Characterizing earthquakes source physics with source scanning algorithms.

A better earthquake analysis

Frederick Massin[1] & Alison Malcolm[2]

February 19, 2016

[1]Post-doc & [2]Pr. & Chevron Chair in Reservoir Characterization, Earth Sciences Department, MUN.

Outline

1. Shift & stack approaches
2. Characteristic functions
3. Source mechanism preliminary analysis
4. Conclusion

Shift & stack approaches

Why?

- Quantify the earthquakes physical properties & uncertainties from continuous signals.

Why?

- Quantify the earthquakes physical properties & uncertainties from continuous signals.
  - Probabilistic earthquake nucleation understanding and hazard assessment.

Why?

- Quantify the earthquakes physical properties & uncertainties from continuous signals.
  - Probabilistic earthquake nucleation understanding and hazard assessment.
    - Earthquakes could be triggered by local stress perturbation from many sources, natural or not, with implications for the rupture characteristics.

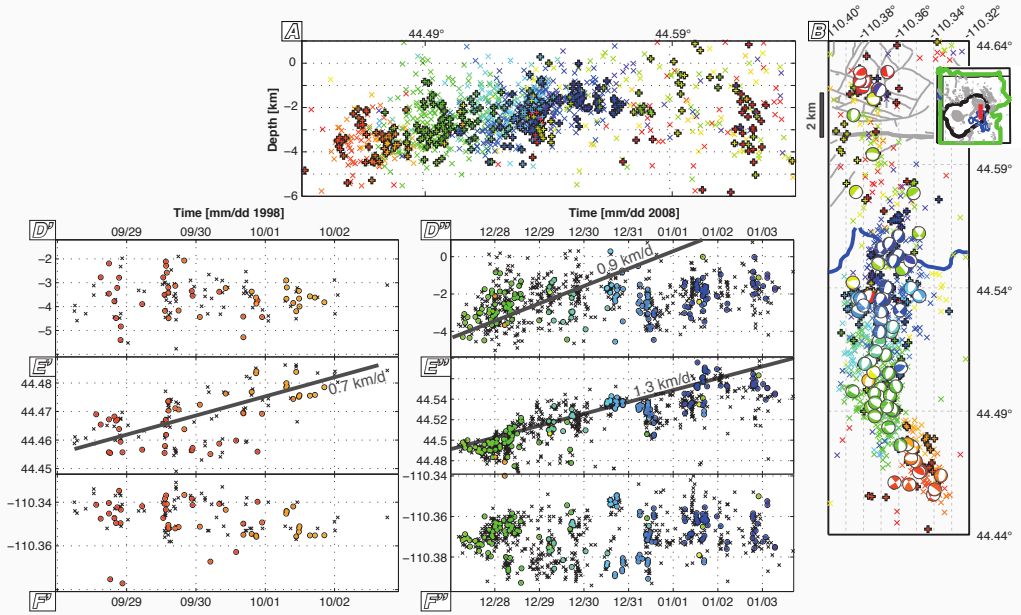

Figure 1: The 2008-9 Yellostone Lake eq. swarm [6].

Conventional approach

- Arrival times (data reduced to minimum) => Hypocenter

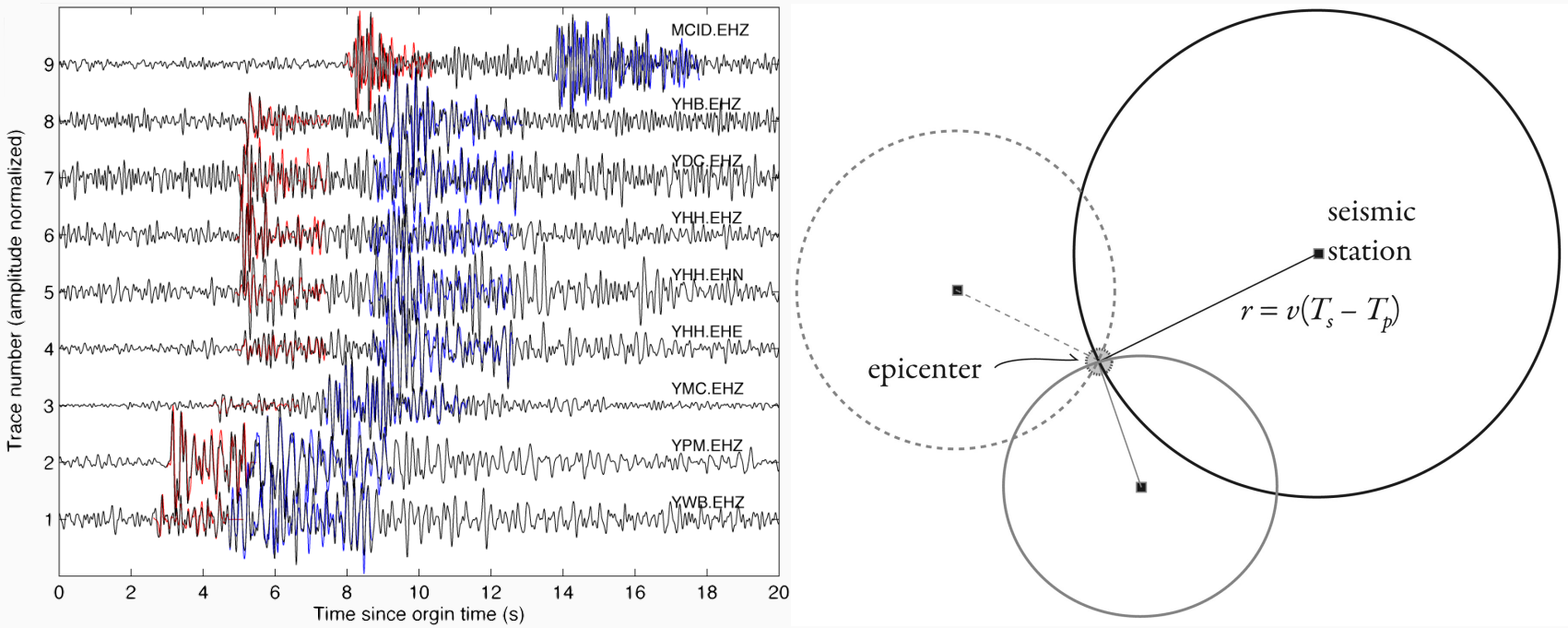

Figure 2: From picks to precise location [8, 9, 10].

Conventional approach

- Arrival times (data reduced to minimum) => Hypocenter
- Long period signals (filtered data) => Moment tensor

