Locating seismic sources with an automatic multi-scale, array-based detection and location scheme

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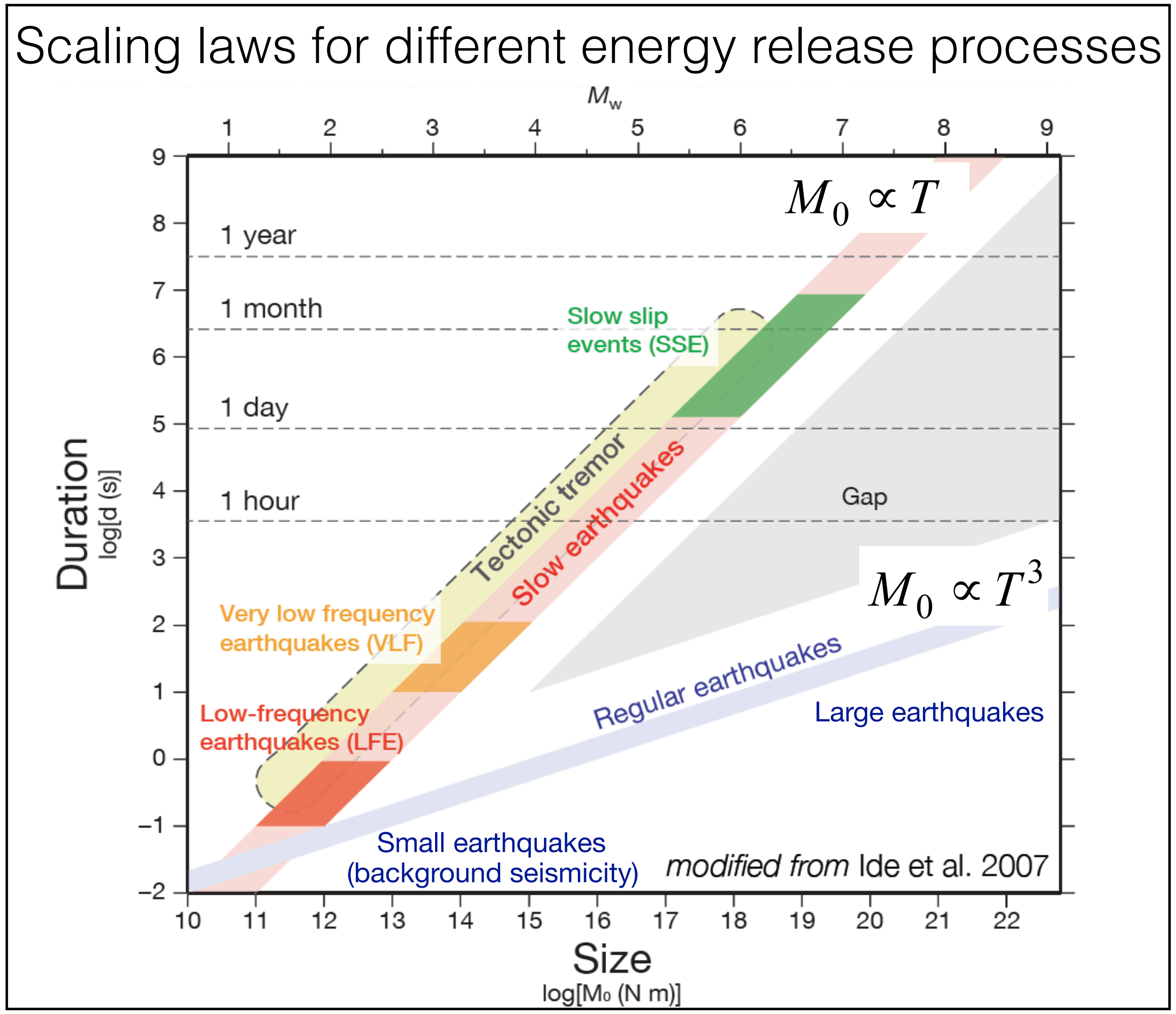
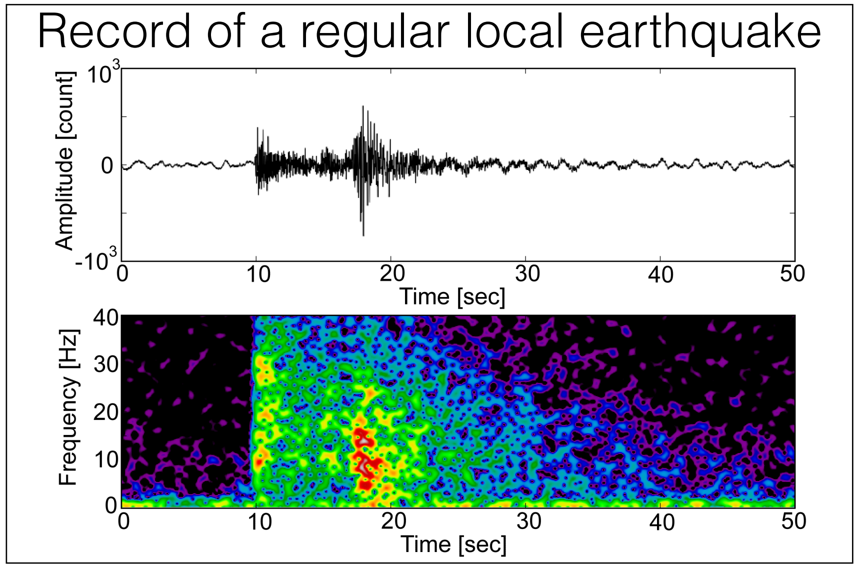
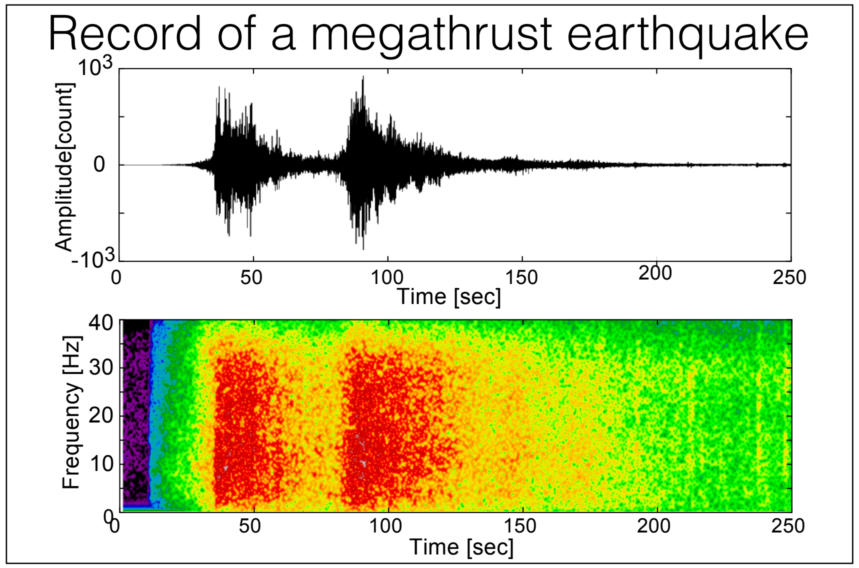
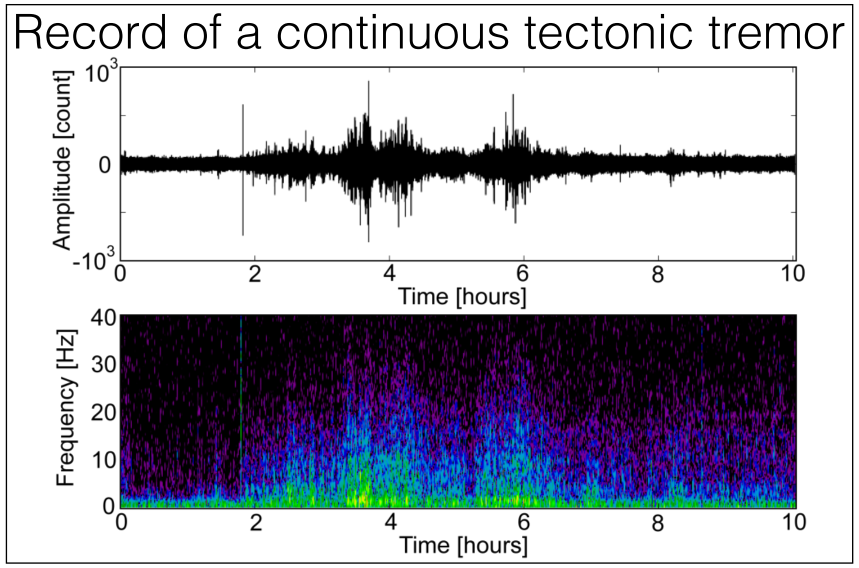
1. Motivation: Variability of seismic sources







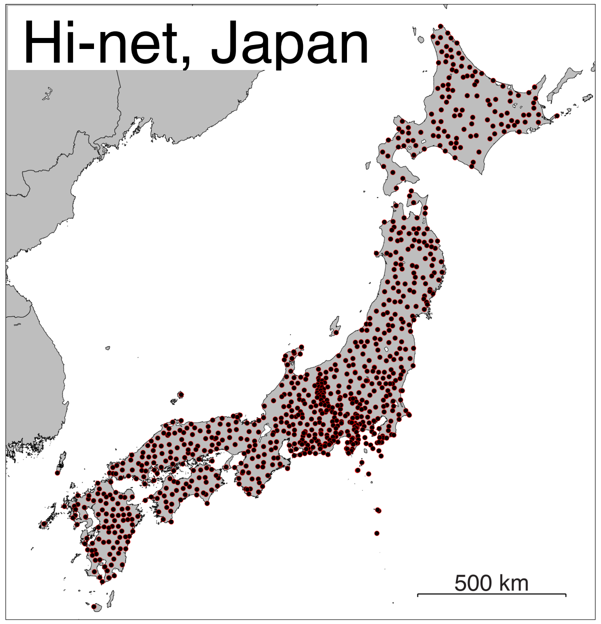


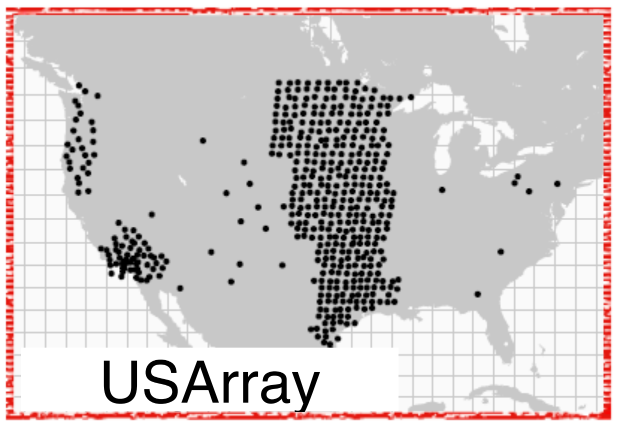
Variety of seismic sources

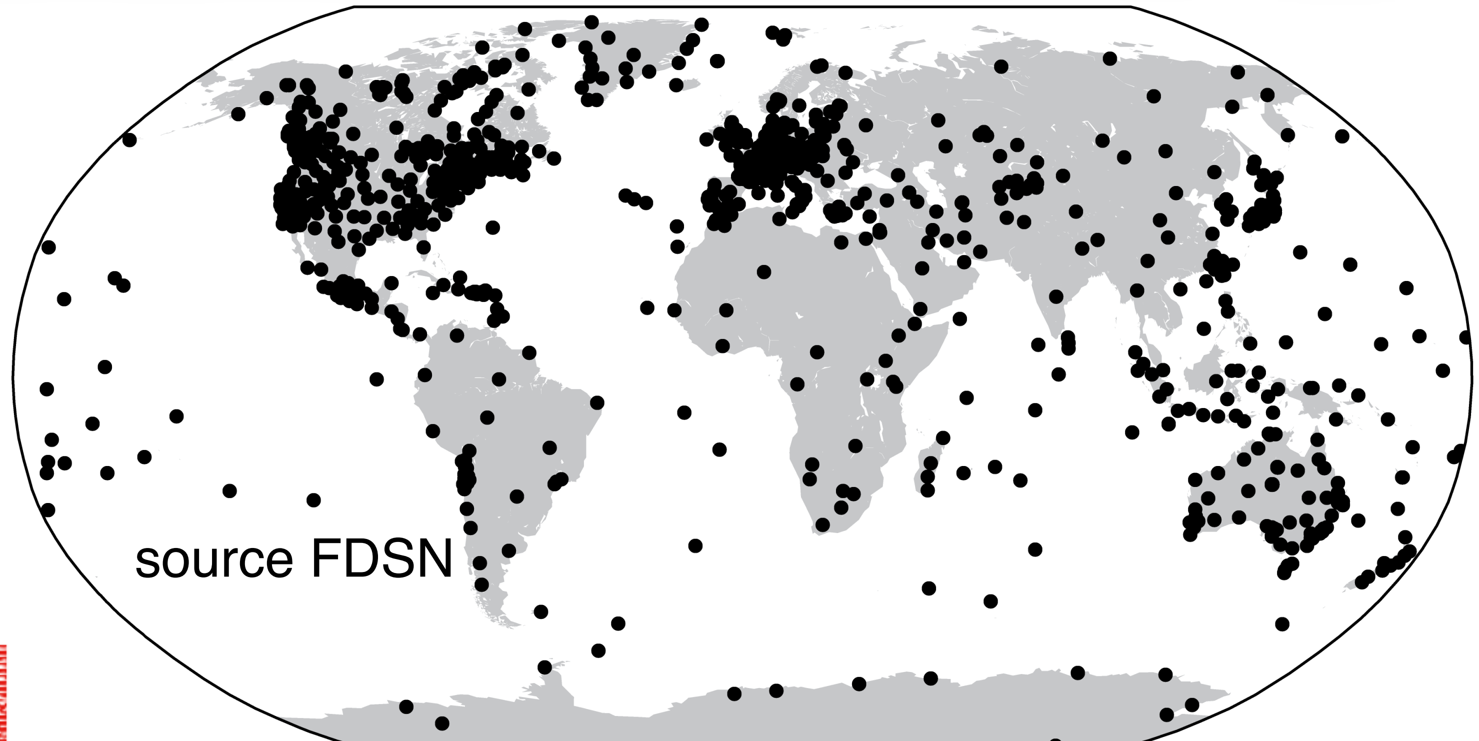
Wide range of space and time scales

Accurate and detailed detection and location - important for understanding underlying processes

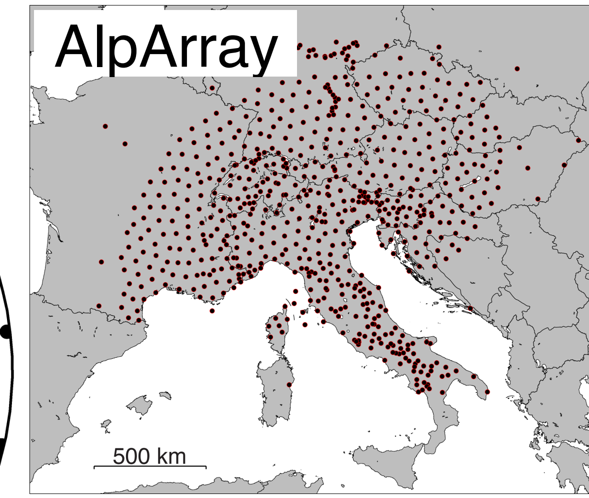
1. Motivation: Big data in seismology

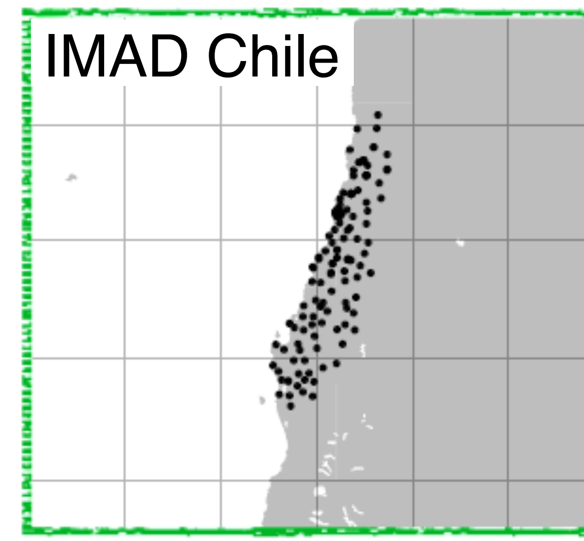






Global distribution of stations





Seismology has large datasets

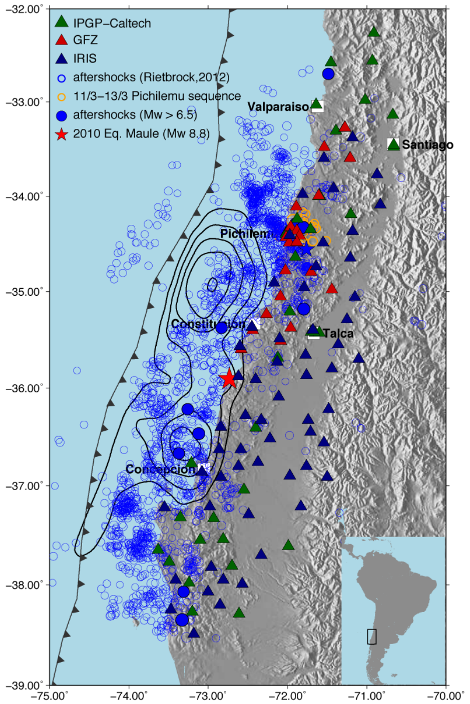
- Long duration
  - ~ 10 years of continuous waveform data
- Big networks
  - ~ 10^2 - 10^3 stations stations

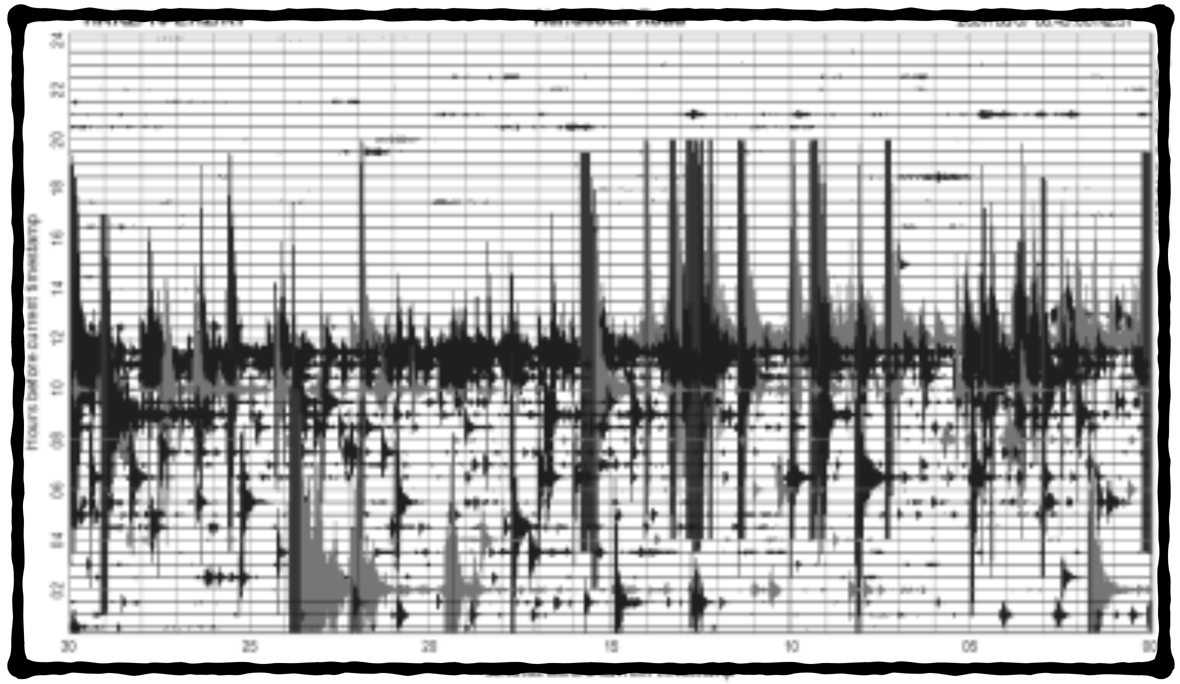
- The volume of data will definitely grow in the following years
- Schemes for efficiently extracting the information from large data volumes are needed

1. Motivation: Challenges for “classical” detection and location methods

Intense seismic activity: aftershocks, seismic swarms, volcanic eruptions

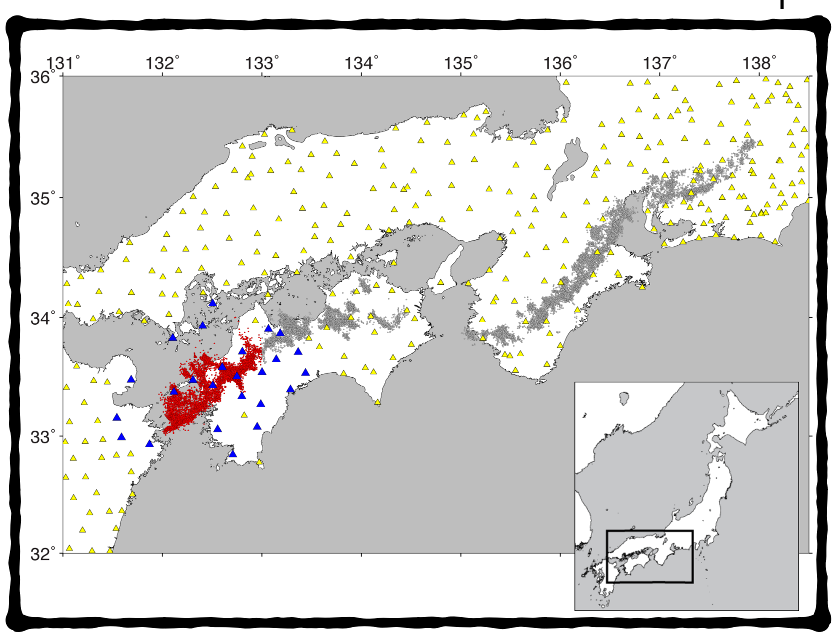
Aftershocks of 2012 Maule eq.

