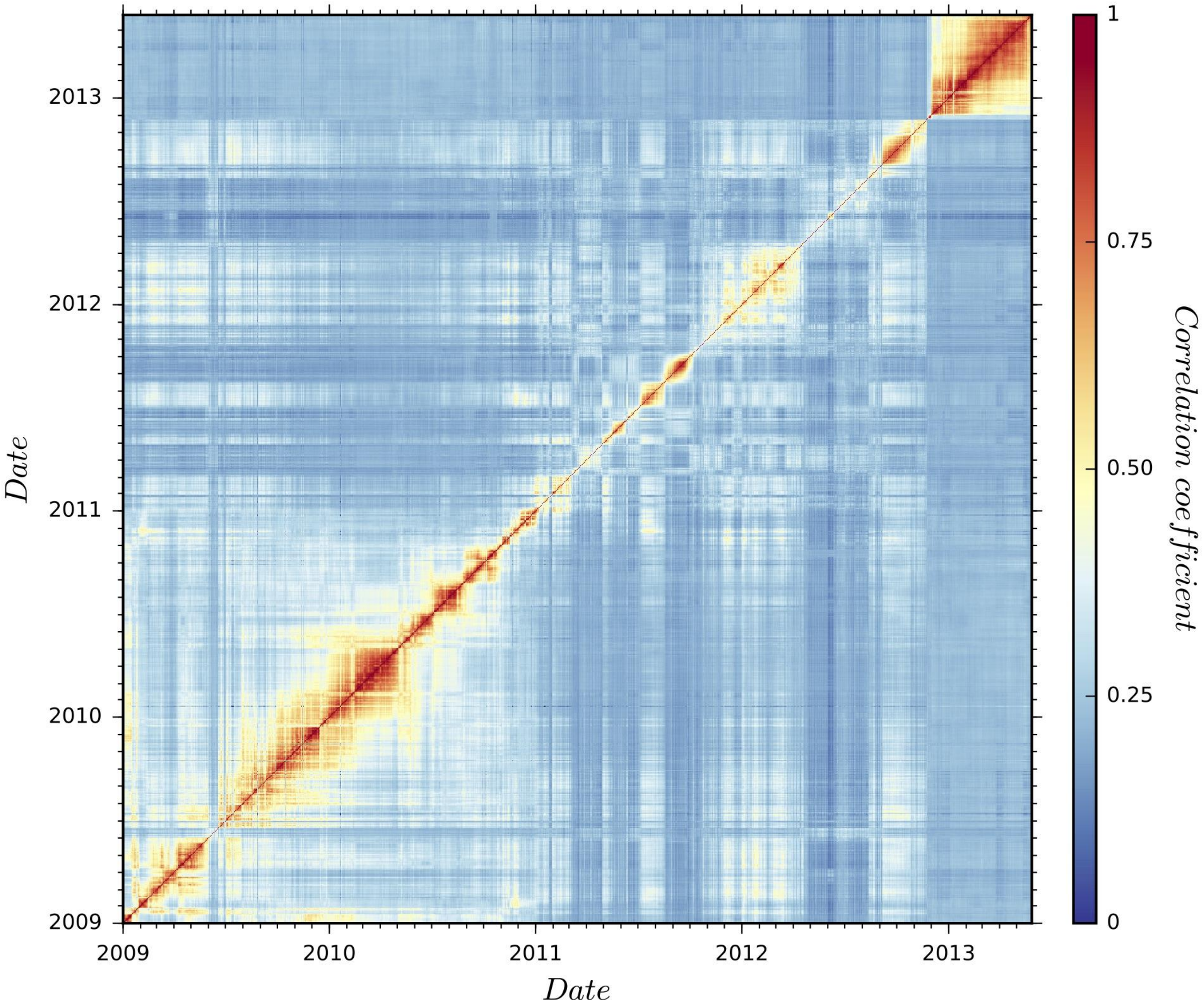
Network Covariance Matrix: **dominant eigenvector** wavefield corresponding to **dominant source**

$$C_{i,j}(f) = |S(f)|^2 P_s(r_i, f) P_s^*(r_j, f)$$



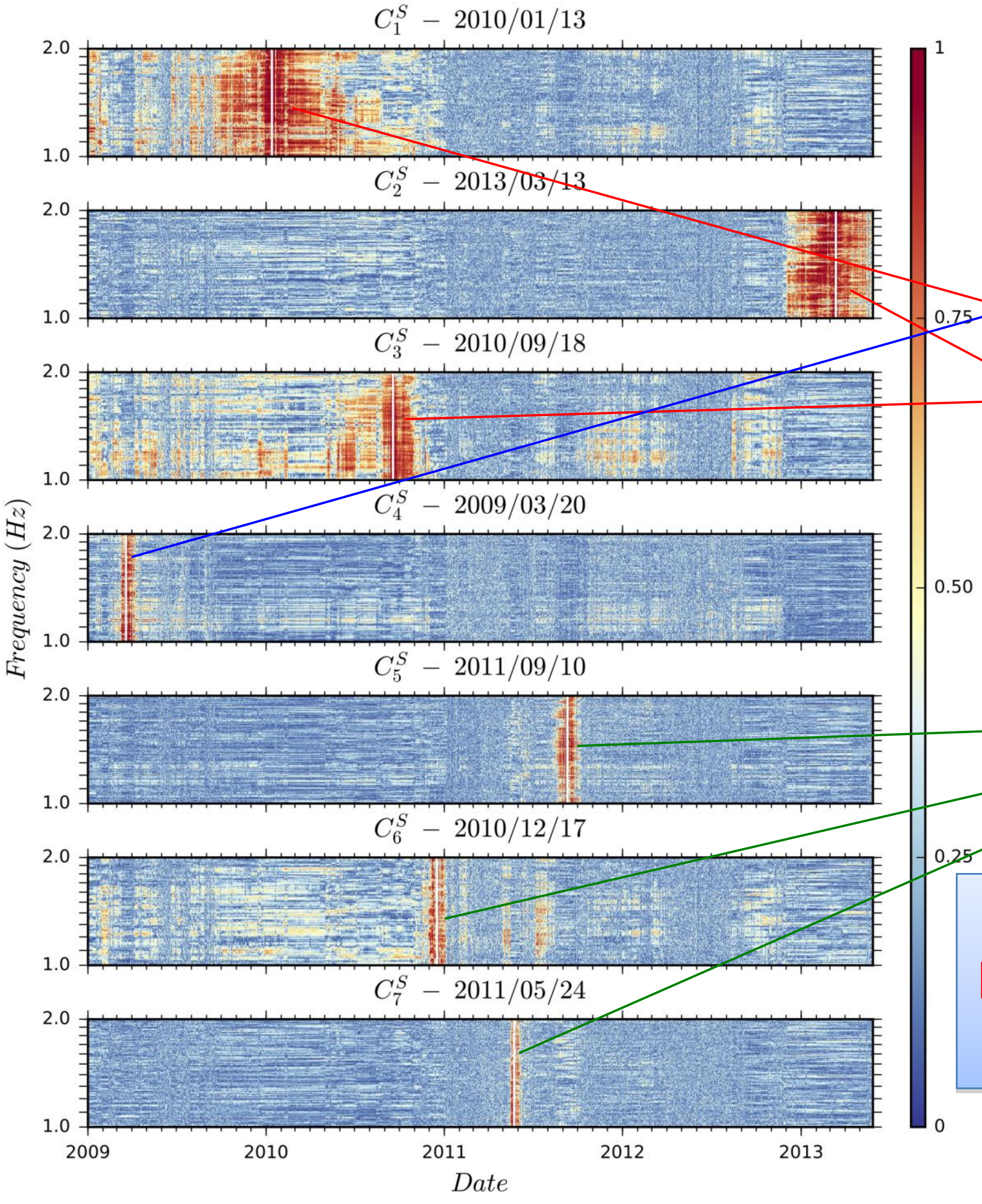
from Soubestre et al, 2017

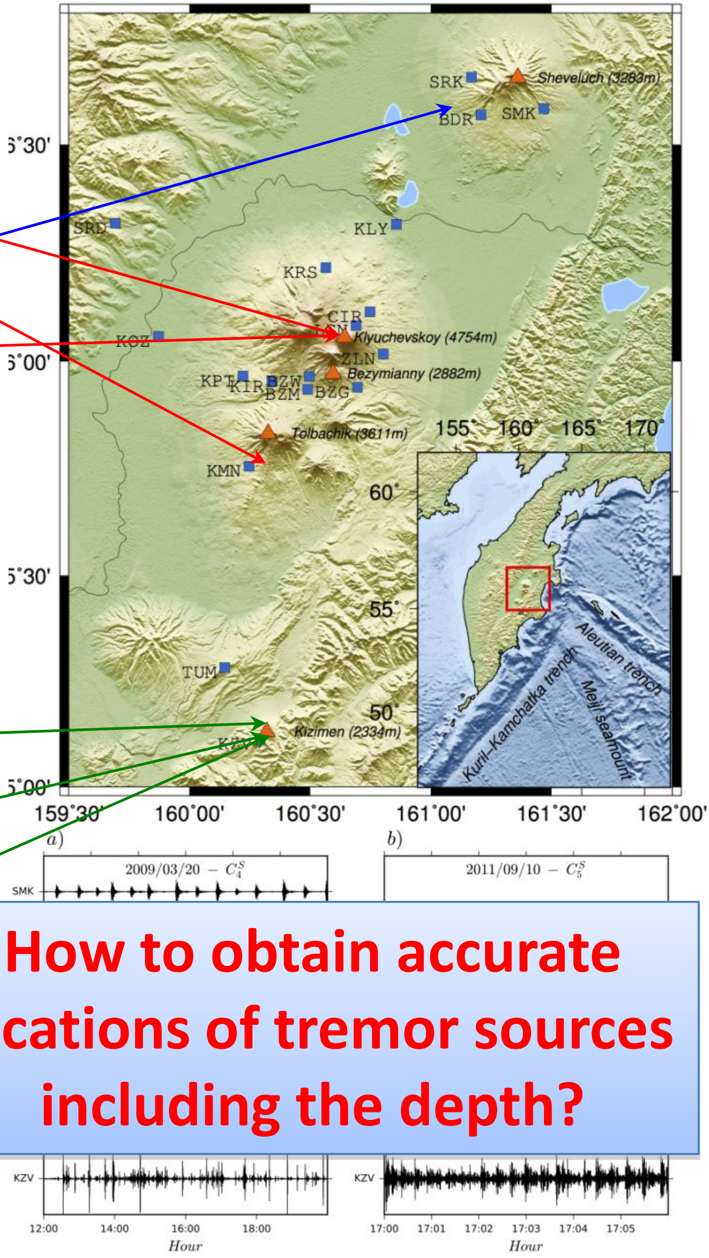
Network Covariance Matrix for the Klyuchevskoy group of volcanoes: correlation coefficients between dominant eigenvectors