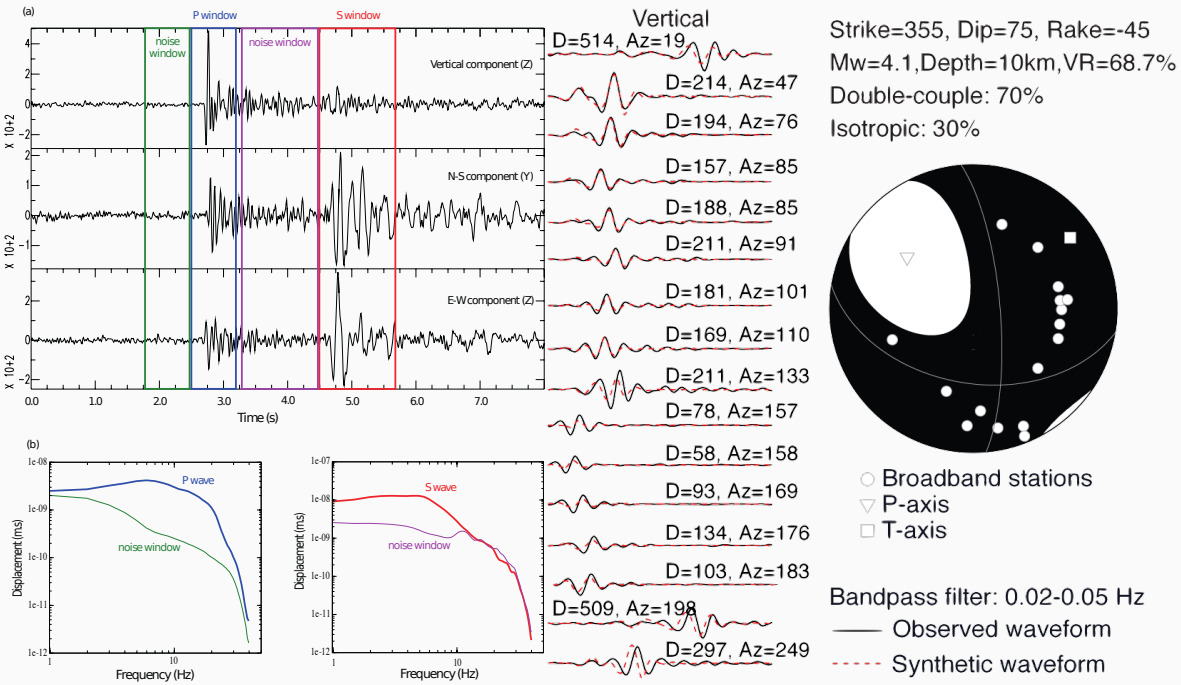

Figure 2: ... to moment tensor [3, 8].

Conventional approach

- Arrival times (data reduced to minimum) => Hypocenter
- Long period signals (filtered data) => Moment tensor
- Modeling of:
  - slip distribution,
  - stresses perturbation,
  - ground deformation.

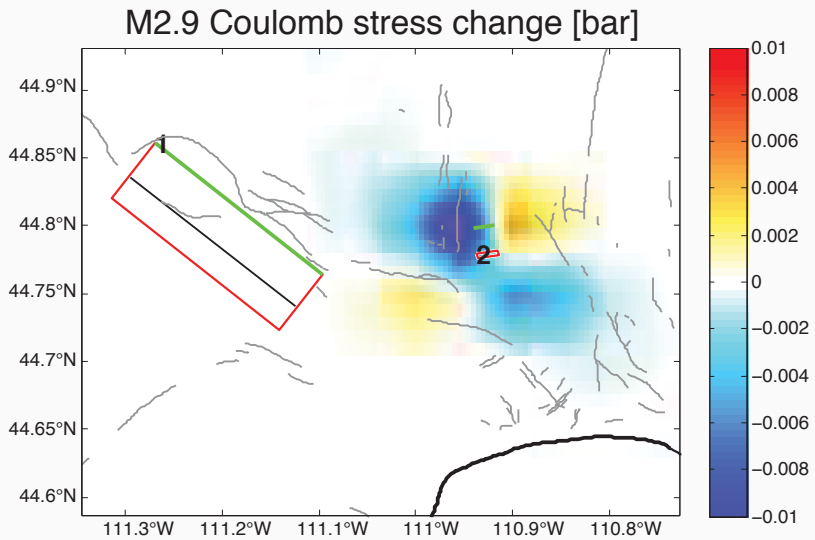

Figure 2: ... to stress change.

Conventional approach

- Arrival times (data reduced to minimum) => Hypocenter
- Long period signals (filtered data) => Moment tensor
- Modeling of:
  - slip distribution,
  - stresses perturbation,
  - ground deformation.

How to use more data in source parameter analysis ? In a more direct way ?

Shift-&-stack approach (or source scanning, or SSA)

Hypocenter scanning [11, 2, 5, 4]

- Grid pre-calculation of travel time for trial source positions,
- Signal pre-processing with body-wave characteristic functions,
- stacking using pre-defined travel times :
  - probability grid,
  - centroïd are defined with bayesian approach.

How *to explore more spaces?*

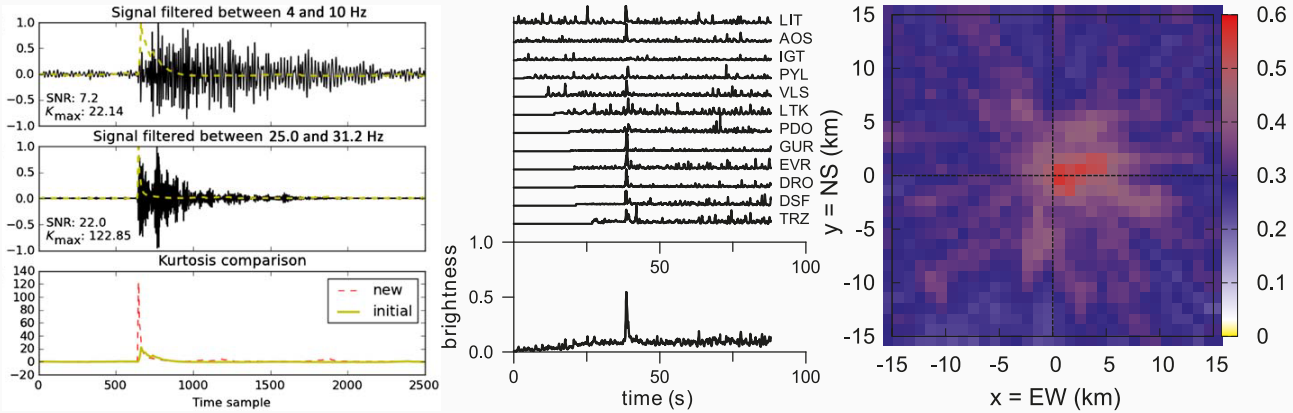

Figure 2: From signal to location

Shift-&-stack approach (or source scanning, or SSA)

Hypocenter scanning [11, 2, 5, 4]

- Grid pre-calculation of amplitudes for take off angles,
- Signal pre-processing with body-wave wavelets,
- stacking using pre-defined amplitudes:
  - probability sphere,
  - P-T axis are defined with bayesian approach.

How *is this better?*

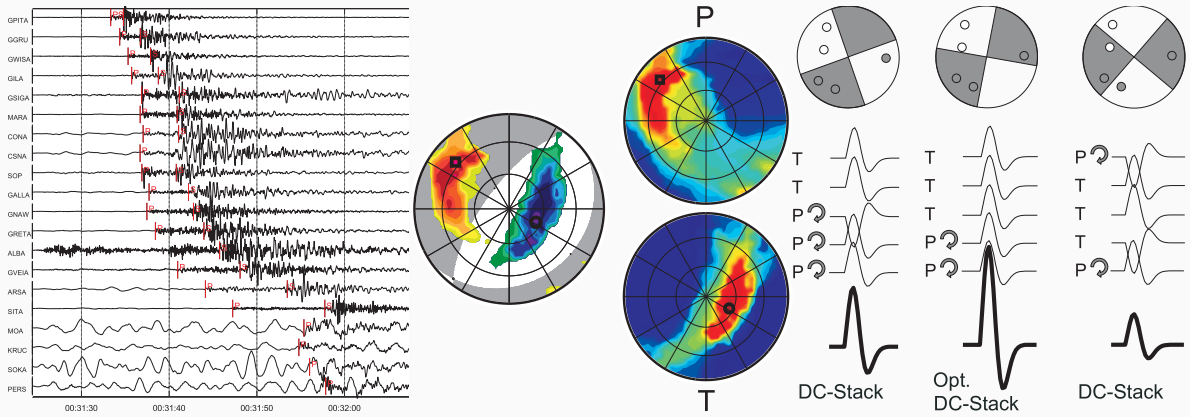

Figure 2: From signal to source mechanism

SSA advantages

System simplicity => Robust, stable & applicability.

- constant volume of computation,
- apparent lack of
  - optimization,
  - complex logic.

What do we need?

Characteristic functions

Existing CF

Body-waves arrival => Δ[Amplitude, Frequency].

- CF_A:
  - $\frac{Short Term Average}{Long TA}$
  - $\frac{Right Part A}{Left PA}$

Existing CF

Body-waves arrival => Δ[Amplitude, Frequency].

