Energy release patterns and shaking effects of earthquakes in the Japan Trench: A Hilbert-Huang Transform approach

Swapnil Mache and Kusala Rajendran

Indian Institute of Science (IISc), Bangalore, India

1. Key Points

1. Specific Intrinsic Mode Functions (IMFs) represent energy release at the earthquake source.
2. Energy Rate Functions (ERFs) generated from Hilbert spectral analysis of such IMF combinations.
3. Proposed ERFs match well with the Moment Rate Functions (MRFs) from teleseismic waveform modeling.
4. ERF-MRF match is controlled by the station azimuth and shaking intensity, and frequency and energy-based selection of IMFs.

A short video explaining our work:

2. Motivation

1. Subduction zone earthquakes showcase different energy release patterns and frequency content depending on the **tectonic setting and depth**.
2. Interplate earthquakes, originating on the plate interface, show enhanced high-frequency energy (HFE) with increasing depth (Lay et al., 2012).
3. Outer-rise intraplate earthquakes produce enhanced HFE and ground shaking despite their high epicentral distances (Ye et al., 2013).
4. Intraslab earthquakes originate within the subduction slab (usually beneath population centers). They are more damaging than other similar Mw events due to enhanced HFE release and associated ground motion in a short duration, along with higher stress

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1. **Teleseismic data** from International Research Institutions for Seismology (IRIS). P and SH waveforms from 30-40 stations, epicentral distance 30° to 90°.
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Table: Earthquake details (from GCMT).

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1. **26 May 2003 Miyagi Intraslab Earthquake (Mw 7.0, depth 67.0 km)**
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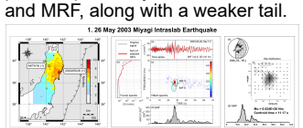
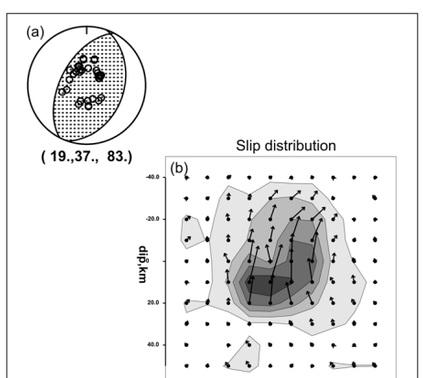
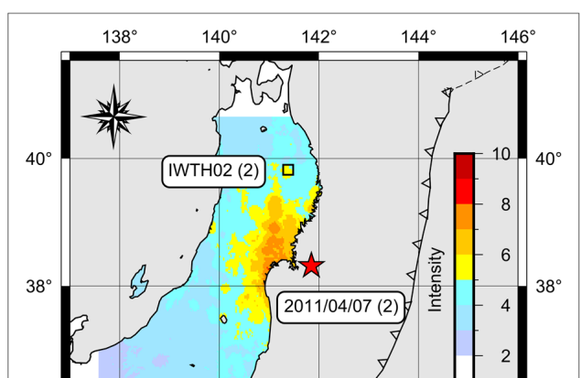
   - 
2. **07 April 2011 Miyagi Intraslab**

Waveform Modeling



Strong motion station selection



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3. **ERF captures complex ruptures** (2005 Miyagi-Oki event) and sub-events or multiple independent events (2012 Kamaishi event).

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5. Conventional time-frequency analysis methods (Fourier transform, short-time Fourier transform, continuous wavelet transform) are deficient in resolving the above properties. They have a priori defined bases, are not suitable for nonlinear and nonstationary earthquake signals, and have limited resolution (Huang et al., 1998; Tary et al., 2014).
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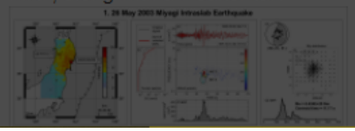

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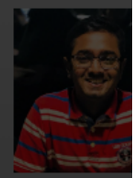

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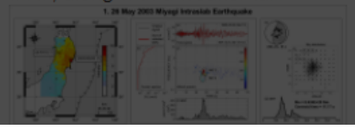

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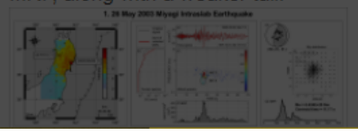

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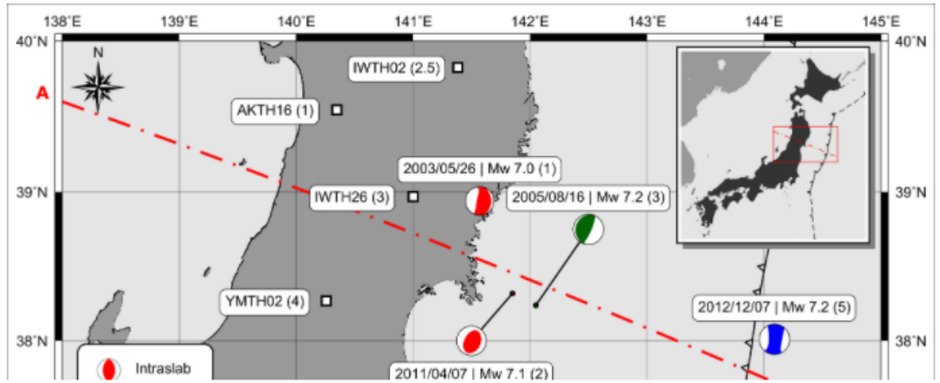

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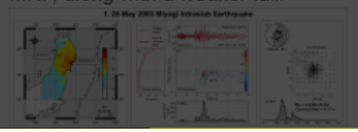

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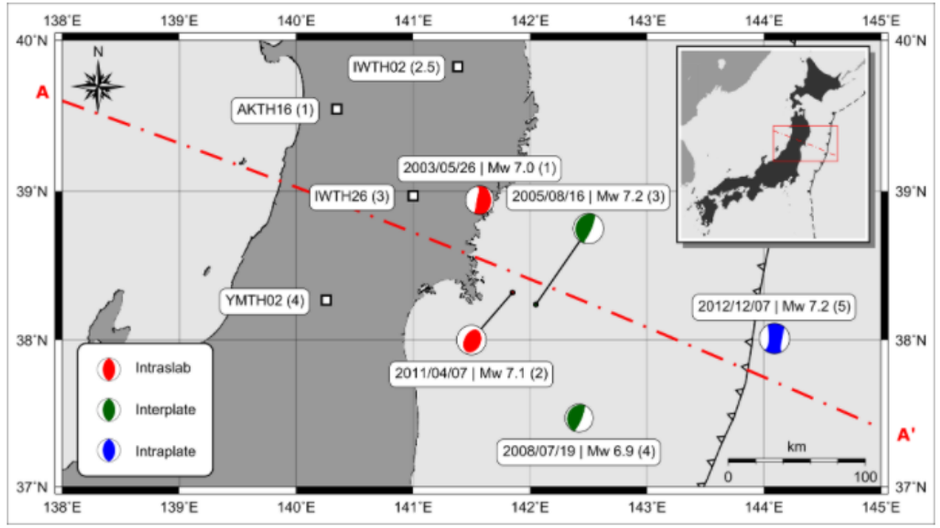
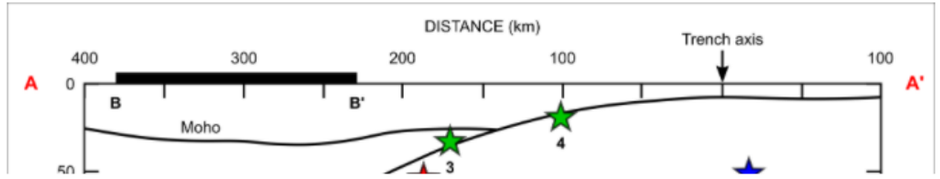


Figure: Map of the study region showing the five earthquakes and corresponding stations used for analysis.



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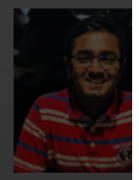

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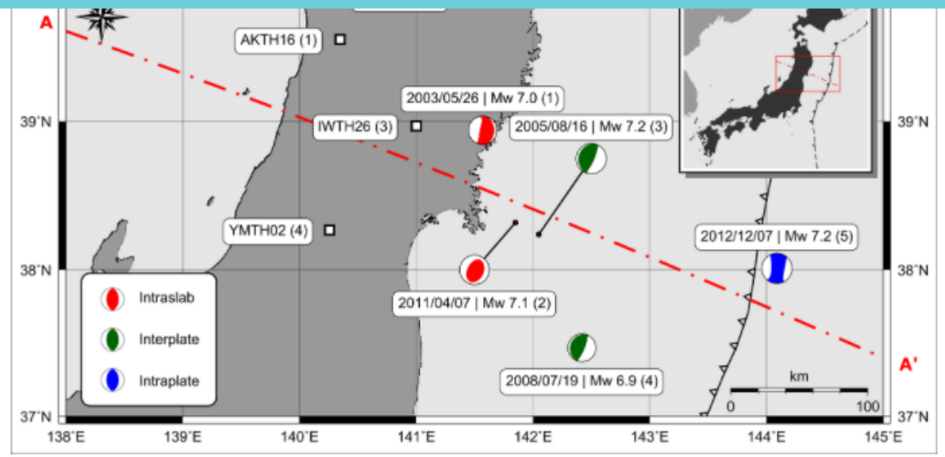

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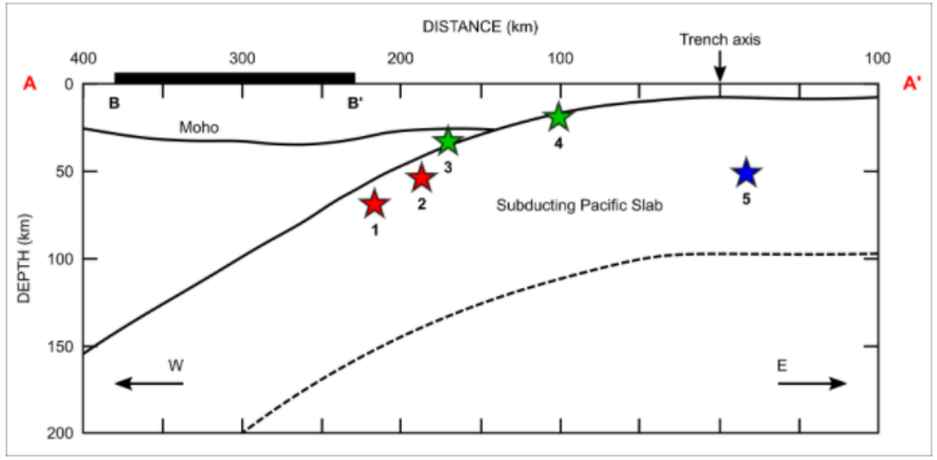

Figure: Cross-section showing the event distance from the trench, and depth, in km.

