Energy Rate Functions: An Overview of HHT-based Earthquake Source Characterization using Strong Motion Data

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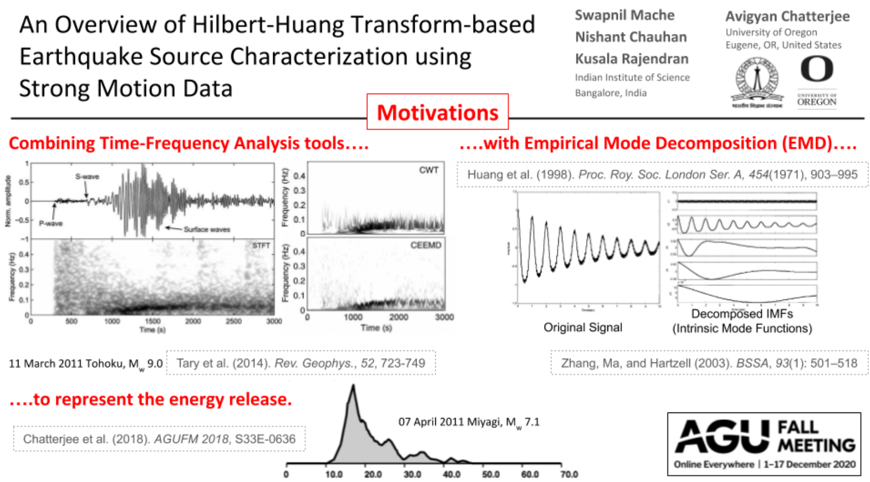
Abstract

Subduction zone earthquakes show varying energy release patterns and frequency content, based on their tectonic settings and hypocentral depths. Resolving these features from the nonlinear and non-stationary seismograms is a challenge. Our work in the Japan Trench follows studies by Huang et al. (1998, 2001) and Zhang et al. (2003), who demonstrated the use of empirical mode decomposition to separate records into multiple timescales, or intrinsic mode functions (IMFs). Zhang et al. observed that IMFs 2-5 represented the source rupture process for the 1994 Northridge earthquake. Chauhan (master's thesis, 2019) used time-frequency distributions, short-time Fourier and continuous wavelet transforms, of IMFs of strong-motion data for a pair of interplate-intraslab earthquakes to identify the dominant, short duration, low-frequency energy release for the intraslab event. He found a high correlation between the original signal and a linear combination of IMFs 3 and 4, possibly representing the source. Chatterjee et al. (AGU, 2018) observed an association between time-frequency-energy distributions of certain IMFs and moment rate functions (MRFs) from teleseismic waveform models, for five earthquakes. Chatterjee et al. (AGU, 2019) and Mache et al. (AGU, 2019) used Hilbert spectral analysis (Huang et al., 1998) of IMFs selected based on their frequency and energy and observed better match between the two. This new function, which they regard as the Energy Rate Function (ERF), can reproduce the MRF's essential elements, i.e., its duration and shape, but Mache (master's thesis, 2020) observed that results depended on the selection of stations. As the next step, Mache and Rajendran (JpGU-AGU, 2020) based the selection criteria on the slip distribution, strike, and JMA intensity distribution maps (JMA 1996) and applied the method to 7 earthquakes from various tectonic settings of the Japan Trench. Here we present an overview of the various methods for analyzing KiK-net strong-motion data for selected earthquakes to extract information on their time-frequency-energy distributions. The ERF generated through this analysis is a physically compatible expression of the MRF and, therefore, more useful in predicting the shaking effects of earthquakes.



An Overview of Hilbert-Huang Transform-based Earthquake Source Characterization using Strong Motion Data
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Motivations
Combining Time-Frequency Analysis tools….
….with Empirical Mode Decomposition (EMD)….
Huang et al. (1998). Proc. Roy. Soc. London Ser. A, 454(1971), 903–995
S-wave
P-wave
Surface waves
CWT
STFT
CEEMD
Time (s)
Original Signal
Decomposed IMFs
(Intrinsic Mode Functions)
11 March 2011 Tohoku, Mw 9.0
Tary et al. (2014). Rev. Geophys., 52, 723-749
Zhang, Ma, and Hartzell (2003). BSSA, 93(1): 501–518
….to represent the energy release.
Chatterjee et al. (2018). AGUFM 2018, S33E-0636
07 April 2011 Miyagi, Mw 7.1
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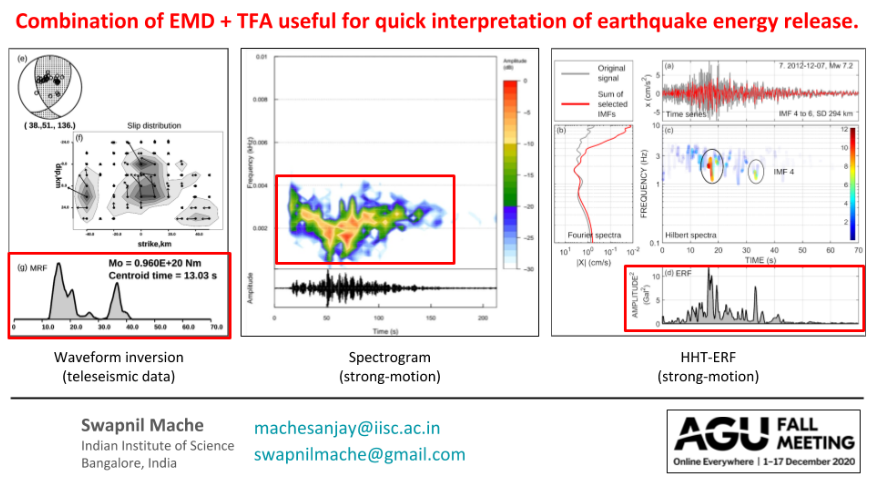

Combination of EMD + TFA useful for quick interpretation of earthquake energy release.
Slip distribution
Mo = 0.960E+20 Nm
Centroid time = 13.03 s
Waveform inversion
(teleseismic data)
Spectrogram
(strong-motion)
HHT-ERF
(strong-motion)
Hilbert spectra
Fourier spectra
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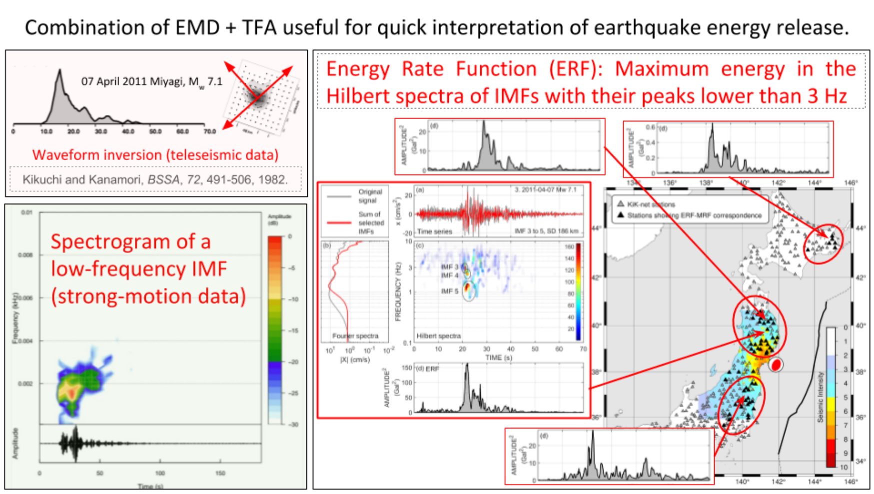

Combination of EMD + TFA useful for quick interpretation of earthquake energy release.
07 April 2011 Miyagi, Mw 7.1
Waveform inversion (teleseismic data)
Kikuchi and Kanamori, BSSA, 72, 491-506, 1982.
Spectrogram of a low-frequency IMF (strong-motion data)
Energy Rate Function (ERF): Maximum energy in the Hilbert spectra of IMFs with their peaks lower than 3 Hz
KiK-net stations
Stations showing ERF-MRF correspondence
Seismic Intensity

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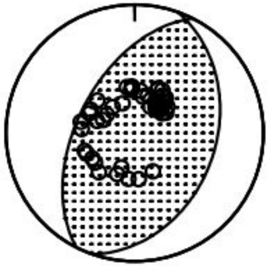
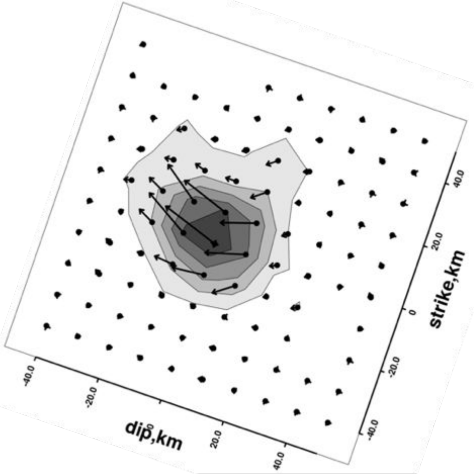
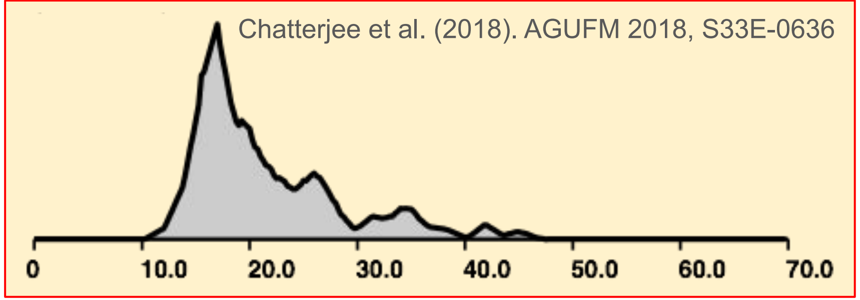




07 April 2011

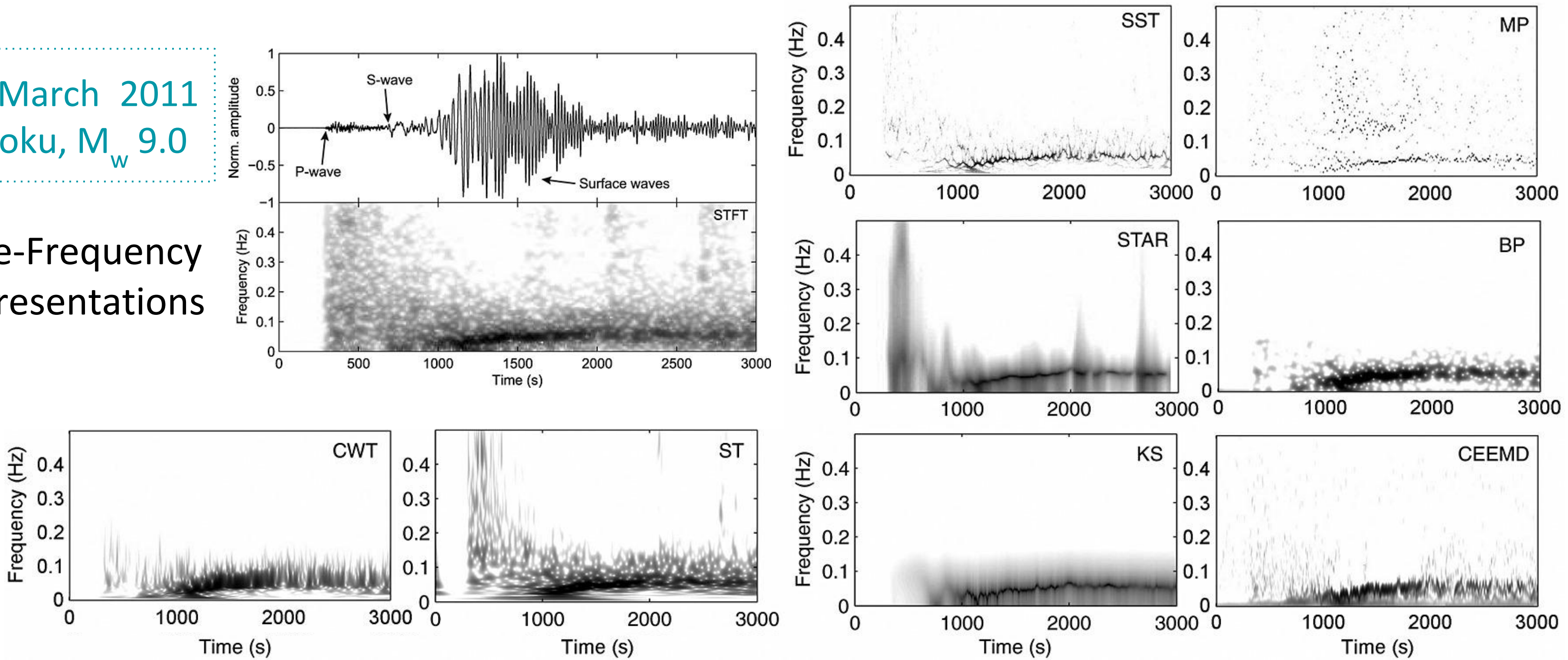
Miyagi, M_w 7.1



Harnessing **time-frequency analysis tools** + empirical mode decomposition to represent energy release