- CF_A:
  - $\frac{Short Term Average}{Long TA}$
  - $\frac{Right Part A}{Left PA}$
- CF_F:
  - Multiscale (based on $\frac{STA}{LTA}$)
  - Kurtosis (based on $\frac{STA}{LTA}$, envelop ...)
  - Auto-regressive (based on any of the other)
  - Wenner filter <=> Match filter (based on any of the other).

Existing CF

Body-waves arrival => Δ[Amplitude, Frequency, Polarization].

- CF_A:
  - $\frac{ShortTermAverage}{LongTA}$
  - $\frac{RightPartA}{LeftPA}$
- CF_F:
  - Multiscale (based on $\frac{STA}{LTA}$)
  - Kurtosis (based on $\frac{STA}{LTA}$, envelop ...)
  - Auto-regressive (based on any of the other)
  - Wenner filter <=> Match filter (based on any of the other).
- CF_P:
  - Component Energy Correlation Method (CECM[7], based on RMS)

A better CF using CECM

Advantages:

- based on specific property of body-waves,
- scaled between 0 and 1

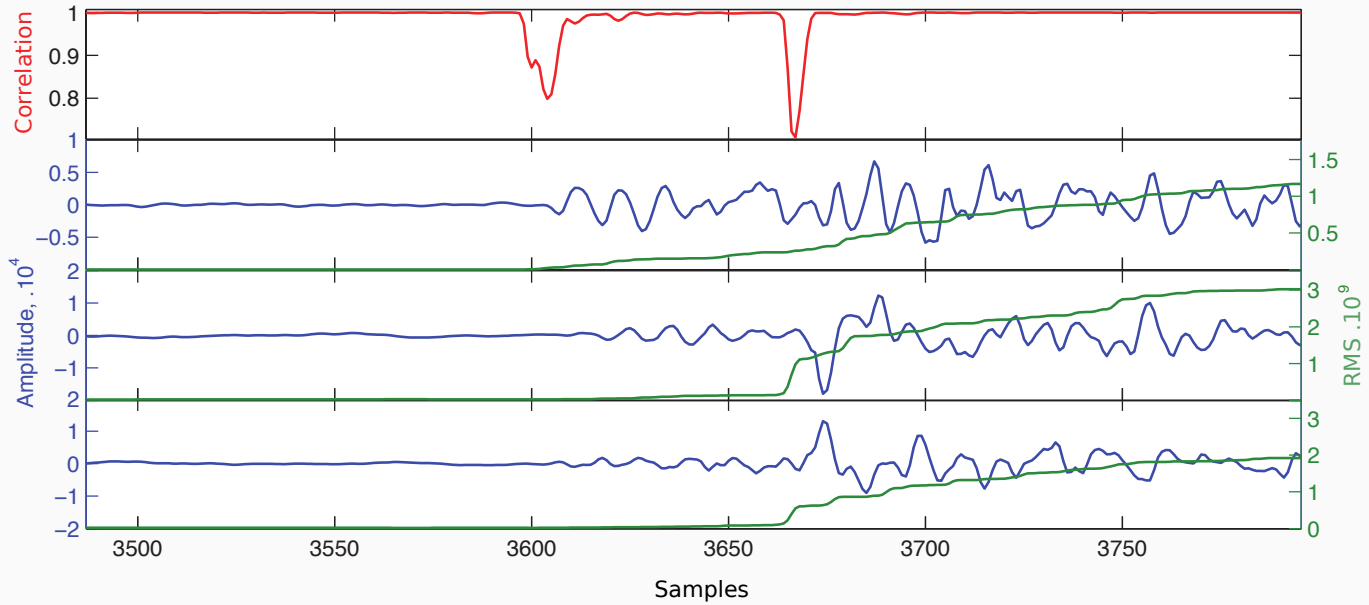

Figure 3: The $C_{omponent}E_{nergy}C_{orrelation}M_{ethod}$.

A better CF using CECM

Advantages:

- based on specific property of body-waves,
- scaled between 0 and 1,
- easy wave-type discrimination.

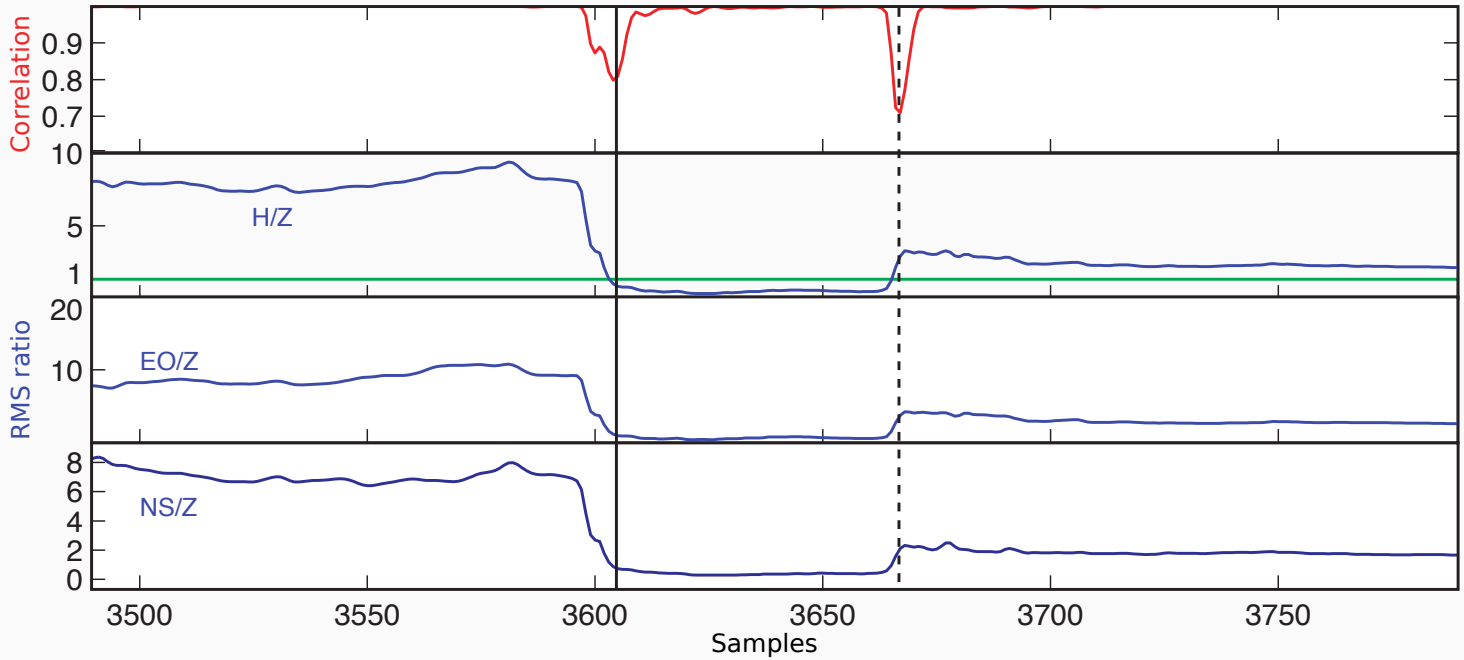

Figure 3: Wave type discrimination.