from Soubestre et al, 2017

Cluster analysis of the dominant eigenvectors



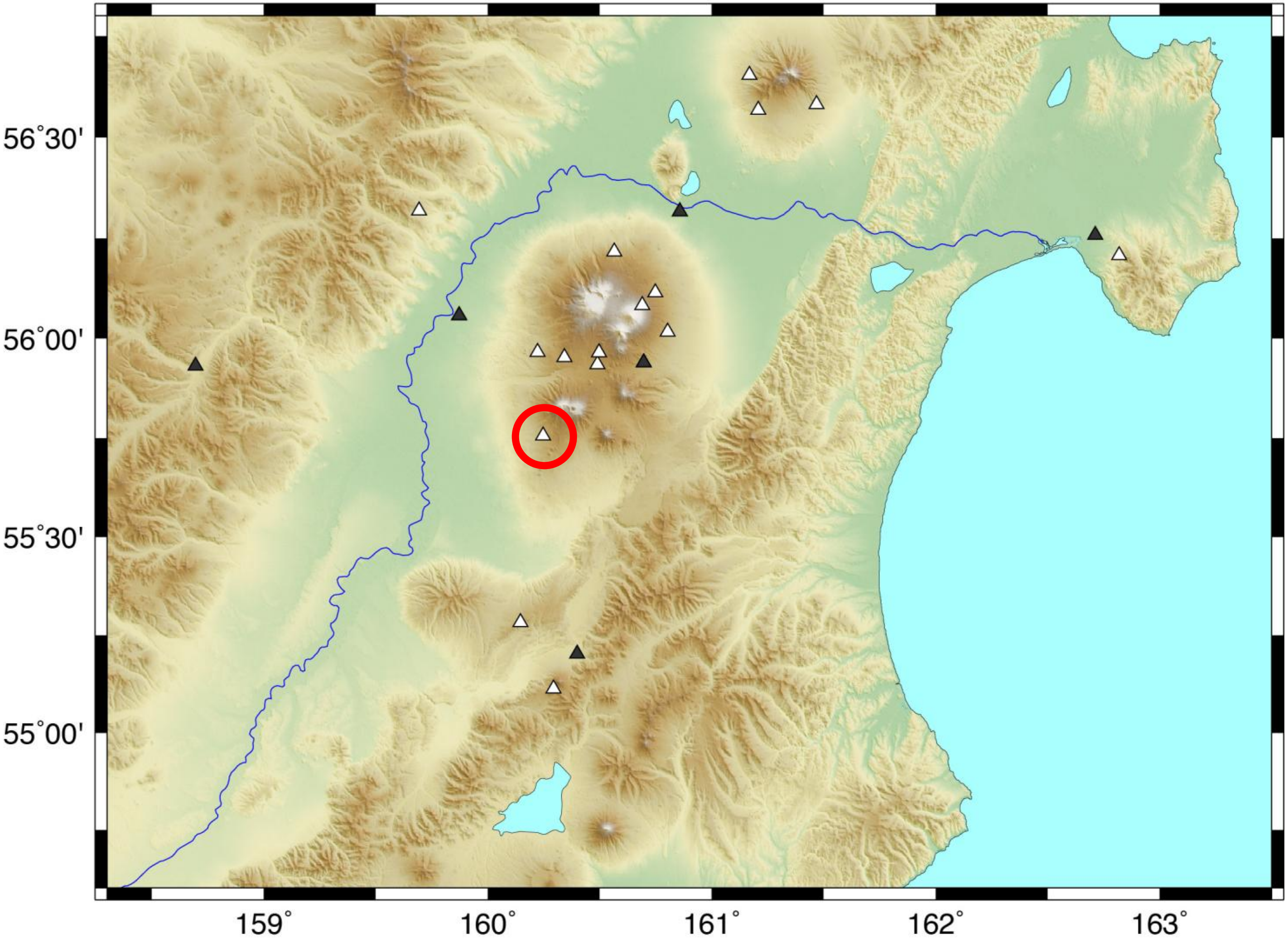


How to obtain accurate locations of tremor sources including the depth?

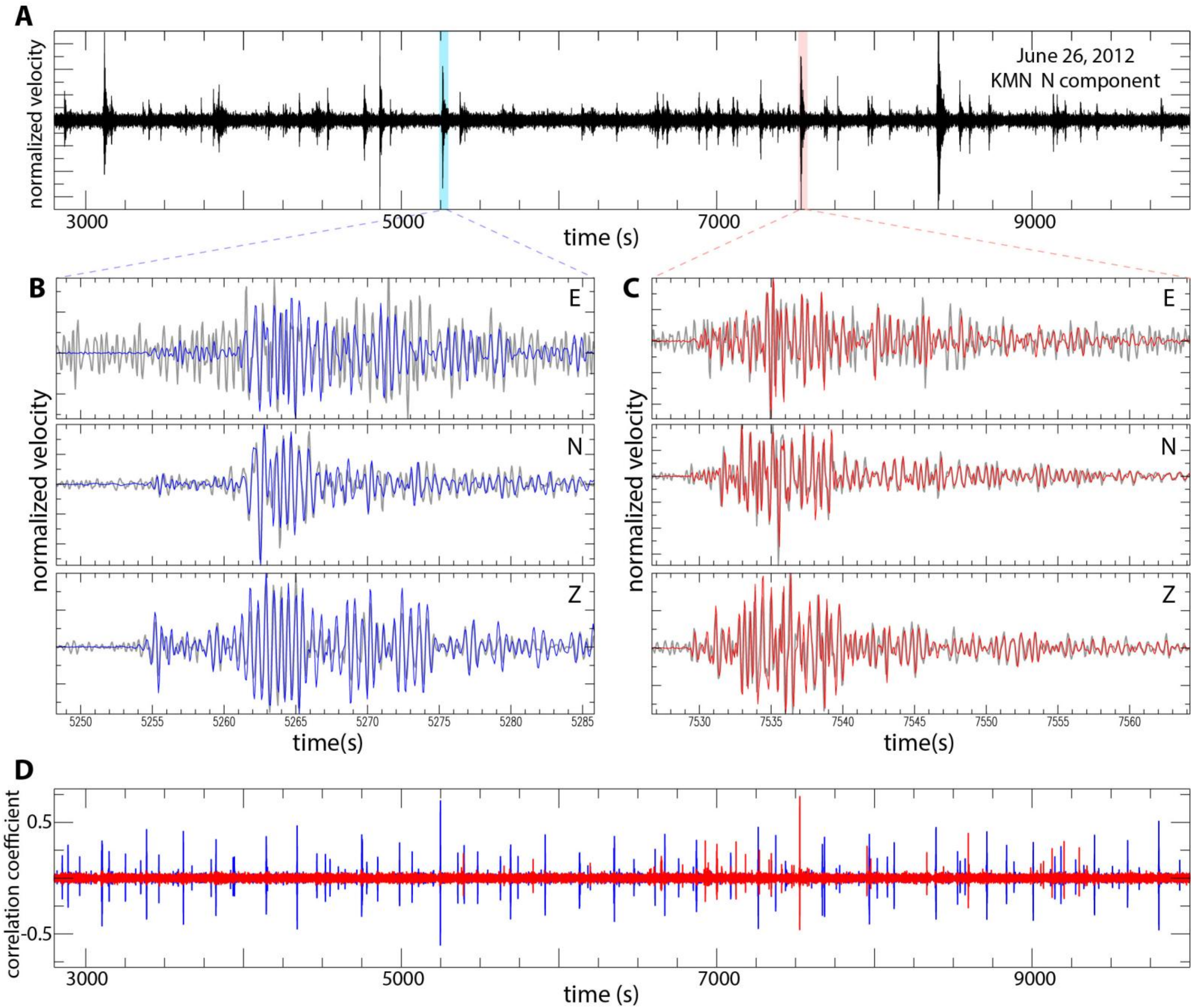
from Soubestre et al, 2017

Low-frequency (long-period LP) earthquakes within tremors

studied period: 01.01.2011 – 31.12.2012



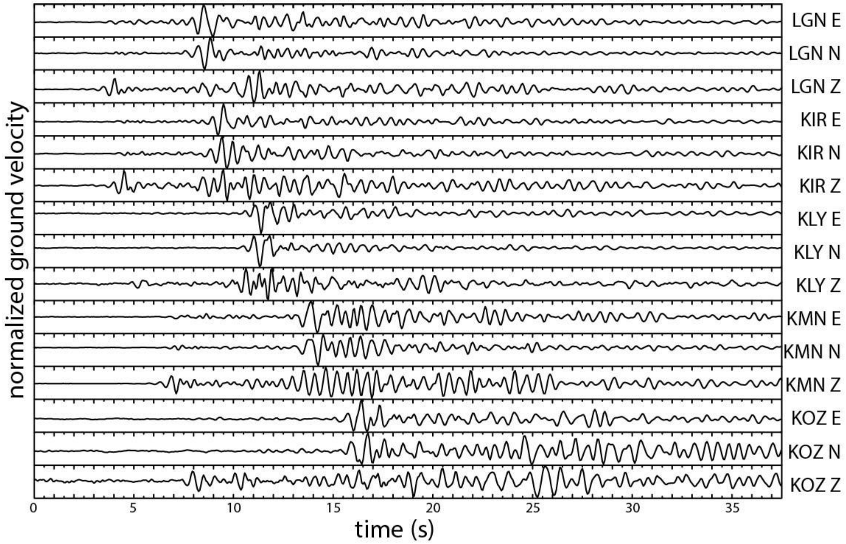
Example of LP earthquakes sequence

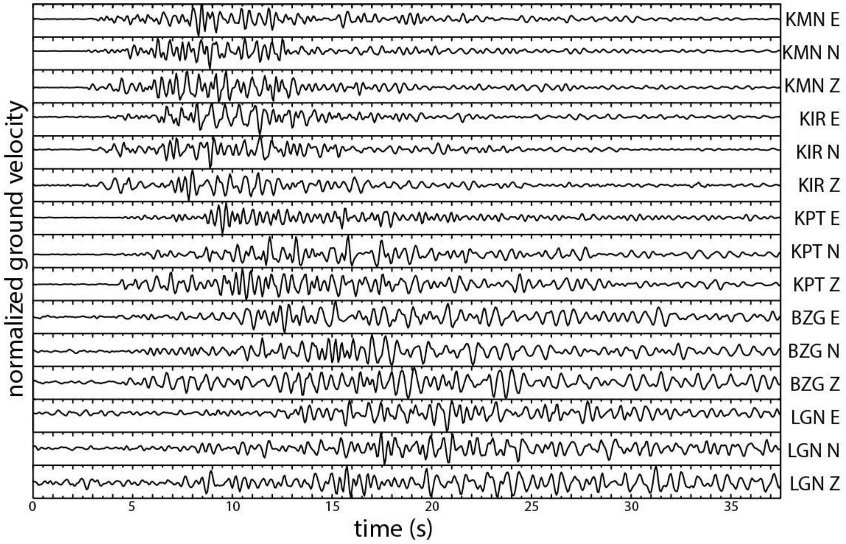


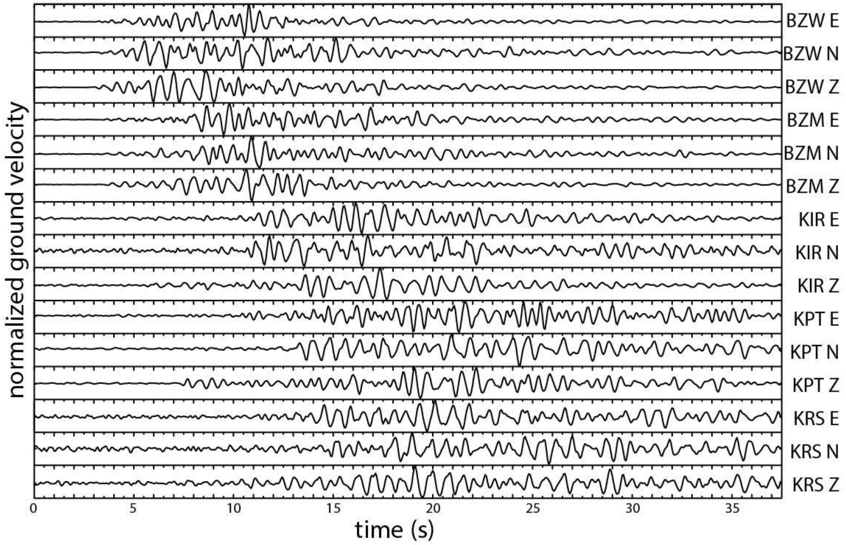
Systematic matched-filter detection of LP events