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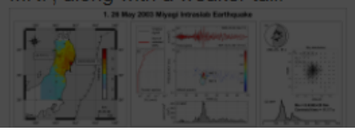

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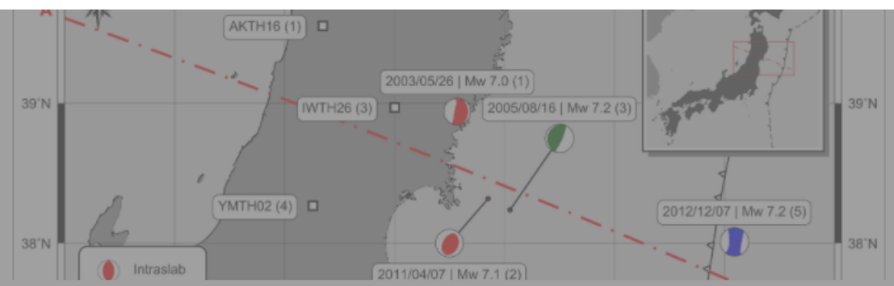

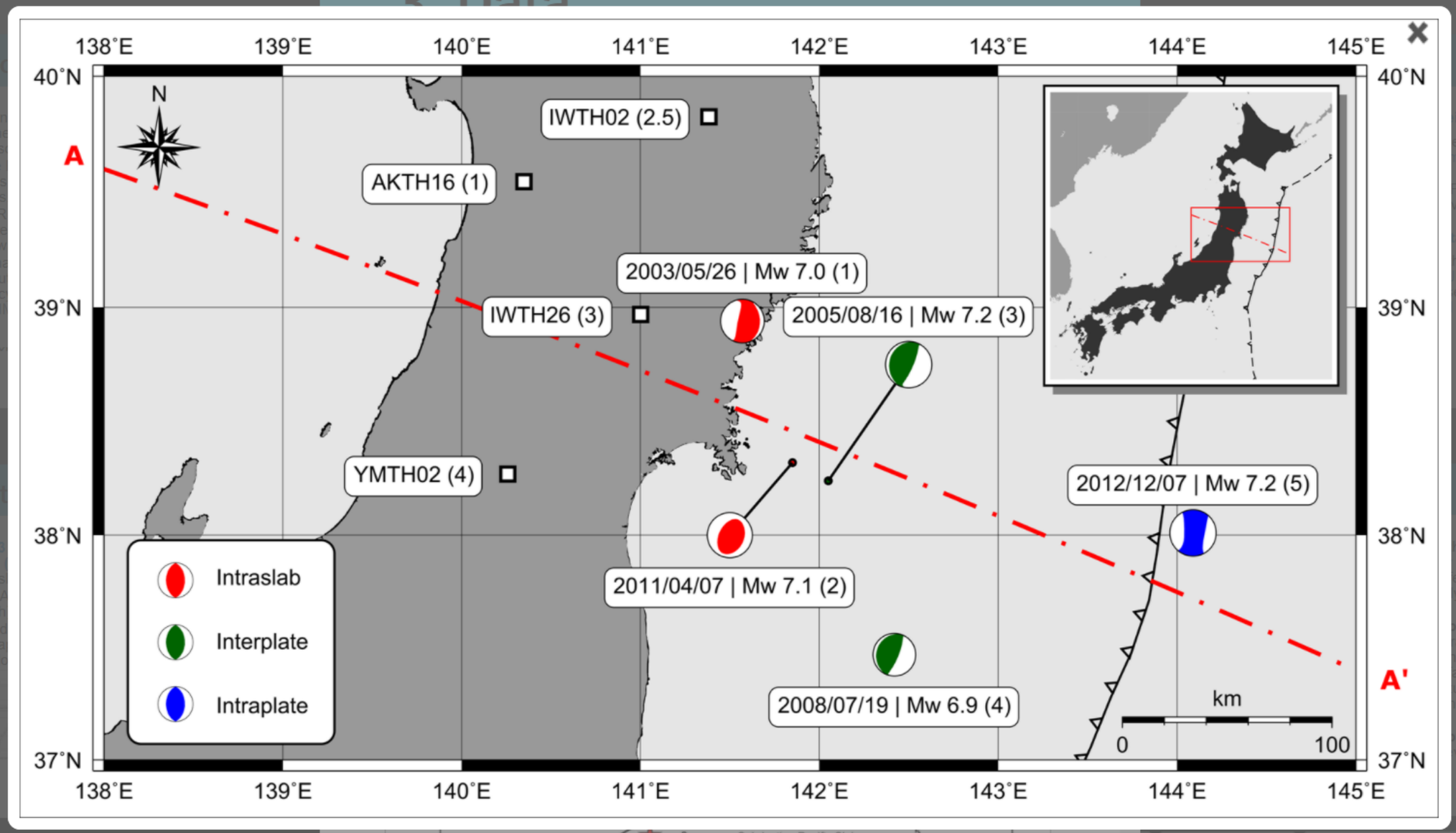
138°E
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AKTH16 (1)
IWTH26 (3)
YMTH02 (4)
2003/05/26 | Mw 7.0 (1)
2005/08/16 | Mw 7.2 (3)
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2008/07/19 | Mw 6.9 (4)
2012/12/07 | Mw 7.2 (5)
Intraslab
Interplate
Intraplate
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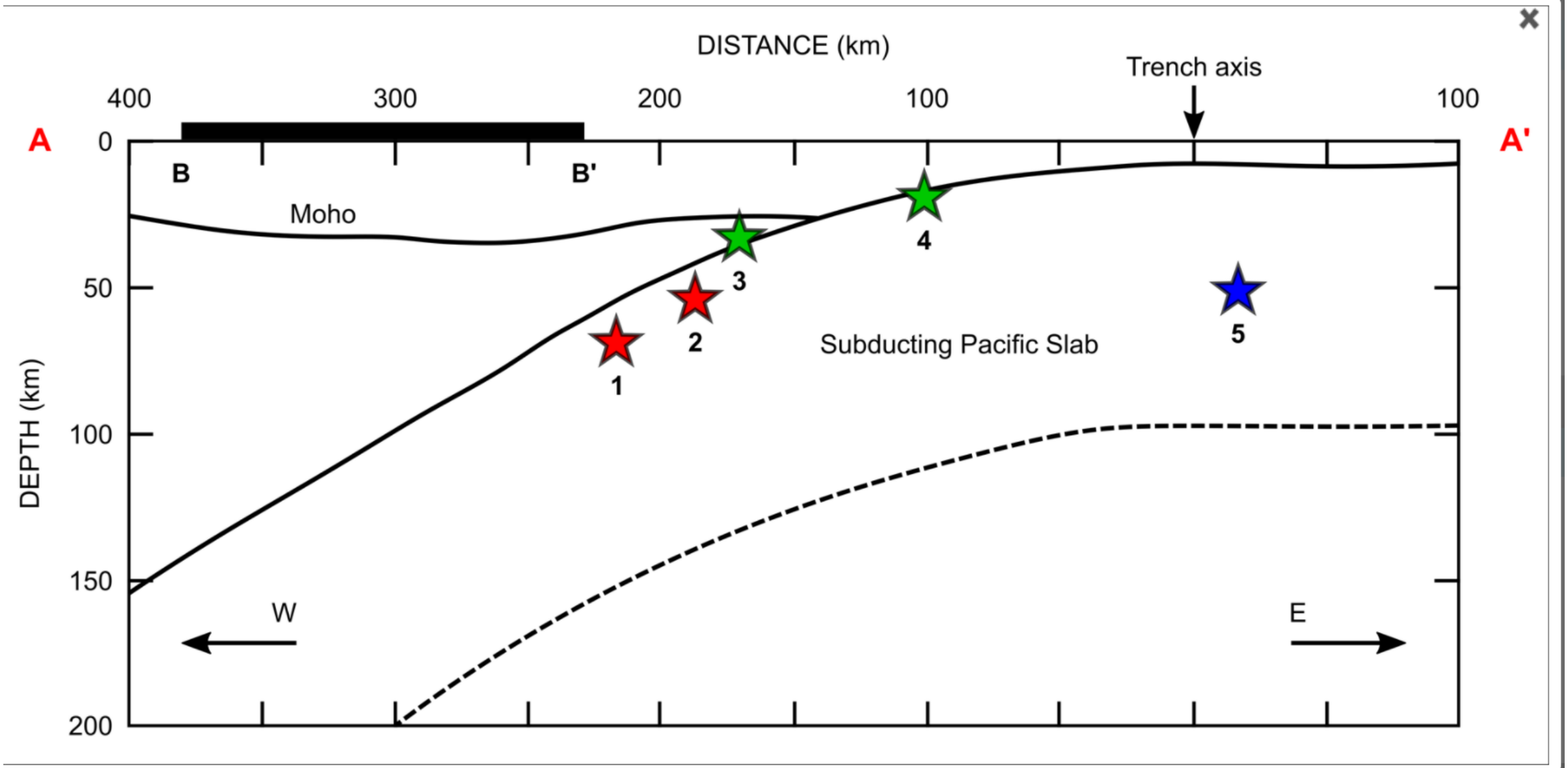
DISTANCE (km)
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300
200
100
Trench axis
100
A
A'
0
B
B'
Moho
50
100
150
200
DEPTH (km)
1
2
3
4
5
Subducting Pacific Slab
W
E

4. Methodology

Waveform inversion of teleseismic data

1. Kikuchi-Kanamori body-wave inversion program (Kikuchi and Kanamori, 1991) used for the analysis.
2. Moment Rate Function (MRF) generated from waveform modeling to validate the ERF algorithm.

Selection of strong-motion stations

1. Slip distribution, along with the seismic intensity distribution maps (JMA, 1996; ShakeMap, 2017), used to select stations within the inferred azimuthal range and seismic intensity > 3.

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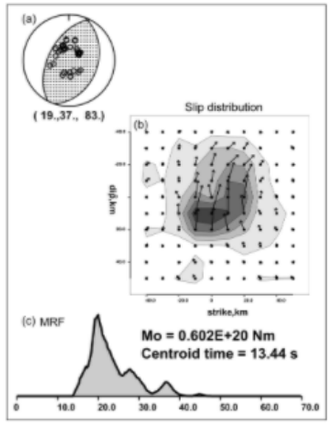
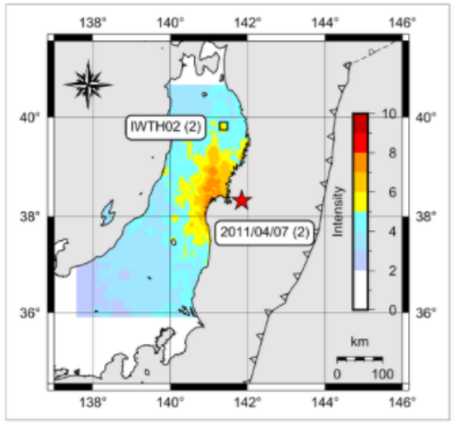


Teleseismic waveform modeling result.

Strong motion station selection



Shakemap with epicenter (star) and station (square).