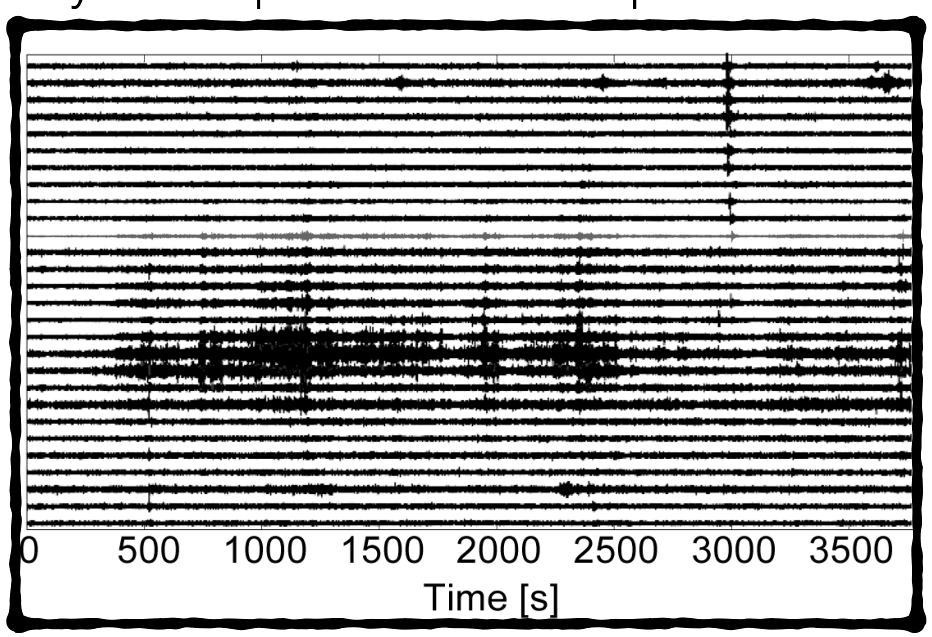


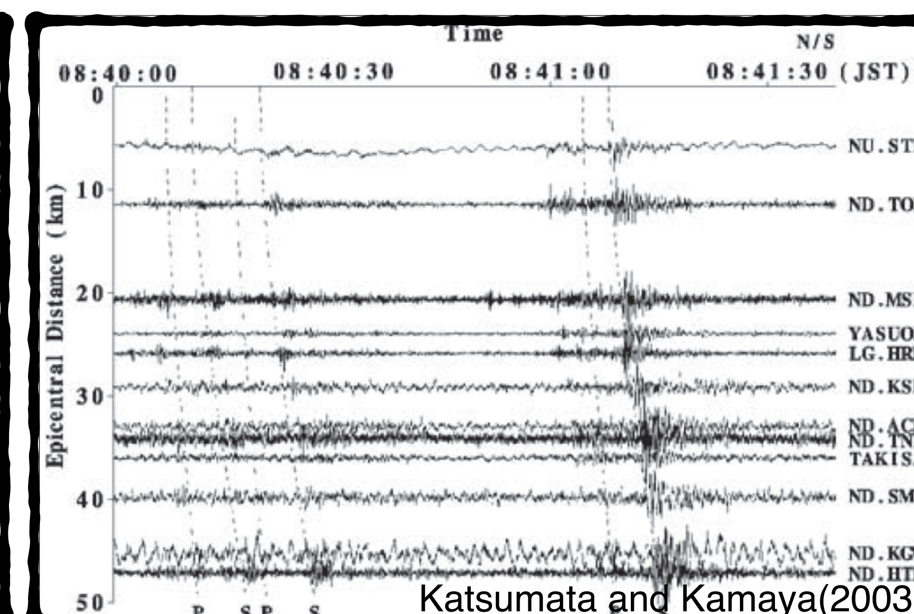


Events with emergent arrivals, mixed or weak signals

Tectonic tremor and low-frequency earthquakes in SW Japan

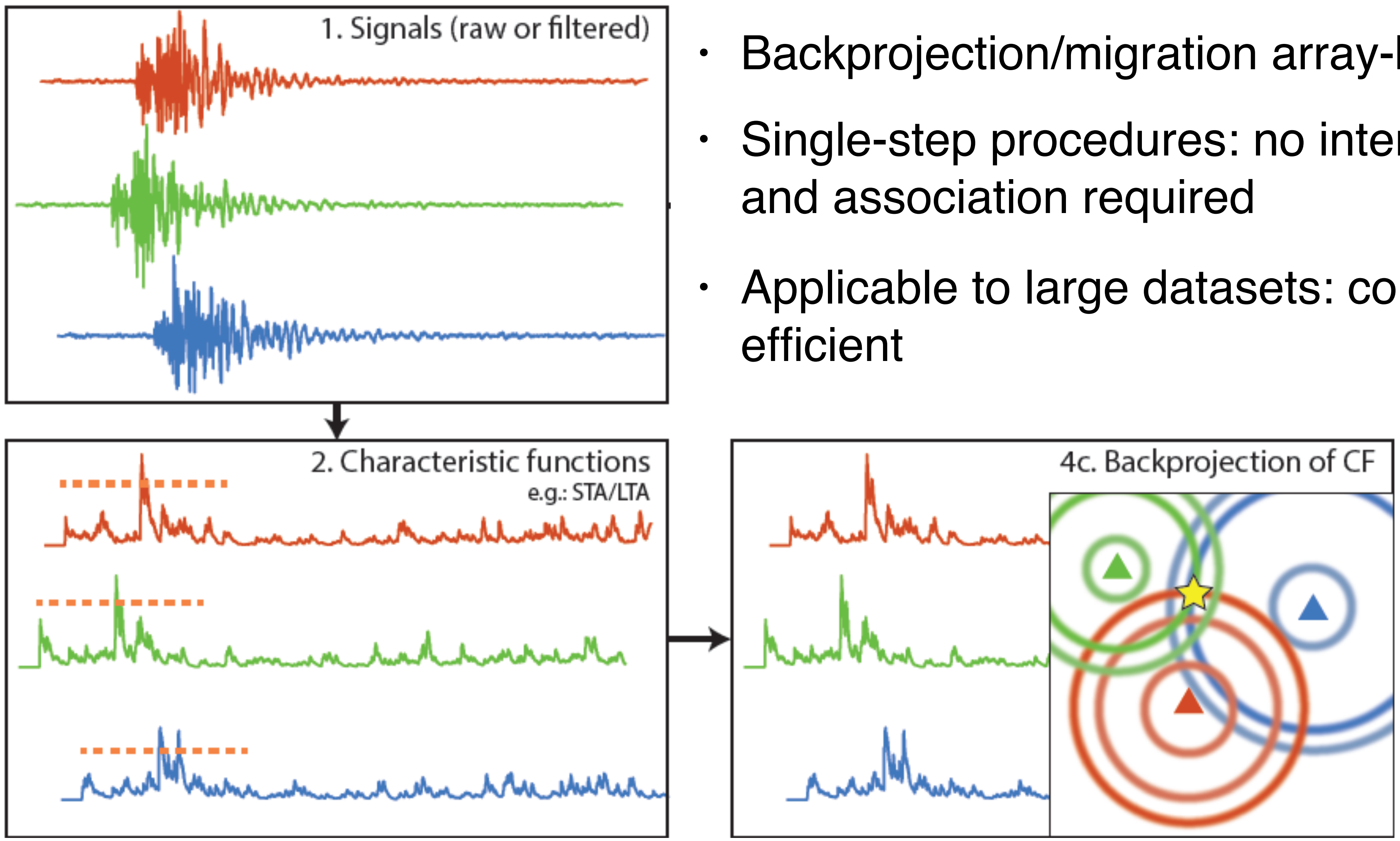






- Need for new detection and location methods that can address these issues

Automated detection and location schemes



- Backprojection/migration array-based methods
- Single-step procedures: no intermediate picking and association required
- Applicable to large datasets: computationally efficient

e.g.:
Kao and Shan (2004)
Drew et al. (2013)
Grigoli et al. (2014)
Langet et al. (2014)
Poiata et al. (2016)

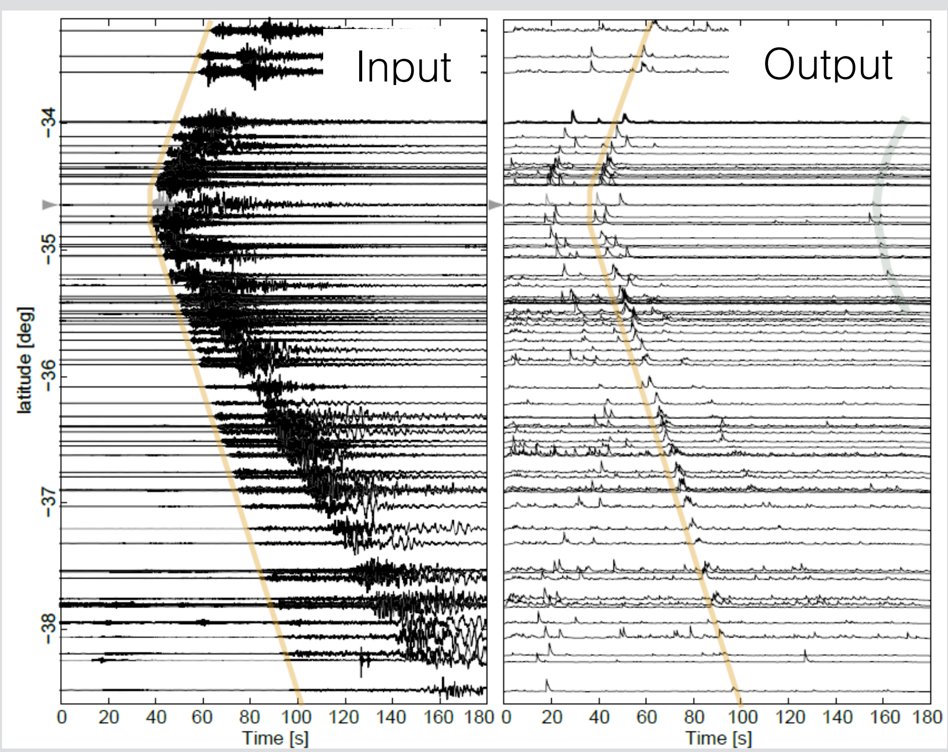
Multi-scale array-based detection and location scheme

- No intermediate picking and phase association required
- Applicable to large datasets and continuous data
- Computationally efficient

Back-Tracking the **B**road**B**and signal to the origin (seismic source)

Step 1: Signal Processing

Transforms signals to Characteristic Functions



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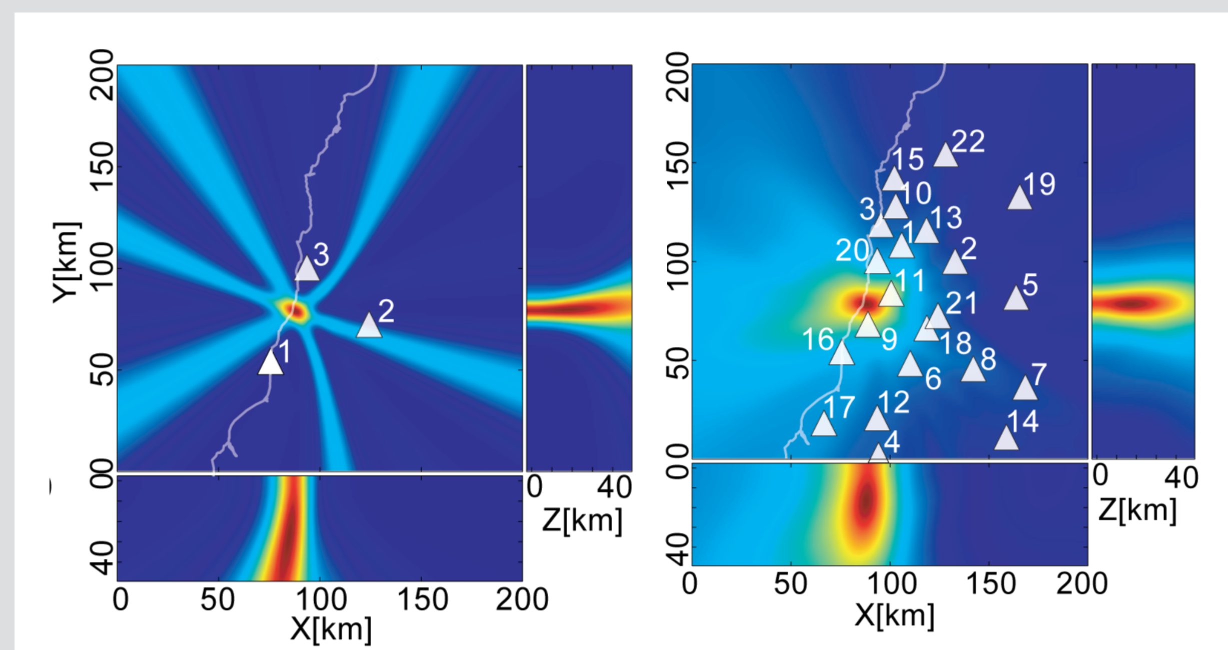
Step 2: Detection and location

Backprojecting station-pair time-delay estimates according to theoretical time-delays

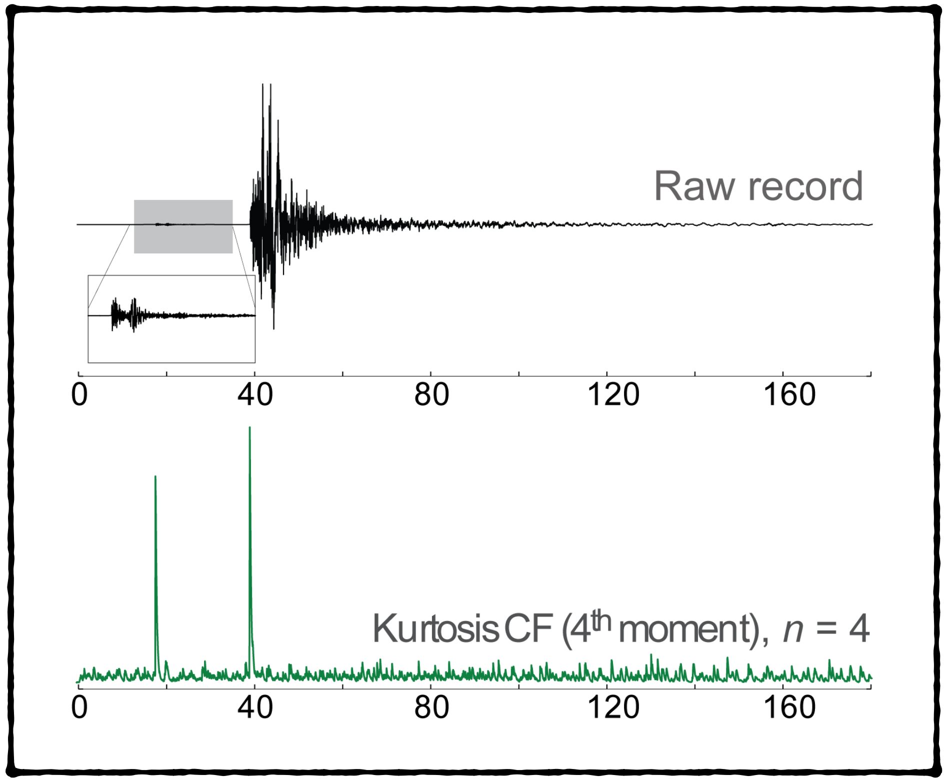
Exploiting coherence across the stations



Step 1. Signal processing - signal's Characteristic Functions (CFs)

- Higher-Order Statistics (HOS)

$$CF_{HOS}(t) = \frac{E[(u(t)-\mu)^n]}{(E[(u(t)-\mu)^2])^{n/2}} = \frac{\mu_n}{{\mu_2}^{n/2}}$$

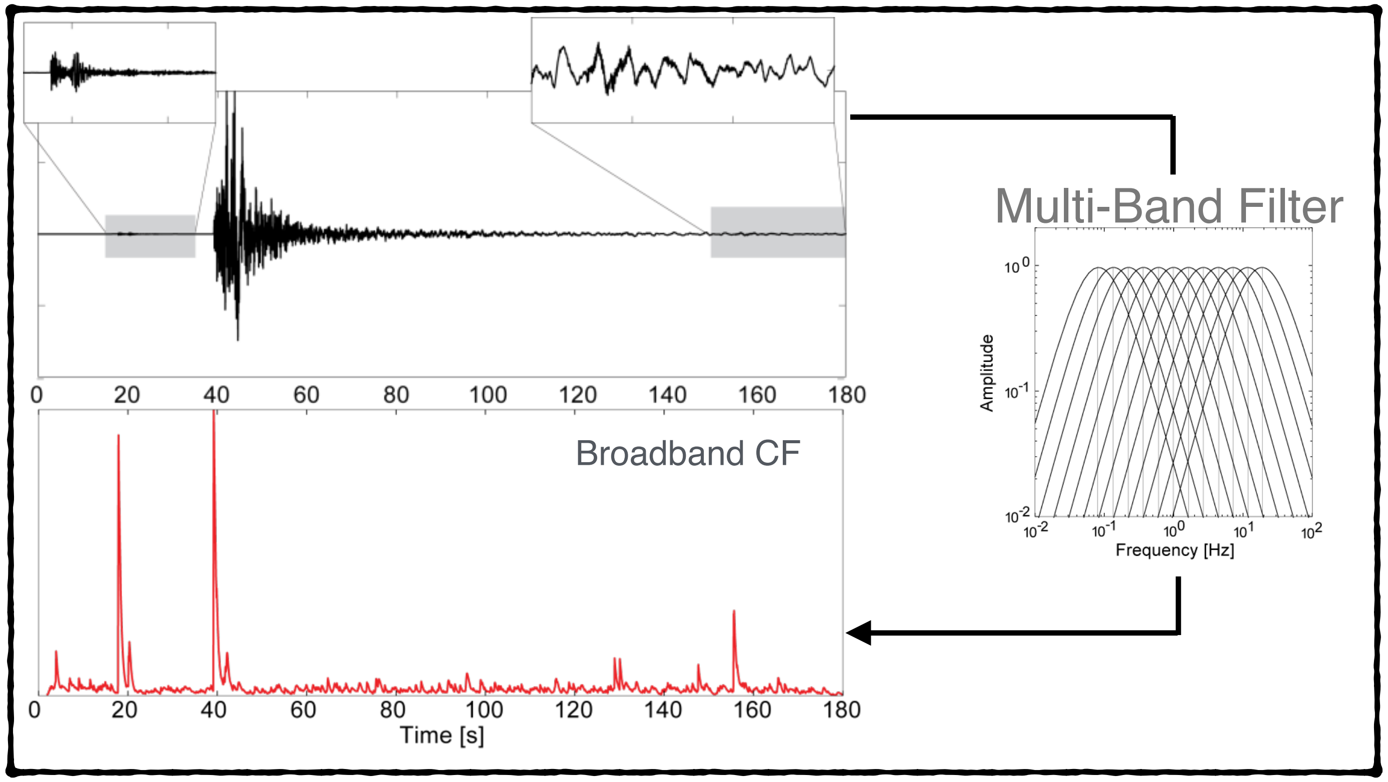


Detects changes in signal's statistics

Efficient for short transient and impulsive events:
earthquakes, low-frequency eq.