1. Analysis of **continuous** records at individual stations
2. Detecting impulsive events as **templates** for **matched-filter** search
3. Detecting all **multiplets** of these templates
4. Stacking waveforms at all stations based on detection times of one-station templates
5. Use **stacked** waveforms to locate template sources

Example of LP template stacks


template 1


template 6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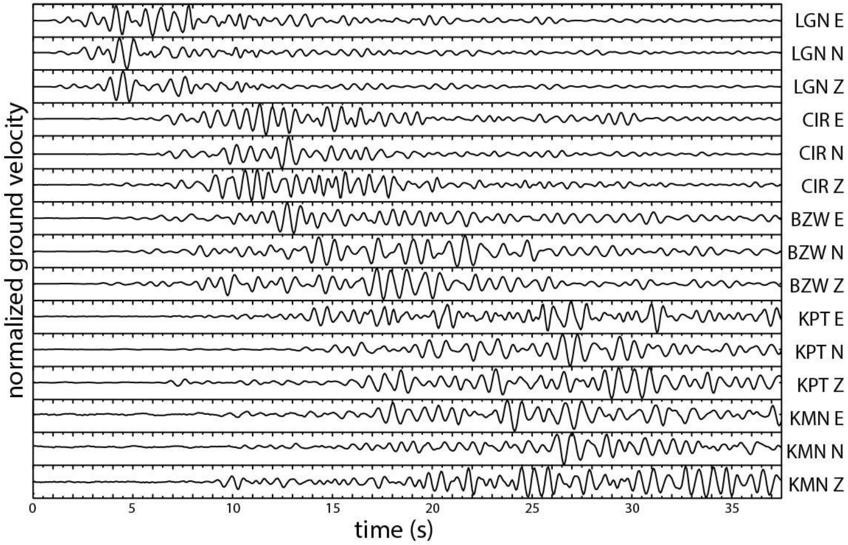
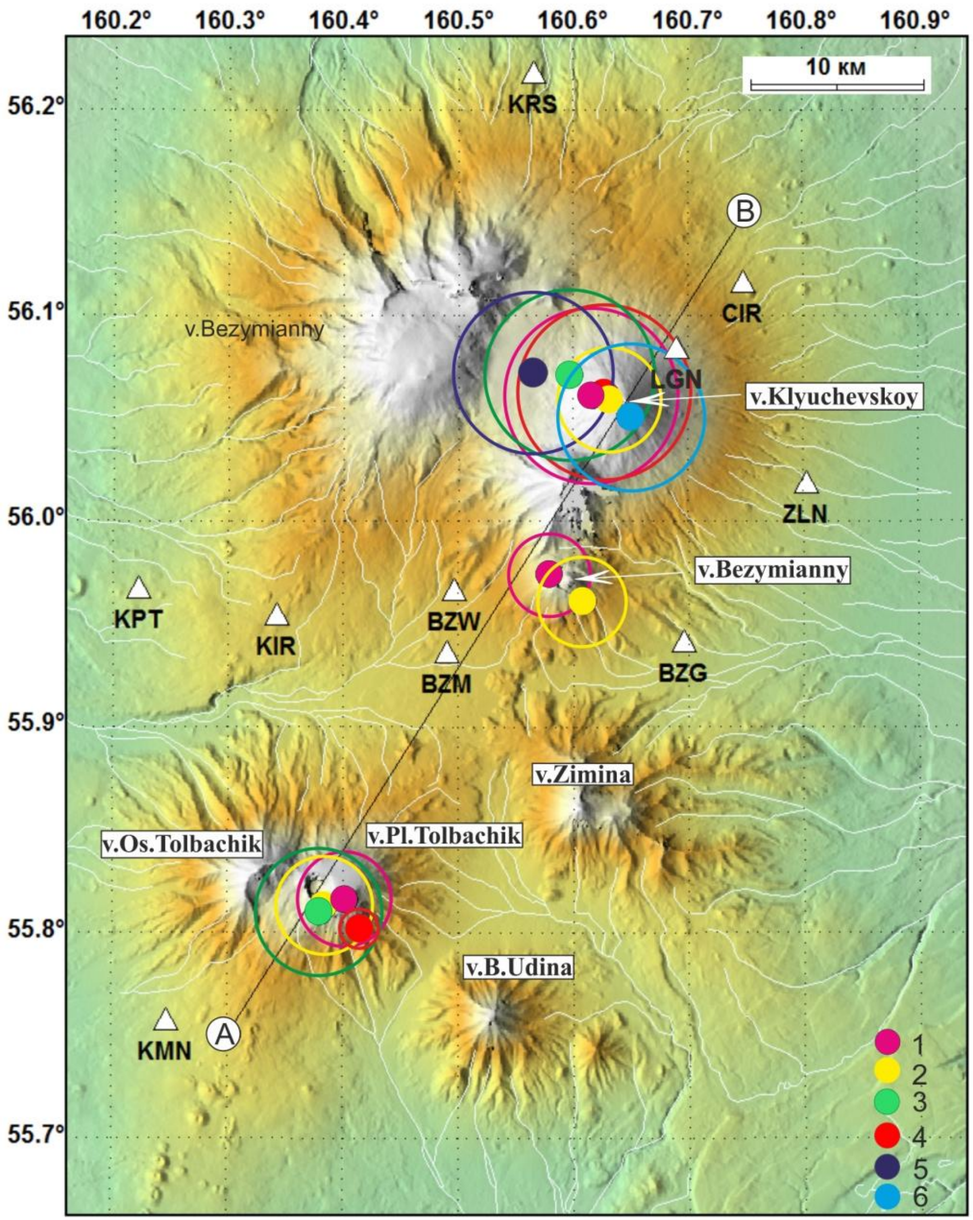
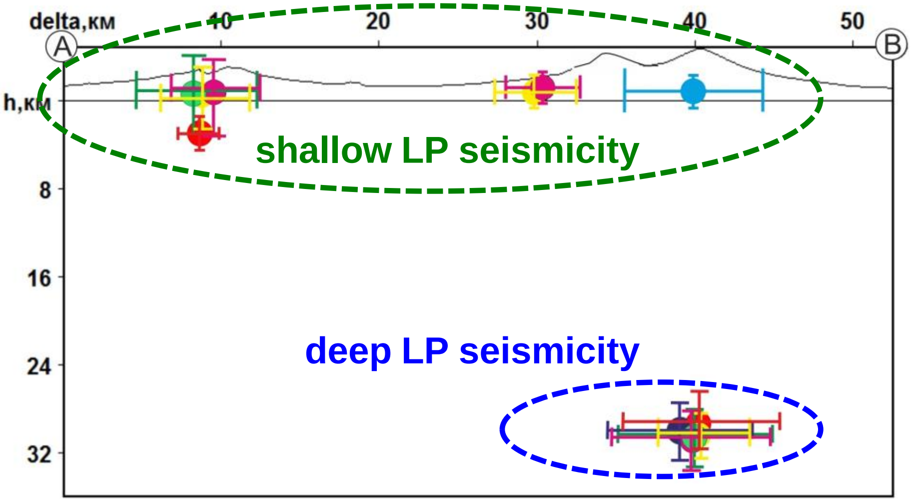

template 12

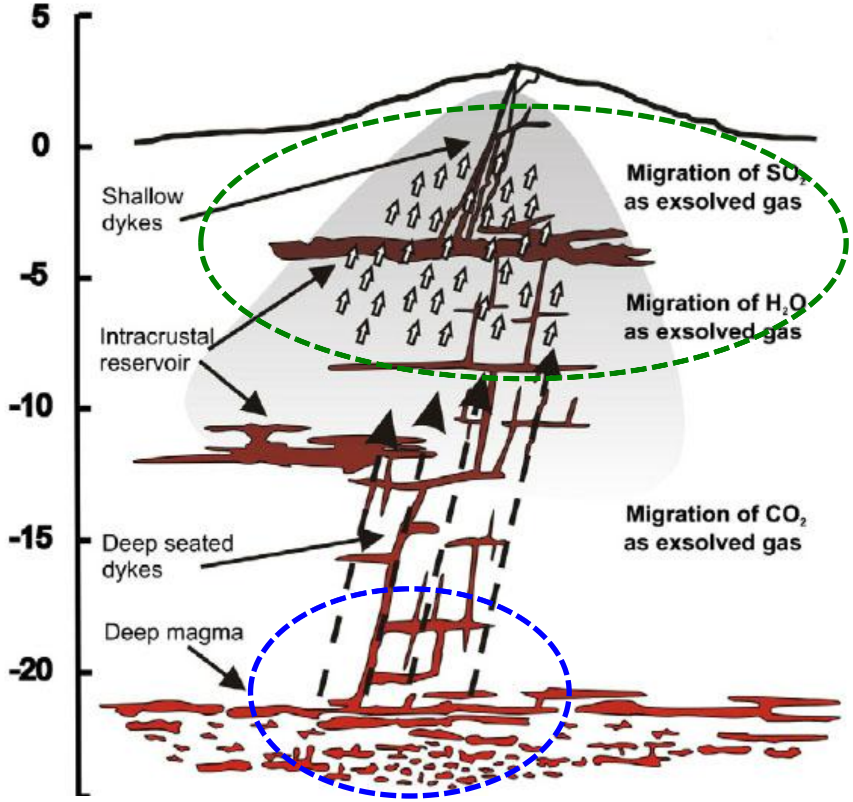
Epicenters of “stacked” templates





shallow LP seismicity

deep LP seismicity



Volcanic LP tremors and earthquakes

1. **Dominating frequencies 0.5-5 Hz**
2. **Sequences of highly repetitive events**

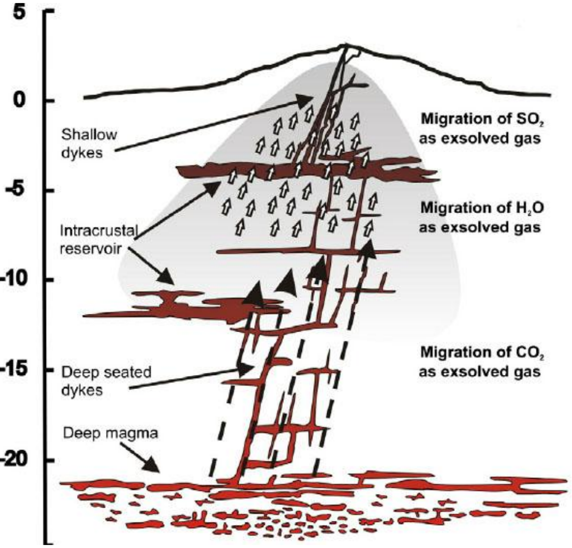
Long-period volcano seismicity: its source and use in eruption forecasting

Bernard A. Chouet

At an active volcano, long-period seismicity (with typical periods in the range 0.2–2 s) reflects pressure fluctuations resulting from unsteady mass transport in the sub-surface plumbing system, and hence provides a glimpse of the internal dynamics of the volcanic edifice.