Examples

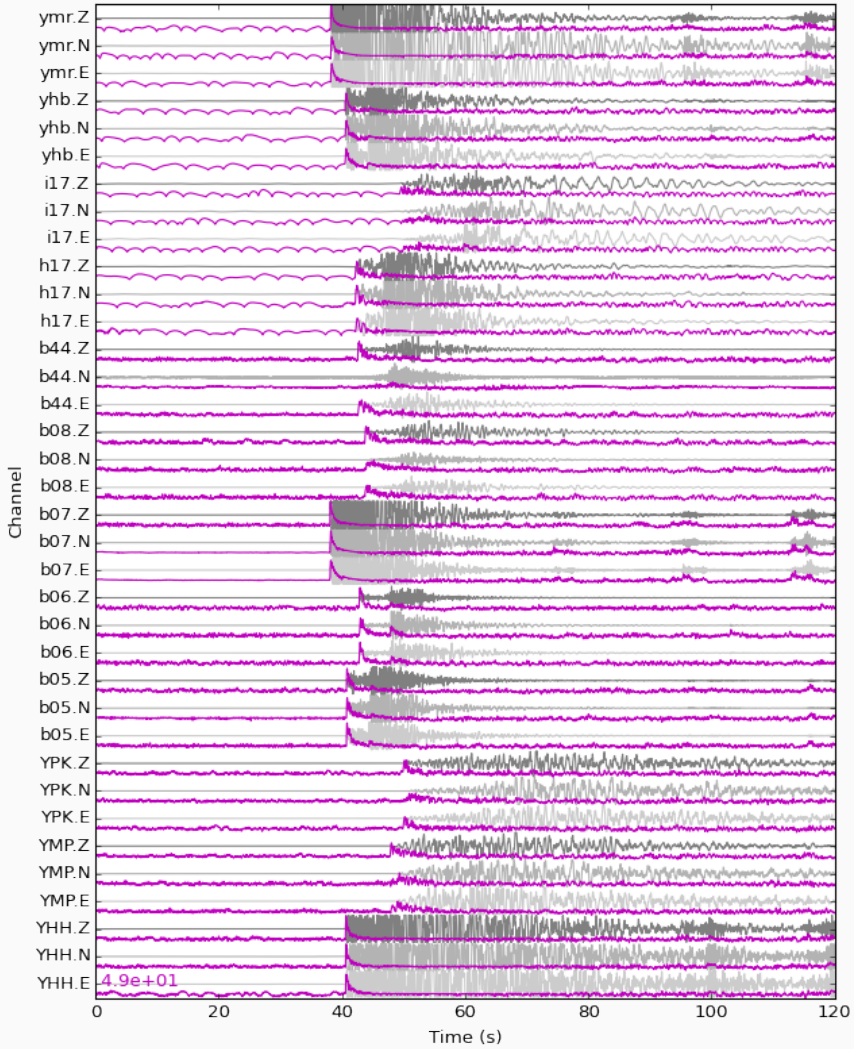

Figure 4: Data and $\frac{STA}{LTA}$.

Examples improvements with CECM

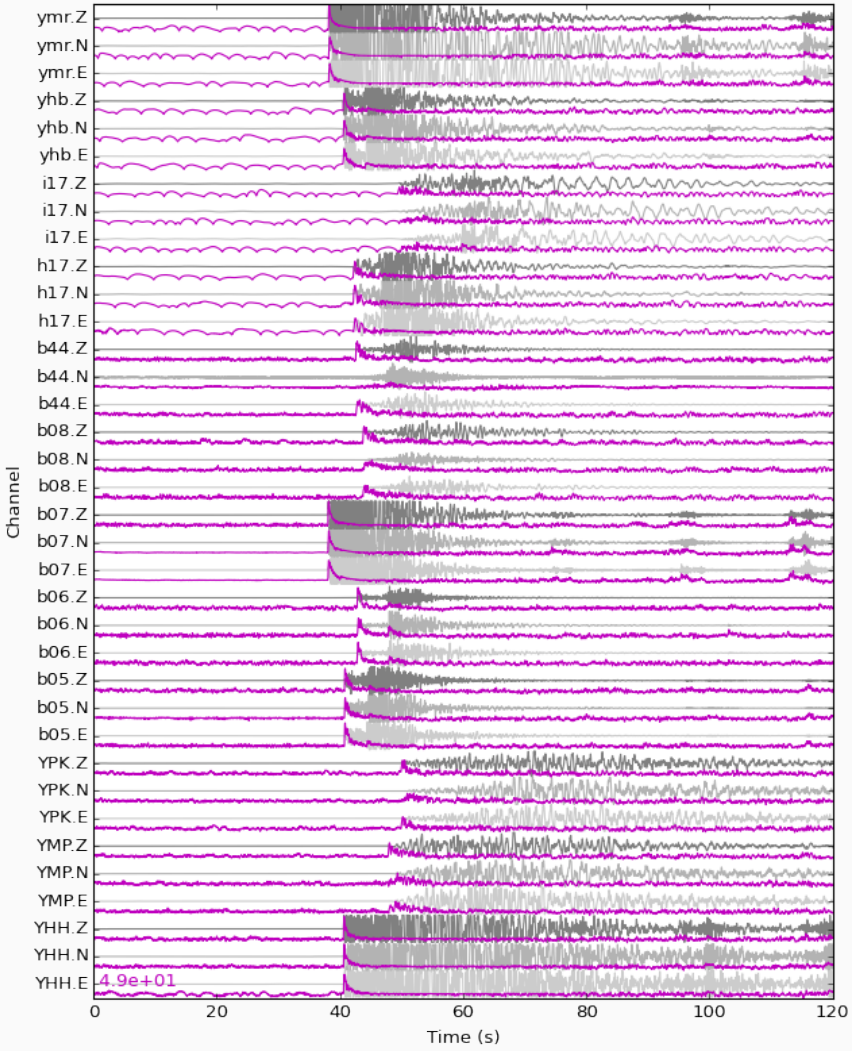

Figure 4: Data and $\frac{STA}{LTA}$.

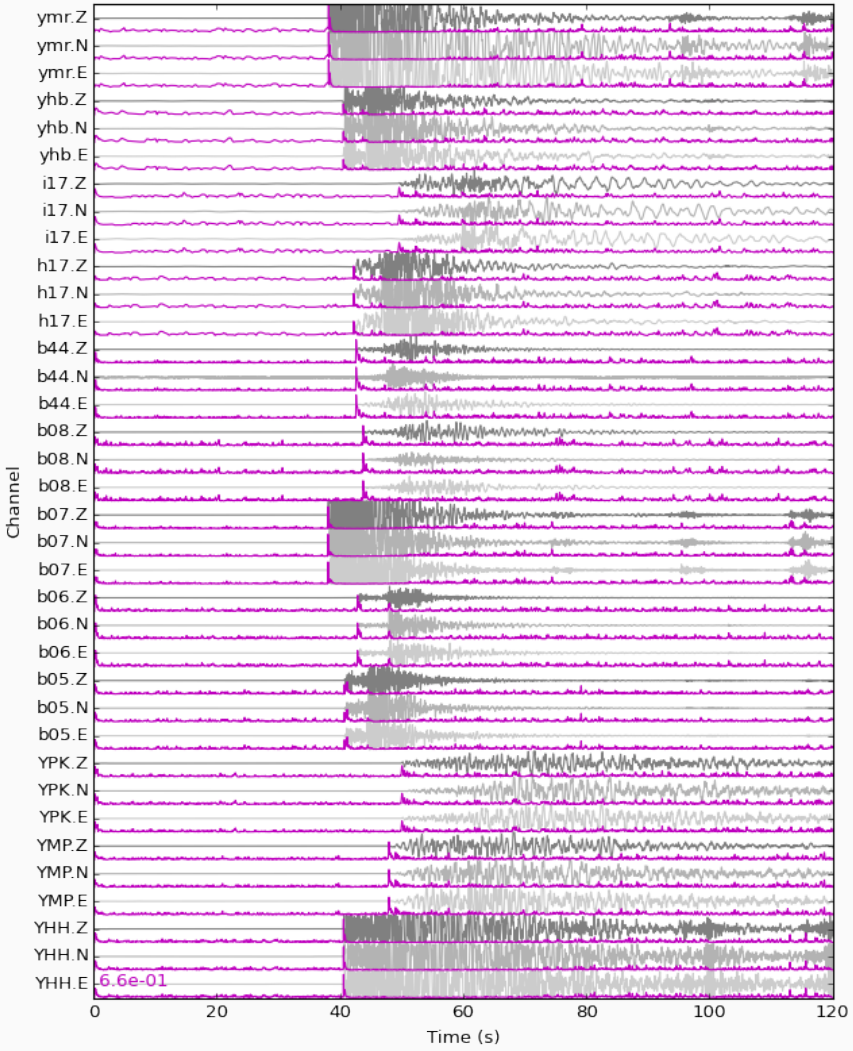

Figure 5: Data and CECM.