11 March 2011
Tohoku, M_w 9.0

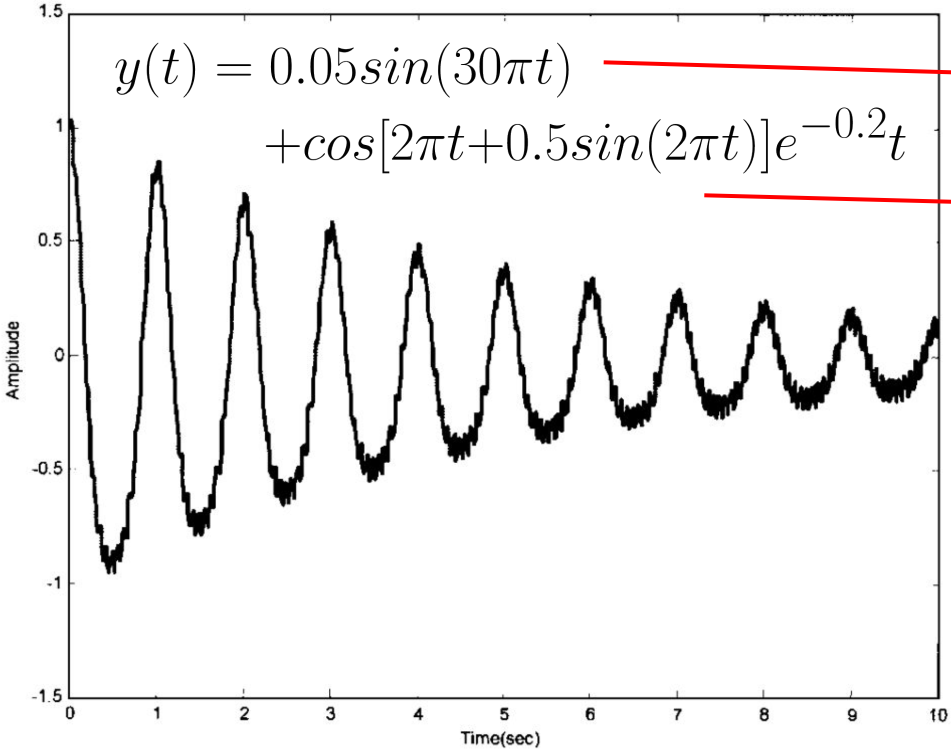
Time-Frequency Representations



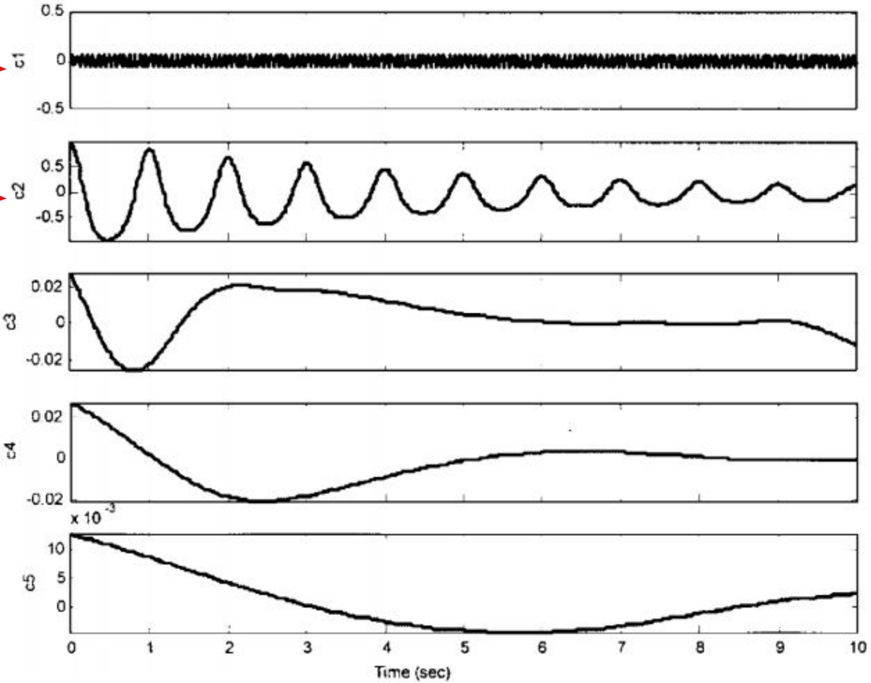
Tary et al. (2014). *Rev. Geophys.*, 52, 723-749

Harnessing time-frequency analysis tools + **empirical mode decomposition** to represent energy release

$$y(t) = 0.05sin(30\pi t) + cos[2\pi t + 0.5sin(2\pi t)]e^{-0.2t}$$



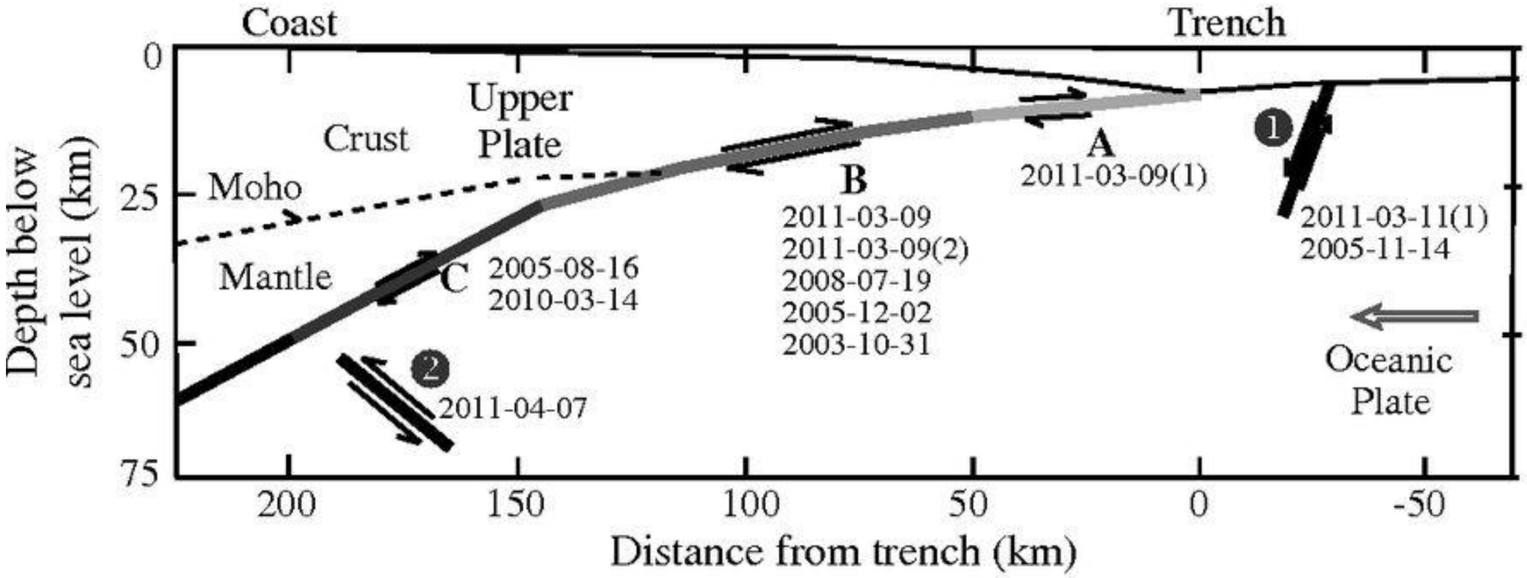
Signal y(t)



Intrinsic Mode Functions

Zhang, Ma, and Hartzell (2003). BSSA, 93 (1): 501–518

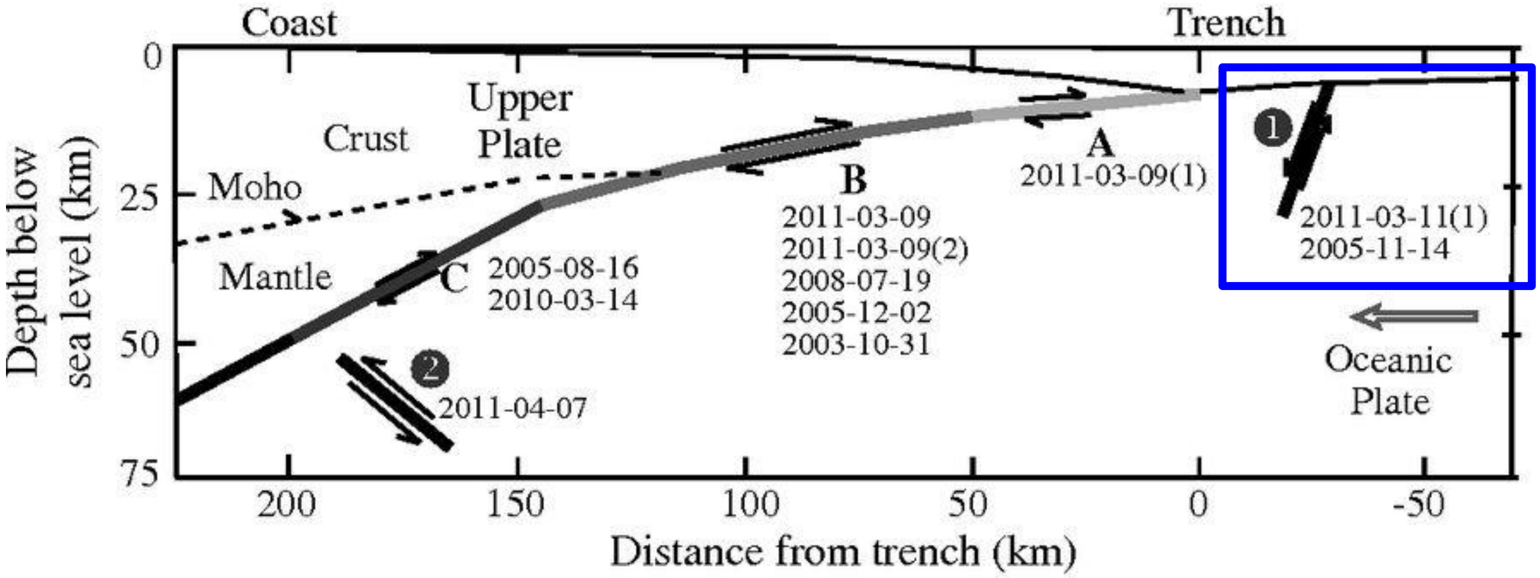
Heterogeneous energy-release and frequency content depending on tectonic setting and depth



Ye, Lay, and Kanamori (2013). BSSA, 103, 1221-1241

Heterogeneous energy-release and frequency content depending on tectonic setting and depth

Intraplate



Ye, Lay, and Kanamori (2013). BSSA, 103, 1221-1241

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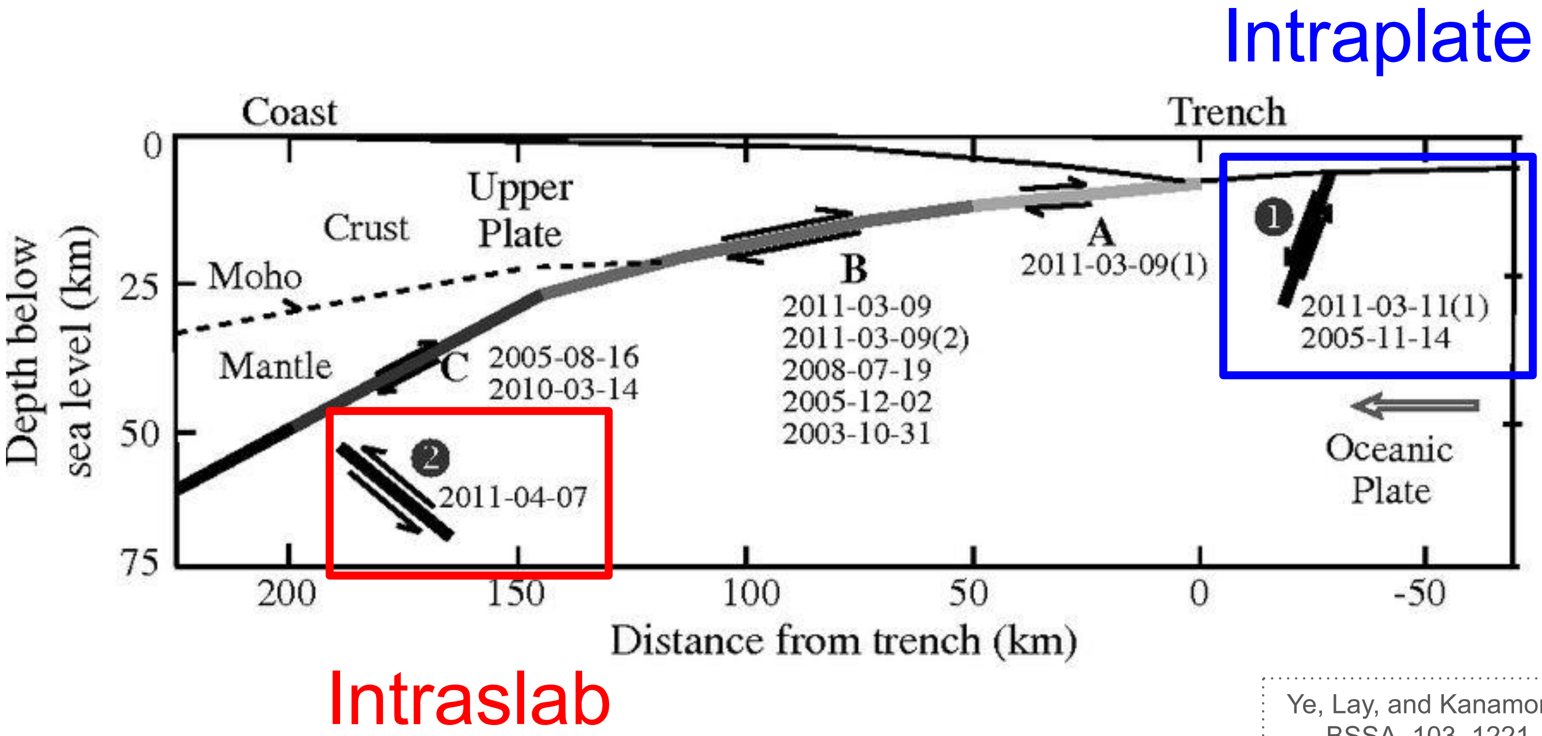