4. Methodology

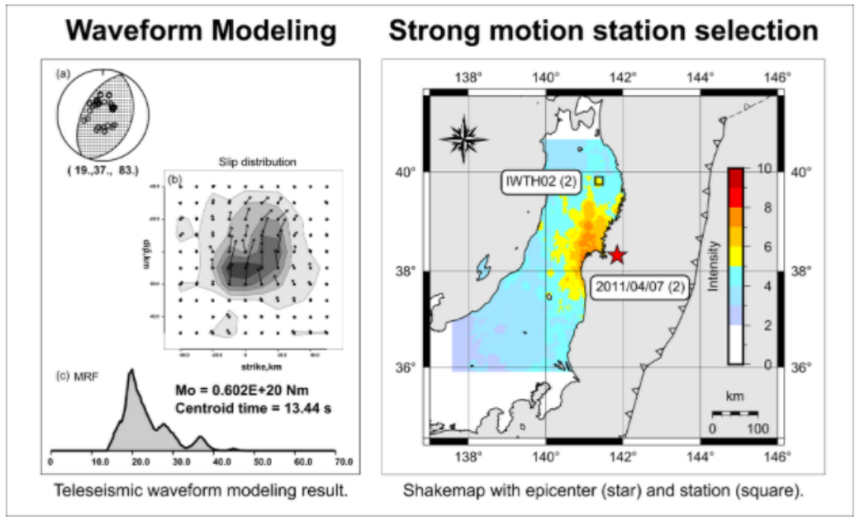


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Figure: Waveform modeling results. Shakemap (along with slip distribution), used for strong-motion station-selection.

HHT-based strong-motion analysis

1. Hilbert-Huang Transform (HHT) is a combination of Empirical Mode Decomposition (**EMD**) and Hilbert Spectral Analysis (**HSA**) (Huang et al., 1998).
2. EMD decomposes the data into multiple frequency components (IMFs).
3. **IMFs** selected in the **frequency range 0.1 to 3 Hz**. Hilbert energy spectrum, a time-frequency-energy

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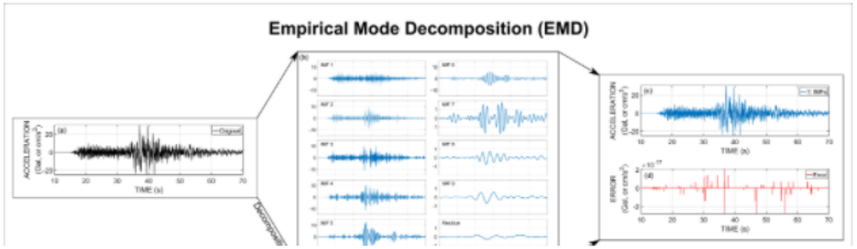
3. **IMFs** selected in the **frequency range 0.1 to 3 Hz**. Hilbert energy spectrum, a time-frequency-energy representation of the signal, generated for each selected IMF.
4. **Maximum amplitude-squared values** obtained from the Hilbert spectra of selected IMFs used to generate the Energy Rate Function (ERF).
5. ERF is representative of energy release at the earthquake source, validated by its comparison with the MRF.



Key Points
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26 May 2003 Miyagi Intraslab Earthquake (Mw 7.0, depth 67.0 km)
OPEN

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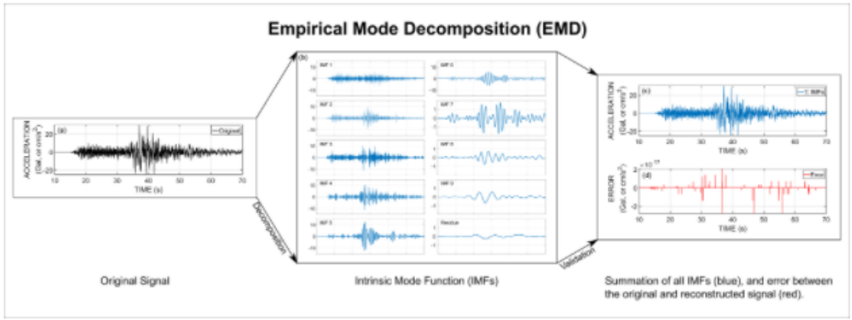


Figure: EMD and validation.

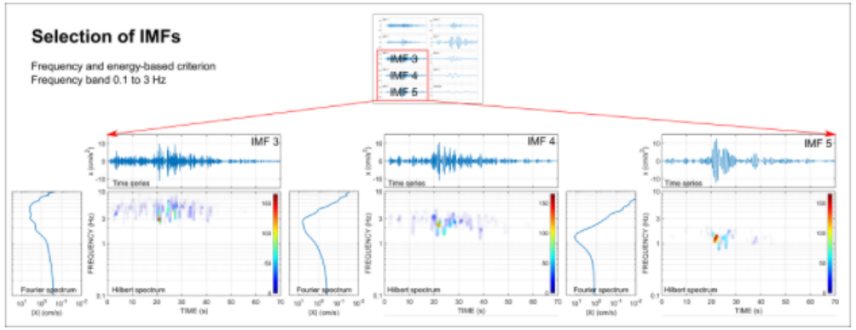
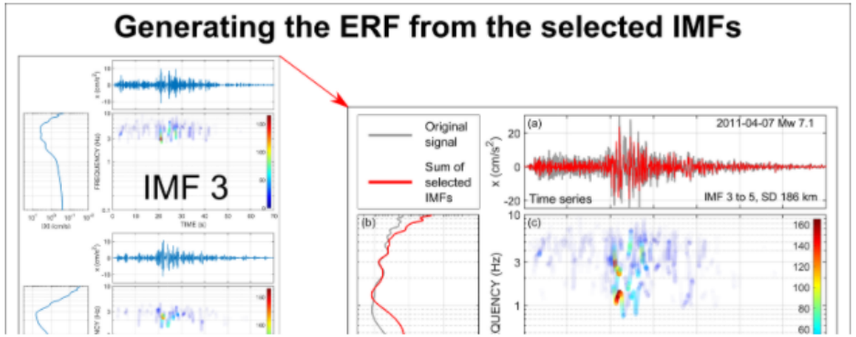


Figure: Selection of IMFs.



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short video explaining our work:

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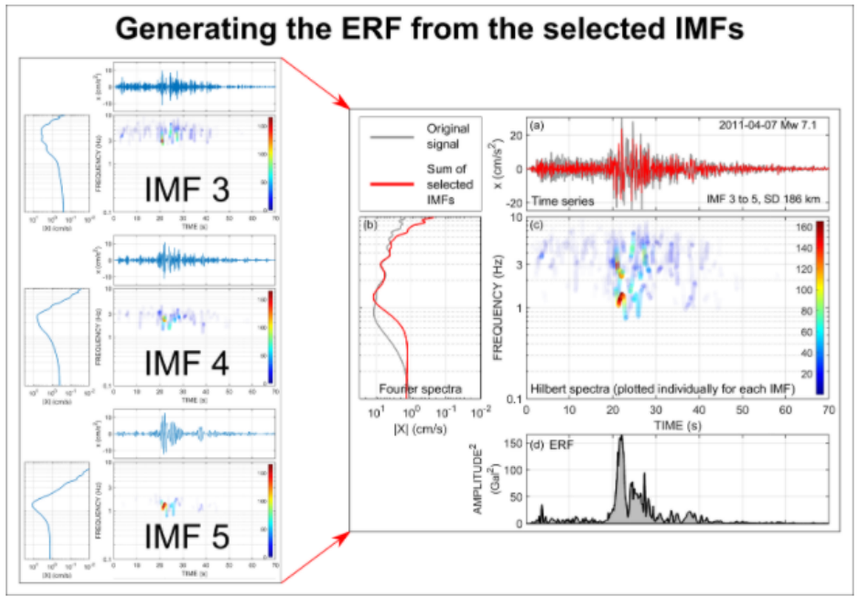
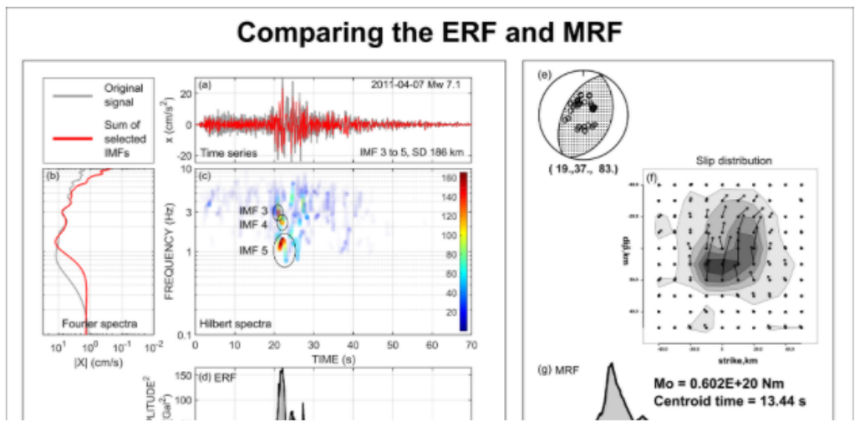


Figure: Using the selected IMFs to generate the Energy Rate Function (ERF).



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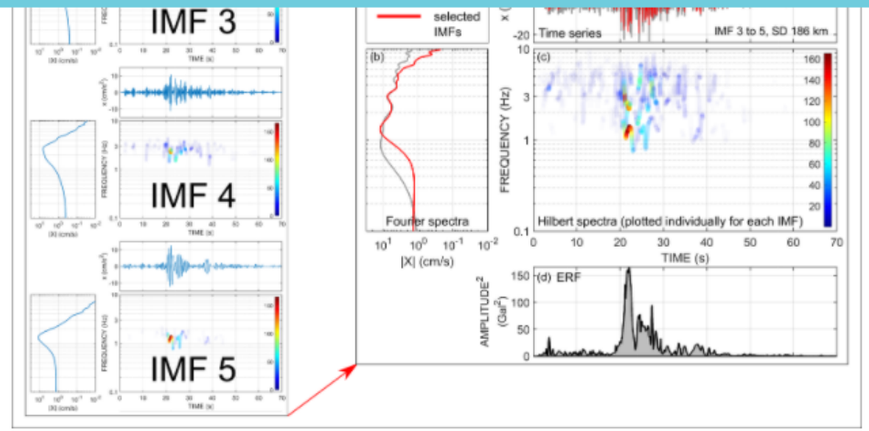