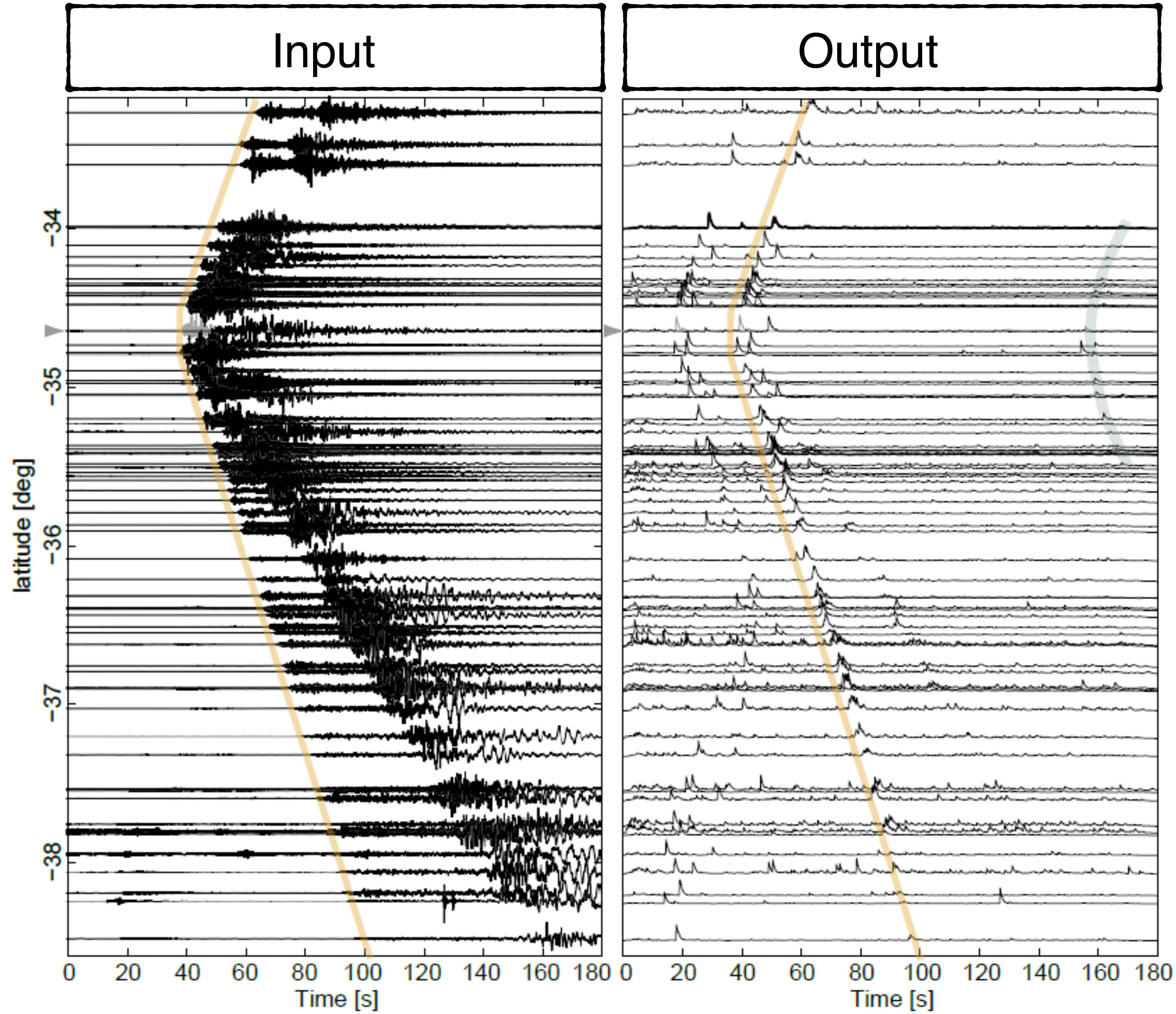
Other characteristic functions can be included

- Time-frequency analysis & broadband CF



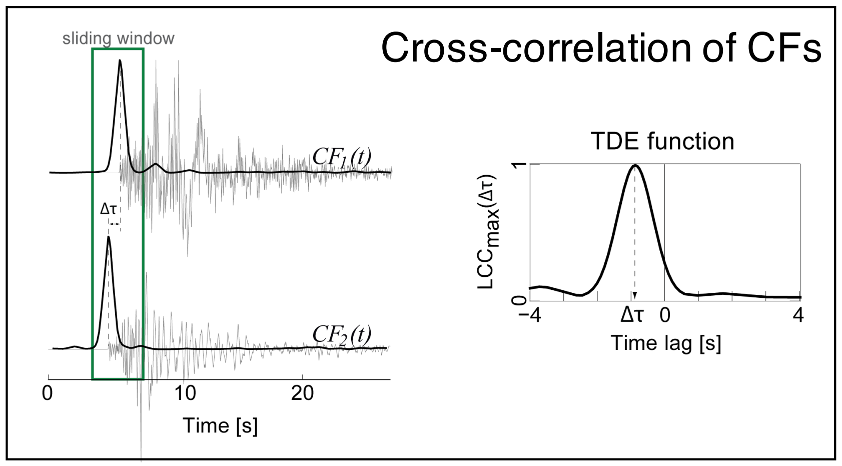
An efficient way to extract narrow-band signals hidden in noise

Step 1. Signal processing - signal's Characteristic Functions (CFs)

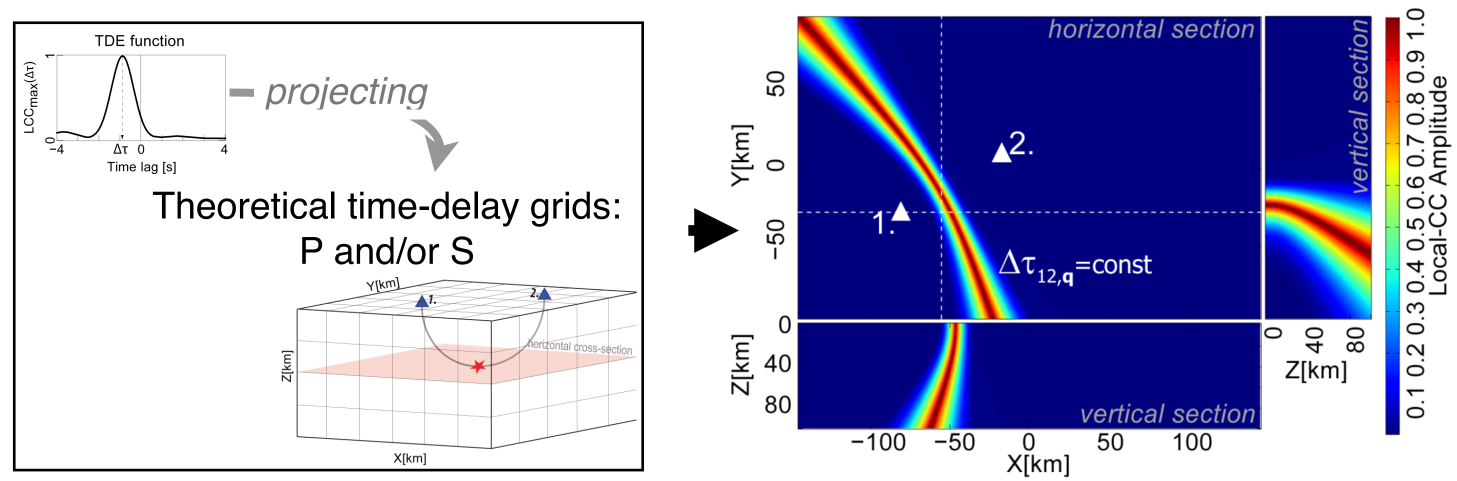


Step 2. Detection and location scheme

Measurement: Time Delay Estimate (TDE)

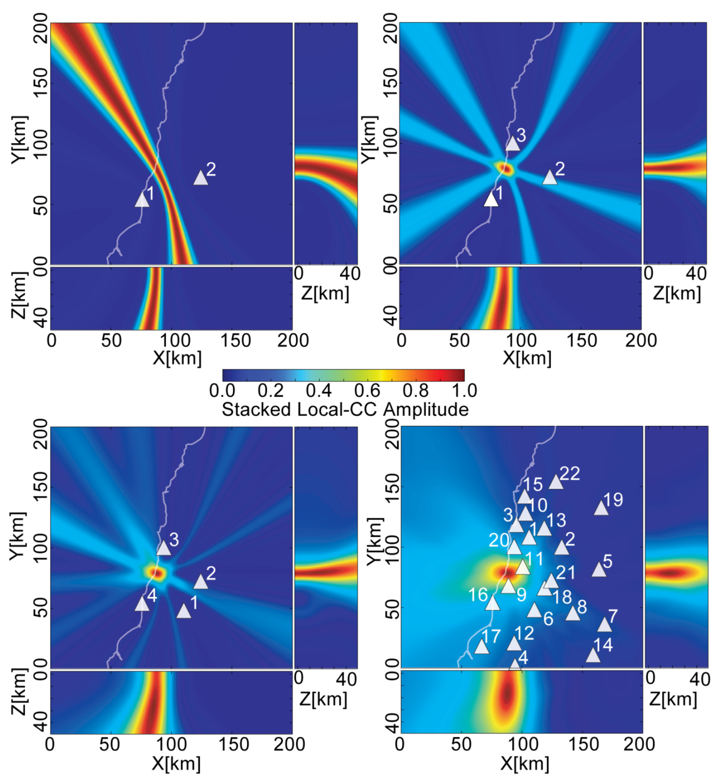


Mapping TDE functions - Spatial Likelihood Functions (SLF)

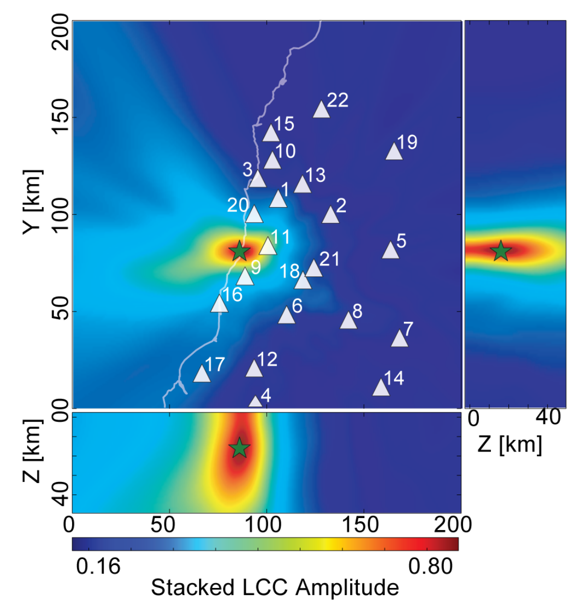


No explicit grid-search (win in speed)

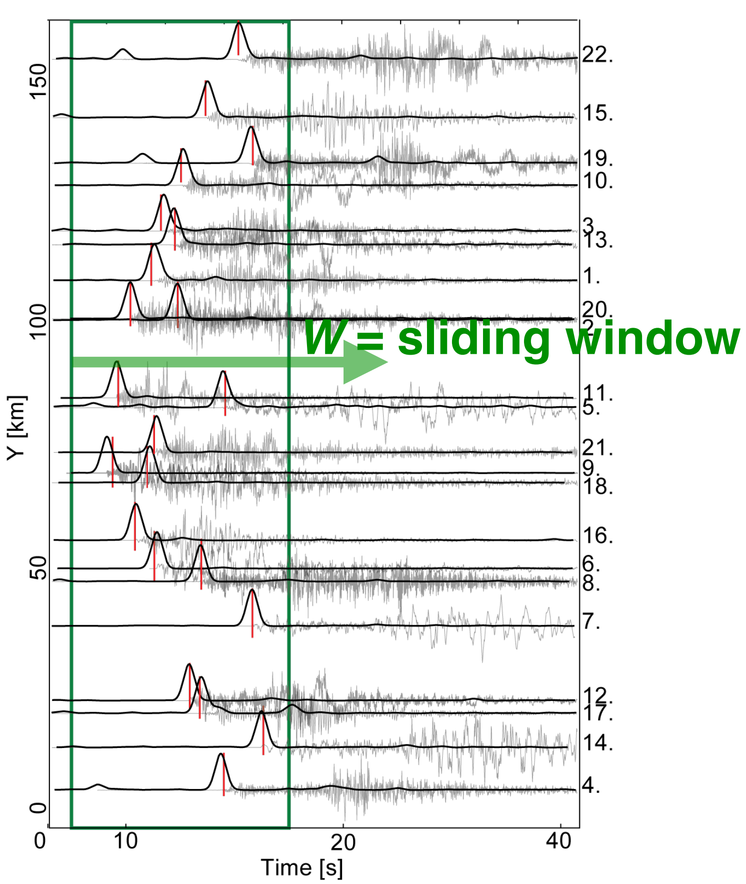
Array-based imaging - summing pairwise SLF



Detection and location - Triggering



Maximum likelihood location of the source (X, Y, Z, T0)



Tectonic tremor sequence in western Shikoku (Japan)

- automatic location of low-frequency earthquakes

Crustal seismicity in SE Romania

- 2013 seismic swarm of Galati - case of potentially induced seismicity

Preparatory phase of 2014 Iquique earthquake (Chile)

- analysing foreshock activity of the earthquakes (~ 1 year of data)

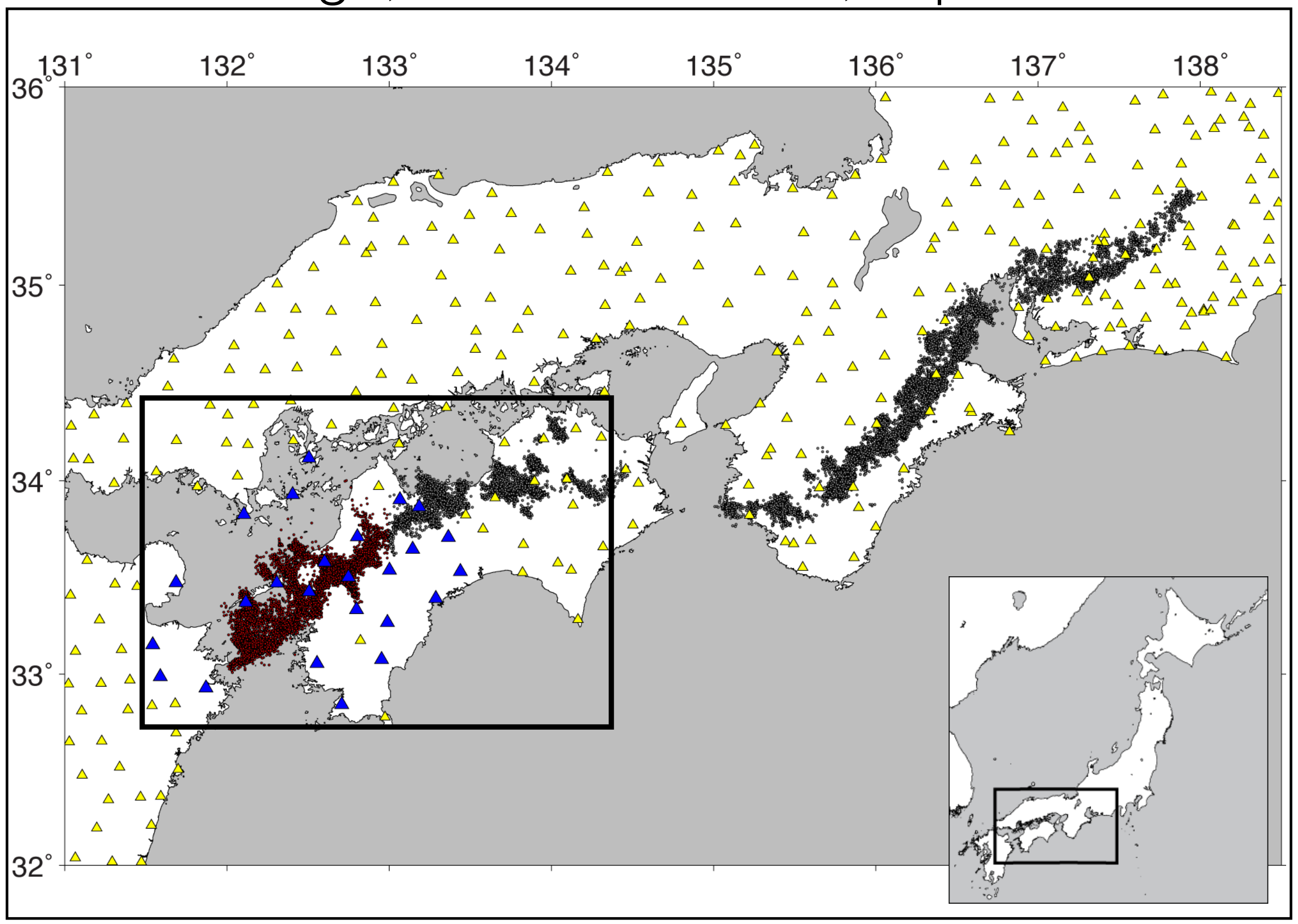
(Aden-Antoniow - PhD student IPG Paris)

3. Application examples: Imaging tectonic tremor activity

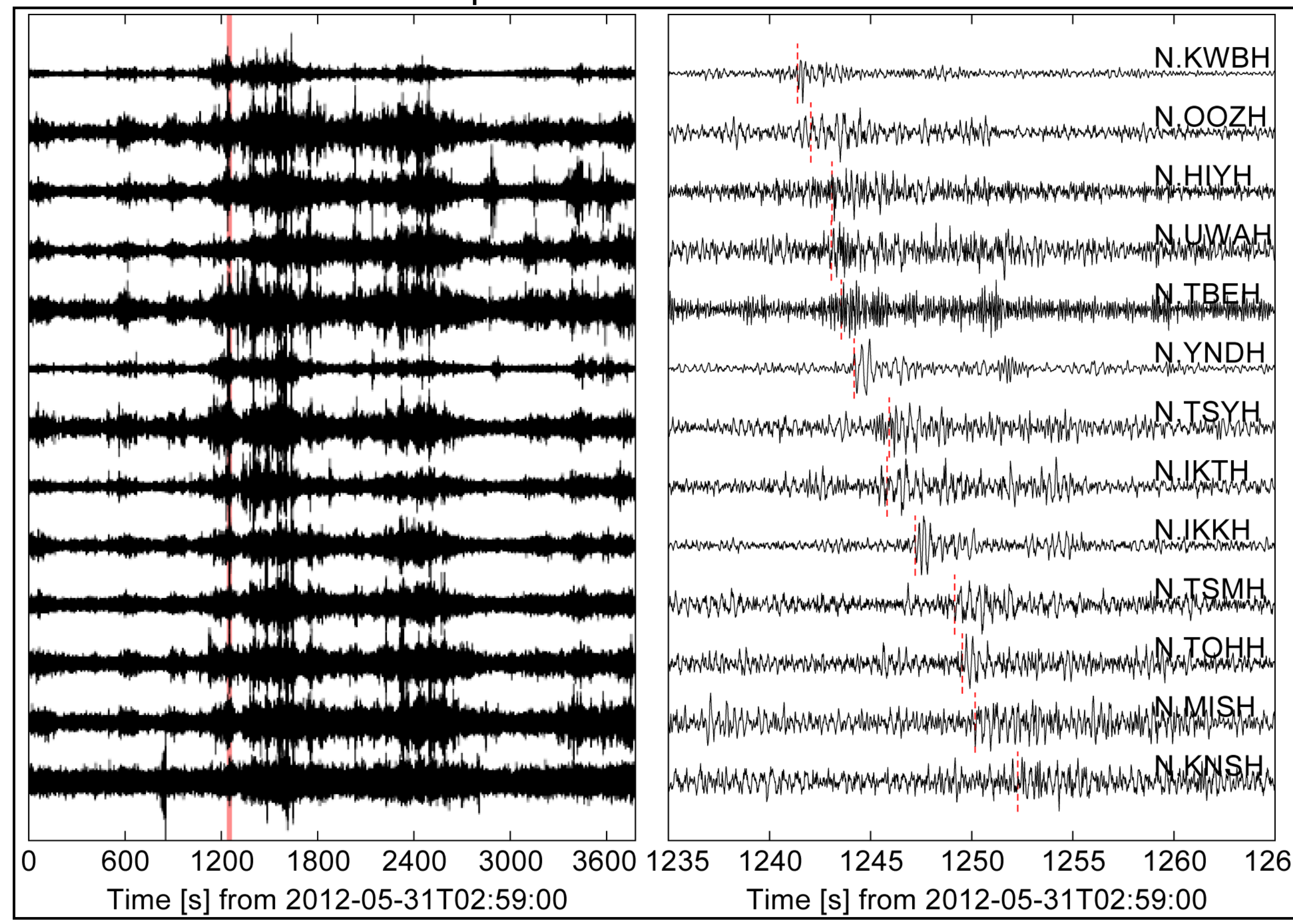
Collaboration with IPGP, France & ERI, Japan