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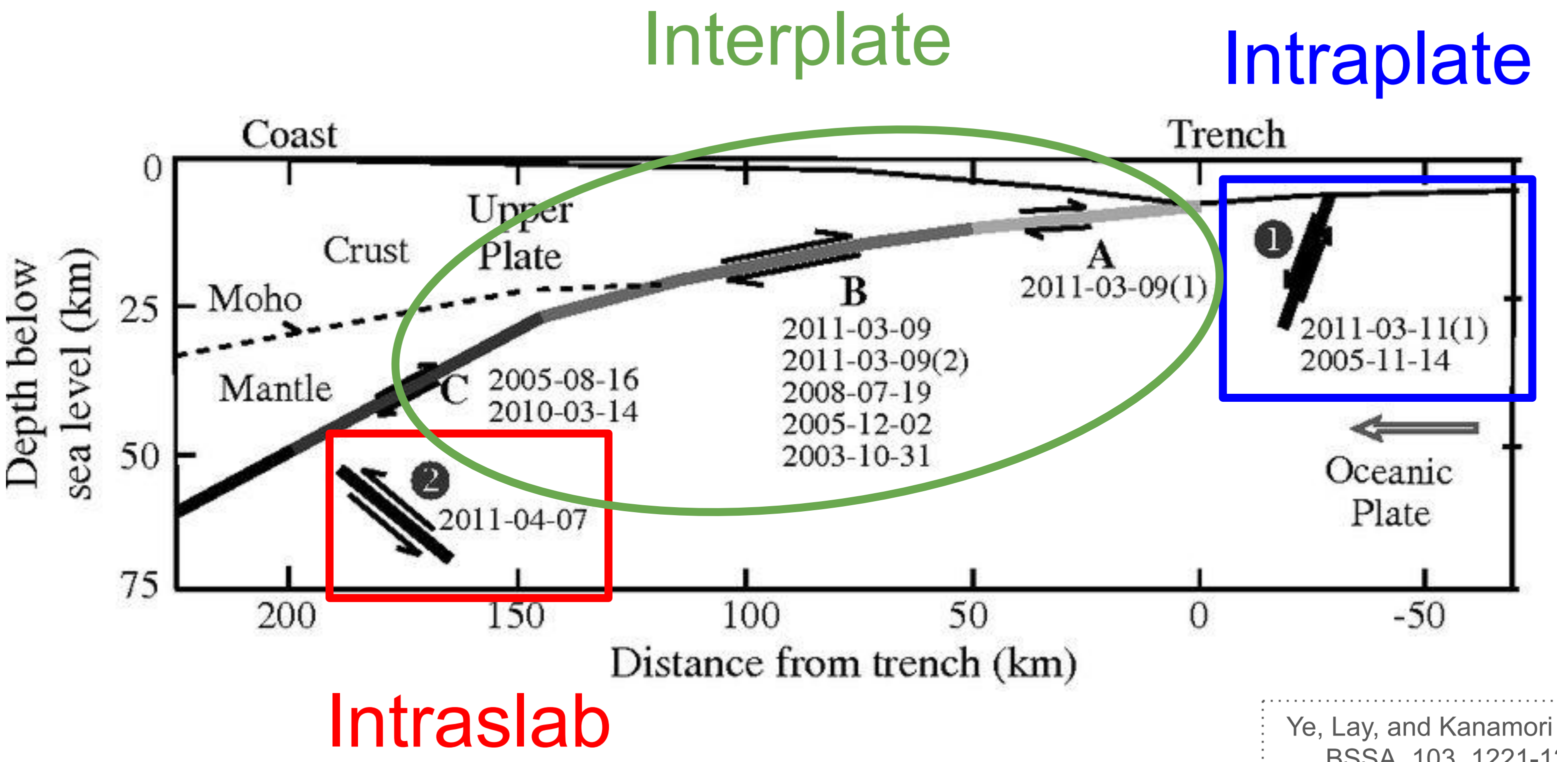
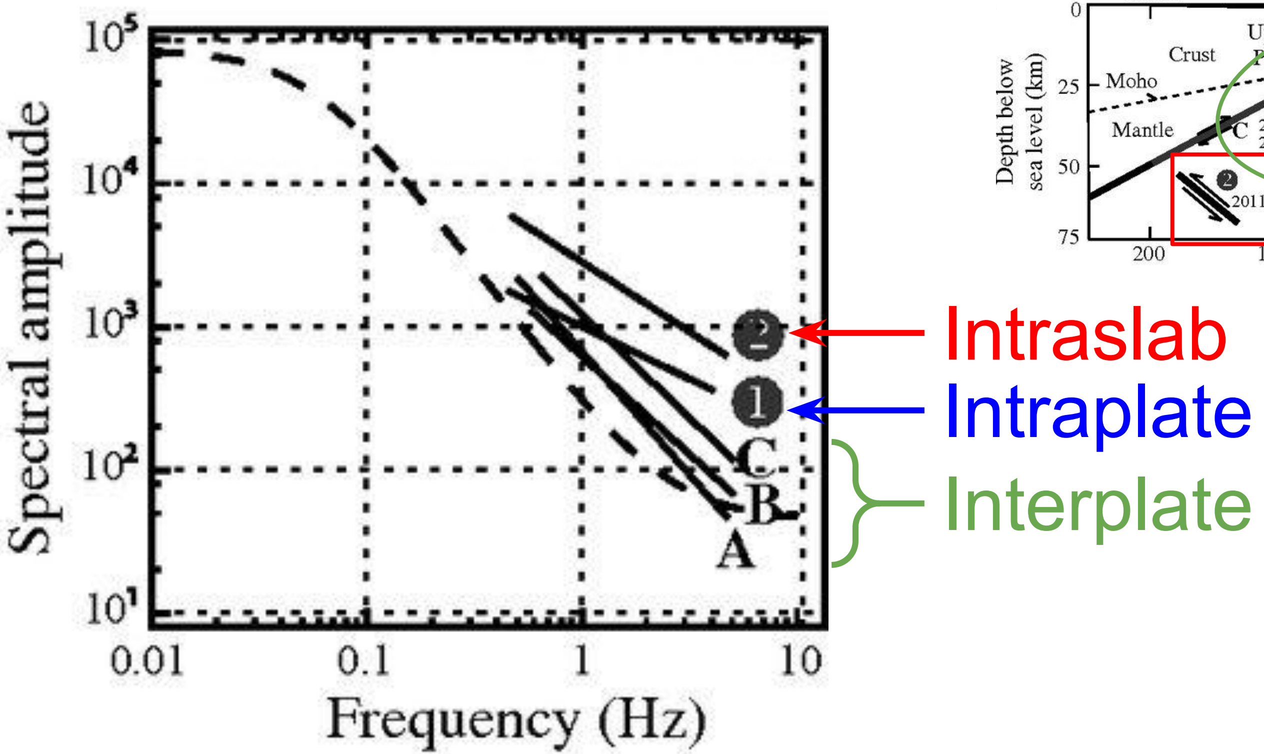
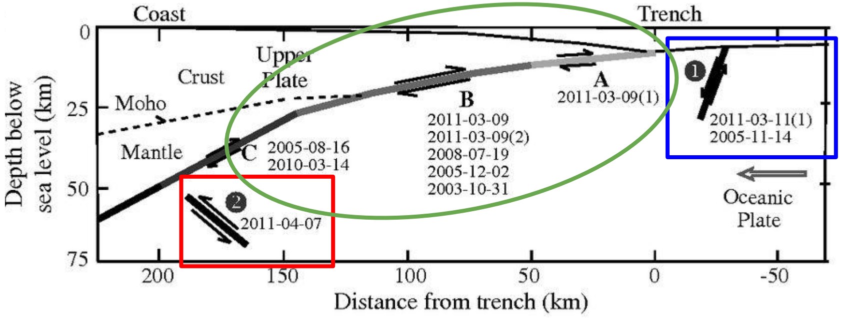


Ye, Lay, and Kanamori (2013). BSSA, 103, 1221-1241

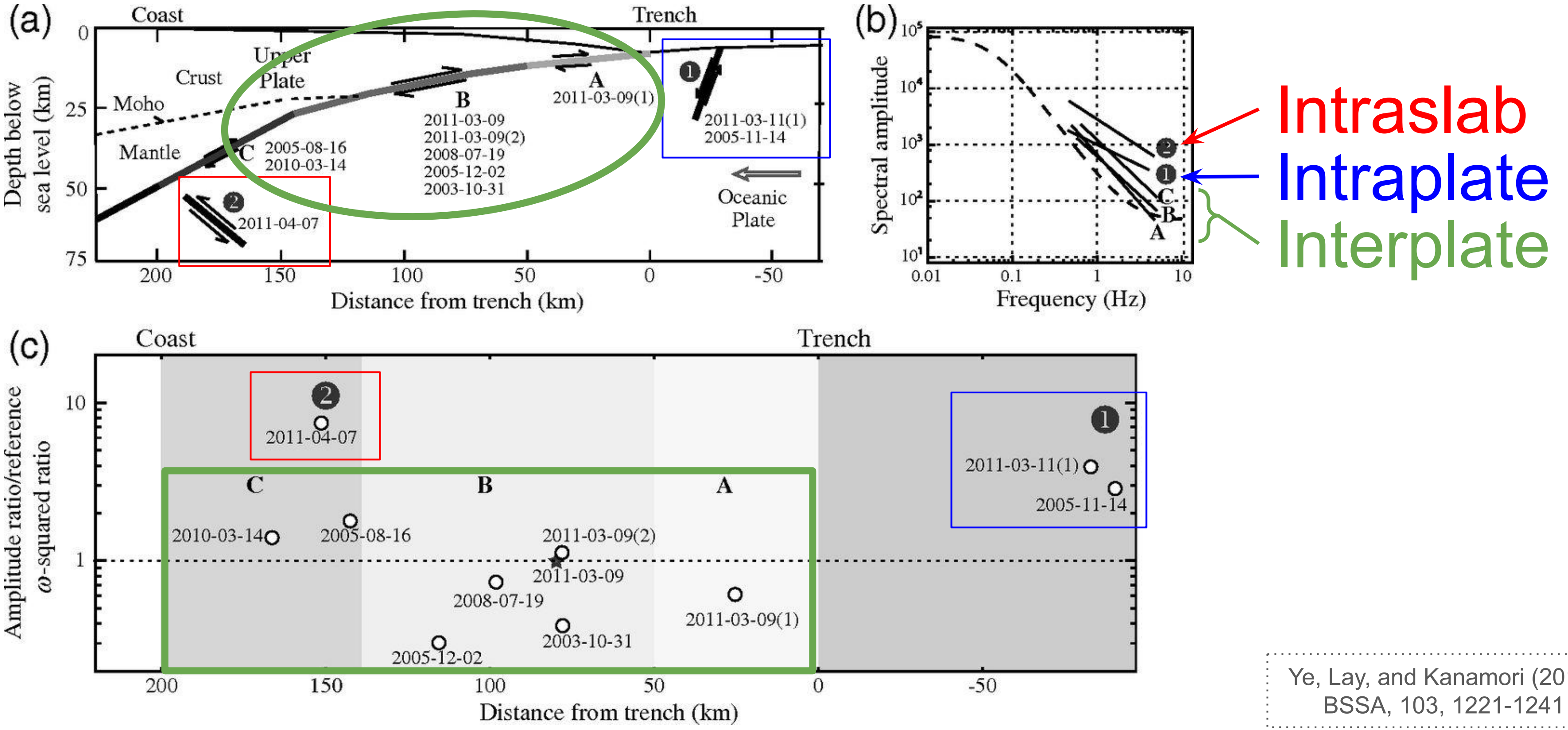
Spectral amplitudes: Interplate < Intraplate < Intraslab





Ye, Lay, and Kanamori (2013). BSSA, 103, 1221-1241

Interplate: increasing high-frequency energy and energy/moment with depth



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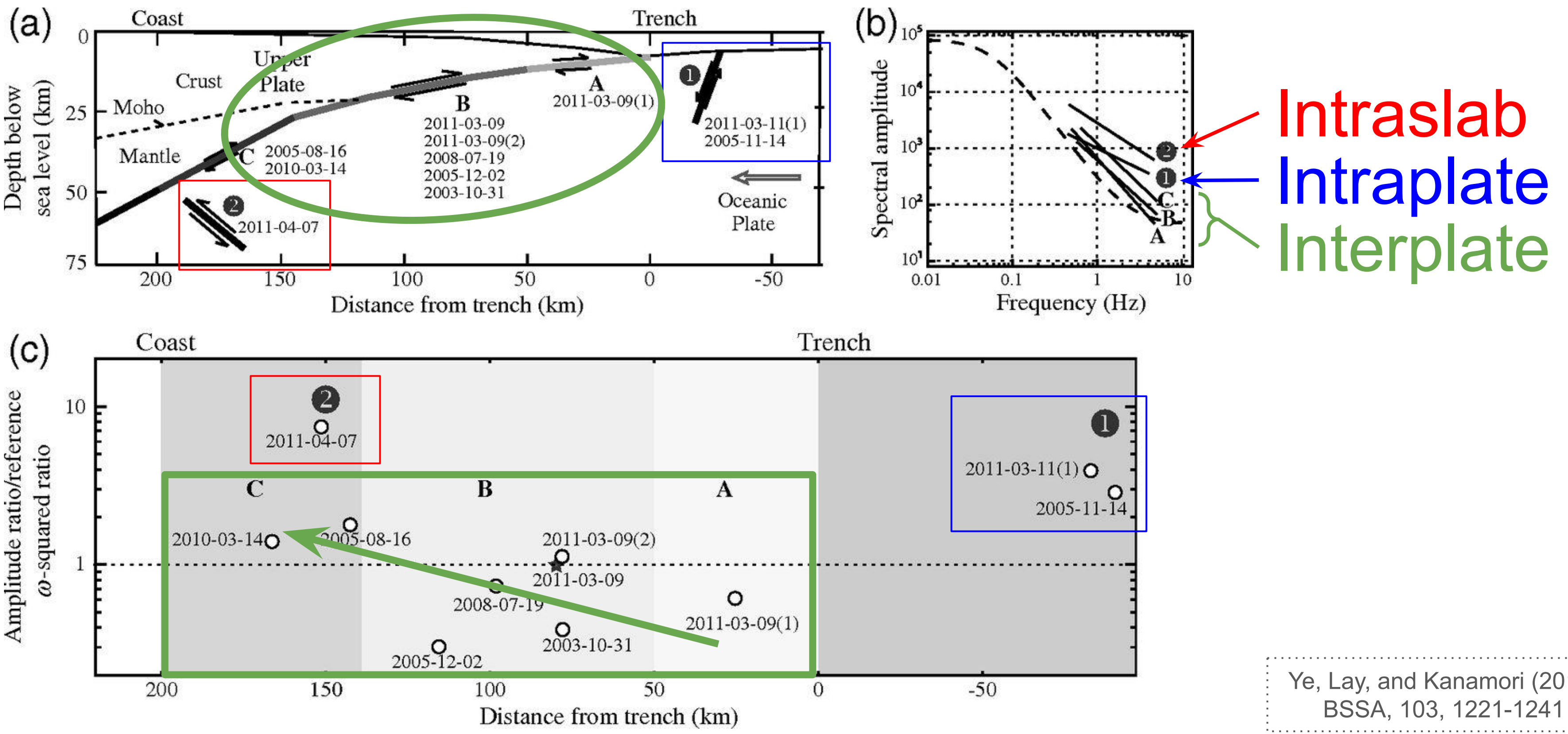
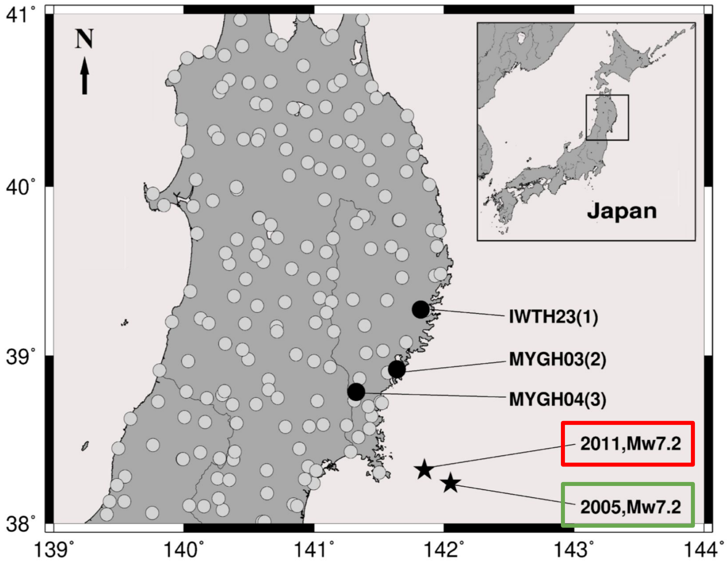
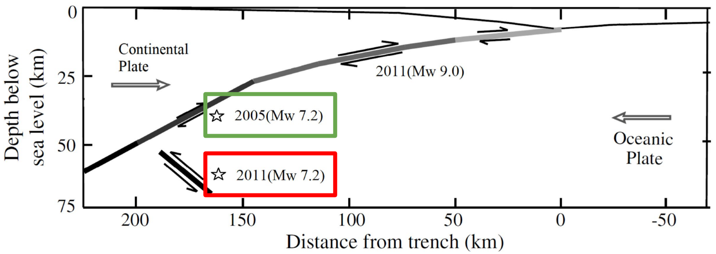
Interplate: increasing high-frequency energy and energy/moment with depth