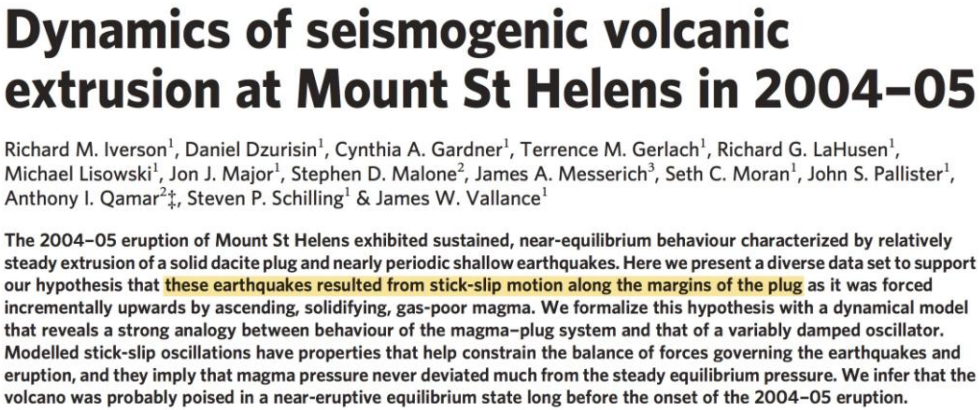
Widely accepted interpretation**:**

Seismo-volcanic LP activity is related to unsteady transport of the fluids (magmatic and/or hydrothermal) within the conduit system



Volcanic LP earthquakes: alternative interpretations

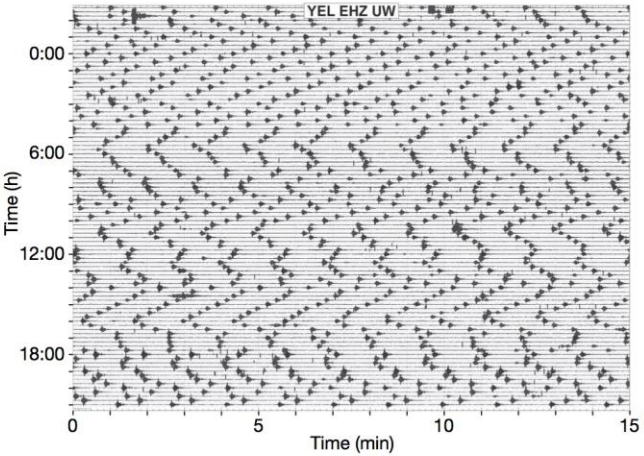
Stick-slip motion along the margins of the magma plug

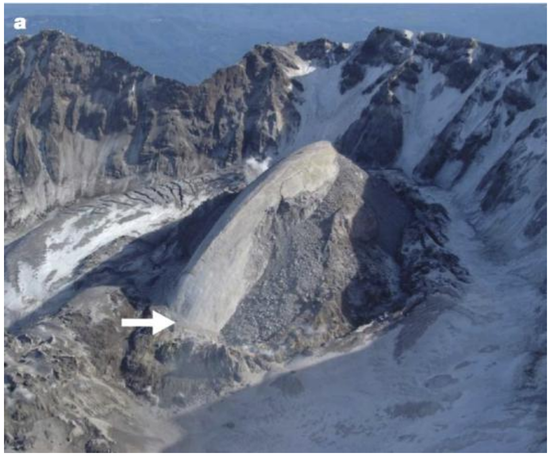


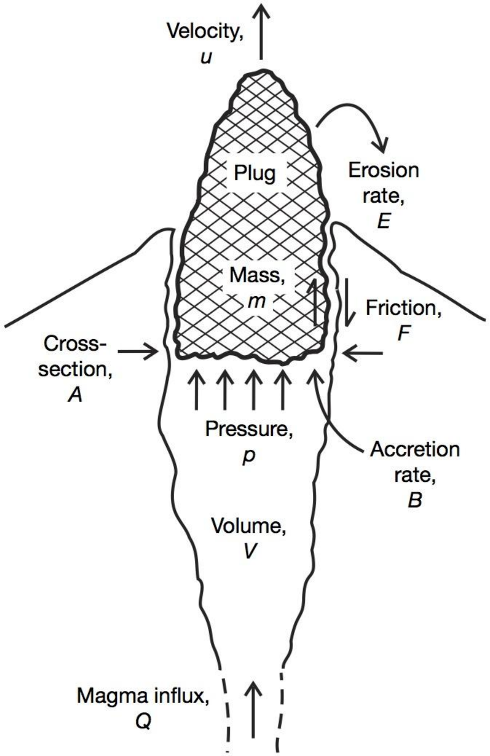
Dynamics of seismogenic volcanic extrusion at Mount St Helens in 2004–05

Richard M. Iverson[1], Daniel Dzurisin[1], Cynthia A. Gardner[1], Terrence M. Gerlach[1], Richard G. LaHusen[1], Michael Lisowski[1], Jon J. Major[1], Stephen D. Malone[2], James A. Messerich[3], Seth C. Moran[1], John S. Pallister[1], Anthony I. Qamar[2]‡, Steven P. Schilling[1] & James W. Vallance[1]

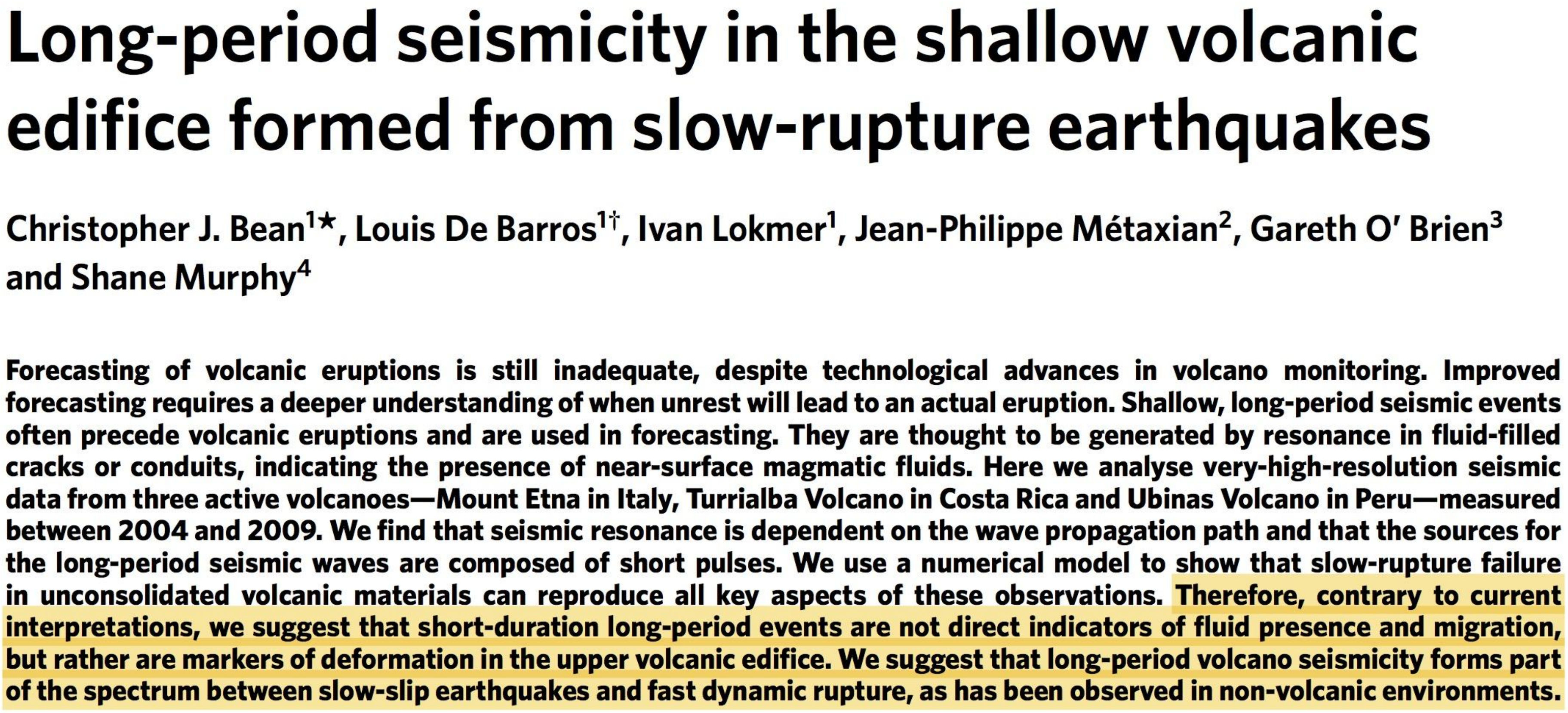
The 2004–05 eruption of Mount St Helens exhibited sustained, near-equilibrium behaviour characterized by relatively steady extrusion of a solid dacite plug and nearly periodic shallow earthquakes. Here we present a diverse data set to support our hypothesis that these earthquakes resulted from stick-slip motion along the margins of the plug as it was forced incrementally upwards by ascending, solidifying, gas-poor magma. We formalize this hypothesis with a dynamical model that reveals a strong analogy between behaviour of the magma–plug system and that of a variably damped oscillator. Modelled stick-slip oscillations have properties that help constrain the balance of forces governing the earthquakes and eruption, and they imply that magma pressure never deviated much from the steady equilibrium pressure. We infer that the volcano was probably poised in a near-eruptive equilibrium state long before the onset of the 2004–05 eruption.







Volcanic LP earthquakes: alternative interpretations



Long-period seismicity in the shallow volcanic edifice formed from slow-rupture earthquakes

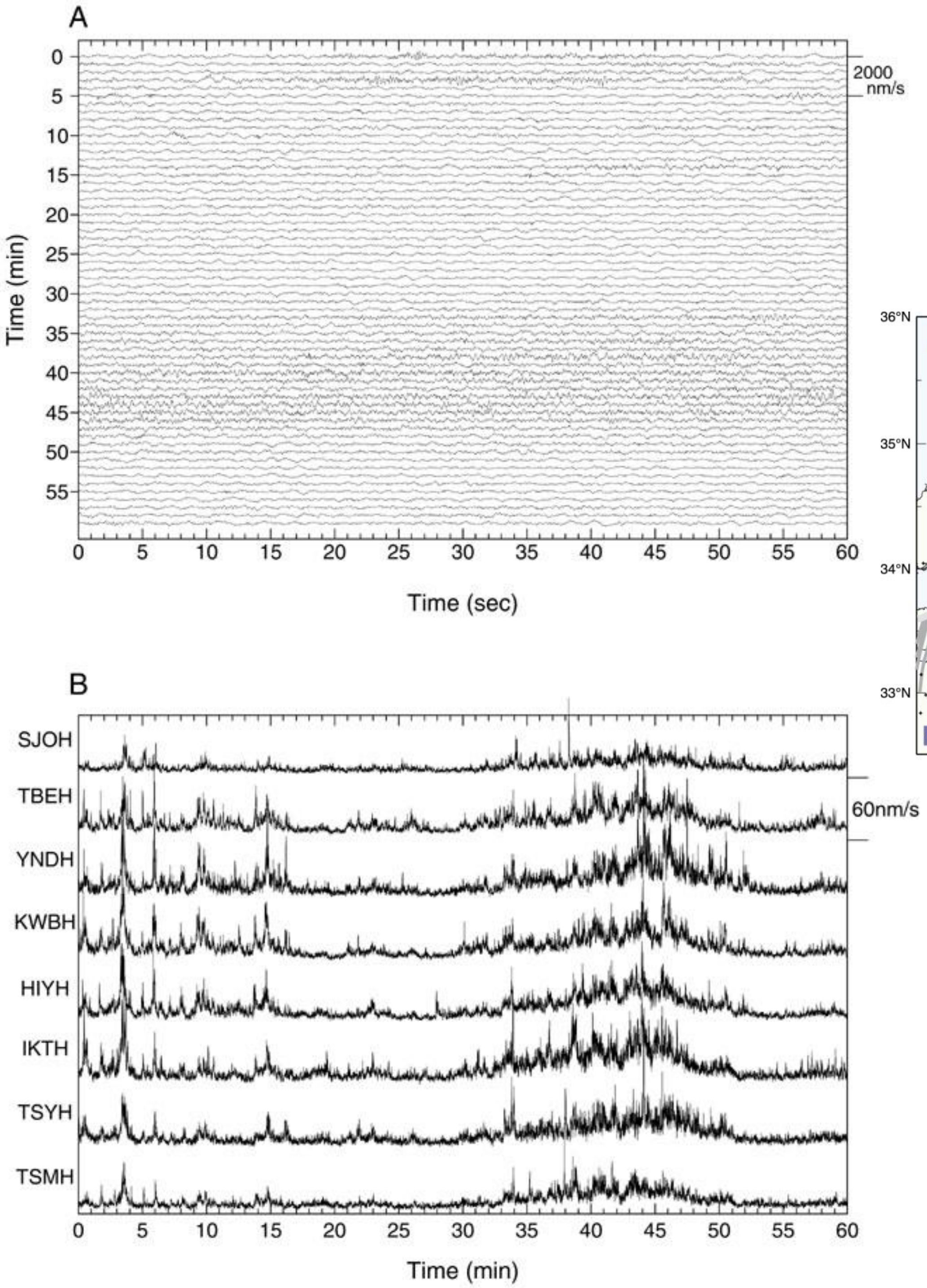
Christopher J. Bean[1]*, Louis De Barros[1†], Ivan Lokmer[1], Jean-Philippe Métaxian[2], Gareth O' Brien[3] and Shane Murphy[4]