Study area and data

Nankai trough, western Shikoku, Japan



Tectonic tremor episode & Hi-net stations



Tectonic tremor | Low-frequency earthquake

Data:

- 9-day tectonic tremor sequence (2012/05/25-2012/06/02)
- 22 Hi-net stations

Existing catalogs:

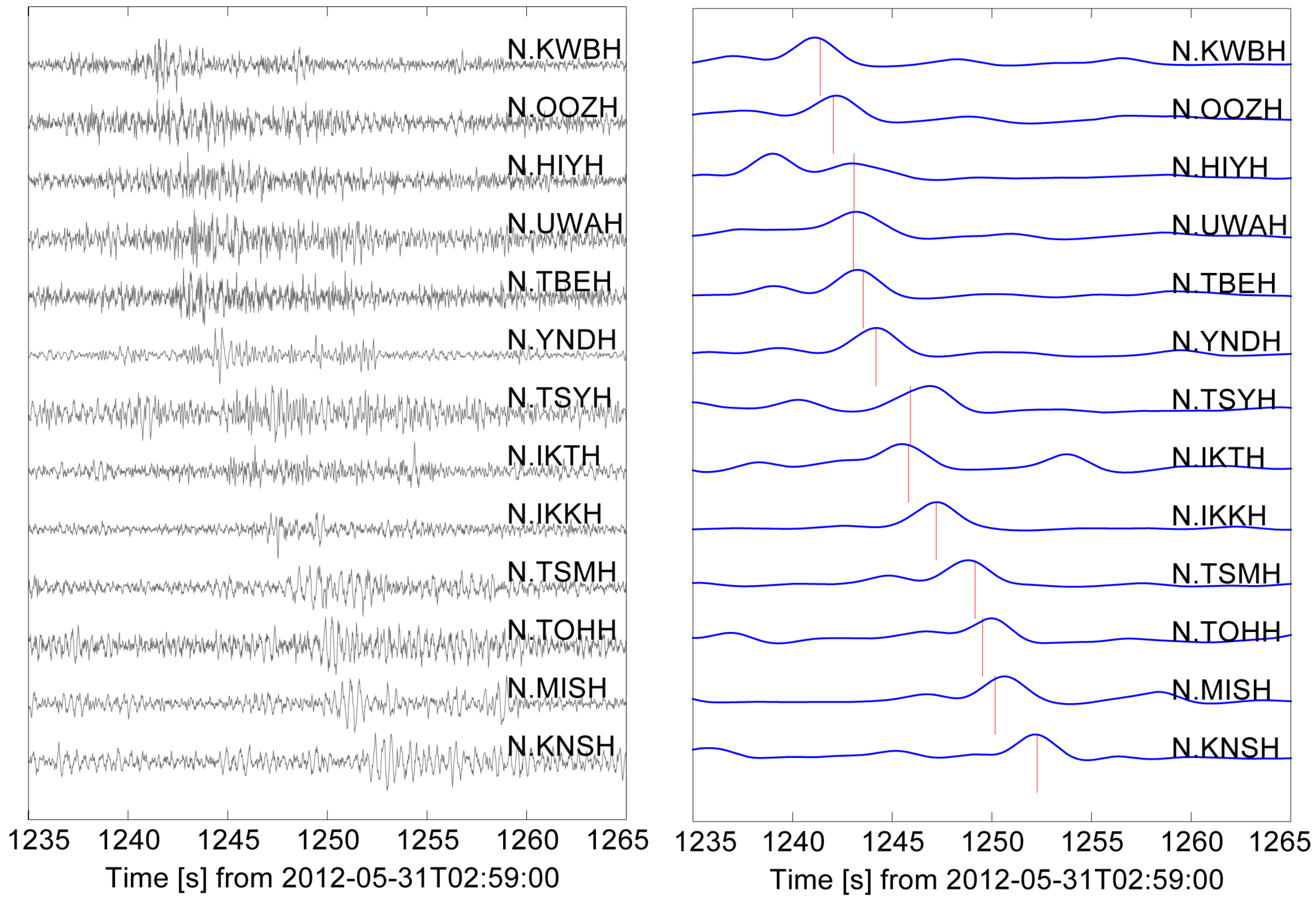
- JMA catalog - manual picking & template events catalog (not available)

Main goal:

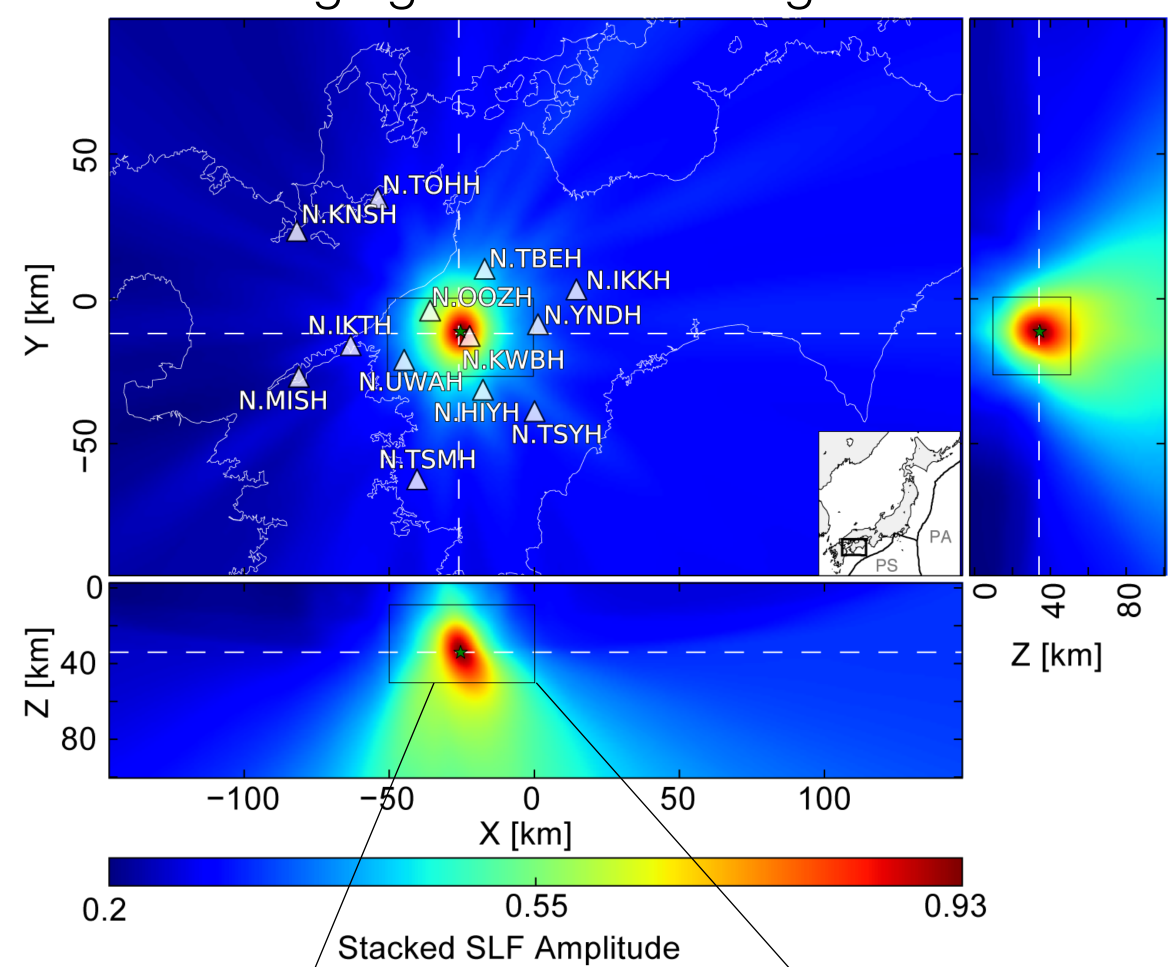
- Performance of BackTrackBB in automatic detection of low-frequency earthquakes

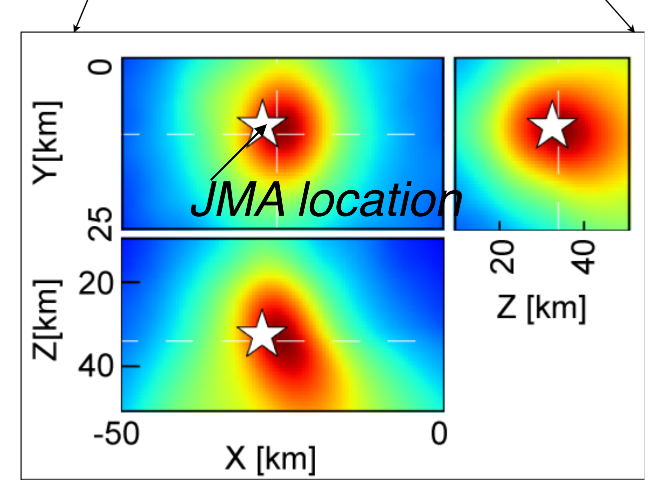
- Detection and location of low-frequency earthquakes

Recorded waveforms · Broadband kurtosis CFs



SLF imaging function for single LFE





Comparison with JMA catalog

Continuous data (9 days)

Horizontal components (EW & NS)

2.0-15.0 Hz filter-bank frequency range

Kurtosis HOS CF (25 sps)

S-wave assumption; 1-D velocity model

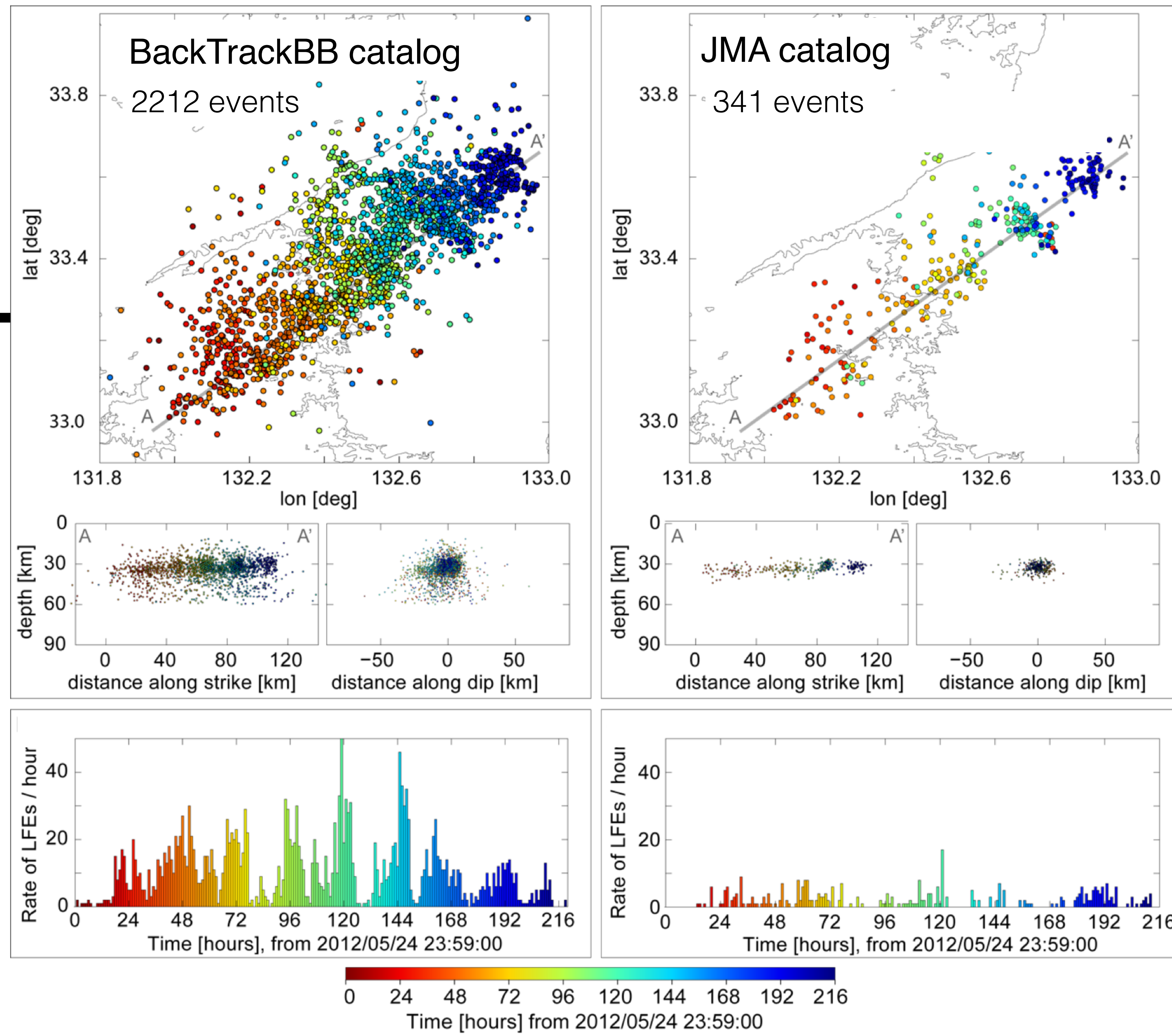
Fully automatic analysis

3. Application examples: Imaging tectonic tremor activity

- Detection and location of low-frequency earthquakes

Results: Comparison with JMA catalog

automatic *S*-wave locations (no template requirement)



manual *S*(&*P*)-wave locations

- 2212 events detected (341 in JMA catalog)
- 89% of JMA events located
- clear migration and space-time clustering

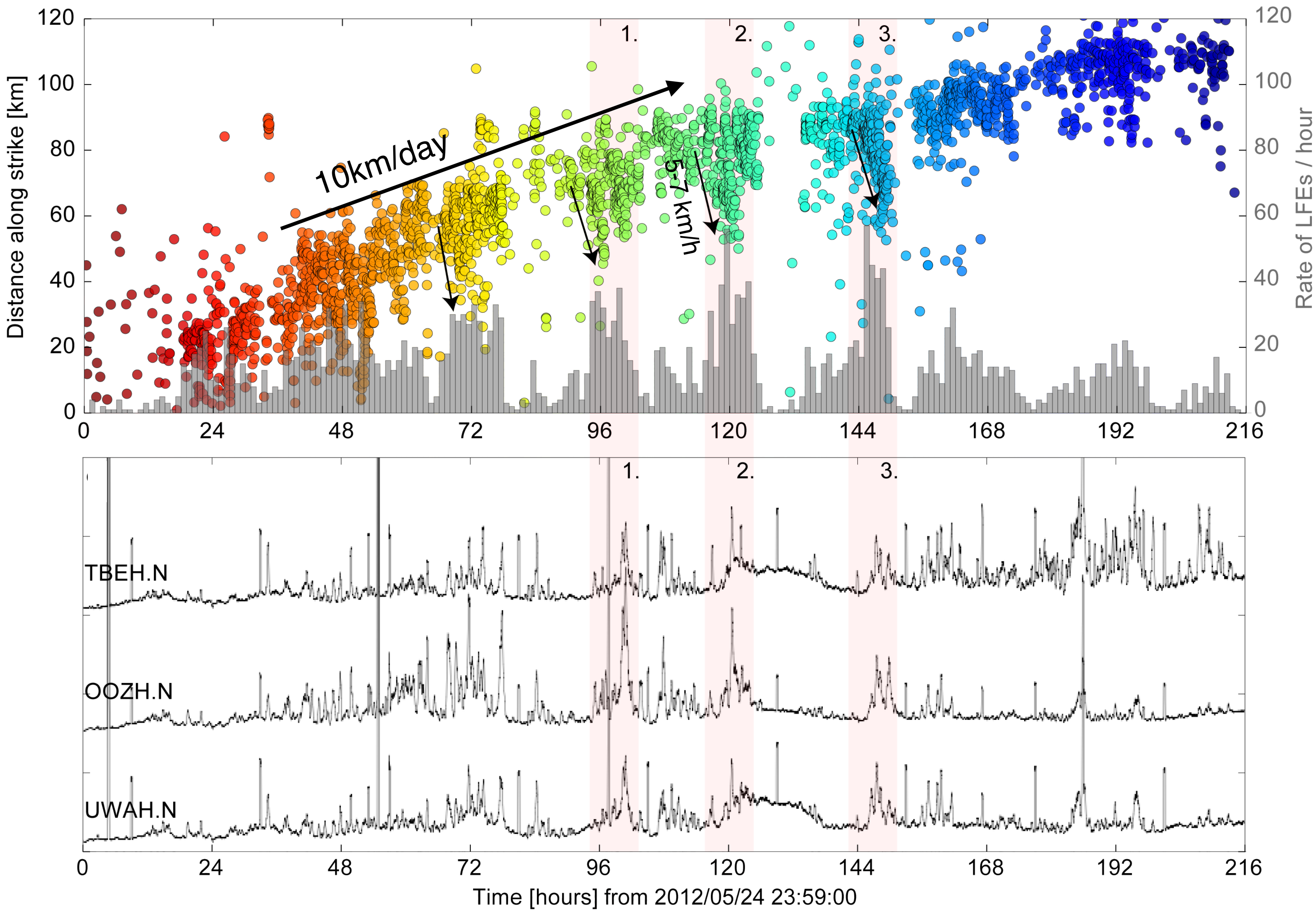
3. Application examples: Imaging tectonic tremor activity

Results: Space-time evolution and clustering of activity - highly complex features

- Migration patterns: slow along strike ~ 10km/day
  rapid reverse-strike ~ 5-7 km/h
- Tidal influence