Examples improvements with CECM

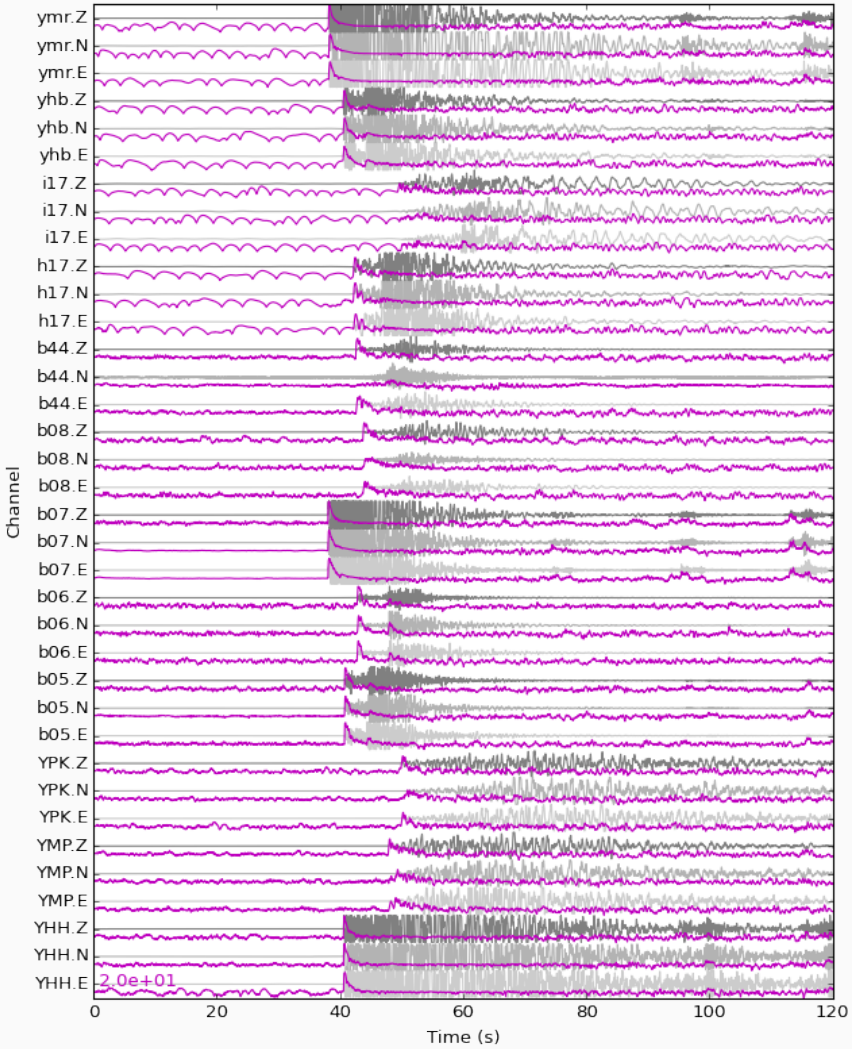

Figure 4: Data and $^{M}\frac{STA}{LTA}$.

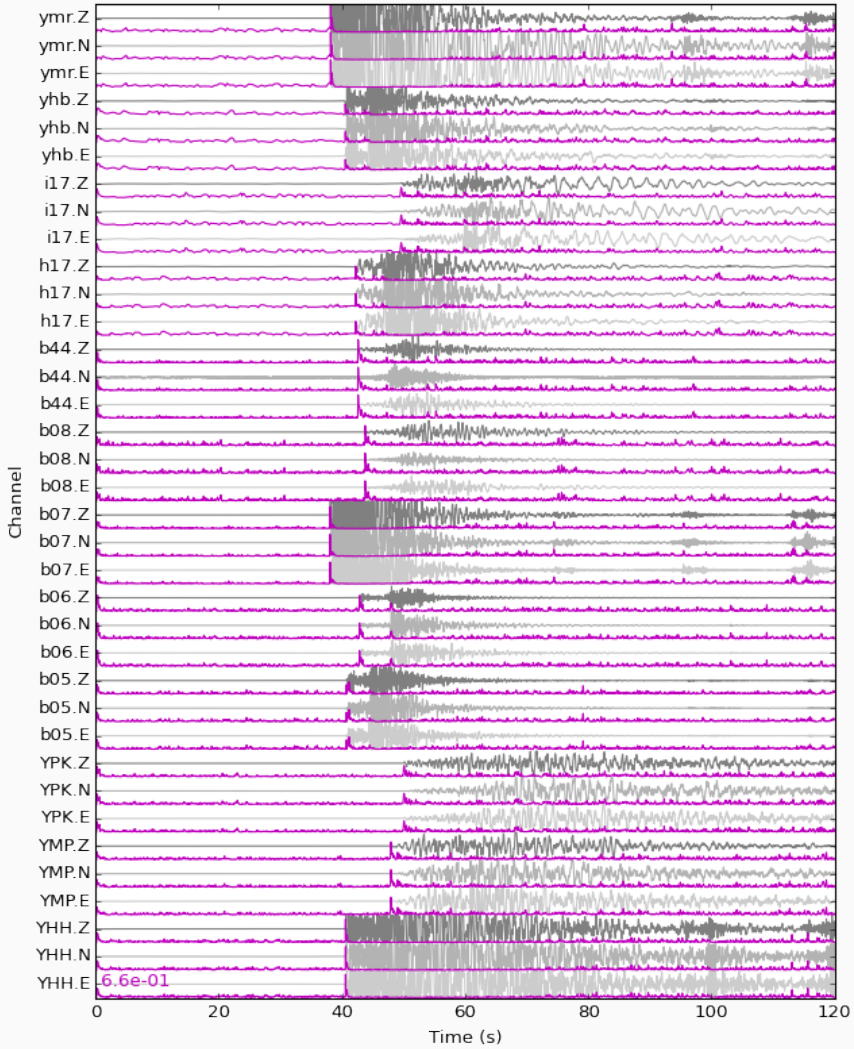

Figure 5: Data and CECM.