Ye, Lay, and Kanamori (2013). BSSA, 103, 1221-1241

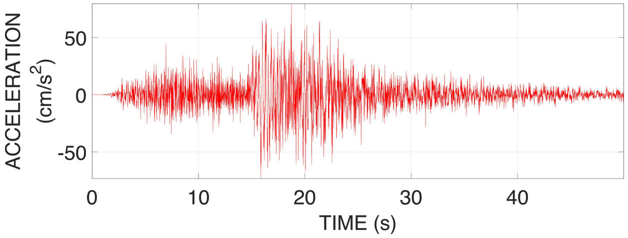
Time-frequency analysis of intrinsic mode functions decomposed from earthquake strong-motion data

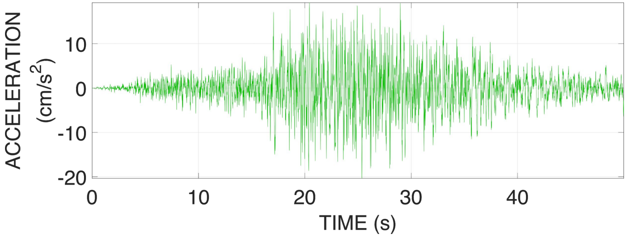


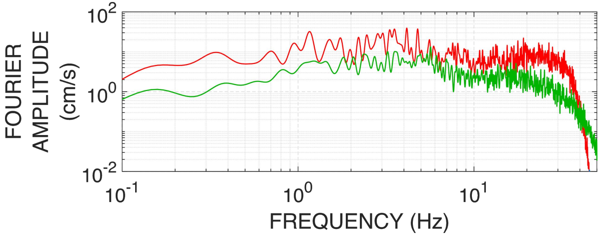


Intraslab

Interplate

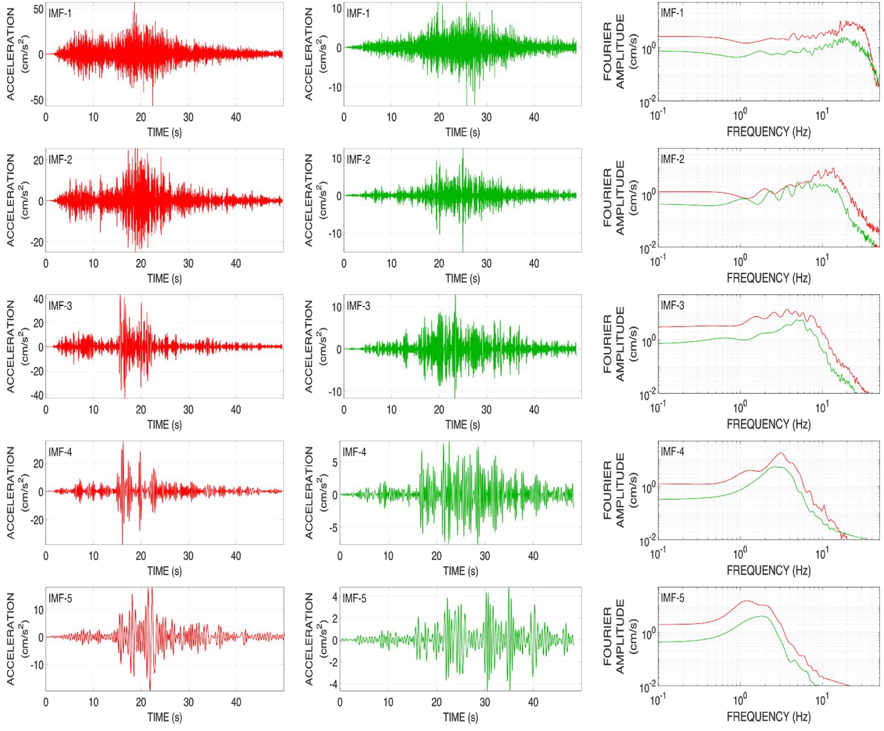




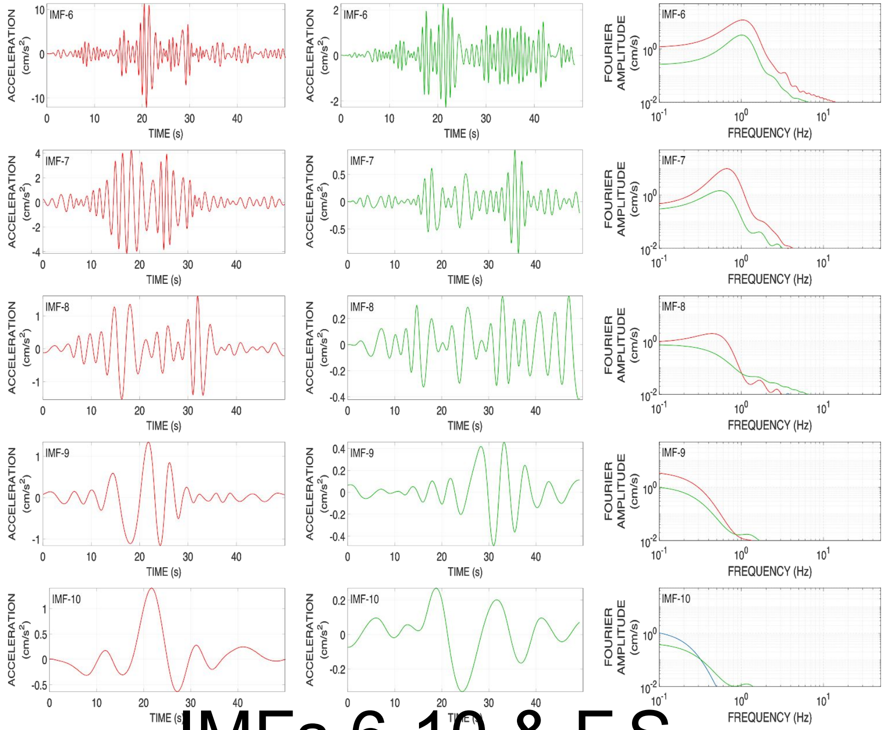


Chauhan (2019) Master's thesis, Indian Institute of Science, Bangalore, India

Time-frequency analysis of intrinsic mode functions decomposed from earthquake strong-motion data



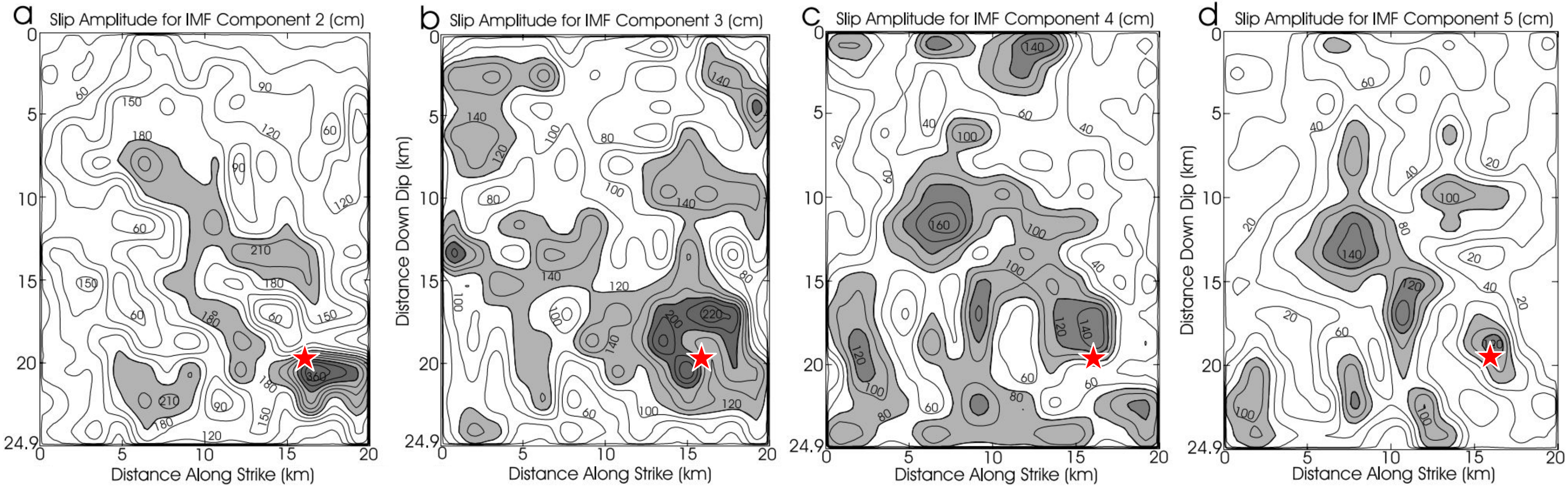
IMFs 1-5 & Fourier Spectra



IMFs 6-10 & F.S.

Chauhan (2019) Master’s thesis, Indian Institute of Science, Bangalore, India

Studies show source signal contained in combination of IMFs



IMF 2

IMF 3

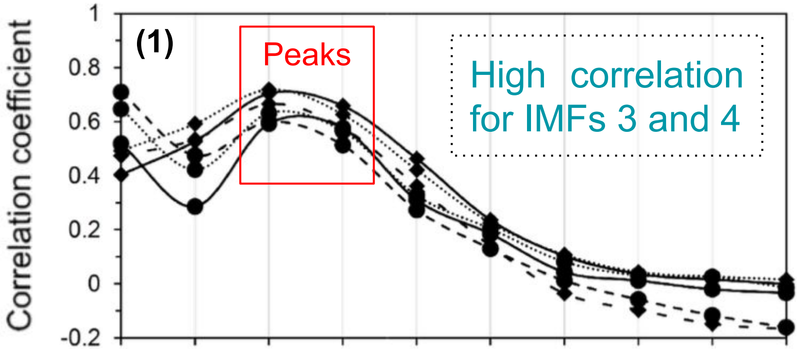
IMF 4

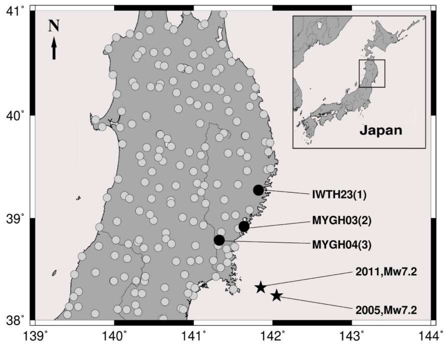
IMF 5

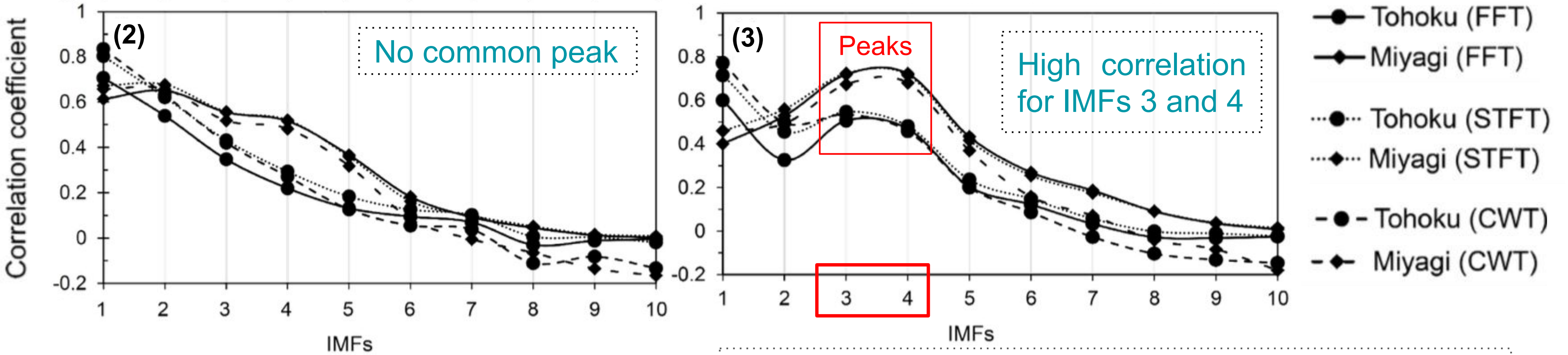
Progression of slip away from hypocenter from IMF 2 to 5

Zhang, Ma, and Hartzell (2003). BSSA, 93 (1): 501–518

High correlation between original signal and IMFs that best capture the original signal—possibly represent the source.