→ Complexity of underlying processes

Influence of structural context

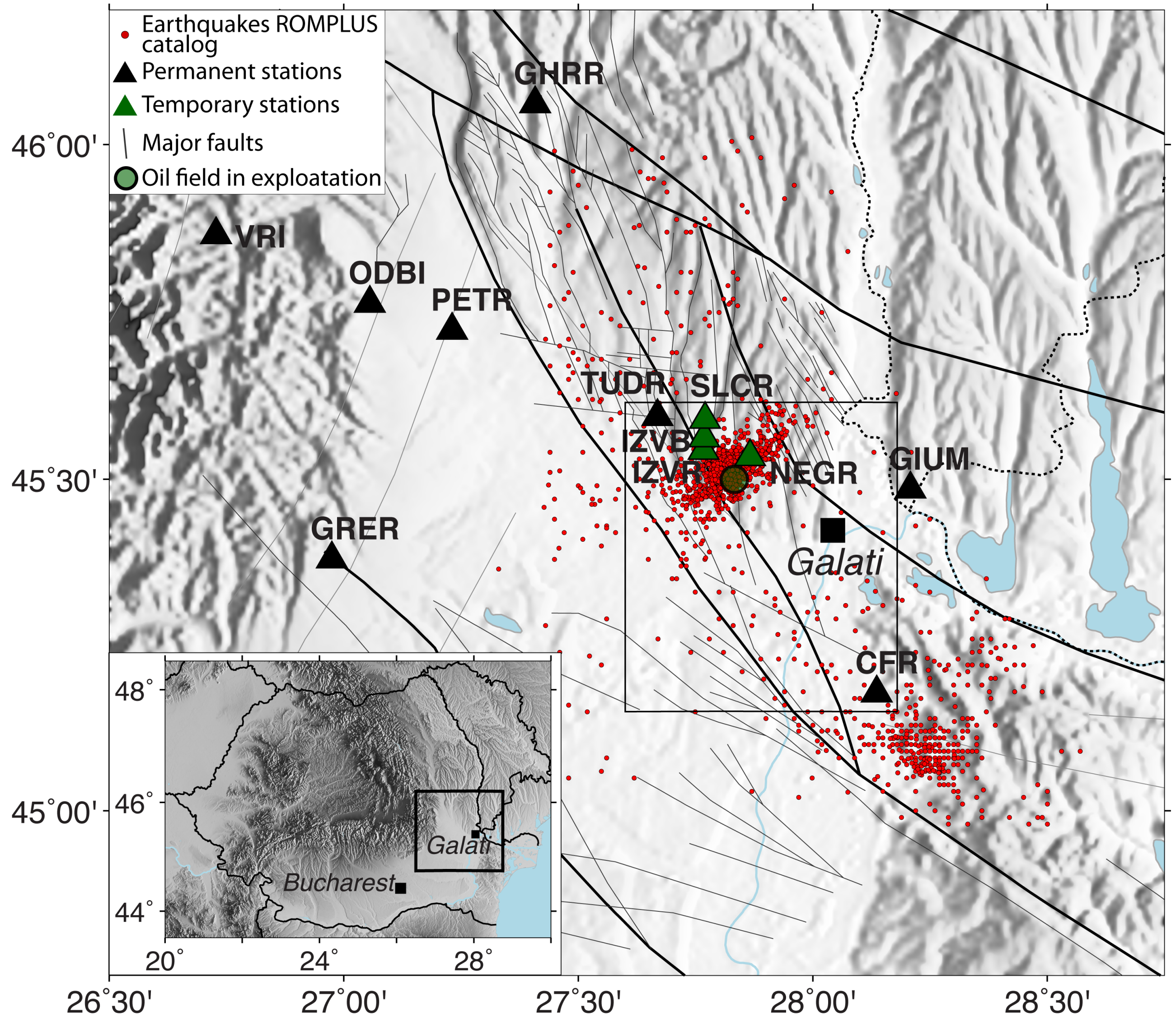


3. Application examples: Crustal activity in SE Romania

Collaboration with INFP, Romania

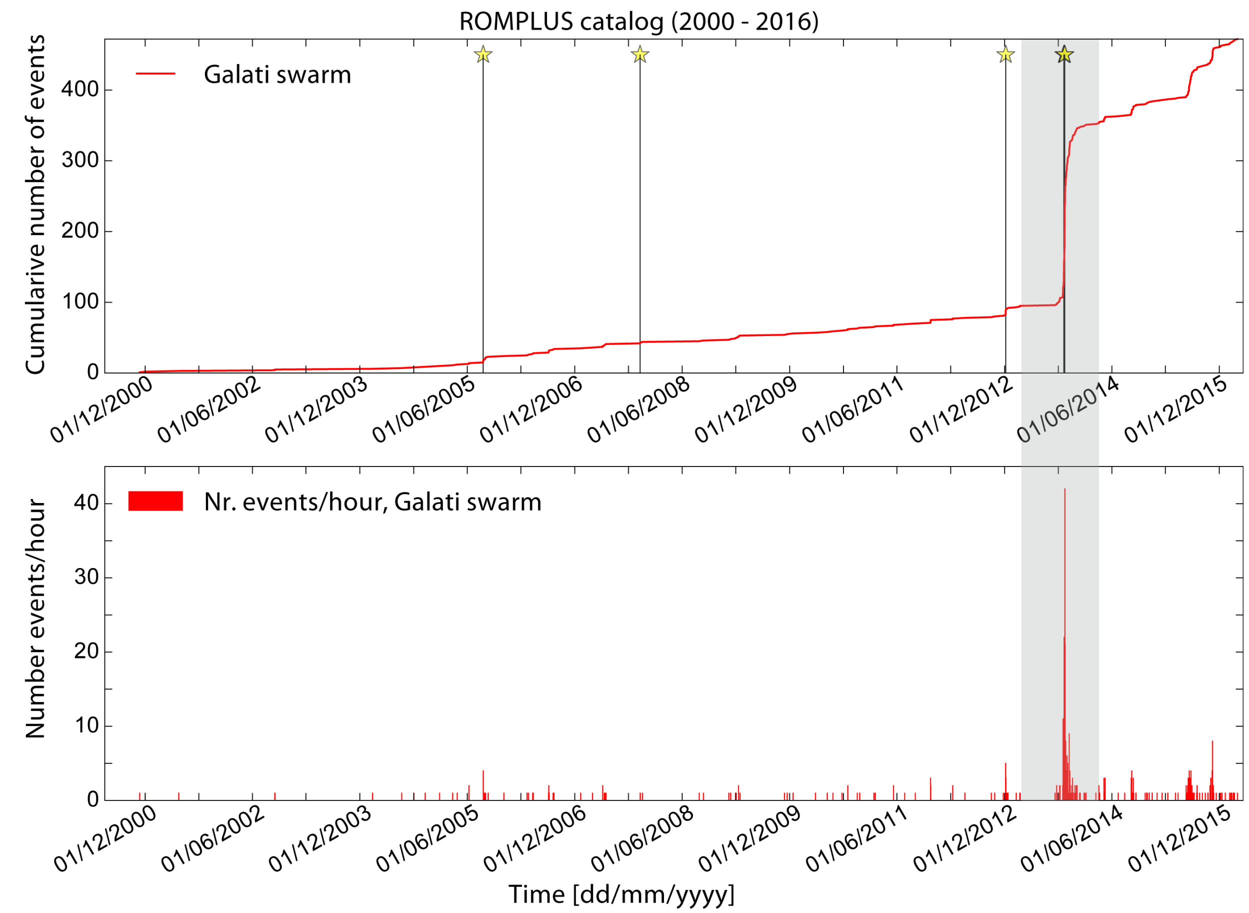
- 2013 Galati seismic swarm

Potential case of induced seismicity ?



Seismic swarm activity:

- 2 month period: Sept. 2013 - Nov. 2013
- M_L = 0.1 - 4.0



Main goals:

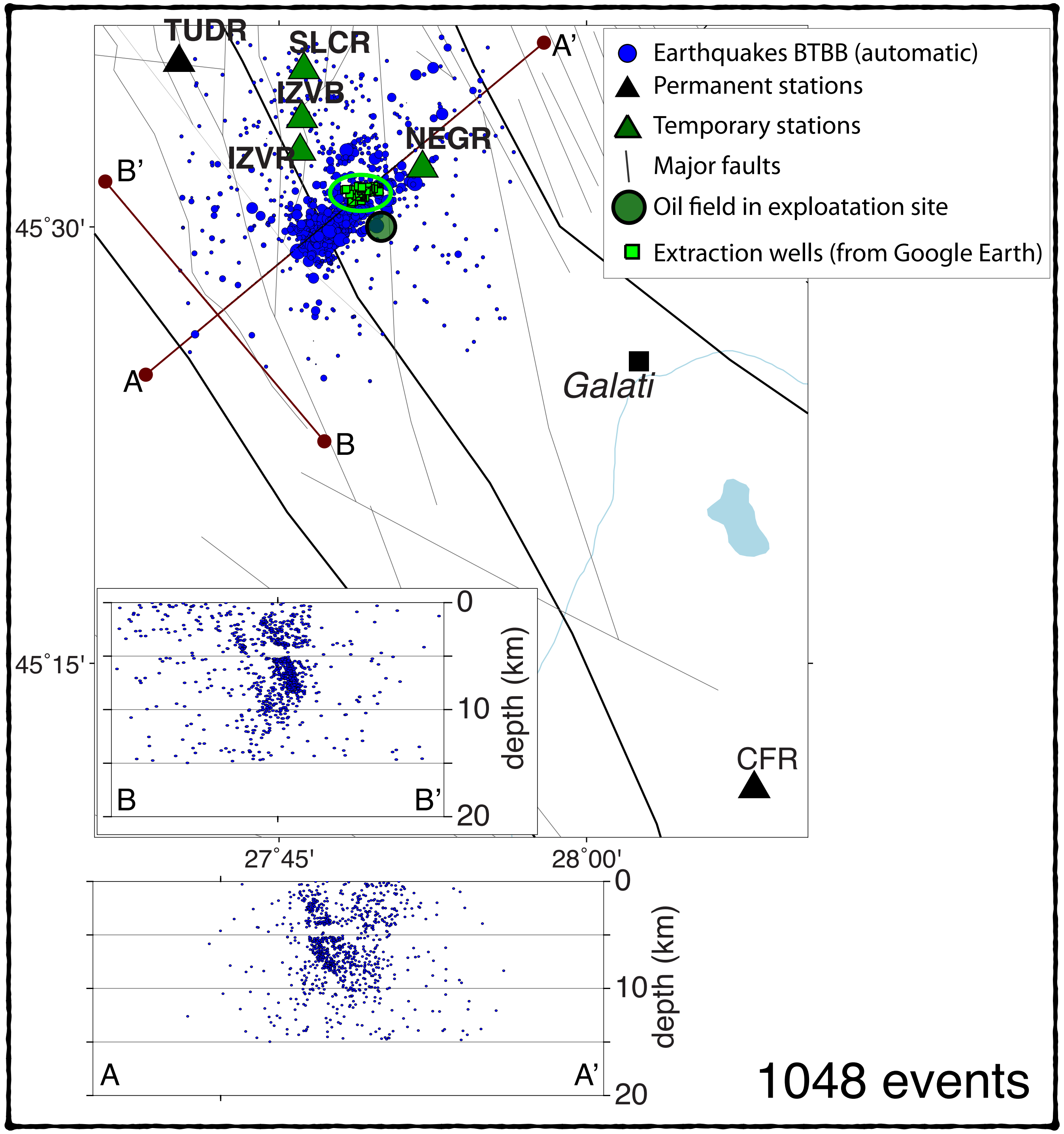
Performance evaluation

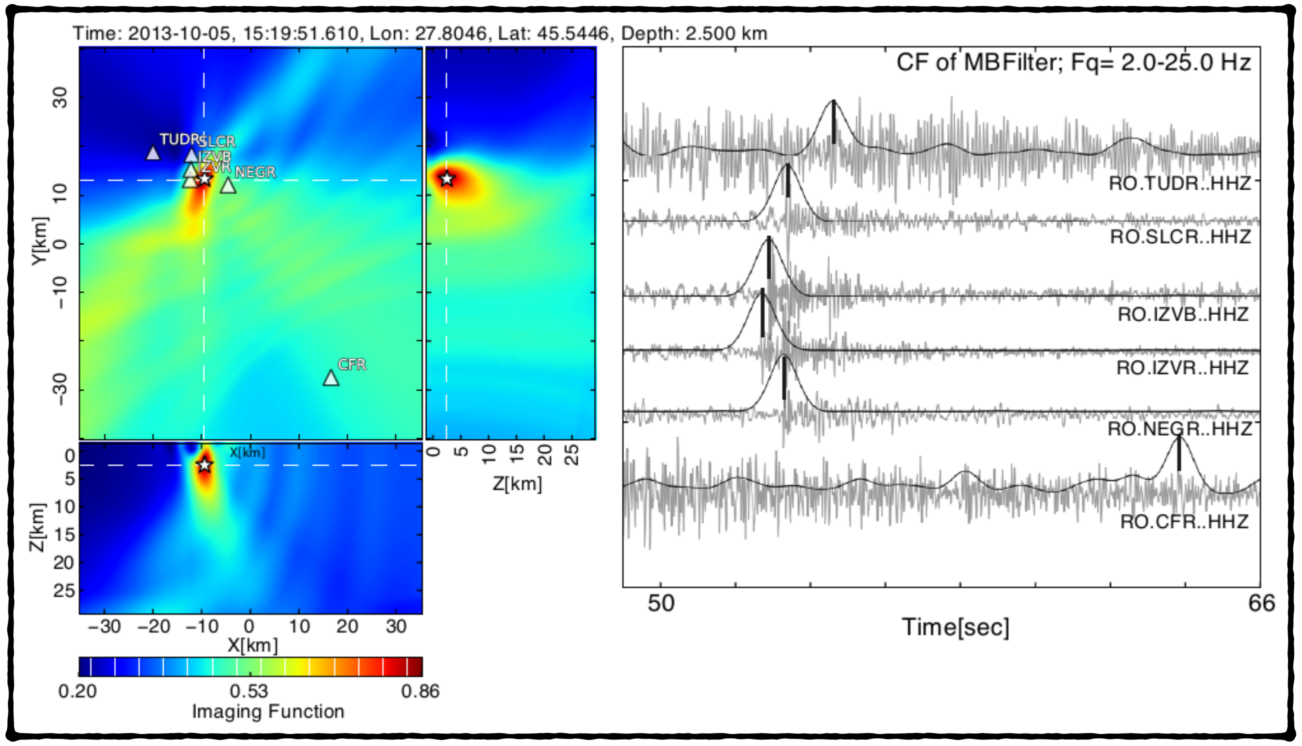
Comparing fully automatic catalog with manually (re)located events

Evaluating monitoring capabilities

3. Application examples: Crustal activity in SE Romania

- 2013 Galati seismic swarm: results of automatic analysis with BackTrackBB





Settings:

1-D local velocity model

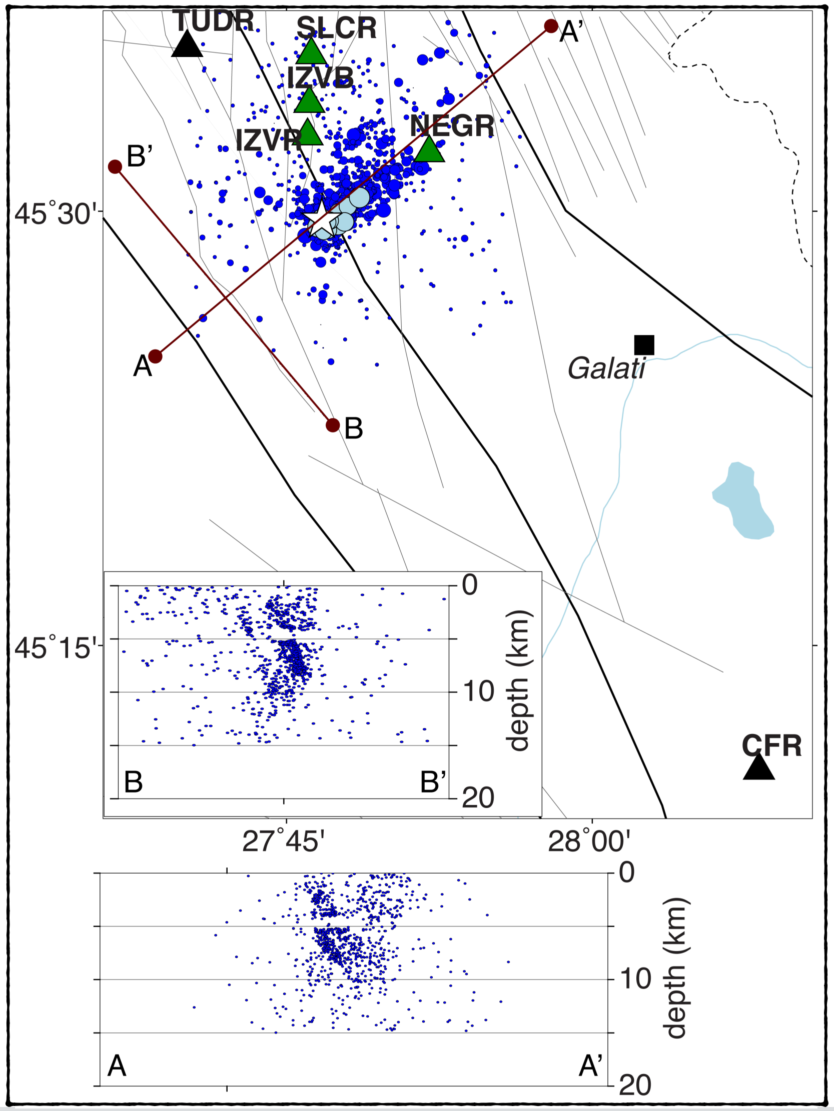
Data: UD components, 6 near-field stations

P-wave only

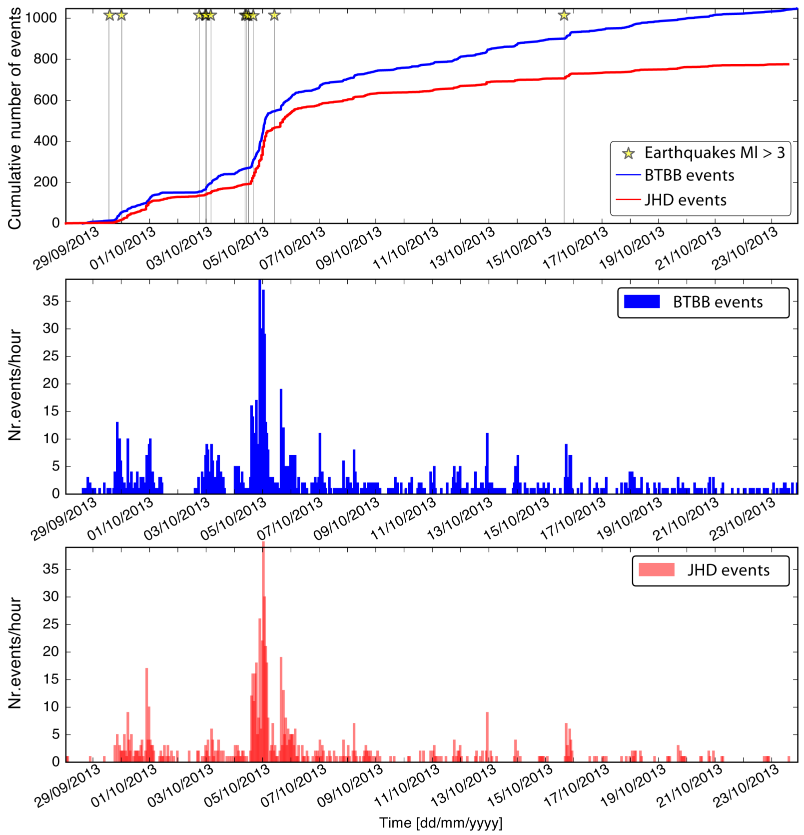
continuous records > 1 month

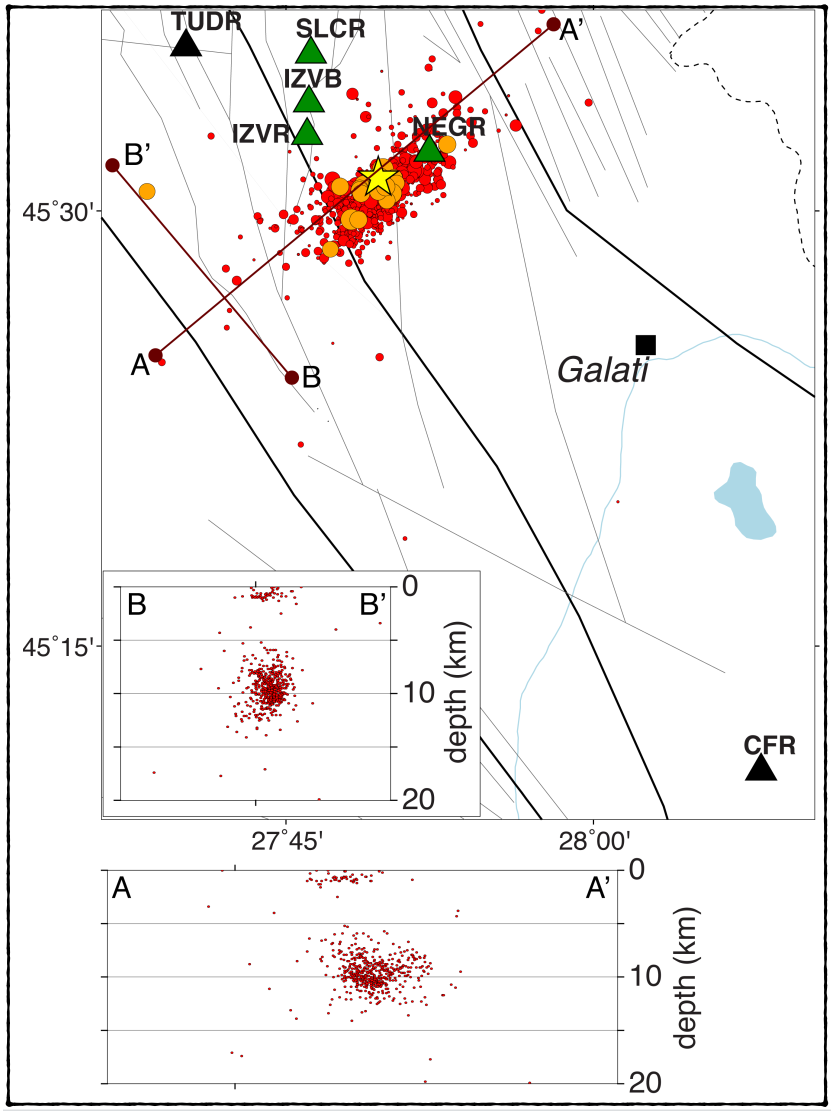
3. Application examples: Crustal activity in SE Romania