Forecasting of volcanic eruptions is still inadequate, despite technological advances in volcano monitoring. Improved forecasting requires a deeper understanding of when unrest will lead to an actual eruption. Shallow, long-period seismic events often precede volcanic eruptions and are used in forecasting. They are thought to be generated by resonance in fluid-filled cracks or conduits, indicating the presence of near-surface magmatic fluids. Here we analyse very-high-resolution seismic data from three active volcanoes—Mount Etna in Italy, Turrialba Volcano in Costa Rica and Ubinas Volcano in Peru—measured between 2004 and 2009. We find that seismic resonance is dependent on the wave propagation path and that the sources for the long-period seismic waves are composed of short pulses. We use a numerical model to show that slow-rupture failure in unconsolidated volcanic materials can reproduce all key aspects of these observations. Therefore, contrary to current interpretations, we suggest that short-duration long-period events are not direct indicators of fluid presence and migration, but rather are markers of deformation in the upper volcanic edifice. We suggest that long-period volcano seismicity forms part of the spectrum between slow-slip earthquakes and fast dynamic rupture, as has been observed in non-volcanic environments.

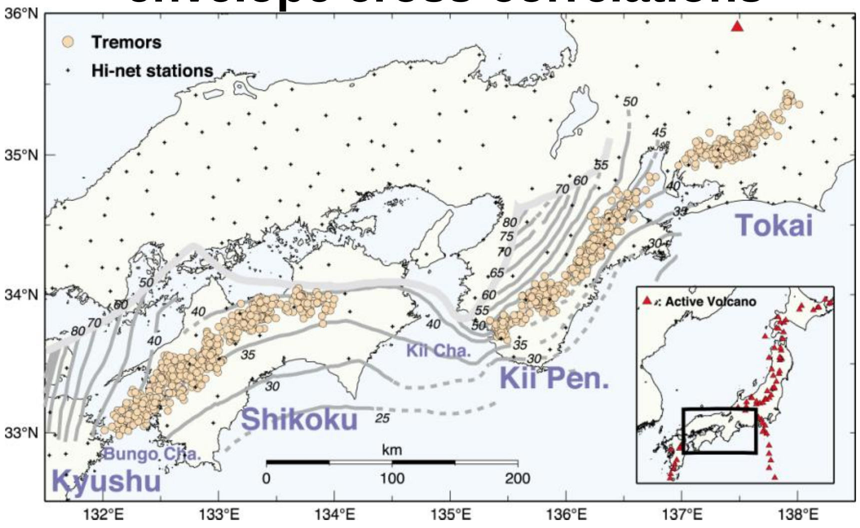
Outline

- Main types of observed Earth’s seismic signals
- Volcanic tremors
- Tectonic tremors
- Challenges with the interpretation

Tectonic Tremors



Source locations based on envelope cross-correlations

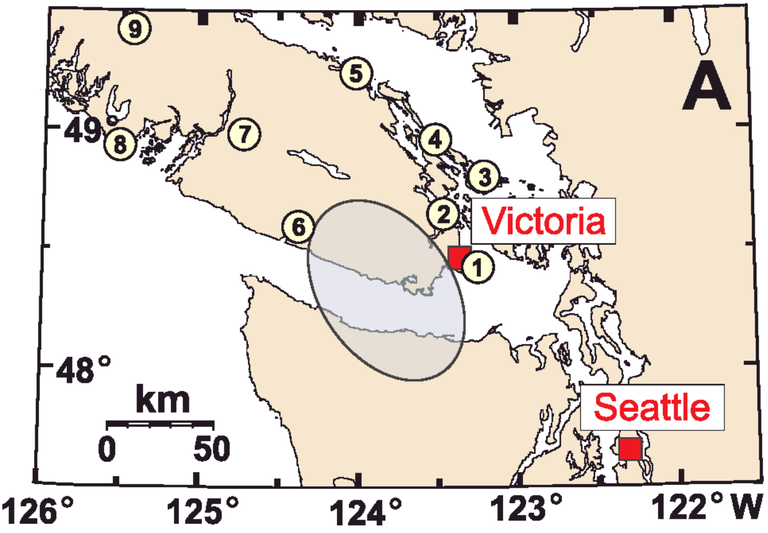


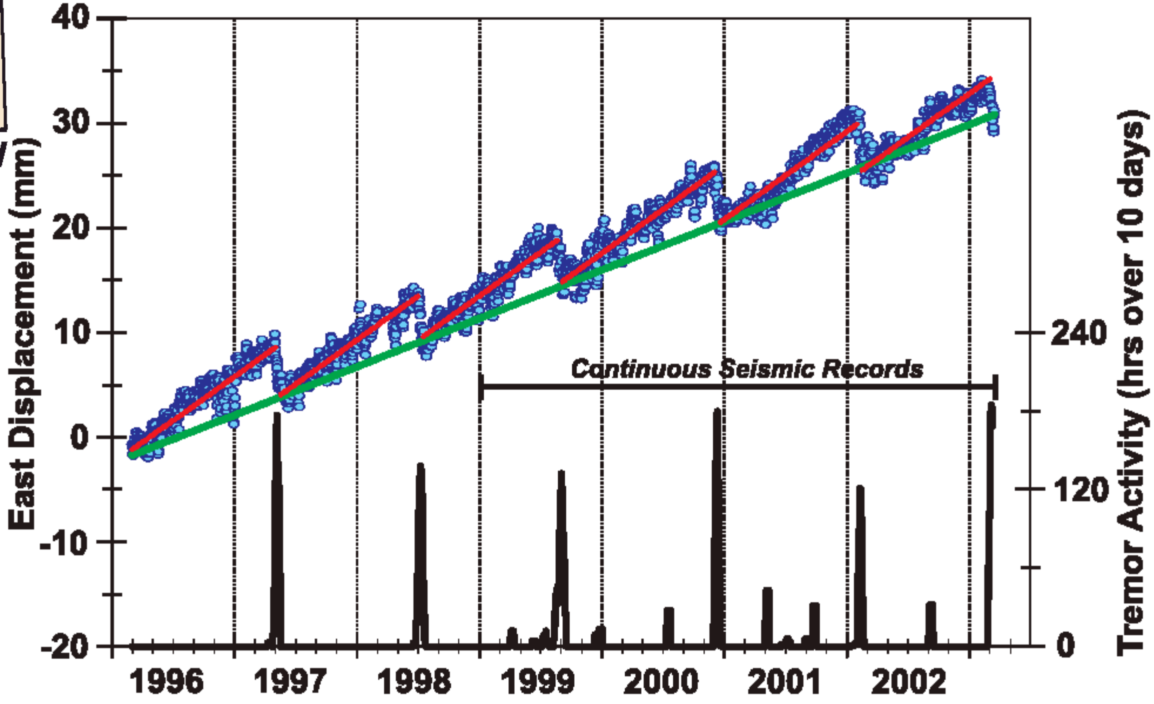
Obara, 2002

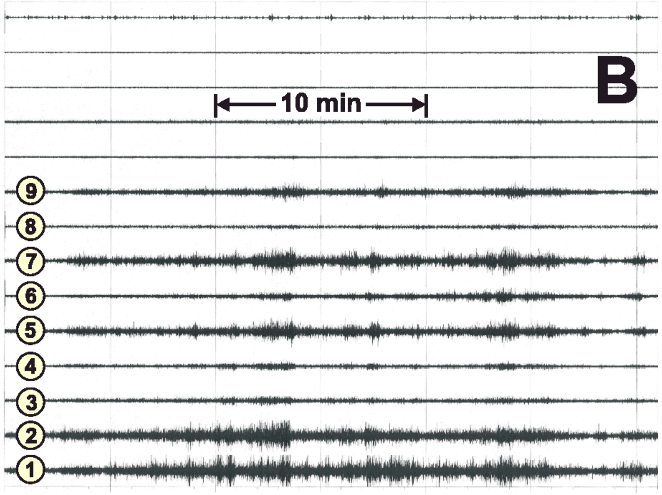
Seismic manifestation of slow processes in fault zones during inter-seismic periods