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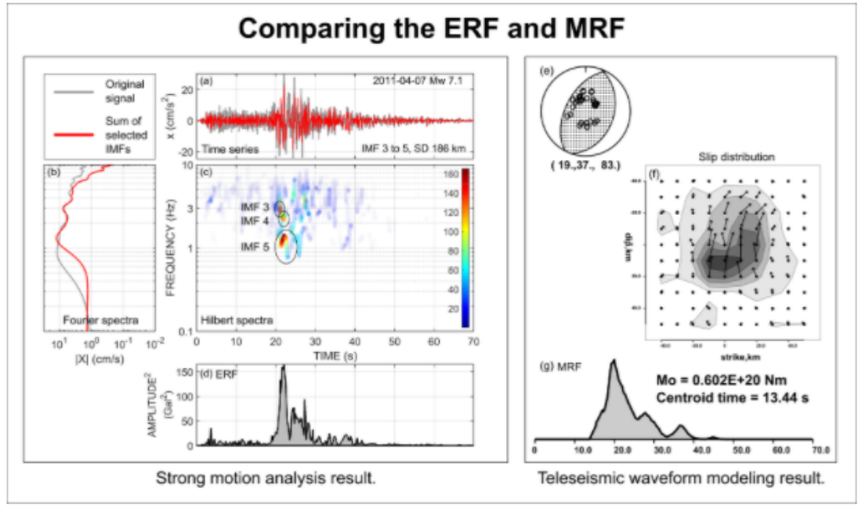
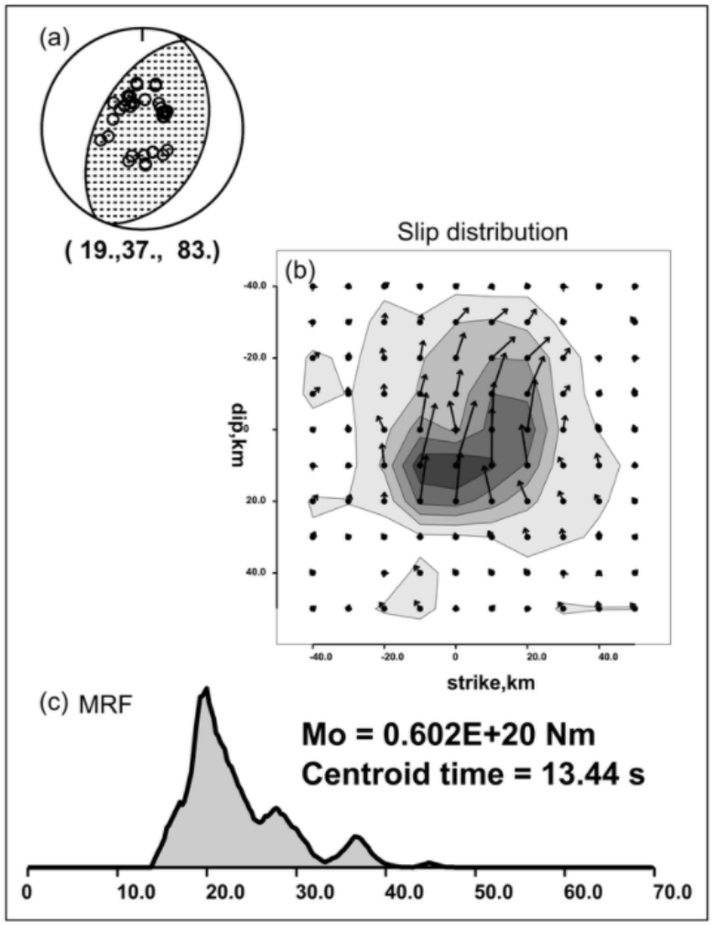


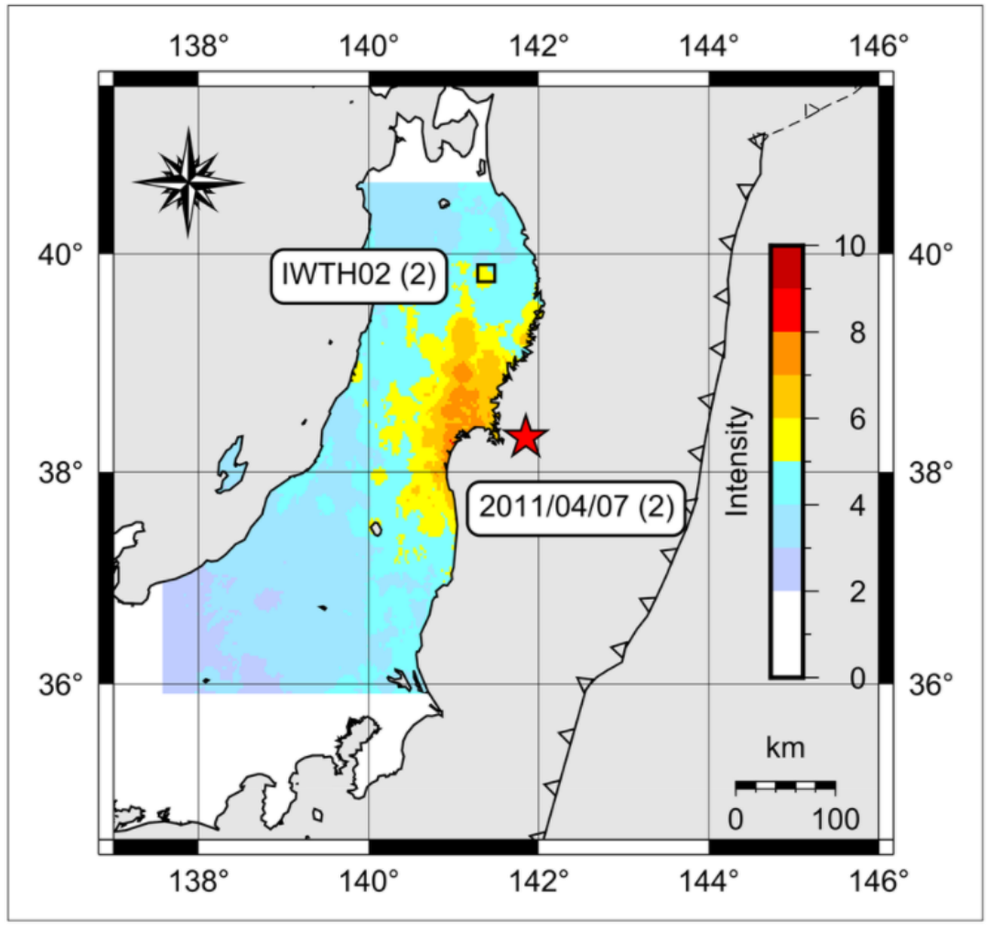
Figure: Comparison of the ERF with the MRF.

Waveform Modeling



Teleseismic waveform modeling result.

Strong motion station selection



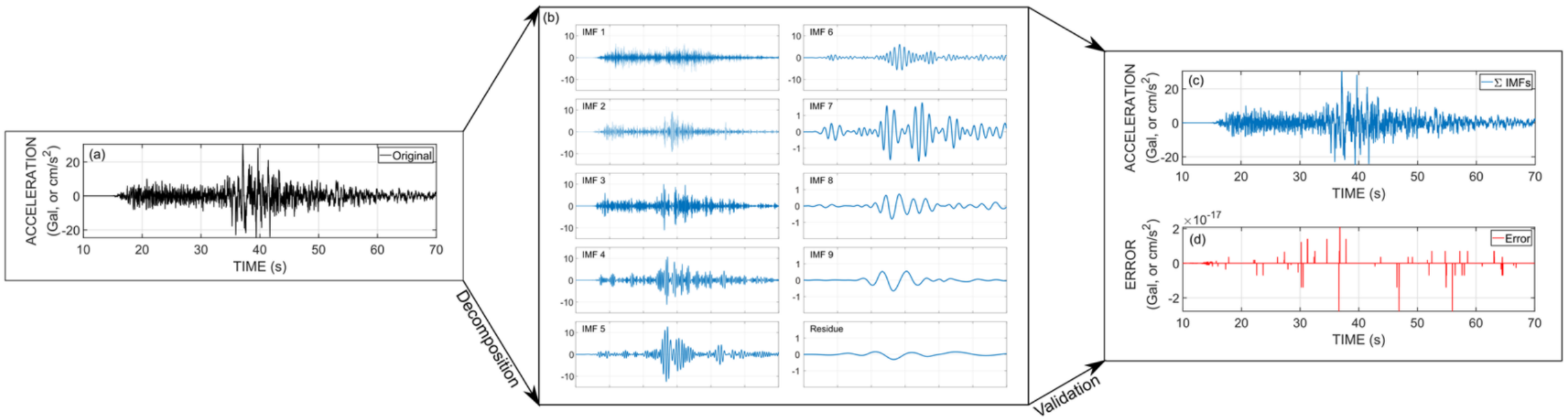
Shakemap with epicenter (star) and station (square).

Figure: Waveform modeling results. Shakemap (along with

4. Methodology

Hilbert spectra of selected IMFs used to generate the

Empirical Mode Decomposition (EMD)



Original Signal

Intrinsic Mode Function (IMFs)

Summation of all IMFs (blue), and error between the original and reconstructed signal (red).

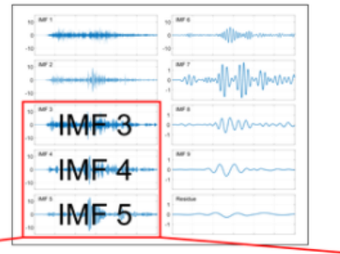
Figure: Selection of IMFs.

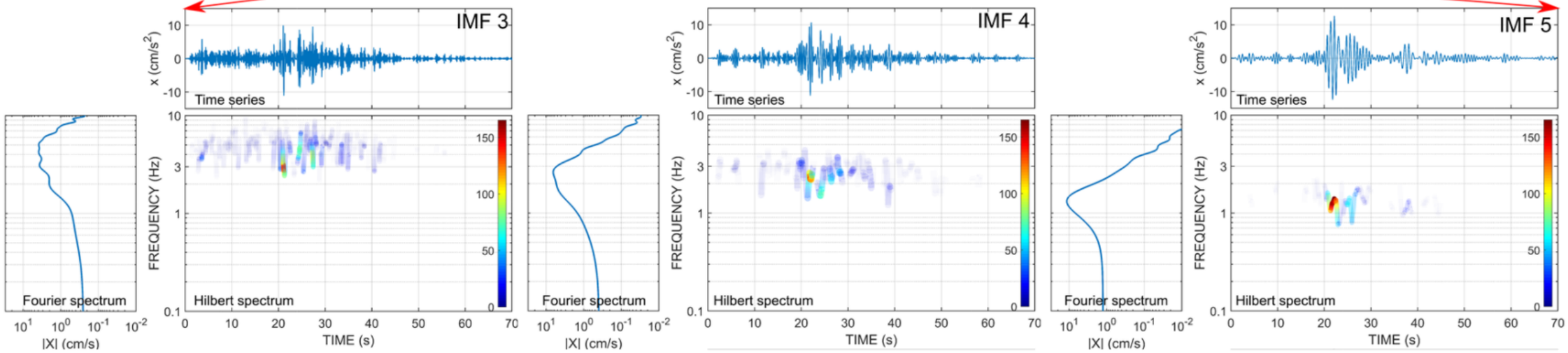
Generating the ERF from the selected IMFs