- 2013 Galati seismic swarm: results of automatic analysis with BackTrackBB



Automatic BTBB locations (P only) (preliminary results) - 1048 events



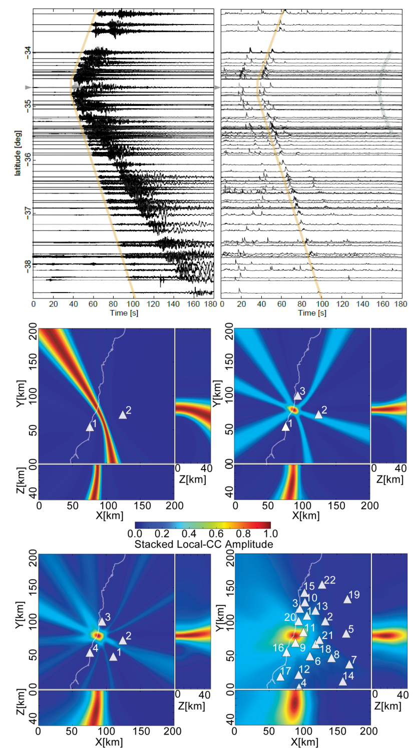


JHD, with manual picks (P&S) Popa *et al.* (2015) - 704 events

- 4 days to process (parallel mode on 12 processors) > 1 month of data
- Temporal evolution - recovered well
- Potential for a fully automatic monitoring of seismicity in the area

4. Concussions

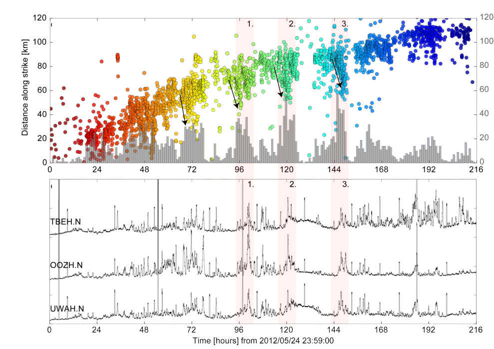
Increasing volumes of seismological data require new methods



Methods using advance signal processing and exploiting coherency of signal’s feature across stations can be very efficient in providing details features of seismic activity

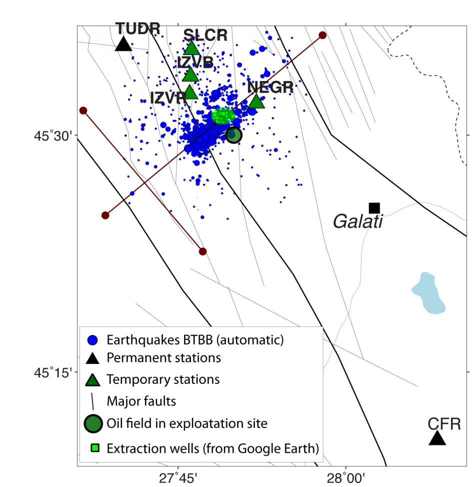
BackTrackBB:

- Array-based automatic method applicable to (dense) networks and continuous data
- Computationally efficient (parallel capabilities)
- Suitable for small-amplitude signals and complex activity
- Not requires preliminary information about the seismic sources (templates)



Application to detection of low-frequency earthquakes in Japan:

- Detailed catalog of LFEs (~2212 events in 9 days of activity)
- Complex space-time patterns (clustering, migration, tidal modulation)
- Potential for monitoring tremor activity through LFEs



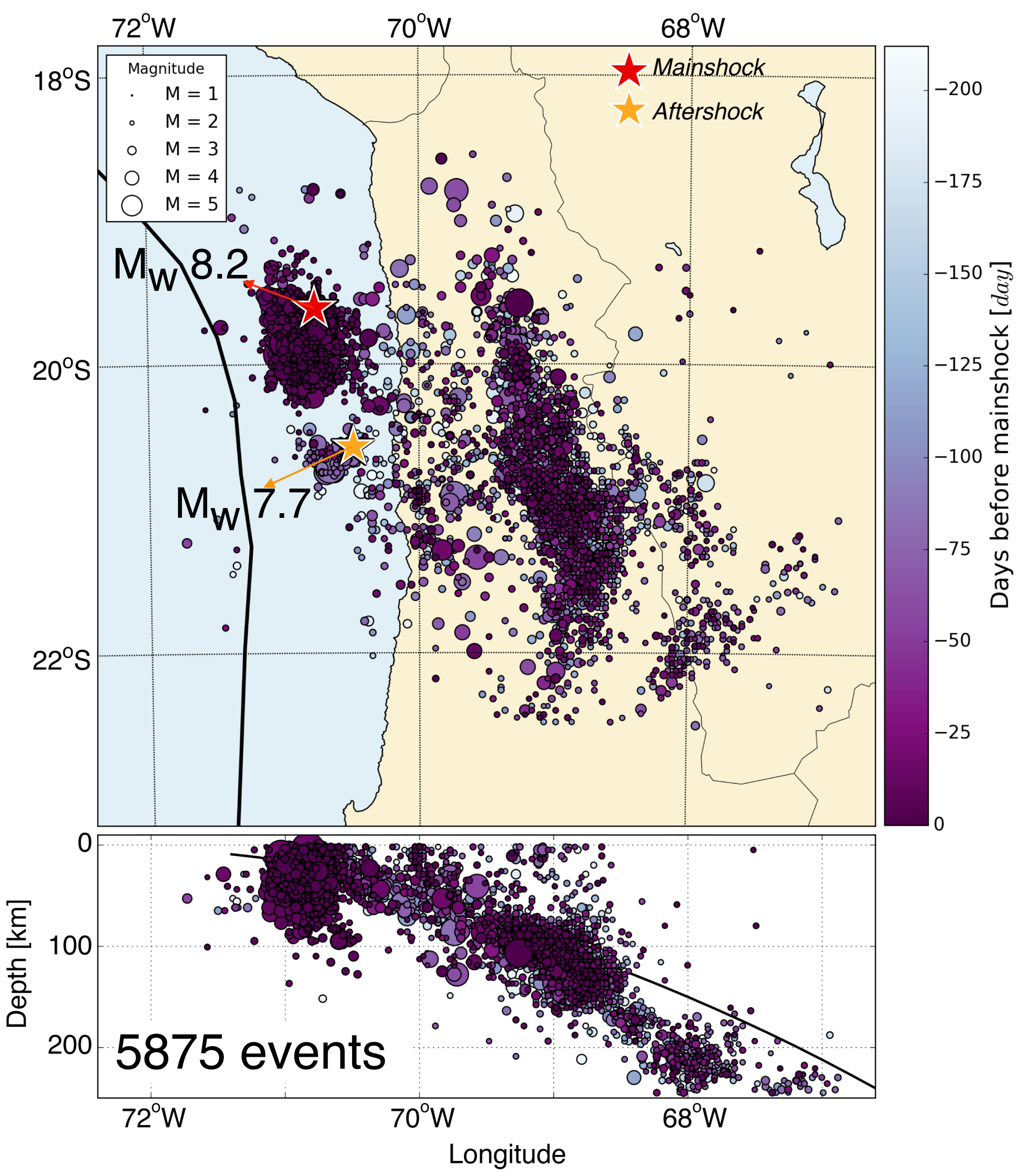
Application to seismic swarm in Romania:

- Good recovery of temporal seismicity pattern
- Potential for development of automatic monitoring system in the area (ongoing)

Thank you!

Collaboration with IPGP, France

The preparatory phase of 2014 Iquique earthquake (N. Chile)



Aden-Antoniow et al. (in preparation)

BackTrackBB detection and location scheme:

- 11 stations (3-components)
- Continuous data - 7 month period
- Combined P & P-S location (polarization analysis)

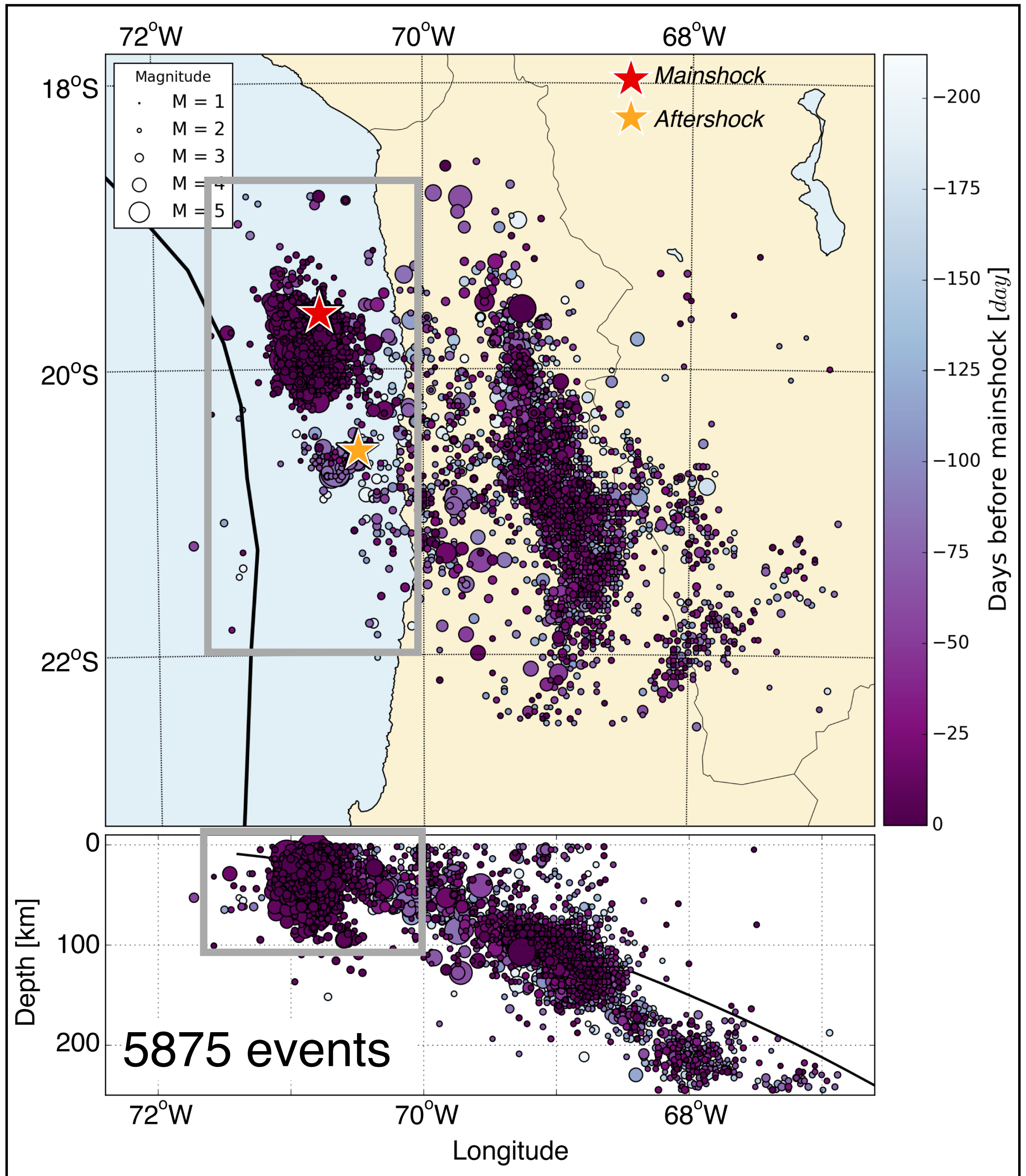
2-D local velocity model

Strict selection of events - removal of outliers

Event catalog September 2013 - March 2014

Collaboration with IPGP, France

The preparatory phase of 2014 Iquique earthquake (N. Chile)



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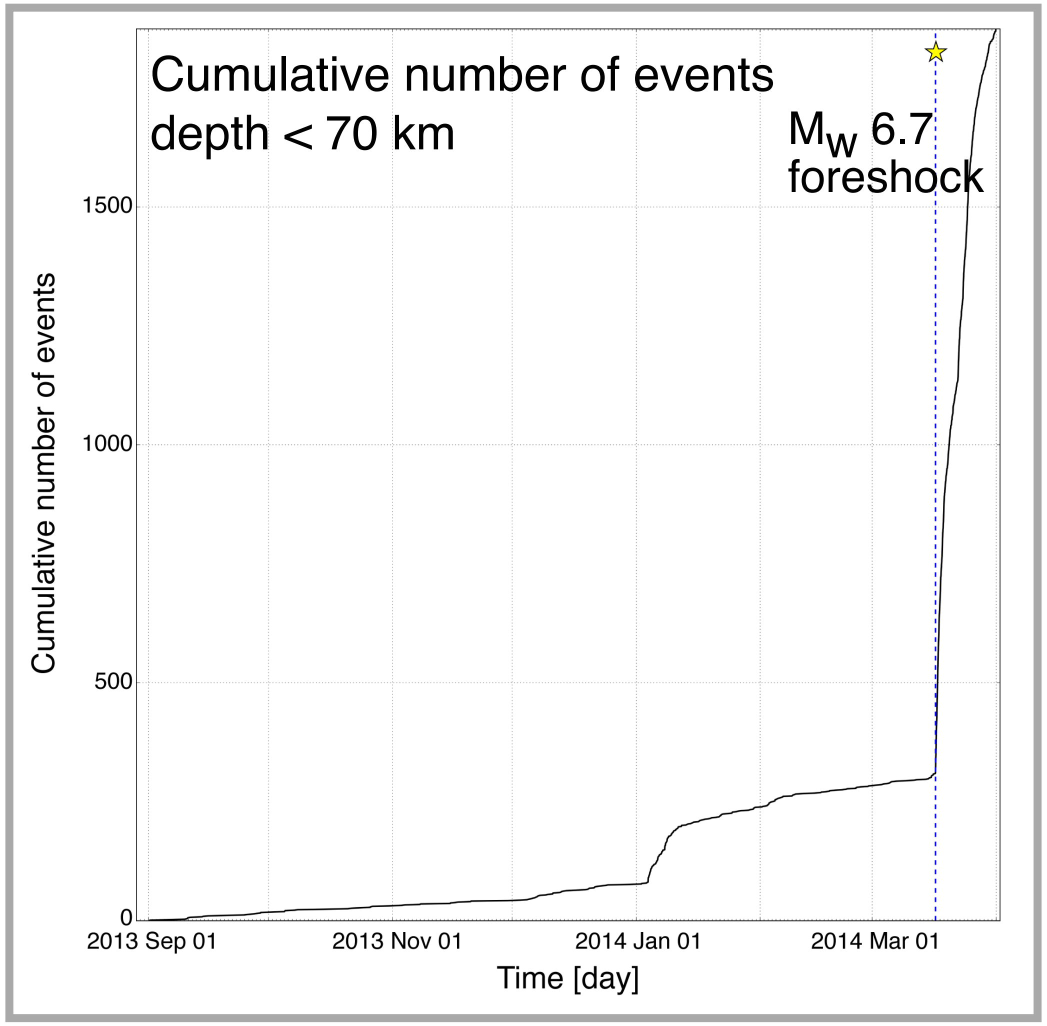
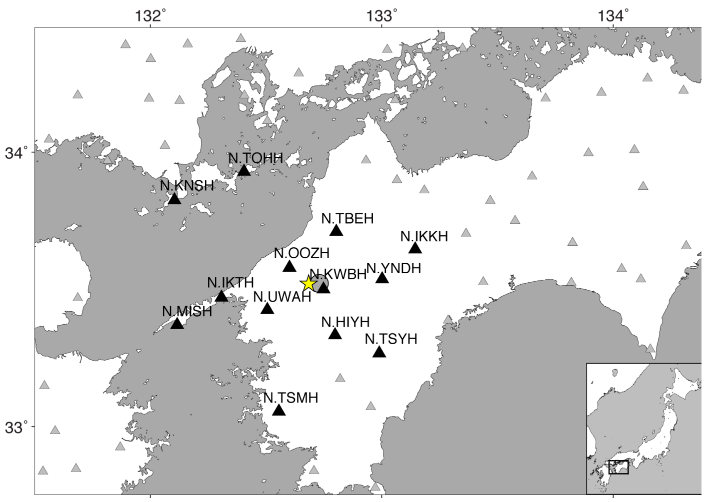


Continuous reactivation of shallow cluster close to mainshock

Migration of activity - potential indicator of ongoing slow slip

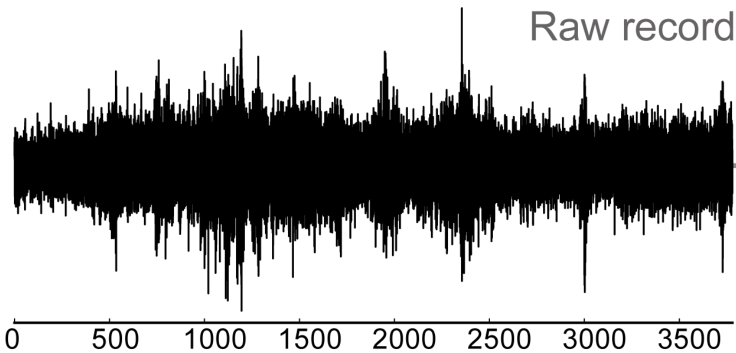
Different components of tectonic tremor: long duration and short transient events



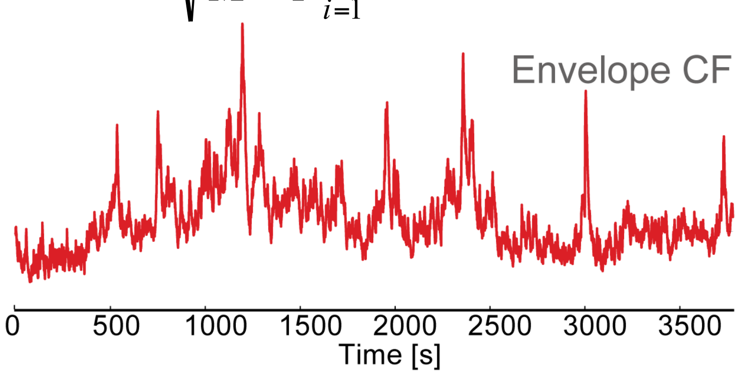
- BackTrackBB signal processing scheme

Using 2 CFs to image different components of a tremor sequence

RMS envelopes

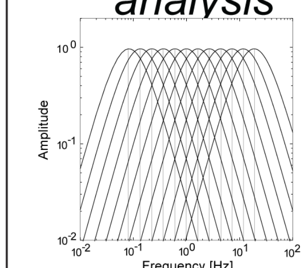


$$CF(t) = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}(u(t_i))^2}$$



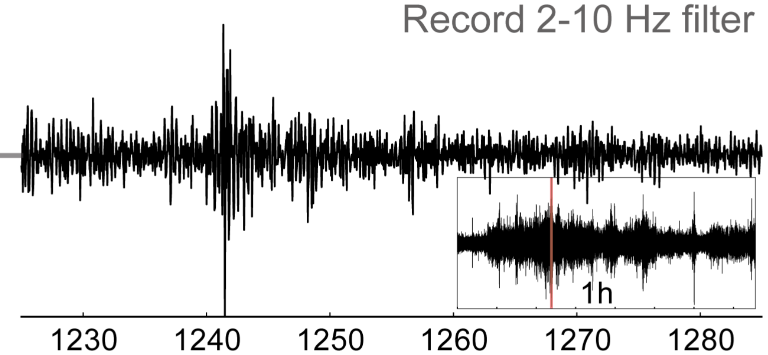
Long-duration energy variation

Time-frequency analysis

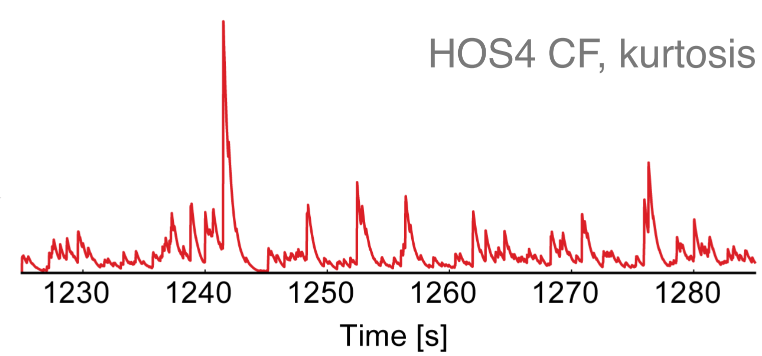


multi-band filter

Higher-order statistics (HOS)