Examples improvements with CECM and muti-scaling

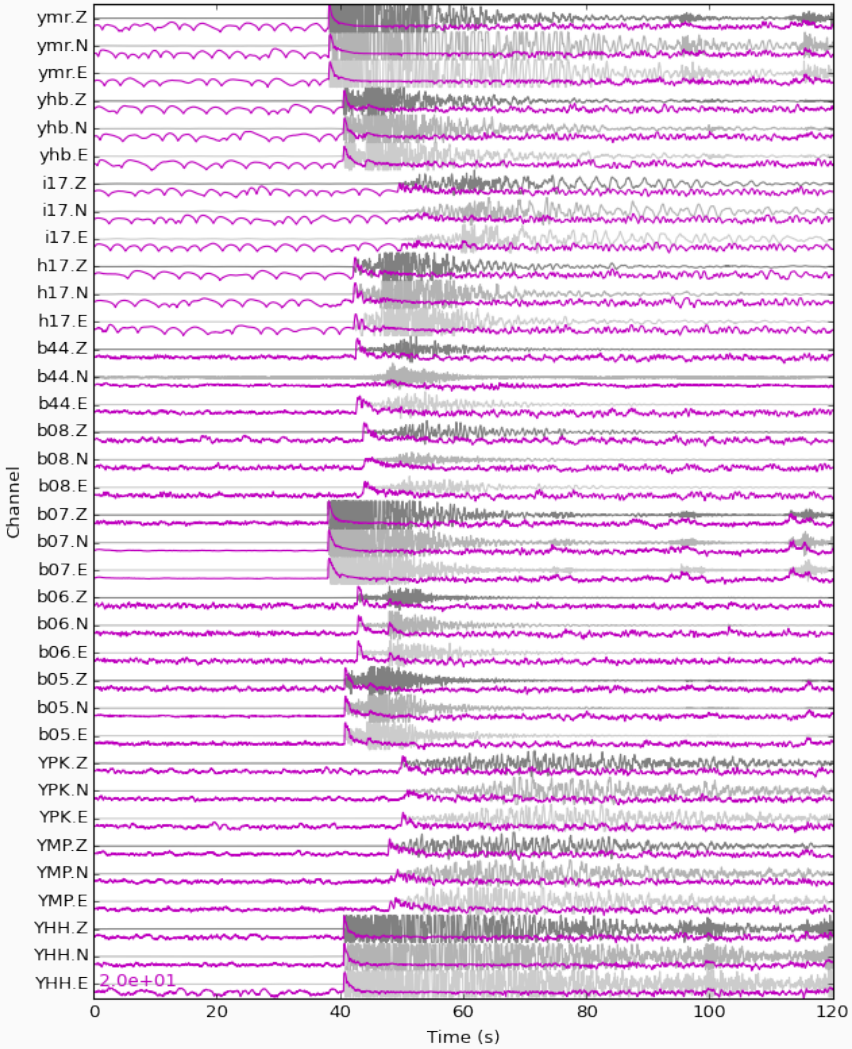

Figure 4: Data and $^{M}\frac{STA}{LTA}$.

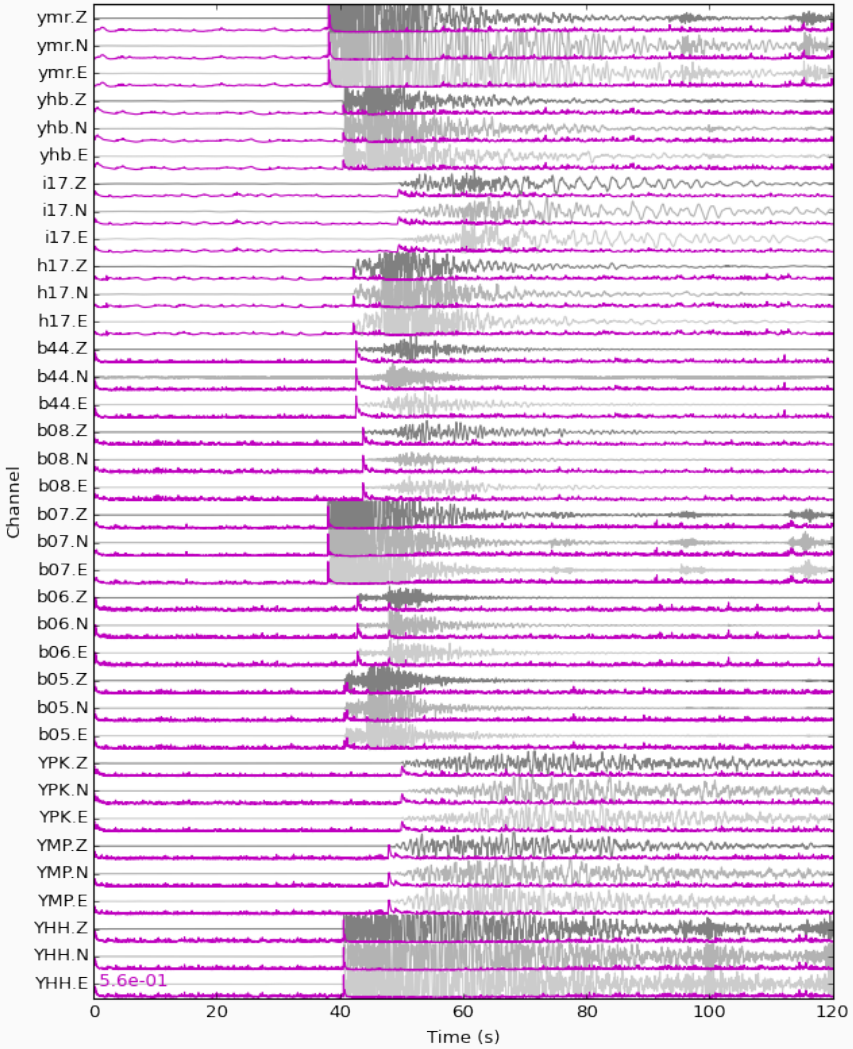

Figure 5: Data and ^{M}CECM.

Source mechanism preliminary analysis

Body-wave wavelets

The wavelet parameters:

- onset estimated by correlation based CF,
- length estimated by time-frequency analysis.

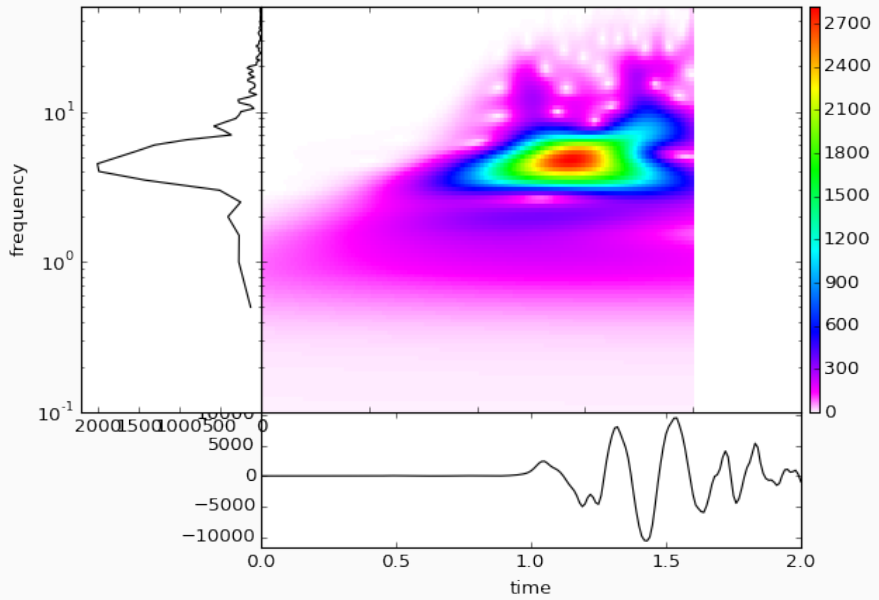

Figure 6: Data and frequency analysis, centered on arrival.

Body-wave wavelets

The wavelet parameters:

- onset estimated by correlation based CF,
- length estimated by time-frequency analysis.

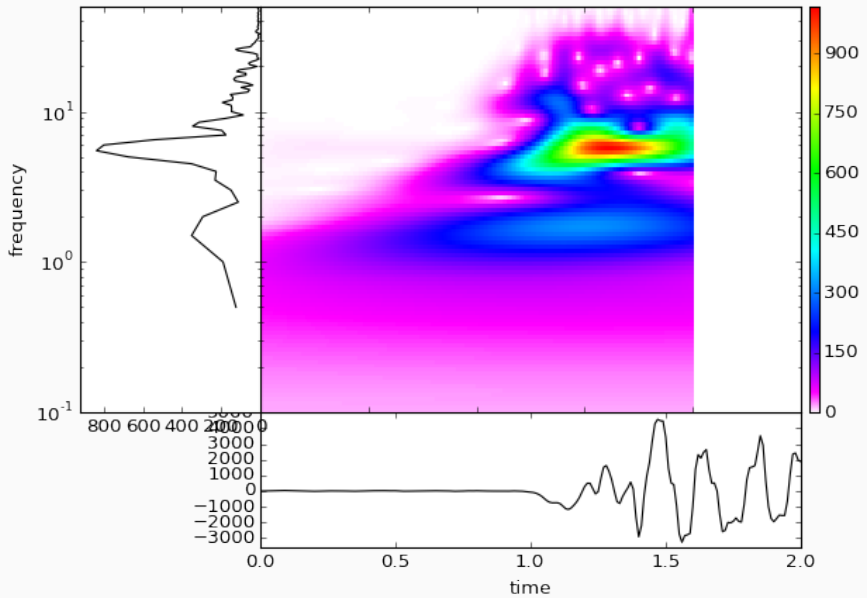

Figure 6: Data and frequency analysis, centered on arrival.