4. Methodology

Selection of IMFs

Frequency and energy-based criterion
Frequency band 0.1 to 3 Hz





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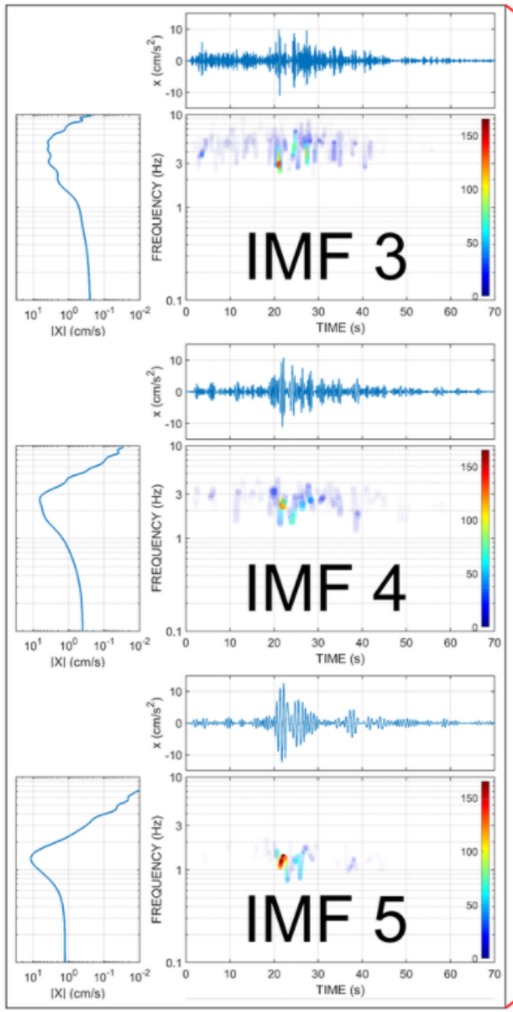
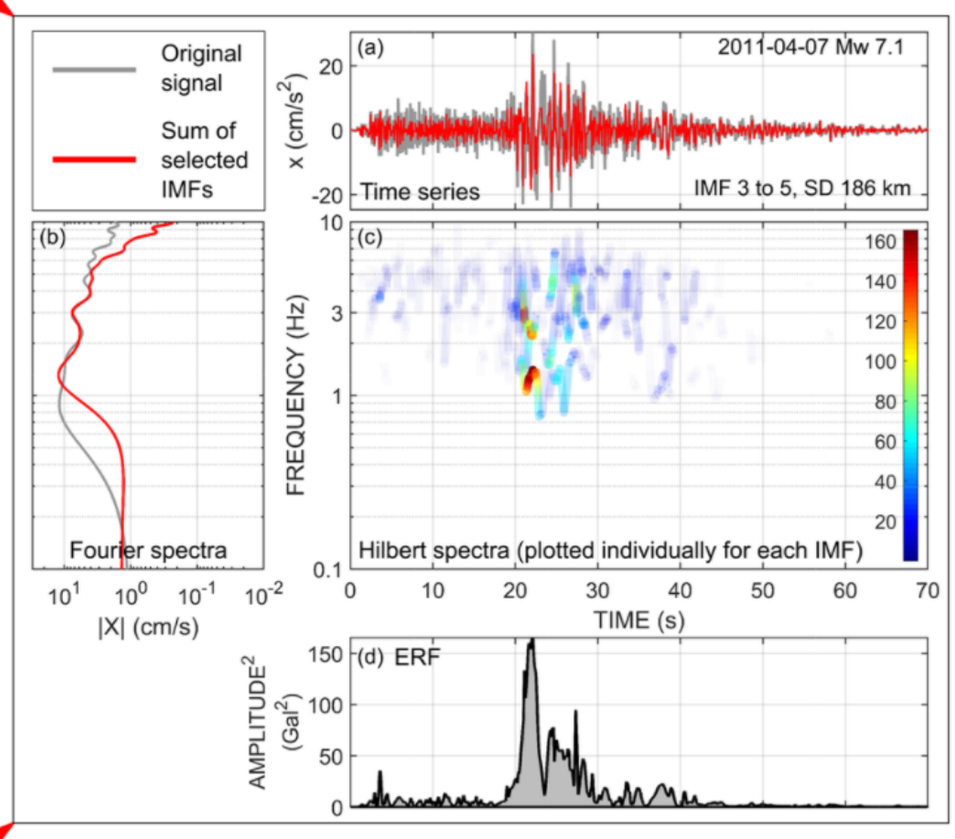
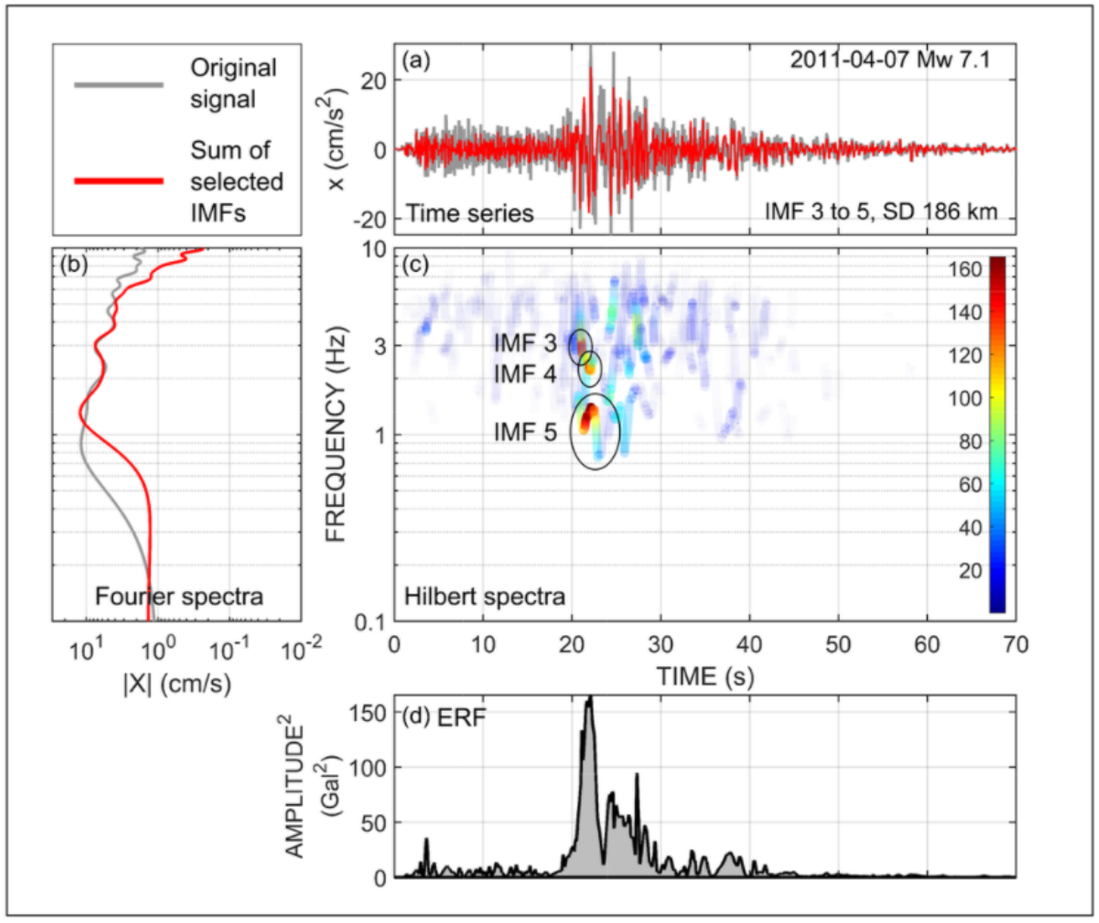
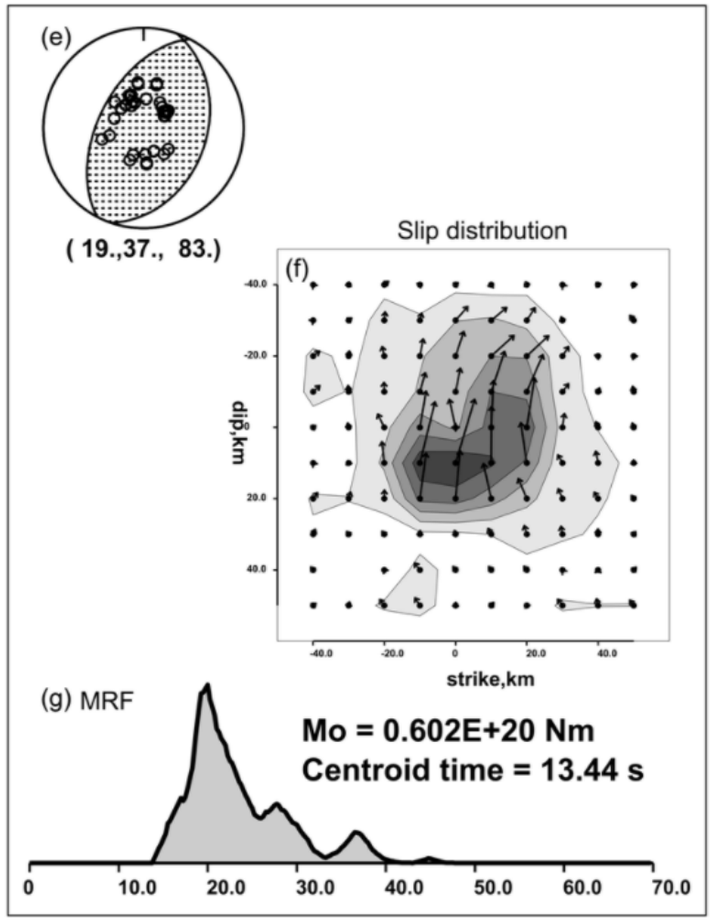




Comparing the ERF and MRF



Strong motion analysis result.



Teleseismic waveform modeling result.

5. Results

1. **26 May 2003 Miyagi Intraslab Earthquake (Mw 7.0, depth 67.0 km)**
   - Up-dip slip (towards east-northeast).
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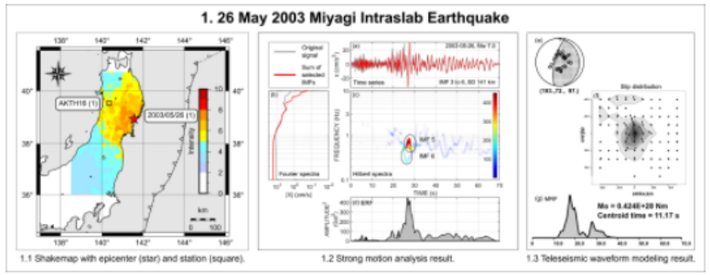
   - 

2. **07 April 2011 Miyagi Intraslab Earthquake (Mw 7.1, depth 53.3 km)**
   - Slip direction northwest.
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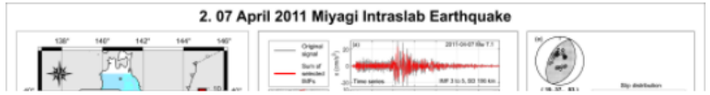
   - 

1. Key Points
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6. Summary
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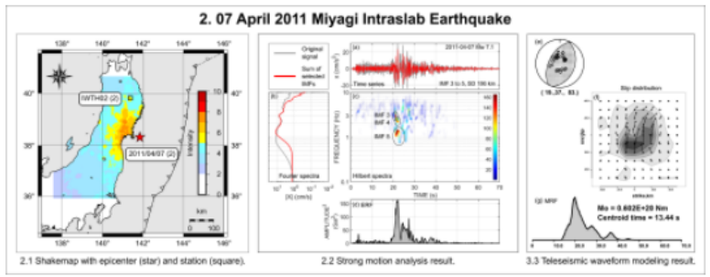

3. **16 August 2005 Miyagi-Oki Interplate Earthquake (Mw 7.2, depth 37.0 km)**
   - Station IWTH26, azimuth 309.76°, SI 5-upper.
   - **Rough MRF** observed by Lay et al. (2012) and Yaginuma et al. (2006).
   - ERF and MRF both match well with the above studies.
   - A deeper interplate event, and shows **enrichment in high-frequency energy** (0.4 to 5 Hz range).