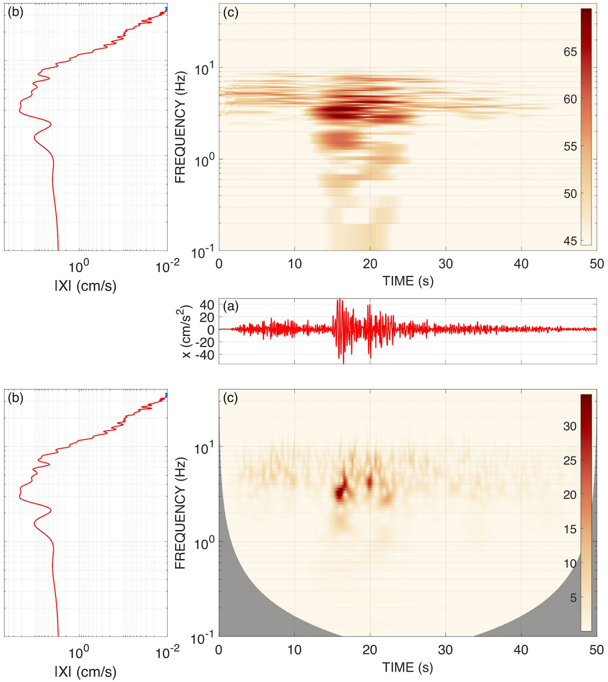






Chauhan (2019) Master's thesis, Indian Institute of Science, Bangalore, India

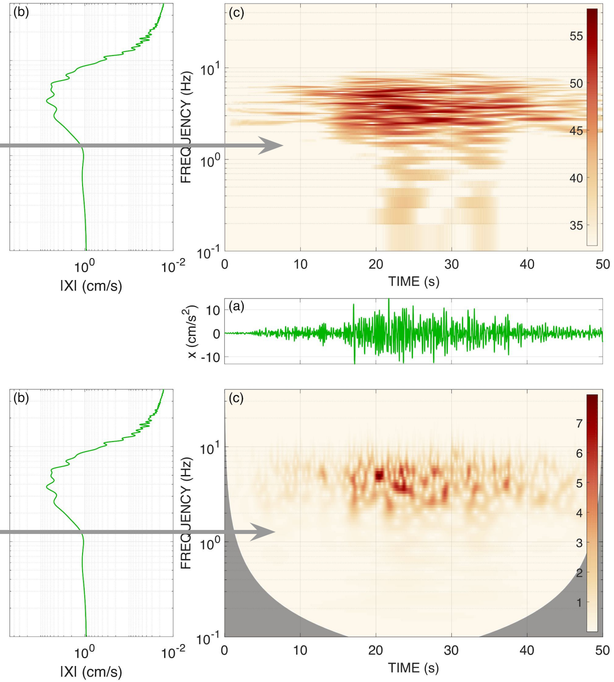
Linear combination of well-correlated IMFs gives a possible time-frequency representation of energy release.



Spectrograms

IMF 3 + 4

Scalograms

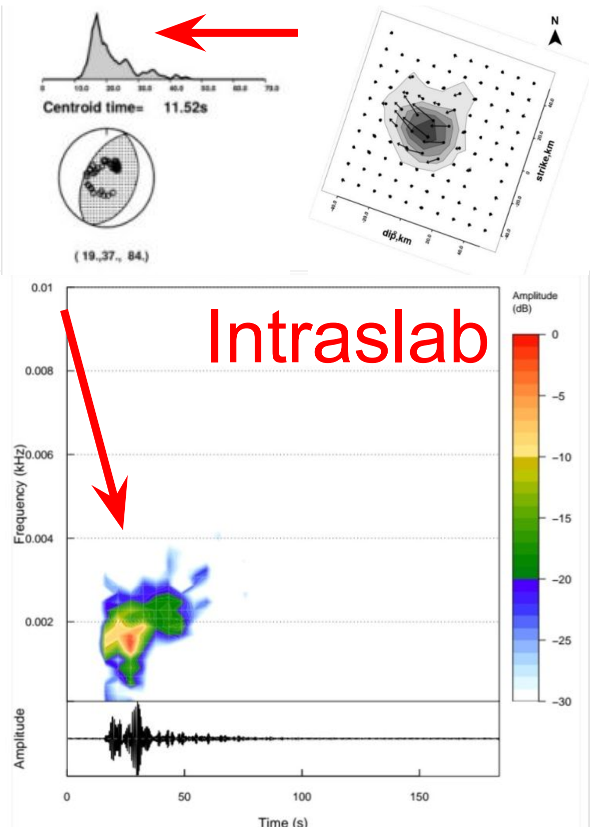


Intraslab

Interplate

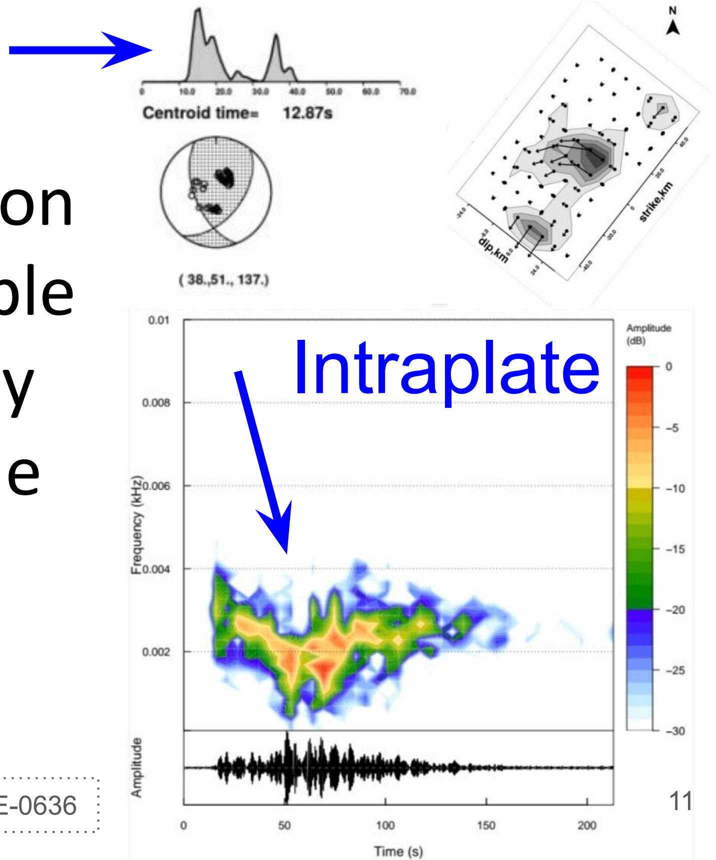
Chauhan (2019) Master's thesis, Indian Institute of Science, Bangalore, India

Joint study of teleseismic and strong-motion data connecting the energy release obtained from both



Shape and duration of MRF comparable with high-energy pulses & multiple patches in spectrograms

Chatterjee et al. (2018). AGUFM 2018, S33E-0636



Improved resolution using the Hilbert-Huang Transform (HHT) = EMD + Hilbert Spectral Analysis

Hilbert transform, $\hat{c}_k(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{c_k(\tau)}{(t-\tau)} d\tau$

Convolution with 1/t.
Focus on local properties of signal

Analytic signal, $c_k(t) + j\hat{c}_k(t) = a_k(t)e^{j\theta_k(t)}$

Amplitude $a_k(t)$ and frequency of each IMF as a *f*(time)

Instantaneous frequency, $\omega_k(t) = \frac{d\theta_k(t)}{dt}$

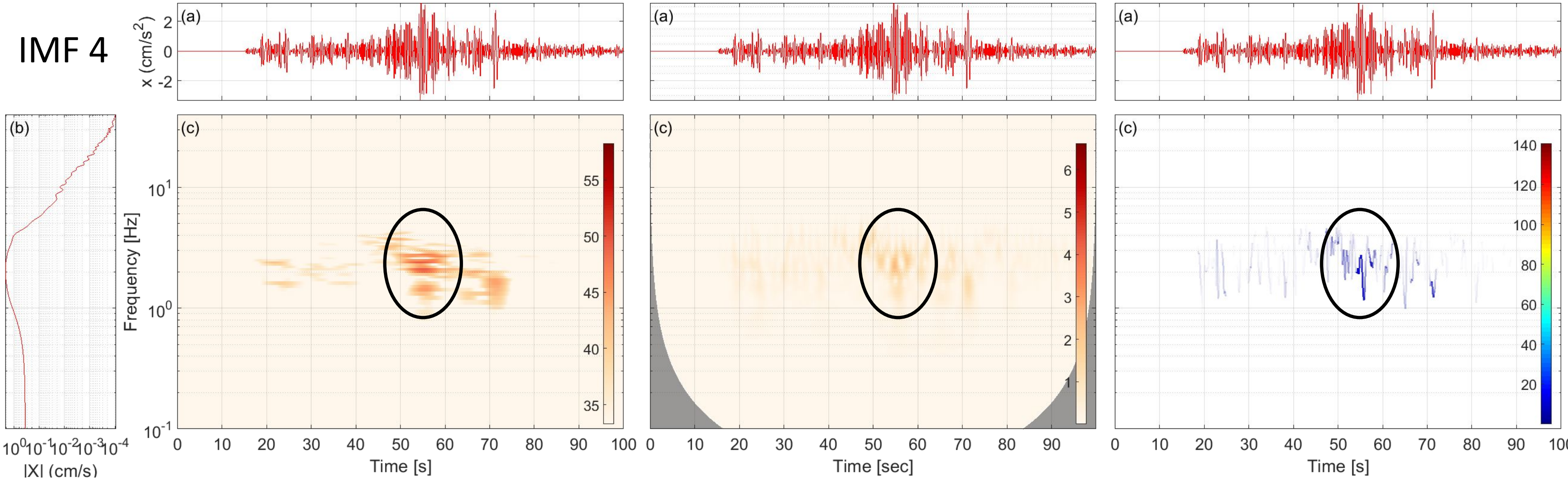
Local measure of frequency

Hilbert energy spectrum : **Amplitude² [$a^2_k(t)$]** values on time-frequency plane

Huang et al. (1998). Proc. Roy. Soc. London Ser. A, 454(1971), 903–995

HHT gives better resolution over spectrogram & scalogram

IMF 4



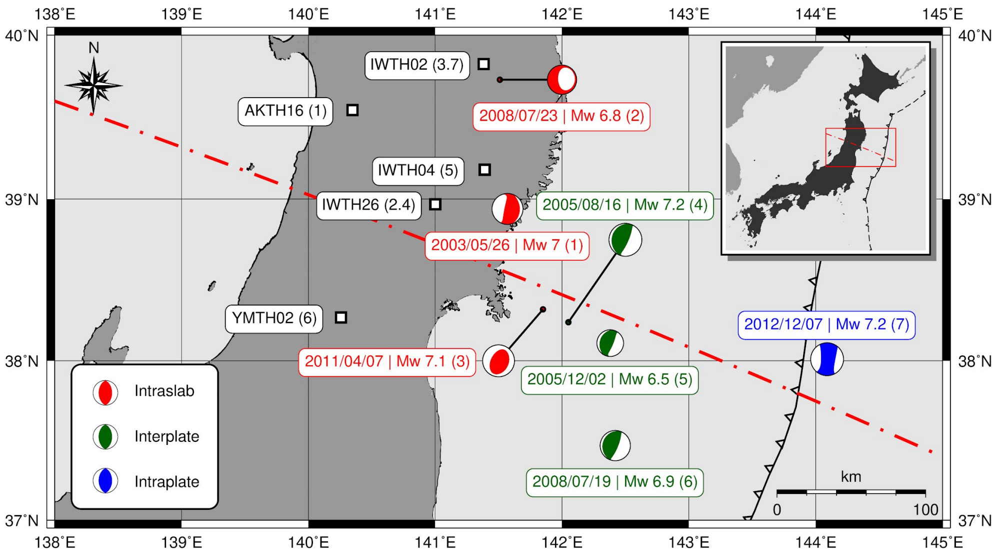
Spectrogram (STFT)

Scalogram (CWT)

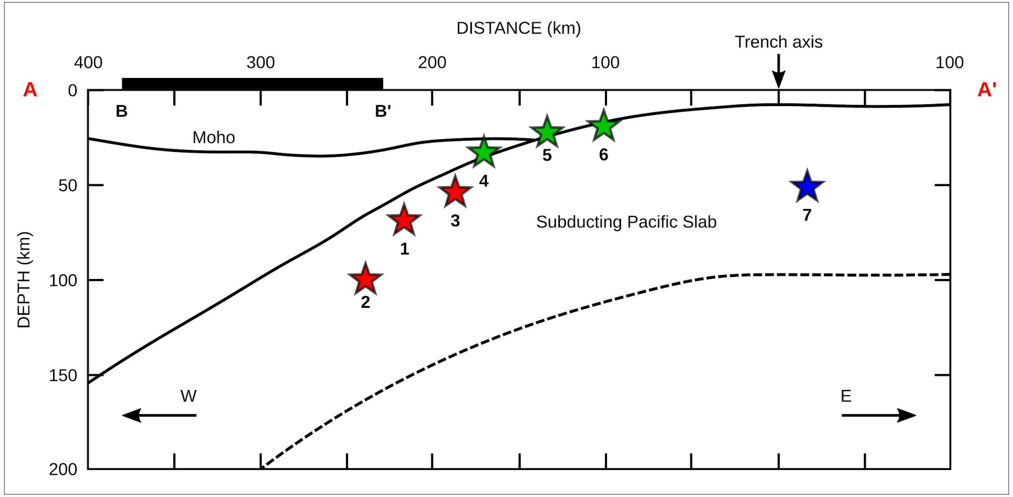
Hilbert Spectrum (HHT)