Tectonic Tremors

Rogers and Dragert, 2003



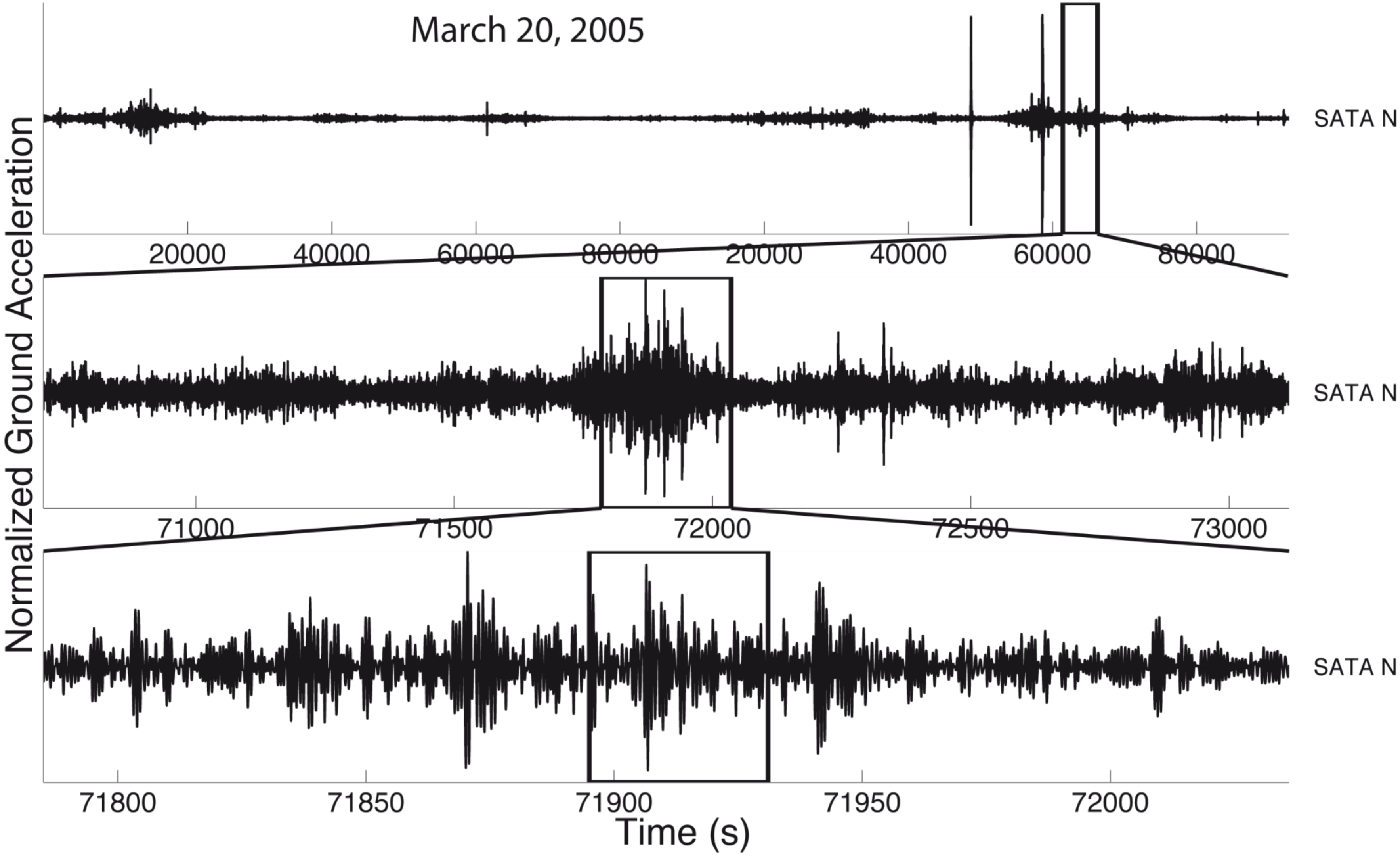




Tremors are strongly correlated with Slow Slip

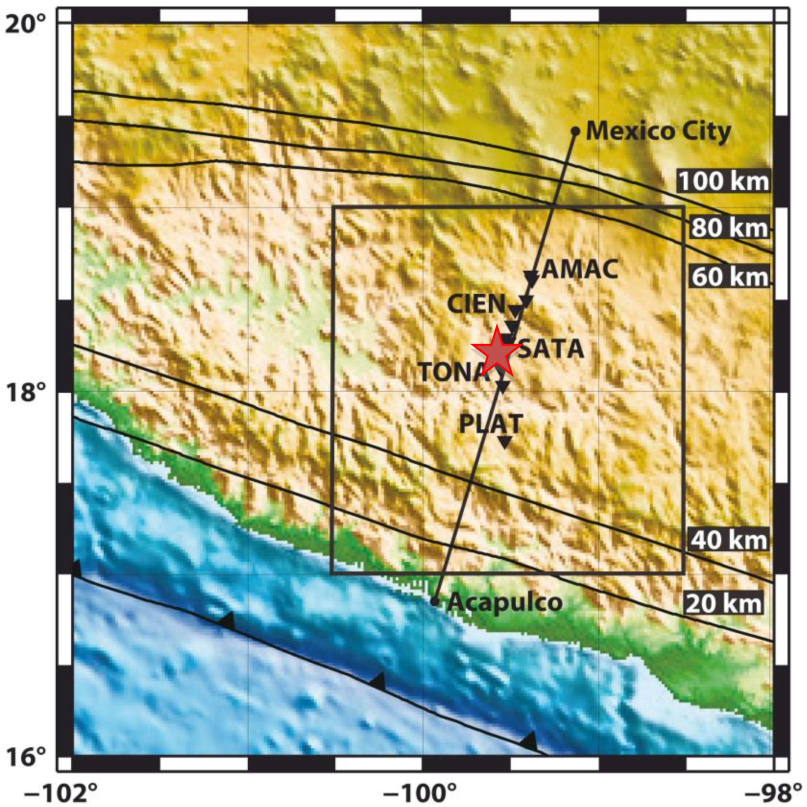
Low-Frequency Earthquakes (LFE) within tremors

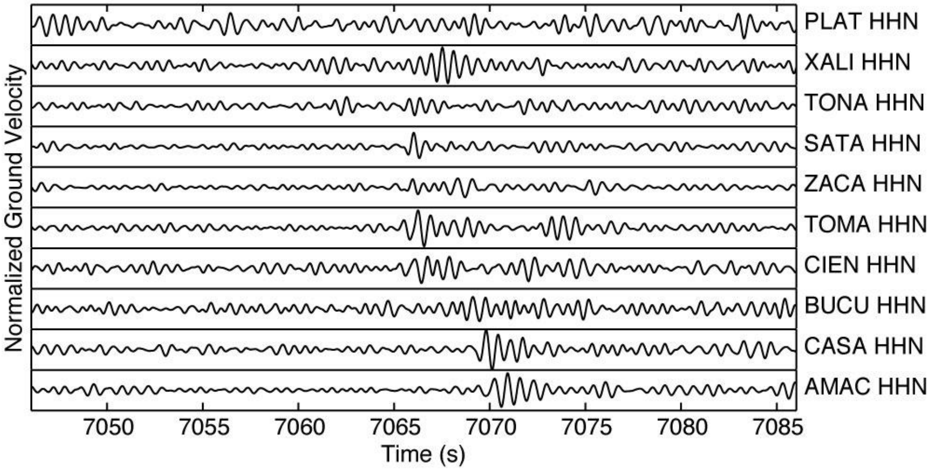
Frank et al.,



Studying the Low-Frequency Earthquakes (LFE) in Mexico

Frank et al.

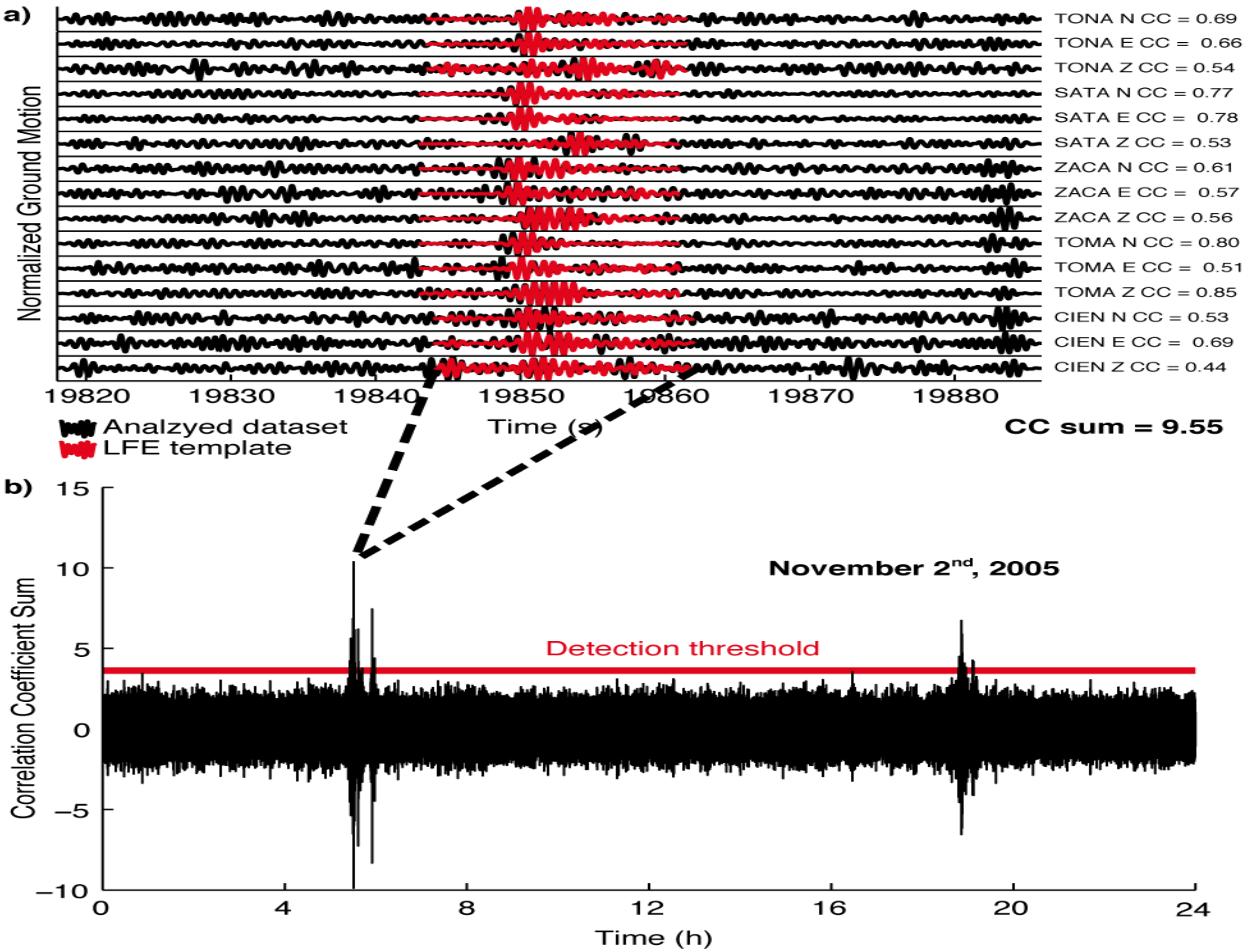




Studying the Low-Frequency Earthquakes (LFE) in Mexico

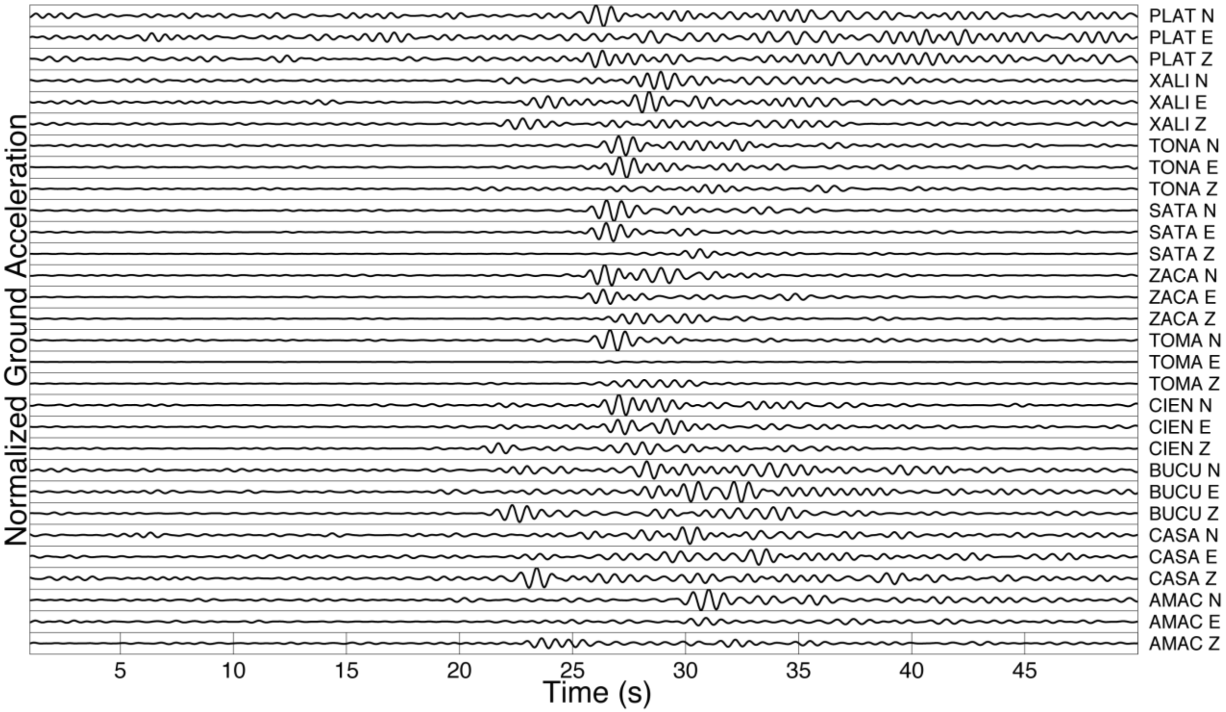
Frank et al.