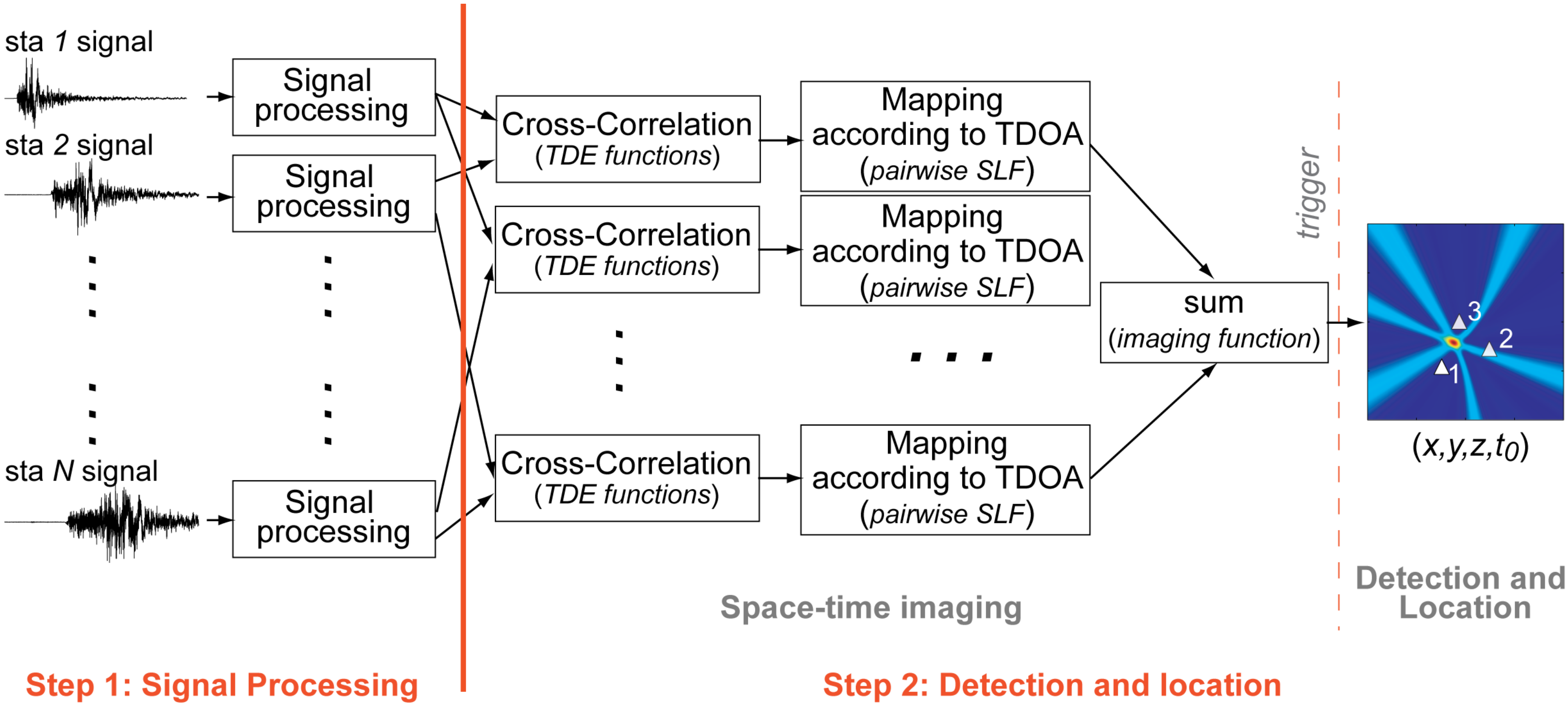
$$CF(t) = \frac{E\left[(u(t)-\mu)^n\right]}{\left(E\left[(u(t)-\mu)^2\right]\right)^{n/2}} = \frac{\mu_n}{\mu_2^{n/2}}$$



Short transients:
low-frequency earthquakes

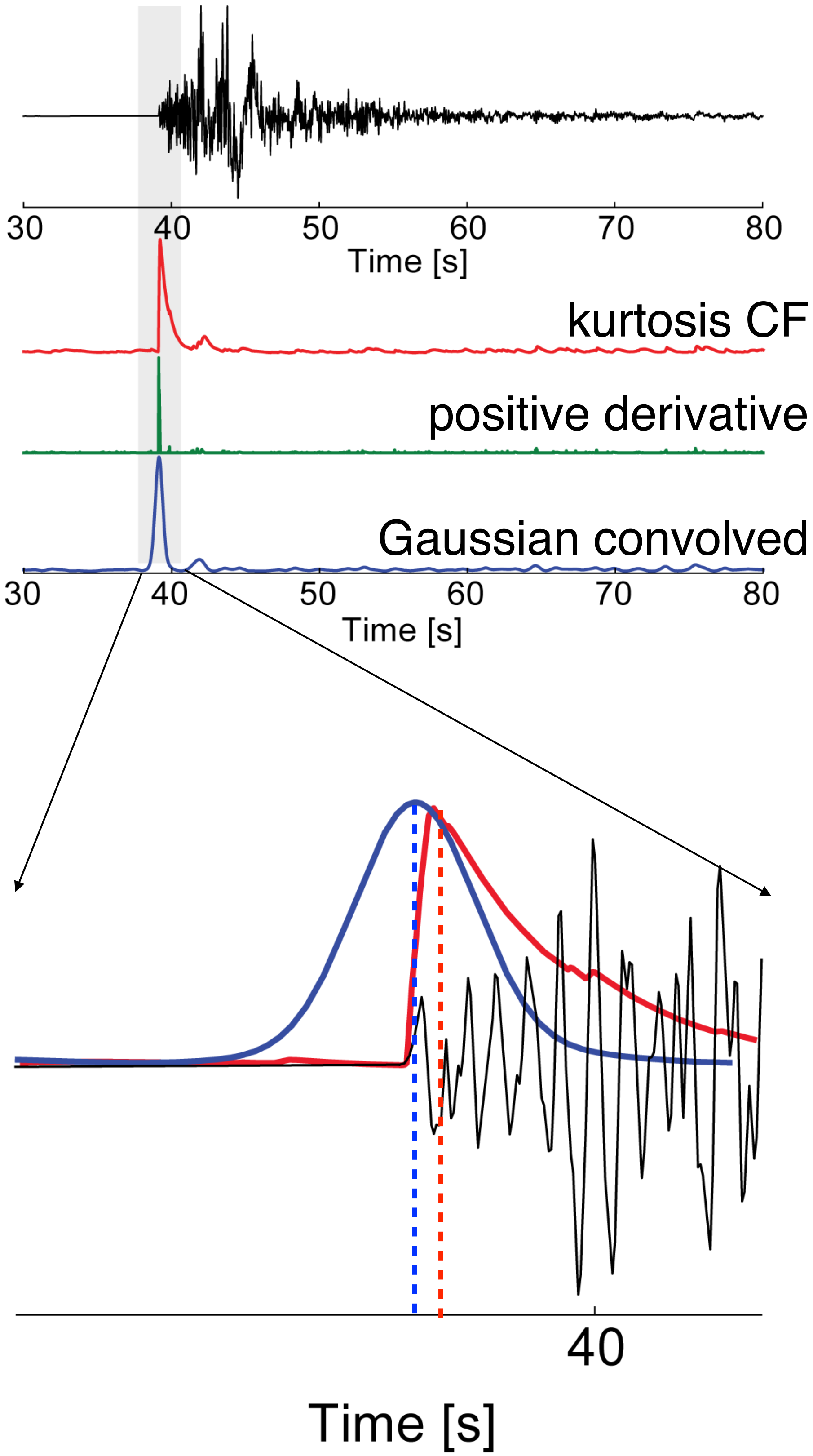
Multi-scale array-based detection and location scheme

BackTrackBB schematic representation



Back-Tracking the **Broad****B**and signal to the origin (seismic source)

Step 1. Signal processing - a note on HOS (kurtosis) broadband CFs



Generic HOS CF:

$$CF_{HOS}(t) = \begin{cases} \dot{CF}_{kurt}(t) * e^{-t^2/4\sigma^2} & if\ \dot{CF}_{kurt}(t) \geq 0 \\ 0 & elsewhere \end{cases}$$

$\dot{CF}_{kurt}(t)$ – time derivative of the broadband kurtosis CF

σ – half-width of Gaussian window, $\sigma = T_{decay}/2$

Managing delayed onset of HOS maxima

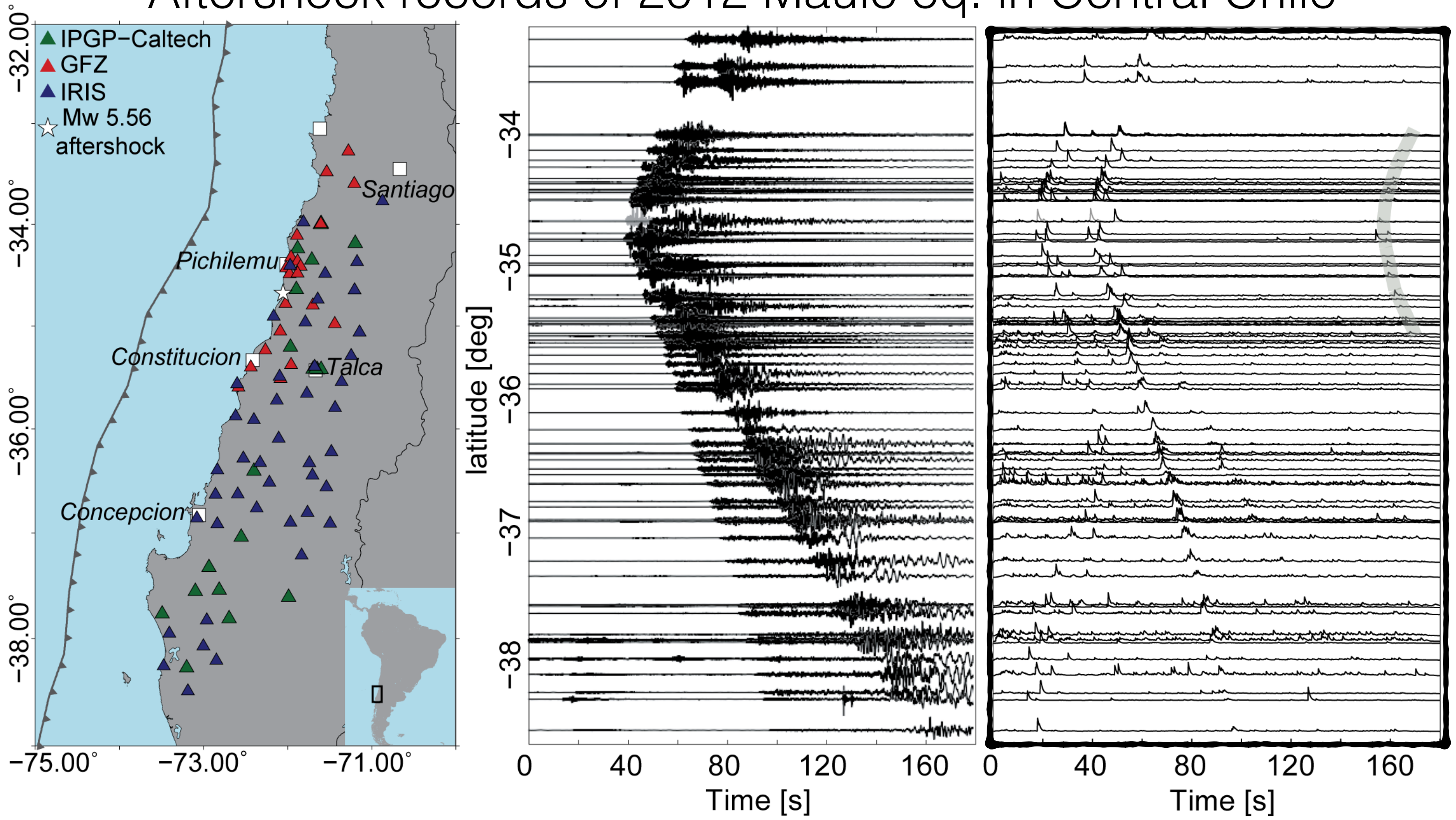
Step 1. Signal processing - general view

Adaptive scheme for different energy release processes

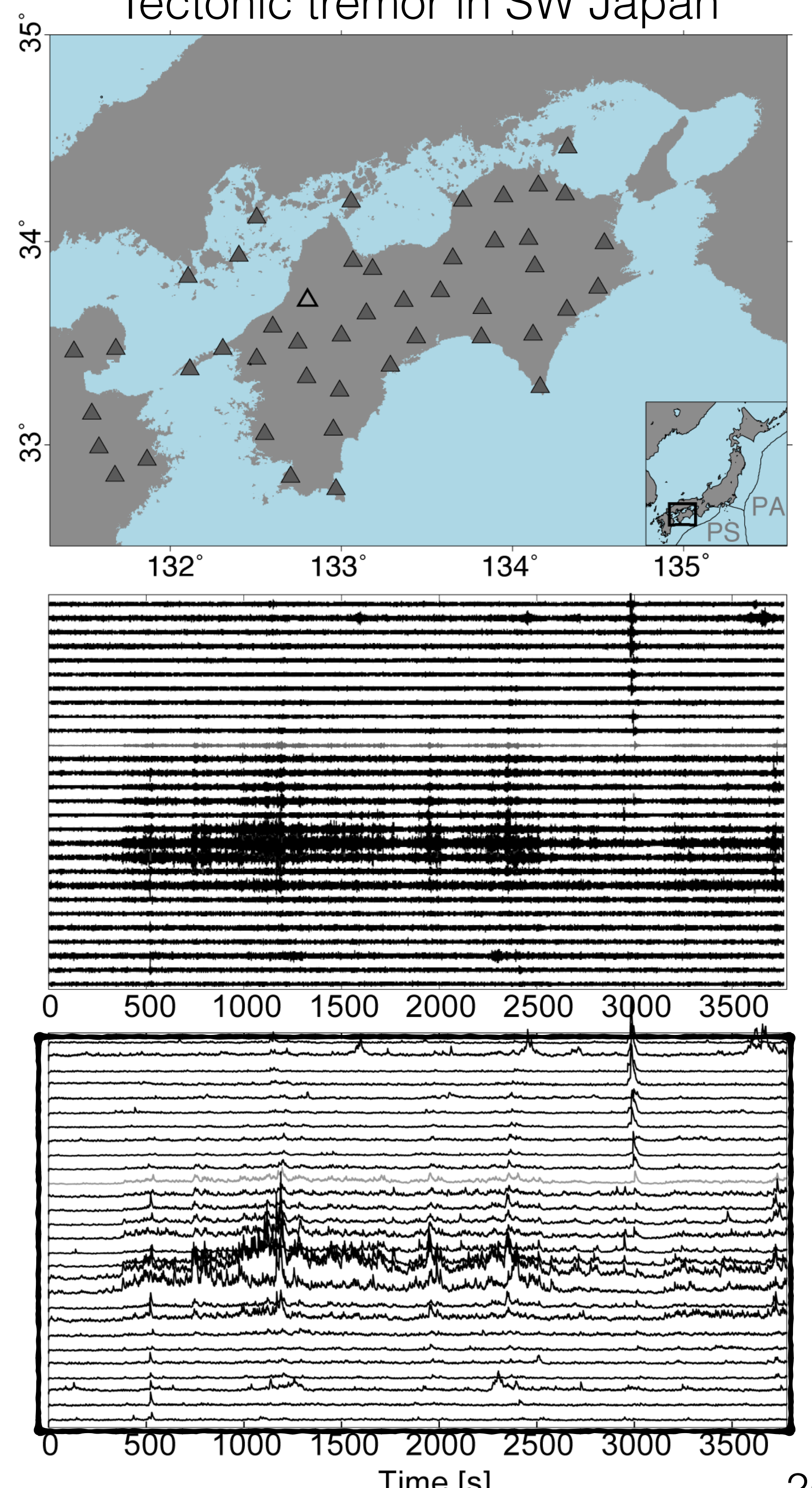
- Aftershock sequence: time-frequency kurtosis
- Tectonic tremor activity: time-frequency envelopes

Extracting different properties of the signal

Aftershock records of 2012 Maule eq. in Central Chile



Tectonic tremor in SW Japan



2. Methodology: BackTrackBB

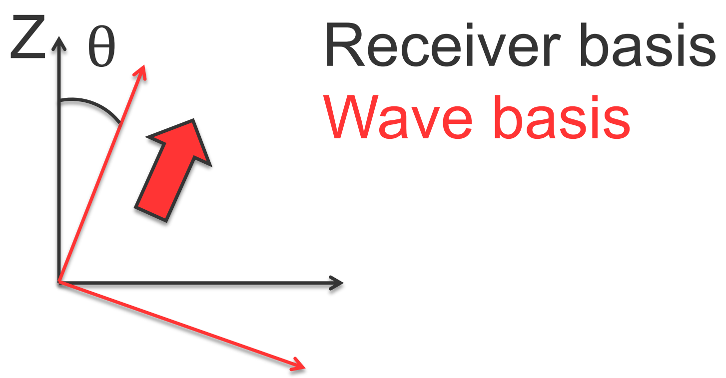
Including P and S-wave information into detection and location scheme

Polarization analysis

Separating P and S components using polarisation analysis; 3 component data

Introducing joint location using P and S-based HOS CFs

Rosenberger, BSSA, 2010



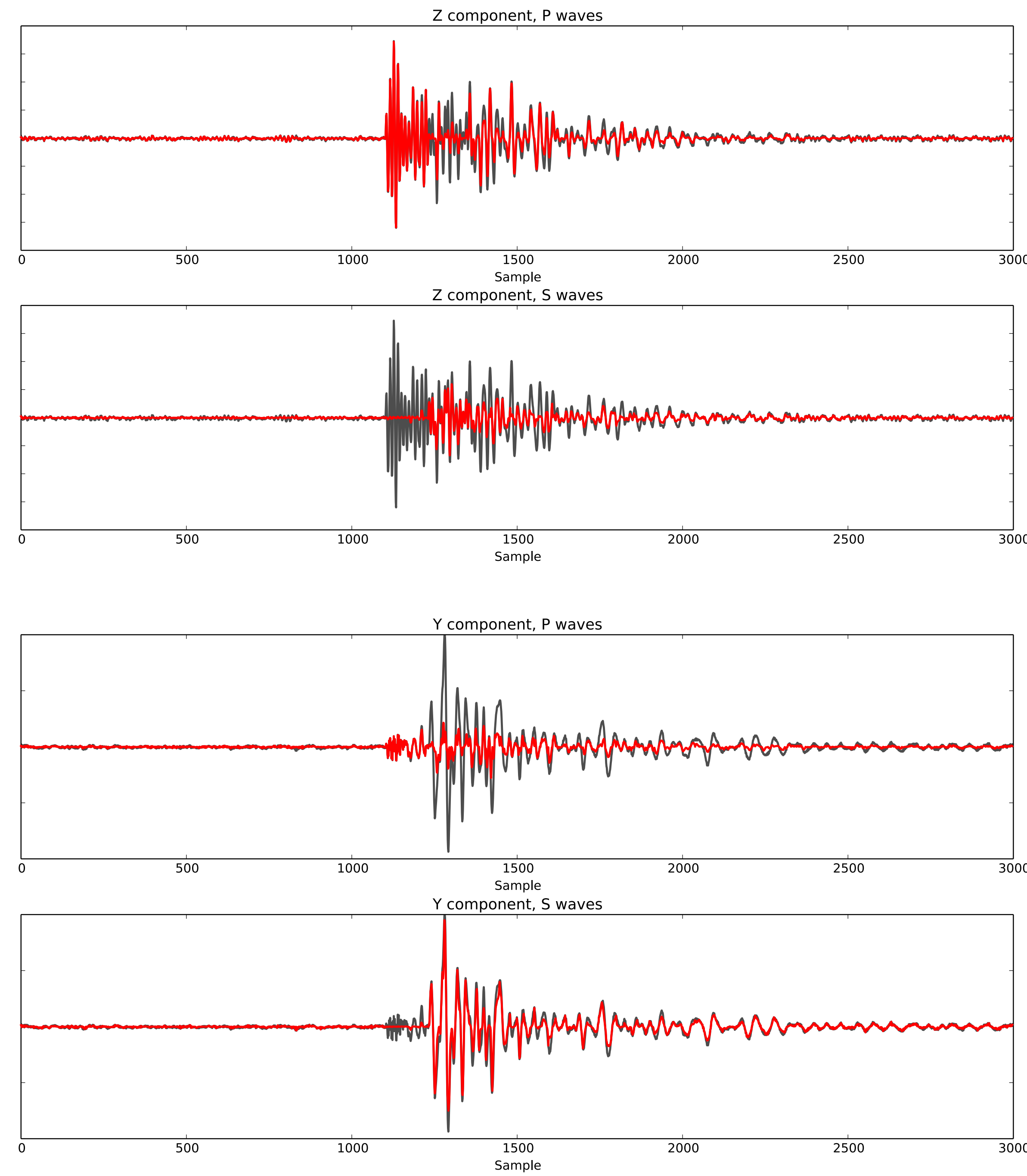
θ ≈ 0 for P-wave, cos(θ) ≈ 1

θ ≈ π/2 for S-wave, cos(θ) ≈ 0

$$X_n = \begin{bmatrix} z_0 & z_1 & \cdots & z_n \\ x_0 & x_1 & \cdots & x_n \\ y_0 & y_1 & \cdots & y_n \end{bmatrix}$$