Body-wave wavelets

The wavelet parameters:

- onset estimated by correlation based CF,
- length estimated by time-frequency analysis.

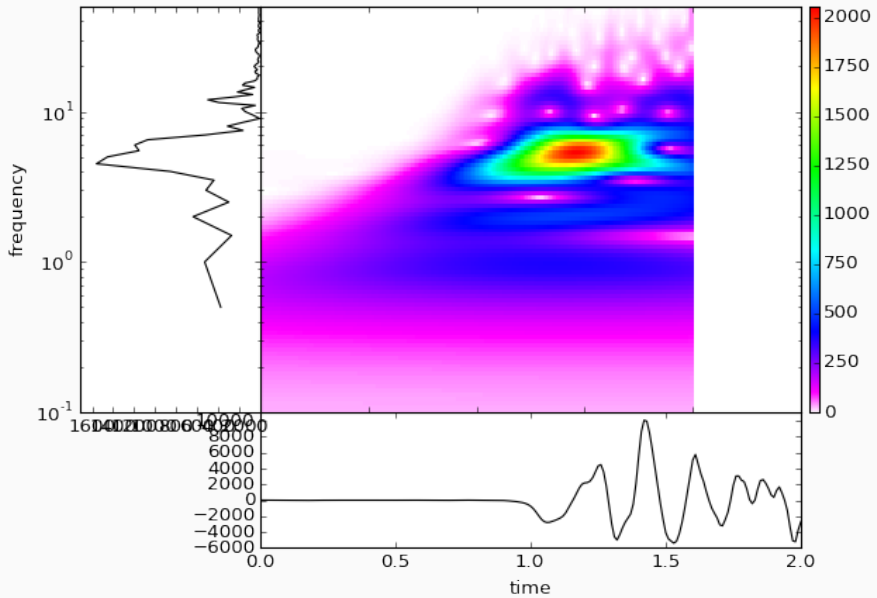

Figure 6: Data and frequency analysis, centered on arrival.

Source models

The moment tensor components spaces:

- polarities of P, S_V, S_H => double-couple component,

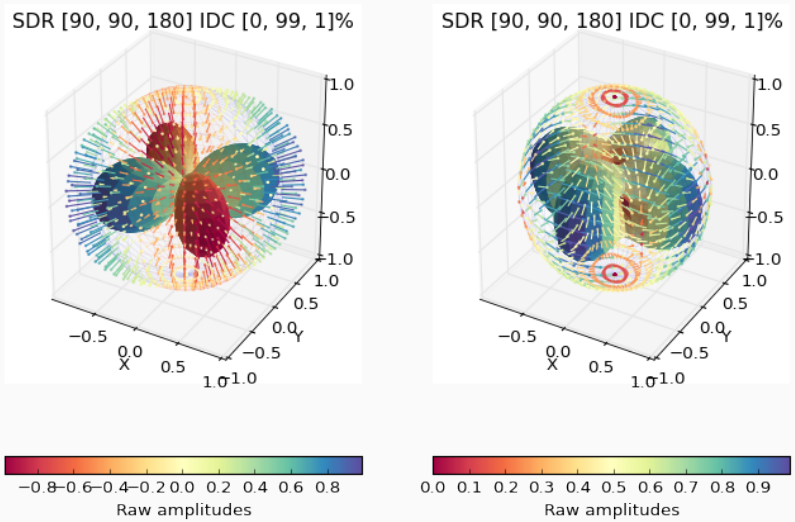

Figure 7: Source model, P & S waves displacements [1].

Source models

The moment tensor components spaces:

- polarities of P, S_V, S_H => double-couple component,

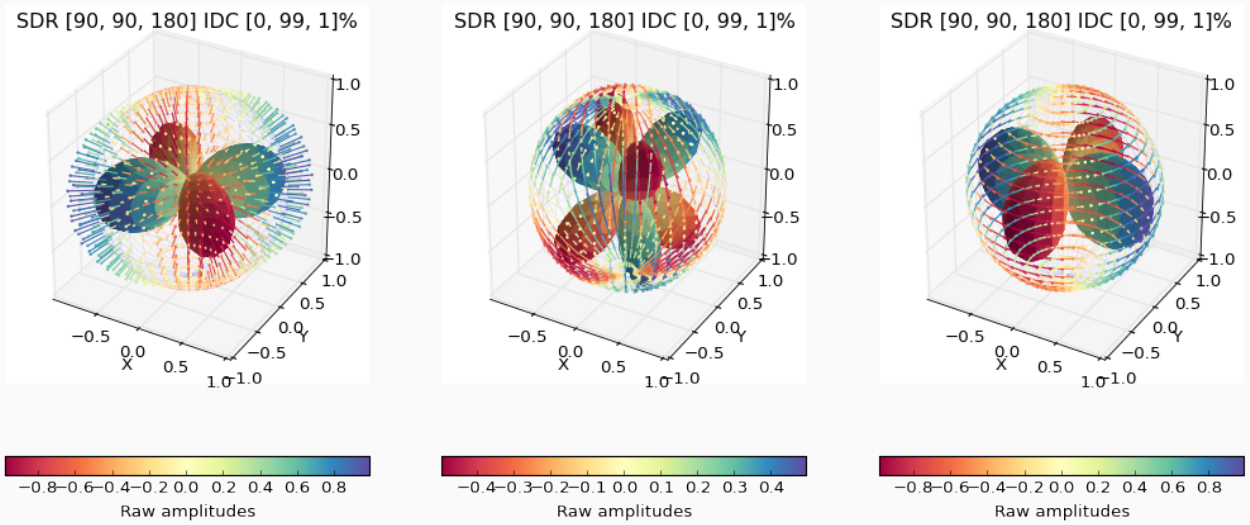

Figure 7: Source model, P, S_V & S_H waves displacements [1].

Source models

The moment tensor components spaces:

- polarities of P, S_V, S_H => double-couple component,

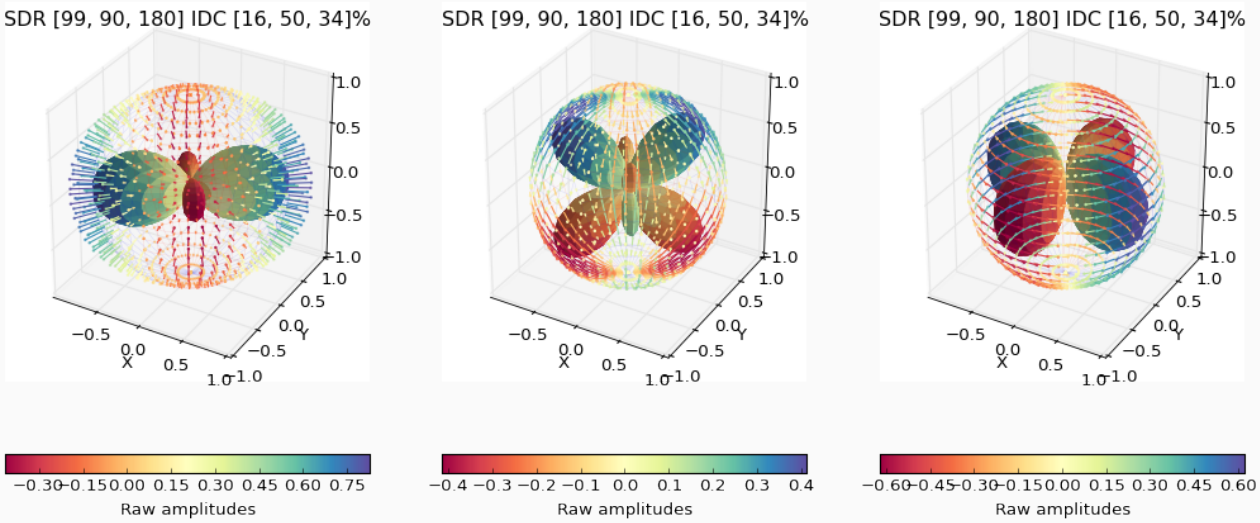

Figure 7: Source model, P, S_V & S_H waves displacements [1].