Detecting template multiplets: Multi-station multi-component correlation



Studying the Low-Frequency Earthquakes (LFE) in Mexico

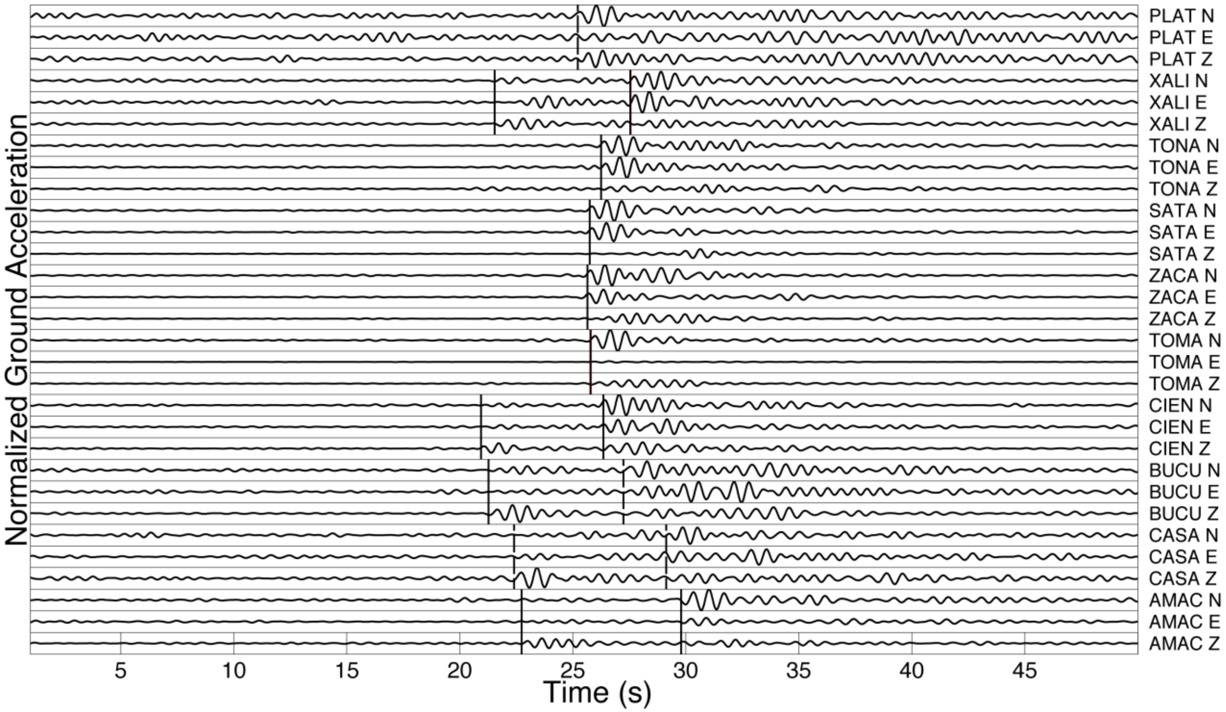
Frank et al.



- Stacking all detections

Studying the Low-Frequency Earthquakes (LFE) in Mexico

Frank et al.

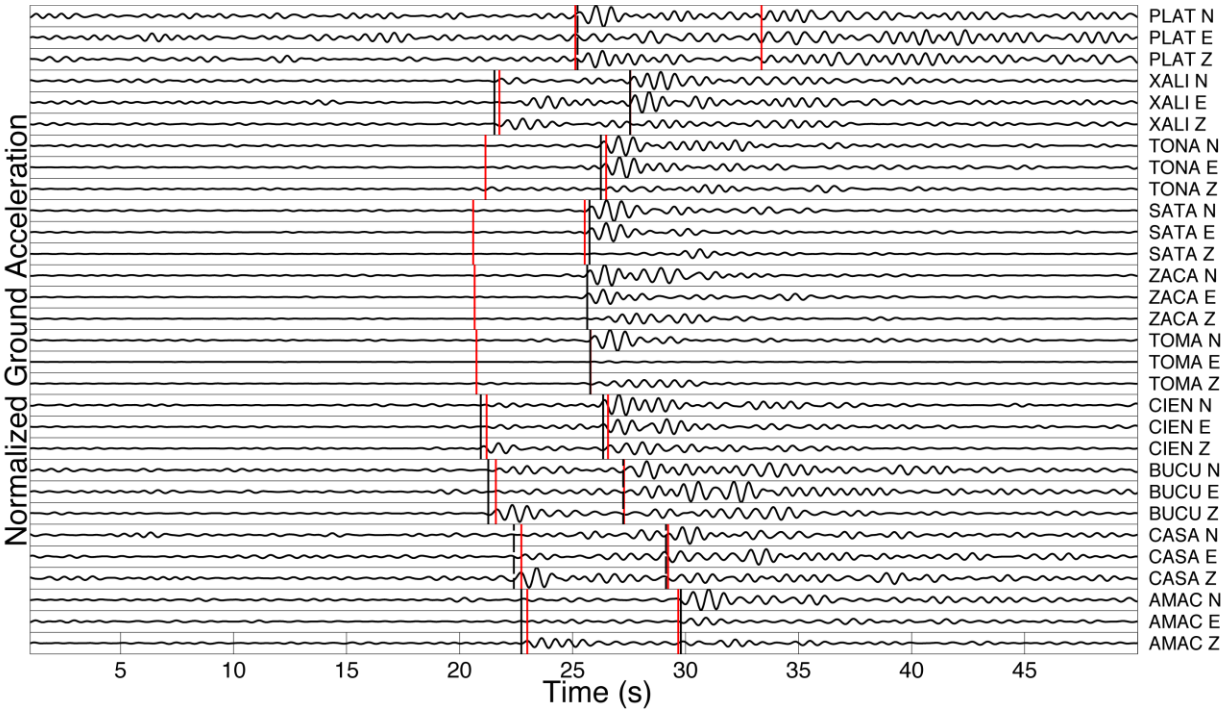


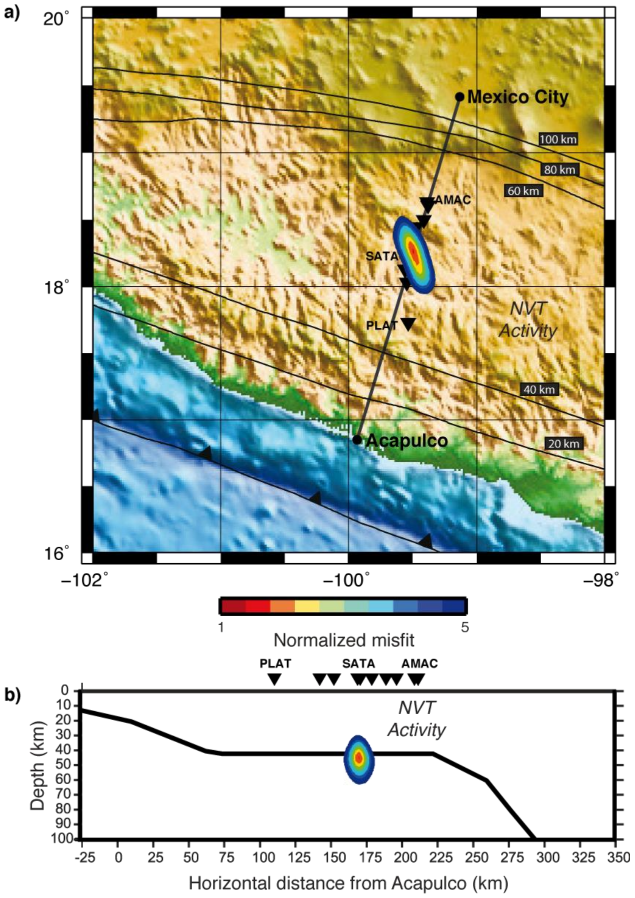
- **Stacking all detections**
- **Picking travel times**

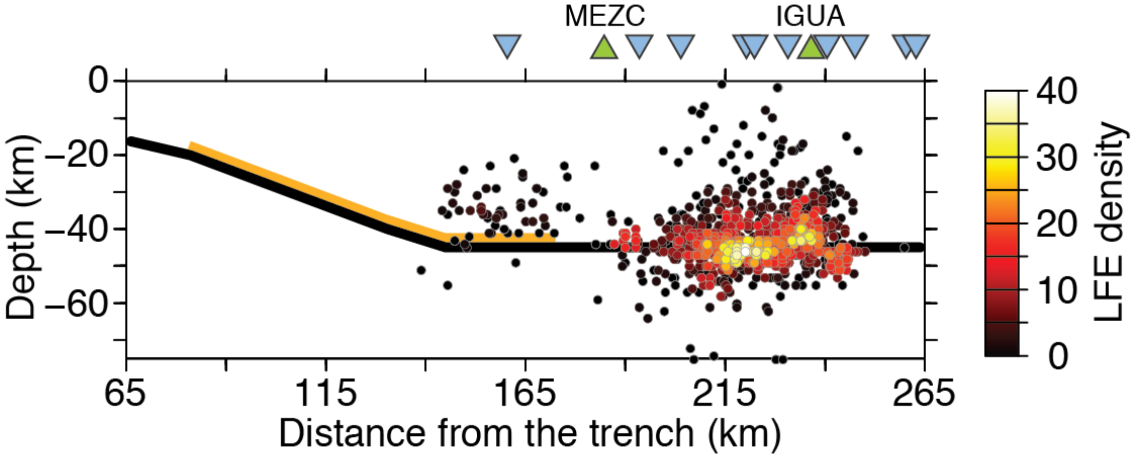
Studying the Low-Frequency Earthquakes (LFE) in Mexico

Frank et al.

- **Stacking all detections**
- **Picking travel times**
- **Locating the source**

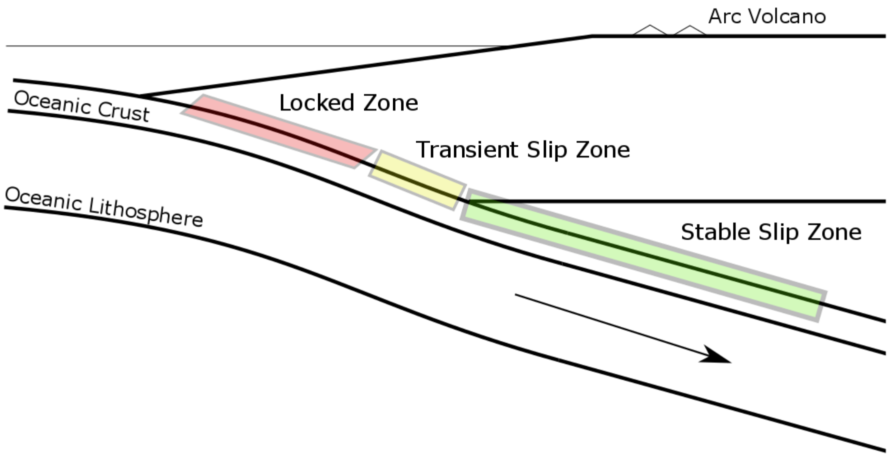






Tectonic LF tremors and earthquakes

1. **Dominating frequencies 0.5-5 Hz**
2. **Sequences of highly repetitive events**



Widely accepted interpretation:

Seismic radiation produced by small seismogenic asperities in deep “**slow slip**ping” parts of the faults