Improving resolution

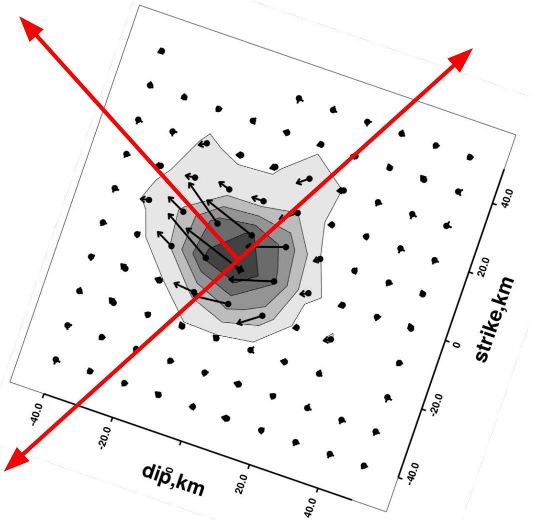
Proposing station and IMF-selection criteria and <u>expanding the analysis</u>



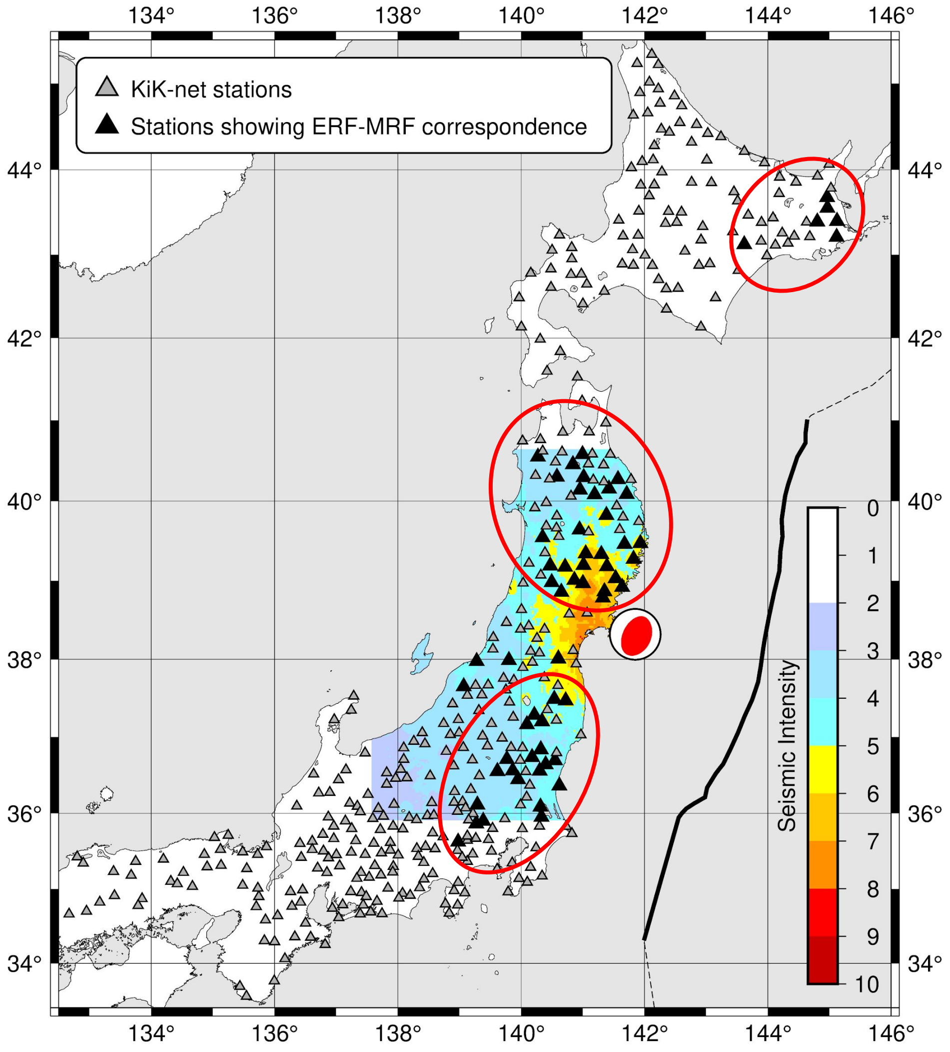
- Strong motion data (KiK-net, NIED, Japan)
- Borehole sensors (> 100 m)
- Vertical component



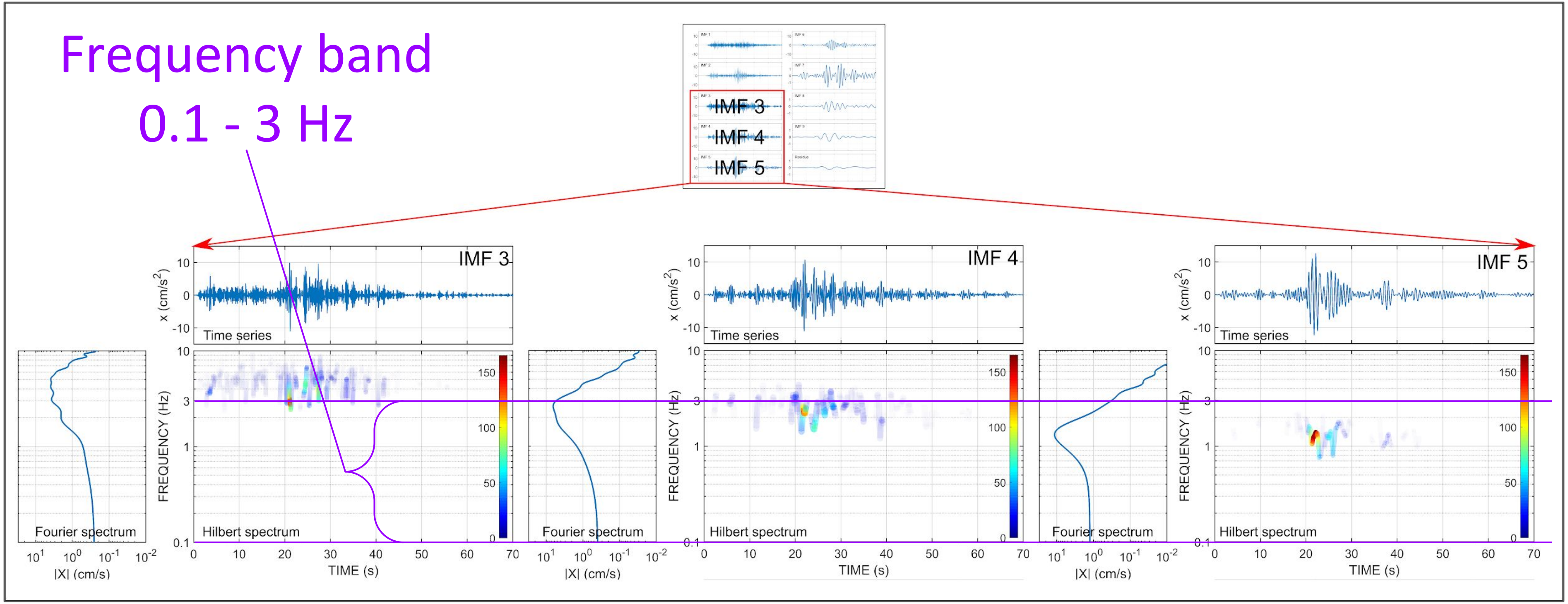
"Best" stations?
In the direction of rupture propagation and orthogonal to it.



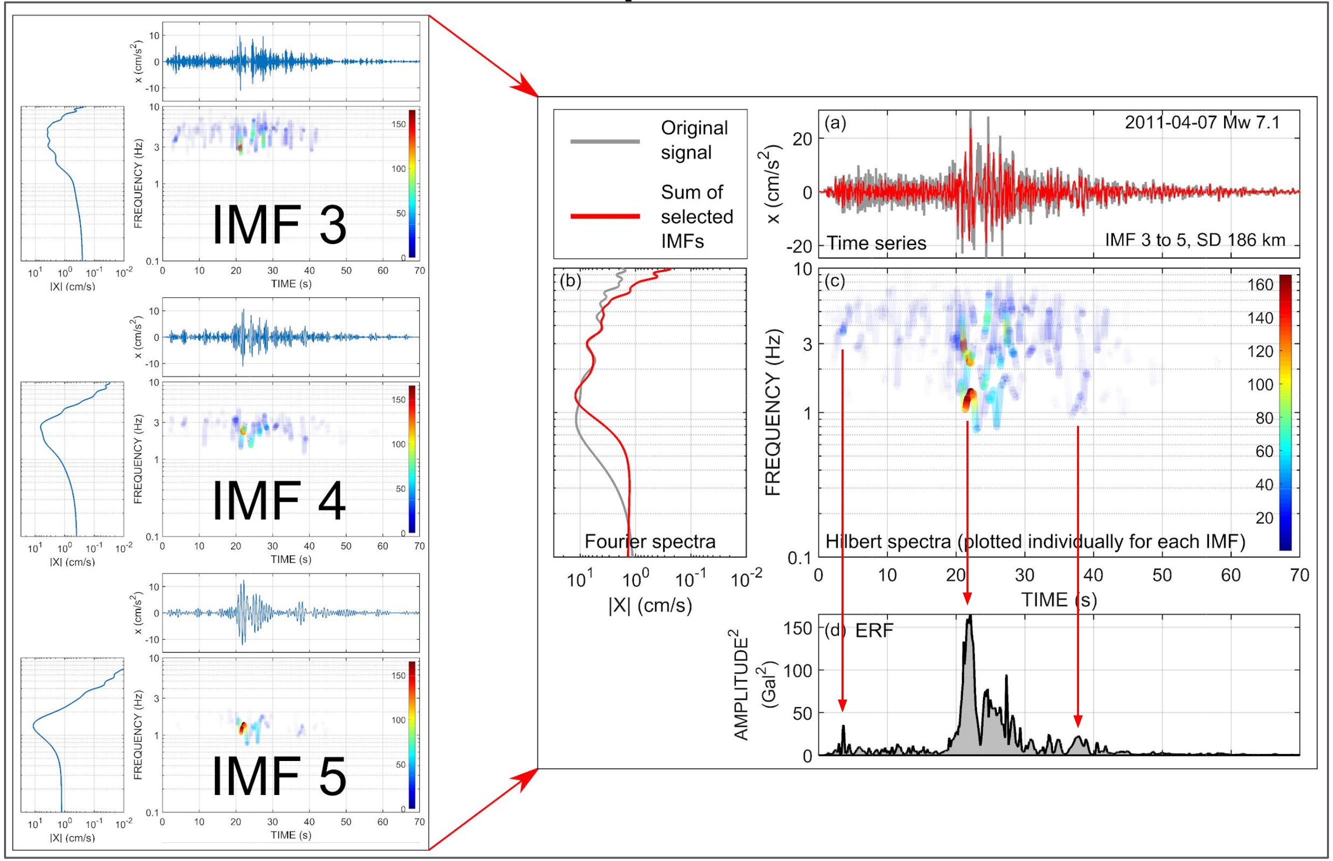
07 April 2011 Miyagi, M_w 7.1



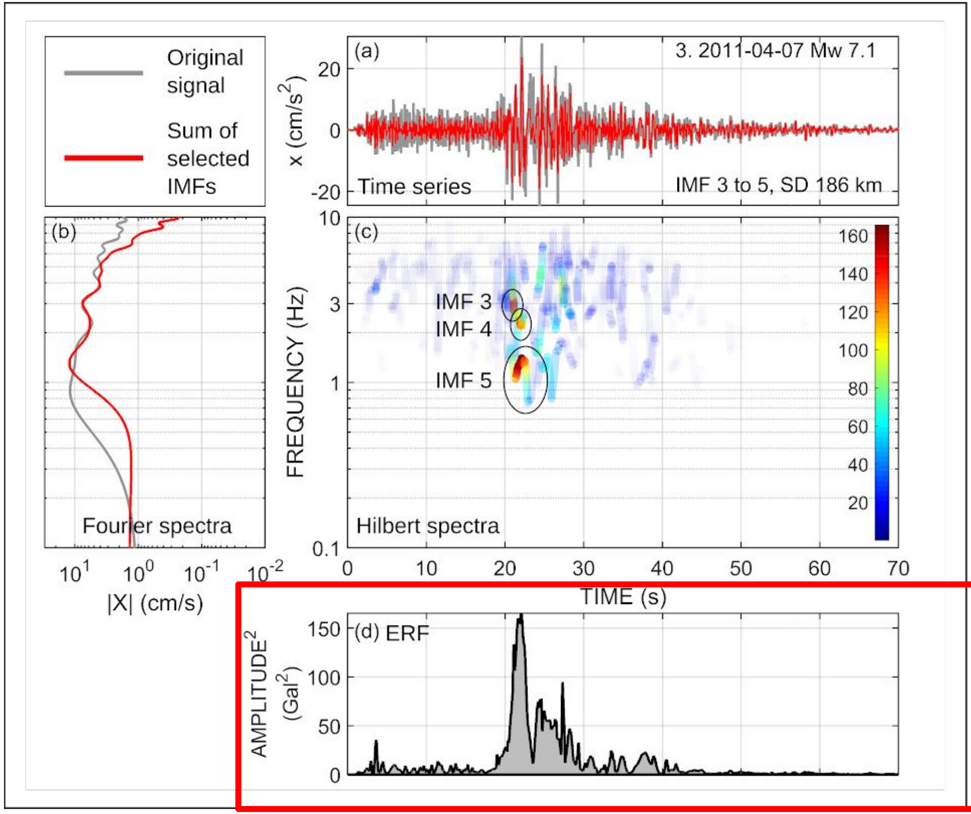
"Best" IMFs? Based on the frequency band, not the IMF number.