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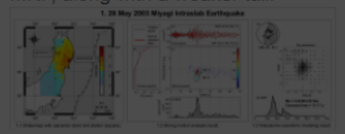

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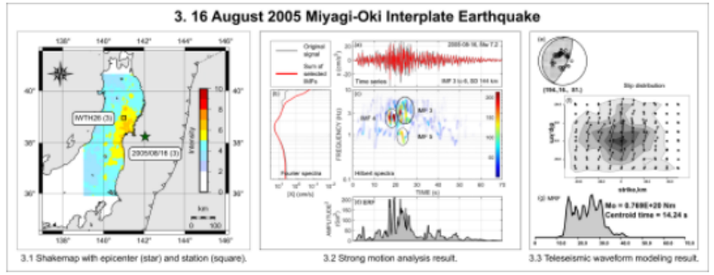
   - 

4. **19 July 2008 Fukushima ken-Oki Interplate Earthquake (Mw 6.9, depth 21.8 km)**
   - Slip directed up-dip (east-southeast).
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   - **ERF-MRF match** obtained even for **low SI** at the station location.
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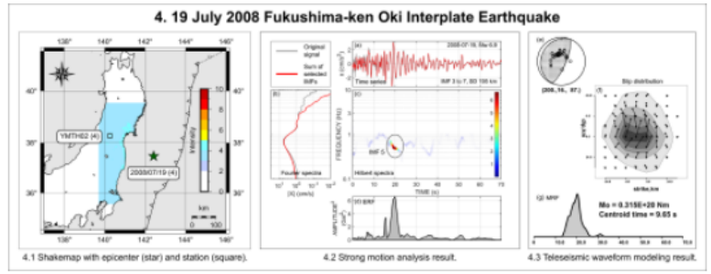
   - 

5. **07 December 2012 Kamaishi Intraplate Earthquake (Mw 7.2, depth 50.8 km)**
   - Station IWTH02, azimuth 313.85°, SI 5-lower. Station approximately orthogonal to strike.
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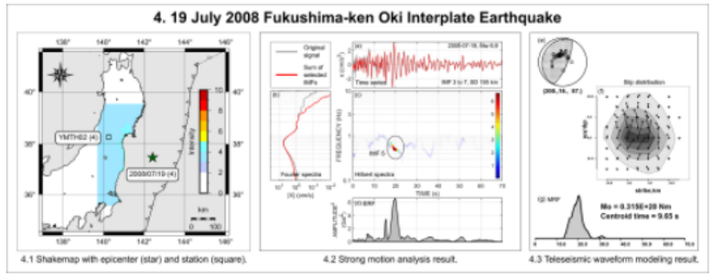
- 

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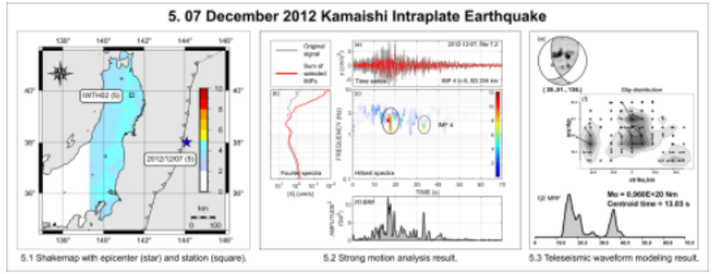
- 

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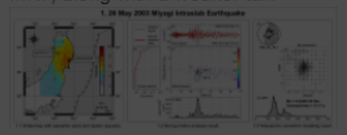
   - 

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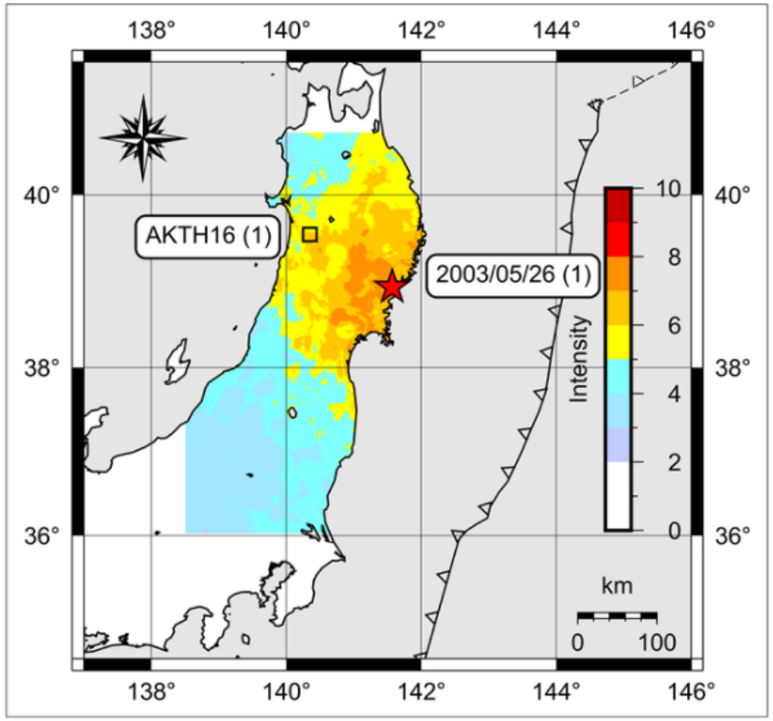

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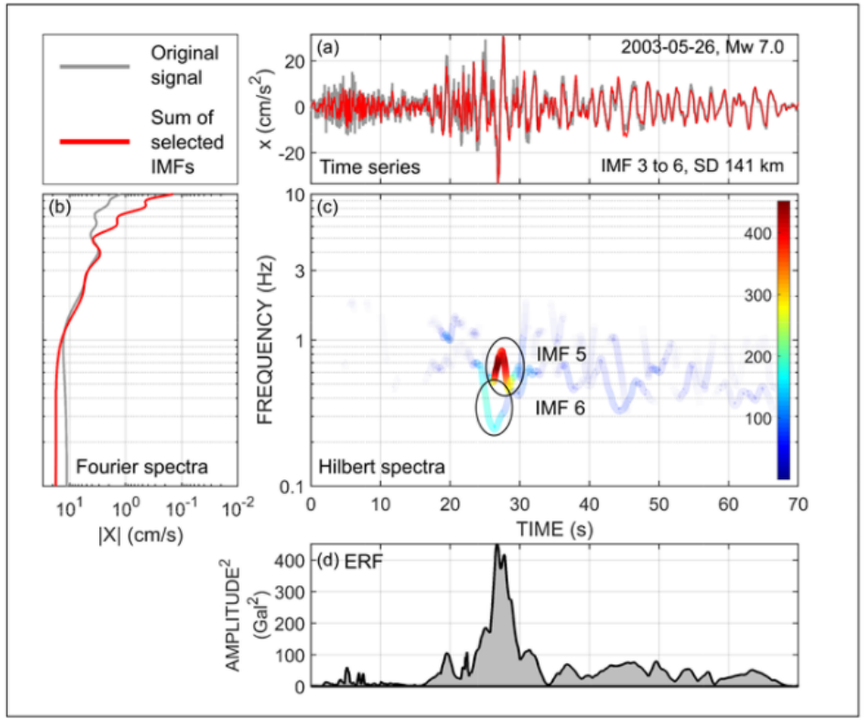

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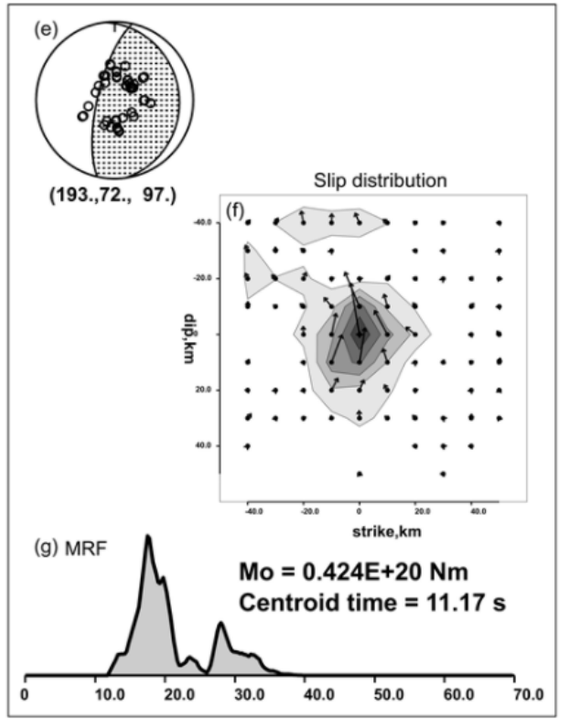
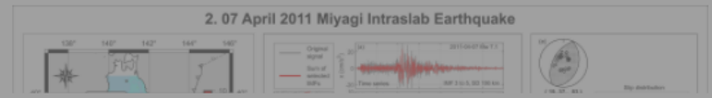


1.3 Teleseismic waveform modeling result.

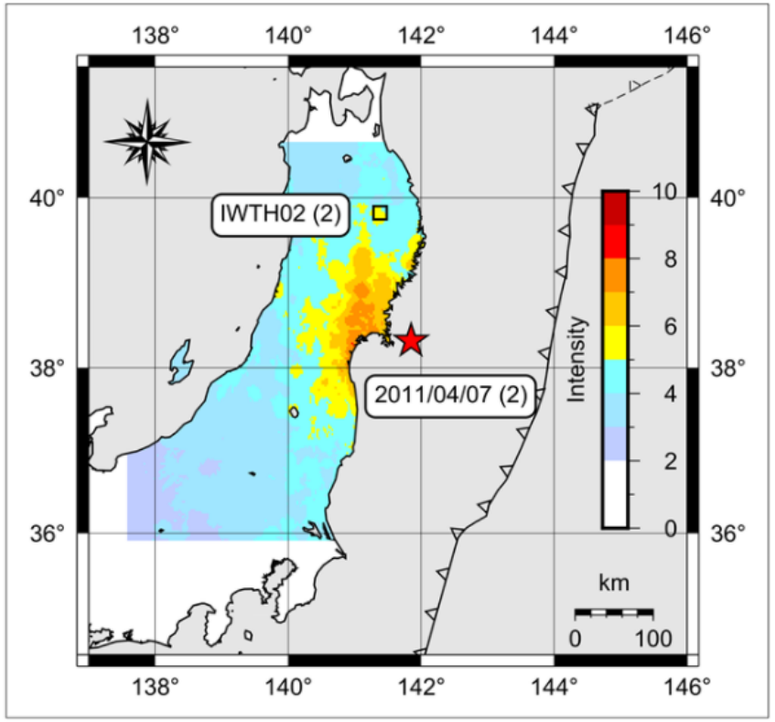
seconds and decaying gradually up to 40 seconds captured by both the ERF and MRF.