Source models

The moment tensor components spaces:

- polarities of P, S_V, S_H => double-couple component,

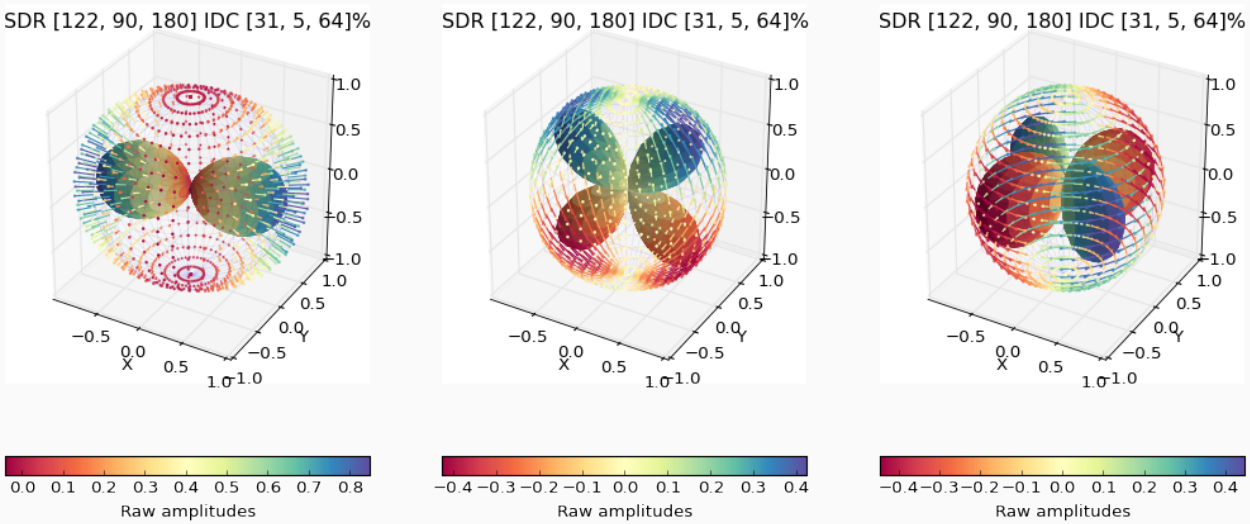

Figure 7: Source model, P, S_V & S_H waves displacements [1].

Source models

The moment tensor components spaces:

- polarities of P, S_V, S_H => double-couple component,
- ratios of P, S_V, S_H => tensile component.

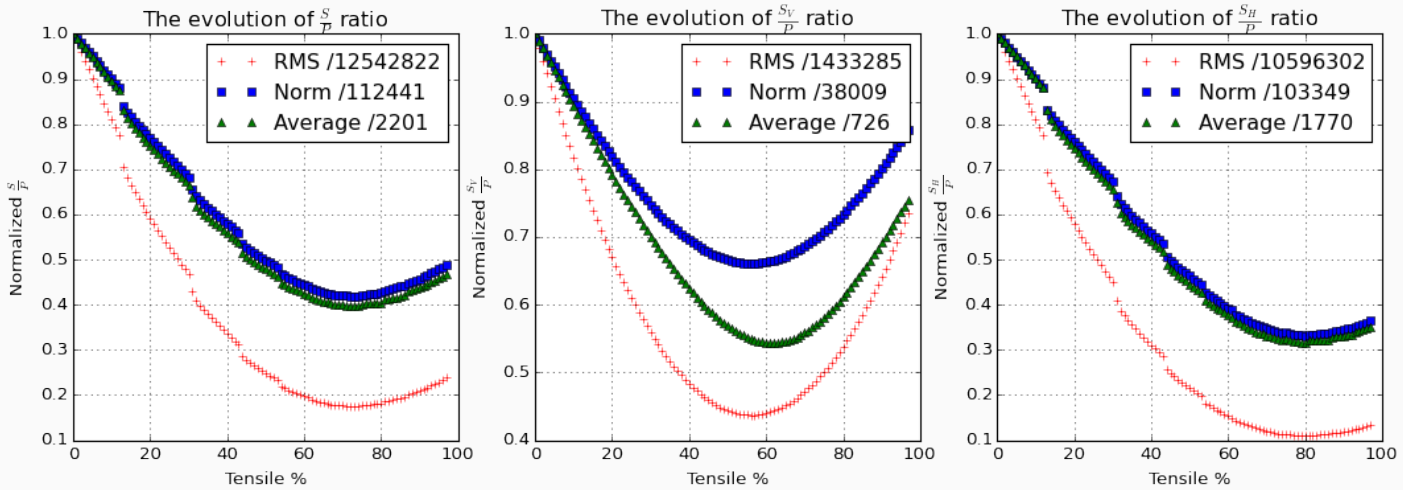

Figure 7: $\frac{S}{P}$, $\frac{S_V}{P}$ & $\frac{S_H}{P}$ from double couple to tensile source models.

Conclusion

Summary

We are obtaining:

- precise body-wave characteristic functions,
- automatic wavelets extractions,
- source mechanism scanning approach.

Summary

We are obtaining:

- precise body-wave characteristic functions,
- automatic wavelets extractions,
- source mechanism scanning approach.

We are aiming at:

- estimating applicability,
- interfacing SSA with the source mechanism scanner,
- a broader earthquake scanner approach.

Questions?

References I

[1] Keiiti Aki and Paul G Richards.
Quantitative Seismology.
2nd Edition. University Science Books, 2 edition, 2002.

[2] W B Frank and N M Shapiro.
Automatic detection of low-frequency earthquakes (LFEs) based on a beamformed network response.
Geophysical Journal International, 197(2):1215–1223, April 2014.

[3] Maxime Godano, Pascal Bernard, and Pierre Dublanchet.
Bayesian inversion of seismic spectral ratio for source scaling. Application to a persistent multiplet in the Western Corinth rift.
Journal of Geophysical Research, 2015.

References II

[4] Honn Kao and Shao-Ju Shan.
The Source-Scanning Algorithm: mapping the distribution of seismic sources in time and space.
Geophysical Journal International, 157(2):589–594, May 2004.

[5] Nadège Langet, Alessia Maggi, Alberto Michelini, and Florent Brenguier.
Continuous Kurtosis-Based Migration for Seismic Event Detection and Location, with Application to Piton de la Fournaise Volcano, La Réunion.
Bulletin of the Seismological Society of America, 104(1):229–246, February 2014.

References III

[6] Frédérick Massin, Jamie Mark Farrell, and Robert B Smith.
Repeating earthquakes in the Yellowstone volcanic field: Implications for rupture dynamics, ground deformation, and migration in earthquake swarms.
Journal of Volcanology and Geothermal Research, 257:159–173, May 2013.

[7] K Nagano, H Niitsuma, and N Chubachi.
Automatic algorithm for triaxial hodogram source location in downhole acoustic emission measurement.
Geophysics, 54(4):508–513, 1989.

References IV

[8] David R Shelly, David P Hill, Frédérick Massin, Jamie Mark Farrell, Robert B Smith, and Taka'aki Taira.
A fluid-driven earthquake swarm on the margin of the Yellowstone caldera.
Journal of Geophysical Research: Solid Earth, 118(9):4872–4886, September 2013.

[9] D Sarah Stamps and Robert Smalley.
Strings and Things for Locating Earthquakes.
Seismological Research Letters, 77(6):677–683, November 2006.

[10] Felix Waldhauser and W L Ellsworth.
A Double-Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, California.
Bulletin of the Seismological Society of America, 90(6):1353–1368, 2000.

References V

[11] J Zahradník, J Janský, and V Plicka.
Analysis of the source scanning algorithm with a new P-wave picker.
Journal of Seismology, 19(2):423–441, 2015.