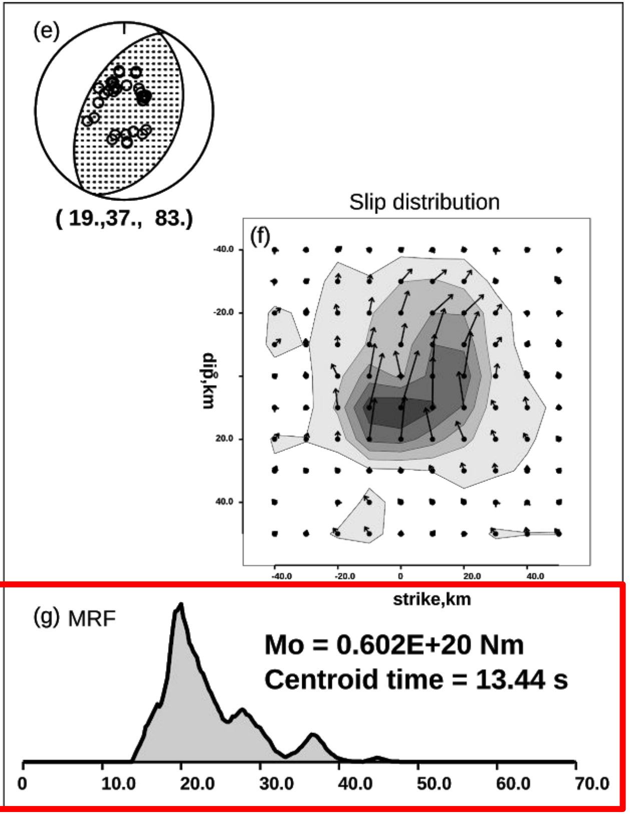


Generating an 'Energy Rate Function' by picking maximum energy values in the Hilbert spectra of the selected IMFs.

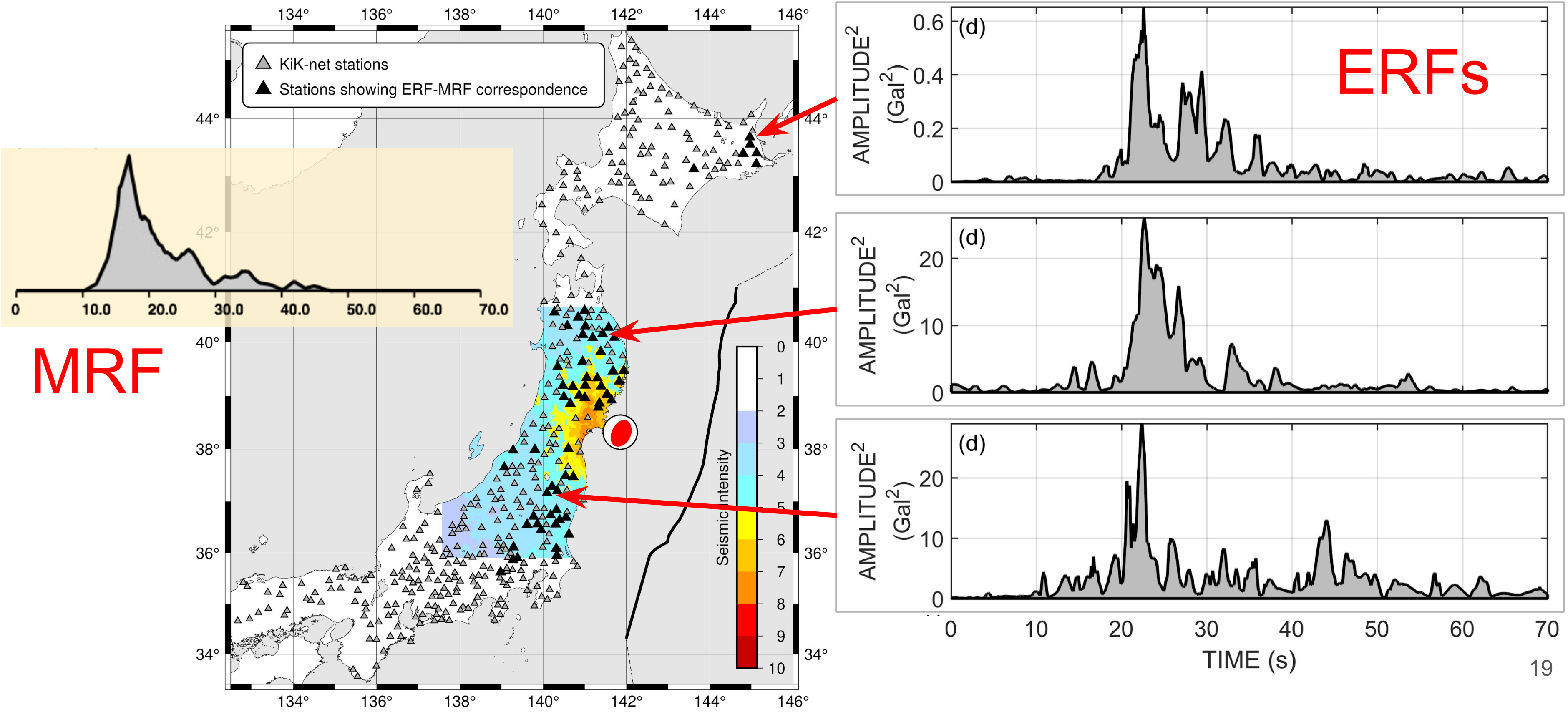


Correspondence of the ERF with the MRF, with a few caveats (Time-frequency analysis vs. Waveform inversion)





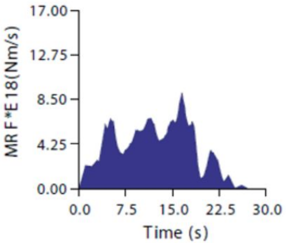
ERF-MRF correspondence observed at "best" stations (In the direction of rupture propagation and orthogonal to it).



ERF-MRF correspondence for other tectonic settings

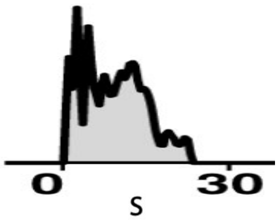
ERF-MRF correspondence for other tectonic settings

Interplate (2005 Miyagi-Oki): Complex rupture; rough ERF & MRFs.



Yaginuma et al. (2006). Earth, planets and space, *58*(12), 1549-1554.

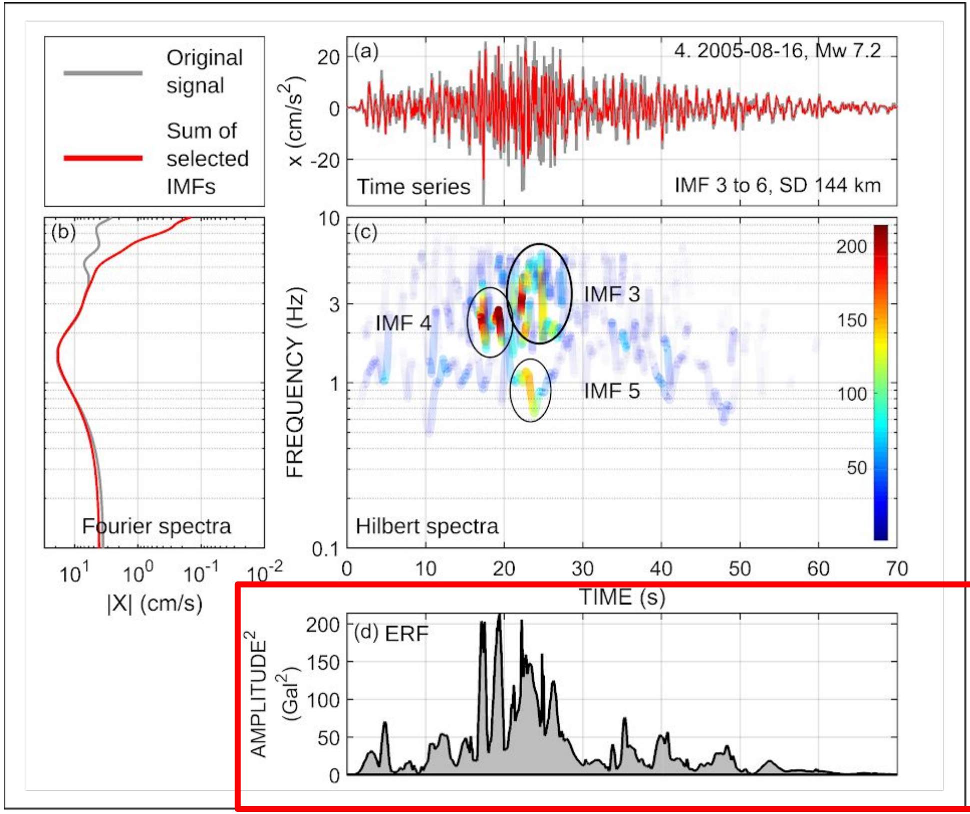
Mo= 0.9×10^{20} Nm
Depth 36 km

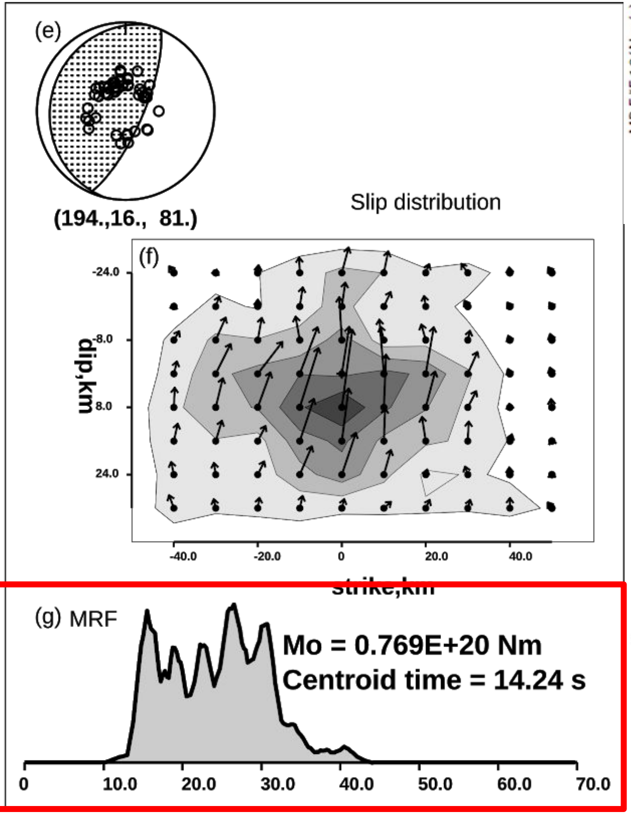


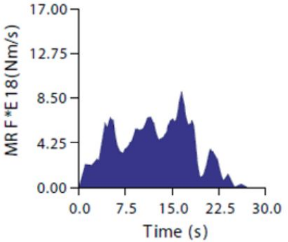
Lay et al. (2012). *JGR: Solid Earth*, *117*(B4).

ERF-MRF correspondence for other tectonic settings

Interplate (2005 Miyagi-Oki): Complex rupture; rough ERF & MRFs.







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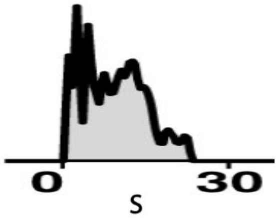
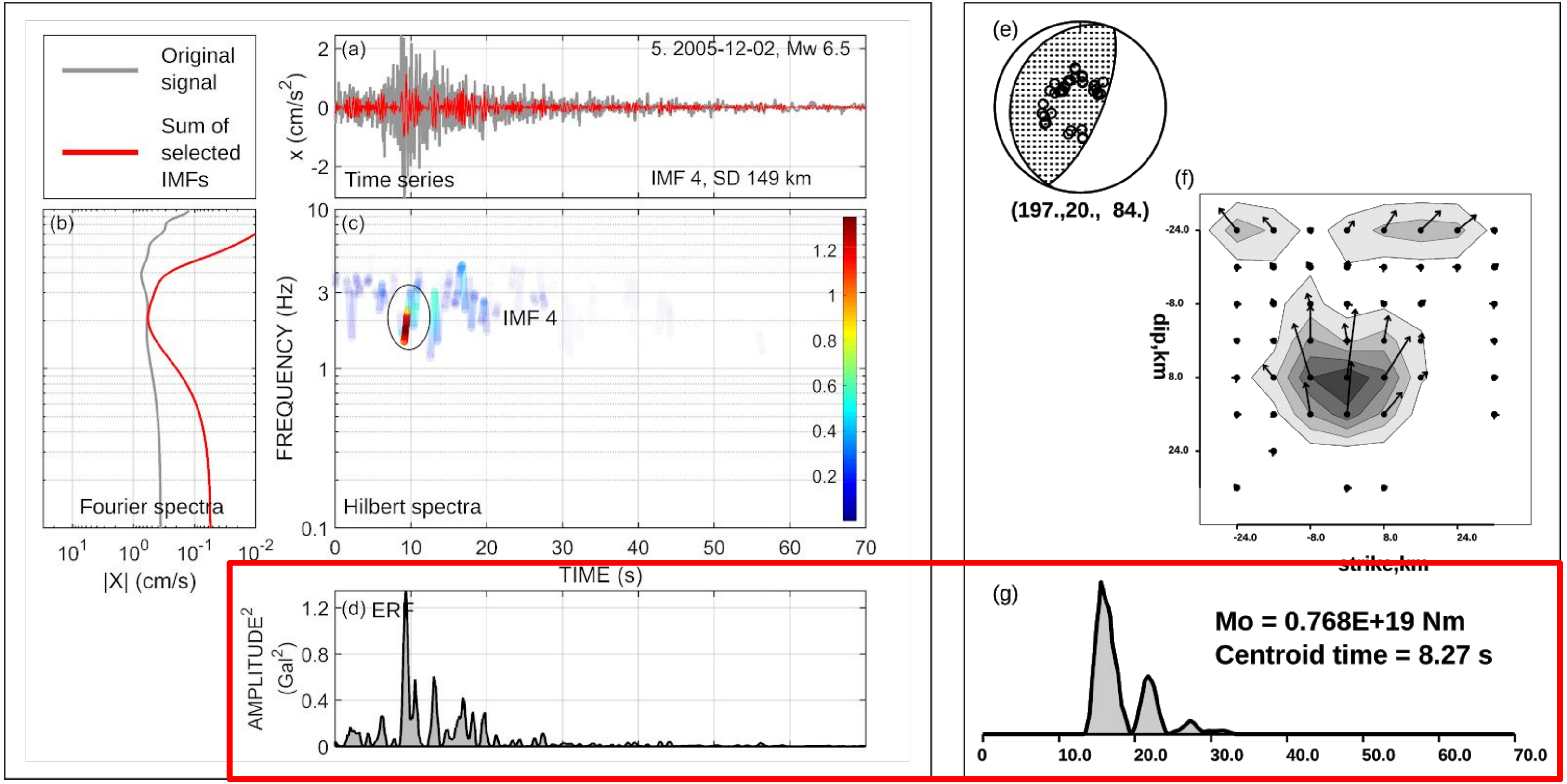


Lay et al. (2012). *JGR: Solid Earth*, *117*(B4).