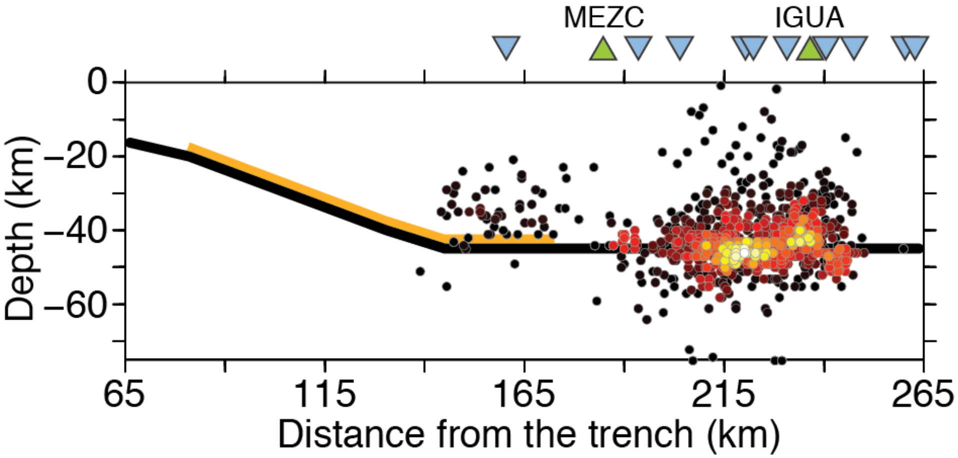
Outline

- Main types of observed Earth’s seismic signals
- Volcanic tremors
- Tectonic tremors
- Challenges with the interpretation

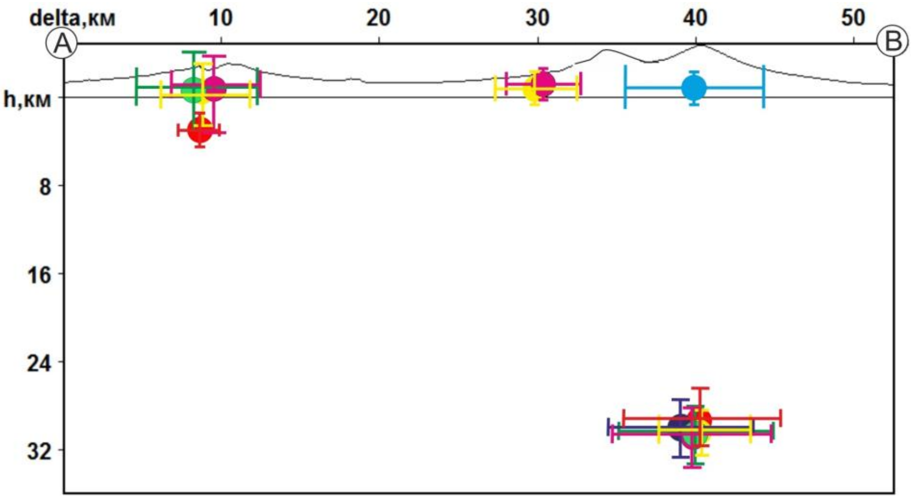
Source regions and possible mechanisms of tectonic and volcanic tremors

- Difference -> depth and confining pressure (except VDLP)

Tectonic tremors



Volcanic tremors

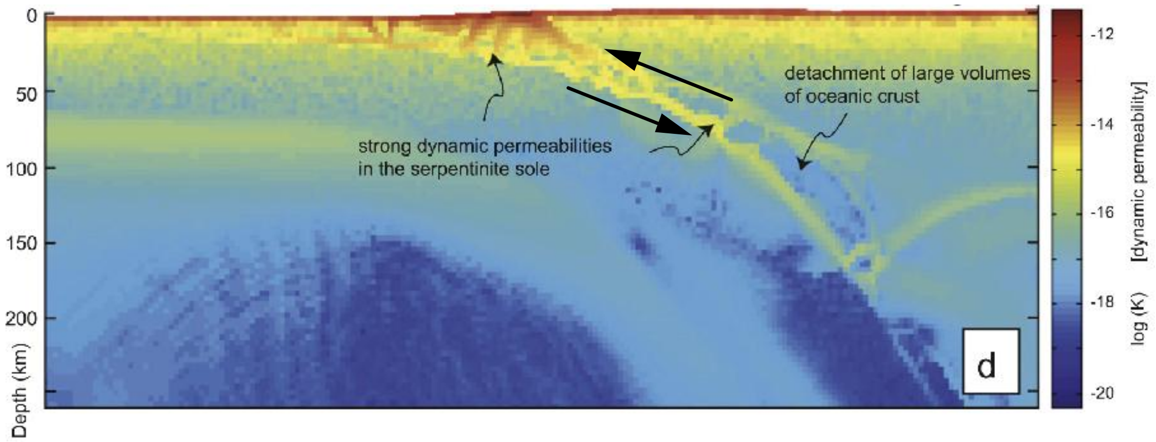


Source regions and possible mechanisms of tectonic and volcanic tremors

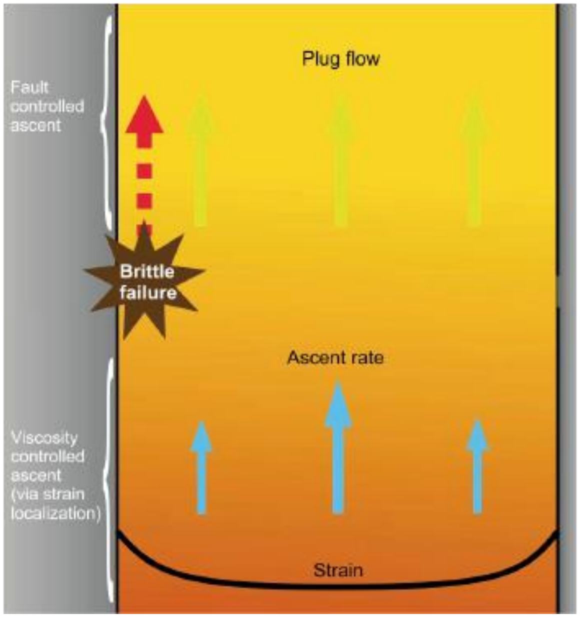
- Difference -> depth and confining pressure (except VDLP)
- Similarity -> combination of shearing with fluid transport

Multiplet behavior -> nondestructive source mechanisms

Subduction zone (Angiboust et al., 2015)



Volcanic conduit
(Hornby et al., 2015)



Low frequency tremors cans be used to understand **slow processes** within faults and volcanoes

Understanding Earth's processes with seismological observations

STUDIED PHENOMENA

direct problem

Modeling physical processes

Modeling seismic radiation

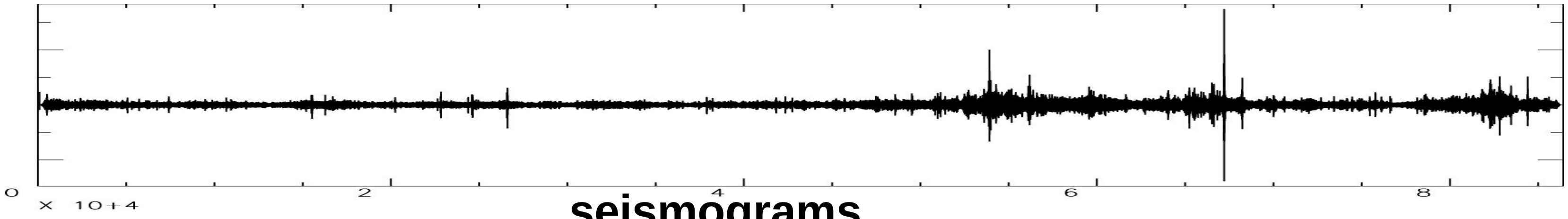
Modeling wave propagations

Inverse problem

Inferences about physical processes

Seismic source parameters

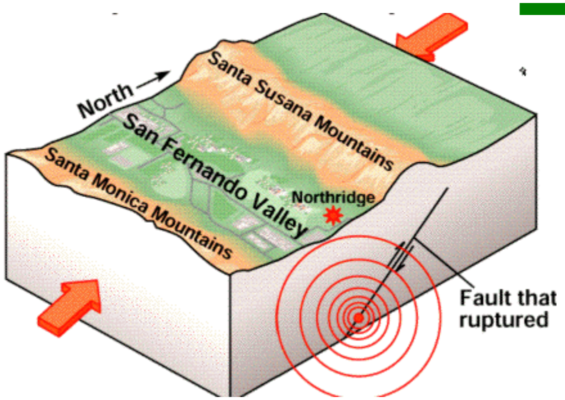
Backprojecting seismic waves



seismograms

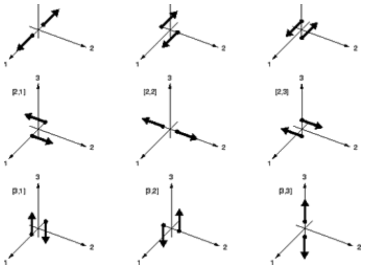
Studying tectonic processes with **earthquakes**

Earthquakes on seismogenic faults



Rupture physics

Seismic moment tensor

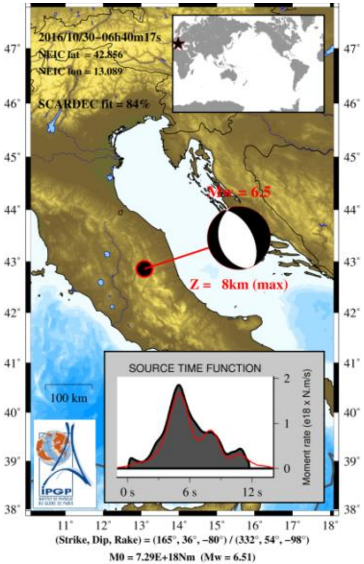


$$M_{kj} = \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$

Wave propagation

Earthquake-generated seismograms

Earthquake source parameters:
location, seismic moment,
focal mechanism, source time function



(Strike, Dip, Rake) = (165°, 36°, −80°) / (332°, 54°, −98°)

M0 = 7.29E+18Nm (Mw = 6.51)

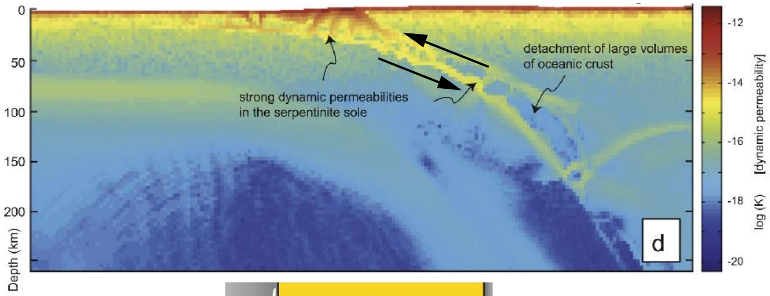
INVERSION

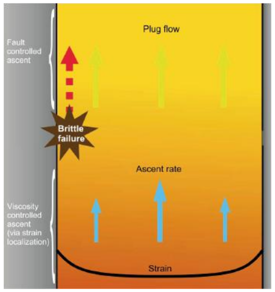
INFERENCE

- fault properties
- mechanical stresses
- scaling laws
- seismic hazard
- plate tectonics

Studying slow processes with **tremors**

Slow processes within Volcanoes and faults

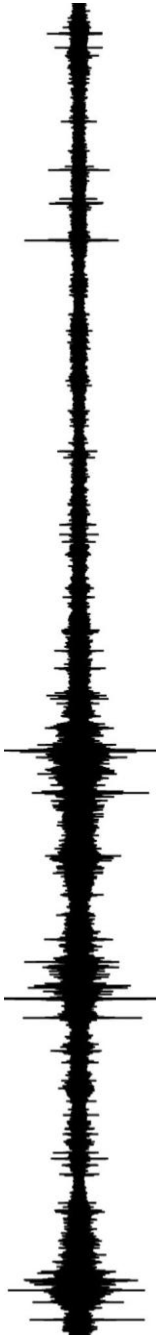




Description of wave sources

???

Wave propagation



Seismic tremor

Seismic source parameters

- slow slip
- fluids in the faults
- magma migration
- magma degassing
- hydrothermal systems

INFERENCE ??? INVERSION

Thank you