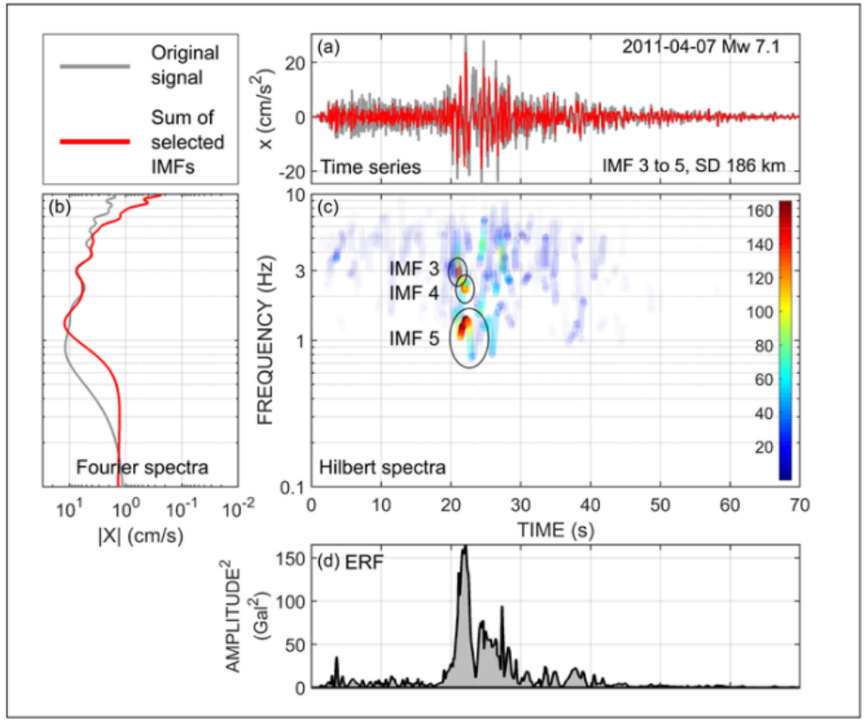
5. Results

1. 26 May 2003 Miyagi Intraslab Earthquake (Mw 7.0,

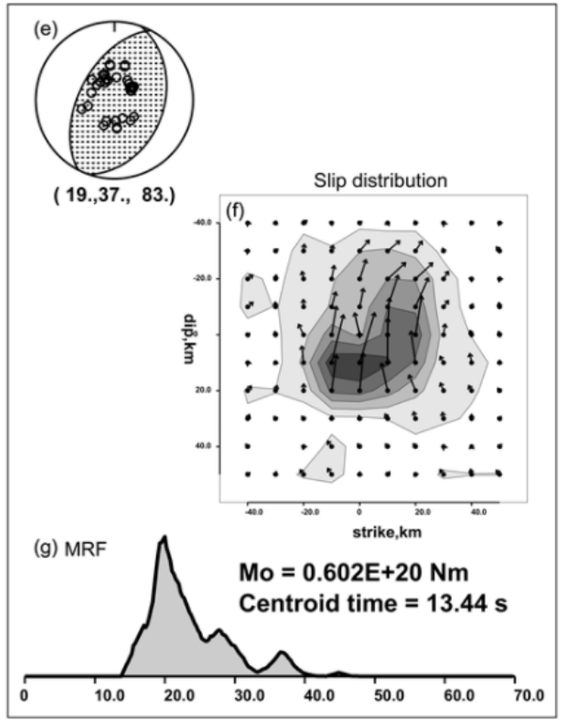
2. 07 April 2011 Miyagi Intraslab Earthquake



2.1 Shakemap with epicenter (star) and station (square).

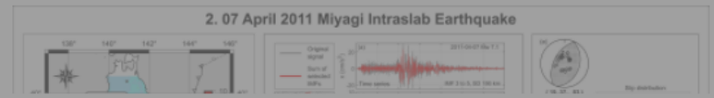


2.2 Strong motion analysis result.



3.3 Teleseismic waveform modeling result.

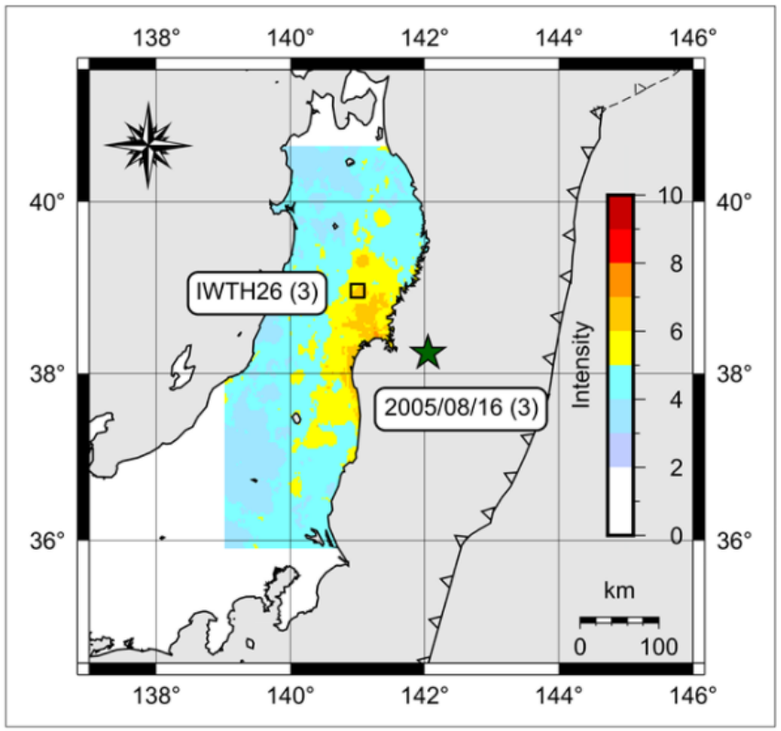
seconds and decaying gradually up to 40 seconds captured by both the ERF and MRF.



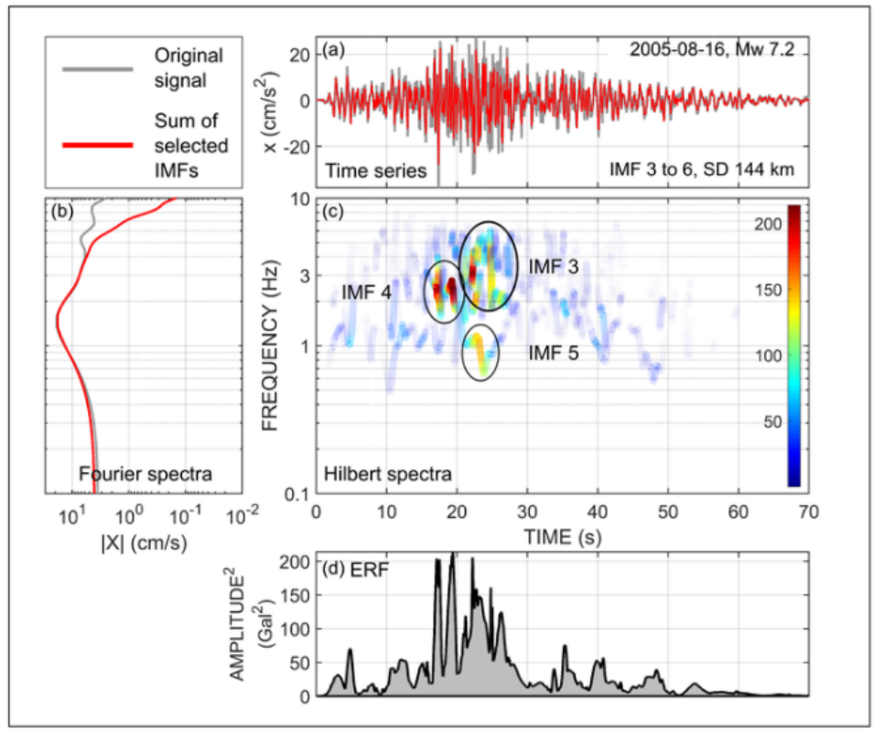
5. Results

studies.

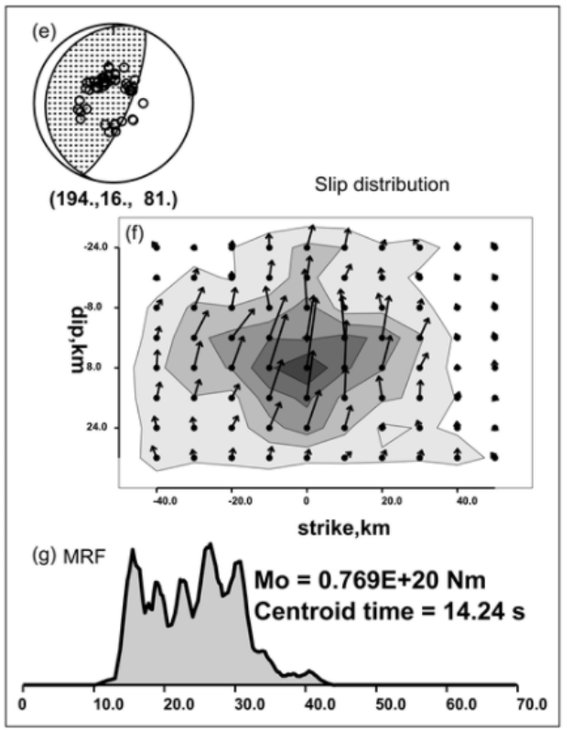
3. 16 August 2005 Miyagi-Oki Interplate Earthquake