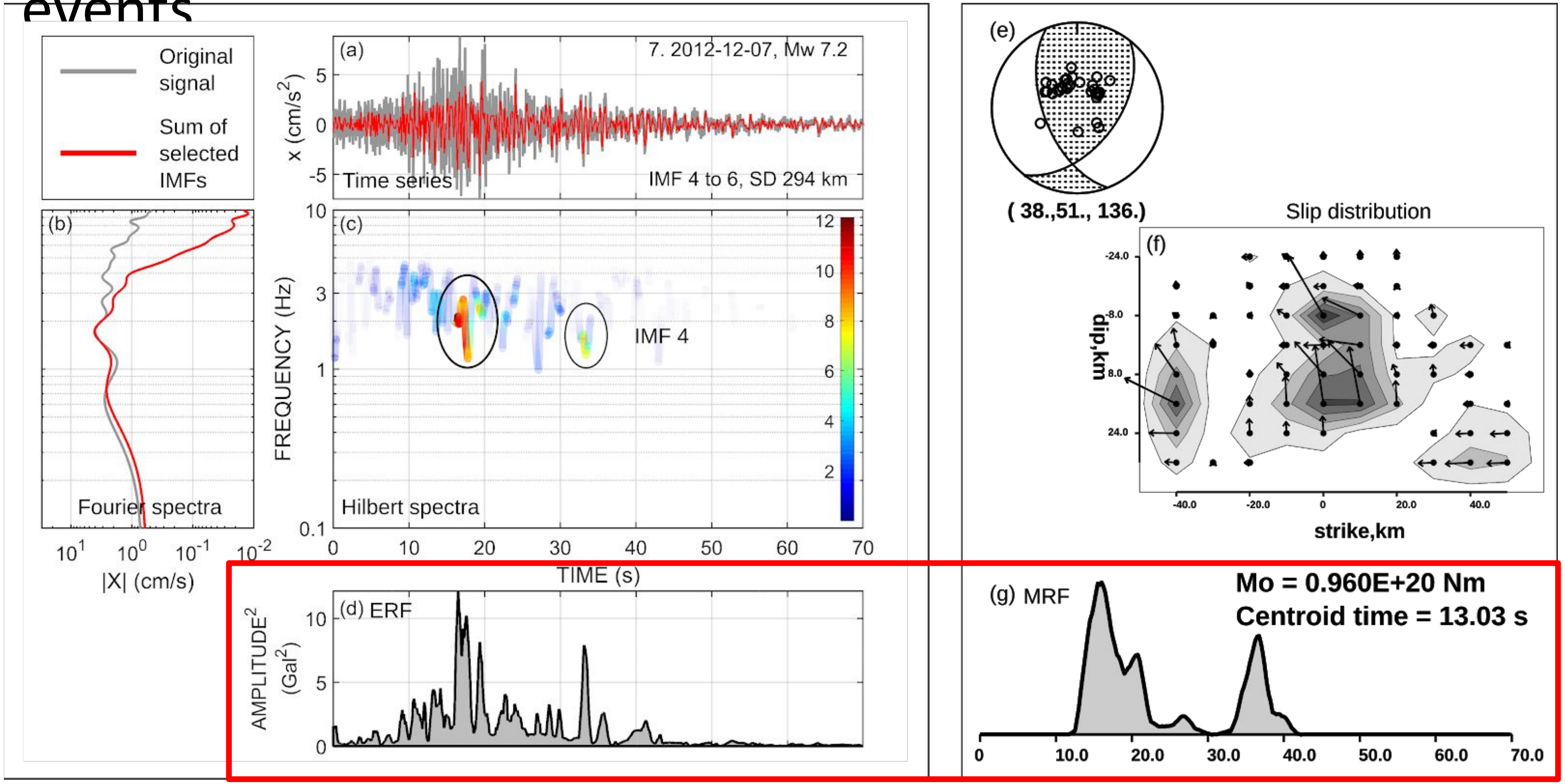
ERF-MRF correspondence for other tectonic settings

Interplate (2005 Honshu): Low seismic intensity stations; one IMF.



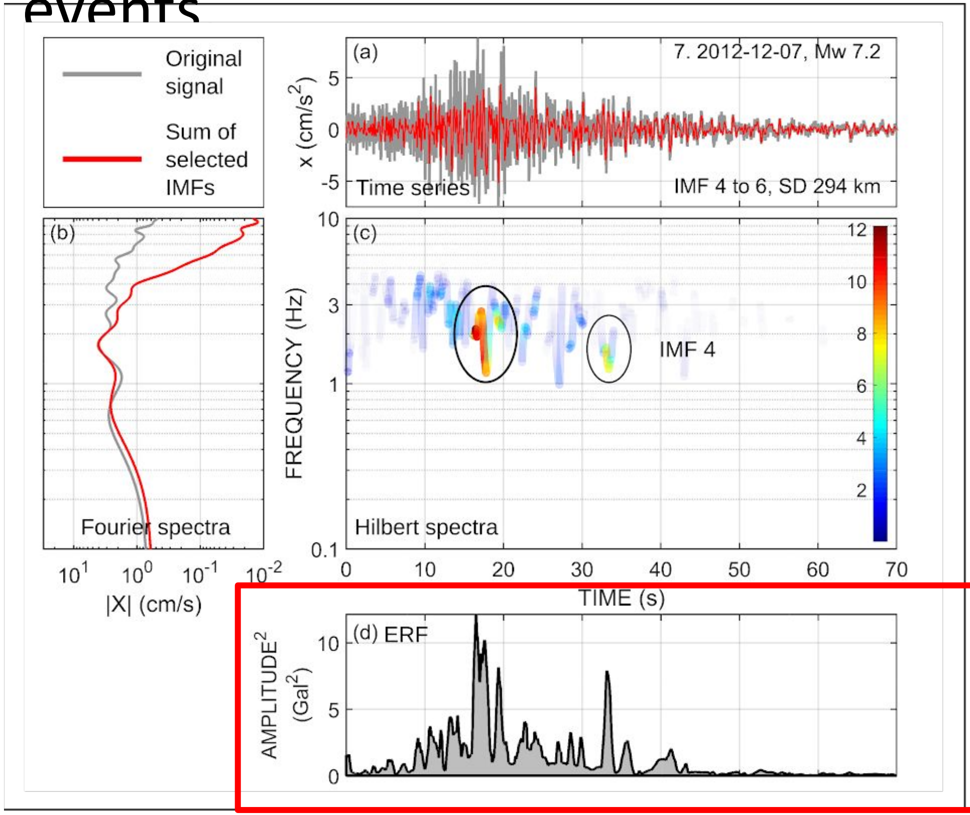
ERF-MRF correspondence for other tectonic settings

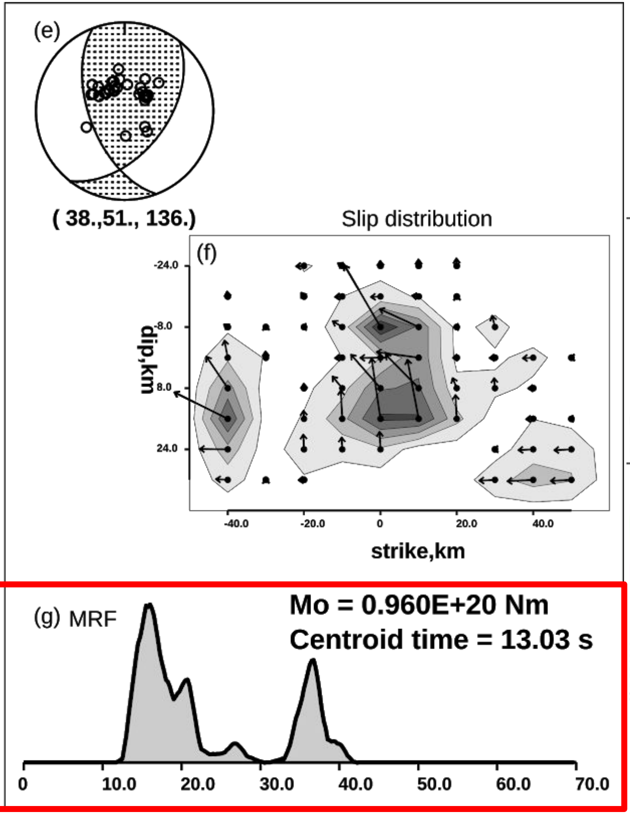
Intraplate (2012 Kamaishi): Complex rupture; 2 independent events



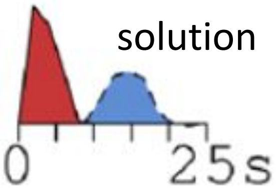
ERF-MRF correspondence for other tectonic settings

Intraplate (2012 Kamaishi): Complex rupture; 2 independent events

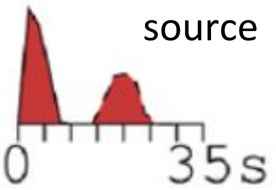




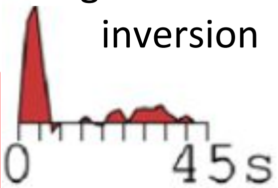
min.-misfit solution



double thrust source

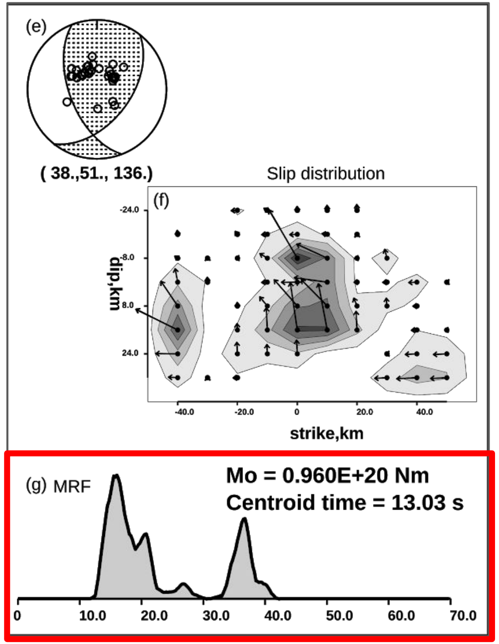


single-source inversion

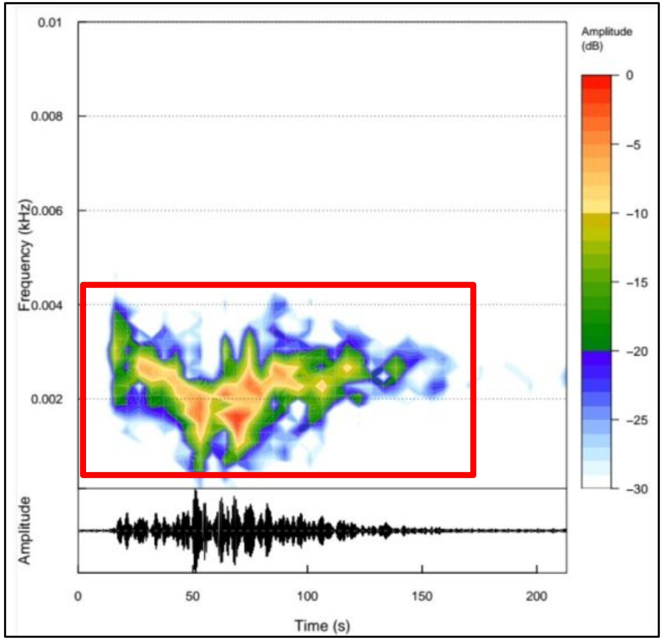


Craig, T. J., Copley, A., & Jackson, J. (2014). *GJI*, *197*(1), 63-89.

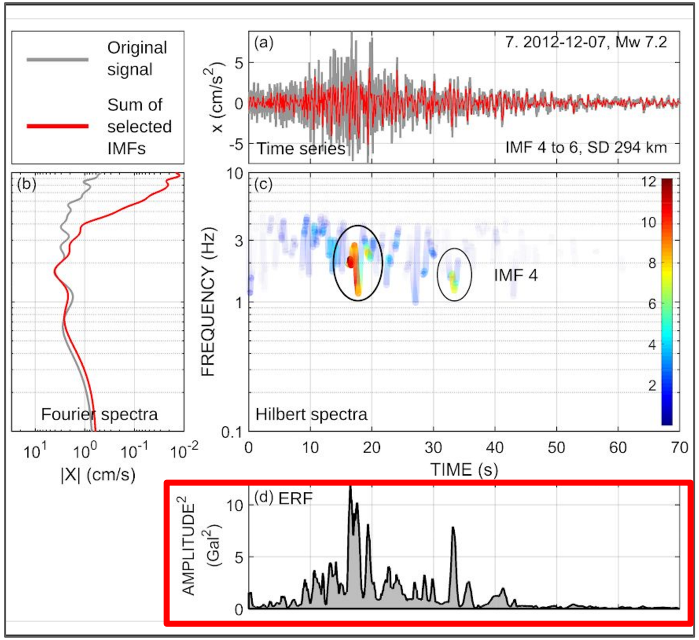
In conclusion, the combination of EMD with TFA tools is useful for quick interpretation of earthquake energy release.



Waveform inversion



Spectrogram (strong-motion)



HHT-ERF (strong-motion)