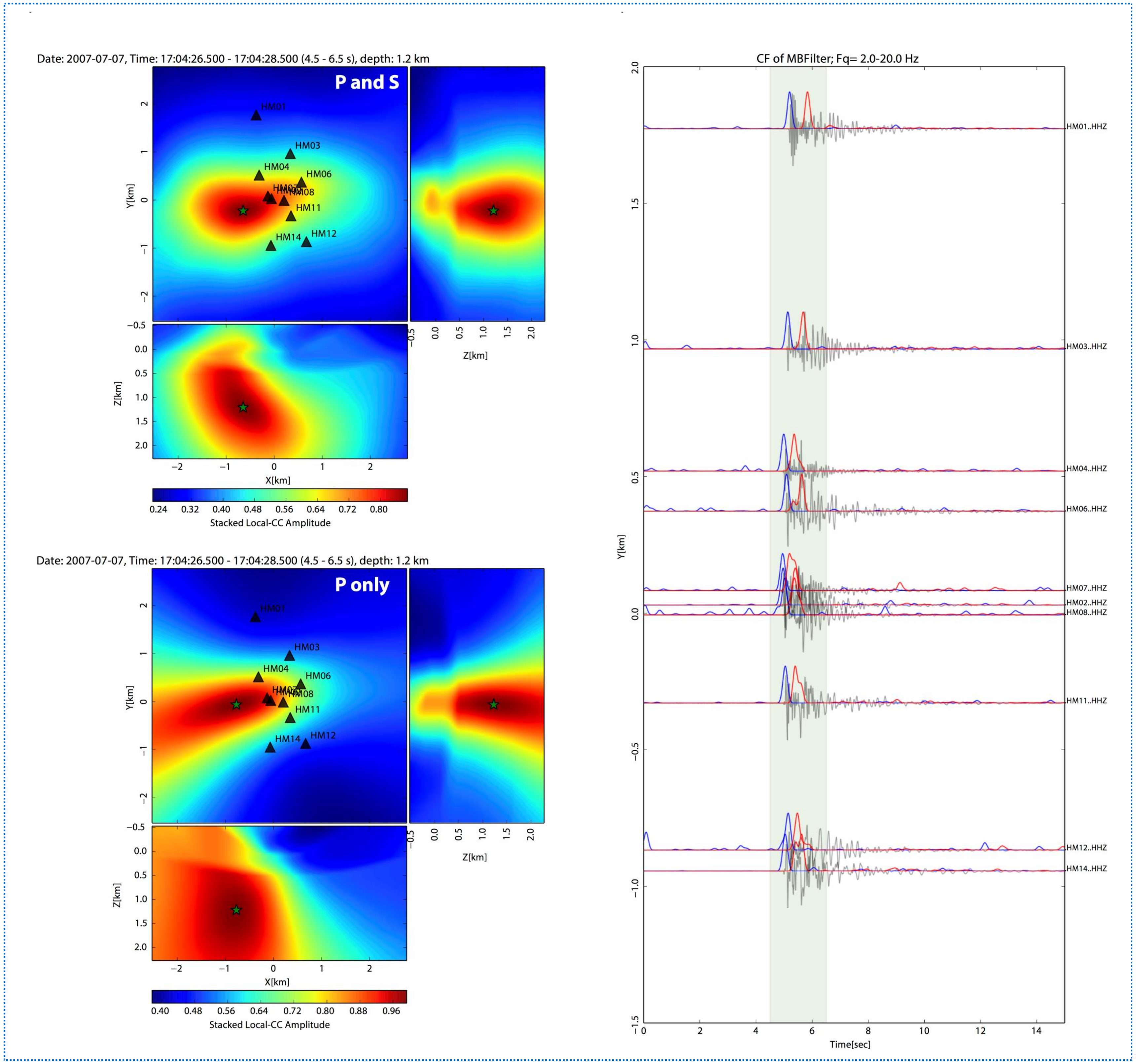
Singular Value Decomposition:

$$\boxed{U_n^T} X_n V_n = \Sigma_n = diag(\sigma_0, \cdots, \sigma_{k-1})$$

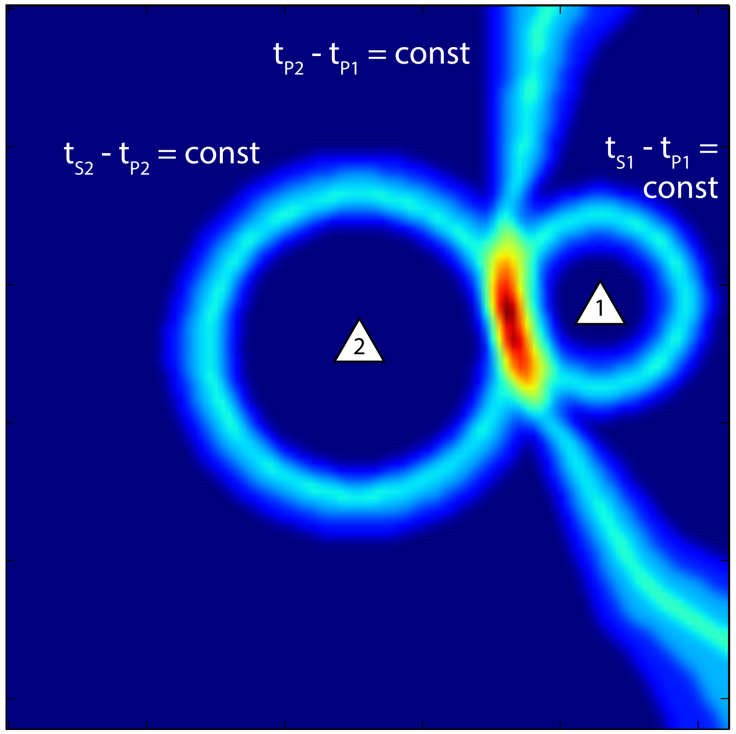


Including P and S-wave information into detection and location scheme

Example of joint P-S location

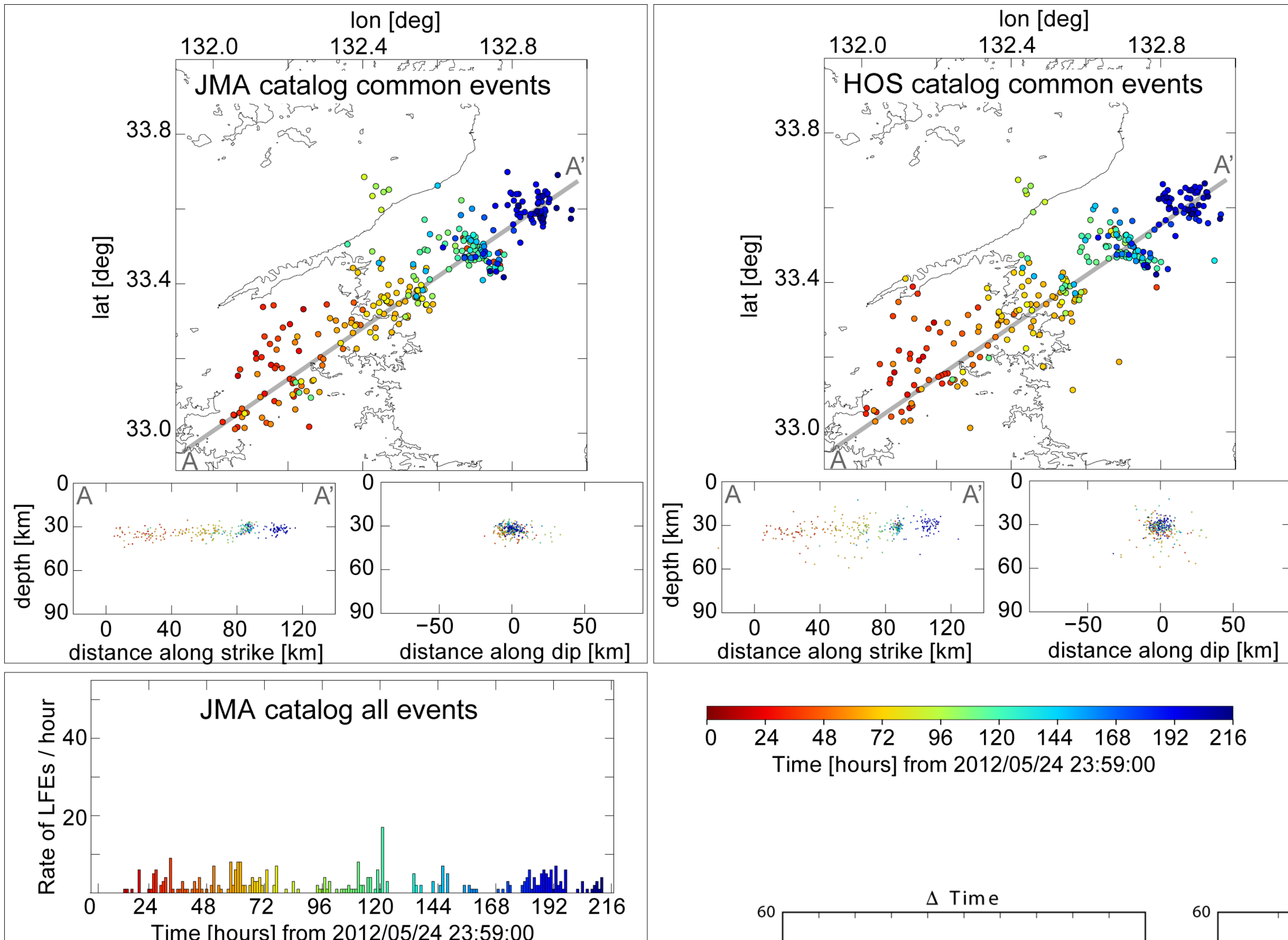


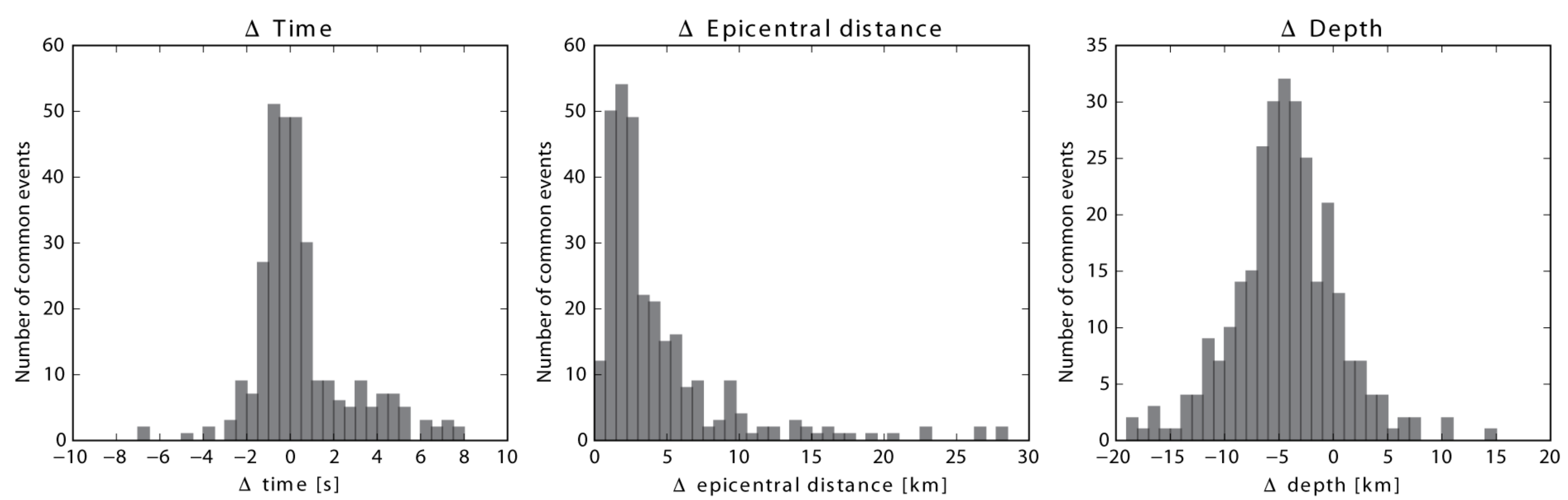
Schematic view of imaging function



3. Application examples: Imaging components of tectonic tremor

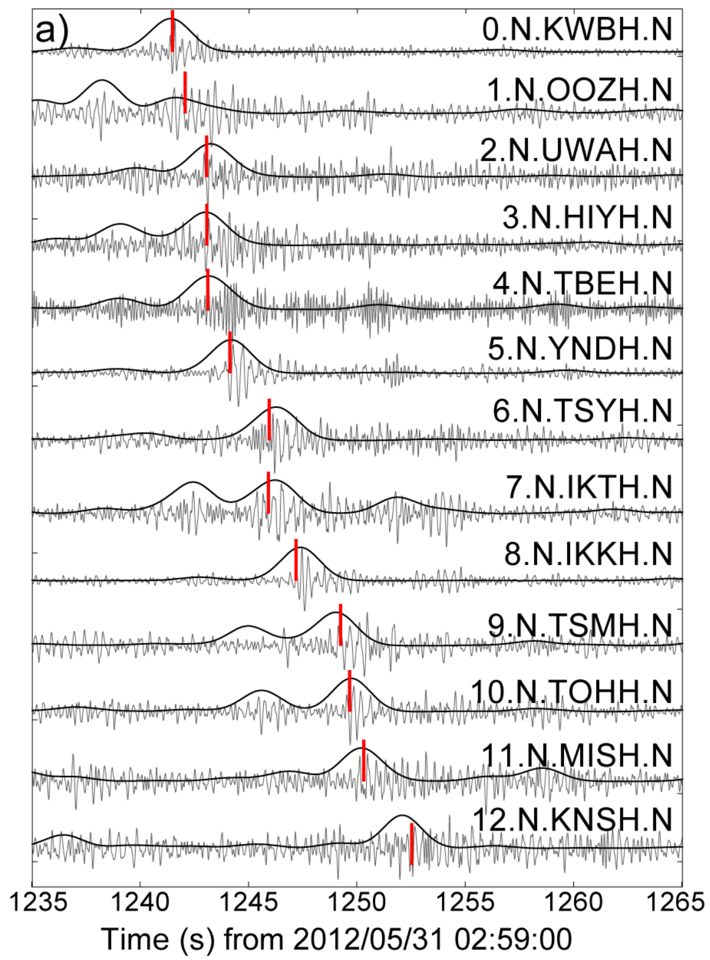
Comparison with existing LFE catalog(s): JMA unified catalog

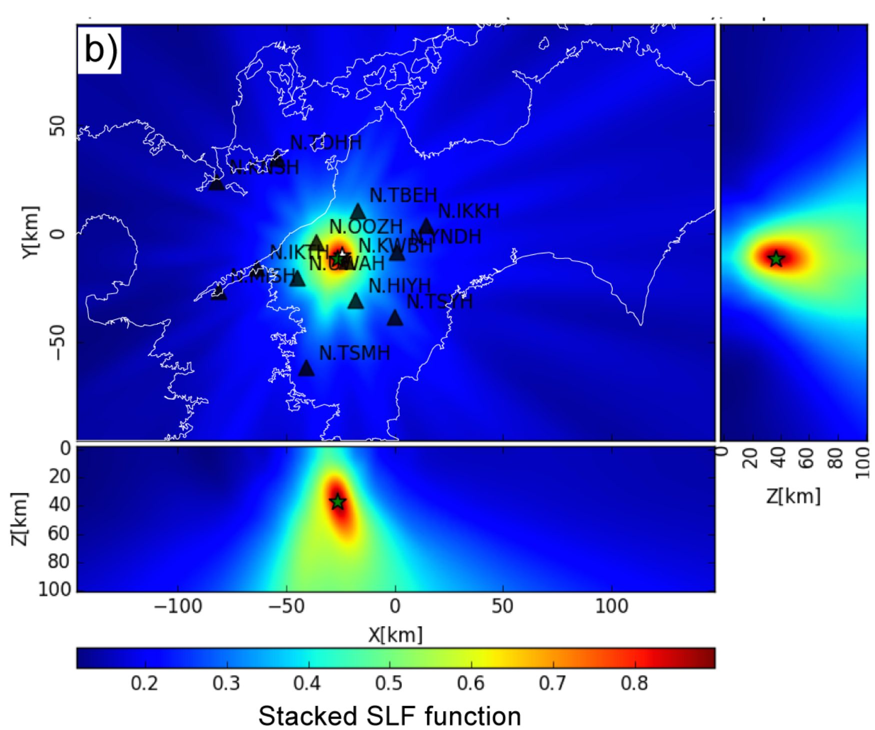


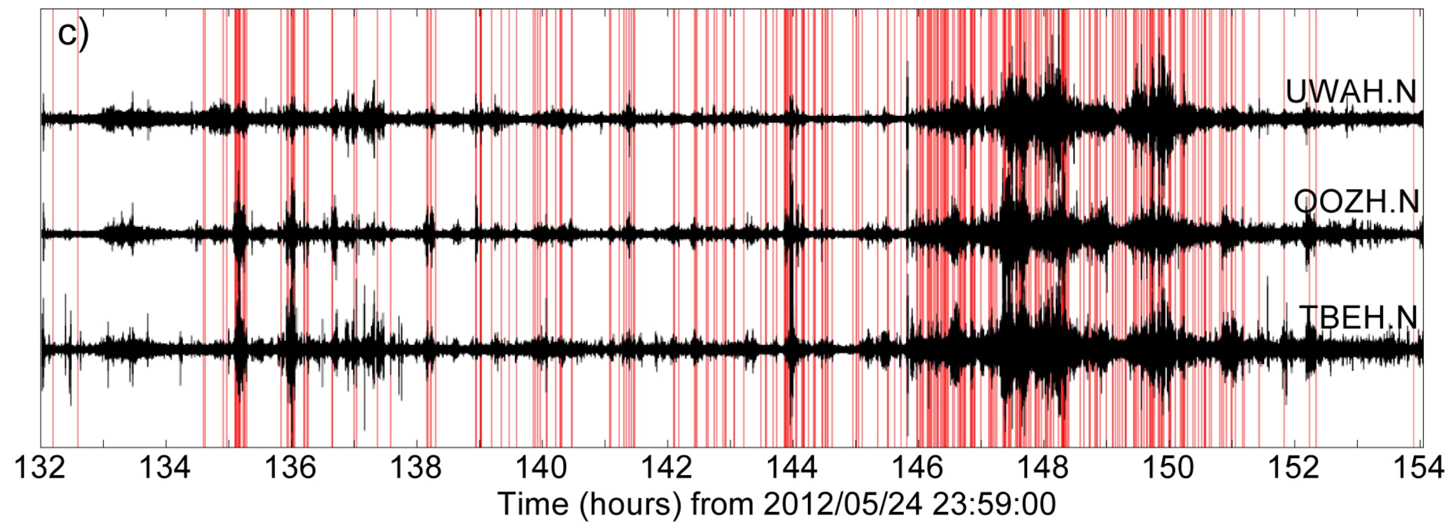


BackTrackBB - application examples

Imaging the complexity of tectonic tremor: detection and location of LFEs







LFE catalog for 9 days of tremor activity (> 2000 events)