3.1 Shakemap with epicenter (star) and station (square).



3.2 Strong motion analysis result.

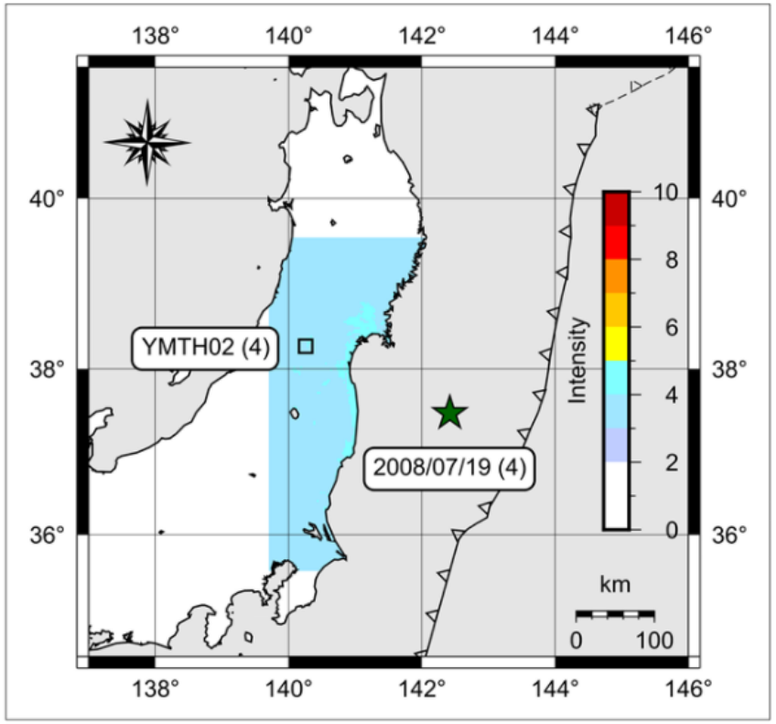


3.3 Teleseismic waveform modeling result.

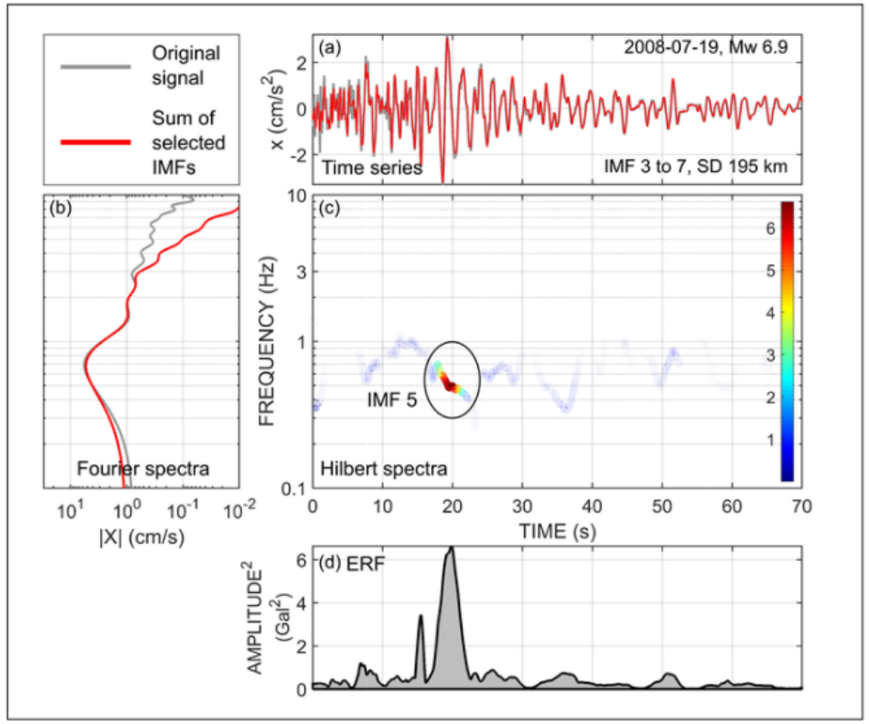
5. Results

- A shallow interplate event; **low-frequency energy**

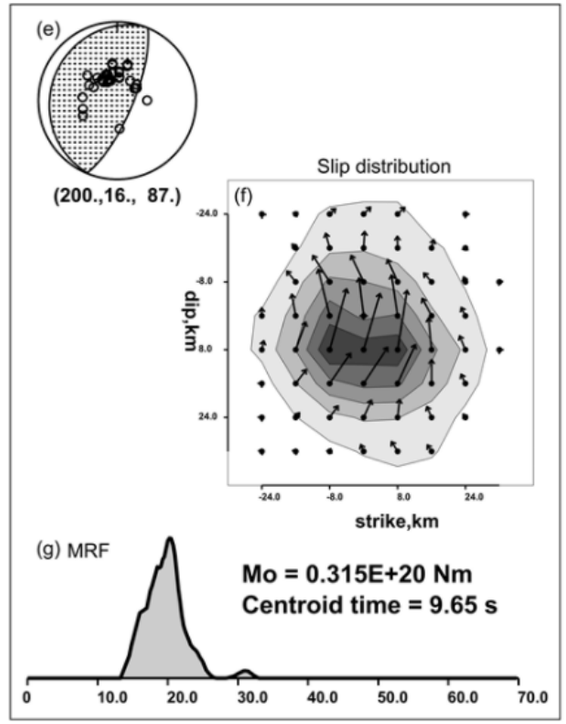
4. 19 July 2008 Fukushima-ken Oki Interplate Earthquake



4.1 Shakemap with epicenter (star) and station (square).



4.2 Strong motion analysis result.



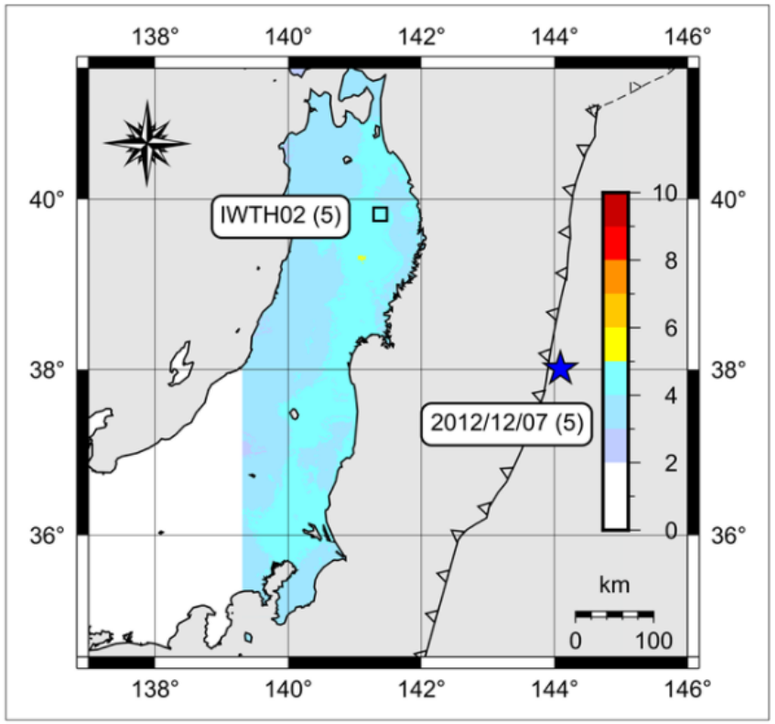
4.3 Teleseismic waveform modeling result.

5. Results

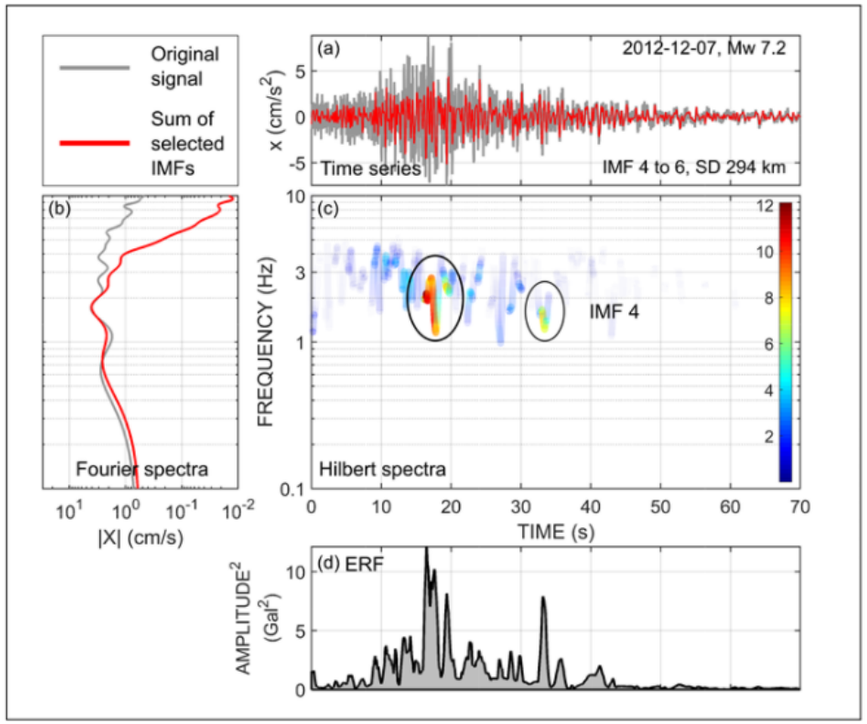
(Ye et al., 2013).

4. 19 July 2008 Fukushima-ken Oki Interplate Earthquake

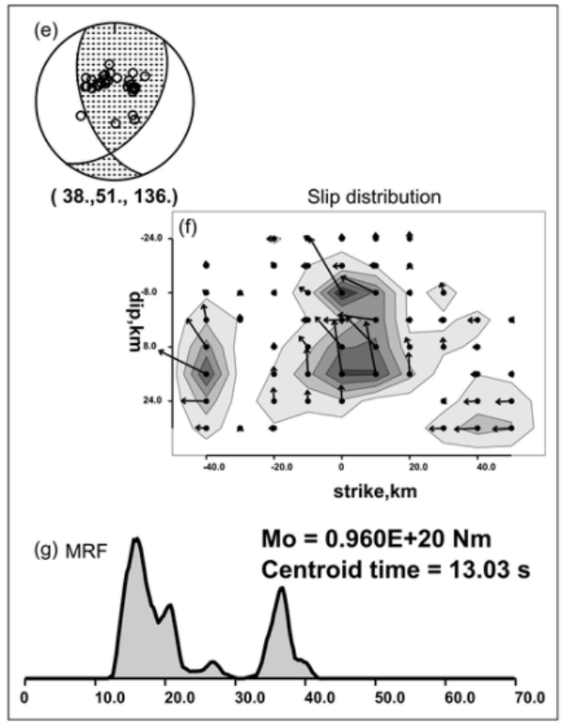
5. 07 December 2012 Kamaishi Intraplate Earthquake



5.1 Shakemap with epicenter (star) and station (square).



5.2 Strong motion analysis result.



5.3 Teleseismic waveform modeling result.

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REFERENCES

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6. Summary

1. HHT-based **ERF captures the earthquake source energy release**, with a **higher resolution** offered by HHT as compared to Fourier analysis methods and wavelet transform.
2. **ERF retains frequency information**, is computationally faster for a rapid interpretation of an event, and **does not entail assumptions** of the fault geometry and velocity structure. These are clear advantages over the traditional MRF.
3. **ERF captures complex ruptures** (2005 Miyagi-Oki event) and sub-events or multiple independent events (2012 Kamaishi event).
4. **Improvement** in the criterion for the **selection of stations** based on their **azimuth**, inferred from the slip distribution. Strike of the Japan Trench provides an important starting point. Further, stations with **seismic intensity** > 3 provide optimal results.
5. **Improvement in the selection of IMF(s)**, based on a **frequency and energy** criterion corresponding with the bandpass filtering in waveform inversion.

1. Key Points

1. Specific Intrinsic Mode Functions (IMFs) represent energy release at the earthquake source.
2. Energy Rate Functions (ERFs) generated from Hilbert spectral analysis of such IMF combinations.
3. Proposed ERFs match well with the Moment Rate Functions (MRFs) from teleseismic waveform modeling.
4. ERF-MRF match is controlled by the station azimuth and shaking intensity, and frequency and energy-based selection of IMFs.

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4. Methodology

2. Moment Rate Function (MRF) generated from waveform modeling to validate the ERF algorithm.

Selection of strong-motion stations

1. Slip distribution, along with the seismic intensity distribution maps (JMA, 1996; ShakeMap, 2017), used to select stations within the inferred azimuthal range and seismic intensity > 3.

Waveform Modeling
Strong motion station selection

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5. Results

1. 26 May 2003 Miyagi Intraslab Earthquake (Mw 7.0, depth 67.0 km)
   - Up-dip slip (towards east-northeast).
   - Station AKTH16, WNW (305.98° azimuth), seismic intensity (SI) 4.
   - Single, dominant, ~10 s energy pulse captured by both the ERF and MRF, along with a weaker tail.

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6. Summary

1. HHT-based **ERF captures the earthquake source energy release**, with a **higher resolution** offered by HHT as compared to Fourier analysis methods and wavelet transform.
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